PEDOGENESIS OF ANCIENT DUNE SOILS IN THE SOKOTO SEDIMENTARY BASIN, NORTHWESTERN NIGERIA

BY

BASHIRU ADEMOLA RAJI

B.SC (Ife), M.Sc (ABU), Diplomu (The Netherlands)

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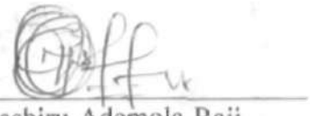
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The Department of Soil Science
Ahmadu Bello University
Zaria, Nigeria

1995

DECLARATION

I, hereby, declare that the contents of this thesis are products of my imagination, formulation and execution. 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 a higher degree at the Ahmadu Bello University or any other University.



Bashiru Ademola Raji

15-11-95

Date

Declaration confirmed by



Prof. I.E. Esu
Chairman, Supervisory Committee

15-11-95

Date

CERTIFICATION

This thesis entitled "Pedogenesis of Ancient Dune Soils in the Sokoto Sedimentary Basin, Northwestern Nigeria", by **Bashiru Ademola Raji**, meets the regulations governing the award of the degree of DOCTOR OF PHILOSOPHY of the Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

Prof. I.E. Esu
Chairman, Supervisory Committee
Dept. of Soil Science, Unical, Calabar

17-11-95
Date

Dr. V.O. Chude
Member, Supervisory Committee
Dept. of Soil Science, ABU, Zaria

17-11-95
Date

Prof. J.J. Owonubi
Member, Supervisory Committee
Dept. of Soil Science, ABU, Zaria

17/11/95
Date

Dr. V.O. Chude
Ag. Head, Dept. of Soil Science,
Ahmadu Bello University, Zaria

17-11-95
Date

26/7/96
Dean, Postgraduate School
Ahmadu Bello University, Zaria

26/7/96
Date

DEDICATION

This thesis is dedicated to my late mother, *Madam Wosilat Raji* (Nee Lawal) and my late Grandmother, *Princess Asunmawu Oyepe Raji* (Nee Ariwajoye), who died on the 16th May, 1994. May their gentle souls continue to rest in peace, Amen.

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ABSTRACT

The morphological, physical, chemical and mineralogical characteristics of ancient dune soils of the Sokoto sedimentary basin of northwestern Nigeria were studied with a view to elucidating their pedogenesis. The phosphorus forms and adsorption characteristics of the soils were also examined.

The results of the studies show that the dune soils presently are characterized by a Sudano-Sahelian climate bordering on semi-aridity towards the northern part, that is around lllela town. The dune soils have similar properties especially in the surface horizons but expectedly differ mainly in their physical properties since they are mainly Entisols.

The soils are mainly deep to very deep and have a colour with strong chroma, > 4 throughout their profiles. They are generally sandy except in the Sokoto dunes where sandy loam textures are encountered. Structurally, the surface horizons exhibit weak development and are, therefore susceptible to some amount of erosion hazard.

All the soils are characterized by high bulk densities, low total poaisities and high macroporosities of more than 30 percent. The soils therefore have very low water retention capacities.

Organic carbon contents are extremely low, being less than 2 g kg^{-1} in all the soils. The available phosphorus levels are low to moderate in Sangiwa and Sokoto dunes and moderate to very high in the lllela dunes.

Soil pH indicates an extremely acid to moderately alkaline soil reaction while the total exchangeable bases are very low, often less than 1.% cmol(+) kg^{-1}, in all the soils. Exchange acidity is also low and less than 2.0 cmol(+) kg^{-1} soil. The soils have very low CEC, which range from 1.0 to 4.6 cmol(+) kg^{-1} soil in all the pedons and low to moderate base saturation reflecting the rather siliceous nature of the parent material.

Electrical conductivity (EC), exchangeable sodium percent (ESP) and free carbonate values are all very low, with EC values of less than 0.24 dS m^{-1}, ESP of less than 4 percent and free carbonate contents of less than 10 g $CaC0_3$ Kg^{-1} soil in all the soils.

The values of DTPA cationic micronutrients, Cu, Zn, Mn and Fe are all well above the critical limits of 0.2, 0.8, 1.0 and 4.5 µg g^{-1} respectively. Phosphorus fractions and adsorption capacities are similar in all the dunes. The soils have a high total-P

content, ranging from 404 to 1881 µg g^{-1}, but the occluded forms account for proportionately higher percentages than the other forms of P. Adsorb-P followed by Al-P are the dominant extraclable inorganic-P forms. The soils have very low P sorption capacities which average about 100 mg kg^{-1} soil. The P-sorption capacities at standard P solution concentration of 0.3 mg/1 are low and average about 20 mg kg^{-1} soil. The soils also have very low bond energy.

The mineralogy of the soils are similar. Magnetite is the dominant magnetic mineral while quartz is the dominant non-magnetic mineral in the fine sand fractions. In the silt fractions, quartz is dominant followed by kaolinite in all the soils. Kaolinite is the dominant mineral in the clay fraction of all the soils.

Parent material, topo-drainage and paleoclimatology were presumed to have had the most profound effect on the dune soils. Organic matter mineralization, limited clay eluviation-illuviation, horizonation, textural and structural differentiation are the main significant pedogenic processes occurring in the soils but these processes are better expressed in the Sokoto dunes and in pedon LDS 2 of Illela dunes, thereby producing Bt horizons.

According to the criteria of the USDA Soil Taxonomy, all the soils on the Sangiwa and Mela dunes are classified as Ustic Quartzipsamments except pedon LDS 2 on Illela dunes which is classified as Arenic Haplustult. Soils on the Sokoto dunes are classified as Kanhaplic Haplustults except for pedons SDS 3 and 4 which are classified as Lithic Haplustult and Ustic Quartzipsamment respectively. In the FAO/UNFSCO soil map of the world legend, the soils on Sangiwa dunes are placed as Ferralic Arenosols while those on Sokoto dunes are placed as Haplic Alisols except for pedon SDS 4 which is placed as Ferralic Arenosol. Pedons LDS 1, 3 and 4 on the Mela dunes are all placed as Ferralic Arenosols, while pedons LDS 2 is placed as Haplic Acrisols.

Organic matter and related properties, exchangeable cationic bases, especially K. low water and nutrient holding capacities are the major constraints to productivity in all the soils. In addition, phosphorus is also a constraint to productivity in the Sangiwa dunes. Micronutrients are however, adequate for most crops.

TABLE OF CONTENTS

Title Page i
Declaration ii
Certification iii
Dedication iv
Acknowledgement v
Abstract vi
Table of Contents viii
List of Tables xi
List of Figures xii
List of Plates xiii

1. INTRODUCTION 1
2. LITERATURE REVIEW 4

2.1 Soil Forming factors in Arid Environment 4

2.1.1 General 4
2.1.2 Climate 4
2.1.3 Vegetation 5
2.1.4 Parent material 6
2.1.5 Relief 7
2.1.6 Time 8

2.2 Pedogenetic Processes in Arid Environments 9

2.2.1 General 9
2.2.2 Horizonation 10
2.2.3 Argilluviation 10
2.2.4 Calcification 11
2.2.5 Gypsification 13
2.2.6 Salinization 13
2.2.7 Sodication 13
2.2.8 Plinthization 14
2.2.9 Forms of phosphates 14

3. PHYSICAL SETTING OF STUDY AREA 16

3.1 Location 16
3.2 Climate 16
3.3 Vegetation 19
3.4 Geomorphology 21
3.5 Geology 22
3.6 Landuse 25

4. MATERIALS AND METHODS 26

4.1 Field Studies 26
4.2 Laboratory Studies 27

4.2.1 Sample preparation 27

4.2.2 Particle size distribution 27
4.2.3 Bulk density 27
4.2.4 Total porosity and macroporosity 27
4.2.5 Soil pH 28
4.2.6 Exchangeable bases 28
4.2.7 Cation Exchange Capacity 29
4.2.8 Exchangeable acidity 29
4.2.9 Effective CEC 29
4.2.10 Electrical conductivity (EC) 29
4.2.11 Exchangeable sodium percentage (ESP) 29
4.2.12 Base saturation (BS) 30
4.2.13 Carbonate equivalent 30
4.2.14 Organic carbon 30
4.2.15 Total and available phosphorus 30
4.2.16 Forms and adsorption of phosphorus 30
4.2.17 0.1M HCl extractable micronutrients 31
4.2.18 0.05M DTPA-TEA extractable micronutrients 31
4.2.19 Total micronutrients 31
4.2.20 Acid ammonium oxalate extractable Fe & Al 32
4.2.21 0.1M Sodium pyrophosphate extractable Fe & Al 32
4.2.22 CBD Extractable Fe & Al 32
4.2.23 Sand mineralogy 32
4.2.24 Silt mineralogy 33
4.2.25 Clay mineralogy 33
4.2.26 Phosphate adsorption 34
4.2.27 Data analysis 34
4.2.28 Soil classification 34

5. RESULT AND DISCUSSION 35

5.1 Soil morphology 35

5.1.1 Soil depth 35
5.1.2 Colour 35
5.1.3 Soil texture 36
5.1.4 Soil structure 46
5.1.5 Consistence 46
5.1.6 Horizonation 46
5.1.7 Miscellaneous 47

5.2 Physical Properties 48

5.2.1 Particle size distribution 48
5.2.2 Bulk density 54
5.2.3 Total porosity 57
5.2.4 Macroporosity 57

5.3 Chemical Properties 59

5.3.1 Soil pH 59
5.3.2 Organic matter 67
5.3.3 Available and total phosphorus 68

5.3.4 Forms of phosphorus 72
5.3.5 Adsorption of phosphorus 79
5.3.6 Exchange acidity 88
5.3.7 Exchangeable Bases 88
5.3.8 Cation exchange capacity 92
5.3.9 Base saturation 93

5.4 Salt Related Properties 94

5.4.1 Electrical conductivity (EC) 94
5.4.2 Exchangeable Sodium Percentage (ESP) 97
5.4.3 Free carbonate 97

5.5 Micronutrients levels in the soils 99

5.5.1 Available and total copper 99
5.5.2 Available and total zinc 104
5.5.3 Available and total manganese 106
5.5.4 Available and total iron 109

5.6 Mineralogy of the Soils 111

5.6.1 Free iron oxides 111
5.6.2 Active Fe and clay/fe_d ratios 117
5.6.3 Free aluminium oxides 118
5.6.4 Fine sand mineralogy 120
5.6.5 Silt mineralogy 122
5.6.6 Clay mineralogy 125

5.7 Soil Classification 128

5.7.1 Criteria for classification 128
5.7.2 Classification 130

6. SUMMARY AND CONCLUSIONS 134

REFERENCES 139
APPENDIX 152

LIST OF TABLES

Table 1	Climatic data of studied area	18
Table 2	Stratigraphic sequence of sediments in the Sokoto basin	24
Table 3	Morphology and classification of pedons	43
Table 4	Particle-size distribution of pedons	49
Table 5	Bulk density and porosity of pedons	55
Table 6	Mean values of physical properties	58
Table 7	Exchangeable bases, exchange acidity and pH of pedons	60
Table 8	Organic carbon, phosphorus, CEC and percent base saturation of pedons	63
Table 9a	Mean values of surface soil properties	70
Table 9b	Mean values of subsoil properties	71
Table 10	Phosphorus fractions of selected pedons	73
Table 11	Extractable inorganic forms as percentages of total extractable inorganic-P	74
Table 12	Total extractable inorganic-P, residual-P, and organic-P as percentages of Total-P	75
Table 13	Correlation matrix for phosphorus and selected soil properties	80
Table 14	Langmuir isotherms best fit equation for phosphate adsorption	85
Table 15	Phosphorus adsorption characteristics of the dune soils	86
Table 16	Electrical conductivity, exchangeable sodium percent (ESP) and free carbonate equivalent of pedons	95
Table 17	Micronutrient Cu, Zn, Mn and Fe levels of pedons	100
Table 18	Correlation matrix for micronutrients	107
Table 19	Correlation matrix for micronutrients and sesquioxides	110
Table 20	Extractable Fe/Al oxyhroxides	112
Table 21	Correlation matrix for sesquioxides	116
Table 22	Petrographic microscope data	121
Table 23	Summary of soil classification (USDA and FAO/UNESCO systems)..	132

LIST OF PLATES

Plate 1 Sokoto sand dune, 1.5 Km south of Gwadabawa village, overlying a petroferric layer (Petroferric cap) of the Kalambaina deposits. The topography is nearly flat and table-like 37

Plate 2 Pedon SDS 1, at Gidan Gara village, showing modal soil characteristics for the Sokoto dunes..... 38

Plate 3 Illela sand dune with a clear pronounced meso-relief at Tungantudo village..... 39

Plate 4 Pedon LDS 2, at Tundu Muala village, showing modal soil characteristics for the Illela dunes..... 40

Plate 5 Sangiwa sand dune with a moderate meso-relief and an undulating topography at Bijeje village..... 41

Plate 6 Pedon GDS 2, at Bijeje village, showing modal soil characteristics for the Sangiwa dunes..... 43

Plate 7 Calcium carbonate rings in the subsoil horizon of pedon LDS 3 of the Illela sand dunes, at Tungantudo village, indicative of incipient calcification in the soil..... 66

1. INTRODUCTION

Aeolian deposits refer to wind deposited sediments. These sediments occur widely in the arid environments, where aridity enables wind to effectively erode and transport sand and also silt and clay particles. The transported particles are deposited in various forms and shapes along topographic or vegetative barriers (Dregne, 1983). These wind deposits when dominated by sand particles are called sand dunes or sand drift (Bagnold, 1941). About one fifth of the world desert, about 9,771,600 Km^2, is covered with aeolian sand (Holmes, 1965). In Nigeria, aeolian deposits cover some 170,000 Km^2, out of which the Sokoto sedimentary basin make up about 70,000 km^2 (Jones, 1948) in the northwestern part of the country.

The composition of dune materials varies, although all dunes usually are called sand dunes. This is because quartz sand is the most common dune material although the white sand dunes of Southern New Mexico and Kopi dunes of South Australia are composed of nearly pure gypsum (Bettanary, 1962; Fuller, 1975). The sand dune at Sonora, the continuation of the Yuma dunes has a composition largely of shell fragments derived from recently elevated bottom marls. The sand dunes in the Sokoto sedimentary basin are dominantly quartz in composition (Sombroek and Zonneveld, 1971).

Soils developing on aeolian deposits exhibit the least degree of horizonation and total solum development (Steila, 1976). The soils have been reported to be mainly immature and skeletal (Don Nir, 1974; Choudhari, 1984). Texturally, sand dominate these soils. The percent clay and organic matter content are usually very low. The volume of pedogenetic soil is also very small. The soils are therefore inherently low in both native fertility and water holding capacity.

A common problem with soils developed in the arid zone is the tendency for them to accumulate salts within 2 metres of the soil profile (Buol, 1965; Carter and Inskeep, 1988). Very common is the accumulation of calcium carbonate and other more soluble

salts (Gile *et al.*, 1966; Schlesinger, 1985). These accumulations hinder root and water penetration into the soil and when they occur on the surface, cause water logged condition (Richard, 1954). The salts also prevent or delay the germination of seedlings (Dhankar *et al.*, 1980). Many arable lands under irrigation have been rendered unproductive as a result of salt accumulation (Jewitt, 1966).

Another problem, likely to be inherited from a past more humid climate but prevalent in the soils of the arid regions, is the occurrence of petroplinthites (Sivarajasingham *et al.*, 1962; FAO, 1969). Although petroplinthite is not surficial initially, it may be exposed to the surface through erosion. It`s appearance makes the land quite unusable for agriculture (Sivarajasingham *et al.*, 1962).

Despite the problems posed to agriculture by sand dune soils, the soils developed in the ancient sand dune of the Sokoto basin have not been characterized in detail. Past research work has concentrated on the Fadama (alluvial soils) bordering the few major rivers. Aside from the soil and water resources survey work of FAO (1969) which covered the entire basin, there has been only few other works (Ogunwale, 1973; Agbu, 1982; Ojuola, 1985; Odunze, 1987; Esu *et al.*, 1991) covering parts of the basin. Indeed, none of the work done pays enough attention to the stabilized ancient dune soils of the basin, even though they constitute well over 70 percent of the pedosphere. The dunes are currently extensively used for crop production and livestock grazing. To prevent a likely deterioration of these fragile soils, detailed and intensive pedological characterization is necessary and urgent. The result of the study will enable the utilization of the soils to be carried out scientifically and on a sustainable basis.

Phosphorus deficiency has been found to be widespread (Olsen and Engestad, 1972; Udo and Ogunwale, 1977) in the humid tropics. The low availability has been attributed to the highly weathered nature, high contents of oxides of Fe and Al and the low organic matter content of the soils (Adepetu, 1976; Enweazo and Moore, 1966;

Weaver *et al.*, 1975). In the Sokoto basin under study, Jones (1948) and Kogbe (1979), have reported the occurrence of irregular shaped phosphatic nodules in the Sokoto group of rocks. These nodules could serve as a source of phosphorus in the soils of the basin. Phosphorus is as important as nitrogen in importance in plant nutrition and because of this a whole section would be devoted to forms, adsorption and desorption studies of phosphorus. The availability of phosphorus to plants is influenced by the P-Sorption capacity and transformation of added phosphorus. For a better understanding of P-transformation in soils and the estimation of P-requirements for crops, information on the forms, adsorption and desorption characteristics of the soils is required.

The objectives of this study were therefore:-

(a) To pedologically characterize soils developed on aeolian parent materials in the Sokoto Basin. This has been done by using the physiographic and lithologic map of Sombroek and Zonneveld (1971) as a base map (1: 250,000).

(b) To classify the soils using the USDA Soil Taxonomy system (Soil Survey Staff, 1975, 1990) and also the FAO/UNESCO Soil Map of the World legend (FAO/UNESCO, 1974, 1985).

(c) To investigate the phosphorus forms and adsorption characteristics of the soils.

(d) To highlight the constraints to productivity and the most appropriate management practices for the soils.

2. LITERATURE REVIEW

2.1 Soil Forming Factors in Arid Environments

2.1.1 General

Simonson (1959) proposed that soil genesis be considered as two overlapping steps, namely, the accumulation of parent materials, and the differentiation of horizons in the profile. To understand the distinctiveness of pedogenesis of arid soils, we first isolate the factors which control their formation, and then examine the processes within the profile that lead to their distinctive features. In doing this, we use two models: Jenny`s (1941, 1980) view of the factors of soil formation and Simonson`s (1959) generalization of soil-profile processes. Soil characteristics can be seen as functions of several factors, principally climate, vegetation, parent material, relief, and time (Jenny, 1941). Climatic influences and parent material are, of course, the primary contributors to the distinctiveness of arid zone soils. The impact of all other soil forming factors are reduced by aridity especially the influence on soil formation of vegetation, topography and time (Armitage, 1985; Steila, 1987).

Of the soil environmental factors (Jenny, 1945, 1980) that contribute to the formation of soils, the influences of parent material, topo-drainage and climate, both past and present, have had the most profound effects on the morphological, physical, chemical and mineralogical properties of the soils in the area studied.

2.1.2. Climate

Climatic variability is an important characteristic of arid regions. Soils especially are a reflection of the less than average precipitation that falls in majority of the years rather than of the mean annual precipitation (Steila, 1987). The pedogenetic power of the present arid climate being slight, the characteristics inherited from earlier climates are

more likely to persist. The present climate is hardly able to obliterate these characteristics, except in the case of certain features of the distribution and quantity of organic matter, and to a lesser degree, certain types of structure (Wild, 1958; Syers *et al.*, 1970). Arid climate is unfavourable to intense chemical weathering. Water, which is the principal reactant in hydrolysis, the most important of the transformation processes, and the solvent in the leaching process (Barshad, 1962; Keller, 1962) is limited in most of the arid regions. In effect, the leaching and recrystallization at depth of soluble salts, and the eluviation and illuviation of clay particles, ions and organic matter are hindered within the soil profile (Van der Merwe and Heystek, 1955; Scott, 1962). Mechanical or physical weathering is dominant in arid regions. The result is the development of young and immature skeletal soils (Moss, 1968; Don Nir, 1974).

The present climate of the Sokoto sedimentary basin is that of the sudano-sahelian savanna bordering on semi-aridity in the extreme north, close to Illela. There has been climatic fluctuation in the past, between wetter and drier periods, similar to those experienced in central Europe (Sombroek and Zonneveld, 1971). Thus, any soil property could either had been formed by the present climate or inherited from the past. The soils are therefore, likely to be polygenetic in origin. This further make difficult, the arduous task of unravelling the genesis of the soils.

2.1.3. Vegetation

Arid zone vegetation has low biomass, low productivity and consist of mainly annual species (Cody, 1989). In the hotter and drier parts, biomass is often zero. Arid zone vegetation therefore, contributes very little to organic weathering, which is considered necessary in turning "geologic soil" (parent material) into a biologic soil. Cumulization is also expected to be low. However, the root system of most plants in the arid zone is well developed (Cloudsley-Thompson and Chadwick, 1965), and a high

portion of the added organic matter is consequently added to the subsoil.

Arid zone vegetation, which in places contains a high proportion of leguminous plants, algae and sometimes lichens, accumulates nitrogen more than humid vegetation as a response to the harsh environment (Rodin and Bazilevich, 1965; Whitake *et al.*, 1968). This imparts a relatively low C/N ratios to most arid zone soils (Jenny, 1929; Fuller *et al.*, 1960). In some situations, notably with halophytic vegetation, the litter may be rich in salts and so contribute to surface soil salinity (Rodin and Bazilevich, 1965). In general, the number and diversity of fauna: bacteria, fungi, and insects are small (Sullivan, 1989) and are therefore expected to play a smaller role in desert soils than elsewhere. The genetic diversity however, increases for species approaching the desert with decreasing annual rainfall and an increase in rainfall variation (Nevo and Beiles, 1989). It has been established that the 200 mm isohyet is the border line beyond which decreasing annual rainfall and increasing rainfall variation become unimportant (Cooke and Warren, 1973).

2.1.4. Parent material

The soil cover in the arid zone originates from a great variety of parent materials as do occur in other climatic regimes. There are, however, distinctive arid zone substrates. In the arid regions, the rate of wind erosion usually exceeds the rate of weathering and the surface has only a thin, coarse, weathered mantle. In most cases, young and transported sediments are the most important soil parent materials. Many arid zone soils are developed on alluvial surfaces composed of coarse cobbles, boulders and sands (Jewitt, 1966; Ruhe, 1956) and the saline and alkali soils of most arid zones are found on the alluvium of large floodplains where sediments are usually fine-grained and deep (Grove, 1958; Esu, 1989b). It is generally agreed that under conditions of very advanced weathering, similar soils may develop on a range of parent materials but even then, contrasting rocks such as sandstone and carbonates will produce different soils (Jewitt, 1966). Where the soil forming processes have not gone on for a very long time, the nature

of the parent material influences the kind of soil formed.

In the arid zone, many of the parent materials are alluvial deposits which receive large additions of transported and partly weathered materials in formation (Litaov, 1987). The soils therefore do not show marked effects of soil forming processes as a result of the youthfulness of the parent materials. Under low rainfall and high temperature, leaching is hindered and irrespective of the parent material, subsurface formation of salts: calcic, salic, and natric horizons are common and their depth of occurrence will depend on the amount of rainfall.

The parent materials for the soils studied are the sandy aeolian materials derived locally from the thoroughly weathered Gundumi sandstone. The Gundumi sandstone was essentially the erosional products of basement complex rocks, and the presence of secondary minerals, such as iron, aluminum and manganese oxides in the parent material (FAO, 1969) signify an advanced stage of weathering. The three dunes types identified within the studied area have a common origin (FAO, 1969). Sangiwa dunes, the oldest, were formed through saltation of the weathered products of the Gundumi sandstone about 200,000 years ago (Sombroek and Zonneveld, 1971). The Sangiwa dunes were reworked and redeposited about 50,000 years ago, into what is now known as the Sokoto dunes. Illela dunes, the youngest of the three dunes, were formed through saltation of the Sokoto dunes, following another period of aridity about 5,000 years ago. The last phase of aeolian reworking and redeposition occurred in about 5,000 years and therefore gives a maximum possible time of weathering and soil development of 5,000 years on the Sokoto and Illela dunes and probably much longer period (about 50,000 years) on the Sangiwa dunes, if not affected by the last phase of aeolian reworking.

2.1.5 Relief

The contrasts between soils on different parts of a slope are often more pronounced in arid areas than in humid ones, because of three principal factors. Firstly,

the erosion/weathering balance at certain slope angles either favours stable soil development or hinders it. Secondly, the groundwater table, dictated by slope through capillary rise develops saline or alkaline soils, distinctive of arid areas. Thirdly, lateral surface water flow, depending on the slope angle, removes weathering products to lower slope areas hence promoting the formation of skeletal soils upslope and deposits downslope.

Topography as a soil forming factor, has an indirect effect on soil properties, through its influence on the effective rainfall and drainage condition (Daniels and Gamble, 1967). The Illela dunes still exhibit a pronounced meso-relief while the Sokoto dunes, in the main part, have acquired planar configuration. The Sangiwa dunes, even though have been denuded seriously, still exhibit a moderate meso-relief. The effective rainfall would therefore be greatest on the Sokoto followed by Sangiwa and finally the Illela dunes.

2.1.6 Time

The effect of the time factor is difficult to appraise because of the near dominance over all other processes by the low and variable rainfall (Dan *et al.*, 1982). It suffices to say that most pedogenetic processes depend strongly on time. This is especially true in the arid environment (Ahmad *et al.*, 1977). In some cases, several hundreds of thousands of years are required for completion of a process. It is, however, difficult to assign precise age to most of the processes because that depends on the rate of the process which is dependent on environmental factors.

A few studies of soils in the arid climates have suggested that these soils tend to form at constant rates, modeled by a linear time function (Muhs, 1982; Reheis *et al.*, 1989). Constant rates of soil formation are most logically attributed to incremental additions of materials, either by incorporation of aeolian dust in near surface horizons or by translocation of constituents, derived from dust or from weathering products that formed in near surface horizons and that accumulate lower in the profile (Bockheim, 1980).

2.2 Pedogenetic Processes in Arid Environment

2.2.1 General

In considering pedogenetic processes and conditions, two overlapping trends in soil development have been recognised (Jenny, 1961). These are horizonation and haploidization. Horizonation includes the proanisotropic processes and conditions by which initial materials are differentiated into soil profiles with many horizons. Haploidization includes proisotropic processes and conditions by which horizonation is inhibited. Horizonation can be seen as functions of several processes, principally additions, removals, transformations and translocations (Simonson, 1959). These pedogenetic processes are similar to those in other environment but progress at a much slower rate and there are also differences in the relative importance of the various reactions. Additions both to the surface and subsurface become the major pedogenetic action, while the influences of removal, transformation and translocation are greatly reduced by aridity. Since soil horizons, particularly subsurface ones, are usually more persistent features of soils, they are particularly likely to survive changes in the soil environment, and to persist, say, from a wetter past into a drier present. This makes the discussion of profile development under arid conditions complicated, in that, much of the evidences can be given paleoclimatic or paleopedogenetic interpretation. There are, however, distinctive soil forming processes producing soils peculiar to the arid regions. Of particular importance in the arid environment are the processes of calcification, salinization, sodication, ferrugination, mineralization of organic matter, and smectification (Steila, 1976; Hooke, 1967).

2.2.2 Horizonation

Of all the regionally distributed soils, arid soils exhibit the least depth of horizon and total solum development (Choudhari, 1984; Steila, 1987). This has earlier been attributed to the youthfulness of the parent materials and the slow rate of both the chemical and biological weathering. The general, pedogenetic processes of addition, removal, transformation and translocation are reduced to their barest minimum. Horizonation therefore, proceed at a very slow rate. The profile development of many arid soils may be partly the product of past climates that were characterized by higher and more uniform rainfall (Gile and Hawley, 1969).

Where the water regime allows it, the surface horizons are leached of materials, both weatherable and chemically unstable additions (Smith and Buol, 1968). In most locations, however, because of moisture shortage for downward leaching, the surface horizons become enriched in materials through capillary actions. Such surface horizons are characterized by the occurrence of sodium as cation and anions such as chloride, sulphate, bicarbonate and carbonate (Makin *et al.*, 1969).

The products of weathering in the surface horizon, as well as chemically unstable additions to the soil surface, are translocated downward to illuvial horizons where many of them are immobilized. Indeed, little material passes beyond the depth to which percolating rainwater normally penetrates (Arkley, 1963; Yaalon, 1965). The principal subsurface horizons representative of the arid region soils are calcic, gypsic, salic, natric horizons and their indurated derivatives (Buol, 1965; Gile, 1966).

2.2.3 Argilluviation

The formation of argillic horizons in arid climates has been a controversial subject for many years and probably will remain so for sometime. The question is whether an argillic horizon as defined by the USDA Soil Taxonomy (1975) can develop under an arid

climate. Early views (Nikiforoff, 1937; Barshad, 1955; Oertel, 1968) were in agreement that because of the low rainfall, poor plant growth, youthful and arenaceous parent materials and a high base saturation, induced flocculation will hinder clay mobilization. The occurrence of clay in the subsurface horizon was attributed mainly to "in situ" weathering of materials in a wetter sandy subsoil. More recently, Smith and Buol (1968), and Nettleton *et al.* (1975) have found evidence that clay illuviation in subsoils does occur in the arid regions. Buol and Hole (1961) have shown that clay skins and orientated clay, taken as an indication of clay illuviation, could very easily be disturbed by pedoturbation in soils. Repeated drying and wetting, and shrinkage and swelling of vertic soils would probably easily destroy clay orientations (Buol and Yesiksoy, 1964).

The presence of an argillic horizon is indicative of old age and high intensity of weathering, contrary to present day pedogenesis of arid environments. A paleopedogenetic origin has therefore been advanced for the more distinctive argillic horizons found in arid environments (Brewer, 1956; Gile, 1967, 1968). The argillic horizons, they reasoned could be relict of an earlier more humid climate.

2.2.4 Calcification

Horizons with orthogenic carbonate are common in soils of arid regions and are in many of these soils the most prominent horizon (Gile, 1966). Various terms have been used in the literature to refer to this carbonate-rich horizon. It is widely called calcic horizon, caliche in the United States, carbonate crust, calcrete or croute calcaire (Gile, 1961; Stuart and Dixon, 1973; Dregne, 1976). The carbonate accumulation, designated as k is normally found in the C-horizon, but it may encroach into the B-horizon under intensely arid conditions. Various forms of occurrence have been discerned. Broadly, there are those distributed throughout the horizon and those segregated within. Gile (1961) distinguished macroscopic forms such as nodular, cylindrical, concretionary, flaky and massive, bedded, blocky for the segregated and uniformly distributed carbonate

accumulations, respectively. Jenny (1980) examined the relationship between rainfall intensity and the depth of carbonate accumulation. They found that k-horizon becomes thicker and more diffuse, and occurs lower in the profile as rainfall becomes intense. Buursink (1971) working in Sudan, reported that k-horizon develops in soils with annual rainfall less than 750 mm. From other arid environments, carbonate accumulations have been reported for areas experiencing between 250-600 mm of annual rainfall (Machette, 1985; Gile *et al.*, 1965).

The source of carbonate and the mode of development have been matters of controversy. Most workers agree that k-horizon are formed by the downward eluviation and immobilization of carbonates in an essentially pedological process (Staurt *et al.*, 1961; Gile *et al.*, 1966; Ahuja and Khanna, 1984). This view is supported by the fact that k-horizon appear to be associated with semi-arid areas than with arid regions, and also by the near constant depth of occurrence in soil profile. The chief alternative to this downward eluviation hypothesis is the deposition of carbonate from the water table by evaporation. Cooke and Warren (1973) reported that this hypothesis has indeed been used with some success by Coque in Tunisia and Ruhe in New Mexico to explain the occurrence of carbonate horizons in those areas.

A more serious issue of contention is that of the source of the carbonate. Five possible sources are: (i) the parent material of the soil; (ii) deposition from the atmosphere in form of dusts; (iii) upward movement of dissolved carbonate from a water table; (iv) mineralization of plant residues; and (v) deposition of carbonate from run-off or irrigation water. World wide, calcareous parent material and carbonate rich dust appear to be the major sources of soil carbonates (Schlesinger, 1985). Schlesinger (1982) reported that whatever the parent material might be, in the arid region, carbonate is usually found somewhere in the profile, often but not always in a visible horizon of accumulation. The occurrence of k-horizon on non-calcareous parent material has been attributed by Junge and Werby (1958) in Southern New Mexico to the yearly downward movement of about

3 mg/l of carbonate from carbonate rich dusts. Carbonate rich dusts have been reported extensively in the literature (Jessup, 1960; Burns, 1980; Litaor, 1987; Moberg *et al.*, 1991). It is therefore, not surprising that carbonate accumulation is a common feature of most arid environment.

2.2.5 Gypsification

Gypsum accumulation is another important feature of the arid regions. Gypsum accumulates at greater depth and in drier areas than calcium carbonate (Parker *et al.*, 1987; Carter and Inskeep, 1988). Gypsum is also more restricted in its occurrence in toposequences, being confined to low areas because it is readily soluble in well drained upland soils (Reheis, 1987). Gypsiferous parent materials, airborne calcium sulphate, and run-off water from gypsum bearing rocks are the principal sources of soil gypsum (Carter and Inskeep, 1988). Extensive gypsic horizons have been reported from northern Iraq, Arabia,and North Africa (Smith and Robertson, 1962; Glennie and Evamy, 1968) and in many other arid zone soils.

2.2.6 Salinization

Salic horizons, as defined by the USDA Soil Taxonomy (1975),must contain secondary enrichment of salts more soluble than gypsum. The common soluble salts are chlorides and nitrates. Soil parent materials, airborne salts, runoff water, groundwater and plant residues are the common sources for these soluble salts (Dewon and Famouri, 1964; Munn and Boehm, 1983). Owing to their high solubility, salic horizons are found only under poor drainage condition or in extremely arid environments and in upland soils if the parent material is saline (Dan *et al.*, 1982).

2.2.7 Sodication

Natric horizon is an argillic horizon with an ESP of 15 or SAR value of 13 or more (Richard, 1954).Many soils in the arid regions have horizons with an ESP of more

than 15, especially vertisols, but they do not have natric horizons. For a natric horizon to form, there must be a source of sodium salts, leaching of excess salts, and an induced clay dispersion which will provide for clay eluviation. Classical theory of the genesis of solonetzic complex requires the presence of a water table, either permanent or ephemeral, close enough to the soil surface to be affected by evapotranspiration, with a consequent upward convective movement of sodium.

An alternative theory does not consider the presence of water table. It involves lateral subsurface movement of salty, silica-rich water into the subsoils of a depression from the surrounding soils. This water movement occurs due to a matric and osmotic potential gradient resulting from reduced infiltration into the depression and increases steadily as the surrounding becomes more clay-rich and saltier (Schlichting and Schweikle, 1980; Munn and Boehm, 1983).

On a global scale, natric horizons are commonest in depressions in the drier parts of the arid region and in both depressions and upland positions in the semi-arid regions (Dregne, 1976).

2.2.8 Plinthization

The formation of plinthite is favoured by the abundance of ferromagnesian minerals and a strong wet and dry seasons (Sivarajasingham *et al.*, 1962). It is therefore expected to be uncommon in the arid region having sandy parent materials. Their occurrence in this environment has therefore been attributed to a more humid climate in the past or a paleoclimatic origin.

2.2.9 Forms of phosphates

The nature of inorganic and organic phosphates are useful indicators both for fertility and genetic studies. However, the nature of the inorganic phosphate is difficult to determine directly (Larsen, 1967). Chemical methods of extraction, often employed,

may be of doubtful value since they can cause redistribution of soil compounds during extraction (Rhodes, 1977). Despite this problem, several workers have made use of the Chang and Jackson (1957) or a modification of their method (Petterson and Corey, 1966) to obtain some indication of the nature of phosphate compounds (Enwezor, 1977; Udo, 1981). The quantity and forms of phosphates provide an index of the relative degree of pedogenetic weathering. This is because, parent materials have been discovered to be the only source of phosphorus in soils, apart from the minimal amounts in rainwater (Smeck, 1973). Furthermore, phosphorus is considered to be essentially immobile in soils but is subjected to redistribution in soils during the long period of soil profile development. In unweathered parent material, phosphorus is generally present as the less resistant forms - Ca-P and Al-P (Chang and Jackson, 1958), at soil pH around 7. However, as the soil pH decreases with increasing pedogenetic weathering, the solubility of phosphorus also decreases and the P is convected into the insoluble Fe-P forms.

3. PHYSICAL SETTING OF STUDY AREA

3.1 Location

The area studied covers the aeolian deposits of the Sokoto Basin in the northwestern tip of the Federal Republic of Nigeria or the present day Sokoto and Kebbi states. The Sokoto Basin is the south eastern portion of the Iullemenden Basin which occurs in Nigeria (Jones, 1948). The Sokoto Basin covers an area of about 70,000 square kilometres and lies between longitude 3° 50` to 6° 50`E and latitude 10° 20` to 13° 45`N (Figure 1). The aeolian deposits spread all over the basin, constitute over 70 percent of the total land area of the basin. Their boundary in most part is marked by a distinct dune meso - relief except when found on plinthite caps.

3.2 Climate

The present day climate of the Sokoto Basin is hot sudan savanna bordering on semi-arid conditions of the Sahel savanna zone towards the north. The climate is determined by the movement of the intertropical convergence belt (FAO, 1969). The northern air masses, locally called harmattan, with cool, dry, often dust loaded winds from the NE direction, prevail from November till April. The southern air masses,the West African monsoon, with humid winds from the SW direction, prevails from April till October.

The wet season is characterized by frequent and torrential rains of relatively short duration. The rainy season lasts about three and half months at its northern border and about five months in the southern part (Table 1). The mean annual rainfall therefore decreases gradually from south to north (1090 mm at Funtua, 710 mm at Sokoto and 600 mm at Illela).

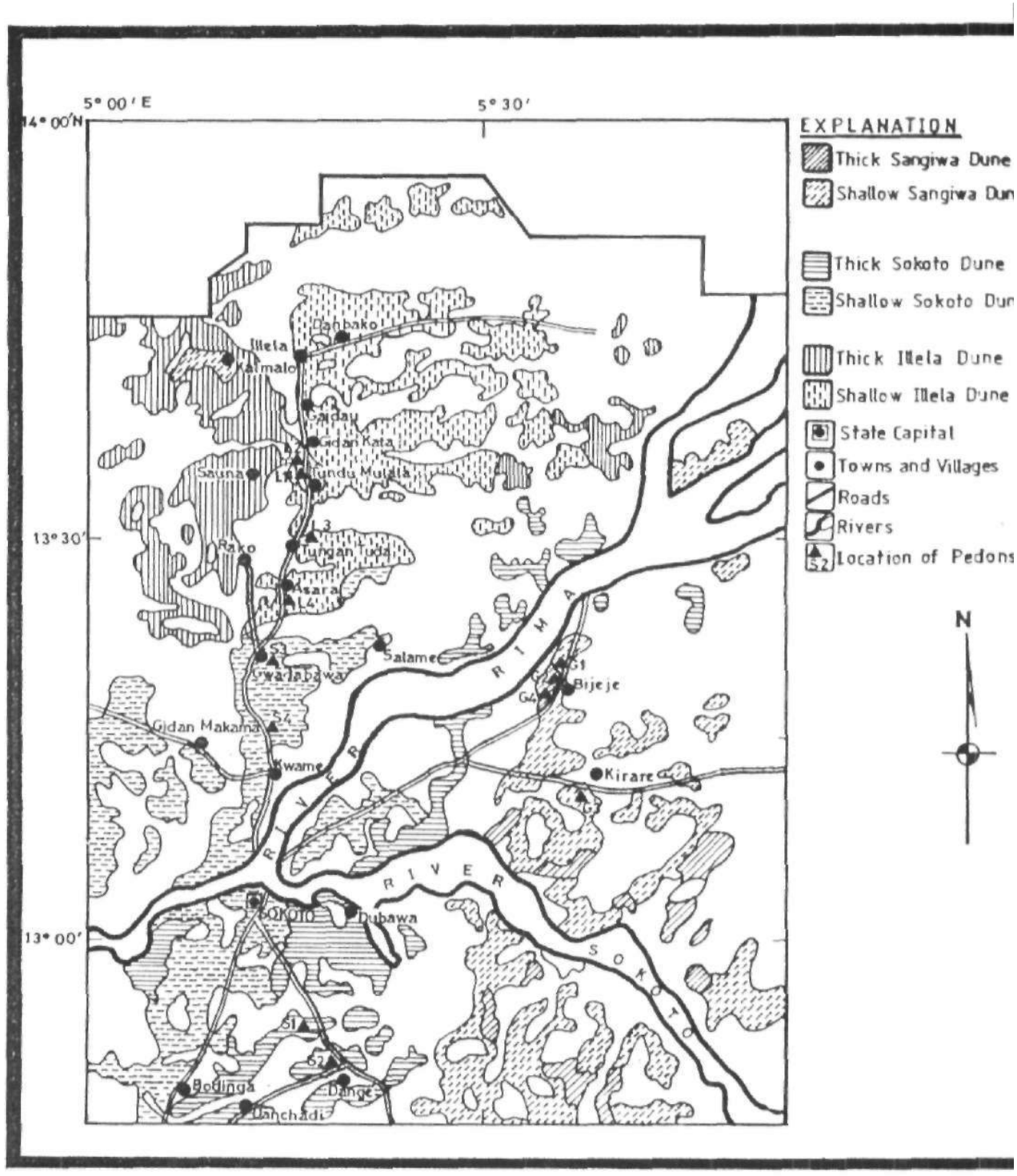


Fig. 1. Distribution of aeolian deposits in part of the Sokoto Basin and the location of the pedons studied.

Table 1. Climatic Data of the Study Area

Site	Old Airport
Location	13° 01' N ; 05° 15' E
Height above mean sea level	345m
Mean annual rainfall 25 years (1951 - 75)	669 mm
Number of rainy days (1951 - 71)	120

Months	Mean monthly rainfall (mm)	Mean monthly daily average temperature (°C)	Relative humidity (%)
January	0	23.7	17.4
February	0	27.3	12.0
March	1	30.1	17.0
April	9.75	32.6	29.4
May	39.75	32.4	41.5
June	87.50	29.3	54.4
July	174.75	27.4	66.9
August	219.75	25.9	70.7
September	117.50	27.1	67.5
October	19.50	28.4	59.9
November	0	26.1	27.8
December	0	24.7	21.9

Source: Meteorological Station, Institute for Agricultural Research, Ahmadu Bello University, Zaria.

The temperature, unlike the rainfall, remains relatively uniform throughout the year, except for the difference between day and night. The monthly maximum temperature are lowest in December and January (13°C) during which time a dust-carrying Harmattan desert wind blows from the north-east (Sombroek and Zonneveld,1971). The maxima are highest in April (38°C), just before the advance of the rain front from the south. Relative humidity increases gradually towards the south according to the longer lasting influence of the monsoon. The monthly relative humidity is over 70 % in August, and only 12 to 17 % January and February.

The question of climatic change has been investigated in the past. In 1935, Stebbing was the first to postulate the idea that the climate of the area immediately south of the Sahara was becoming drier and desert conditions were spreading southward (Kogbe, 1979). Jones (1948) and a Forestry Commission set up jointly by the French and British Governments in 1937 to investigate this problem did not find any evidence to support a change in the climate. What is being observed from hydrological data indicate a gradual change towards less dry conditions than in the past centuries (FAO, 1969). Jensen (1990), however, observed that there has been a gradual but consistent decrease in the rainfall with major decline every ten years.

3.3 Vegetation

Under natural conditions, as in the forest reserves, the vegetation of the Sokoto Basin is largely that of the typical Sudan savanna, which contains savanna woodland on the better soils and tree and shrubs savanna on the poorer soils (Clayton, 1960). The vegetation merges into the Sahel vegetation in the extreme northern part, consisting of shrubby and thorny vegetation. In the extreme south-west, there exists a relatively dense wooded vegetation belonging to the Guinea savanna. As a result of continuous cultivation, the original vegetation is now restricted to the poorest soils and far away from permanent sources of water (Sombroek and Zonneveld, 1971). De Leeuw (1966) and FAO (1969)

have classified the vegetation into nine units based on formation and the botanical composition:

(a) Woodland: characterized by a more or less closed canopy of medium-sized trees 10 to 15m in height. This unit is dominated by *Parkia clappertonia. Anogeissus leiocarpus, Loudetia togoensis.*

(b) Savanna woodland: characterized by an open stand of medium-sized trees 8 to 10m with open patches of grass vegetation. *Guiera senegalensis. Acacia nilotica, Combretum glutinosum* are the dominant trees.

(c) Tree savannas: are rather open units of vegetation, with low shrubs or grasses and regularly distributed, single, medium-sized trees. *Combretum nigricans, Acacia ataxacantha, Loudetia togoensis* are the dominant trees and grasses.

(d) Shrub savannas: consist only of shrubs at various densities. Under prolonged cultivation, most of the original vegetation has been transformed into shrub savanna. The dominant shrub are *Combretum micrantlum. Piliostigma reticulata.*

(e) Farm (park) land: is characterized by scattered trees. The most dense tree cover is found in the southern areas (FAO,1969). *Acacia albida. Parkia clappertonia, Isoberlinia* species are the common plant species.

(f) Riparian forest or woodland: is a complex mixture of trees and shrubs occupying floodplains and on Solonetz. Most common trees are *Borassus. Flabellifer, Mitragyng inermis. Pennisetum pedicellatum. Vetiveria nigritans.*

(g) Semi aquatic non-tree vegetation of grasses, herbs and some shrubs occurs on regularly flooded but not permanently waterlogged soils. Dense stands of wild rice, *Seripus* and *Cyperus* spp with some domestic rice varieties.

(h) Aquatic vegetation: on constantly wet or flooded soils of limited extent. Dominant species are *Lymnophitic spp, Seripus and Cyperus spp.*

The ancient sand dune soils are in most cases characterized by reminant of the original vegetation such as *Guiera senegalensis, Ipomoea asarifolia, Acacia* spp.

3.4 Geomorphology

The relief of the basin as a whole is virtually flat, but with a very gentle regional dip, less than 2° in places, towards the northwest. The landscape to a large degree is determined by the lithological differences among the rocks and the widespread occurrence of lateritic ironstone forming resistant capping on weaker rocks (Grove, 1958; Grove and Warren, 1968). Steep-sided, flat-topped hills and denuded convex-saucer shaped dunes interrupt the flat plains of the Sokoto Basin.

The most prominent of the steep-sided, flat-topped hills is the "Dange Scarpe" which is currently undergoing intensive erosion. As a result of this, numerous outliers and remnants of the "Dange scarpe" occur as tabular hills or hummocks over the Palaeocene strata. The relief intensity is often high in the southern part of the basin. The altitude varies from about 250m near the mouth of the Rima river to about 600m at the upper reaches of the south-eastern tributaries.

The meso-relief of the different dune types varies. The Illela ancient dune has the most pronounced meso relief. It consists of groups of elliptic dunes, which are 400-500 m long. (E-W), 300-400 m wide (N-S) and 10-30 m high (Sombroek and Zonneveld, 1971). The grouping results in a fortress dune type. The inherent meso-relief of the Sokoto ancient dune is only preserved in the extreme west-northwest of the basin. It consists of longitudinal dunes (Seifs), 500-5000 m long, 200-1000 m wide and 5-20 m high in a east-northeast - west-southwest direction. In other locations, the Sokoto ancient dune has been denuded to flat or nearly flat plains. The original dune relief of the Sangiwa ancient sand dune has been flattened through denudation and erosion in most part except in the extreme North (above the 13° 30' N parallel) where the inherent meso-relief is still preserved. It consists of transversal parabolic dunes with a height of about 10 m or less.

3.5 Geology

In the Sokoto Basin, sedimentation started with Cretaceous sediments, in a synclinal basin, unconformably over the Pre-Cambrian Basement rocks. The rocks are mainly Cretaceous and Tertiary sediments (Falconer, 1911; Jones, 1948). The deposits show a slight dip of about 3.5m per kilometre to the north-northwest. Sedimentation in the Sokoto Basin can be phased into three:-

(a) Pre-Maastrichtian deposits of mainly continental sediments.

(b) Maastrichtian and Palaeocene deposits consisting mainly of brackish and marine sediments.

(c) Tertiary deposits of mainly continental sediments.

(d) Quaternary deposits of sand drifts.

The Pre-Cambrian Basement Complex is overlain uncomformably by the Pre-Maastrichtian Illo and Gundumi Formations made up of grit and clays which make up what is known as the "Continental Intercalaire". The thickness of Gundumi/Illo Formation is about 350m (Kogbe, 1979). The Pre-Maastrichtian deposits are overlain by the Maastrichtian deposits made up of Wurno, Dukamaje and Taloka Formations which make up the Rima group. The Rima group consist of mudstone and friable sandstone. The Maastrichtian deposits are in turn overlain by Palaeocene deposits of Gamba, Kalambaina and Dange formation which make up the Sokoto group. They consist essentially of shale and some thin bands of limestones. The Sokoto group of deposits have been reported to contain phosphatic gypsum especially near the villages of Wurno and Gada (Jones, 1948; Kogbe, 1979). The next phase of sedimentation resulted in the deposition of Tertiary sediments unconformably over the Palaeocene deposits. These deposits are continental and are better known as the `continental terminal' while the lateral equivalent in French West Africa is known as `Cres du Niger' (Kogbe, 1979).

Finally,after the series of sedimentation, the whole basin was covered in Quaternary deposits of sand drifts. Five aeolian deposits and fourteen aqueous ones have been recognised within the basin (FAO, 1969; Sombroek and Zonneveld, 1971). Of these, only three of the aeolian deposits, covering over 90 % of the surface area, have been identified within the Sokoto sedimentary basin. The other two are restricted to the Basement Complex. Table 2 shows the stratigraphic sequence of sediments in the Sokoto Basin.

The aeolian deposits include:-

(a) The Sangiwa coversand deposits which are concentrated in the central north-eastern part of the area (Isa, Lamba-Tureta) and in the north-western part (Argungu). The deposits occur uniformly over wide stretches of most of the flattened parts of the areas with either Cretaceous Gundumi or Tertiary Gwandu deposits. The present thickness ranges from 1 to 10 metres.

(b) The Sokoto coversand deposits are found in the north-west central part of the basin. Marked concentrations occur around Sokoto and Tambawal towns. The deposits occur over wide stretches in the area of the Tertiary Kalambaina-Dange deposits. They are scattered in the area of the Tertiary upper Gwandu formation, and occur very locally in the area of the Cretaceous Rima and Gundumi formations. The present day thickness varies between 5 and 40 metres near scarps, and between 0.5 and 5 metres on plains and flat structural plateau parts.

(c) The Illela coversand deposits are found in a small area north of Sokoto town, and at Illela and Raka. The deposits occur as continuous cover near tableland outcrops of the middle Gwandu, as discontinuous stretches on plateau land of Kalambaina formation, and as patches near plinthite outcrops of the upper Gwandu and the Dukamaje formations. The present day thickness varies from 0.5 metres to more than 30 metres.

Table 2: Stratigraphic sequence of sediments in the Sokoto Sedimentary Basin.

Age	Formation	Group	Environment
Quaternary	Sand drifts	-	Continental
Eocene-Miocene	Gwandu	Continental Terminal (Cres du Niger)	Continental
Upper Palaeocene	Gamba Kalambaina Dange	Sokoto	Marine
Maastrichtian	Wurno Dukamaje Taloka	Rima	Brackish
Lower most Cretaceous or older	Illo and Gundumi	Continental Intercalaire	Continental
	Pre-Cambrian Basement Complex		

For each of the coversand, shallow and deep forms have been recognized based on thickness. Deposits less than 2 metres in thickness are classified as shallow (Sombroek and Zonneveld, 1971).

3.6 Landuse

Landuse in the Sokoto basin is fairly extensive and variable among the different physiographic and lithologic units. A high proportion of all cultivatable land is utilized including the ancient sand dune soils. Short season crops, mainly cereals, requiring less amount of water are grown to meet the short but intensive rainfall period. Landuse intensity is highest on the Sokoto ancient sand dune soils followed by soils of Illela and Sangiwa ancient dunes in that order.

In the Sokoto basin, FAO (1969), and Sombroek and Zonneveld (1971) identified the following land utilization types.

(a) Semi-permanent wet season cropping with a year of fallow from time to time. This is restricted to the more fertile good upland soils.

(b) Shifting cultivation (wet season) with long period of fallow. This is restricted to poor upland soils with admixture of natural vegetation.

(c) Irrigated all season permanent cropping on floodplains and places very close to a permanent water supply.

(d) Semi-Nomadic grazing of principally cattle with some sheep and goats, on both cultivated and uncultivated plots.

(e) Planned and unplanned forest reserves, mainly on the very poor soils with a lot of plinthites, termite mounds and rich sodic micaceous soils.

4. MATERIALS AND METHODS

4.1 Field Studies

An exploratory field survey was undertaken to obtain a first hand impression of the project area which covers a total area of 70,000 Km^2 since most of the available base maps were produced in the 50's and early 60's. The reccee exercise offered the opportunity to assess the transportation needs, possible routes, sample areas and possible sites for profile pit locations for the eventual fieldwork.

Three ancient sand dunes have been recognised within the Sokoto basin (Sombroek and Zonneveld, 1971). The physiographical and lithological map (1:250,000) of Sombroek and Zonneveld (1971) formed the basis for their identification. During the reccee exercise, several auger holes in transects were used to confirm the map where its accuracy was in doubt. The ancient sand dunes were further subdivided into shallow and deep phases based on thickness. The deep phases were recognized as those dunes which are deeper than 2 m to any sedimentary or impenetrable layer. Four pedons were sited on each sand dune, distributed two each among the two phases. The location of the study area and the pedons are shown in Figure 1.

When the actual fieldwork commenced, a total of 12 pedons were located and dug within crests of each of the three sand dunes. Before the pedons were sampled (undisturbed and bulk soil samples), their morphological properties were described, following the revised edition of the guidelines for profile description contained in the Soil Survey Manual (Soil Survey Staff, 1981). Undisturbed core samples were taken using core ring sampler from pedogenic horizons for the laboratory determination of bulk density. Bulk soil samples were also taken from pedogenic horizons for the laboratory determination of both routine and specialized analyses. Bulk soil samples were transported in plastic bags to the laboratory.

4.2 Laboratory Studies

4.2.1 Sample preparation

Disturbed samples taken from pedogenic horizons were air-dried in laboratory quadrangles for several days, gently crushed with porcelain pestle and mortar and passed through a 2 mm sieve. The less than 2 mm portion (fine earth) was stored in clean plastic containers for laboratory analysis. The portion retained on the 2 mm sieve (gravel) was weighed and its percentage to whole soil calculated. For mineralogical and phosphate studies, the Ap and a subsoil horizon of each pedon were used.

4.2.2 Particle size distribution

To ensure complete dispersion of the soil aggregates, the soil samples were dispersed in 5 % calgon (sodium hexametaphosphate) solution by shaking on a reciprocating shaker for 6 hours. The particle size distribution was then determined by the hydrometer method as described by Day (1965). The total sand fraction was further fractionated by using a set of sieves (1000, 500, 200 and 53 µm sieves) and shaking for 20 minutes on a mechanical sieve shaker.

4.2.3 Bulk density

Bulk density was determined by oven-drying the undisturbed soils samples collected in 100 cm^3 metal cylinders to a constant weight at 105°C, and dividing the oven-dried weight of the sample by the total volume of the sample.

4.2.4 Total porosity and macroporosity

Total porosity was calculated mathematically from the results of bulk density determination using the formula

$$f = 100\ [1 - \frac{Db}{Dp}]$$

where, f = total porosity,

Db = bulk density determined in 4.2.3 and

Dp = particle density assumed to be 2.65 g/cm^3.

Macroporosity was also calculated mathematically using the formula given below

$$fa = f - \theta \times \frac{Db}{Dw}$$

where, fa = Macroporosity,

θ = percent moisture content (dry weight), and

Dw = density of water (Black, 1965).

4.2.5 Soil pH

Soil pH was determined in both water and 1M CaCl solutions using a 1:2.5 soil/water or solution ratio (Peech, 1965). The pH was then read with a glass electrode on a Pye Unicam model 290 MK pH meter upon equilibration.

4.2.6 Exchangeable bases

The exchangeable bases were extracted with neutral (pH 7.0) ammonium acetate (NH_4OAc) solution by shaking on a reciprocating shaker for 2 hours and centrifuging at 10,000 rpm for 20 minutes (IITA, 1979). Potassium and sodium were read from the undiluted extracts on a Gallenkamp flame Analyser. The extracts were diluted 2 times with the addition of 2 ml of 6.5 % lanthanum chloride solution to prevent ionic interference before calcium and magnesium were determined. Calcium and magnesium in solution were read on a Pye Unicam model Sp 192 atomic absorption spectrophotometer (AAS) at 423 and 285 nm wavelenghts respectively. The sum of the bases gave total exchangeable bases.

4.2.7 Cation exchange capacity (CEC)

The CEC was determined by the neutral (pH 7.0) ammonium saturation method (Chapman, 1965; Rhoades, 1982) by repeated leaching. The method of Sombroek and Zonneveld (1971) was followed in the calculation of the CEC of the clay fraction using the formula below

$$\text{CEC - Clay} = \frac{\text{CEC} - (3.5 \times \% \text{ O.C})}{\% \text{ Clay}} \times 100$$

where, CEC = NH_4OAc (pH 7.0) or ECEC

O.C = Organic carbon.

4.2.8 Exchangeable acidity

The soils were leached with 1M KCl solution. Exchangeable acidity (H + Al) was determined by titrating the extract with standard NaOH solution (Thomas, 1982).

4.2.9 Effective CEC

Effective CEC was obtained by summing up the total exchangeable bases (by NH_4OAc) with the values of exchangeable acidity (by 1M KCl).

4.2.10 Electrical conductivity (EC)

The Ec was determined on a 1: 2.5 soil / water ratio using a wheatstone bridge at 27 °C (Bower and Wilcox, 1965).

4.2.11 Exchangeable sodium percentage (ESP)

The ESP was calculated as the proportion of the cation exchange capacity occupied by sodium cations as follows

$$\text{ESP} = \frac{\text{Exchangeable sodium}}{\text{CEC (pH 7.0)}} \times 100$$

4.2.12 Base saturation (BS)

Base saturation was calculated for both NH_4OAc-CEC and ECEC from the formula

$$\% \text{ BS} = \frac{\text{Total exchangeable bases}}{\text{CEC}} \times 100$$

where, CEC = NH_4OAc-CEC or ECEC.

4.2.13 Carbonate equivalent

Carbonate equivalent was determined by the acid neutralization method as described by Nelson (1982). The soils were saturated with warm 0.5M HCl solution and the extract titrated against 0.25M NaOH solution

4.2.14 Organic carbon

The organic carbon was determined by the Walkley-Black dichromate wet oxidation method as described by Nelson and Summers (1982). Concentrated H_2SO_4 was added to act as a catalyst.

4.2.15 Total and available phosphorus

Total phosphorus was determined by the sodium bicarbonate fusion method (Kanehiro and Sherman, 1965). 6M HCl solution was used for the transfer and dissolution of the melt. Phosphorus in solution was then determined by the ascorbic method (Murphy and Riley, 1962). Available phosphorus was extracted by the Bray No 1 method (Bray and Kurtz, 1945). Phosphorus in solution was then determined by the ascorbic acid method (Murphy and Riley, 1962).

4.2.16 Forms of phosphorus

The organic phosphorus was determined by the ignition method (Saunder and Williams, 1955) while the different inorganic phosphorus forms were determined

according to the modified procedure of Chang and Jackson (Petterson and Corey, 1966). The adsorbed phosphorus was extracted by shaking with 1M NH_4Cl solution, for 30 minutes and centrifuged. The Al-P was determined from the same soil sample by extracting with 0.5M NH4F (pH 8.2), for 1 hour and centrifuged. The Fe-P was determined from the same soil sample by extracting with 0.1M NaOH solution, for 17 hours and centrifuged. The Ca-P fraction, in the same soil sample, was extracted with 0.5M H_2So_4 solution, for 1 hour and centrifuged. At each interval, the soil sample was washed twice with saturated NaCl solution. In each case, the phosphorus in solution was determined by the ascorbic acid method (Murphy and Riley, 1962). The residual phosphorus was calculated as the difference between the sum of the different phosphorus fractions (inorganic and organic) and the total phosphorus.

4.2.17 0.1M HCl extractable cationic micronutrients (Cu ,Zn , Mn and Fe)

The soil sample was extracted with 0.1M HCl solution, shaken for 4 hours and then centrifuged at 10,000 rpm. The Cu, Zn, Mn and Fe contents in the extract were then determined on the AAS at 325, 214, 280 and 373.9 nm wavelengths respectively.

4.2.18 0.05M DTPA-TEA extractable cationic micronutrients (Cu, Zn, Mn and Fe)

The soil sample was saturated with diethylene triamine penta-acetic acid (DTPA) and Triethanolamine (TEA) solutions (Baker and Amacher, 1982) and shaken for 2 hours on a reciprocating shaker. The suspension was then centrifuged and Cu, Zn, Mn, and Fe in the extract determined as in section 4.2.16.

4.2.19 Total cationic micronutrients (Cu, Zn, Mn and Fe) by the sodium bicarbonate fusion

The soil sample was fused with sodium bicarbonate grains at 850 °C until the mixture turned into a melt. The melt was dissolved in 6 M HCl and subsequently transferred into volumetric flask with 2M HCl solution. The cations (Cu, Zn, Mn, Fe,) were then determined in the solution using the AAS as in section 4.2.16.

4.2.20 Acid ammonium oxalate (pH 3) extractable Iron and Aluminium

The amorphous inorganic bound iron and aluminium oxyhydroxides were extracted using acidified ammonium oxalate (pH 3) solution (Schwertmann, 1964). The saturated soil sample was shaken in the dark on a reciprocating shaker for 4 hours and then centrifuged. The iron in the extract was determined after ten times dilution on the AAS at 373.9 nm wavelength while aluminium was determined by the aluminon method as described by Jackson (1958).

4.2.21 0.1M Sodium pyrophosphate ($Na_4P_2O_7$) extractable Iron and Aluminium

The amorphous oxyhydroxides were extracted using 0.1M sodium pyrophosphate solution (McKeague, 1967). The saturated soil sample was shaken in the dark overnight on a reciprocating shaker. The suspension was then centrifuged for 20 minutes at 5,000 rpm. Iron and aluminium in the extract were then determined as outlined under the oxalate extract in section 4.2.19.

4.2.22 Citrate-Bicarbonate-Dithionite (CBD) extractable Iron and Aluminium

The total free crystalline iron and aluminium oxyhydroxides were extracted using CBD solution (Mehra and Jackson, 1960; Olson and Ellis, 1982). 0.2 gram of soil sample which has passed a 0.1 mm sieve was saturated with 0.3M sodium citrate and 1M $NaHCO_3$ solutions. The suspension was heated on a water bath at between 70 - 80 °C. One gram of sodium dithionite salt was added and stirred continuously for one minute and occasionally for 15 minutes while in the water bath. The suspension was then centrifuged. The above treatment was repeated once. Iron and aluminium in the extract were determined as in section 4.2 19.

4.2.23 Sand mineralogy

The fine sand fraction (250 µm) was used for the mineralogical analysis. The fine sand mineral fraction was further separated into the magnetic and non-magnetic fractions by passing them through a magnetic separator. Two methods were later used in the

mineralogical study of the fine sand - XRD and petrology. For the petrological examination, the procedure of Cady (1965) was followed. The magnetic and non-magnetic fractions were examined separately. The particles were finely sprinkled on a hard paper with white and black surface for the magnetic and the non-magnetic portions respectively. Ten grids were drawn on the hard paper and the mineral grains counted per grid. The average for all the grids was taken. The low and medium objectives were used in the identification of the minerals via their colour, shape, fracture, cleavage, extinction angle and lustre. A portion of the non-magnetic fraction was ground into powder until there was no feel of grains between the fingers. The samples were scanned on XR diffracting machine at 40 Kv and 30 mA with a scanning speed of 2° 2θ per minute. Scanning was done fron 5° 2θ up to 50° 2θ using a copper target and nickel filter. The diffractograms were however, drawn from 10° 2θ since no peak was detected between 5° 2θ and 10° 2θ. The minerals were identified from their characteristic peaks and their relative proportion estimated from the areas and sharpness of the peaks.

4.2.24 Silt mineralogy

The silt was separated from the clay by the sedimentation method as described by Kunze (1965). The silt was saturated with Mg and air-dried. It was then ground into fine powder. The samples were also determined by XRD technique. Scanning was done using the same XRD settings as were used for the fine sand.

4.2.25 Clay mineralogy

The clay mineralogy was also determined by the XRD technique. Non-oriented samples were used after saturation with magnesium. Magnesium saturation of the samples was achieved by washing the flocculated clay four times with 0.5M MgOAc (pH 7). The surplus MgOAc was then removed by washing four times with ethanol. The samples were then air-dried and ground into fine powder. The non-oriented samples were also scanned using the same XRD settings as in 4.2.23. All the XRD were run at the Center for Energy Research and Training (CERT), Ahmadu Bello University, Zaria.

4.2.26 Phosphate adsorption

The procedure outlined by Fox and Kamprath (1970) and Rhodes (1975) was followed. Three grams (air-dry basis) soil samples were equilibrated with 30 ml of 0.01M $CaCl_2$ solutions containing 0, 100, 200, 300 and 400 µg g^{-1} of H_2PO_4- from KH_2PO_4. These correspond to 0, 32, 64 96 and 128 µgP g^{-1} soil respectively. The mixture was equilibrated at 25 °C for 24 hours on a reciprocating shaker. After equilibration the soils were centrifuged at 10,000 rpm for 5 minutes. Phosphate in solution was determined by the ascorbic acid method (Murphy and Riley, 1962). Phosphate adsorbed was considered to be that not recovered in the supernatant solution after equilibrium had been attained.

4.2.27 Data analysis

The data obtained during the laboratory work was analysed statistically. The types of dunes were considered as treatments, while the number of pedons on a dune were taken as replicates and soil properties taken as variables. A completely randomized design was employed using a one-way analysis of variance (ANOVA) and simple regression analysis. These analyses provided the means by which the characteristics of the various dune soils were compared statistically.

4.2.28 Soil classification

Both the field and laboratory results were used in the classification of the soils. The criteria of the USDA Soil Taxonomy System (Soil Survey Staff, 1975; 1990) and that of the FAO/UNESCO Soil Map of the World Legend (FAO/UNESCO, 1974; 1988) were followed in the classification of the soils.

5. RESULTS AND DISCUSSION

5.1. Soil Morphology

The ancient sand dune soils of the Sokoto sedimentary basin are formed on stabilized Quaternary deposits of varying thickness and inherent meso-relief (Plates 1, 3 and 5). The aeolian materials are underlain in some pedons by petroferric material as in the pedons of the Sokoto dunes and in most cases by sedimentary rocks of varying lithology (Table 2). The sedimentary rocks encountered in the course of the fieldwork were mainly fine grained friable ferruginous sandstone and calcareous clay-shale (Table 2).

A summary of the morphological properties is presented in Table 3 while details are given in Appendix A. Plates 2, 4 and 6 also show modal profiles for each of the dune soils of Illela, Sokoto and Sangiwa respectively. The important morphological properties for soil characterization and classification are however, discussed below.

5.1.1. Soil depth

The soils were generally deep to very deep (i.e >150 cm depth) except where underlain by petroferric material - as encountered in pedons of the Sokoto dunes. The shallowest pedon, SDS 3, measured only 40 cm to the petroferric material. In all the shallow pedons, restriction was by the occurrence of petroferric layer. The soil depth is influenced by the meso-relief of the dunes. Deep soils are encountered on dunes with pronounced meso-relief as obtainable in Illela and Sangiwa dunes, while the shallow soils occur mainly in the Sokoto dunes, where petroferric caps of the Kalambaina formation occur very close to the soil surface.

5.1.2. Soil colour

Soils on the shallow phase of Illela dunes showed no colour differentiation with depth. They had a uniform dark brown (7.5YR 4/4) colour throughout their profile. On

the Sokoto dunes, the soils had a strong brown (7.5YR 5/6) surface horizon over a yellowish red (5YR 4/8) subsurface horizon. Soils on the Sangiwa dunes had a light brown (7.5YR 6/4) Ap horizon over a reddish yellow (5YR 6/6) subsoil horizon except in pedons GDS 1 and GDS 3 where strong brown (7.5 YR 5/6) subsoil horizons occurred. The soils generally exhibited good colour development as shown by matrix colour with strong chroma, > 4, throughout the profile and increased reddening with hue varying from 7.5YR to 5YR with depth, especially on the Sokoto and Sangiwa dunes. This may be attributed to the good drainage conditions of the soils, lack of melanization at depth (Cook and Warren, 1973) and ferritization, which under normal circumstances are typical of humid to subhumid tropical environments (Leneuf and Aubert, 1960). The Sokoto dunes had the most pronounced reddish subsoil colours and this is collaborated by their relatively high content of iron and aluminum oxides (Table 19). This might suggest that the Sokoto dunes are the most intensely weathered of the three dune soils(Juo *et al.* 1974 and Mckeague and Day, 1966). The Illela dunes which mostly have brown colours throughout the profiles, are perhaps subjected more to the process of braunification and might therefore be the least weathered.

5.1.3. Soil texture

As the soil of the project area are derived from sand dune, the textures as expected, are generally sandy, especially in the Ap horizons of all the pedons studied. Soils on the Illela dune have a sand texture throughout their profile except for pedon LDS 2, which had sandy loam subsoil horizons. Soils on the Sokoto dunes had a sandy Ap horizon and sandy loam subsoil horizons except for pedon SDS 4 which has a sand texture throughout its profile and SDS 1 with a sandy clay loam texture in the deepest part of the subsoil horizons (from 56 to 105 cm). On the Sangiwa dunes, the soils have sandy surface horizons and loamy sand subsoil horizons except for pedon GDS 1 which was sandy throughout the profile. The relatively higher clay contents in soils of the



Plate 1: Sokoto sand dune, 1.5 Km south of Gwadabawa village, overlying a petroferric layer (plinthic cap) of the Kalambaina deposits. The topography is nearly flat and table-like.



Plate 2: Profiles SDS 1, at Gidan Gara village, showing modal soil characteristics for the Sokoto dunes.



Plate 3: Illela sand dune with a clear pronounced meso-relief at Tungatundo village.



Plate 4: Profile LDS 2, at Tungatundo village, showing modal soil characteristics for soils of the Illela dunes.



Plate 4: Profile LDS 2, at Tungatundo village, showing modal soil characteristics for soils of the Illela dunes.



Plate 5: Sangiwa sand dune with a moderate meso-relief and an undulating topography at Kirare village.



Plate 6: Profile GDS 2, at Bijeje village, showing modal soil characteristics for soils of the Sangiwa dunes.

Table 3. Morphology and classification of pedons studied.

Horizon	Depth (cm)	Munsell colour (moist)	Texture	Structure	Conistence			Boundary	Other feature
					Wet	Moist	Dry		
					Illela Dunes				
Pedon LDS1 (Ustic Quartzipsamment, isohyperthermic)									
AP	0-28	7.5YR 5/6	s	1fabk	sopo	vfr	so	gs	Common very fine roots; many fine quartz grains.
AC	28-63	7.5YR 5/6	s	1fabk	sopo	vfr	sh	gs	Common fine roots; common fine quartz few ant holes.
C1	63-142	5YR 5/6	s	1mabk	sopo	fr	sh	gs	Few medium to common fine roots; common quartz; few ant holes.
C2	142-175	2.5YR 5/6	s	2mabk	sopo	fr	sh	-	Few medium roots; common quartz grains.
Pedon LDS2 (Arenic Haplustult, coarse-loamy, mixed, isohyperthermic)									
AP	0-18	7.5YR 5/6	s	1fabk	sopo	vfr	ls	cs	Common very fine roots; common fine quartzl slight stratification.
AB	18-52	5YR 5/6	s	1mabk	sopo	vfr	sh	gs	Few medium to common fine roots; common fine quaqrtz; few ant holes.
Bt1	52-95	2.5YR 5/6	sl	2mabk	sopo	fr	sh	gs	Common fine roots; common quartz; few ant holes.
Bt2	95-170	2.5YR 5/8	sl	2mabk	sopo	fr	sh	-	Few fine roots; common quartz grains; few ant/termite holes.
Pedon LDS3 (Ustic Quartzipsamment, isohyperthermic)									
Ap	0-27	7.5YR 4/6	s	1fabk	sopo	vfr	so	cs	Common very fine roots; common quartz grains; few ant holes.
AC	27-73	7.5YR 4/4	s	1fabk	sopo	vfr	sh	gs	Common fine roots; common fine quartz; few ant/termite holes.
C1	73-130	7.5YR 4/4	s	1mabk	sopo	fr	sh	gs	Few fine roots; common fine quartz and few laterite stones.
C2	130-210	7.5YR 4.4	s	2mabl	sopo	fr	sh	-	Few fine roots; common quartz grains and laterite stones.
Pedon LDS4 (Ustic Quartzipsamment, isohyperthermic)									
AP	0-12	7.5YR 4/4	s	sg	sopo	l	l	gs	Few fine to medium roots; many fine quartz grains.
AC	12-60	7.5YR 4/4	s	1fabk	sopo	vfr	so	gs	Few medium roots; common fine quartz; few ant holes; few laterite stones.
C1	60-100	7.5YR 4/4	s	2mabk	sopo	vfr	sh	gs	Few medium to common fine roots; common quartz; few ant holes.
C2	142-175	7.5YR 4/4	s	2mabk	sopo	vfr	sh	cs	Few medium roots; common quartz grains.
C3	140-190	7.5YR 6/4	s	2fabk	sopo	vfr	sh	-	Common quartz grains; fibre of dark brown (7.5YR 4/4) clay spaced 5 cm and less than 1 cm thick.

1 = symbols as in Soil Survey Manual (Soil Survey Staff, 1951, 1981).

Table 3 cont'd.

Horizon	Depth (cm)	Munsell colour (moist)	Tex-ture	Struc-ture	Conistence			Boun-dary	Other feature
					Wet	Moist	Dry		
Sokoto Dunes									
Pedon SDS1 (Kanhaplic Haplustult, fine-loamy, mixed, isohyperthermic)									
AP	0-22	7.5YR 5/6	s	2msbk	sopo	vfr	sh	gs	Common fine roots; common fine quartz; few ant holes.
AB	22-39	5YR 5/8	ls	2msbk	sopo	fr	sh	cs	Common fine roots; common fine quartz and few laterite gravels; few ant holes.
Bt1	39-56	5YR 5/8	sl	1fsbk	sopo	fr	sh	gs	Common quartz grains and few laterite gravels; few termite nest.
Bt2	56-85	5YR 5/8	scl	2mabk	sopo	fr	sh	gs	Common fine quartz; thin clay cutans in pores;
Bt3	85-105	5YR 5/8	scl	2msbk	sopo	fi	sh	-	Common quartz grains; few laterite gravels.
Pedon SDS2 (Kanhaplic Haplustult, fine-loamy, mixed, isohyperthermic)									
Ap	0-15	7.5YR 5/6	s	1fabk	sopo	vfr	so	gs	Common fine roots; common fine quartz; few ant holes.
AB	15-26	7.5YR 5/8	ls	2msbk	sopo	fr	sh	cs	Common fine roots; common fine quartz grains; few ant holes.
Bt1	26-52	5YR 5/6	sl	2msbk	ssps	fr	sh	gs	Common quartz grains and few laterite gravels.
Bt2	52-80	5YR 5/8	sl	2msbk	ssps	fr	sh	gs	Common fine quartz; thin clay cutans in pores.
Bt3	80-105	5YR 5/8	sl	2msbk	sps	fi	sh	-	Common quartz grains; few laterite gravels.
Pedon SDS3 (Lithic Haplustult, coarse-loamy, mixed, isohyperthermic)									
AB	0-15	7.5YR 5/8	s	1fabk	sopo	vfr	so	gs	Common fine roots; common fine quartz grains.
Bt	15-52	5YR 5/6	sl	2msbk	ssps	vfr	sh	-	Common quartz grains and few laterite gravels.
Pedon LDS1 (Ustic Quartzipsamment, isohyperthermic)									
AP	0-15	7.5YR 5/8	s	1fabk	sopo	vfr	so	cs	Few fine roots; common fine quartz grains.
AC	15-35	7.5YR 5/6	s	1fabk	sopo	vfr	sh	gs	Common fine roots; common fine quartz; few ant holes.
C1	35-60	7.5YR 5/8	s	1mabk	sopo	vfr	sh	gs	Common fine quartz grains; few ant/termite holes.
2C2	60-115	7.5YR 4/4	s	1mabk	sopo	vfr	sh	gs	Common fine quartz; few ant holes.
2C3	140-190	7.5YR 6/4	s	2fabk	sopo	vfr	sh	-	Common fine quartz grains; very few laterite stones.

1 = symbols as in Soil Survey Manual (Soil Survey Staff, 1951, 1981).

Table 3 cont'd.

Horizon	Depth (cm)	Munsell colour (moist)	Tex-ture	Struc-ture	Conistence			Boun-dary	Other feature
					Wet	Moist	Dry		
					Sangiwa Dunes				
Pedon GDS1 (Ustic Quartzipsamment, isohyperthermic)									
AP	0-33	10YR 4/6	s	2fsbk	sopo	vfr	so	gs	Few fine roots; common fine quartz grains; few ant holes.
AC	33-65	7.5YR 5/6	s	2msbk	sopo	vfr	sh	gs	Common medium roots; few ant holes.
C1	65-108	7.5YR 5/6	s	2msbk	sopo	vfr	sh	gs	Common fine quartz grains; few laterite; stones; few charcoal.
C2	108-185	7.5YR 5/6	s	2msbk	sopo	vfr	h	-	Common fine quartz grains; few laterite stones; few charcoal.
Pedon GDS2 (Ustic Quartzipsamment, isohyperthermic)									
Ap	0-24	7.5YR 6/4	s	1fabk	sopo	vfr	so	cs	Common fine roots; common fine quartz grain.
AC	24-45	7.5YR 6/6	ls	1msbk	sopo	vfr	sh	gs	Common medium roots; few ant holes.
C1	45-100	7.5YR 6/6	ls	2fsbk	sspo	fr	sh	cs	Common fine roots; common fine quartz grains; few ant holes.
C2	100-190	7.5YR 6/4	ls	2msbk	ssps	fr	h	-	Common fine quartz grain; few large ant holes.
Pedon GDS3 (Ustic Quartzipsamment, isohyperthermic)									
AP	0-21	7.5YR 6/4	s	1fabk	sopo	vfr	so	gs	Common fine roots; common fine quartz grains; few ant holes.
AC	21-50	7.5YR 6/4	s	2msbk	ssps	vfr	sh	cs	Common medium roots; few ant holes.
Ct	50-110	7.5YR 5/8	ls	2msbk	sspo	fr	h	gs	Common fine quartz grains; few ant holes.
C2	110-160	7.5YR 6/6	ls	2msbk	ssps	fr	h	-	Few coarse roots; common fine quartz grains; few fine charcoal pieces.
Pedon GDS4 (Ustic Quartzipsamment, isohyperthermic)									
Ap	0-30	7.5YR 6/4	s	2fsbk	sopo	vfr	so	cs	Common fine roots; common fine quartz grains.
AC	30-60	7.5YR 6/6	s	2msbk	sopo	vfr	sh	gs	Common medium roots; few ant holes.
C1	60-110	7.5YR 6/6	ls	2msbk	sspo	fr	h	gs	Common fine quartz grains holes.
C2	110-160	7.5YR 6/8	ls	2msbk	sspo	fr	h	-	Common fine quartz grains.

1 = aymbols as in Soil Survey Manual (Soil Survey Staff, 1951, 1981).

Sokoto dunes might be attributed to their nearly level planar configuration which increases the effective rainfall and promotes maximum argilluviation.

5.1.4 Soil structure

Soils of the Illela and Sokoto dunes have weak structural development in the surface horizons and moderate structures in the subsoil horizons. Better structural development in the subsoil may be attributed to increased clay content and the effect of soil compaction over time. On the Sangiwa dunes, the soils have a moderate structure throughout the entire profile. Generally, blocky structures dominated in the soils (Plates 2, 4 and 6).

5.1.5 Soil consistence

Soils of the Illela and Sokoto dunes are generally non-sticky and non-plastic (wet), very friable (moist) and soft to loose (dry) in the Ap horizons. In the subsoil horizons, the Illela dunes have soils with non-sticky and non-plastic (wet), friable to firm (moist) and slightly hard (dry) consistence while on the Sokoto dunes, the soils are slightly sticky and non-plastic (wet) friable to firm (moist) slightly hard to hard (dry) (Table 3). Soils of the Sangiwa dunes are generally non-sticky and non-plastic (wet) very friable (moist) and slightly hard to hard (dry) in the surface horizons. In the subsoil horizons, however, the Sangiwa dunes have soils with slightly sticky and slightly plastic (wet), friable to firm (moist) and slightly hard to hard(dry) consistence. The sticky consistence obtained for the soils of Sokoto and Sangiwa dunes is attributable to their relative higher clay contents. In general, the soils develop harder consistences down the profile due to increasing compaction.

5.1.6 Horizonation

Generally, horizonation in all the soils were not quite pronounced. Colour, textural and structural differentiations within the profiles were generally limited, due largely to

the sandy (near inert) nature of the parent material and the climate which borders on semi-aridity. In such conditions, additions to the surface become the major pedogenetic action, while the influences of removal, translocation and transformation are greatly minimized (Dregne, 1976 and Steila, 1987). As a consequence, proisotropic processes are therefore dominant over proanisotropic processes. Boundaries between horizons were mainly gradual except in few surface horizons, where incipient melanization as a result of humification had resulted in clear boundaries such as in pedons LDS 2, SDS 4, GDS 2 and GDS 4.

5.1.7 Miscellaneous observations

Fine quartz grains were many in the soils indicative of the sandy parent material and the low level of weathering. Slight stratification in part of the Ap horizons as in pedon LDS 2 confirms the importance of annual addition of aeolian materials to the soils of the area (Moberg *et al.*, 1990). Few ant and termite holes and nests in most of the soils indicate faunal pedoturbation within the profiles.

The morphological properties show clearly the influence of the parent material on the soils, which are mainly sandy or loamy sand except on the Sokoto dunes where the subsoil horizons are sandy loam because of the better effective rainfall and maturity. Despite a relatively moist climate, the soils have undergone only slight changes from their parent material. In effect, the soils are characterized by very low degree of horizonation; as shown by the AC profiles and the gradual to diffuse soil boundaries. There is also little or no textural, colour and structural differentiation thereby making the soils mainly Entisols (Graham *et al.*, 1988). The only exceptions are the soils on the Sokoto dunes. In these soils, because of better moisture conditions through time (past and present) , moderate horizonation has produced A-B-C profiles, and has increased substantially the colour, textural and structural development in these soils.

5.2 Physical Properties

Some of the physical properties considered include, particle-size distribution, bulk density, total and macro-porosities. Data on the physical properties are given in Tables 4 and 5.

5.2.1 Particle-size distribution

The particle-size distribution data for the soils is presented in Table 4. Sand is the dominant size fraction in all the soils. The total sand content ranged between 92 and 96 (mean, 94), 89 and 95 (91.5), and 87 and 91 (89) percent in the surface horizons of the Illela, Sokoto and Sangiwa dunes respectively. The means were not significantly different. In the subsoil horizons, values and means (in parentheses) for the Illela , Sokoto and Sangiwa dunes, were 83 to 93 (mean, 90.7), 71 to 95 (81.9), and 75 to 91 (83.7) percent respectively. The means for Sokoto and Sangiwa dunes were significantly lower ($p=0.01$) than that for Illela dunes (Table 6). The distribution pattern of the sand fraction follows the degree of sorting among the three dunes, with the Illela dunes which is the best sorted having the highest sand content. The dominant sand subfraction in all the soils was the medium sand (i.e 500 to 250 μm); a texture characteristics of aeolian transportation through saltation process (Bagnold, 1941 and Holmes, 1965).

The range in values and means (in parentheses) of medium sand in the surface horizons varied from 48.4 to 57.2 (53.1), 26.4 to 54.2 (39) and 26.8 to 32.1 (29.5) percent, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values also varied from 44.5 to 55.6 (49.8), 22.1 to 48.4 (31.3) and 22.9 to 29.3 (26.9) percent. The means of the medium sand for the Illela dunes were significantly higher ($P = 0.01$) than the means for Sokoto and Sangiwa dunes, whose means were at par. This seems to suggest that there had been increasing concentration of the medium sand with each redeposition of the sand dune from Sangiwa through Sokoto to Illela dunes. Sorting, calculated as the percentage weight of any two adjacent sand subfractions with highest

Table 4: Particle-size distribution of pedons studied.

Horizon	Depth (cm)	Gravel (µm) >2000	Sand (µm) VCS 2000 to 1000	CS 1000 to 500	MS 500 to 250	FS 250 to 100	VFS 100 to 50	TS 2000 to 500	Silt (µm) 50 to 2	Clay (µm) < 2	Textural class
Illela Dunes											
Pedon LDS 1											
Ap	0–28	0.1	1.2	15.9	48.4	26.9	4.1	96	1	3	Sand
AC	28–63	0.1	2.3	18.1	47.8	27.9	3.8	96	1	3	Sand
C1	63–142	0.1	1.9	15.6	47.6	23.3	3.1	91	2	7	Sand
C2	142–175	0.2	2.6	14.4	51.1	21.7	2.8	92	1	7	Sand
Pedon LDS 2											
AP	0–18	0.1	2.2	13.6	52.6	23.1	3.5	95	2	3	Sand
AB	18–52	1.8	4.0	16.9	49.3	19.7	3.7	93	2	5	Sand
Bt1	52–95	0.2	2.9	19.9	44.8	13.5	2.5	83	2	15	Sandy loam
Bt2	95–170	0.2	3.5	13.5	47.2	16.4	2.8	83	2	15	Sandy loam
Pedon LDS 3											
AP	0–27	0.3	0.3	5.1	57.3	25.6	4.3	92	1	7	Sand
AC	27–73	0.1	0.1	4.1	55.6	27.3	3.5	90	1	9	Sand
C1	73–130	0.5	0.1	3.9	50.0	32.9	3.7	90	1	9	Sand
C2	130–210	0.4	0.1	3.4	49.5	34.8	3.8	91	2	7	Sand
Pedon LDS 4											
AP	0–12	0.1	0.3	4.3	54.2	30.0	4.8	93	2	5	Sand
AC	12–60	0.2	0.1	3.4	50.5	33.1	4.4	91	2	7	Sand
C1	60–100	0.1	0.1	4.3	55.0	31.1	3.0	93	2	5	Sand
C2	100–140	–	0.1	5.1	54.6	30.6	3.2	93	2	5	Sand
C3	140–190	–	0.1	4.9	44.5	34.6	3.4	93	2	5	Sand
Sokoto Dunes											
Pedon SDS 1											
Ap	0–22	0.6	0.5	4.8	26.4	45.3	11.9	89	2	9	Sand
AB	22–39	0.3	0.6	5.1	23.2	41.4	12.1	83	6	11	Loamy sand
Bt1	39–56	0.9	0.3	4.5	23.2	37.2	10.4	76	6	18	Sandy loam
Bt2	56–85	0.6	0.6	4.7	24.1	34.1	11.5	75	4	21	Sandy clay loam
Bt3	85–105	1.9	1.9	4.6	22.1	31.9	10.5	71	8	21	Sandy clay loam

Table 4: cont'd.

Horizon	Depth (cm)	Gravel (µm) >2000	Sand (µm) VCS 2000 to 1000	CS 1000 to 500	MS 500 to 250	FS 250 to 100	VFS 100 to 50	TS 2000 to 500	Silt (µm) 50 to 2	Clay (µm) < 2	Textural class
Pedon SDS 2											
Ap	0–15	0.6	0.4	5.2	28.7	45.2	9.4	89	4	7	Sand
AB	15–26	0.4	0.6	5.5	25.6	42.0	9.2	83	6	11	Loamy sand
Bt1	26–52	1.0	0.6	4.7	25.3	36.6	9.8	77	8	15	Sandy loam
Bt2	52–80	0.7	0.5	4.3	22.6	35.3	10.3	73	8	19	Sandy loam
Bt3	80–95	2.7	0.3	4.5	22.7	32.7	10.8	71	10	19	Sandy loam
Pedon SDS 3											
AP	0–15	0.2	0.3	5.2	46.7	34.5	6.3	93	2	5	Sand
Bt	15–40	0.5	0.4	4.0	35.5	34.1	9.0	83	2	15	Sandy loam
Pedon SDS 4											
Ap	0–15	–	0.2	10.7	54.2	27.0	2.9	95	2	3	Sand
AC	15–35	–	0.4	5.1	48.4	35.1	6.0	95	2	3	Sand
C1	35–60	–	0.2	4.2	44.1	39.0	7.1	95	2	3	Sand
2C2	60–115	–	0.4	7.0	43.7	32.9	6.8	91	2	7	Sand
2C3	115–180	–	0.1	8.9	45.4	28.0	7.6	91	2	7	Sand
					Sangiwa Dunes						
Pedon GDS 1											
Ap	0–33	–	0.7	20.7	26.8	22.9	19.8	91	8	3	Sand
AC	33–65	–	1.5	22.7	24.8	20.0	17.7	87	6	7	Sand
C1	65–108	–	0.2	19.4	22.9	18.2	14.1	75	16	9	Sand
C2	108–185	–	0.4	26.5	27.4	22.3	13.9	91	4	7	Sand
Pedon GDS 2											
AP	k0–24	–	0.3	15.2	31.0	29.1	12.1	87	8	5	Sand
AC	24–45	–	0.2	14.8	30.9	27.5	13.0	87	2	11	Loamy sand
C1	45–100	–	0.2	13.5	28.3	28.1	13.5	83	4	13	Loamy sand
C2	100–190	–	0.2	13.2	27.4	27.3	13.3	81	6	13	Loamy sand

Table 4: cont'd.

Horizon	Depth (cm)	Gravel (µm) >2000	Sand (µm) VCS 2000 to 1000	CS 1000 to 500	MS 500 to 250	FS 250 to 100	VFS 100 to 50	TS 2000 to 500	Silt (µm) 50 to 2	Clay (µm) < 2	Textural class
Pedon GDS 3											
Ap	0–21	–	0.2	18.8	27.9	26.1	16.5	89	6	5	Sand
AC	21–50	–	0.2	22.2	26.6	22.8	13.8	85	6	9	Sand
C1	50–110	–	0.4	21.7	24.6	22.1	12.7	81	6	13	Loamy sand
C2	110–160	–	0.4	22.4	23.6	21.8	13.3	81	6	13	Loamy sand
Pedon GDS 4											
Ap	0–30	–	0.3	16.3	32.1	28.8	11.7	89	8	3	Sand
AC	30–60	–	0.3	14.3	28.6	29.1	13.2	85	6	9	Sand
C1	60–110	0.2	0.3	15.0	15.0	26.9	14.6	85	4	11	Loamy sand
C2	110–160	–	0.4	16.4	16.4	24.6	12.8	83	6	11	Loamy sand

values, was rated as well, moderate and poor for soil of Illela, Sokoto and Sangiwa dunes respectively (Figure 2). This trend tends to support the hypotheses of Sombroek and Zonneveld (1971), that the Illela dunes were reworked from the Sokoto dunes, which were in turn, reworked from the Sangiwa dunes. There is therefore increasing sorting and increase in the finer sand subfraction at each stage of redeposition.

The silt fraction was the lowest of the fine earth fraction in all the soils (Table 4). The Sangiwa dune soils had higher silt content, both in the Ap and subsoil horizons, than soils of Illela and Sokoto dunes, whose means were at par in the surface horizons. In the subsoil horizons, the mean for Illela dunes was significantly lower (p=0.01) than those of Sokoto and Sangiwa dunes, while the means for Sokoto and Sangiwa dunes were at par. The means were 1.50, 2.50, 7.50 (in surface horizons) and 1.69, 5.08 and 6.00 (in subsoil horizons) percent for the Illela, Sokoto and Sangiwa dunes respectively. This low values support the findings of previous workers (Sombroek and Zonneveld, 1971; Bennett, 1980) that the three dunes are near-source aeolian deposits and were transported through saltation, hence, the silt was transported further south into what is known as the Funtua loess (FAO, 1969; Sombroek and Zonneveld, 1971). Similar low silt values have been reported by Ogunwale *et al.* (1975) for sandstone derived soils of the Nigerian savanna.

Clay was the next dominant fraction after sand. There were no significant difference (p=0.05) in clay contents in the surface soils. The means were 4.50, 6.00 and 4.00 percent for the Illela, Sokoto and Sangiwa dunes respectively. The means for the subsoil horizons show that Sokoto dunes had a higher clay content (mean, 13.08 percent) than Illela dunes but was at par with the means for Sangiwa dunes mean, 10.50 percent) which in turn was par with that of Illela dunes (mean, 7.62 percent) (Table 6). There was a general increase in clay with depth, depicting some amount of clay illuviation. This process of argilluviation was highest in the Sokoto dunes, as a result of the near-level topography which enhances the effective rainfall and consequently accelerates the rates

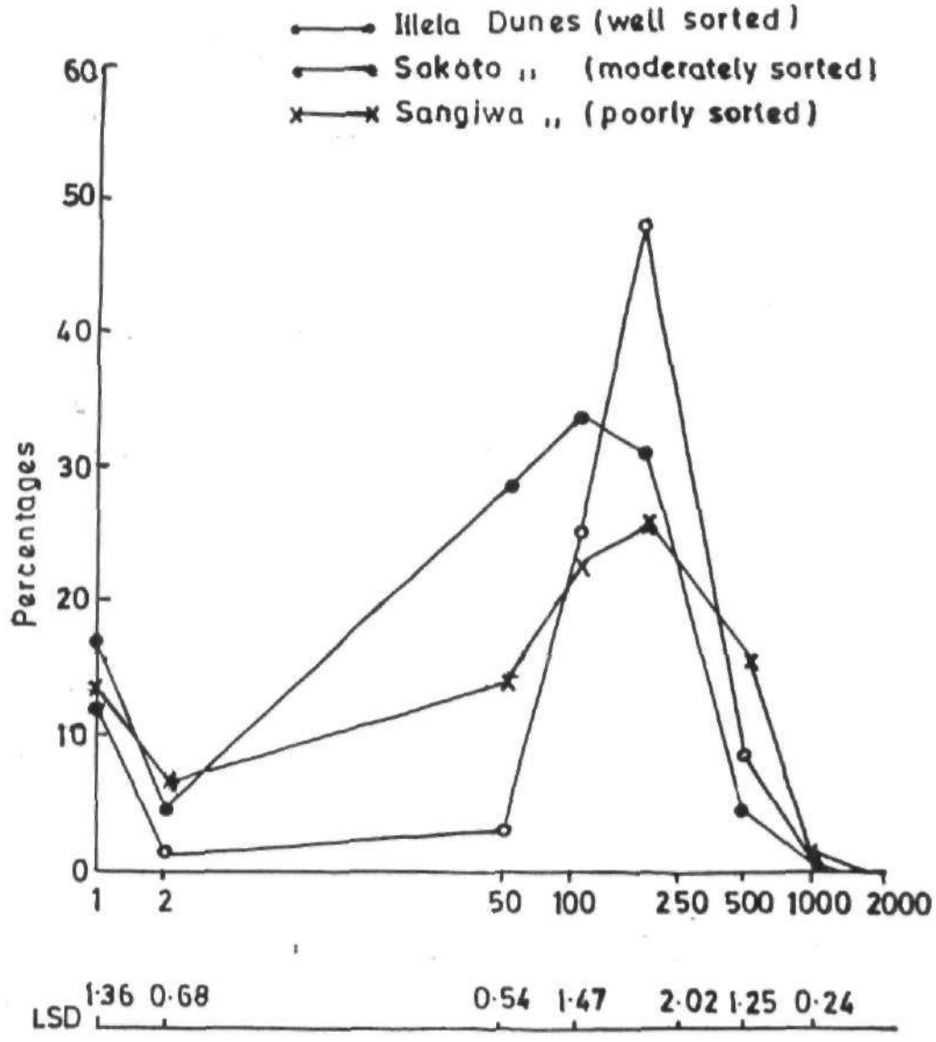


Fig. 2 Grain-size distribution of the three Dunes

of weathering. Sombroek and Zonneveld (1971) however, attributed the higher clay contents in the Sokoto dunes to colluviation of materials from the Dange formation. This seems highly improbable, as in most cases, the Dange formation was not observed in the vicinity of the pedons studied. Ashaye (1969), Ojanuga (1979), Esu (1982) and Kparmwang (1993) had earlier attributed the increase in clay with depth, to clay translocation and erosion of clay in the surface horizon.

5.2.2. Bulk density

The range in values and the means (in parentheses) for bulk density for surface horizons were 1.64 to 1.77 (1.70), 1.55 to 1.66 (1.60) and 1.55 to 1.67 (1.59) Mg m^{-3}, in the Illela, Sokoto and Sangiwa dunes respectively (Table 5). In that order, subsoil horizons values ranged from 1.47 to 1.67 (1.61), 1.39 to 1.78 (1.52), and 1.24 to 1.50 (1.41) Mg m^{-3}. The means for Sokoto and Sangiwa dunes were significantly lower ($p=0.01$) than that for Illela dunes in the surface horizons while that for Sangiwa was significantly lower ($p=0.01$) than those for Illela and Sokoto dunes in the subsoil horizons. The relatively higher content of sand in the Illela dunes may be responsible for the higher bulk density (Byrd and Cassel, 1980). The higher subsoil values of bulk density in the Sokoto dunes may be attributed to the relatively higher contents of clay (Anderson *et al.*, 1988).

The general trend was a high bulk density in the Ap horizon followed by a decrease in value in the subsoil horizons. Such trends were also reported by Esu (1982, 1984) and were attributed to surface compaction due to either mechanical or animal traction, and the better structural development in the subsoil horizons. Increase in the bulk density and loss of macropore space in the surface horizons upon compaction have been reported to be less severe in sandy soils (Mace, 1970). It is therefore, not surprising that the bulk density values were not high enough to impede root penetration, as they were generally lower than 1.85 Mg m^{-3} (Vepraskas, 1988) (Table 5).

Table 5: Bulk density and porosity of pedons studied.

Horizon	Depth (cm)	Bulk Density (Mg m^{-3})	Porosity	
			Total (%)	Macro (%)
		Illela Dunes		
Pedon LDS 1				
AP	0-28	1.77	25.66	25.62
AC	28-63	1.67	36.98	36.87
C1	63-142	1.66	37.36	37.29
C2	142-175	1.70	35.85	35.76
Pedon LDS 3				
Ap	0-27	1.70	35.85	35.71
AC	27-73	1.63	38.85	38.57
C1	73-130	1.65	37.74	37.18
C2	130-210	1.54	41.89	41.16
Pedon LDS 4				
Ap	0-12	1.64	38.11	38.02
AC	12-60	1.57	40.75	40.41
C1	60-100	1.62	38.87	38.74
C2	100-140	1.47	44.53	44.42
C3	140-190	1.58	40.38	40.28
		Sokoto Dunes		
Pedon SDS 1				
Ap	0-22	1.55	41.50	41.00
AB	22-39	1.42	46.40	45.60
Bt1	39-56	1.46	44.90	42.90
Bt2	56-85	1.60	39.60	36.50
Bt3	85-105	1.39	47.60	44.30
Pedon SDS 3				
Ap	0-15	1.59	40.00	39.91
Bt	15-40	1.44	45.66	45.28
Pedon SDS 4				
Ap	0-15	1.66	37.36	37.31
AC	15-35	1.60	39.62	39.52
C1	35-60	1.78	32.38	32.76
2C2	60-115	1.50	43.40	43.08
2C3	115-180	1.46	44.91	44.57

Table 5 cont'd.

Horizon	Depth (cm)	Bulk Density (Mg m^{-3})	Porosity	
			Total (%)	Macro (%)
		Sangiwa Dunes		
Pedon GDS 1				
AP	0-33	1.67	36.98	33.94
AC	33-65	1.50	43.40	43.24
C1	65-108	1.52	42.64	41.66
C2	108-185	1.24	52.32	50.95
Pedon GDS 2				
Ap	0-24	1.56	41.13	41.04
AC	24-45	1.31	50.57	50.22
C1	45-100	1.37	48.30	47.34
C2	100-190	1.50	43.40	40.47
Pedon GDS 3				
AP	0-21	1.55	41.51	41.39
AC	21-50	1.42	46.41	46.11
C1	50-110	1.44	45.66	42.98
C2	110-160	1.43	46.04	45.96

5.2.3 Total porosity

Total porosity exhibits an inverse relationship with the soil bulk density (Table 5). The ranges in values and the means (in parentheses) for surface horizons were 25.66 to 38.11 (33.21), 37.36 to 41.5 (39.62) and 36.98 to 41.51 (39.87) percent, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, subsoil values varied from 36.98 to 44.53 (39.32), 32.38 to 47.60 (42.71) and 43.40 to 50.52 (46.53) percent. In general, porosity increased with depth due to better structural development in the subsoil horizons. The means, for the surface horizons, in the Sokoto and Sangiwa dunes were significantly higher (p=0.01) than that for Illela dunes while in the subsoil, the mean for Sangiwa dunes was significantly higher (p=0.01) than those for Illela and Sokoto dunes, while the means for Illela and Sokoto dunes were in turn, at par. The higher total porosity observed for the Sokoto and Sangiwa dunes in their surface horizons than that in Illela dunes may be attributed to the better structural development in the former.

5.2.4. Macroporosity

The macroporosity of the surface soils ranged between 25.62 and 38.02 (mean, 33.12), 37.31 and 41.00 (mean,39.41), and 33.94 and 41.39 (mean, 38.79) percent, in the Illela, Sokoto and Sangiwa dunes respectively. The means were not significantly different (p=0.05). In the same order, the subsoil values varied from 36.87 to 44.42 (39.27), 36.50 to 45.60 (41.61), and 40.47 to 50.95 (45.44) percent. In the subsoil, the mean for Sangiwa was significantly higher (p=0.01) than the means for Illela and Sokoto dunes, whose means were at par (Table 6).

The high macroporosity values simply reflect the somewhat excessively drained conditions observed in the field. It also indicates that water retention will be a limiting factor in the soils (Vomocil and Flocker, 1961; Germann and Beven, 1981).

Table 6: Mean values of physical properties of the dunes studied.

Soil properties	Illela	Sokoto	Sangiwa	P-Level
Surface Horizons				
	94.00	91.50	89.00	NS
Sand (%)	1.50a	2.50a	7.50b	**
Silt (%)	4.50	6.00	4.00	NS
Clay (%)	33.21a	39.62a	39.87b	**
Porosity (%)	1.77b	1.60a	1.59a	**
Bulk density (Mg m^{-3})				
Subsurface Horizons	90.69b	81.85a	83.67a	**
Sand (%)	1.69a	5.08b	6.00b	**
Silt (%)	7.62a	13.08b	10.50ab	**
Clay (%)	39.32a	42.71a	46.53b	**
Porosity (%)	1.61b	1.52b	1.41a	**
Bulk density (Mg m^{-3})				

NS = Not significant at P 0.05, * = P 0.05, ** = P 0.01

5.3 Chemical properties

The chemical properties of the soils that were considered include: soil reaction, organic carbon, available and total phosphorus, exchange acidity, exchangeable bases, cation exchange capacity and base saturation. Data on these properties are presented in Tables 7 and 8.

5.3.1 Soil pH

The pH values, measured in water, for surface horizons of the Illela, Sokoto and Sangiwa dunes ranged from 4.8 to 8.0 (mean, 5.83), 5.0 to 6.7 (5.88), and 5.1 to 6.1 (5.40) respectively. The soil reaction is thus very strongly acid to moderately alkaline in the Illela dunes, very strongly acid to neutral in the Sokoto dunes, and strongly to slightly acid in the Sangiwa dunes (Soil Survey Staff, 1951). In the subsoils, in the same order, values varied from 4.4 to 7.8 (mean, 6.15), 4.0 to 6.5 (mean, 5.0), and 3.9 to 5.2 (mean, 4.47), indicating extremely acid to mildly alkaline reaction in the Illela dunes, extremely to slightly acid in the Sokoto dunes and extremely to strongly acid in the Sangiwa dunes. These low pH values could be attributed to the siliceous parent material of the soils, and to the leaching of bases out of the solum. The soil reactions were generally acidic within the area studied except on pedons LDS 3 and LDS 4 of the Illela dunes where incipient calcification is taking place (Plate 7) and probable admixture with the underlying calcareous rocks.

Soil pH values were in most cases, except in the Illela dunes, higher in the Ap horizon than the subsoil horizons, though such difference was not significant (p=0.05). Ojanuga (1971), Jones and Wild (1975), Mosugu (1989) and Moberg *et al.* (1990) have variously attributed this to the biogenetic cycling of bases, and the annual addition of bases from the harmattan dust. The observed decrease of pH with profile depth within the dune soils, seems to be related more to the addition of aeolian dust and the less intensive

Table 7: Exchangeable bases, exchange acidity and pH of pedons studied.

Horizon	Depth (cm)	pH			Exchangeable bases				Total	Exch. acidity H+Al
		H_2O	$CaCl_2$	dpH	Ca (cmol(+)kg^{-1})	Mg (cmol(+)kg^{-1})	K (cmol(+)kg^{-1})	Na (cmol(+)kg^{-1})		
					Illela Dunes					
Pedon LDS 1										
Ap	0–28	4.8	4.5	–0.3	0.32	0.10	0.02	0.02	0.46	0.2
AC	28–63	5.0	4.6	–0.4	0.33	0.10	0.02	0.03	0.48	0.4
C1	63–142	4.6	3.8	–0.8	0.35	0.12	0.02	0.04	0.51	0.8
C2	142–175	4.6	4.0	–0.6	0.35	0.12	0.02	0.03	0.50	0.6
Pedon LDS 2										
Ap	0–18	5.0	4.8	–0.2	0.61	0.25	0.06	0.03	0.95	0.4
AB	18–52	5.8	5.1	–0.7	0.30	0.08	0.02	0.03	0.43	0.6
Bt1	52–95	4.5	3.5	–0.0	0.41	0.11	0.02	0.03	0.57	1.0
Bt2	95–170	4.4	3.5	–0.9	0.62	0.11	0.02	0.03	0.08	0.8
Pedon LDS 3										
Ap	0–27	5.5	5.3	–0.2	1.40	0.39	0.07	0.07	1.93	0.0
AC	27–73	6.1	6.0	–0.1	2.10	0.51	0.06	0.03	2.70	0.2
C1	73–130	7.1	6.3	–0.8	2.46	0.38	0.06	0.04	2.94	0.2
C2	130–210	7.2	6.2	–1.0	2.23	0.38	0.06	0.03	2.70	0.2
Pedon LDS 4										
Ap	0–12	8.0	7.1	–0.9	1.30	0.50	0.13	0.03	1.96	0.1
AC	12–60	7.5	6.5	–1.0	1.90	0.73	0.06	0.03	2.72	0.1
C1	60–100	7.6	6.2	–1.4	2.06	0.67	0.07	0.05	2.85	0.2
C2	100–140	7.7	6.7	–1.0	1.42	0.45	0.06	0.05	1.98	0.2
C3	140–190	7.8	6.8	–1.0	0.96	0.41	0.04	0.03	1.44	0.4

Table 7 cont'd.

Horizon	Depth (cm)	pH			Exchangeable bases				Total	Exch. acidity
		H_2O	$CaCl_2$	dpH	Ca (cmol(+)kg^{-1})	Mg (cmol(+)kg^{-1})	K (cmol(+)kg^{-1})	Na (cmol(+)kg^{-1})		H+Al
					Sokoto Dunes					
Pedon SDS 1										
Ap	0–22	5.6	4.2	−1.4	0.76	0.26	0.06	0.03	1.11	0.6
AB	22–39	4.4	3.3	−1.1	0.61	0.23	0.08	0.04	0.96	1.0
Bt1	39–56	4.5	4.5	−1.2	0.61	0.23	0.07	0.03	0.94	1.8
Bt2	56–85	4.3	3.4	−0.9	0.55	0.17	0.06	0.04	0.82	3.4
Bt3	85–105	4.7	3.5	−1.2	0.86	0.22	0.05	0.06	1.19	1.6
Pedon SDS 2										
Ap	0–15	5.0	3.6	−1.4	0.85	0.29	0.07	0.03	1.24	0.6
AB	15–26	4.5	3.4	−1.1	0.56	0.20	0.05	0.02	0.83	1.4
Bt1	26–52	4.4	3.4	−1.0	0.58	0.19	0.06	0.06	0.89	1.4
Bt2	52–80	4.0	3.4	−0.6	0.55	0.16	0.05	0.03	0.79	1.6
Bt3	80–95	4.1	3.5	−0.6	0.72	0.19	0.04	0.03	0.98	1.4
Pedon SDS 3										
Ap	0–15	6.2	5.4	−0.8	0.86	0.39	0.02	0.03	1.30	0.2
Bt	15–40	5.5	4.4	−1.1	1.42	0.59	0.02	0.03	2.06	0.4
Pedon SDS 4										
Ap	0–15	6.7	5.7	−1.0	0.95	0.39	0.08	0.04	1.46	0.2
AC	15–35	6.5	5.5	−1.0	0.83	0.39	0.05	0.03	1.30	0.2
C1	35–60	6.1	5.3	−0.8	0.68	0.31	0.02	0.02	1.03	0.2
2C2	60–115	6.2	5.3	−0.9	1.26	0.78	0.04	0.02	2.10	0.2
2C3	115–180	5.8	4.5	−1.3	1.16	0.50	0.06	0.03	1.75	0.4

Table 7 cont'd.

Horizon	Depth (cm)	pH			Exchangeable bases				Total	Exch. acidity H+Al
		H_2O	$CaCl_2$	dpH	Ca (cmol(+)kg^{-1})	Mg (cmol(+)kg^{-1})	K (cmol(+)kg^{-1})	Na (cmol(+)kg^{-1})		
					Sangiwa Dunes					
Pedon GDS 1										
Ap	0–33	6.1	5.5	–0.6	0.67	0.19	0.16	0.03	1.05	0.8
AC	33–65	5.3	4.0	–1.3	0.46	0.16	0.15	0.04	0.81	0.4
C1	65–108	4.4	3.5	–0.9	0.48	0.18	0.10	0.03	0.79	0.8
C2	108–185	4.6	3.5	–1.1	0.47	0.26	0.11	0.07	0.91	0.8
Pedon GDS 2										
Ap	0–24	5.1	4.9	–0.2	0.67	0.21	0.12	0.03	1.03	0.6
AC	24–45	4.1	3.3	–0.8	0.51	0.17	0.14	0.03	0.85	1.4
C1	45–100	3.9	3.1	–0.8	0.62	0.26	0.08	0.06	1.02	2.0
C2	100–190	3.9	3.3	–0.6	0.97	0.38	0.08	0.06	1.49	1.2
Pedon GDS 3										
Ap	0–21	5.1	5.0	–0.1	0.90	0.25	0.08	0.03	1.26	0.4
AC	21–50	4.9	4.5	–0.4	1.42	0.46	0.09	0.04	2.01	0.4
C1	50–110	4.8	3.9	–0.2	2.02	0.61	0.07	0.05	2.75	0.6
C2	110–160	5.2	4.6	–0.6	1.80	0.49	0.06	0.07	2.42	0.8
Pedon GDS 4										
Ap	0–30	5.3	5.0	–0.3	0.58	0.22	0.11	0.04	0.95	0.6
AC	30–60	4.3	3.5	–0.8	0.42	0.16	0.12	0.03	0.73	1.0
C1	60–110	4.0	3.3	–0.7	0.46	0.20	0.09	0.03	0.78	1.4
C2	110–160	4.2	3.5	–0.7	1.04	0.40	0.08	0.04	1.56	1.0

Table 8: Organic carbon, phosphorus, CEC and percent base saturation of pedons studied.

Horizon	Depth (cm)	Organic carbon (gkg^{-1})	Phosphorus		CEC		ECEC		BS	
			Avail. $\mu g\ g^{-1}$	Total $\mu g\ g^{-1}$	Soil $Cmol(+)kg^{-1}$	Clay $Cmol(+)kg^{-1}$	Soil $Cmol(+)kg^{-1}$	Clay $Cmol(+)kg^{-1}$	CEC (%)	ECEC (%)
Illela Dunes										
Pedon LDS 1										
Ap	0–28	0.8	15.87	1011.7	1.0	24	0.66	13	46	70
AC	28–63	0.2	14.04	647.6	1.2	38	0.88	27	40	55
C1	63–142	0.6	33.40	657.5	2.0	26	1.31	16	26	39
C2	142–175	0.2	26.06	708.2	2.0	28	1.10	15	25	45
Pedon LDS 2										
Ap	0–18	0.8	14.97	607.0	1.0	24	1.35	36	95	70
AB	18–52	0.1	11.57	1011.7	1.1	22	1.03	20	39	42
Bt1	52–95	1.0	13.78	849.8	2.7	16	1.57	8	21	36
Bt2	95–170	0.8	12.54	971.2	3.0	18	1.60	9	27	50
Pedon LDS 3										
Ap	0–27	1.0	46.36	505.9	2.5	31	2.73	34	77	71
AC	27–73	0.8	62.69	708.2	3.6	37	2.90	29	75	93
C1	73–130	1.0	143.1	809.4	4.0	41	3.14	31	74	94
C2	130–210	0.8	318.6	1881.8	3.6	47	2.90	37	75	93
Pedon LDS 4										
Ap	0–12	2.0	24.10	809.4	2.5	36	2.06	27	59	95
AC	12–60	0.8	15.07	465.4	4.0	53	2.82	36	68	96
C1	60–100	0.2	60.24	1011.7	3.9	77	3.05	60	73	93
C2	100–140	–	43.05	809.4	2.5	50	2.18	44	61	91
C3	140–190	–	37.68	1011.7	2.4	48	1.84	37	60	78

Table 8 cont'd.

Horizon	Depth (cm)	Organic carbon (gkg^{-1})	Phosphorus		CEC		ECEC		BS	
			Avail. $\mu g\ g^{-1}$	Total $\mu g\ g^{-1}$	Soil $Cmol(+)kg^{-1}$	Clay $Cmol(+)kg^{-1}$	Soil $Cmol(+)kg^{-1}$	Clay $Cmol(+)kg^{-1}$	CEC (%)	ECEC (%)
					Sokoto Dunes					
Pedon SDS 1										
Ap	0–22	1.4	11.37	485.6	2.3	20	1.71	14	48	65
AB	22–39	1.6	8.63	526.1	3.0	22	1.96	13	32	49
Bt1	39–56	1.2	5.32	526.1	3.6	3.6	2.74	13	26	34
Bt2	56–85	0.8	3.56	1011.7	3.8	3.8	4.22	19	22	19
Bt3	85–105	0.8	3.05	809.4	4.2	4.2	2.79	12	28	43
Pedon SDS 2										
Ap	0–15	1.2	6.02	809.4	2.9	35	1.84	20	43	67
AB	15–26	0.6	6.02	404.7	2.7	23	2.23	18	31	37
Bt1	26–52	0.6	4.86	404.7	3.0	19	2.29	14	30	39
Bt2	52–80	1.2	3.45	404.7	3.1	14	2.39	10	25	33
Bt3	80–95	0.2	4.32	607.0	3.4	18	2.38	12	29	41
Pedon SDS 3										
Ap	0–15	0.8	17.82	1011.7	1.9	32	1.50	24	68	87
AC	15–40	0.4	20.19	1214.0	4.6	30	2.48	16	45	83
Pedon SDS 4										
Ap	0–15	1.0	13.00	1214.0	1.7	45	1.66	44	86	88
AC	15–35	0.6	20.19	607.0	1.9	56	1.50	43	68	87
C1	35–60	–	11.10	809.4	1.7	52	1.23	36	61	84
2C2	60–115	–	13.33	930.8	3.0	43	2.30	33	70	91
2C3	115–180	–	9.71	1011.7	2.6	37	2.15	31	67	81

Table 8 cont'd.

Horizon	Depth (cm)	Organic carbon (gkg^{-1})	Phosphorus		CEC		ECEC		BS	
			Avail. $\mu g\ g^{-1}$	Total $\mu g\ g^{-1}$	*Soil* Cmol(+)kg^{-1}	*Clay* Cmol(+)kg^{-1}	*Soil* Cmol(+)kg^{-1}	*Clay* Cmol(+)kg^{-1}	CEC (%)	ECEC (%)
					Sangiwa Dunes					
Pedon GDS 1										
Ap	0–33	1.4	3.06	1214.0	1.5	34	1.85	45	70	57
AC	33–65	0.2	3.66	1214.0	1.6	22	1.21	16	51	67
C1	65–108	0.8	3.91	627.2	1.7	16	1.59	15	46	50
C2	109–185	–	3.35	607.0	1.9	27	1.74	25	48	52
Pedon GDS 2										
Ap	0–24	1.0	5.25	4.4.7	1.4	21	1.63	26	74	63
AC	24–45	0.2	2.94	627.3	1.8	16	2.25	20	47	38
C1	45–100	0.8	2.35	627.3	2.8	19	3.02	21	36	34
C2	100–190	0.2	1.78	708.2	3.1	23	2.69	20	48	55
Bt3	80–95									
Pedon GDS 3										
Ap	0–21	1.2	3.35	809.4	1.5	22	1.66	25	84	76
AC	21–50	0.4	3.45	404.7	3.0	32	2.41	25	67	83
C1	50110	0.6	4.00	809.4	3.9	28	3.35	24	71	82
C2	110–160	0.2	3.77	505.9	3.5	26	3.22	24	69	75
Pedon SDS 4										
Ap	0–30	0.8	5.09	708.2	1.5	41	1.55	42	63	61
AC	30–60	0.6	3.15	809.4	1.8	18	1.73	17	41	42
C1	60–110	–	2.94	607.0	2.0	18	2.18	20	39	36
C2	110–160	–	2.55	1315.2	3.2	29	2.56	23	49	61



Plate 7: Calcium carbonate rings in the subsoil horizon of pedon LDS 3 of the Illela sand dunes, at Tungatundo village, indicative of incipient calcification in the soil.

leaching of bases beyond the surface horizons. This is because, the pH was not significantly correlated with organic carbon (r = 0.0695) (Table 21).

Soil pH measured in 0.1M $CaCl_2$ were in all cases lower than pH measured in water. This indicates small amount of positive charges in the soils (Bennema and Vettori, 1960). Their anion exchange capacity are therefore expected to be low. The values of delta pH [pH ($CaCl_2$) - pH (H_2O)] were negative in all cases and the mean (absolute values) was significantly higher (p=0.01) for the Sokoto dunes, being -1.15, than for the Illela and Sangiwa dunes; whose means were -0.4 and -0.3 respectively in the surface horizons. In the subsoil horizons, the mean of -0.98 for Sokoto dunes was significantly higher (p=0.01) than the mean of -0.74 for Sangiwa dunes but was at par with the mean of -0.82 for the Illela dunes, which was also in turn, at par with that of Sangiwa dunes. The low negative delta values observed in the surface soils of the Illela and Sangiwa dunes (i.e $\leq$ -0.5) indicate a dominance of their exchange sites by variable charge minerals (Uehara and Gillman, 1981).

5.3.2 Organic carbon

The ranges and means (in parentheses) for soil organic carbon for the Illela, Sokoto and Sangiwa dunes were, 0.8 to 2.0 (0.93), 0.8 to 1.4 (1.10), and 0.8 to 1.4 (1.10) g Kg^{-1} respectively in the Ap horizon. In the same order, subsoil values were trace to 1.0 (0.36), trace to 1.6 (0.65) and trace to 0.8 (0.33) g Kg^{-1}. The organic carbon contents of the soil differ significantly (p=0.01) between the Ap and subsoil horizons but not between dunes. The similarity in the contents of organic carbon between the dunes, may be attributed to the uniform vegetation and landuse pattern over the area studied. This is expected, since vegetation pattern is controlled by climatic factors (rainfall and temperature) which are uniform over short distances, as covered by the area studied (Whitaker *et al.*, 1968; Jenny, 1980 and Stevenson, 1982). Though values of organic

carbon varied irregularly with depth, there was a general decrease with profile depth (Table 8). The irregularity of organic carbon with depth is typical feature of soils formed in deposits accumulated intermittently.

The organic carbon contents of the soils were generally very low, less than 2.0 g Kg^{-1}. This low values are however, similar to values reported for the drier areas of the sudano-sahelian savanna (FAO, 1969; Ogunwale, 1973; Sombroek and Zonneveld, 1971; Odunze, 1987; Agbu and Ojanuga, 1989). The low values may be attributable to many factors, among which are the sparse natural vegetation (Sanchez, 1976) as a consequence of the low rainfall. Others include the high rate of organic matter mineralization as a result of the high temperature, while bush burning and the use of plant stalks for building purposes contribute to the destruction and removal of soil organic matter. Continuous cultivation, with little or no fallow periods, has also been documented to lead to organic matter depletion (Quantin, 1965; Ahn, 1970; Jones, 1971; Jones and Wild, 1975 and Bownan *et al.*, 1990).

5.3.3 Available and total phosphorus

The available phosphorus (P) values in the surface horizons, in the Illela, Sokoto and Sangiwa dunes, ranged from 14.97 to 46.36 (mean, 25.33), 6.02 to 17.87 (12.05) and 3.06 to 5.25 (4.24) µgP g^{-1} soil respectively. In the same order, subsoil values ranged from 11.57 to 318.58 (60.21), 3.05 to 20.19 (8.76) and 1.78 to 4.00 (3.15) µgP g^{-1} soil. The soils are therefore rated as medium to very high in available P in the illela dunes, low to medium in the Sokoto dunes and low in the Sangiwa dunes (Awotundun, 1973). The very high value of 318.58 µgP g^{1} soil is within the range of values also reported by FAO (1969) for soils within the Sokoto Basin. Apart from soils on Sangiwa dunes, the available P contents of the surface soils were mostly above 8 µgP g^{-1} soil. The soils are therefore moderately endowed with P in at least their surface horizons as also reported for

other soils in the Nigerian savanna (Bache and Rogers, 1970; Mokwunye, 1974; Udo and Ogunwale, 1977; Kparmwang, 1993). The P values decreased irregularly with depth except on pedon LDS 3 of the Illela dunes, which had a very high P content at depth, likely to be influenced by the underlying phosphatic sediments containing phosphorus nodules (Kogbe, 1979).

The relatively high P contents of the surface horizons compared to those of the subsoil horizons has been attributed to the higher organic matter contents in the Ap when compared to those of the subsoil horizons (Bhat, 1970; Oliver, 1972). However, as also reported by Kparmwarg (1993), available P had a non significant positive correlation with organic carbon (r= -0.0598) and a highly significant positive correlation with pH (r= 0.4577, p=0.001) (Table 21). This seems to indicate that the higher the pH, the less the amount of P fixed by oxides of iron and aluminum (Udo and Uzo, 1972) in acidic soils.

Total phosphorus in the surface soils in the Illela, Sokoto and Sangiwa dunes varied from 505.85 to 1011.70, 485.62 to 1214.04, and 404.68 to 1214.04 µgP g^{-1} soil respectively. The corresponding means were 733.48, 880.18 and 784.06 µgP g^{-1} soil. In the same order, the subsoil values were 465.38 to 1881.76 (mean, 887.18), 404.68 to 1214.04 (mean, 712.85) and 404.68 to 1315.21 (mean, 738.51) µgP g^{-1} soil. The means were not statistically different (P=0.05) between dunes (Tables 9a and 9b). This may be attributed to the similar mineralogy of the three dunes (Table 22). The values of total P were essentially very high when compared with values reported for other tropical soils (Enwezor and Moore, 1966; Uzu *et al.*, 1975; Udo and Ogunwale, 1977; Udo and Dambo, 1979) but compare well with values reported by Loganathan *et al.* (1987) for coastal plain sands in the Niger delta of Nigeria. The high values were attributed to the high phosphate contents of the parent material. In the Sokoto basin under study, phosphatic nodules have been reported (Kogbe, 1979) to be widespread and may be responsible for the high total P contents of the dune soils.

Table 9a: Mean values of surface soil properties of the dunes studied.

Soil property	Illela	Sokoto	Sangiwa	
pH (water)	5.83	5.88	5.40	NS
pH ($CaCl_2$)	5.43	4.73	5.10	NS
Organic carbon (gkg^{-1})	0.9	1.10	1.10	NS
Available P ($mg\ kg^{-1}$)	25.33	12.05	4.24	NS
Exch. Ca ($cmol(+)kg^{-1}$)	0.90	0.86	0.71	NS
Exch. Mg ($cmol(+)kg^{-1}$)	0.31	0.33	0.21	**
Exch. K ($cmol(+)kg^{-1}$)	0.07a	0.06a	0.12b	NS
Exch. Na ($cmol(+)kg^{-1}$)	0.04	0.03	0.03	NS
Exch. acidity ($cmol(+)kg^{-1}$)	0.38	0.40	0.60	NS
Total bases ($cmol(+)kg^{-1}$)	1.32	1.28	1.07	NS
CEC (soil) ($cmol(+)kg^{-1}$)	1.75	2.20	1.48	NS
CEC (clay) ($cmol(+)kg^{-1}$)	28.75	33.00	29.50	NS
ECEC (Soil) ($cmol(+)kg^{-1}$)	1.70	1.68	1.67	NS
ECEC (clay)($cmol(+)kg^{-1}$)	27.50	25.50	34.50	NS
BS (CEC) (%)	69.25	61.23	72.75	NS
EC (dSm^{-1})	0.11a	0.13b	0.09a	**
ESP (%)	2.25	1.50	2.25	NS
$CaCo_3$ (gkg^{-1})	7.75b	3.50a	5.75ab	**
Extractable Fe_p (%)	0.008	0.013	0.009	NS
Extractable Fe_{ox} (%)	0.11a	0.19b	0.06a	**
Extractable Fe_d (%)	0.48	0.54	0.18	NS
Extractable Al_p (%)	0.12a	0.47b	0.45b	**
Extractable Al_{ox} (%)	0.60	0.82	0.66	NS
Extractable Al_d (%)	0.73	1.12	0.81	NS
Avail. (HCl) Cu ($\mu g\ g^{-1}$)	2.35	2.39	1.46	NS
Avail. (HCl) Zn ($\mu g\ g^{-1}$)	7.13	6.60	6.11	NS
Avail. (HCl) Mn ($\mu g\ g^{-1}$)	20.33	28.13	21.60	NS
Avail. (HCl) Me ($\mu g\ g^{-1}$)	33.41	35.05	24.83	NS

NS = Not significant at P=0.05, * = P 0.05, ** = P 0.01

Table 9b: Mean values of surface soil properties of the dunes studied.

Soil property	Illela	Sokoto	Sangiwa	
pH (water)	6.15b	5.00a	4.47a	**
pH ($CaCl_2$)	5.32b	4.02a	3.73a	**
Organic carbon (gkg^{-1})	0.36	0.65	0.33	NS
Available P ($mg\ kg^{-1}$)	60.21b	8.76a	3.15a	*
Exch. Ca ($cmol(+)kg^{-1}$)	1.19	0.80	0.89	NS
Exch. Mg ($cmol(+)kg^{-1}$)	0.32	0.32	0.31	NS
Exch. K ($cmol(+)kg^{-1}$)	0.04a	0.05a	0.10b	**
Exch. Na ($cmol(+)kg^{-1}$)	0.04	0.03	0.05	NS
Exch. acidity ($cmol(+)kg^{-1}$)	0.44a	1.15b	0.98ab	*
Total bases ($cmol(+)kg^{-1}$)	1.59	1.20	1.34	NS
CEC (soil) ($cmol(+)kg^{-1}$)	2.77	3.12	2.53	NS
CEC (clay) ($cmol(+)kg^{-1}$)	38.54	28.31	22.83	NS
ECEC (Soil) ($cmol(+)kg^{-1}$)	2.02	2.36	2.33	NS
ECEC (clay)($cmol(+)kg^{-1}$)	28.38	20.77	20.83	NS
BS (CEC) (%)	51.08	41.08	51.00	NS
EC (dSm^{-1})	0.07	0.09	0.07	NS
ESP (%)	1.62ab	1.15a	1.92b	**
$CaCo_3$ (gkg^{-1})	6.69b	2.15a	5.92b	**
Extractable Fe_p (%)	0.014a	0.024b	0.018a	**
Extractable Fe_{ox} (%)	0.11a	0.22b	0.08a	**
Extractable Fe_d (%)	0.51	1.09	0.34	NS
Extractable Al_p (%)	0.38	0.38	0.33	NS
Extractable Al_{ox} (%)	0.75	0.71	0.68	NS
Extractable Al_d (%)	0.85	1.11	0.87	NS
Avail. (HCl) Cu ($\mu g\ g^{-1}$)	2.40	2.46	1.99	NS
Avail. (HCl) Zn ($\mu g\ g^{-1}$)	8.10	5.55	5.85	NS
Avail. (HCl) Mn ($\mu g\ g^{-1}$)	9.51a	21.18b	25.73b	**
Avail. (HCl) Me ($\mu g\ g^{-1}$)	36.57	37.10	18.69	NS

NS = Not significant at P=0.05, * = P 0.05, ** = P 0.01

5.3.4 Inorganic phosphorus fractions

The values of the phosphorus fractions and those of the extractable inorganic (active) fractions NH_4Cl - soluble (Adsorb-P), NH_4F - soluble (Al-P), NaOH - soluble (Fe-P) and H_2SO_4 - soluble (Ca-P), for all the soils, as well as their expression as percentages of total extractable inorganic P are shown in Tables 10 and 11 respectively. The results of the total extractable inorganic P, residual non-extractable inorganic P and organic P expressed as percentages of the total P in the soils are presented in Table 12.

The 0.5M NH_4Cl extractable P (adsorb-P) was the dominant extractable inorganic P (EIP) fraction in the Sokoto and Sangiwa dunes and the third most important in the Illela dunes (Table 10). Values of adsorb-P varied from 16.58 to 414.62 (mean, 128.53), 16.58 to 82.92 (mean, 45.67) and 16.58 to 66.34 (mean, 47.68) µgP g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. Correspondingly, as a percentage of EIP, it varied from 15.5 to 29.7 (mean, 22.9), 23.8 to 83.7 (49.0) and 22.7 to 55.8(41.7) percent. Values of adsorb-P were generally lower than 90 µgP g^{-1} soil in all the soils except in the subsoil horizon (C2) of pedon LDS 3, which had a value of 414.62 µg g^{-1}. The difference in means between the dunes was not significant (P=0.05). The higher values in the Illela dunes than the other two dunes, may be attributed to the near neutral soil reaction and the occurrence of phosphatic rocks underneath the dunes. The abnormally high value obtained for horizon C2 in pedon LDS 3 is also attributable to the phosphatic rock at depth (Kogbe, 1979). Largely, the surface soil values were higher than or equal to the corresponding subsoil values, except again in pedon LDS 3. The more neutral soil reaction in the surface soils compared to the subsoil reaction, is probably responsible for the relatively high values (Smeck, 1973). Udo (1981) has also reported a similar dominance of adsorb-P, over the other forms of EIP, in some Nigerian soils. The relatively high values of adsorb-P indicate that these soils maintain adequate labile P.

Table 10: Phosphorus fractions of selected pedons.

Horizon	Depth (cm)	Adsorb-P µg g^{-1}	Al-P µg g^{-1}	Fe-P µg g^{-1}	Ca-P µg g^{-1}	Organic-P µg g^{-1}	Total-P µg g^{-1}	Res-P µg g^{-1}
				Illela Dunes				
Pedon LDS 1								
Ap	0-28	16.58	29.37	0.71	20.77	20.09	1011.70	924.10
C2	142-175	16.58	46.15	32.05	12.46	20.32	708.19	580.63
Pedon LDS 3								
Ap	0-27	66.34	67.13	96.14	76.86	20.09	505.85	179.29
C2	130-210	414.62	495.06	78.34	407.17	0.0	1881.76	486.57
				Sokoto Dunes				
Pedon SDS 1								
Ap	0-22	82.92	12.87	49.85	35.32	70.32	485.62	234.34
Bt2	56-85	16.58	1.68	0.71	0.83	20.09	1011.70	971.81
Pedon SDS 4								
Ap	0-15	66.58	46.15	42.73	0.83	60.28	1214.04	997.47
2C2	60-115	16.58	50.34	0.71	2.08	0.0	930.76	861.05
				Sangiwa Dunes				
Pedon GDS 1								
Ap	0-3	66.34	33.56	32.05	14.53	120.55	1214.04	947.01
C1	65-108	66.34	12.59	39.17	0.83	0.0	627.25	508.32
Pedon GDS 4								
Ap	0-30	41.46	41.95	12.46	0.83	20.09	708.19	591.40
C1	60-110	16.58	33.56	12.46	10.39	0.0	647.49	574.50

Table 11: Extractable inorganic phosphorus fractions as percentages of the total extractable inorganic phosphorus.

Horizon	Depth (cm)	Adsorb-P (%)	Al-P (%)	Fe-P (%)	Ca-P (%)
		Illela Dunes			
Pedon LDS 1					
Ap	0-28	24.6	43.6	1.1	30.8
C2	142-175	15.5	43.0	29.9	11.6
Pedon LDS 3					
Ap	0-27	21.6	21.9	31.4	25.1
C2	130-210	29.7	35.5	0.6	29.2
		Sokoto Dunes			
Pedon SDS 1					
Ap	0-22	45.8	7.1	27.5	19.5
Bt2	56-85	83.7	7.1	3.6	4.2
Pedon SDS 4					
Ap	0-15	42.6	29.5	27.3	0.5
2C2	60-115	23.8	72.2	1.0	3.0
		Sangiwa Dunes			
Pedon GDS 1					
Ap	0-33	45.3	22.9	21.9	9.9
C1	65-108	55.8	10.6	32.9	0.7
Pedon GDS 4					
Ap	0-30	42.9	43.4	12.9	0.9
C1	60-110	22.7	46.0	17.1	14.2

Table 12: Total extractable inorganic P, residual P and organic P as percentages of the total phosphorus.

Horizon	Depth (cm)	Total Ext. Inorganic-P (%)	Residual-P (%)	Organic-P (%)
		Illela Dunes		
Pedon LDS 1				
Ap	0-28	6.67	91.35	1.99
C2	142-175	15.14	81.99	2.87
Pedon LDS 3				
Ap	0-27	60.59	35.44	3.97
C2	130-210	74.14	25.86	0.0
		Sokoto Dunes		
Pedon SDS 1				
Ap	0-22	37.26	48.26	14.48
Bt2	56-85	1.96	96.06	1.99
Pedon SDS 4				
Ap	0-15	12.87	48.26	14.48
2C2	60-115	7.49	96.06	1.99
		Sangiwa Dunes		
Pedon GDS 1				
Ap	0-33	12.07	78.00	9.93
C1	65-108	18.96	81.04	0.0
Pedon GDS 4				
Ap	0-30	13.65	83.51	2.84
C1	60-110	11.27	88.73	0.0

The Al-P (NH_4F extractable P) was the most abundant EIP fraction in the Illela dunes and next to adsorb-P, in amount, in the Sokoto and Sangiwa dunes. It constituted about 21.9 to 43.6 (mean, 36.0), 7.1 to 72.2 (29.0) and 10.6 to 46.0 (30.7) percent, of the total EIP, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding values, varied from 29.37 to 495.06 (mean, 159.43), 1.68 to 50.34 (27.76) and 12.59 to 41.95 (30.42) µgP g^{-1} soil. The means were not significantly different (P=0.05), but higher Al-P values were obtained for the more neutral to alkaline soils (i.e Illela dunes) than for acid soils, and in pedons overlying phosphatic rocks - pedon LDS 3. Similar findings have also been reported by Uyovbisere (1979) for some savanna soils. The trend in distribution of Al-P was similar to those of CBD-extractable Al and the high positive correlation between them (r= 0.9629, P=0.001) may suggest that Al-P was contributed largely from Al_d.

The Fe-P (NaOH extractable P) was generally lower than the corresponding values of Al-P in the soils (Table 10). Amounts of Fe-P ranged from 0.71 to 96.14 (mean, 51.81), 0.71 to 49.85 (23.50) and 12.46 to 39.17 (24.04) µg g^{-1}, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding percentages of the total EIP, varied from 0.6 to 31.4 (mean, 15.8), 1.0 to 27.5 (mean, 14.9) and 12.9 to 32.9 (mean, 21.2) percent. The means were not significantly different (P=0.05). The relatively lower values of Fe-P indicate moderate to high degree of weathering (Hawkins and Kunze, 1965). The higher contents of Al_d over Fe_d may also be responsible for the lower Fe-P in the soils. The higher values of Fe-P in the Illela dunes with alkaline reaction over those of Sangiwa and Sokoto dunes with acidic reaction, perhaps signify that most of the Fe-P in the acid soils are in the occluded forms (Smeck, 1973; Enwezor, 1977) and are therefore not extractable.

The H_2SO_4 extractable P (Ca-P) was generally the lowest EIP fractions in the soils, except on the more neutral to alkaline soils of Illela dunes. Ca-P values and means (in parentheses),ranged from 12.46 to 407.17 (129.32), 0.83 to 35.32 (9.77) and 0.83 to 14.53 (6.65) µgP g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The

corresponding percentages of the total EIP, varied from 11.6 to 30.8 (24.2), 0.5 to 19.50 (6.8) and 6.7 to 14.2 (6.4) percent. The low percentages of Ca-P support the hypotheses that these soils are highly weathered (FAO, 1969; Sombroek and Zonneveld, 1971).

The residual (non-extractable) P was the most abundant of all the phosphorus fractions in all the soils (Tables 9 and 10). Amounts varied from 486.57 to 924.18 (mean, 542.67), 234.34 to 971.81 (mean, 766.17) and 508.32 to 947.01 (mean, 655.31) $\mu gP\ g^{-1}$ soil, in the Illela, Sokoto and Sangiwa dunes respectively. As a percentage of the total P, residual P varied from 25.86 to 91.35 (58.66), 48.26 to 96.06 (79.75) and 78.00 to 88.73 (82.82) percent, in the Illela, Sokoto and Sangiwa dunes respectively. The means were not significantly different but the higher values of residual P in the Sokoto dunes may be attributed to the greater pedogenic age and the strongly acid soil reactions. The values of residual P are generally high but are within the range reported for other soils in Nigeria (Udo, 1977; Udo and Ogunwale, 1977).

The relative abundance of the different inorganic forms of P is related to the extent of pedogenetic processes in the soils (Chang and Jackson, 1958; Hawkins and Kunze, 1965; Smeck, 1973). The residual P was, in the main, about 20 times more in amounts than Al-P, which in turn was about twice greater than the amounts of Fe-P and Ca-P (Table 10). The relationship between the inorganic fractions, for the Sangiwa and Sokoto dunes, could simply be stated thus: Occluded-P >>> Adsorb-P > Al-P > Fe-P > Ca-P, while on the Illela dunes, it is : Occluded-P >>> Al-P > Adsorb-P = Ca-P > Fe-P (Figure 3). This sequence of abundance indicates that the soils are essentially highly weathered but the dominance of Ca-P over Fe-P in the Illela dunes place them as the least weathered of the three dunes.

b) Organic phosphorus

The organic P was low in all the soils and contributed not more than 15 percent to the total P (Table 12). The low values are a reflection of the relatively low organic matter contents of the soils and are in agreement with values also reported by Udo (1977) for some Nigeria soils. The C:P ratios calculated for the soils are well below 50 indicating a possibility of mineralization of organic P in these soils (Enwezor, 1967). As also

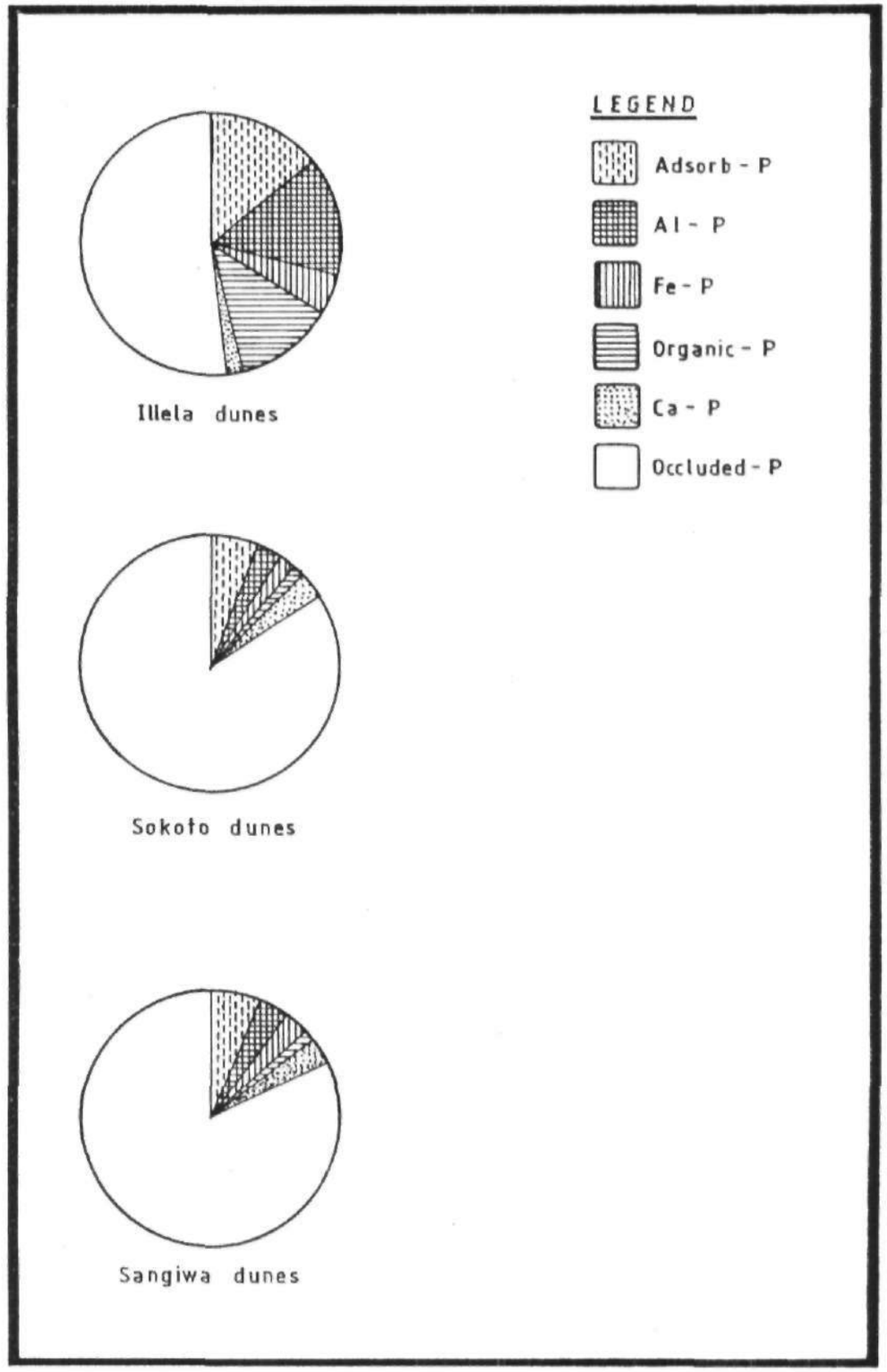


Fig. 3. Phosphorus fractions in the dune soils.

reported by Smeck (1973), organic-P becomes an important fraction of the extractable-P in soils with increasing weathering and age. Except on the Illela dunes, which are pedogenically the youngest and have an alkaline soil reaction, the organic-P was the most abundant of the extractable fractions after the adsorbed-P (Figure 3) in the Sokoto and Sangiwa dunes. With proper organic matter management, organic-P would continue to be the major source of available phosphorus within the basin.

Statistical analyses reveal significant correlations between adsorb-P and Ca-P, Al-P and Fe-P but non significant correlation with organic P (Table 13). The correlation values do indicate that the adsorb-P are largely contributed by these forms of active inorganic P. The reasons for the significant correlation between Al-P, Ca-P and exchangeable Ca (Table 13) are not very clear. The significant correlation may however, be fortuitous simply because Al-P is the first fraction to be extracted after adsorb-P (Smeck, 1973). There was also significant correlation between organic P and organic carbon and between Ca-P and exchangeable Ca (Table 13).

5.3.5 Phosphate adsorption characteristics

The plots of adsorbed phosphates against phosphate concentration in solution are shown in Figure 4. In all cases, gentle curves were obtained with a gentle slope following a much steeper one. This indicates a relatively higher sorption of phosphate at low solution concentration of added phosphate and a decrease in rate at higher concentration. This is, invariably, the case as reported by several other workers (Bache and Williams, 1971; Rhodes, 1975; Udo, 1981; and Loganathan *et al*, 1987). The percentages of added phosphate sorbed decreased from about 92 at the lowest level to 75 at the highest concentration - 128 $\mu g\ g^{-1}$, for all the soils (Figure 5). Similar findings have also been reported by Kparmwang (1993) for sulphate in some basaltic soils in Nigeria. There was no significant difference (P=0.05) in the mean amounts of sorbed phosphate between dunes and between the surface and subsoil horizons. This indicates that the soils have similar capacities to sorb phosphate. The means for the soils studied were 51.91, 52.02

Table 13: Correlation matrix for phosphorus fractions and some soil properties.

	Ads-P	Al-P	Fe-P	Ca-P	Org-P	Tot-P	pH	Clay	Oc	Ca^{2+}	Fe_d	Al_d	
Al-P	.962***												
Fe-P	.601*	.507											
Ca-P	.971***	.983***	.586*										
Org-P	-.112	-.258	.092	-.227									
Tot-P	.724**	.760**	.110	.697*	.076								
Res-P	-.277	-.206	-.677*	-.308	.224	.448							
pH	.641*	.608*	.459	.566*	.316	.659*	.061						
Clay	-.099	-.111	-.182	-.049	-.312	-.140	-.024	-.492					
Oc	.243	.023	.462	.130	.572*	.054	-.205	.311	-.129				
Ca^{2+}	.818**	.831**	.648*	.833**	-.167	.585*	-.280	.781**	-.099	.117			
Fe_d	.170	.142	.336	.250	-.217	-.008	-.255	-.093	.737**	.244	.329		
Al_d	-.170	-.255	.297	-.136	.252	-.449	-.448	.058	.267	.338	.181	.530	
Adsorption	.285	.392	.252	.317	-.363	.190	-.140	.433	-.238	-.285	.585*	-.079	-.027

Significant levels, * = P 0.05, ** = P 0.01, *** = P 0.001

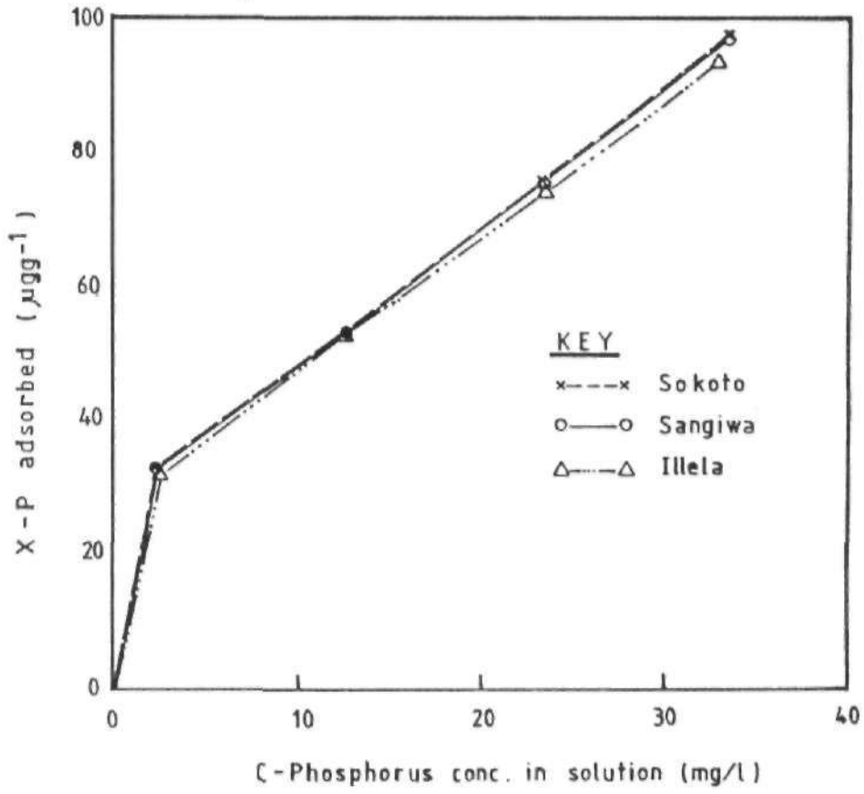


Fig. 4. Relationship between phosphate adsorbed and equilibrium phosphate solution.

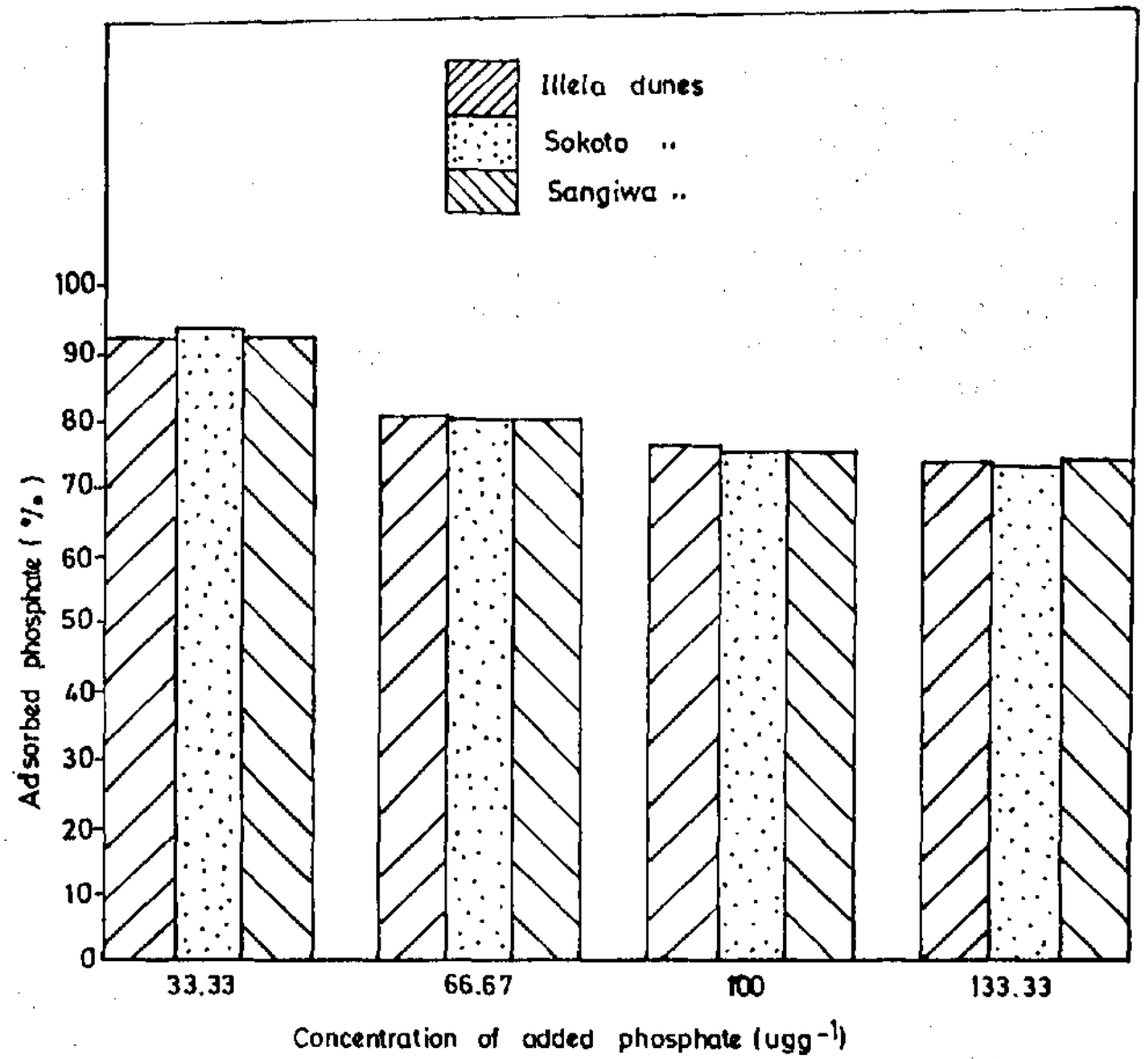


Figure 5 . Mean percentages of added phosphate adsorbed

and 52.17 μg g^{-1}, in the Illela, Sokoto and Sangiwa dunes respectively. The near equal capacities of the soils to sorb phosphate may be attributed to their similar contents of soil properties, such as clay, oxides of Fe and Al, organic carbon, pH known to affect phosphate adsorption (Loganathan *et al.*, 1987). Non significant correlation was observed between adsorption and most soil properties (Table 13). This lack of significant correlation was attributed to the overwhelming effect from other soil properties, most probably Al_{ox} and Fe_p in this study (Van-der Zee and Van Riemsdijk, 1986; Borggaard *et al.*, 1990). The negative correlation between adsorption and the oxides of Fe and Al, indicates that as the content of these oxides increases, there is a corresponding decrease in adsorption. This most probably indicate the coating of more reactive P-sorption sites in the soils by these oxides(Fox and Kamprath, 1970; Gallez *et al.*, 1976; Juo and Fox, 1977).

An attempt at transforming the phosphate adsorption data into one of the adsorption equations showed that the data fit more into the Langmuir equation. The standard form of the Langmuir equation is given below.

$$C/X = 1/kb + C/b$$

where, X = amount of phosphate adsorbed (μg g^{-1})

C = equilibrium concentration of phosphate (μg/L)

b = slope or the maximum amount of phosphate that can be sorbed

k = a constant relating to bond energy of adsorption.

A plot of C/X against C is expected to give a straight line. But several workers (Bache and Williams, 1971; Barrow, 1978, 1985) have observed that in practice, gentle curves are obtained (Figure 6). The Langmuir transformations of the adsorption isotherms and the regression equations are presented in Figure 6 and Table 14 respectively.

The slope, 1/b, of the isotherms which are taken as the adsorption indexes for the soils are given in Table 15. They ranged from 99.3 mg per Kg soil for the Sokoto dunes

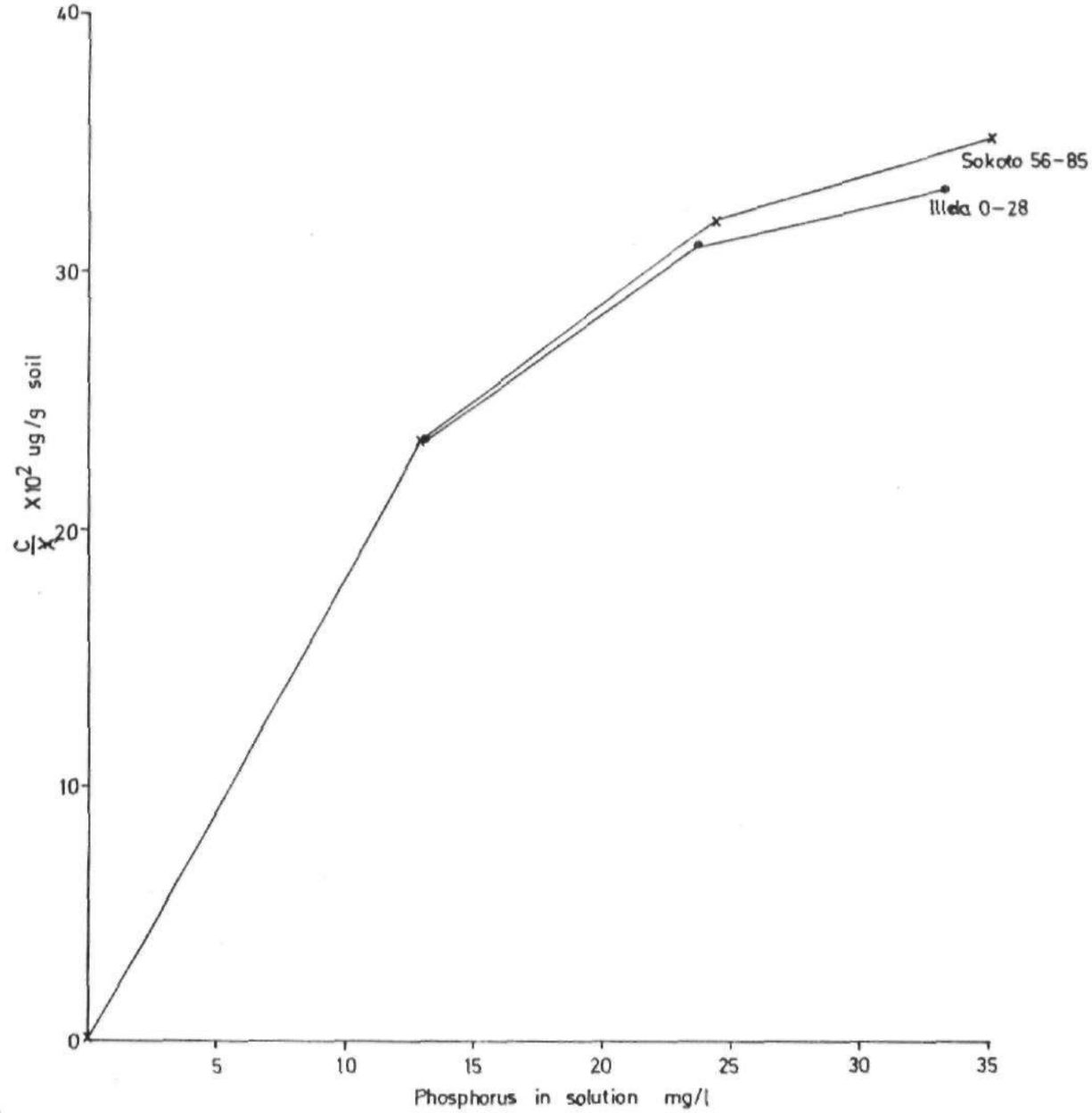


Figure 6. Phosphorus adsorption isotherms for selected horizons plotted according to Langmuir equation 1.

Table 14: Langmuir isotherms best fit equation for phosphate adsorption.

Horizon	Depth (cm)	Equation	r^2 value
		Illela Dunes	
Ap	0-28	$Y = 0.050 + 9.789 \times 10^{-3} X$	0.9453
C2	142-175	$Y = 0.049 + 9.856 \times 10^{-3} X$	0.9509
		Sokoto Dunes	
Ap	0-22	$Y = 0.051 + 9.891 \times 10^{-3} X$	0.9469
Bt1	56-85	$Y = 0.046 + 1.000 \times 10^{-3} X$	0.9541
		Sangiwa Dunes	
Ap	0-33	$Y = 0.053 + 9.796 \times 10^{-3} X$	0.9459
C1	65-108	$Y = 0.046 + 9.974 \times 10^{-3} X$	0.9521

Table 15: Phosphorus adsorption characteristics of the dune soils.

Horizon	Depth (cm)	P sorbed at 0.3 mg/l solution conc. (mg/kg)	Langmuir constants	
			b (l/mg)	k (l/mg)
		Illela Dunes		
Ap	0-28	18.75	102.2	0.050
C2	142-175	19.12	101.5	0.049
		Sokoto Dunes		
Ap	0-22	18.63	101.1	0.051
Bt1	56-85	20.46	99.3	0.046
		Sangiwa Dunes		
Ap	0-33	17.73	102.1	0.053
C1	65-108	20.46	100.3	0.046

to 102.2 mg per Kg soil for the Illela dunes. These values indicate very low capacity of the soils to sorb P. The values are again lower than those reported by Udo and Uzo (1972), Udo (1981) and Loganathan *et al.* (1987), for some Nigerian soils and by Rhodes (1975) for some Sierra Leone soils but compare well with values reported by Enwezor and Moore (1966). These low sorption capacities of the soils are probably due to the coarse or sandy texture of the soils, their low clay and Fe and Al oxides contents. Standard P requirements for soils have been calculated by several workers using a single solution P concentration of between 0.2 and 0.8 mg/L. Following the suggestion of Mokwunye (1977), 0.3 mg/L was selected for these soils because of the sandy nature. The amount of P required to maintain these 0.3 mg/L in solution is also presented in Table 15. The values once again are very low and indicate that the soils require only low application of P fertilizers at a time. The values varied from 17.73 mg per Kg on the Sangiwa dunes to 20.46 mg per Kg on the Sokoto dunes.

The constant, k, which relate to the bond energy of adsorption, varied from 0.046 in the Sokoto dunes to 0.053 in the Sangiwa dunes. The k values were generally similar between dunes, but it showed that the acid soils and the surface soils held the adsorbed phosphate with greater bonding energy than the more neutral dunes (Olsen and Watanabe, 1957) and the subsoils. These bond energies are also low when compared to values obtained for other soils in Nigeria (Udo, 1981; Loganathan *et al.*, 1987).

In effect, the dune soils studied had relatively high total P because of the occurrence of phosphatic rocks within the area, but the bulk of these are found as occluded P. This has been attributed to the highly weathered nature of the soil parent materials. Organic P contents were also very low as a result of the low organic matter contents of the soils, but possible organic P mineralization is indicated by the very low C:P ratios (range from 9.8 to 49.7). The three dune soils have very similar P sorption characteristics. They had virtually the same P sorption capacities, about 100 mg/Kg soil

in terms of the calculated maxima, about 20 mg/Kg soil at standard P solution concentration, and 0.05 for the bond energy. The low levels indicate a limited capacity of the soils to continuously renew the soil solution with P. The similarity in the P characteristics of the soils has been attributed to their similar soil properties, which in most cases were not significantly different (P=0.05) between the dunes (Tables 9a and 9b).

5.3.6 Exchange acidity

The ranges in values and the corresponding means (in parentheses) for exchange acidity in surface soils were 0.1 to 0.8 (0.38) for the Illela dunes, 0.2 to 0.6 (0.40) for the Sokoto dunes and 0.4 to 0.8 (0.60) cmol(+) Kg^{-1} soil in the Sangiwa dunes. In the same order, the subsoil values were 0.1 to 1.0 (0.44), 0.2 to 3.4 (1.15) and 0.4 to 2.0 (0.98) cmol(+) Kg^{-1} soil. The means were not significantly different in the surface horizons (Table 9a) but in the subsoil horizons, the means for Sokoto was higher than that of Illela but was at par with that for Sangiwa dunes while the means for Sangiwa dunes were also at par with that of Illela dunes (Table 9b). The ranking of exchange acidity among dunes is similar to the ranking of pH. This would seem to suggest that the Sokoto dunes have lost more bases than the other dunes, attributable to higher weathering intensity because of its flat topography. Sanchez (1976) observed that at pH 5.5 to 6.0, exchangeable aluminum in tropical soils precipitate out of the soil solution as insoluble gibbsite. Hence, the higher the pH, the lower the content of exchange acidity. With the pH range observed in the dune soils, reserve acidity will not be a problem in the soils (Balasubramanian *et al.*, 1984).

5.3.7 Exchangeable bases

The data on exchangeable bases are presented in Table 7. Calcium was the dominant exchangeable basic cation in all the soils. The values and means (in parentheses)

in the surface soils were, 0.32 to 1.40 (0.90), 0.76 to 0.95 (0.86) and 0.58 to 0.90 (0.70) cmol(+) Kg^{-1} soil. In the same order, the subsoil values were 0.30 to 2.46 (1.19), 0.55 to 1.42 (0.80) and 0.42 to 2.02 (0.89) cmol(+) Kg^{-1} soil. These values are rated as very low in soils with acidic reaction and low in those with alkaline soils reaction as obtained in pedons LDS 3 and LDS 4 (Awotundun, 1973). These low values could probably be due to the dearth of calcium containing minerals such as calcite and feldspars. The subsoil values were generally higher than the surface values and this could be attributed to leaching processes. Though, the differences between the means were not significant (P=0.05), the means tended to be related to the differences in the leaching intensity brought about by differences in meso-relief. Thus, the Sokoto dunes with a flat topography had the lowest content of exchangeable Ca while the Illela dunes with a pronounced meso-relief had the highest values.

Magnesium (Mg) ranked next to exchangeable Ca on the exchange complex, in all the soils. Its value in surface soils ranged between 0.1 and 0.5 (mean, 0.3) on the Illela dunes, 0.26 and 0.39 (mean, 0.33) on the Sokoto dunes and 0.19 and 0.22 (mean, 0.21) cmol(+) Kg^{-1} soil on the Sangiwa dunes. In the same order, the subsoil values were,0.08 and 0.73 (0.32), 0.17 and 0.78 (0.32), and 0.16 and 0.61 (0.31) cmol(+) Kg^{-1} soil. The values were generally low to medium in all the soils with the means at par (P=0.05) between dunes. The low values and the similarity in the exchangeable Mg contents between the dunes perhaps may be due to the dearth of ferromagnesian and feldspathic minerals in all the soils (Table 22). This result tend to corroborate the widespread Mg deficiencies reported by Ogunwale *et al.* (1975) and Lombin and Fayemi (1976) for the Nigerian savanna. Many researchers, however, consider the exchangeable Mg/K ratio and exchangeable magnesium percent (EMP) along side the absolute values of exchangeable Mg, in determining Mg availability (Adams and Henderson, 1962; Prince *et al.*, 1947; Lombin and Fayemi, 1975, 1976). The Mg/K ratio and EMP equal to or less than 0.8 and 6 respectively have been set as critical levels at which yields are affected. The means of

EMP for the Illela, Sokoto and Sangiwa dunes in the surface horizons were 17.71, 15.00 and 14.91 percent respectively. In the subsoil, the corresponding values were 11.55, 10.26 and 12.25 percent. In the same order, the exchangeable Mg/K ratios were 4.4, 5.5 and 1.7 (in surface horizons), and 8.0, 6.4 and 3.1 (in subsoil horizons). From these values of EMP and Mg/K ratios, it would seem that, though the exchangeable Mg values were rated as being low to medium, the soils would be capable of maintaining adequate Mg levels under the present subsistence farming.

Potassium in the surface soils ranged from 0.02 to 0.13 (mean, 0.07), 0.02 to 0.08 (0.06) and 0.08 to 0.16 (0.12) cmol(+) Kg^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding subsoil values varied from 0.02 to 0.07 (0.04), 0.02 to 0.06 (0.05) and 0.06 to 0.14 (0.10) cmol(+) Kg^{-1} soil. All the values are rated as very low but are in the range of values reported by Wild (1971) for some sandstone derived soils. These very low values may be ascribed largely to the scarcity of feldspathic minerals in the sandstone parent rock from which the parent materials for the three dunes were derived (FAO, 1969). The surface soil values were higher, but not significant, than the subsoil values. The means for Sangiwa dunes were higher (P=0.01), both in the Ap and in the subsoil horizons, than the means for the Illela and Sokoto dunes, which were in turn at par. The is a close resemblance in the distribution pattern of exchangeable K in the soils similar to that of silt. This would seem to suggest that silt also contribute to the exchange sites for exchangeable K as suggested by Scott (1962) for some soils in East Africa. The higher exchangeable K values in the Ap horizons may be attributable to the higher organic matter content though the correlation with organic carbon (r= 0.2538) was not significant. Similar findings have been reported for the Nigerian savanna (Ogunwale *et al.*, 1975; Esu, 1982; Kparmwarg, 1993). Similar to exchangeable Mg, exchangeable potassium percent (EPP) is used along side the absolute values of exchangeable K in assessing the K needs of the soils. Boyer (1972) gave an EPP value of 2 to be the limit between K deficient and K adequate soils. The means of EPP in the surface soils in the Illela, Sokoto and Sangiwa dunes were 4.0, 2.7 and 8.1 percent respectively. In the same order, the subsoil values were 1.4, 1.6 and 3.9 percent. Potassium therefore, seems to be

marginally adequate to deficient in the Illela and Sokoto dunes and marginally adequate to adequate in the Sangiwa dunes. It could therefore, be concluded with some degree of certainty that incipient K deficiency is likely in these soils under intensive cultivation.

Exchangeable Sodium was the least on the exchange sites of all the soils. In the surface horizons, the ranges in values were from 0.02 to 0.07, 0.03 to 0.04 and 0.03 to 0.04 cmol(+) Kg^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding means were 0.04, 0.03 and 0.03 cmol(+) Kg^{-1} soil. In the same order, the subsoil values varied from 0.03 to 0.07 (mean, 0.04), 0.02 to 0.06 (mean, 0.03) and 0.03 to 0.07 (mean, 0.05) cmol(+) Kg^{-1} soil. This indicates a very low level of exchangeable sodium in all the soils. There was irregular distribution of exchangeable Na down the profile with subsoil values generally being higher than surface soil values. All the exchangeable bases except potassium, exhibited similar trend and this tend to suggest that they are better retained on clay, which increased down the profiles, than organic matter. The exchangeable Na values are essentially comparable to values reported by Kparmwang (1993) for basaltic soils, Ogunwale and Ashaye (1975) and Ogunwale *et al.* (1975) for sandstone derived soils.

Commonly, the exchangeable bases occurred in the order Ca > Mg > K > Na as earlier reported by other workers for soils in the Nigerian savanna (Ogunwale *et al.*, 1975; Ojanuga and Awujoola, 1979; Esu, 1982, 1986). The ranges in values in surface soils and the means (in parentheses) for the total exchangeable bases were 0.46 to 1.96 (1.32), 1.11 to 1.46 (1.28) and 0.95 to 1.26 (1.07) cmol(+) Kg^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding values and means in the subsoils were 0.43 to 2.94 (1.59), 0.79 to 2.06 (1.20) and 0.85 to 2.75 (1.34) cmol(+) Kg^{-1} soil. Subsoil values were generally higher than surface soil values, indicating that the exchangeable bases were subjected to leaching processes. The differences between the means, both in the surface and subsoil horizons, were not statistically significant (P=0.05) (Tables 7 and 8) but were in the order, Illela > Sangiwa > Sokoto, indicating better base status of the soils in that order.

5.3.8 Cation exchange capacity

The cation exchange capacity (CEC) by ammonium acetate method in the Ap horizons varied from 1.0 to 2.5 (mean, 1.75), 1.7 to 2.9 (2.20) and 1.4 to 1.5 (1.48) cmol(+) Kg^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding subsoil values varied from 1.1 to 4.0 (2.77), 1.7 to 4.6 (3.12) and 1.6 to 3.9 (2.53) cmol(+) Kg^{1} soil. These values are rated as very low for the soils (Awotundun, 1973). The CEC values were not significantly different between the dunes but subsoil values were significantly higher (P=0.01) than surface soil values except for the Sokoto dunes, in which both values were at par. The higher subsoil values are attributable to their higher clay contents (Table 4) while the low surface soil values are attributed to the low organic matter contents of the soils. A positive correlation (r=0.9014, P=0.05) between the CEC and clay and the negative non-significant correlation between CEC and organic carbon, indicate that clay is the major contributor to the CEC of the soils. A possible contribution of sesquioxide to the CEC is shown by the positive significant correlation between CEC and Fep (r=0.8973, P=0.05).

Effective CEC (ECEC) values of the surface soils ranged between 0.66 and 2.73 (mean, 1.70), and 1.50 and 1.84 (mean, 1.68), and 1.55 and 1.85 (mean, 1.67) cmol(+) Kg^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively (Table 7). The corresponding subsoil values, varied from 0.88 to 3.14 (mean, 2.02), 1.23 to 4.22 (2.36) and 1.21 to 3.35 (2.33) cmol(+) Kg^{-1} soil. The means were generally low and did not differ significantly between dunes. The ECEC was largely, lower than the CEC but in most cases, the difference was less than 30 percent. This seems to reflect a moderate degree of base saturation and may be attributed to the well known phenomenon that the CEC of tropical soils is highly pH dependent i.e pH dependent CEC increases with pH (Balasubramanian *et al.*, 1984). The ECEC values, like those of CEC also increased down the profile, for similar reasons.

The CEC values per Kg of the clay in the surface soils ranged from 24 to 36 cmol(+) Kg^{-1} clay in the Illela dunes, 20 to 45 cmol(+) Kg^{-1} clay in the Sokoto dunes and 21 to 41 cmol(+) Kg^{-1} clay in the Sangiwa dunes. The corresponding means were 28.75, 33.00 and 29.50 cmol(+) Kg^{-1} clay respectively. In the same order, the subsoil values varied from 16 to 77 (mean, 38.54), 14 to 56 (28.31) and 16 to 32 (22.83) cmol(+) Kg^{-1} clay. These values are moderate and indicate that the soils may contain ample amounts of halloysite or traces of smectites in addition to kaolinite (Grim, 1968; Sombroek and Zonneveld, 1971).

The effective CEC per Kg of the clay in the surface soils ranged from 13 to 36 (mean, 27.50), 14 to 44 (25.50) and 25 to 45 (34.50) cmol(+) kg^{-1} clay, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding subsoils values also varied from 8 to 60 (mean, 28.38), 10 to 43 (mean, 20.770 and 17 to 25 (mean, 20.83) cmol(+) Kg^{-1} clay. These values are generally greater than the less than 12 cmol(+) Kg^{-1} clay specified by the Soil Survey Staff (1975, 1990), for highly weathered soils. This in effect, shows that the soils possibly still have moderate weathering potential.

5.3.9 Base saturation

The values of base saturation (CEC-NH_4OAc) for surface soils ranged from 46 to 95 (mean, 69.25), 43 to 86 (61.25) and 63 to 84 (72.75) percent, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values ranged from 21 to 75 (mean,51.08), 22 to 70 (41.08) and 36 to 71 (51.00) percent (Table 7). The base saturation for all the soils are therefore rated as low to moderate. There was a general decrease of base saturation with profile depth and such difference was significant (P=0.01) only for the Sangiwa dunes (Tables 9a and 9b). The subsoil clay and CEC values for Sangiwa dunes, were about 2.5 times their surface soil values and this may be responsible for the observed significant difference in its base saturation between depths, since base saturation had a negative significant correlation with clay (r= -0.5964, P= 0.001). The higher surface

soil values of BS may be due to their higher organic matter contents (Scott, 1962). Malgwi (1979) also observed such trend in the Zaria area.

The ranges and means (in parentheses) for base saturation (ECEC) in the surface soils varied from 70 to 95 (76.50), 65 to 88)76.75) and 57 to 76 (64.25) percent, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values varied from 39 to 96 (69.62), 19 to 91 (55.45) and 34 to 83 (56.25) percent. These values are similar to those obtained by the CEC-NH_4OAc method and indicate a near-equal distribution of exchangeable bases and exchange acidity in the soils. The means, like those of CEC-NH_4OAc, also decreased down the profile but such differences were not significant (P=0.05) between the dunes. This reflects the similar levels of leaching of bases and soil reaction in all the soils.

5.4 Salt Related Properties

Soil properties treated under this section are integral part of the chemical properties but because of the importance of salt accumulation in aeolian materials, they are treated separately. The following properties are considered; electrical conductivity, exchangeable sodium percent and free carbonate. Data on these properties are given in Table 16 and are discussed subsequently.

5.4.1 Electrical conductivity (EC)

The ranges and means (in parentheses) for electrical conductivity in the surface soils varied from 0.10 to 0.13 (0.11), 0.07 to 0.24 (0.13) and 0.04 to 0.10 (0.09) dS m^{-1}, in the Illela ,Sokoto and Sangiwa dunes respectively. The corresponding subsoil values also varied from 0.06 to 0.10 (0.070, 0.06 to 0.16 (0.09) and 0.03 to 0.10 (0.07) dS m^{-1}. These indicate very low values of electrical conductivity (Soil Survey Staff, 1975, 1990). The surface values were higher than the subsoil values and this may be attributed to the aeolian addition to the surface soil and the higher organic matter contents (Dewon and

Table 16: Electrical conductivity, exchangeable sodium percent (ESP) and free carbonate equivalent of pedons studied.

Horizon	Depth (cm)	Electrical conductivity (dS m^{-1})	Exch. sodium percentage (%)	Free carbonate equivalent (mg kg^{-1})
		Illela Dunes		
Pedon LDS 1				
Ap	0-28	0.10	2	5
Ac	28-63	0.06	3	5
C1	63-142	0.06	2	8
C2	142-175	0.06	2	8
Pedon LDS 2				
Ap	0-18	0.10	3	8
AB	18-52	0.07	3	6
Bt1	52-95	0.07	1	7
Bt2	95-170	0.06	2	10
Pedon LDS 3				
Ap	0-27	0.10	3	8
AC	27-73	0.10	1	8
C1	73-130	0.10	1	9
C2	130-210	0.08	1	9
Pedon LDS 4				
Ap	0-12	0.13	1	10
AC	12-60	0.07	1	6
C1	60-100	0.06	1	2
C2	100-140	0.08	2	6
C3	140-190	0.07	1	3
		Sokoto Dunes		
Pedon SDS 1				
Ap	0-22	0.24	1	5
AB	22-39	0.06	1	6
Bt1	39-56	0.07	1	2
Bt2	56-85	0.10	1	5
Bt1	85-105	0.06	1	7
Pedon SDS 2				
Ap	0-15	0.07	1	9
AB	15-26	0.07	1	2
Bt1	26-52	0.08	2	0
Bt2	52-80	0.15	1	0
Bt3	80-95	0.15	1	0

Table 16 cont'd.

Horizon	Depth (cm)	Electrical conductivity (dS m^{-1})	Exch. sodium percentage (%)	Free carbonate equivalent (mg kg^{-1})
Pedon SDS 3				
Ap	0-15	0.10	2	0
Bt	15-40	0.07	1	3
Pedon SDS 4				
Ap	0-15	0.10	2	0
AC	15-35	0.08	2	0
C1	36-60	0.07	1	0
2C2	60-115	0.07	1	0
2C3	115-180	0.07	1	0
		Sangiwa Dunes		
Pedon GDS 1				
Ap	0-33	0.10	2	5
AC	33-65	0.10	2	5
C1	65-108	0.08	2	4
C2	108-185	0.03	4	6
Pedon GDS 2				
Ap	0-24	0.04	2	5
AC	24-45	0.05	2	5
C1	45-100	0.05	2	6
C2	100-190	0.03	2	2
Pedon GDS 3				
Ap	0-21	0.10	2	5
AC	21-50	0.07	1	6
C1	50-110	0.10	1	10
C2	110-160	0.10	2	8
Pedon GDS 4				
Ap	0-30	0.10	3	8
AC	30-60	0.07	2	6
C1	60-110	0.08	2	6
C2	110-160	0.07	1	7

Famouri, 1964; Munn and Boehm, 1983). The generally low values indicate that salinization is not a significant soil forming process in the soils. This is in consonance with observed field conditions of good drainage and an ustic soil moisture regime. Salinization has been found to be a common feature under poor drainage conditions and or in extremely arid environment i.e. aridic soil moisture regime (Dan, 1973; Dan *et al.*, 1982).

5.4.2 Exchangeable sodium percent (ESP)

Exchangeable sodium percent values and means (in parentheses) for the surface soils, in the Illela, Sokoto and Sangiwa dunes varied from 1 to 3 (2.25), 1 to 2 (1.50) and 2 to 3 (2.25) percent respectively. Similarly, the subsoil values varied from 1 to 3 (1.62), 1 to 2 (1.15) and 1 to 4 (1.92) percent (Table 9). The ESP means are rated as very low (Richards, 1954). The low ESP values indicate that sodication is not a significant pedogenic process occurring presently within the soils. This is not unexpected, since the presence of sodium salts, leaching of excess salts, presence of water table, either permanent or ephemeral (Munn and Boehme, 1983) or the lateral subsurface movement of salty water (Schlichting and Schweikhe, 1980) which are conditions favourable for sodication, are non existent in the soils studied.

5.4.3 Free carbonate

The range in values of free carbonate and means for surface soils in the Illela dunes were 5 to 10 and 7.75, in the Sokoto dunes were trace to 9 and 3.50 and in the Sangiwa dunes were 5 to 8 and 5.75 g $CaCO_3$ Kg^{-1} soil. In the same order, the subsoil values varied from 2 to 10 (mean, 6.69), trace to 7 (2.15) and 2 to 10 (5.92) g $CaCO_3$ Kg^{-1} soil (Table 9). The free carbonate contents of the soils are rated as being trace to low (Awotundun, 1973). The surface soil values were higher than the subsoil values, although not significant (P=0.05), and may be attributed to the low degree of leaching as a result

of the semi-arid nature of the climate. The general trend in the amount of free carbonate is Illela > Sangiwa > Sokoto dunes. In both the surface and subsoil horizons, the means for Illela dunes were significantly higher (P=0.01) than the means for Sokoto but were at par with the means for Sangiwa dunes, while the means for Sangiwa dunes were in turn at par with those for Sokoto dunes (Table 16). Incipient calcification in the Illela dunes is indicated by the occurrence of very few calcium carbonate rings found within the subsoil horizon of pedon LDS 3 (Plate 4). The above trend indicates increasing aridity (annual rainfall is about 700 mm around Sokoto to 600 mm near Illela town) and decreasing weathering intensity in that same order.

Free carbonate accumulates mostly in the C-horizons of soils, but encroach into the B-horizons under intensely arid conditions (Dregne, 1983). Free carbonate had been reported to accumulate in soils experiencing an annual rainfall of less than 750 mm (Buursink, 1971; Gile *et al.*, 1965; Jenny, 1980; Machette, 1985), as experienced in the area studied (Table 1). Free carbonates have been found to be better associated with the semi-arid regions, where a moderate rainfall enhances calcification which is essentially a calceluviation-calcilluviation process (Staurt and Dixon, 1973; Ahuja and khanna, 1984). World wide, carbonate rich dust appears to be the major source of soil carbonate (Schlesinger, 1982, 1985; Junge and Werby, 1958). Carbonate rich dusts have been widely reported in the literature (Jessup, 1960; Burns, 1980; Litaor, 1987). However, the aeolian dust in the study area has been reported to be poor in carbonate (Moberg *et al.*, 1990). It is therefore, not surprising that, despite favourable climatic conditions for calcification within the study area, it is not a significant pedogenic process in the soils.

The physico-chemical properties of the dune soils studied indicate that there is no detectable argilluviation, ferrugination, and humification processes in soils developed in the Sangiwa and Illela dunes. On the Sokoto dunes, appreciable argilluviation has resulted in the formation of Bt horizons. Pedogenic processes, typical of aeolian deposits, such as

salinization, sodication and calcification (Boul *et al.*, 1980; Boettinger and Southard, 1991) are also non-existent in the soils. This is because an annual rainfall greater than 600 mm is not conducive for the accumulation of salts and is capable of obliterating any evidence of salt accumulation from the past (McFadden *et al.*, 1986). Aside from the process of aeolian addition to the surface soils, there is on a limited scale, mineralization of organic matter evident from the C:P ratio of less than 50 in the soils. It is difficult to conclude on whether ferritization and allitization processes are due to the present climate or are processes which occurred in the past. This is because the parent material for the dunes soils contained appreciable quantity of the oxides of iron, aluminum and manganese at time zero of soil formation (FAO, 1969). The near absence of ferromagnessian minerals in the soils further points to the two processes having taken place in a more humid past. The oxides of iron, aluminum and manganese observed in the soils are therefore likely to be largely paleopedogenetic in origin.

5.5 Micronutrient Levels in the Soils

The micronutrient elements studied included copper, zinc, manganese and iron. The data related to these properties are presented in Table 17.

5.5.1 Available and total copper

The values of 0.1M HCl extractable copper (Cu_H), in the surface soils varied from 1.95 to 2.55, 2.04 to 2.94 and 0.75 to 1.95 µgCu g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding means were 2.35, 2.39 and 1.45 µgCu g^{-1} soil. In the ,same order, the subsoil values and means (in parentheses) varied from 1.74 to 2.97 (2.40), 1.56 to 3.75 (2.46) and 0.75 to 4.65 (1.99) µgCu g^{-1} soil. The means were not significantly different between dunes and this may be attributed to the similar parent material of the three dunes. There is however, a slight increase in values with depth. Such trend was also reported by Udo *et al.* (1979) for soils developed on sedimentary rocks but

Table 17: Micronutrient Cu, Zn, Mn and Fe levels of pedons studied.

Horizon	Depth (cm)	HCl				DTPA-TEA				Total			
		Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)	Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)	Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)
Ilieia Dunes													
Pedon LDS 1													
Ap	0-28	2.55	3.75	7.5	11.70	0.50	1.56	4.00	7.5	65	125	70	1200
AC	28-63	2.61	4.65	6.9	8.25	0.46	1.40	3.20	10.3	60	125	325	1250
C1	63-142	2.07	4.05	4.5	23.70	0.50	1.38	2.56	10.3	125	750	725	2687
C2	142-175	2.25	1.65	3.0	30.00	0.78	1.00	1.60	12.0	115	1250	425	1687
Pedon LDS 2													
Ap	0-18	2.55	3.75	8.7	19.20	0.75	1.96	4.00	5.9	120	125	625	1900
AB	18-52	1.74	3.45	5.1	16.50	0.80	2.04	1.04	8.0	65	250	75	762
Bt1	52-95	1.80	4.05	3.3	30.00	0.79	3.50	1.60	9.1	165	250	725	3600
Bt2	95-170	2.04	5.25	1.5	16.95	0.80	1.50	1.84	5.5	100	500	625	3137
Pedon LDS 3													
Ap	0-27	1.95	12.75	27.6	57.75	0.54	2.3	0.40	6.7	165	175	725	3100
AC	27-73	2.94	15.25	18.0	62.70	0.71	2.0	9.52	12.0	75	312	355	2250
C1	73-130	3.36	18.60	18.0	63.15	0.90	2.0	8.40	7.0	165	250	1025	4250
C2	130-210	2.94	20.55	15.0	90.00	0.75	2.3	6.64	8.5	100	250	375	1937
Pedon LDS 4													
Ap	0-12	2.34	8.25	37.5	45.00	0.79	1.7	12.80	5.1	115	375	475	1625
AC	12-60	2.55	8.85	15.0	34.20	0.75	1.6	10.80	11.5	40	375	175	500
C1	60-100	2.25	6.90	15.6	30.00	0.79	1.5	9.44	8.7	135	125	525	1812
C2	100-140	2.25	6.00	11.7	38.25	0.86	1.8	6.00	6.0	85	125	205	437
C3	140-190	2.31	6.00	6.0	31.65	0.79	1.7	3.20	5.1	70	250	125	387

Table 17 cont'd.

Horizon	Depth (cm)	HCl				DTPA-TEA				Total			
		Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)	Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)	Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)
Sokoto Dunes													
Pedon LDS 1													
Ap	0-22	2.34	5.25	24.0	33.00	0.80	1.2	22.00	9.6	85	125	40	1062
AB	22-39	2.25	3.90	9.9	23.25	0.79	1.8	8.40	13.1	75	375	275	1400
Bt1	39-56	2.40	3.45	16.5	18.75	0.78	1.3	16.56	8.9	90	125	415	1937
Bt2	56-85	2.55	2.40	18.0	28.20	0.70	1.4	17.60	5.9	240	375	1025	3750
Bt3	85-105	1.56	6.68	25.5	30.00	0.86	1.1	24.80	4.5	265	250	940	3500
Pedon SDS 2													
Ap	0-15	2.04	5.55	21.0	23.20	1.58	1.5	19.84	9.9	70	125	355	1437
AB	15-26	2.25	6.45	7.5	23.55	1.27	1.2	7.12	10.0	115	187	440	1937
Bt1	26-52	2.94	3.45	18.0	20.25	0.70	1.4	17.60	5.7	75	125	325	1687
Bt2	52-80	2.55	3.60	22.5	15.00	0.79	1.3	20.80	6.0	70	652	390	1562
Bt3	80-95	2.61	3.75	28.5	21.75	0.78	1.6	26.00	5.5	75	312	550	2312
Pedon SDS 3													
Ap	0-15	2.94	6.75	37.5	47.25	0.70	2.3	14.40	6.0	80	187	750	2475
Bt	15-40	2.64	8.25	43.5	60.00	0.74	1.3	32.80	16.0	80	250	1375	2875
Pedon SDS 4													
Ap	0-15	2.25	8.85	30.0	36.75	0.66	1.8	12.00	6.0	85	500	525	1187
AC	15-35	2.55	4.50	19.5	36.75	0.67	1.7	11.44	8.0	85	250	475	1137
C1	35-60	2.04	4.65	18.0	38.25	0.70	1.5	12.80	8.0	80	187	325	900
2C2	60-115	1.95	8.26	22.5	42.75	0.71	1.3	14.00	9.4	85	312	625	1525
2C3	115-180	3.75	12.80	25.5	123.75	0.62	1.3	21.60	10.5	80	187	495	1037

Table 17 cont'd.

Horizon	Depth (cm)	HCl				DTPA-TEA				Total			
		Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)	Cu (µ g g-1)	Zn (µ g g-1)	Mn (µ g g-1)	Fe (µg g-1)	Cu (µg g-1)	Zn (µg g-1)	Mn (µg g-1)	Fe (µg g-1)
Sangiwa Dunes													
Pedon GDS 1													
Ap	0-33	1.50	6.00	22.5	31.50	0.80	1.6	8.80	5.0	15	500	50	187
AC	33-65	1.35	5.40	18.0	21.80	0.62	1.5	12.40	5.2	5	375	70	562
C1	65-108	1.44	5.18	22.5	14.25	0.78	2.2	17.60	4.8	5	250	105	150
C2	108-185	1.65	12.00	26.4	30.00	0.78	2.7	21.60	4.9	10	275	65	812
Pedon GDS 2													
Ap	0-24	1.95	2.70	17.1	23.25	0.50	1.4	11.20	4.0	15	325	40	100
AC	24-45	1.74	6.00	20.4	23.70	0.70	1.9	16.96	6.7	20	287	60	187
C1	45-100	1.35	4.50	34.5	24.75	0.90	1.2	30.40	6.8	85	62	375	687
C2	100-190	2.55	5.55	43.5	22.20	0.79	1.6	38.80	8.3	85	187	355	750
Pedon GDS 30.75													
Ap	0-21	0.75	4.50	24.3	30.00	0.54	1.4	16.00	6.0	85	150	210	562
AC	21-50	2.34	5.70	23.7	8.25	0.70	2.4	17.60	8.0	80	250	325	1062
C1	50-110	0.75	6.75	27.0	7.95	0.79	1.4	24.80	6.7	85	100	390	1312
C2	110-160	1.05	6.75	19.2	18.15	1.18	1.5	12.80	6.0	65	150	330	1012
Pedon GDS 4													
Ap	0-30	1.65	11.25	22.5	14.55	0.86	1.6	12.80	4.2	60	250	150	437
AC	30-60	4.65	3.00	16.5	12.75	k0.78	1.3	13.20	8.0	75	125	190	725
C1	60-110	2.25	4.65	27.0	20.70	0.58	1.2	27.20	6.3	90	62	300	912
C2	110-160	2.70	4.80	30.0	19.80	0.66	1.3	29.60	8.0	65	125	340	925

values obtained are slightly higher than those reported for sandstone derived soils. The values of Cu_H compare well with values reported for Nigerian soils (Udo *et al.*, 1979; Kparmwang, 1993; Fagbami *et al.*, 1985).

The 0.1M HCl extractable Cu values tend to be higher for the Sokoto dunes followed by those of Illela and Sangiwa dunes in that order. The trend in distribution and the strong positive correlation between Fe_H and Cu_H may indicate that both forms of micronutrients are extracted from the same pedogenic source.

The available Cu extracted with DTPA (Cu_D) in surface soils in the Illela, Sokoto and Sangiwa dunes, varied from 0.5 to 0.79 (mean, 0.65), 0.66 to 1.58 (0.94) and 0.5 to 0.86 (0.68) μgCu g^{-1} soil respectively. In the same order, the subsoil values varied from 0.46 to 0.90 (mean, 0.74), 0.62 to 1.27 (0.78) and 0.58 to 1.18 (0.77) μgCu g^{-1} soil. The values of DTPA-extractable Cu were generally lower than the corresponding values of 0.1M HCl extractable Cu, contrary to results reported by Udo *et al.*, (1979). The low contents of organic matter may be responsible for the lower values of DTPA Cu since DTPA has been shown to correlate significantly with organic carbon (Mekeague, 1967). There was gradual increase of Cu_D with depth, indicating better retaining ability on clay. The Cu_D values were all above the critical value of 0.2 μgCu g^{-1} soil (Lindsay and Norvell, 1978). The values were however, largely higher than 0.5 μgCu g^{-1} soil quoted for highly weathered soils (Karim *et al.*, 1976).

Total copper (Cu_T) in the surface soils ranged from 65 to 165 with a mean of 116.25 μg g^{-1} in the Illela dunes, 70 to 85 with a mean of 80 μg g^{-1} in the Sokoto dunes and 15 to 60 with a mean of 43.75 μg g^{-1} in the Sangiwa dunes. In the subsoil, values of Cu_T varied from 40 to 235 (mean, 112.60), 70 to 265 (mean, 108.85) and 5 to 90 (mean, 55.85) μg g^{-1}, in the Illela, Sokoto and Sangiwa dunes respectively. Cu_T in surface soil was significantly lower (P=0.05) in the Sangiwa dunes than the means for Illela dunes but was at par with the means for Sokoto dunes. The means for Sangiwa dunes were

significantly lower (P=0.05) in the subsoil than the rest of the dunes whose means were at par. The trend in distribution and the positive correlation with oxides of iron, Fe_d (r=0.2880, P=0.05), indicate that total Cu is probably largely contributed by these oxides. The values of Cu_T for the dune soils were slightly higher than those reported by Udo *et al.* (1979) and Kparmwang (1993) for some Nigerian soils and Karim *et al.* (1976) for soils in Louisiana. Sandstone derived soils have generally been reported to be poor in total Cu (Karim *et al.*, 1976; Udo *et al.*, 1979) when compared to other soils. The relatively high values of total Cu in the dune soils could perhaps be due to a possible occurrence of copper bearing minerals such as cuprite, chalcopyrite or azurite in the basement complex rocks, from which the dunes' parent rocks were derived. Total Cu was irregularly distributed down the profiles, but surface values were lower than the subsoil values, confirming earlier reports (Karim *et al.*, 1976; Udo *et al.*, 1979; Boarggaard *et al.*, 1991) that clay tends to retain copper more strongly than organic matter.

5.5.2 Available and total zinc

The available zinc extracted with 0.1M HCl (Zn_H) in the surface soils varied from 3.75 to 12.75 (mean, 7.13), 5.25 to 8.85 (6.60) and 2.7 to 11.27 (6.11) µgZn g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values varied from 1.65 to 20.55 (8.10), 2.40 to 12.80 (5.55) and 3.0 to 12.0 (5.85) µgZn g^{-1} soil. the means were not significantly different between dunes (Tables 9a and 9b). The similar contents of Zn_H between the dunes may be due to the similar parent material between them. Generally, the surface soils contained higher contents of Zn_H than the subsoil horizons. This agrees with the observed relatively immobile nature of zinc in soils (Tisdale *et al.*, 1985). This fact is buttressed by the negative non significant correlation it has with clay (Table 18), which essentially is subjected to eluviation - illuviation process. The means of Zn_H were largely greater than the critical level of 1.0 µgZn g^{-1} soil

(Lombin, 1983). The values of Zn_H are generally similar to values also reported for soils in the Nigerian savanna (Lombin, 1983; Kparmwang, 1993) but in few cases are slightly higher. The soils therefore seem to be adequately endowed with 0.1M HCl extractable Zinc. The relatively higher values of Zn_H in the dune soils may have resulted from the semi-arid nature of the climate, which limits the rate of weathering and leaching, since zinc is relatively immobile (Tisdale *et al.*, 1985).

The values and means (in parentheses) of DTPA extractable zinc (Zn_D) in the surface soils ranged between 1.56 and 2.30 (1.88), 1.24 and 2.30 (1.72), and 1.36 and 1.60 (1.52) µgZn g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values varied from 1.38 to 3.50 (1.83), 1.1 to 1.80 (1.40) and 1.20 to 2.76 (1.70) µgZn g^{-1} soil. The Zn_D values were lower by a factor of about 3 to the Zn_H values. The values were however, generally, above the critical value of 0.8 µgZn g^{-1} soil (Lindsay and Norvell, 1978). The values are however, within the range reported for basaltic soils (Udo and Fagbami, 1979; Kparmwang, 1993) and for granitic soils (Mosugu, 1989). The relatively high values is apparently difficult to account for since DTPA extractable Zn has been shown to correlate significantly with organic carbon (Kparmwang, 1993) which is low in the dune soils. However, the relatively high values of Zn_H in the dune soils may be due to the low rainfall, which limits the intensity of weathering and leaching.

Total zinc (Zn_T) in surface soils ranged from 125 to 375 (mean, 200), 125 to 500 (mean, 234.25) and 150 to 500 (mean, 306.25) µg g^{-1}, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values and means (in parentheses) varied from 125 to 1250 (370.15), 125 to 562 (269.0) and 62 to 375 (187.33) µg g^{-1}. The means were not statistically different (P=0.05) between the dunes but were higher than values reported by Karim *et al.* (1976) for Louisianian soils, Osiname *et al.* (1973) Udo and Fagbami (1979) for soils on sandstone and metamorphic rocks and Kparmwang (1993) for

basaltic soils in Nigeria. The values however, compared well with the values reported by Maclean and Langille (1976) for some Nova Scotia soils in the United States. The high values in the dune soils may again be attributed to a possible occurrence of zinc bearing minerals such as smithsonite and sphalerite in the basement complex rocks from which the dunes' parent materials were derived. Total Zn was irregularly distributed down the profiles, similar to total Cu, but the surface values were higher than the subsoil values except on the Sangiwa dunes. This result suggests that total Zn is not subjected to any single pedogenic process but its content is controlled by organic matter distribution except on the Sangiwa dunes where significant contribution from clay is very likely.

5.5.3 Available and total manganese

The 0.1M HCl extractable manganese (Mn_H) in the surface soils ranged from 7.50 to 37.50, 21.0 to 37.5 and 17.1 to 24.3 µgMn g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding means were 20.33, 28.18 and 21.60 µg g^{-1}. In the same order, the subsoil values varied from 1.5 to 18.0 (mean, 9.51), 7.5 to 43.5 (mean, 21.18) and 16.5 to 43.5 (mean, 25.73) 230gMn g^{-1} soil. The mean values of Mn_H between the dunes were statistically at par (P=0.05) in the surface soils (Table 9a) but in the subsoil, the mean for Illela was significantly lower (P=0.01) than the means for Sokoto and Sangiwa dunes, while the means for Sokoto and Sangiwa dunes were in turn at par (Table 9b). The lower Mn_H values in the subsoil horizons of the Illela dunes are is probably due to the alkaline soil reaction since Mn_H has a negative correlation with soil pH (Table 18). The Mn_H values decreased down the profile, indicating a greater contribution of Mn_H by organic matter (Table 18). The Mn_H values compared well with values given by Shuman (1979) for Quartzipsamments from southern USA but lower than those reported by Kparmwang (1993) for basaltic soils.

The values and means (in parentheses) of DTPA extractable manganese (Mn_D) in the surface soils varied from 4.0 to 12.8 (7.80), 12.0 to 22.0 (17.06) and 8.8 to 16.0

Table 18: Correlation coefficient matrix for oxides of available micronutrient and related soil properties.

	Clay	OC	pH	Cu_H	Mn_H	Fe_H	Zn_H	Cu_D	Zn_D	Mn_D	Fe_D	Cu_T	Zn_T	Mn_T
OC	.0052													
pH	-.5559***	.0695												
Cu_H	.0008	-1041	.1356											
Mn_H	.1659	-.2164	-.0275	-.0178										
Fe_H	-.1477	.2912	.488***	.3843**	.2121									
Zn_H	-.1859	-.1217	.490***	.1934	.2002	.7097***								
Cu_D	.1995	-.2150	-.0002	-.1197	-.0084	-.0955	.0588							
Zn_D	-.1729	.1967	-.3845**	-.0388	-.0922	.1371	.3305*	-.0494						
Mn_D	.479***	-.5261***	.0317	-.0311	.8349***	.0088	-.0325	.0844	-.2907					
Fe_D	.0464	.1282	.0913	.3157*	-.0814	.3198*	-.0959	.0977	-.1207	.0053				
Cu_T	.4356**	-.0022	-.0418	.0913	-.1729	-.1246	-.0439	.0743	-.0116	-.1300	.0186			
Zn_T	-.0060	.1072	.2184	-.0418	-.2800*	-.0104	-.1109	-.1145	-.1027	-.3352*	.1769	.0949		
Mn_T	.4121**	-1016	.2254	.2184	-.2037	.3343*	-.1868	.0288	-.0165	.1255	.2779*	.7060***.1003		
Fe_T	.4728***	-.0332	-.0446	.2254	-.0814	.2491	.2286	.0571	.148	-.1112	.1963	.8214***.1395		.8608***

Significant levels, * = P 0.05, ** = P 0.01, *** = P 0.001

(12.20) μgMn g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values varied from 1.6 to 10.8 (5.11), 8.4 to 32.8 (17.81) and 12.8 to 38.8 (21.91) μg g^{-1}. The means for the Sokoto dunes were at par with the means for Sangiwa but were significantly higher (P=0.01) than the means for the Illela dunes, both in the surface and subsoil horizons (Tables 9a and 9b). The lower values on the Illela dunes are mainly due to their alkaline soil reaction, since manganese is rendered unavailable at high pH (Tisdale *et al.*, 1985). The Mn_D were essentially higher than those reported for granitic soils (Mosugu, 1989) but were comparable to values reported for basaltic soils (Kparmwang, 1993). The Mn_D values were generally much higher than the critical limit of 1.0 μg g^{-1} (Lindsay and Norvell, 1978).

Total manganese (Mn_T) in surface soils ranged from 70 to 725 (mean, 473.75), 40 to 750 (mean, 417.5) and 40 to 210 (mean, 112.5) ug g^{-1}, in the Illela, Sokoto and Sangiwa dunes respectively. Correspondingly, the subsoil values varied from 75 to 1025 (437.3), 275 to 1375 (588.85) and 60 to 390 (242.08) ug g^{-1}. The means of total manganese of the three dunes were not significantly different in the surface soils but in the subsoil, the means for Sangiwa dunes were significantly lower (P=0.05) than the means for Sokoto dunes but were at par with the means for Illela dunes while the means of Illela dunes were in turn at par with the means for Sokoto dunes. The similarity in the ranking of both total Mn and Fe_d and the sigificant correlation between them tend to suggest that a significant amount of Mn_T in the soils studied was associated with oxides of iron in the clay fraction, possibly as occluded manganese.The total Mn values compared well with values reported by Kparmwang (1993) for basaltic soils but lower than those reported by Maclean and Laugille (1976) for some North Shore soils in the United States. Total Mn like the other micronutrients was also irregularly distributed down the profiles, indicating that no single pedogenic process controls its distribution.

5.5.4 Available and total iron

The ranges and means (in parentheses) of 0.1M HCl extractable iron (Fe_H) in the surface soils were 11.7 to 57.75 (33.41), 23.2 to 47.25 (35.05) and 14.55 to 31.5 924.83) μgFe g^{-1} soil, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values varied from 8.25 to 90.0 (36.51), 15.0 to 123.75 (37.10) and 7.95 to 30.0 (18.69) μgFe g^{-1} soil. The means of Fe_H were not significantly different between dunes. The similar contents of oxides of Fe in all the soils may be responsible for the non significant difference. The values were generally lower than the values reported for basaltic soils (Kparmwang, 1993) due probably to the very low contents of ferromagnesian minerals in the dune soils compared with basalts. There was an irregular decrease of Fe_H down the profile with the highest values in the AC and AB horizons.

The DTPA extractable iron (Fe_D) values in the surface soils of Illela, Sokoto and Sangiwa dunes, varied from 5.14 to 7.50 (mean, 6.33), 6.0 to 9.56 (7.78) and 4.0 to 6.0 (4.80) μg g^{-1} respectively. In the same order, the subsoil values varied from 5.06 to 12.0 (8.56), 4.46 to 16.0 (8.58) and 4.8 to 8.3 (6.64) μg g^{-1} . The means were not significantly different between dunes. The trend in distribution and correlation between it and oxides of iron (Table 19) indicate that this form of iron is equally contributed by all types of iron oxides. All the soils had available Fe contents higher than the critical levels of 4.5 μgFe g^{-1} soil (Lindsay and Norvell, 1978). The soils therefore, seem to be endowed with adequate amounts of available iron. Iron deficiency induced by zinc levels as low as 10^{-4} M (6 μg g^{-1}) has been, however, well documented (Wallace *et al.*, 1976). Such levels of available zinc are present mainly on the Illela dunes.

Total iron (Fe_T) in surface soils in the Illela dunes ranged from 1200 to 3100 (mean, 1956.25), in the Sokoto dunes, it ranged from 1062 to 2475 (mean, 1540.25) and in the Sangiwa dunes, it ranged from 100 to 437 (321.50) μg g^{-1}. In the subsoil, the values and means (in parentheses) were 500 to 4250 (1899.69), 900 to 3750 (1966.07) and 150 to 1312 (758.0) μg g^{-1}, in the Illela, Sokoto and Sangiwa dunes respectively. The means for the Sangiwa dunes were significantly lower (P=0.01) than the rest of the dunes whose

Table 19: Correlation coefficient matrix of oxides of Fe/Al and available micronutrient.

	Cu_H	Zn_H	Mn_H	Fe_H	Fe_D	Mn_D	Zn_D	Cu_D	Fe_p	Fe_{ox}	Fe_d	Al_p	Al_{ox}	Al_d	Cu_T	Zn_T
Mn_H	.1934															
Zn_H	-.0275	.2002														
Fe_H	.488***	.7079***	.2121													
Fe_D	.0317	-.0959	-.0814	.3198*												
Mn_D	-.3845**	.0325	.8349***	.0088	.0053											
Zn_D	-.1689	.3305*	-.0922	.1371	-.1207	-.2907*										
Cu_D	-.0002	.0588	-.0955	.0977	.0844	-.0494										
Fe_p	-.3372*	-.0026	.0519	.0513	.2354	.3126*	-.0418	.1909								
Fe_{ox}	.2709	.1548	.3544*	.3360*	.3267*	.2955*	-.1986	.1213	.3229*							
Fe_D	-.1230	.1786	.2614	.2628*	.4212**	.3031*	-.1120	.1061	.4389**	.8605***						
Al_p	.0186	.1074	.0597	.1952	.1976	.0805	.1339	.0296	.3170*	.1839	.2005					
Al_{ox}	-.0679	-.2182	.0558	-.1970	.1040	.2057	-.1179	-.1159	.0659	.2633	.2065	.0463				
Al_d	-.0248	.1277	.3830**	.1565	.3680**	.3877**	-.1208	.2097	.2832*	.6407***	.6949***	.1570	.1778			
Cu_T	.0913	.0439	-.1729	.1246	.0186	-.1300	-.0116	.0743	.1726	.2986*	.2880*	.0293	.0657	.0512		
Zn_T	-.0418	-.1109	-.2800*	.0104	.1769	-.3350*	-.1027	-.1145	-.1492	.0230	.0029	.0223	.2558	-.1911	.0949	
Mn_T	.2184	.1858	.2037	.3343*	.2779*	.1255	-.0165	.0288	.2415	.7612***	.6539***	.1394	.1340	.3903**	.7060**	.1003
Fe_T	.2254	.2286	-.0814	.2491	.1963	-.1112	.1480	.0571	.2914*	.5631***	.6061***	.1378	.0990	.3278*	.8214***	.1395	.8608***

Significantlevels, * = P 0.05, ** = P 0.01, *** = P 0.001

means were at par. The strong correlation between total Fe and the various forms of iron and aluminium oxides indicates probably the extraction of Fe_T and the oxides of Fe and Al from the same pedogenic source. Total Fe content in the dune soil were lower than values reported by Kparmwang (1993) for basaltic soils, most probably due to the low contents of ferromangnessian minerals.

5.6 Mineralogy of the Soil

The mineralogy of the sand, silt and clay separates and the free forms of iron (Fe) and aluminum (Al) oxides and oxyhydroxides are discussed. Data on these properties of the soils are presented in Tables 20 and 22.

5.6.1 Free iron oxides

The sodium pyrophosphate extractable iron (Fe_p) in the surface soils in the Illela, Sokoto and Sangiwa dunes varied from 0.01 to 0.02 (mean, 0.01), 0.01 to 0.02 (mean, 0.02) and 0.01 to 0.02 (mean, 0.01) percent respectively. The corresponding subsoil values varied from 0.01 to 0.03 (0.02), 0.01 to 0.03 (0.02) and 0.01 to 0.04 (0.02) percent. The means were not statistically different in the surface soils. In the subsoil, the means for the Sokoto dunes were significantly higher (P=0.01) than those for Illela and Sangiwa dunes, whose means were in turn at par. The trend in distribution of Fe_p is similar to that of organic carbon (Tables 9a and 9b) which has been shown to contribute largely to Fe_p (Mckeague, 1967). The values of Fe_p increased irregularly with profile depth with subsoil values significantly higher (P=0.01) than values in the surface soils for Sokoto and Sangiwa dunes. The Fe_p values were essentially low, reflecting the low organic matter contents of the soils. It was the lowest of the other fractions of iron oxides in the soils as also reported by Juo *et al.* (1974), Mosugu (1989) and Kparmwang (1993) for other savanna soils, constituting only 2 % of the total free iron oxides (CBD) on the Illela and Sokoto dunes and 5 % on the Sangiwa dunes. A negative non significant correlation was observed between Fe_p and organic matter (Table 21) contrary to reported relationship for

Table 20: Extractable Fe and Al oxyhydroxides, active Fe ratios and Fed/Clay ratios of pedons studied.

Horizon	Depth (cm)	Fe_p (%)	Fe_{ox} (%)	Fe_d (%)	Al_p (%)	Al_{ox} (%)	Al_d (%)	Ratios	
								Fe_{ox}/Fe_d	Clay/Fe_d
				Illela Dunes					
Pedon LDS 1									
Ap	0-28	0.01	0.09	0.27	0.02	0.08	0.12	0.35	11.32
AC	28-63	0.01	0.10	0.21	0.05	0.08	0.18	0.47	14.28
C1	63-142	0.01	0.09	0.36	0.02	0.03	0.08	0.25	19.44
C2	142-175	0.01	0.10	0.37	0.10	0.08	0.08	0.27	18.91
Pedon LDS 2									
Ap	0-18	0.01	0.05	0.28	0.03	0.09	0.10	0.19	10.91
AB	18-52	0.01	0.06	0.24	0.04	0.06	0.17	0.23	20.83
Bt1	52-95	0.03	0.05	0.50	0.08	0.05	0.12	0.11	30.30
Bt2	95-170	0.02	0.16	0.51	0.05	0.08	0.12	0.30	29.40
Pedon LDS 3									
Ap	0-27	0.01	0.11	1.08	0.09	0.03	0.31	0.11	6.51
AC	27-73	0.02	0.17	1.50	0.09	0.09	0.13	0.11	6.00
C1	73-130	0.02	0.18	1.14	0.10	0.08	0.18	0.16	7.89
C2	130-210	0.02	0.17	0.70	0.09	0.09	0.11	0.24	10.00
Pedon LDS 4									
Ap	0-12	0.01	0.20	0.32	0.04	0.08	0.15	0.61	15.63
AC	12-60	0.02	0.07	0.34	0.06	0.06	0.20	0.21	20.90
C1	60-100	0.01	0.09	0.46	0.07	0.08	0.18	0.20	10.99
C2	100-140	0.01	0.09	0.19	0.02	0.08	0.15	0.49	27.03
C3	140-190	0.01	0.04	0.13	0.02	0.05	0.08	0.35	40.00

Table 20 cont'd.

Horizon	Depth (cm)	Fe_p (%)	Fe_{ox} (%)	Fe_d (%)	Al_p (%)	Al_{ox} (%)	Al_d (%)	Ratios	
								Fe_{ox}/Fe_d	Clay/Fe_d
				Sokoto Dunes					
Pedon SDS 1									
Ap	0-22	0.02	0.16	0.60	0.10	0.09	0.12	0.27	15.00
AB	22-39	0.02	0.21	0.94	0.05	0.06	0.26	0.22	11.70
Bt1	39-56	0.03	0.24	1.30	0.10	0.06	0.24	0.19	13.85
Bt2	56-85	0.03	0.25	1.31	0.07	0.12	0.13	0.19	16.03
Bt3	85-105	0.02	0.29	0.07	0.09	0.11	0.22	0.22	16.03
Pedon SDS 2									
Ap	0-15	0.02	0.14	0.63	0.10	0.08	0.10	0.22	11.20
AB	15-26	0.03	0.18	0.84	0.07	0.05	0.08	0.21	13.10
Bt1	26-52	0.03	0.21	1.35	0.09	0.05	0.11	0.15	11.11
Bt2	52-80	0.02	0.22	1.30	0.07	0.11	0.18	0.17	14.62
Bt3	80-95	0.03	0.21	1.25	0.09	0.09	0.16	0.17	15.20
Pedon SDS 3									
Ap	0-15	0.01	0.32	0.69	0.05	0.09	0.11	0.47	7.30
Bt	15-40	0.02	0.50	3.12	0.07	0.14	0.36	0.16	4.81
Pedon SDS 4									
Ap	0-15	0.01	0.13	0.25	0.05	0.08	0.08	0.50	12.00
AC	15-35	0.01	0.10	0.30	0.04	0.06	0.08	0.33	10.00
C1	35-60	0.01	0.09	0.29	0.07	0.05	0.08	0.32	10.34
2C2	60-115	0.03	0.16	0.40	0.10	0.08	0.13	0.41	17.50
2C3	115-180	0.03	0.17	0.48	0.09	0.08	0.11	0.35	14.71

Table 20 cont'd.

Horizon	Depth (cm)	Fe_p (%)	Fe_{ox} (%)	Fe_d (%)	Al_p (%)	Al_{ox} (%)	Al_d (%)	Ratios	
								Fe_{ox}/Fe_d	Clay/Fe_d
				Sangiwa Dunes					
Pedon GDS 1									
Ap	0-33	0.01	0.04	0.19	0.05	0.05	0.12	0.24	16.23
AC	33-65	0.02	0.07	0.33	0.05	0.08	0.10	0.20	21.54
C1	65-108	0.02	0.09	0.44	0.07	0.09	0.24	0.20	20.69
C2	108-185	0.01	0.09	0.29	0.05	0.08	0.23	0.30	24.14
Pedon GDS 2									
Ap	0-24	0.01	0.08	0.19	0.05	0.06	0.16	0.42	27.03
AC	24-45	0.02	0.08	0.31	0.10	0.08	0.14	0.27	35.48
C1	45-100	0.01	0.09	0.25	0.05	0.08	0.24	0.38	53.06
C2	100-190	0.01	0.05	0.29	0.05	0.05	0.24	0.19	44.83
Pedon GDS 3									
Ap	0-21	0.01	0.04	0.20	0.10	0.06	0.13	0.20	25.64
AC	21-50	0.03	0.04	0.35	0.09	0.08	0.08	0.13	25.71
C1	50-110	0.04	0.07	0.48	0.05	0.11	0.18	0.15	27.38
C2	110-160	0.02	0.13	0.49	0.05	0.08	0.26	0.26	26.53
Pedon GDS 4									
Ap	0-30	0.01	0.09	0.15	0.09	0.06	0.13	0.59	20.00
AC	30-60	0.02	0.06	0.30	0.07	0.05	0.26	0.19	20.00
C1	60-110	0.02	0.07	0.25	0.04	0.06	0.16	0.30	16.32
C2	110-160	0.01	0.09	0.27	0.04	0.08	0.18	0.33	22.22

other soils (Mckeague, 1967; Juo *et al.*, 1974). It however, shared a significant correlation with clay (r= 0.6154, P=0.001) and BS (r= -0.2800, P=0.05) (Table 21). This significant correlation with clay and BS, probably may be due to the indirect effect of clay on organic matter. Scott (1962) also reported such findings which he noted was not significant for some East African soils.

The oxalate extractable iron (Fe_{ox}) in the surface soils ranged between 0.05 and 0.20 (mean, 0.11), 0.13 and 0.32 (0.19), and 0.04 and 0.09 (0.06) percent, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values varied from 0.04 to 0.18 (0.11), 0.10 to 0.50 (0.22) and 0.04 to 0.13 (0.08) percent. The means for Sokoto dunes were significantly higher (P=0.01) than the means for Illela and Sangiwa dunes (Tables 9a and 9b). The relative greater profile development in the Sokoto dunes may be responsible for the higher contents of Fe_{ox}. The values of Fe_{ox} were generally slightly lower than values reported by Juo *et al.* (1974) and Gallez *et al.* (1975) for sandstone soils, by Mosugu (1989) for granitic soils and Kparmwang (1993) for basaltic soils. The low values may be due to the very low contents of ferromagnesian minerals in the dunes soils. The values were however, higher in the order of 10 than values reported for soils overlying limestone (Udo, 1980; Ogunsola *et al.*, 1989) which had alkaline soil reaction. There was a general increase in Fe_{ox} values down the profile indicating that it is to some extent subjected to eluviation-illuviation process.

The ranges in surface soil values and the means (in parentheses) for citrate-bicarbonate-dithionite (CBD) extractable iron (Fe_d) in the Illela, Sokoto and Sangiwa dunes were 0.27 to 1.08 (0.48), 0.25 to 0.69 (0.54) and 0.15 to 0.20 (0.18) percent respectively. The corresponding subsoil values were 0.13 to 1.50 (0.51), 0.29 to 3.12 (1.09) and 0.25 to 0.49 (0.34) percent. The means were not significantly different in the surface soils, however, in the subsoil, the means for Sokoto were significantly higher (P=0.01) than the means for Illela and Sangiwa dunes, whose means were in turn at par.

Table 21: Correlation coefficient matrix of oxides of Fe/Al and related properties.

	Clay	BS	P_2O_5	TBases	OC	Sand	pH	Fep	Fe_{ox}	Fe_d	Alp	Al_{ox}
BS	-.5964***											
P_2O_5	-.1341	.2880*										
TBases	-.0555	.6231***	.4781***									
OC	.1083	.0316	.0598	-.0218								
Sand	-.8851***	.5738***	.2429	.1493	-.0751							
pH	-.4932***	.6089***	.4577***	.6131***	.0695	.6197***						
Fep	-.6154***	-.2800*	-.0409	.1609	-.0182	-.5866***	-.2850*					
Fe_{ox}	.5193***	-.2629	.0884	.1275	.2008	-.3635**	-.0053	.2856*				
Fe_d	.5139***	-.2088	.1289	.2060	.1440	-.3680***	-.0972	.3898**	.7788***			
Alp	.3492*	-.0525	.1614	.1535	.1618	-.2548	.1338	.4833**	.2179	.3431*		
Al_{ox}	.2864*	-.0128	.0742	.2000	.0089	-.1944	-.0145	.2174	.5109***	.3927**	.1540	
Al_d	.3449*	-.1316	-.0940	.1718	.0402	-.3839**	-.2173	.0190	.3173*	.3956**	.0186	.1356

Significant level * = P 0.05, ** = P 0.01, *** = P 0.001.

The ranking of Fe_d in the dunes was therefore, similar to the ranking of Fe_{ox} and clay. This seems to suggest that Fe_d and Fe_{ox} are co-translocated with clay down the profile (Table 21). The relative greater age of the Sokoto dunes may be responsible for the higher contents of Fe_d, since more iron is liberated with increasing weathering (Scwertmann, 1964; Mckeague and Day, 1966). The common trend of increased Fe_d down the profile depth is similar to trends observed for Fe_{ox} and also reported by other workers (Blume and Schwertmann, 1969; Juo *et al.*, 1974; Kparmwang, 1993). The proportion of Fe_{ox} to Fe_d in the dunes, which was about 1:4 is much greater than values reported for some tropical soils (Juo *et al.*, 1974; Kparmwang, 1993), but compare well with values reported by Mckeague and Day (1966) and Mckeague *et al.* (1971) for soils of temperate regions. This ratio indicates that a higher proportion of iron oxides are in the amorphous forms as a result of the lesser degree of weathering and mineral recrystalization within the semi-arid climate (Lekwa and Whiteside, 1986).

5.6.2 Active Fe and clay/dithionite-Fe ratios

The ratio of oxalate to dithionite extractable Fe commonly known as the active Fe ratio, in the surface soils varied from 0.11 to 0.61 (mean, 0.315), 0.22 to 0.50 (0.366) and 0.20 to 0.59 (0.361), in the Illela, Sokoto and Sangiwa dunes respectively. In the subsoil, the values and means (in parentheses) in the same order, were 0.11 to 0.47 (0.262), 0.15 to 0.41 (0.238) and 0.13 to 0.38 (0.240). The values of active Fe ratio for all the soils studied were high and in the main, decreased with depth. This clearly indicates that higher proportions of iron oxides are present as crystalline forms in the subsoil horizons than in the surface horizons. The means of the ratio were however, statistically not different between dunes. Iron extracted with ammonium oxalate constituted approximately 35 percent in the surface soils and 25 percent in the subsoil horizons, of the total dithionite Fe_d. The higher ratio in the surface horizons has been attributed to the inhibition of

crystallization of iron by organic matter (Schwertmann, 1966). Ratios less than 0.5 had been ascribed to old age or high degree of weathering in soils (Alexander, 1974). The ratios being lower than 0.3 in most of the dunes soils, is probably because of the highly weathered nature of the parent material (FAO, 1969), from which the soils were derived.

The clay/Fe_d ratio in the surface soils and the means (in parentheses) varied from 6.51 to 15.63 (11.09), 7.30 to 15.0 (11.38) and 16.23 to 27.03 (22.22), in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding subsoil values were 6 to 40.0 (19.69), 4.81 to 17.50 (13.0) and 16.32 to 53.06 (28.16). The means for Sangiwa dunes were significantly higher (P=0.01) both in the Ap and subsoil horizons, than the means for Illela and Sokoto dunes, whose means were, in turn at par. In the case of Sangiwa dunes, the higher translocation of clay over Fe_d reflects the relatively lower Fe_d contents while on the Illela dunes, both clay and Fe_d are in relatively lower amounts. There was a general increase in the ratio down the profile in the Sangiwa and Illela dunes. This indicates that clay has moved in greater proportion than Fe in these two dunes. The low mobility of Fe may be attributed to the low organic matter, a principal agent in the cheluviation process. The ratio however, was constant with depth in the Sokoto dunes. This in effect, indicates a co-migration of Fe and clay in about equal proportion. This again reflects the relatively higher amounts of clay and Fe_d in the Sokoto dunes than in the other dunes. Such co-migration has been reported by other workers (Juo *et al.*, 1974; Udo, 1980) for sandstone derived soils of the Nigerian savanna and other aeolian derived soils(Smith and Buol, 1968: Choudhari, 1984).

5.6.3 Free aluminum oxides

The ranges and means (in parentheses) for pyrophosphate extractable aluminum (Al_p) for surface horizon in the Illela, Sokoto and Sangiwa dunes were 0.02 to 0.09 (0.05), 0.05 to 0.10 (0.08) and 0.05 to 0.10 (0.07) percent respectively. In the same order, the

subsoil values were 0.02 to 0.10 (0.08), 0.04 to 0.10 (0.05) and 0.04 to 0.10 (0.06) percent. The means were not significantly different in the subsoil but in the surface horizons, the means for Illela was lower (P=0.05) than the means for Sokoto and Sangiwa dunes (Tables 9a and 9b). The lower content of organic carbon in the Illela dunes compared to those of Sokoto and Sangiwa dunes may be responsible for the observed differences in the Al_p values. Aluminium oxide extracted with pyrophosphate increased irregularly down the profile, similar to Fe_p (Table 20). Aluminium oxide extracted with pyrophosphate constituted about 50 percent of the total free Al in the soils, much higher than for the corresponding forms of Fe_p. This indicates that organic matter is much more effective in chelating aluminum than iron in the dune soils. Aluminium oxide extracted with pyrophosphate values were generally slightly higher than the corresponding Fe_p values as also reported by several workers for the Nigerian savanna soils(Juo *et al.*, 1974; Gallez *et al.*, 1975; Loganathan *et al.*, 1987; Kparmwang, 1993). The Al_p values are within the values reported by Juo *et al.* (1974) and Wang and Mckeague (1982) for sandy Podzolic soils in New Brunswick.

Oxalate extractable aluminum (Al_{ox}) in surface soils ranged from 0.03 to 0.09 (mean, 0.08), 0.08 to 0.09 (mean, 0.08) and 0.05 to 0.06 (0.06) percent, in the Illela, Sokoto and Sangiwa dunes respectively. The corresponding subsoil values also varied from 0.03 to 0.09 (mean, 0.07), 0.05 to 0.14 (0.07) and 0.05 to 0.11 (0.08) percent. The means were not statistically different (P=0.05) between dunes (Tables 9a and 9b). The Al_{ox} values increased irregularly with depth and were lower than the corresponding values of Fe_{ox} by a factor of between 2 and 4. The Al_{ox} constituted about 80 percent of the dithionite aluminum, in the Illela and Sangiwa dunes and about 70 percent in the Sokoto dunes. This indicates that the free aluminum oxides are mainly in the amorphous forms in the dunes. The percentages and values of Al_{ox} were generally within the range of values reported by Juo *et al.* (1974) for soils developed on sedimentary and metamorphic rocks.

Gallez *et al.* (1975) for soils developed on sandstone, igneous and basaltic rocks but lower to values reported for soils of the temperate regions (Mckeague *et al.*, 1971) and Laganathan *et al.* (1987) for some Niger delta soils of Nigeria.

The values and means (in parentheses) of dithionite extractable aluminum (Al_d) in the surface soils were 0.10 to 0.31 (0.17), 0.08 to 0.12 (0.10) and 0.0.13 to 0..16 (0.14) percent, in the Illela, Sokoto and Sangiwa dunes respectively. In the same order, the subsoil values were 0.08 to 0.20 (0.85), 0.08 to 0.36 (0.14) and 0.08 to 0.26 (0.19) percent. The means were not significantly different between dunes. The values of Al_d were generally lower than the corresponding values of Fe_d. The Al_d values are also lower than values reported for basaltic soils (Juo *et al.*, 1974; Kparmwang, 1993) and soils developed on arenaceous sedimentary and igneous rocks (Gallez *et al.*, 1975). These lower values are probably due to the lower contents of alumino-silicate minerals in these soils (Table 22). The crystallinity of the aluminium oxides seems very poor, in as much as Al_{ox} is similar to Al_d and this seems to suggest that gibbsite is unlikely to be present in the dune soils (Blume and Schwertman, 1969).

5.6.4 Fine sand mineralogy

Magnetite dominated the magnetic fraction of the fine sand being abundant (> 70 %) in both the surface and subsoil horizons of all the soils, except in pedon SDS 4 of the Sokoto dunes, where it was many (50-70 %). Hematite was many (55 %) in pedon SDS 1 of the Sokoto dunes and few (15-20 %) in the Sangiwa dunes and in pedon SDS 4 of the Sokoto dunes. The occurrence of hematite in Illela dunes was common (20-30 %) (Table 22). The higher contents of hematite in the Sokoto dunes than the other dunes tends to corroborate the point that they are pedogenically the oldest, since hematite represents the most advanced stage of iron oxide aging (Schwertmann, 1966). Goethite occurred in trace amount (<10 %) in all the dune soils. The lower contents of goethite in all the dunes indicate that the dunes are all highly weathered, since goethite represents an initial stage of weathering (Schwertmann, 1966).

Table 22: Petrological data of the fine sand fraction.

Horizon	Depth (cm)	Magnetic fraction			Non-magnetic fraction	
		Magnetite (%)	Hematite (%)	Goethite (%)	Quartz (%)	Feldspars (%)
			Illela Dunes			
Pedon LDS 1						
Ap	0-28	77	18	5	100	-
C2	142-175	78	21	1	100	-
Pedon LDS 4						
Ap	0-12	73	25	2	100	-
C3	140-190	78	20	2	100	-
			Sokoto Dunes			
Pedon SDS 1						
Ap	0-22	50	48	2	100	-
Bt2	56-85	43	55	2	100	-
Pedon SDS 4						
Ap	0-15	80	18	2	100	-
2C2	60-115	77	19	4	100	-
			Sangiwa Dunes			
Pedon GDS 1						
Ap	0-33	81	17	2	100	-
C1	65-108	83	16	1	100	-
Pedon GDS 3						
Ap	0-21	77	20	3	100	-
C2	110-160	80	18	2	100	-

The non-magnetic fraction of the fine sand separate was composed almost entirely of quartz in all the dunes. The near absence of weatherable minerals like feldspars and biotite, can not be attributed to an advanced stage of weathering under the present climate of the area (FAO, 1969) but rather reflects the chemical character of the parent rock (i.e sandstones).

X-ray diffractograms of the powdered non-magnetic fine sand fraction are presented in Figure 7. The non-magnetic fraction, in all the dunes, was composed almost entirely of quartz, identified by the 0.427 and 0.335 nm strongest peaks and also by a series of other peaks at 0.245, 0.228, 0.224, 0.213, 0.198 and 0.182 nm. The 0.439 and 0.370 nm peaks may be for feldspars particularly, microcline. The x-ray result confirms the results of the petrographic microscope analysis (Table 22).

5.6.5 Silt mineralogy

Quartz (0.427, 0.335, 0.245, 0.228, 0.213, 0.198, 0.182 nm peaks) dominated the mineralogy of the silt fraction in all the dunes (Figure 8). It was followed by kaolinite (0.719 and 0.359 nm peaks) in all the dunes. Other minerals identified include magnetite (0.370, 0.294 and 0.256 nm peaks) and haematite (0.276 nm peak) in all the soils. The diffraction peaks for the iron oxides were weak and very difficult to recognize (Figure 8). Similar findings were also reported by Mckeague *et al.* (1971) and Moore (1976) for sesquioxide-cemented horizons in northern Quebec, Canada. The lack of recognizable peaks has been attributed to the occurrence of the iron oxides in amorphous or poorly ordered forms or are in low concentrations to respond to x-ray diffraction analysis especially for non-oriented samples (Moore, 1976). This lack of recognizable peaks seems probable for the dune soils which, in all cases, had less than 2 percent magnetic minerals in the fine sand fraction (Table 22).

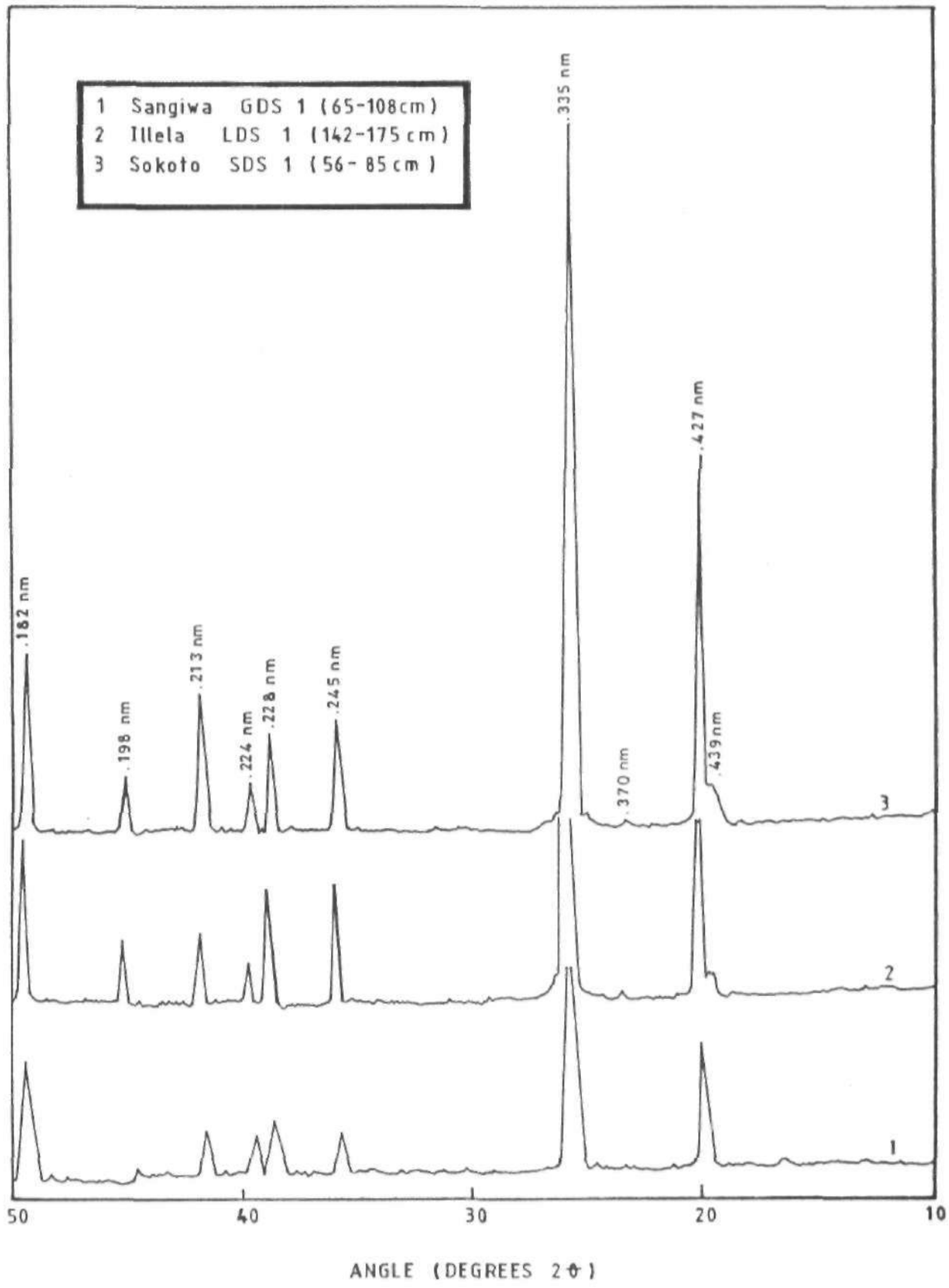


Fig. 7. X-ray diffractograms of sand fraction (Cu Kα).

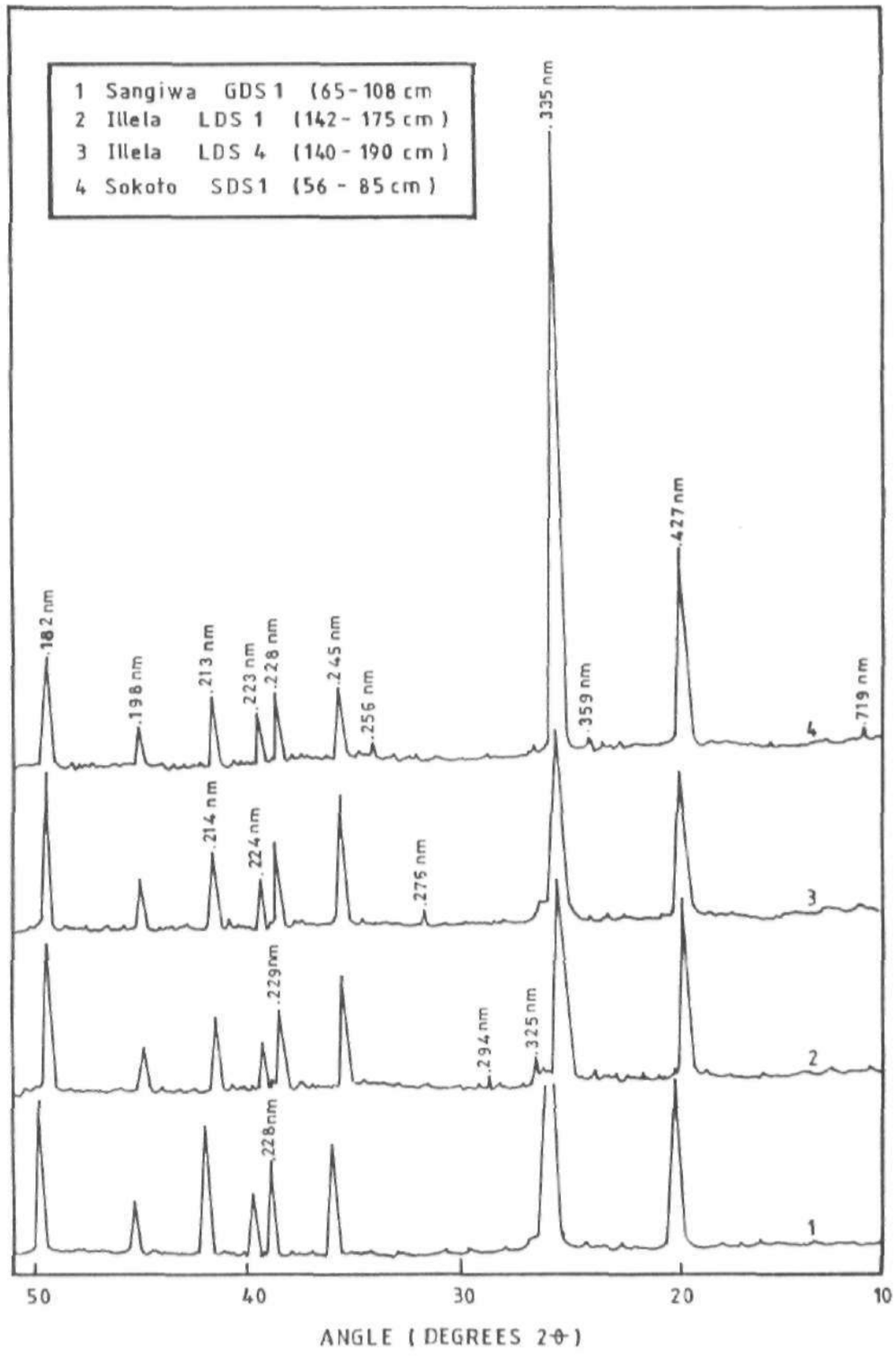


Fig. 8. X-ray diffractograms of silt fraction (Cu K α).

5.6.6 Clay mineralogy

X-ray diffractograms of non-deferrated and non-oriented clay samples are presented in Figure 9. Kaolinite (0.719, 0.448, 0.359 and also 0.259, 0.235 nm peaks) occurred in the mineralogy of the clay fraction in all the soils. Quartz (0.427, 0.335, 0.230, 0.214 nm peaks) was also detected in all the dunes. Okusami *et al.* (1985) reported such assemblage of minerals on sandstone soils in Ilaro, western Nigeria. Probable occurrence of halloysite is indicated by 0.443 and 0.256 nm peaks. Such occurrence of halloysite has also been reported by Ogunwale (1973) in a soil in Daddin Kowa in Sokoto state. The main Fe oxide in the clay fraction is goethite (0.421, 0.258, 0.246 nm peaks) which were detected mainly on the Illela dunes. The near absence of sesquoxide clay in the soils may be due to their amorphous nature (largely) as explained earlier.

The oriented, deferrated air-dried (25 °C) diffractograms showed a dominance of kaolinite (0.715, 0.427 and 0.300 nm peaks) in all the soils. The 0.715 nm peak which are also characteristics of chloritic minerals were, however, confirmed to be for kaolinite upon heating the potassium saturated, oriented samples to 550 °C. The 0.715 nm peak collapsed (Figure 10), confirming it to be for kaolinite. Quartz (0.425 and 0.334 nm peaks) was also common in all the soils (Figure 10). The dominance of kaolinite in all the soils, indicates that kaolinization is a major process in these soils. The similarity in the mineralogy of these soils, perhaps, may be attributed to the common origin they all share (FAO, 1969) and the fact that the present mild arid climate is not able to obliterate most inherited soil properties.

In summary, the mineralogy indicates that all the soils are essentially highly weathered with kaolinite and quartz dominating their mineralogy. Relatively, the Sokoto dunes are considered the most weathered or pedogeneticaly the most mature. The presence of oxides of iron in the diffractograms confirm this assessment. The Illela dunes are the least weathered or the youngest pedogenetically as indicated by the stubble peaks of its

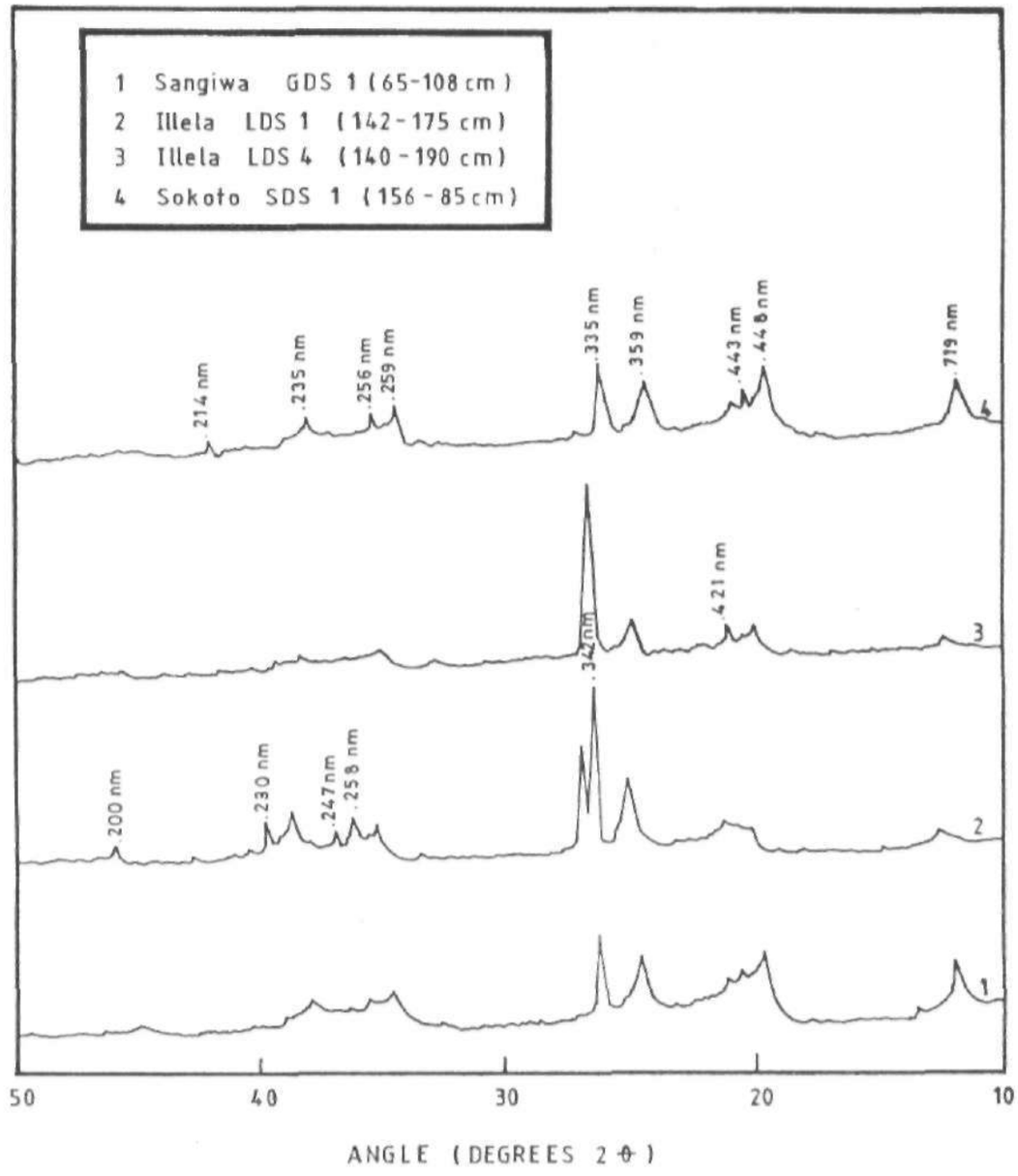


Fig. 9. X-ray diffractograms of nonorieted nondefferrated clay (Cu Kα).

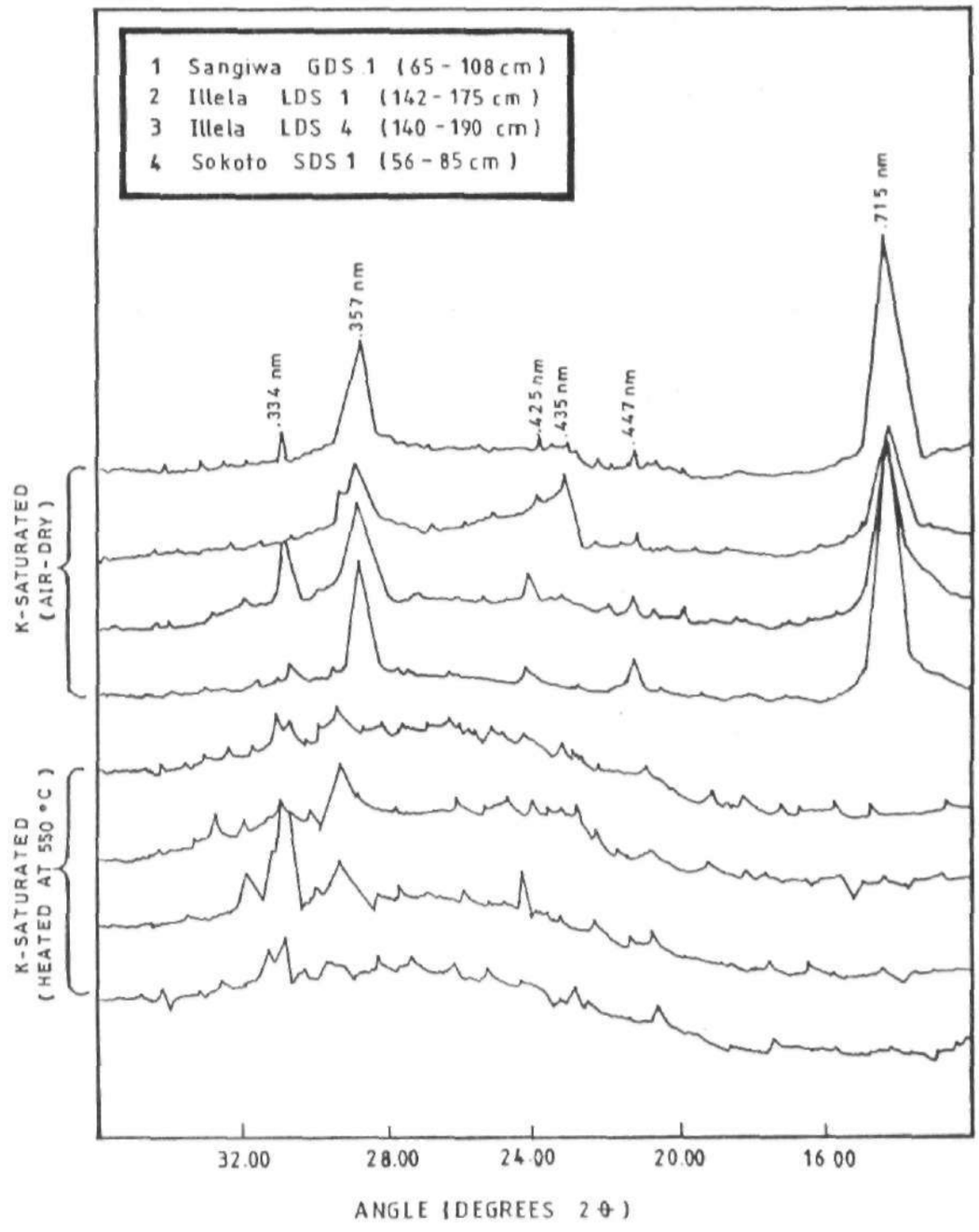


Fig. 10. X-ray diffractograms of oriented clay.

diffractograms indicative of the amorphous nature of the minerals (Figure 10). The Sangiwa dunes are in between the two.

Mineralogical properties of the dune derived soils clearly show the dominance of kaolinite in the clay fraction and quartz in the sand and silt fractions (Figures 7, 8, 9, 10). This indicates that kaolinization and silication have occurred in all the soils. The scarcity of weatherable minerals in the soils, however, cannot be attributed to the intensity of weathering processes under the present semi-arid climate. FAO (1969) identified an extensive period of kaolinization in the Holocene, which affected the basement complex soils, from which the Gundumi sandstone (parent material for the dunes) was derived. It is therefore, more probable that the aeolian parent materials contained kaolinite at time zero of soil formation. The frequent occurrence of non-crystalline colloidal materials, indicated by the high active Fe ratios in the soils, may indicate that at present a re-synthesis and neoformation of clay minerals may be taking place. This is however, not quite evident from the x-ray diffractograms.

5.7 Soil Classification

5.7.1 Criteria for classification

(a) Soil moisture regime

The annual rainfall within the study area varies from about 600 mm at Illela in the north to about 700 mm at Sokoto in the south. The rains are concentrated within 4 to 5 months (Table 1) in an average year. The soils would likely be moist for more than 180 cumulative days when conditions are suitable for plant growth (Soil Survey Staff, 1975, 1990), equivalent to the rainy season in Nigeria. The soils are also likely to be dry for more than 90 cumulative days. All the pedons were well drained and would, therefore have ustic moisture regimes.

(b) Soil temperature regime

The mean annual temperature in the area was 28 °C (Table 1), which is higher than 22 °C limit set for hyperthermic temperature regime (Soil Survey Staff, 1975, 1990). The mean hottest and wettest three months air temperature differ by 4.8°C, hence the corresponding soil temperature will also differ by less than 5°C which therefore imparts an isohyperthermic soil temperature regime to the soils.

(c) Diagnostic surface horizons (epipedons)

All the epipedons had a chroma of 4 or more, contained organic carbon content of less than 2 g Kg^{-1} soil and citrate extractable phosphorus content that was less than 50 µg g^{-1}. The soils therefore possess ochric epipedons because they are too light, poor in humus and low in phosphorus, to be either mollic, anthropic, umbric, melanic or plaggen epipedons.

(d) Diagnostic subsurface horizons

All the pedons on the Sangiwa dunes, pedons LDS 1, LDS 3 and LDS 4 on the Illela dunes and pedon SDS 4 on the Sokoto dunes, had no evidence of soil development from their perceived parent material. These pedons therefore, have no discernable subsurface B-horizon. Pedon LDS 2 on the Illela dunes and pedons SDS 1, SDS 2 and SDS3 on the Sokoto dunes had increased clay contents with depth and sketchy clay cutans in pores. The argillic horizons were confirmed to be present by the clay ratio of the illuvial to the eluvial horizons of 1.2 or greater (Soil Survey Staff, 1975, 1990). The subsurface horizons are argillic B-horizons because they had:

1. more than 3 percent more clay in the argillic horizons than the eluvial horizons, which contained less than 15 percent total clay in their fine earth fraction,
2. a total thickness that was more than 15 cm in all the pedons where they occurred and,
3. some thin clay skins in the lowest part of the subsoil horizons.

5.7.2 Classification

(a) USDA Soil Taxonomy System

At the order level, all the pedons on the Sangiwa dunes, pedons LDS 1, LDS 3 and LDS 4 on the Illela dunes, and pedon SDS 4 on the Sokoto dunes are classified as Entisols because they had no diagnostic B-horizon but only ochric epipedons. Pedons LDS 2 on the Illela dunes, and pedons SDS 1, SDS 2 and SDS 3 on the Sokoto dunes are classified as Ultisols because they had low base saturation of less than 50 percent (by NH_4OAc) and less than 90 percent (by ECEC) in addition to the argillic B-horizons.

At the suborder level, all the Entisols are classified as Psamments because they contain less than 10 percent weatherable minerals (Table 22). The Ultisols are all Ustults because of their ustic moisture regime.

At the greatgroup level, all the Psamments are further classified as Quartzipsamments because they contain more than 90 percent quartz in the sand fraction (Table 22). All the Ustults are also classified as Haplustults because they have simple profile arrangement, CEC of more than 16 cmol(+) per Kg clay in the major part of the argillic horizons and no mottles nor plinthite.

At the subgroup level, all the Quartzipsamments fall within the Ustic group because of their ustic moisture regime. They are therefore, classified as Ustic Quartzipsamments. In the Haplustults, pedon LDS 2 of the Illela dunes is classified as Arenic Haplustults because it had an argillic horizon underlying a sandy surface horizon that was more than 50 cm thick. Pedons SDS 1 and SDS 2 are classified as Kanhaplic Haplustults because they had a CEC of less than 24 cmol(+) per Kg clay in their argillic horizons while pedon SDS 3, had a lithic contact at 40 cm, hence it is classified as Lithic Haplustults.

At the family level, the two differentiating criteria used, particle size and mineralogy classes, become redundant in the cases of the Ustic Quartzipsamments,

because by definition, the Quartzipsamments are sandy and siliceous. The particle size and mineralogical classes are therefore not used in the case of Quartzipsamments (Soil Survey Staff, 1975, 1990). At this level, they are therefore classified as Ustic Qaurtzipsamments, isohyperthermic. Pedons LDS 2 and SDS 3 had a coarse-loamy particle size class because by weight, they contained more than 15 percent fine sand and less than 18 percent clay. They are therefore, classified as Arenic Haplustults, coarse-loamy, mixed, isohyperthermic and Lithic Haplustults, coarse-loamy, mixed, isohyperthermic for pedons LDS 2 and SDS 3 respectively. Pedons SDS 1 and SDS 2, both are classified as Kanhaplic Haplustults, fine-loamy, mixed, isohyperthermic because by weight, they had more than 15 percent fine sand and between 18 and 34 percent clay in their fine earth fraction, while no singular mineral dominated the clay fractions of all the pedons (Figure 10). Summary of the classification is given in Table 23.

(b) FAO-UNESCO System

At the first level of the soil map of the world legend (FAO, 1974, 1988), pedons LDS 1, LDS 3 and LDS 4 in the Illela dunes, all pedons on the Sangiwa dunes and pedon SDS 4 on the Sokoto dunes, are placed in the unit Arenosols. These are soils which are coarser than sandy loam to a depth of at least 100 cm of the surface, and have no fluvic or andic properties except an ochric A horizon. They are placed in the subunit Ferralic Arenosols because they show Ferralic properties - have CEC that is less than 4 cmol(+) per Kg soil in some parts of the subsurface horizons.

Pedon SDS 3 in the Sokoto dunes is placed in the unit Alisols, because it has an argic B-horizon which has a CEC of more than 24 cmol(+) per Kg clay and a base saturation (by NH_4OAc) of less than 50 percent in the B-horizon. The pedon also lacked E-horizon and properties characteristics for Planosols, Nitisols and Podzoluvisols. At the subunit level, it is placed as Haplic Alisols, because it had a simple profile arrangement and lacked humic, ferric, plinthic, gleyic and stagnic properties within 125 cm of the

Table 23: Summary of soil classifications (USDA and FAO/UNESCO systems).

Pedons	USDA	FAO/UNESCO
	Illela Dunes	
LDS1	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
LDS2	Arenic Haplustult, coarse-loamy, mixed, isohyperthermic	Haplic Acrisols
LDS3	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
LDS4	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
	Sokoto Dunes	
SDS1	Kanhaplic Haplustult, fine-loamy, mixed, isohyperthermic	Haplic Acrisols
SDS2	Kanhaplic Haplustult, fine-loamy, mixed, isohyperthermic	Haplic Acrisols
SDS3	Lithic Haplustult, coarse-loamy, mixed, isohyperthermic	Haplic Alisols
SDS4	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
	Sangiwa Dunes	
GDS1	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
GDS2	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
GDS3	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols
GDS4	Ustic Quartzipsamment, isohyperthermic	Ferralic Arenosols

surface. It however, had a petroferric layer within a depth of 40 cm of the surface. Because of the implication of such petroferric layers to the management practices of the soil, a phase is further identified for this pedon and is therefore placed as Lithic Haplic Alisols.

Pedons SDS 1 and SDS 2 in the Sokoto dunes along with pedon LDS 2 in the Illela dunes are placed in the unit Acrisols. These are soils having an argic B-horizon with a CEC of less than 24 cmol(+) per Kg clay and a base saturation (by NH_4OAc) of less than 50 percent in the B-horizons. At the subunit level, they are all placed as Haplic Acrisols because their profiles are simple and lacked humic, ferric, plinthic and gleyic properties within 125 cm of the surface. The FAO-UNESCO classification is also summarized in Table 23.

6. SUMMARY AND CONCLUSIONS

This study was carried out in the Sokoto sedimentary basin on soils developed on ancient dunes of varying meso-relief.The main objective of the study was to understand the pedogenetic factors and processes influencing soil development on the dunes. In pursuance of the objective, the morphological, physico-chemical and mineralogical properties of the soils were investigated. The soils were also classified following the criteria of the USDA Soil Taxonomy system (Soil Survey Staff, 1975; 1990) and FAO/UNESCO soil map of the world legend (FAO/UNESCO, 1974; 1988).

All the dune soils have nearly similar morphological properties especially in the surface horizons. The soils are mainly deep to very deep. They all had a colour hue of 7.5YR and strong chroma, > 4 throughout their profiles. All the soils have sand textural class in the Ap horizon while in the subsoil have increasingly reddish colouration from Illela the youngest through Sangiwa to the Sokoto dunes, the pedogenetically oldest. This has been attributed to increasing ferritization as pedogenesis progresses. Subsoil textures vary from being outright sand in the Illela to loamy sand in the Sangiwa and sandy loam in the Sokoto dunes. The increasing clay contents is in the order : Sokoto > Sangiwa > Illela indicating increasing weathering and argilluviation as a result of increasing effective rainfall and chronological age.

Statistical analyses showed that the main differences between the dune soils are largely in their physical properties (Tables 9a and 9b) suggesting that the soils are relatively young (Dregne, 1986). The Sangiwa and Sokoto dunes have better physical development than the Illela dunes but they are all characterized by high bulk densities which range from 1.55 to 1.77 Mg m^{-3} in the surface horizons and rather high macroporosities which range between 25.62 to 41.39 percent in the surface soils and 36.87 and 50.95 percent in the subsoils. Structurally, the surface horizons exhibit weak development and are, therefore susceptible to some amount of erosion hazard.

The chemical properties indicate nearly similar fertility levels in all the dune soils. Soil pH indicates a wide range of reaction from 5.0 to 6.7 in the Sokoto and Sangiwa dunes and 4.8 to 8.0 in the Illela dunes. The corresponding soil reactions are very strongly acid to nearly neutral and very strongly acid to moderately alkaline. In the subsoils, the soil pH vary from 4.4 to 7.8 in the Illela, 4.0 to 6.5 in the Sokoto and 3.9 to 5.2 in the Sangiwa dunes. Organic carbon are extremely low, less than 2 g kg^{-1} in all the soils. These extremely low levels of organic matter reflect the low biomass of the sudano-sahelian ecosystem. The available phosphorus in the surface horizons are low in the Sangiwa with a range of 3.06 to 5.25 µg g^{-1}, low to moderate in the Sokoto dunes with a range of 6.02 to 17.82 µg g^{-1} and moderate to very high in the Illela dunes with a range of 14.97 to 46.36 µg g^{-1}.

Statistical analyses indicate similar levels of exchangeable bases, which were essentially very low in all the soils. For instance, exch. Ca^{2+} ranges from 0.32 to 2.46 cmol(+) Kg^{-1}; exch. Mg^{2+} from 0.08 to 0.78 cmol(+) Kg^{-1}; and exch. K^{+} from 0.02 to 0.16 cmol(+) Kg^{-1} in the surface horizons. The soils have low CEC, which range from 1.0 to 2.9 cmol(+)Kg^{-1} soil in the surface horizons and 1.1 to 4.6 cmol(+)Kg^{-1} soil in the subsoil horizons. Base saturation is also low to moderate reflecting the rather siliceous nature of the parent material which was dominated principally by quartz (Table 21).

Electrical conductivity (EC), exchangeable sodium percent (ESP) and free carbonate values are all very low. These are indications that the soils are neither saline, sodic nor calcic except for incipient calcification in parts of the Illela dunes.

The values of DTPA extractable cationic micronutrients elements Cu, Zn, Mn and Fe are all well above the generally accepted critical limits of 0.2, 0.8, 1.0 and 4.5 µg g^{-1} respectively. The main differences in the chemical properties of the dunes are mainly in properties such as available P, exchange acidity and available Mn, all of which are more related to the soil reaction. In this regard, the Illela dunes differ from the two other dunes, as a result of their alkaline soil reaction and incipient calcification.

Phosphorus fractions and adsorption capacities are similar in the dunes. The soils have a high total-P content, ranging from 404 to 1881 μg g^{-1}, because of the occurrence of phosphatic nodules within the rocks of the area, but the bulk of these are found as occluded P. This has been attributed to the highly weathered nature of the parent material of the soils. Adsorb-P followed by Al-P are the dominant extractable inorganic-P forms. The soils have very low and similar P sorption capacities which average about 100 mg Kg^{-1} soil. The P-sorption capacities at standard P solution concentration are also low and average about 20 mg Kg^{-1} soil. The similarity in the P-characteristics of the dunes has been ascribed to the similar soil properties of the dunes. The soils also have very low bond energy. Organic P contents are also low in all the dunes as a result of the very low organic matter contents of the soils, but possible organic P mineralization is indicated by the low C:P ratios.

The mineralogy of the soils are similar. Magnetite is the dominant magnetic mineral while quartz is the dominant non-magnetic mineral in the fine sand fraction of all the dunes. Hematite is many in the Sokoto dunes and few to common in the Sangiwa and Illela dunes. This would suggest that the Sokoto dunes are the oldest pedogenetically. Quartz also dominated the silt fractions of all the dunes followed by kaolinite. The dominance of the silt fraction by quartz again suggest the siliceous nature of the parent material. The subtle and unrecognizable peaks of the oxides of iron are attributed to their low concentrations and their high amorphous contents. Kaolinite was abundant in all the clay fraction of all the dunes indicating that kaolinization has been a major pedogenic process in the soils.

From the soil properties, it is evident that the parent material, topo-drainage and paleoclimate have had the most profound effects on the dunes. Pedogenesis which probably started at about 5,000 years ago has only produced AC profiles on the Sangiwa and Illela dunes and A-B-C profiles on the Sokoto dunes and pedon LDS 2 of the Illela

dunes. The main pedogenic processes operating in the soils include organic matter mineralization, clay eluviation-illuviation, limited horizonation, textural and structural differentiation which are better expressed in the Sokoto dunes as evidenced by the production of Bt horizons. This difference has been attributed to the better effective rainfall brought about by the planar topography. Kaolinization, ferritization and alitization are all largely ascribed to a more humid past climate, most probably in the Holocene (FAO, 1969). The dominance of occluded P in the phosphorus forms suggests that all the soils are highly weathered and are pedogenically mature.

Owing to the absence of any discernable B-horizon and morphological, physico-chemical and mineralogical similarities, all the pedons of the Sangiwa and Illela dunes (except pedon LDS 2) and pedon SDS 4 on the Sokoto dunes are all classified together at the family level as Ustic Quartzipsamment, isohyperthermic. All other pedons on the Sokoto dunes together with pedon LDS 2 on Illela dunes are classified as Haplustults at the greatgroup level, because of their low base saturation and simple profile arrangement. Pedons SDS 1 and SDS 2 are classified at the subgroup level as Kanhaplic Haplustults, because they have a CEC of less than 24 cmol(+)Kg^{-1} clay in their argillic horizons while pedon SDS 3 had a lithic contact at 40 cm, hence it fitted in the subgroup of Lithic Haplustults. Pedon LDS 2 on the Illela dunes is classified as Arenic Haplustult, because it has an argillic horizon underlying a sandy surface horizon that is more than 50 cm thick.

From the foregoing, the common constraints of the soils to increasing agricultural productivity are low contents of organic matter, inadequate contents of exchangeable Ca and K, and low water and nutrients holding capacities. All the soils would therefore require high doses of N and K inorganic fertilizers for optimum productivity. The Sangiwa and Sokoto dunes would also require the application of liberal doses of phosphorus. A balanced application of NPK fertilizer would most probably provide the

needed nutrients cheaply. All the soils would require management practices that would increase the water and nutrient holding capacities, such as organic matter build up and split application of fertilizers and irrigation water.

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APPENDIX

Profile number	:	GDS 1
General site information		
Soil mapping unit	:	Sangiwa dunes
Location	:	Bijeje village and 50 meters off the Sokoto - Sabon Birin road to the west.
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Rima group, mainly mudstone and friable sandstone.
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape.
Topography	:	Crest, nearly level with 0-2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea Corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 190 cm
Depth to impenetrable layer	:	None encountered at 190 cm
Described by	:	B.A. Raji
Date sampled	:	7th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 33	Dark yellowish brown (10YR 4/6) pinkish grey (7.5YR 7/3 dry) loamy sand; moderate fine subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few medium and common fine pores; few fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
AC	33 - 65	Strong brown (7.5YR 5/6) reddish yellow (7.5YR 6/6 dry) loamy sand; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine pores; common fine roots; common fine quartz grains; few ant holes; few fine charcoal; gradual smooth boundary.

C1	65 -108	Strong brown (7.5YR 5/6) reddish yellow (7.5YR 6/6 dry) loamy sand; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine pores; fine few roots; common fine quartz grains; few laterite stones; few fine charcoal; gradual smooth boundary.
C2	108 -185	Strong brown (7.5YR 5/6) reddish yellow (7.5YR 6/6 dry) loamy sand; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few medium pores; few very fine roots; common fine quartz grains; few laterite stones; few fine charcoal.

Profile number	:	**GDS 2**
General site information		
Soil mapping unit	:	Sangiwa dunes
Location	:	Bijeje village and 500 metres west of pedon GDS 1.
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Rima group, mainly mudstone and friable sandstone
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape.
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	About 4 metres in a nearby well
Depth to impenetrable layer	:	None encountered at 190 cm
Described by	:	B.A. Raji
Date sampled	:	7th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 24	Light brown (7.5YR 6/4) pink (7.5YR 7/3 dry) loamy sand; weak fine subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) soft (dry); few medium and common fine pores; common fine roots; common fine quartz grains; few ant holes; clear smooth boundary.
AC	24 - 45	Reddish yellow (7.5YR 6/6) sand loam; weak medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine to medium pores; few coarse and common medium roots; common fine quartz grains; few ant holes; gradual smooth boundary.
C1	45 - 100	Reddish yellow (7.5YR 6/6 dry) loam; moderate fine subangular blocky structure; non- sticky and non-plastic (wet) friable (moist) slightly hard (dry); many fine pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.

C2	100 -190	Light brown (7.5YR 6/4) pink (7.5YR 7/4 dry) loam; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) friable (moist) slightly hard (dry); very thin clay lamellae in pores; common fine pores; few fine roots; common fine quartz grains; few ant holes; few fine charcoal;few laterite stones.

Profile number	:	**GDS 3**
General site information		
Soil mapping unit	:	Sangiwa dunes
Location	:	Kirare village and 50 metres off the road
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Rima group, mainly mudstone and friable sandstone.
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 160 cm
Depth to impenetrable layer	:	None encountered at 160 cm
Described by	:	B.A. Raji
Date sampled	:	8th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 21	Light brown (7.5YR 6/4) pink gray (7.5YR 7/4 dry) loamy sand; moderate fine subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine to medium pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
AC	21 - 50	Light brown (7.5YR 6/4) pink (7.5YR 7/4 dry) loamy sand; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common medium pores; few fine roots; common fine quartz grains; few ant holes; charcoal; gradual smooth boundary.
C1	50 - 110	Strong brown (7.5YR 5/8) reddish yellow (5YR 6/6 dry) sandy loam; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) friable (moist) hard (dry); very few thin clay lamellae in pores; few medium pores; few fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.

C2	110 - 160	Reddish yellow (5YR 6/6) sandy loam; moderate fine subangular blocky structure; slightly sticky and slightly plastic (wet) firm (moist) hard (dry); few medium pores; few coarse roots; common fine quartz grains; few ant holes; common fine charcoal pieces.

Profile number	:	GDS 4
General site information		
Soil mapping unit	:	Sangiwa dunes
Location	:	Bijeje village and 200 metres west of pedon GDS 2.
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Rima group, mainly mudstone and friable sandstone
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 200 cm
Depth to impenetrable layer	:	None encountered at 200 cm
Described by	:	B.A. Raji
Date sampled	:	7th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 30	Light brown (7.5YR 6/4) pink gray (7.5YR 7/4 dry) loamy sand; moderate fine subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few medium and common fine pores; few fine roots; common fine quartz grains; few ant holes; clear smooth boundary.
AC	30 - 60	Reddish yellow (7.5YR 6/6) sandy loamy; moderate medium subangular blocky structure; slightly sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine pores;few coarse and common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
C1	33 - 65	Reddish yellow (7.5YR 6/6) loam; moderate medium subangular blocky structure;slightly sticky and non-plastic (wet) friable (moist) hard (dry); very few thin clay lamellae in pores; common fine to

		medium pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
C2	110 -160	Reddish yellow (7.5YR 6/8) loam; moderate medium subangular blocky structure; slightly sticky and slightly plastic (wet) friable (moist) hard (dry); very few thin clay lamellae in pores; common fine to medium pores; common fine roots; common fine quartz grains; few ant holes; few laterite stones.

Profile number	:	**SDS 1**
General site information		
Soil mapping unit	:	Sokoto dunes
Location	:	Gidan Gara and 150 metres off the Sokoto - Dange road.
Taxonomic classification	:	Kanhaplic Haplustult
Soil parent material	:	Aeolian deposit over laterite
Geology	:	Rima group, mainly mudstone and friable sandstone.
Geomorphology/physiography	:	Nearly level plain
Topography	:	Plain, gently sloping with 0 - 2 % slope
Vegetation/Landuse	:	Sudan savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Water table at about 8 metres in a nearby well
Depth to impenetrable layer	:	Laterite encountered at 105 cm
Described by	:	B.A. Raji
Date sampled	:	5th February, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 22	Strong brown (7.5YR 4/6) reddish yellow (7.5YR 7/3 dry) sand; moderate medium Subangular blocky structure; non- sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common medium pores common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
AB	22 - 39	Strong brown (7.5YR 5/8) reddish yellow (7.5YR 6/8 dry) loamy sand; moderate medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine to medium pores; common fine to medium roots; common fine quartz grains; few ant holes; very few laterite ; gradual smooth boundary.
Bt1	39 - 56	Yellowish red (5YR 5/8) reddish yellow (5YR 6/8 dry) loamy sand; weak fine subangular blocky structure; slightly sticky and slightly plastic (wet) friable (moist) slightly hard (dry); common fine pores; common very fine to fine roots; common fine quartz

		grains; few ant holes; few laterite gravels; gradual smooth boundary.
Bt2	56 - 85	Yellowish red (5YR 5/8) reddish yellow (5YR 6/8 dry) sandy loamy; moderate medium subangular blocky structure; slightly sticky and slightly plastic (wet) friable (moist) slightly hard (dry); thin clay cutans in pores; common very fine pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
Bt3	85 - 105	Yellowish red (5YR 5/8) reddish yellow (5YR 6/8 dry) sandy clay loam; moderate medium subangular blocky structure; sticky and slightly plastic (wet) firm(moist) slightly hard (dry) few fine pores; very few fine roots; common fine quartz grains common laterite gravels; few termite holes

Profile number	:	SDS 2
General site information		
Soil mapping unit	:	Sokoto dunes
Location	:	Dange - Danchadi road, 50 metres opposite primary school
Taxonomic classification	:	Kanhaplic Haplustult
Soil parent material	:	Aeolian deposit over laterite
Geology	:	Rima group, mainly mudstone and friable sandstone
Geomorphology/physiography	:	Nearly level plain topography: Plain, gently sloping with 0 - 2 % slope
Vegetation/Landuse	:	Sudan savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 100 cm
Depth to impenetrable layer	:	Laterite encountered at 95 cm
Described by	:	B.A. Raji
Date sampled	:	4th February, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap1	0 - 15	Strong brown (7.5YR 4/6) reddish yellow (7.5YR 7/3 dry) sand; weak fine subangular blocky structure; non- sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common medium pores common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
AB	15 - 26	Strong brown (5YR 5/6) reddish yellow (5YR 6/6 dry) sandy loamy; moderate medium subangular blocky structure; slightly sticky and non-plastic (wet) friable (moist) slightly hard (dry); common fine to medium pores; few fine roots; common fine quartz grains; few ant holes; very few laterite ; gradual smooth boundary.
Bt1	26 - 52	Yellowish red (5YR 5/6) reddish yellow(5YR 6/6 dry) sandy loamy; moderate medium subangular blocky structure; slightly sticky and slightly plastic (wet) friable (moist) slightly hard (dry); common fine pores; few fine roots; common fine quartz grains; few ant holes; few laterite gravels; gradual smooth boundary.

Bt2	52 - 80	Yellowish red (5YR 5/8) reddish yellow (5YR 6/8 dry) sandy loam; moderate medium subangular blocky structure; slightly sticky and slightly plastic (wet) friable (moist) slightly hard (dry); thin clay cutans in pores; few fine pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
Bt3	80 - 95	Yellowish red (5YR 5/8) reddish yellow (5YR 6/8 dry) sandy clay loam; moderate medium subangular blocky structure; sticky and slightly plastic (wet) firm (moist) slightly hard (dry) few very fine pores; very few very fine roots; common fine quartz grains common laterite gravels; few termite holes

Profile number	:	**SDS 3**
General site information		
Soil mapping unit	:	Sokoto dunes
Location	:	1.5 km south of Gwadabawa and 100 metres east of the Sokoto - Illela road.
Taxonomic classification	:	Lithic Haplustult
Soil parent material	:	Aeolian deposit over laterite
Geology	:	Sokoto group, mainly shale with mudstone and limestone
Geomorphology/physiography	:	Nearly level, gently sloping planar surface
Topography	:	Plain, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudan savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of acolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 40 cm
Depth to impenetrable layer	:	Laterite encountered at 40 cm
Described by	:	B.A. Raji
Date sampled	:	6th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 15	Strong brown(7.5YR 5/8) reddish yellow (7.5YR 6/8) loamy sand; weak fine angular blocky structure; non-sticky and non- plastic (wet) very friable (moist) soft (dry); common fine to medium pores; common fine roots; common fine quartz grains; gradual smooth boundary.
Bt	15 - 40	Yellowish red (5YR 4/8) sandy loam;moderate medium subangular blocky structure; slightly sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine pores; common fine roots; common fine quartz grains; few ant holes;gradual smooth boundary.

Profile number	:	**SDS 4**
General site information		
Soil mapping unit	:	Sokoto dunes
Location	:	8.5 km north of Kware and 50 metres east of the Sokoto-Illela road.
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Sokoto group, sandstone, mudstone, shale and limestone
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudan savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Profile ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 190 cm
Depth to impenetrable layer	:	None encountered at 190 cm
Described by	:	B.A. Raji
Date sampled	:	6th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 15	Strong brown (7.5YR 5/8) reddish yellow (7.5YR 7/8 dry) sand; weak fine subangular blocky structure; non- sticky and non-plastic (wet) very friable (moist) soft (dry); few medium pores; few fine roots; common fine quartz grains; gradual smooth boundary.
Ac	15 - 35	Strong brown (7.5YR 5/6) reddish yellow (7.5YR 6/8 dry) sand; weak fine subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common medium pores; few coarse and common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
C1	35 - 60	Strong brown (7.5YR 5/8) reddish yellow(7.5YR 6/8 dry) sand; weak medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few medium pores; few fine roots; common fine quartz grains; few ant holes; clear smooth boundary.

2C2	60 - 115	Dark brown (7.5YR 4/6) strong brown (7.5YR 5/6 dry) loamy sand; weak medium subangular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few fine pores; few fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
2C3	115 - 180	Yellowish red (5YR 5/8) reddish yellow (5YR 6/8 dry) loamy sand; weak to moderate fine angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few very fine pores; few fine roots; common fine quartz grains and few laterite stones; few ant holes

Profile number	:	**LDS 1**
General site information		
Soil mapping unit	:	Illela dunes
Location	:	Tundu Muala, 250 metres off the Sokoto-Illela road to the west.
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Gwandu formation, mainly clay and friable sandstone
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a dune landscape
Topography	:	Shoulder, nearly level with 0-2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 175 cm
Depth to impenetrable layer	:	None encountered at 175 cm
Described by	:	B.A. Raji
Date sampled	:	6th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 28	Strong brown (7.5YR 4/6) pink (7.5YR 7/3 dry) sand; granular to weak fine angular blocky structure; non-sticky and non- plastic (wet) very friable (moist) soft(dry); few medium pores; common very fine to fine roots; common fine quartz grains; gradual smooth boundary.
AC	28 - 63	Strong brown (7.5YR 5/6) reddish yellow (7.5YR 7/6 dry) sand; weak medium angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few fine pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.

C1	63 -142	Yellowish red (5YR 5/6) sand; weak medium angular blocky structure; non-sticky and non-plastic (wet) friable (moist) slightly hard (dry); common fine pores; few medium to common fine roots; common fine quartz grains and few laterite stones; few ant holes; gradual smooth boundary.
C2	142 -175	Red (2.5YR 5/6) light red (2.5YR 6/6 dry) sand; moderate medium angular blocky structure; non-sticky and non-plastic (wet) friable (moist) slightly hard (dry); few fine pores; few medium roots; common fine quartz grains;

Profile number	:	LDS 2
General site information		
Soil mapping unit	:	Illela dunes
Location	:	Tundu Muala and 500 metres west of pedon LDS1.
Taxonomic classification	:	Arenic Haplustult
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Gwandu formation, mainly clay and fined-grained sandstone.
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a dune landscape
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 210 cm
Depth to impenetrable layer	:	None encountered at 210 cm
Described by	:	B.A. Raji
Date sampled	:	6th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 18	Strong brown (7.5YR 5/6) reddish yellow (7.5YR 7/3 dry) sand; weak fine angular blocky structure; non-sticky and non- plastic (wet) very friable (moist) loose to soft(dry); few fine pores; common very fine to fine roots; common fine quartz grains; slight stratification near the surface; gradual smooth boundary.
AB	18 - 52	Yellowish red (5YR 5/6) light reddish brown (5YR 6/4 dry) sand; weak medium angular blocky structure; non-sticky and non- plastic (wet) very friable (moist) slightly hard (dry); common fine pores; few medium to common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
Bt1	52 - 95	Red (2.5YR 5/6) light red (2.5YR 6/6)sand; moderate medium angular blocky structure; slightly sticky and slightly plastic (wet) firm (moist) hard (dry); thin lamellae of Fe-clay oxides in pores;

		few fine pores; few medium to common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
Bt2	95 -170	Red (2.5YR 5/8) light red (2.5YR 6/6 dry) sandy loam; moderate medium angular blocky structure; slightly sticky and slightly plastic (wet) firm (moist) slightly hard (dry); thin lamellae of Fe-clay oxides in pores; few fine pores; few fine to medium roots; common fine quartz grains; few ant/termite holes

Profile number	:	**LDS 3**
General site information		
Soil mapping unit	:	Illela dunes
Location	:	1 km north of Tundgantudo and 100 metres off the Sokoto - Illela road to the east
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Sokoto group, mainly shale with mudstone and limestone.
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudano-sahelian savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Water table at about 5 metres in a nearby well
Depth to impenetrable layer	:	None encountered at 210 cm
Described by	:	B.A. Raji
Date sampled	:	6th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 27	Dark brown (7.5YR 4/6) strong brown (7.5YR 5/6) sand; weak fine angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) soft (dry); common fine to medium pores; common very fine roots; common fine quartz grains; few ant holes; clear smooth boundary.
AC	27 - 73	Dark brown (7.5YR 4/4) loamy sand; weak fine angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); few fine pores; common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
C1	73 -130	Dark brown (7.5YR 4/4) loamy sand; weak moderate angular blocky structure; non-sticky and non-plastic (wet) friable (moist) slightly hard (dry); few very fine pores; very few fine roots;

		common fine quartz grains; few ant holes; gradual smooth boundary.
C2	130 -210	Dark brown (7.5YR 5/6) loamy sand; moderate medium angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); very few fine roots; common fine quartz grains; few ant holes.

Profile number	:	*LDS 4*
General site information		
Soil mapping unit	:	Illela dunes
Location	:	1.5 km south of Asara and 100 metres off the Sokoto-Illela road to the east.
Taxonomic classification	:	Ustic Quartzipsamment
Soil parent material	:	Aeolian deposit over sedimentary rock
Geology	:	Sokoto group, mainly shale, mudstone and limestone.
Geomorphology/physiography	:	Nearly level, gently sloping planar surface in a denuded dune landscape
Topography	:	Crest, nearly level with 0 - 2 % slope
Vegetation/Landuse	:	Sudan savanna, cultivated to millet, Guinea corn.
Erosion	:	None, but slight deposition of aeolian materials.
Soil moisture conditions	:	Ustic
Drainage	:	Very well drained
Depth to water table	:	Not encountered at 190 cm
Depth to impenetrable layer	:	None encountered at 190 cm
Described by	:	B.A. Raji
Date sampled	:	6th May, 1994.

HORIZONAL DESCRIPTIONS

Horizon	Depth (cm)	Description
Ap	0 - 12	Dark brown (7.5YR 4/4) brown (7.5YR 5/4) loamy sand; singled grained; non-sticky and non-plastic (wet) loose (moist) loose (dry); few fine to medium roots; many fine quartz grains; clear smooth boundary.
AC	12 - 60	Dark brown (7.5YR 4/4) brown (7.5YR 5/4 dry) loamy sand; weak fine angular blocky structure; non-sticky and non-plastic (wet) very friable (moist soft (dry); common fine to medium pores; few medium and common fine roots; common fine quartz grains; few ant holes; gradual smooth boundary.
C1	60 -100	Dark brown (7.5YR 4/4) brown (7.5YR 5/4 dry) loamy sand: moderate medium angular blocky structure; non-sticky and non-plastic (wet) friable (moist) slightly hard (dry); common fine quartz grains and laterite stones; few ant holes; gradual smooth boundary.

C2	100 - 140	Dark brown (7.5YR 4/4) light brown (7.5YR 6/4 dry) loamy sand; moderate medium to fine angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); very few very fine pores; few very fine roots;common fine quartz grains; few charcoal pieces; few concentric carbonate layers, effervescent with dilute HCl; clear smooth boundary.
C3	140 -190	Light brown (7.5YR 6/4) pink (7.5YR 7/4 dry) sand; moderate fine angular blocky structure; non-sticky and non-plastic (wet) very friable (moist) slightly hard (dry); common fine quartz grains;fibre of dark brown (7.5YR 4/4) clay.