EVALUATION OF SOME OXISOLS, ULTISOLS AND INCEPTISOLS WITH THEIR PRACTICAL SIGNIFICANCE IN SIERRA LEONE

By

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ABSTRACT

EVALUATION OF SOME OXISOLS, ULTISOLS AND INCEPTISOLS WITH THEIR PRACTICAL SIGNIFICANCE IN SIERRA LEONE

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Eleven representative profiles from four physiographic groups were studied. The soils of the Upland Surfaces of Highly Weathered Material are Oxisols. Segbwema and Timbo series of the Steep Hills and Slopes were Ultisols and Inceptisols, respectively. In the soils of the Colluvial Footslopes and Upper River Tributary Terraces, Pendembu series belongs to Oxisols and Masuba series to Ultisols. The soils of the Alluvial Terraces and Floodplains are all Inceptisols.

Following are some of the other findings and relationships. Percent clay values, when free Fe oxide is removed before particle size analysis, are higher than when free Fe oxide is not removed and are also commonly higher than clay estimated by the factor 2.5 x 15 bar moisture content. 3.0 x 15 bar H_2O seems to give a better estimate of the percent of clay in these soils.

The criterion:

$$\frac{\text{sum of exchangeable cation + exch. Al x 100}}{\text{\% Clay (Fe removed)}} \leq 10 \text{ me/100g}$$

does not separate the oxic from non-oxic horizons of the soils studied; all pedons studied meet this criterion. A critical value

of 0.06 for the ratio

$$\frac{\%\ Fe_2O_3d\ -\ \%\ Fe_2O_3ox}{\%\ clay\ (Fe\ removed)}^{*}$$

gives a better separation of the soils, but is also unsatisfactory.

Ironstone nodules adsorbed a relatively smaller percent of P than did the fine earth fractions of representative gravelly soils. P adsorbed by the surface and subsurface horizons of the fine earth fractions is correlated with percent organic C, Al_2O_3ox, Fe_2O_3d and Fe_2O_3ox. The ironstone nodules have a diluting effect on the total amount of P fixed by the gravelly soils.

The dominant clay mineral in the total and fine clay is kaolinite, which is less ordered in the fine clay. Clay mineralogy of the ironstone nodules is similar to that of the fine earth fractions of two representative profiles. Mica flakes in the medium and fine sand fractions of Segbwema and Timbo series are mainly inter-layered illite-chlorite and kaolinite.

Thin section studies of B horizons of whole soils showed that most of the soils lack argillic horizons. Thin sections of ironstone nodules showed two main types: one derived from rock fragments and the other from plinthite. Argillans lined old channels of some nodules, indicating past genetic processes. The term petroplinthite is suggested in place of skeletal at the family level when the >2mm fraction is dominantly ironstone nodules.

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*Fe_2O_3 and Al_2O_3 total, and sodium bicarbonate citrate dithionite, ammonium oxalate, or sodium pyrophosphate extractable components are referred to as Fe_2O_3t and Fe_2O_3d, Fe_2O_3ox or Fe_2O_3pp and Al_2O_3d, Al_2O_3ox or Al_2O_3pp, respectively.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure		Page

LIST OF PLATES

INTRODUCTION

Less than 10% of the total land area in Sierra Leone has been soil surveyed to date. The surveyed areas are distributed within six of the sixteen soil provinces in Sierra Leone.

Work done on many of the soils in these areas has shown that some of the soils have properties that could qualify them to be placed in two of three soil orders in Soil Taxonomy, e.g., Inceptisol and Oxisol or Oxisol and Ultisol.

In the case of the Inceptisol-Oxisol alternative, most of the soils are presently classified as Oxisols because they do not meet the requirement of at least 3% of weatherable minerals within the profile. Most of the soils so classified are found on the lower terraces of the major rivers or they are alluvial in nature with minimal profile development. The source of their parent material is believed to be the soils of the old erosional surfaces, which are presently classified as Ultisols. Also, by virtue of their physiographic positions, they are considered to be the youngest soil landscapes. Should these soils be classified as Oxisols derived from Ultisols?

Soils presently classified as Ultisols mostly occupy the oldest positions on the landscape. Many have hardened plinthite gravels (ironstone gravels) that extend from the surface to depths greater than 1.5 meter within the profiles. Generally, the ironstone gravels account for 20-70% of the total soil weight. These ironstones are believed to be the result of active soil formation processes within the profile. They are believed to represent the irreversibly hardened form of plinthite. Plinthite (which represents an earlier stage in the formation of ironstone gravel) is important in the separation of Oxisols from Inceptisols and Oxisols from Ultisols in Soil Taxonomy. However, ironstone gravel does not appear to be useful in making the above-mentioned separations in the Taxonomy.

Also, the argillic horizons that are present in some soils of the upland erosion surfaces (based on the B/A clay ratio) could be a result of secondary development in areas dominated by termite mounds high in water-dispersible clays. Termites, through their activity in the soil, bring fine textured material from the subsoil to the surface horizons where they are used for building mounds. The mounds may eventually be eroded, and fine fractions can move through the surrounding soils by mechanical means.

Eleven profiles representing soils from three of the six soil provinces where soils have been surveyed are studied in this research. These soils are selected from four cited physiographic positions on the landscape.

The objectives are:

1. To determine additional mineralogical, physical, and chemical characteristics of these soils.

2. To study the micromorphology of the profiles.

3. To evaluate some mineralogical, physical, chemical and micromorphological characteristics of the ironstone gravels.

4. To evaluate the present criteria and/or limits used in separating the Oxisols, Ultisols and Inceptisols in the light of 1, 2 and 3 above and to make suggestions for possible modifications.

5. To present a hypothesis concerning the genesis of the soils studied.

6. Finally, to relate the characteristics of these soils to their potential uses and management for agricultural purposes.

LITERATURE REVIEW

Laterite and Lateritic Soils

Definitions (Laterite, Lateritic Soils, Plinthite and Ironstone)

The term laterite has been used for many years to describe sesquioxide-rich material found in soils of tropical and subtropical regions. This material has been studied since the 19th century by many researchers who have defined it in different ways.

Buchanan in 1807 (cited in Humbert) was the first to define the material that was called laterite. His definition was "an iron-oxide-rich, indurated quarryable slag-like or pisolitic illuvial horizon developed in the soil profile." This definition is restrictive and the material so defined occurs to only a limited extent in the tropics. Evans, in 1910, referred to laterite as material that contains some Al oxide and Fermor, in 1911, considered use of the term only for soft material (that contains Fe) that can be cut into bricks.

Prescott (1931) defined laterite to include hard ferruginous surface formations and Al rich material. Walther (1889, 1915 and 1916) (cited in Sivarajasingham et al., 1962), thought that laterite signified red colors and proposed that the term be used for all red-colored alluvial material.

Later, as the need for a standard definition of laterite became important, chemical analyses of the material were conducted. The

SiO_2/Al_2O_3 and SiO_2/R_2O_3 ratios were adopted as the basis for calling a soil laterite, lateritic and non-lateritic (Martin and Doyne, 1927 and 1930).

Baldwin et al. (1938) and Thorp and Smith (1949) used the terms laterite and lateritic soils for zonal great soil groups, found in humid tropical and subtropical areas.

In 1946, Pendleton and Sharasuvana defined laterite soils as "one in which a laterite horizon is found in the profile." du Prez (cited in Sivarajasingham et al., 1962) supported Pendleton and Sharasuvana definitions of laterite soil and lateritic soil, but did not include the presence of Al as an important criterion.

Mohr and van Baren (1954) supported the use of laterite and lateritic for soils composed of similar weathering products that produce soil as well as material that hardens.

In 1949, Kellogg used the term laterite to describe four kinds of material that are hard or that harden upon exposure. These materials include (a) soft mottled clays that change irreversibly to hardpans or crust when exposed; (b) cellular and mottled hardpan and crusts; (c) concretions or nodules in a matrix of unconsolidated material; and (d) consolidated masses of such material, i.e., concretions or nodules.

Alexander and Cady (1962) gave a concise definition of laterite as a highly weathered material rich in secondary oxides of Fe, Al, or both. It is nearly void of bases and primary silicates, but it may contain large amounts of quartz and kaolinite.

In the USDA Soil Survey Staff (1960) Soil Classification System, a new term was introduced, plinthite, with the intention to avoid confusion arising from the use of the term laterite. Plinthite as defined in this system referred to the soft laterite material. It is a sesquioxide rich, humus poor, highly weathered mixture of clay with quartz and other diluents, which commonly occur as red mottles usually in platy, polygonal, or reticulate pattern. Plinthite changes irreversibly to hardpans or irregular aggregates, on repeated wetting and drying. It is a form of the material which has been called laterite.

This definition is also used by the FAO System (FAO-UNESCO, 1974) for Fe-rich clay which can be cut with a spade.

The hardened form of this material is called ironstone in both systems. In this dissertation laterite is considered to include both plinthite and ironstone.

Genesis and Mode of Formation of 'Laterite' (Plinthite and Ironstone)

Several theories on the genesis and formation of laterite have been proposed, dating back to mid to late 19th century. Some of the theories proposed, included residual weathering in place and volcanic origin with subsequent weathering. Holland (1903) supported the idea of weathering of material in place to give laterite, but concluded that a simple chemical weathering cannot explain the abrupt transition from laterite to weathered rock. Humbert (1948) conducted studies on laterite found in New Guinea. He concluded that under conditions of abundant moisture and high temperature in humid equatorial regions, a rigorous weathering and transformation of parent material occurs. At the final stages of these processes, laterization occurs in which oxides of Fe are concentrated, which become indurated

upon exposure. He also advanced the idea that three main stages are involved in the genesis of laterites: (a) advanced decomposition of the mineral constituents of the parent rock, release and removal of Si from the surface horizons and separation of the sesquioxides; (b) formation of free Fe oxides by decomposition of ferromagnesium material; and (c) dehydration resulting in color change. "As dehydration progresses the surface is reduced and eventually a compact concretion is obtained.

The Fe oxide is dehydrated and irreversibly fixed. This is the concretion stage. As the hydrated oxides are precipitated in the vicinity of the concretions, a concentration gradient is established, Fe moves with the gradient and the concretion grows in size as the supply of Fe moves into position through voids and channels of the weathering matrix. Growth of the concretion continues until an indurated crust is formed."

D'Hoore (1955) suggested two chemical processes that are involved in the formation of laterites: (a) concentration of sesquioxides by removal of Si and bases; or (b) concentration of sesquioxides by accumulation from outside sources.

Alexander and Cady (1962) suggested that materials within the observed range of composition of laterite may be developed from rock in place by several possible courses of weathering and mineral transformation, all of which involve almost complete removal of bases and at least substantial losses of the combined Si of primary minerals.

Hamilton (1964) and Schmidt (1964) observed fine droplets of Fe oxyhydrates in micromorphological studies they conducted on laterite. The latter relates the development of laterite to a coalescence of these droplets. Later, micromorphological studies on laterite by some researchers, including Eswaran and Mohan (1973), did not tend to support Schmidt's theory. What is clear in these theories is that all of the researchers agreed that the removal of Si is necessary for the formation of laterite.

Classification of Laterite (Plinthite and Ironstone)

Several classifications of laterite have been proposed which are either based on genetic or morphological (including micromorphological) properties.

Genetic classifications have been suggested by Aubert (1963), Maignen (1959) and D'Hoore (1954).

Pendleton and Sharasuwana (1946) classified laterites by their morphological properties. They suggested two forms, (1) vesicular and (2) pisolitic, with many intermediate types; vesicular laterite may be soft or of varying hardnesses. Alexander and Cady (1962) recognized three main types of laterite: (a) residual laterite, which has evidence of rock structure; (b) laterite with features that resemble those of soil; and (c) pisolitic laterite composed of pisolitic bodies more or less closely packed together.

Sivarajasingham et al. (1962) used the term nodular laterite as material consisting of individual concretions, pisolites or other crudely round masses, usually the size of a pea but commonly larger or smaller. It is generally ferruginous and cementation of the nodules gives rise to pisolitic or concrete-like laterite.

Young (1976) proposed a morphological classification of laterite based on that of Pullman (cited in Young). He recognized five main types of laterite: (a) Massive laterite: This material possesses a continuous hard fabric, its subdivisions are cellular laterite and vesicular laterite. (b) Nodular laterite: This consists of individual, approximately rounded, concretions for which he suggested four subdivisions, (i) cemented nodular laterite, (ii) partly cemented nodular laterite; (iii) non-cemented nodular laterite, and (iv) iron concretions. (c) Recemented laterite. (d) Ferrugenized rock: Rock structure is still visible, but with substantial isomorphous replacement by Fe. (e) Soft laterite: Mottled Fe-rich clay which hardens irreversibly on exposure to air or to repeated wetting and drying.

The nodular types of laterite have been called different names in the literature. These include lateritic concretions, ironstone nodules and glaebules (Brewer and Sleeman, 1964).

Young's (1976) ferruginized rock is what has been referred to as residual laterite by Alexander and Cady (1962), and his definition of soft laterite is envisaged in the definition of plinthite in the Soil Taxonomy, USDA (1975).

Westerveld (1969) recognized two types of nodular laterite in an upland soil of Sierra Leone based on their external morphology. One type he called SLC (Smooth Laterite Concretion). These are rounded and darker in color than the RLC (Rough Laterite Concretions), which are more angular and lighter colored. Eswaran and Mohan (1973) observed that the matrix of indurated laterite concretions which they studied were predominantly clay which had been coated by Fe deposition. Plinthite has been recently classified by Daniels et al. (in press) into platy and nodular forms.

Classification of Lateritic Soils
(Oxisols, Ultisols and Inceptisols)

Lateritic soils have been classified in various classification systems, including the USDA, French, Belgian and FAO-UNESCO (Soil Map of the World).

In Marbut's time, these soils were referred to as Ferruginous Laterite soils. In 1938 Thorp and Baldwin considered Lateritic soils as zonal soils with great soil groups such as Reddish-Brown Lateritic soils, Yellowish-Brown Lateritic soils and Laterite soils. In the FAO-UNESCO (1974) system, Ferralitic soils are classified in the highest category as Nitosols, Acrisols and Ferralsols. In the French system they can be classified as Sols Ferrallitigues and Sols Hydromorphes.

Young (1976), using a modified form of the CCTA (Commission for Technical Co-operation in Africa) 1964 Soil Map of Africa, suggested three major divisions of Latosols. (The term Latosol was first used by Kellogg in 1949 to include the zonal soils in tropical equatorial regions that have their dominant characteristics associated with low Si-sesquioxide ratios of clay fractions, low base exchange capacity, low activities of the clay, low content of most primary minerals.) Young's divisions were: Ferrallitic soils, Ferruginous soils, and soils derived from basic rocks (Basisols).

In the USDA Soil Survey Staff (1960-67) Soil Classification and in Soil Taxonomy (1975), soils that were described as great groups of Lateritic soils in the 1938 classification were absorbed into four of the ten orders in the system. These orders include Oxisols, Ultisols, Alfisols and Inceptisols. The Ferrallitic soils of Young and the Ferrasols of the FAO-UNESCO system are mainly Oxisols and

Ultisols in the USDA Soil Taxonomy. The Ferruginous soils of Young are the Ultisols and Alfisols and the Basisols can be put in the orders Oxisols, Ultisols, and Alfisols, depending on the degree of weathering. The Reddish-Brown Lateritic and Yellowish-Brown Lateritic soils of the 1938 classification fall mainly in the order Ultisols and a few in the Alfisols and Oxisols. A majority of the Laterite soils are Oxisols in Soil Taxonomy.

The single most diagnostic properties of Oxisols, Ultisols and Inceptisols, respectively, in Soil Taxonomy (1975) are the presence of oxic, argillic and cambic horizons (the genesis of these three diagnostic horizons is discussed in the next section).

A major criterion for separating the Oxisols from the Ultisols and Inceptisols is the presence of plinthite within 30cm of the soil surface. Plinthite that forms a continuous phase or constitutes more than half the matrix of some sub-horizon within 1.25m of the surface is considered as diagnostic at the great group level, e.g., Plinthaqualf, Plinthaquepts, Plinthustalf, Plinthudult, etc. If plinthite occurs in the soil but does not constitute a continuous phase, a plinthic subgroup is used (Soil Survey Staff, 1960, and Soil Taxonomy, 1975).

However, hardened laterite (irreversible) materials, which include ironstone (by definition), are not plinthite, and are therefore excluded as diagnostic properties at the great group and subgroup levels discussed above. However, hard materials rich in secondary Al oxides are diagnostic at the great group level in the order Oxisols, e.g., Gibbsiaquox.

A diagnostic petroferric layer is recognized as separate from a lithic contact. The petroferric layer is more or less a laterite sheet (vesicular laterite). Most laterite materials are rich in Fe oxides. These are excluded from the limits of an oxic horizon that apply to <2mm material.

In other classification systems, e.g., the French system, concretionary laterite and lateritic crust (sheets) are diagnostic at the subgroup level, and hardened (indurated) subgroups have been described within the Ferrallitic groups.

Sys in 1968 proposed the inclusion of great groups and subgroups in the Ultisols, Oxisols and Inceptisols with hardened lateritic materials as diagnostic features. He proposed the name petroplinthic for Fe and/or Al oxide individualizations which have hardened irreversibly. When moist it cannot be cut with a spade. It appears as hard concretions in a clayey matrix or as a hard crust or sheet. He suggested the use of petroplinthic horizon as a diagnostic horizon for classification at the group level, and also the presence of petroplinthite in the profile as a diagnostic subgroup property.

Genesis of Oxic, Argillic and Cambic Horizons

Oxic horizon: The oxic horizon is the major requirement for the Oxisols as defined in the USDA Soil Taxonomy (1975). The current theory endorsed by the U. S. Soil Conservation Service is that it occurs in soils of very old, stable geomorphic surfaces (Mid-Pleistocene or older rather than late or post-Pleistocene). The old age of the oxic horizon has allowed time for mixing by plant roots and animals so that there is little or no evidence of original rock structure, with the exception that if Fe oxides or gibbsite coat and cement fragments of weathered rock, the original rock structure may be retained in the interior of the cemented parts. Weatherable minerals are absent or present only in traces, which makes this horizon low in bases except for those held in exchange complexes and plant tissues.

Most of the soils with oxic horizons are found in tropical and subtropical climates. They usually occur on nearly level or gentle slopes. The geomorphic position is one in which weathered sediments could have been deposited and not one in which recent unweathered sediments could accumulate.

Argillic horizon: The horizon of illuvial silicate clays in soils has been recognized in the USDA Classification Systems (Soil Survey Staff, 1960, and USDA Soil Taxonomy, 1975) as a diagnostic horizon at the highest level of classification. This horizon is called an argillic horizon and it is a major diagnostic property of Ultisols and Alfisols.

Several theories concerning the dispersion, migration and accumulation of the silicate clay in this horizon have been proposed by various researchers (Jenny and Smith, 1934; Hallsworth, 1963). One such theory is that of Kubiena, as cited by Stephen (1960). He suggested that the presence of colloidal Si acts as an efficient peptizing agent to confer on kaolinite and halloysite, swelling capacity and plasticity as well as extraordinary hardness when dry. Kubiena's idea was recognized by other workers (Hallsworth, 1963), who also suggested that particles can be kept in a condition of suspension under the protective influence of organic matter and Si. Studies on clay migration have also been conducted by Jenny and Smith (1934), Buol and Hole (1961) and Hallsworth (1963). However, there seems to be no general agreement among researchers about the processes involved in clay movement from the A to the B horizons.

The current theory recognized by the Soil Survey Staff (1975) is that of mechanical migration. The stages involved are: (a) The parent material contains very fine clays or weathering must produce them. The very fine clays carry negative charge, as does the soil matrix, and tend to disperse, unless flocculated by salts, including carbonates and free oxides. (b) Wetting of the dry soil leads to disruption of the fabric and to dispersion of clay. Once dispersed, the clay is believed to move with percolating water and to stop where the percolating water stops. Water percolating in noncapillary voids commonly is stopped by capillary withdrawal into the soil fabric. During the withdrawal the clay is believed to be deposited on the walls of the noncapillary voids. Carbonates can also be effective in stopping the moving clay.

Mixing of horizons by animals, frost, shrinking and swelling must be slow or absent to permit formation of an argillic horizon.

Cambic horizon: This is a major diagnostic horizon for the order Inceptisols. In Soil Taxonomy (Soil Survey Staff, 1975), a cambric horizon is considered to be an altered horizon in which the texture of the <2mm fraction is very fine sand or loamy very fine sand or finer. Two types of alterations in this horizon are physical and chemical.

Physical alteration is the result of (a) movement of soil particles by frost, roots or animals to a point at which most of the original rock structure is destroyed, including the fine stratification of silt, clay and very fine sand in alluvial or lacustrine deposits, and (b) aggregation of the particles into peds.

Chemical alteration is the result of (a) hydrolysis of some of the primary minerals to form clays and liberation of sesquioxides, (b) solution and redistribution, and (c) reduction and segregation or removal of free Fe oxide along with biologic decomposition of inherited organic matter.

Criteria and Limits of Oxic, Argillic and Cambic Horizons in Soil Taxonomy (1975)

Oxic horizon: This horizon must be at least 30cm thick and have 10me or less of NH_4OAC extractable bases plus Al extractable with 1.0N KCl per 100g clay; C.E.C. of fine-earth fraction (NH_4OAC) of 16 me or less per 100g clay; only traces of weatherable minerals; and <5% by volume that shows rock structure. The soil texture is sandy loam or finer in the fine-earth fraction and has >15% clay and soil horizon boundaries are gradual or diffuse.

Argillic horizon: This is an horizon that contains illuvial silicate clay. If an eluvial horizon remains and there is no lithologic discontinuity, the argillic horizon contains more total clay, and more fine clay, than the overlying eluvial horizon as follows: If the eluvial horizon has <15% clay in the fine-earth fraction, the illuvial horizon should have 3% more total clay or the ratio of fine clay to total clay in the illuvial horizon should be one-third greater than that in the overlying eluvial horizon or underlying horizon.

If the total clay in the eluvial horizon is >15% but less than 40% in the fine-earth fraction, the ratio of illuvial/eluvial horizon clay should be 1·2 or greater. The ratio of fine clay to total clay in the illuvial horizon is normally one-third or more greater than in the eluvial horizon.

If the total clay is >40% in the eluvial horizon, the illuvial horizon should have 8% more clay, or if the total clay is >60%, 8% more fine clay is required in the illuvial horizon. These clay increases are reached within 30cm or less vertically. The argillic horizon should be at least one-tenth as thick as the sum of the thickness of all overlying horizons or it should be 15cm or more thick if the eluvial and illuvial horizons together are >1.5m thick. If the argillic horizon is sand or loamy sand, it should be at least 15cm thick. If the argillic horizon is loamy or clayey, it should be at least 7.5cm thick. Clay skins should be present on ped surfaces (vertical and horizontal) or thin sections should show oriented clays in 1% or more of the cross section. If the horizon is clayey, if the clay is kaolinitic, and if the surface horizon has >40% clay, it should have some clay skins on peds and in pores in the lower part of the horizon that has blocky or prismatic structure.

If there is a lithologic discontinuity in the profile between the eluvial horizon and the argillic horizon, or if only a plow layer overlies the argillic horizon, the argillic horizon needs to have clay skins in only some part, either in some fine pores or, if peds exist, on some vertical and horizontal ped surfaces. Either

thin sections should show that some part of the horizon has about 1% or more of oriented clay bodies, or the ratio of fine clay to total clay should be greater than in the overlying or the underlying horizon.

Cambic horizon: For a cambic horizon in soils such as those in this study, soil texture should be very fine sand or loamy very fine sand or finer in the fine-earth fraction; there should be soil structure or absence of rock structure in at least half the volume; significant amounts of weatherable minerals (enough amorphous or 2:1 lattice clays to give >3% weatherable minerals or >6% muscovite); evidence of some alterations, e.g., gray colors, an aquic moisture regime or artificial drainage; and cation exchange capacity >16 me/100g clay; regular decrease in amounts of organic C with depth; and a content of <0.2% organic C at a depth of 1.25m below the surface or immediately above a sandy-skeletal substratum that is at a depth of <1.25m; evidence of removal of carbonates; stronger chroma, redder hue or higher clay content than underlying horizon; lack of an argillic or spodic horizon; and no cementation or induration. The base of the horizon should be at least 25cm below the soil surface.

Oxides and Hydroxides of Fe and Al

A number of investigators have studied methods by which free oxides of Fe and Al can be extracted from soils (Bascomb, 1968; Franzmeier et al., 1965; McKeague and Day, 1966). Mehra and Jackson (1960) developed a dithionite-citrate-bicarbonate method for extracting Fe and Tamm used acid ammonium oxalate to determine free Fe oxides. This method of Tamm has been modified by McKeague and Day (1966).

Bascomb (1968) used K-pyrophosphate to extract Fe and Al organic complexes and so did Franzmeier et al. (1965), using Na-pyrophosphate-dithionite extraction.

All of these extractants have been shown to extract different forms of Fe and Al oxides (Bascomb, 1968; McKeague and Day, 1966). The dithionite-bicarbonate procedure of Mehra and Jackson (1960) is assumed to dissolve a large proportion of crystalline oxides as well as much of the amorphous materials. The acid ammonium oxalate extraction of soil (Tamm as modified by McKeague and Day, 1966) is supposed to remove mainly amorphous forms of Fe. Fe and Al extracted by Franzmeier's method are believed to be those associated with organo-mineral complexes. However, studies conducted by McKeague (1967) showed that some crystalline and amorphous Fe oxides are also extracted. The Na-pyrophosphate extraction is the most specific and has been shown to extract mainly Fe and Al associated with organic complexes (McKeague, 1967). The distinction among the forms of Fe extracted by the various methods is clearer than those of Al. This is particularly true when considering the kinds of Al extracted by dithionite and oxalate extractants (McKeague et al., 1971; Juo et al., 1974).

The amounts of Fe oxide extracted by the various extractants differ. Dithionite has been shown (McKeague and Day, 1966) to extract more Fe oxides than do acid ammonium oxalate and Na-pyrophosphate extractants. However, the distinction is not so clear between the amounts of Fe extracted by acid ammonium oxalate and Na-pyrophosphate (McKeague et al., 1971; Juo et al., 1974). Na-pyrophosphate-dithionite extracts more Fe than do Na-pyrophosphate and acid ammonium oxalate (Karmanova, 1975).

The kinds and distribution of Fe oxides have been used by some workers to identify diagnostic horizons and to distinguish various soil groups (Blume and Schwertmann, 1969; Franzemeier et al., 1965; Karmanova, 1975). Lundblad (1934) observed that oxalate extracted Fe oxide was useful in differentiating between Podzols and Brown Forest soils. McKeague and Day (1966), Blume and Schwertmann (1969), and Alexander (1974) have used the ratio of oxalate to dithionate-extractable Fe_2O_3 as a relative measure of the degree of aging of the free Fe oxides. McKeague and Day (1966) and McKeague et al. (1971) showed that the oxalate Fe constitutes 30-60% of the dithionite-Fe in Podzols, Gleysols and Brown Forest soils which they studied. Juo et al. (1973) reported 8% for the oxalate-Fe/dithionite Fe. Rhodes and Sutton (1978) observed a constant pattern of profile distribution of oxalate Fe/dithionite (active Fe ratio) for some soils of the same physiographic unit, but derived from different parent materials.

Blume and Schwertmann (1969) also observed for some soils of the temperate zone that certain great soil groups can be differentiated by typical depth functions of these oxides, and that even intergrades that could not be recognized in the field have distinct depth functions. Franzmeier et al. (1965) suggested that the following ratios, Na-pyrophosphate-dithionite Fe/clay, *P-D and citrate-dithionate Fe/Clay, or P-D or C-D extractable Al/Clay, can be used to separate spodic horizons from cambic horizons. Karmanova (1975) showed that the ratio and distribution of the identified forms of Fe in some USSR soils can

*P-D Na-pyrophosphate-dithionite
C-D Citrate dithionite

serve as diagnostic criteria of the group and subgroup characteristics of soils (according to parent materials).

Soil Phosphorus (Adsorption)

The adsorption of P in soils has been studied in both temperate (Olsen and Watanabe, 1957) and tropical regions (Udo and Uzu, 1972). The behavior of P applied to acid tropical soils has been looked at by some workers (Haseman et al., 1950; Kittrick and Jackson, 1956; Hsu, 1965). Two mechanisms of P fixation in these soils have been observed: (a) chemical adsorption and (b) precipitation. Kittrick and Jackson (1956) and Hsu (1965) have suggested that both mechanisms are the result of the same chemical force.

The adsorption characteristics have been determined with the aid of adsorption isotherms and anion exchange capacity measurements. Ozanne and Shaw (1967) and Fox and Kamprath (1970) have used P adsorption procedures to estimate P required for crops. The Langmuir adsorption isotherm has been frequently used to predict adsorption maxima for soils. At low P concentrations in equilibrium solution the adsorption could be satisfactorily described by the Langmuir isotherm equation (Harter and Baker, 1977).

The amounts of P fixed by the soil in relation to the sesquioxide content have been studied by various investigators, such as Saunders (1965). These investigators have shown that the sesquioxides of Al and Fe are mainly responsible for adsorbing P in soils. Sree Ramulu et al. (1967) observed significant correlations between P fixation and dithionite and oxalate extracted Fe oxide. The correlation for oxalate Fe was higher than that of dithionite Fe. They also observed higher fixation of P by soils high in kaolinite clay. Udo and Uzu (1972) obtained significant correlations, for some Nigerian soils, of P adsorption with Al and Fe, as well as with clay content and pH. The citrate-dithionite and the oxalate extractable oxides were of equal significance in the P adsorption, but the role of Al was more important than that of Fe.

Rhodes (1975) reported a relationship between soil organic matter, oxalate extractable sesquioxide and adsorption maxima, and a negative correlation between adsorption maxima, for some Sierra Leone soils, and pH. Saunders (1965) reported close correlations in New Zealand soils between P retention and organic matter, total N, loss on ignition, organic P as well as the sesquioxides, for topsoils. Subsoil P retention correlated closely with Fe and Al extracted by oxalate and dithionite-citrate-bicarbonate extractants. However, he did not consider organic matter to be directly involved in P retention. The close correlation with P retention followed from a close correlation between soil organic matter and Al and Fe extracted by ammonium oxalate.

Geology and Soils of Sierra Leone

Physiography, Geology and Parent Material

Sierra Leone is basically divided into four physiographic areas (Clarke, 1966; Pollet, 1951): (a) the Peninsula Mountains, (b) the Coastal Plain; (c) the Interior Plain; and (d) the Interior Plateau and Hill Region. The soils studied in this research come from two of these four broad physiographic units: the Interior Plain and the Interior Plateau and Hill region.

<u>The Interior Plain</u> is a strip 97 kilometers wide (Odell and Dijkerman, 1967). It is an old, gently undulating erosion surface that rises from 15 to 154 meters moving from west to east. There are a number of isolated monadnocks in this unit, possibly representing an earlier plateau. This plain is underlain by crystalline schist and gneiss, of the Kasila series, mudstone, siltstone and sandstone of the Rokel River series, and schist and quartzite of the Marampa series, plus some granite and acid gneiss. These parent rocks are old and are of Precambrian age.

The soils selected from this physiographic unit are underlain by rocks from the Rokel River series. Since the soils, especially those of the more stable Uplands, e.g., Njala, are old and have been extremely weathered, the influence of the parent rock on the present-day soil is very minor. The parent material of the Alluvial soils in this area (e.g., Gbesebu series) is actually previously weathered material from the older land surfaces.

There are many swamps, especially in the boliland regions (underlain by members of the Rokel River series). There are four main rivers that go through this unit, viz., Rokel, Taia, Mabole and Pampana.

<u>The Interior Plateau and Hill Region</u> covers the eastern part of Sierra Leone and rises from 305 to 610 meters. It is part of the Guinea Highlands, which is a major watershed in West Africa. Many hills and mountains are found in this unit, the highest peak being over 1829 meters (Loma mountains). The southern part of this physiographic unit is comparatively flat with elevation ranging between 152 and 305 meters. This area includes the Upper Moa basin. The

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predominant parent rock is granite and acid gneiss. Small intrusions of basic schists, amphibolites, and serpentine also occur in this unit. The granite and acid gneiss together with members of the Kambui schists are Precambrian in age.

The soils in this area, especially those of the stable upland and steep slopes, are derived directly from the parent rocks. Those on the alluvial terraces are mainly formed from weathered material derived from the uplands. The influence of the parent rock is still evident on soils of the steep slope, which are usually sandier.

Representative soils studied from this physiographic unit are Segbwema, Manowa, Baoma, Pendembu, Moa, Makeni, Timbo, Masuba and Makundu series. Strictly, the parent material of the Alluvial soils in the two physiographic units is recent in age.

Time

The effects of time on soil formation and development are difficult to determine because of the long time it takes for significant changes in soil properties to occur. However, compared with the age of the bedrocks, the soils are young. From a pedological point of view, many of the soils are old (Clarke, 1966). Soils of the Upland Erosional Surfaces of the Interior Plain are probably Late Tertiary (Stobbs cited from Odell et al., 1974). The age of the soil from the Interior Plateau and Hill regions is unknown.

The Alluvial Terrace soils and those on Colluvial Foot Slopes are Pleistocene and Recent (Odell and Dijkerman, 1967). However, as mentioned in the previous section, the parent material from which these soils are derived may be quite weathered.

Climate

Sierra Leone experiences two main climatic seasonal variations, i.e., wet and dry seasons. These seasons have been divided into four main weather types (Clark, 1966): (a) Thunderstorms and squalls in May and November; (b) Steady rains: July through September. Most of the rainfall occurs during this period. (c) Dry weather with high humidity: December to April. (d) Short periods of dry weather with low humidity - the Harmattan season. These variations are similar throughout the country. The main difference between the regions of the country is the amount and distribution of the *precipitation*. The highest mean annual rainfall is along the coastal areas and the lowest is in the northern part of the country. Rainfall distribution is more even in the eastern part of the country, from which Segbwema, Manowa, Baoma, Pendembu and Moa soils were collected. The mean annual rainfall in this area is between 250-275cm. In the north and south the rainfall distribution is less uniform. In the Makemi area from which Timbo, Makeni, Masuba and Makundu series were collected, the mean annual rainfall is between 300-325cm. In the Njala area, where the remainder of the samples were collected, the mean annual rainfall is between 275-300cm.

The mean monthly maximum *temperatures* for February, March and April (the hottest days) is 30-34°C in the Interior and 34-37°C along the Coasts. The coolest nights are in December, January and February with mean monthly minimum temperatures as low as 12°C. During most of the year the mean monthly temperature is between 20-23°C.

Soil temperatures recorded at Njala, over a period, showed very slight annual variations, that is, <5°C (Odell et al., 1974).

Moisture loss from evaporation is highest during February and March. The lowest loss is in August. A period of water deficit is experienced by the soils during the dry season. This drought period varies according to the texture of the soil and the location. The drought period ranges from 1-5 months. In general, soils in the east have shorter drought periods than those from the north and south. The length of the drought period is the highest for soils of the Upland Surfaces.

Organisms

Vegetation: Details on the vegetation of Sierra Leone are given in Clarke (1966). Vegetation is a factor that affects the organic matter content of soils and, to some extent, the development of the profile. There are five major vegetation types in Sierra Leone: (a) forest, (b) farm bush (secondary bush), (c) savanna, (d) grassland, and (e) mangrove.

The *forest* is mainly a secondary one. Common species are: *Elaeis guineensis* (oil palm), *Chlorophora regia, Pycnanthus kombo, Macrolobium dawei* and *Anisophyllea meniandi* (Odell and Dijkerman, 1967). The *farm bush* is dense evergreen woodland vegetation that is farmed occasionally. Common species include: *Elaeis guineensis* (oil palm), *Albizzia gummifera,* and *Macrolobium macrophyllum,* to name a few.

Savanna vegetation is in the north, which is comparatively drier than the other parts of the country. Three types of savanna vegetation have been recognized (Clarke, 1966; Odell and Dijkerman, 1967): (a) savanna woodland, (b) open savanna, and (c) Lophira savanna.

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Grassland is widespread in the Boliland region and on some alluvial floodplains. Details of the grass species are given elsewhere (Stobbs, 1963).

Mangrove swamps occur along the coast and in creeks with saline tidal environment. There are two main types of mangrove vegetation: (a) *Rhizophora racemosa* and (b) *Avicennia nitida*. *Rhizophora racemosa* occurs on soft fibrous muds that are waterlogged continuously and *Avicennia nitida* occurs on firmer nonfibrous soils. The acid sulfate soils are associated with mangrove vegetation.

In general, soils developed under forest and grassland have higher organic matter content than soils on which farm bush occurs. The lowest organic matter content is found in soils of the savanna areas.

With the exception of the Alluvial soils, which may have developed under grass vegetation, the soils that are being studied here may have been developed under forest, but because of shifting cultivation, their present vegetation is farm bush.

Animals active in these areas include termites and man. The activities of termites are evident in Sierra Leone by the presence of termite mounds. Miedema (1971) conducted studies on termite mounds in the Makeni area, and concluded that the mounds have higher pH values, base saturation, C.E.C. and exchangeable Ca, Mg and K than the surrounding soil material. The mound material is predominantly subsoil material. The occurrence of a thin gravel-free A horizon of upland soils and a high concentration of ironstone nodules in some subsoils have been attributed to the activities of termites (Plate 1C, termite mound). Earthworms have been observed to be more active on Alluvial soils of the floodplains.

Man has been very active in clearing the land. This has led to increased erosion. The presence of charcoal fragments has been used in Sierra Leone as an index of human activity.

Topography

There is a strong correlation between topography, parent material and soil type in Sierra Leone. On older Upland Surfaces derived from basic and ultrabasic rocks, the soils are generally shallow over laterite sheet. Soils derived from non-basic rocks usually have a thick layer of gravelly soil over the parent rock. The depth is usually >210cm. On Steep Slopes, the soils are shallow over parent rock and on Colluvial Footslopes the soils usually have a gravel-free colluvial layer between 60 and 120cm thick. On the alluvial terraces the soils are usually developed on deep alluvium.

The soils of the Upland Surfaces are probably on former peneplains (Stobbs, 1963) from the Tertiary Period.

On the Alluvial Terraces and Floodplains, different levels of terraces may occur, i.e., upper, middle and lower terraces. The Upper Terraces can be associated with the soils of the Colluvial Footslopes. The different levels of terrace are more obvious in soils associated with the Rokel River series. The differences in terrace levels probably occurred during the Pleistocene Epoch.

Taxonomy of the Major Kinds of Soils in Sierra Leone

The major diagnostic horizons recognized in Sierra Leone to date (Odell et al., 1974) are as follows: (a) surface horizons - ochric and umbric epipedons, and (b) subsurface horizons - argillic, oxic,

spodic, cambic, and sulfuric horizons and also plinthite. The definitions of these horizons are given in Soil Taxonomy (Soil Survey Staff, 1975).

Oxisols, Ultisols, Inceptisols, Entisols and Spodosols are the five soil orders that have been recognized to date. According to the present taxonomic classification of the soils (Odell et al., 1974), the majority of the soils in Sierra Leone belong to the order Ultisols. The classification of the eleven profiles that will be studied in this research are given below, as reported by R. T. Odell et al., in 1974:

Baoma series (144801A)	Typic Paleudults (or Tropeptic Haplorthox), clayey over clayey - skeletal, kaolinitic
Manowa series (Kpaubu I)	Orthoxic Palehumults (or Typic Umbriorthox), clayey-skeletal, oxidic
Njala series (N109)	Orthoxic Palehumults, clayey-skeletal, oxidic
Makeni series (P2)	Typic Paleudults, clayey-skeletal, oxidic
Segbwema series (145005)	Tropeptic Haplorthox (or Udoxic Dystropepts), fine-loamy, mixed
Timbo series (pl9)	Typic Umbriorthox (or Udoxic Dystropepts), fine-loamy, skeletal, mixed
Pendembu series (Kpuabu 2)	Typic Paleudults, fine-loamy, mixed
Masuba series (p9)	"Plinthic" Udoxic Dystropepts, fine-loamy mixed
Moa series (Kpuabu 3)	Tropeptic Haplorthox (or Fluventic Udoxic Dystropepts), clayey, kaolinitic
Gbesebu series (N125)	Fluventic Udoxic Dystropepts, fine-clayey, kaolinitic
Makundu series (P104)	Plinthic "Tropeptic" Umbriorthox, clayey, kaolinitic

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Most of these soils may have evidence of diagnostic properties of another soil order. The second classification in parentheses indicates the problem of placing the soils in Soil Taxonomy, a major concern in this dissertation.

Present Land Use and Management in Sierra Leone

The most common systems of cultivation in Sierra Leone are upland farming and swamp farming (Sivarajasingham, 1968; Waldock et al., 1951). These are done mainly by peasant farmers.

Upland farming is basically shifting cultivation or what is sometimes called a bush-fallow system. The system involves felling the forest or farm bush, farming the land for a few years before returning it to fallow, while newly cleared land is farmed. The period of cultivation of the cleared land varies from one to three years. The fallow period also varies from four to ten years, depending on the population pressure on the land. In the Makeni area it is about four to five years, six to seven years in the Njala area, and up to ten years in the Kenema area. The main advantage of this system is that it helps to restore the natural fertility of the soils during the fallow period.

The major operations involved in shifting cultivation are: (a) brushing (cutting down vegetation); (b) burning; (c) planting; (d) weeding; and (c) harvesting. The major crop is upland rice, but within the rice, a large number of subsidiary crops, such as pumpkin, tomatoes, cassava, maize and other vegetables, can be found. On the Njala and Makeni sample sites, the upland soils are used mainly for rice production. On the Kenema site (Figure 1), aside from upland rice cultivation, permanent tree crops, such as cocoa and coffee, are also grown (Plate 1 A,B,C).

PLATE 1. Some representative soil profiles and land uses.

(a)

Baoma Profile

(b)

Baoma soil under cocoa plantation

PLATE 1 (continued)

(c)

Landscape associated with Pendembu series and termite mound. Trees are cocoa plants.

(d)

Makeni profile (Pit 49). Note the thick Umbric epipedon.

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During the second year of farming of the uplands that have been cleared, rice is not grown. Cassava (sometimes already planted during the first year) and groundnuts (peanuts) are the second year crops. Groundnuts are more common in the Makeni area.

There are about three main types of swampland farming in Sierra Leone, viz.: (a) inland swamps, usually found in valleys between two uplands; (b) bolilands, which include individual swamps and areas of flat treeless grasslands (Stobbs, 1963); and (c) mangrove swamps. Inland swamps and bolilands are common in the sample areas, but none of the soils in this study are from such areas.

In the swamps, rice is grown during the rainy season and vegetables are often grown during the dry season. The same swampland is cultivated for many years, unlike the uplands. The original grassy vegetation is cut and then piled into mounds where it is allowed to rot. The seedbed is prepared by hoeing and spreading the rotted organic material. Rice is transplanted from a nearby nursery. After the rice is harvested, the stubble is buried again in mounds, which are then used for vegetable production during the dry season. The above procedures are frequently practiced in the Njala and Makeni sample areas. The swamps are utilized less in the Kenema area.

The two farming systems described are time-consuming and very labor-intensive. All the operations are done by hand. Crop yields are usually very low and are commonly only sufficient for the farmer's needs. Improved swamp-rice growing practices are now being introduced into the three sample areas.

MATERIALS AND METHODS

Field Investigations

The field investigations were carried out in Sierra Leone, West Africa. The samples were collected from three governmental provinces in the country, viz., Eastern, Southern and Northern Provinces (Figure 1). They also represent the soils of three major soil provinces, of Sierra Leone (Odell and Dijkerman, 1967). These soil provinces are: (a) L-soils of the Upper Moa Basin; (b) G-soils of the Rokel River series under secondary bush; and (c) J-soils of the Escarpment Region from granite and acid gneiss under secondary bush and forest, respectively.

Eleven pits were sampled. Five of these are from soil province L, two from soil province G, and four from soil province J. (Odell et al., 1974; van Vuure and Miedema, 1973). The soil series studied from each province, their reported tentative classifications, and their moisture regimes are as follows:

Soil Province L	Subgroup	Moisture Regime
Baoma Series	Typic Paleudults (or Tropeptic Haplorthox)	WD (4 months)*
Manowa Series	Orthoxic Palehumults (or Typic Umbriorthox)	MWD-WD (4 months)*
Segbwema Series	Tropeptic Haplorthox (or Udoxic Dystropepts)	WD (3 months)*

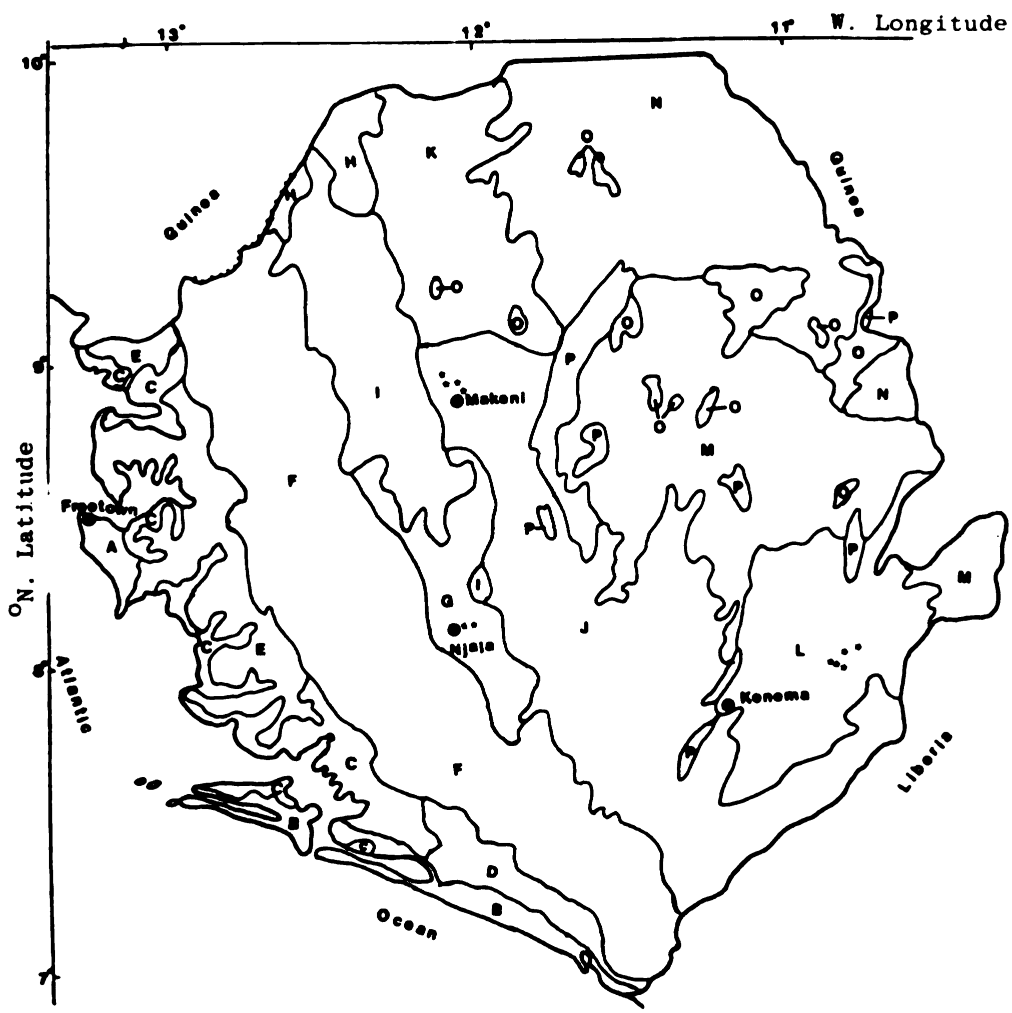

Figure 1. Asterisks indicate the locations from which soil samples were collected. Also shown are the soil province boundaries of A thru P.

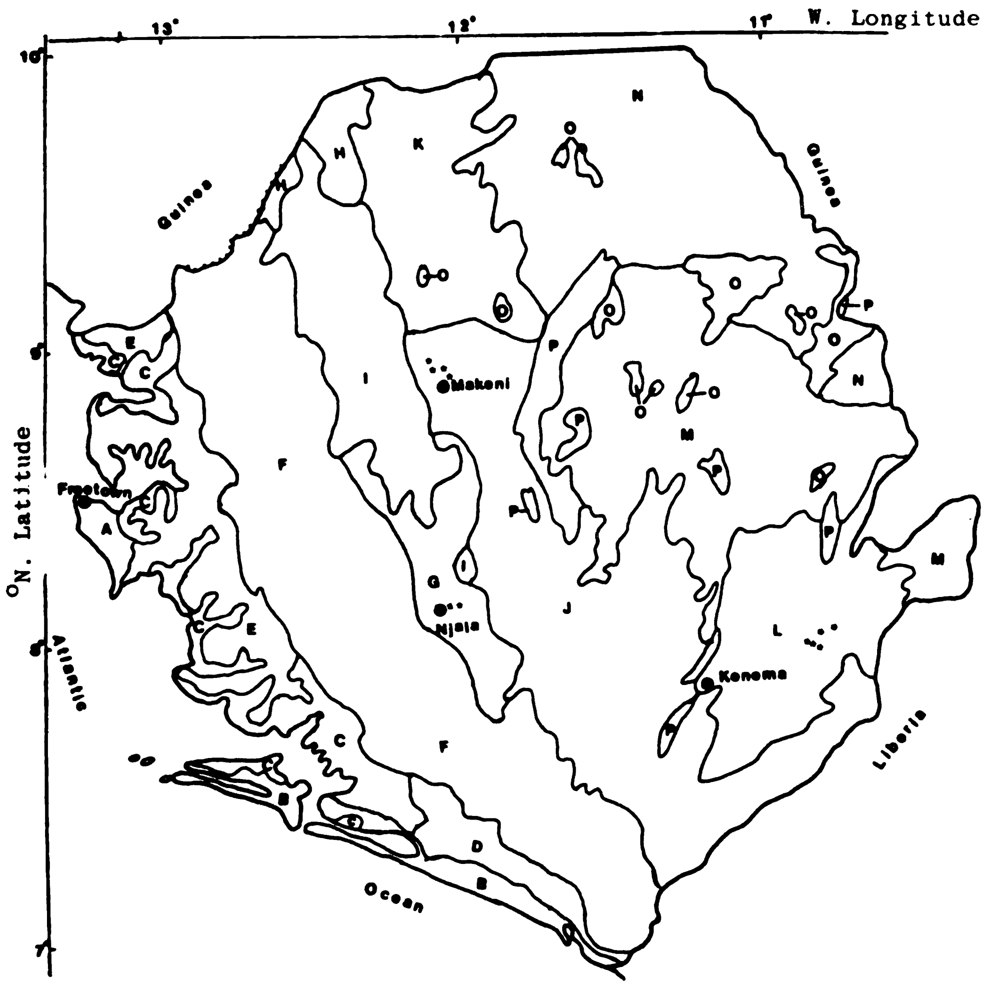

Figure 1. Asterisks indicate the locations from which soil samples were collected. Also shown are the soil province boundaries of A thru P.

Soil Province L	Subgroup	Moisture Regime
Pendembu Series	Typic Paleudults	MWD (2 months)*
Moa Series	Tropeptic Haplorthox (or Fluventic Udoxic Dystropepts)	WD (1 month)*
Soil Province G		
Njala Series	Orthoxic Palehumults	WD (5 months)*
Gbesebu Series	Fluventic Udoxic Dystropepts	WD (2 months)*
Soil Province J		
Makeni Series	Typic Paleudults	WD (5 months)*
Timbo Series	Typic Umbriorthox (or Udoxic Dystropepts)	WD (4 months)*
Masuba Series	Plinthic Udoxic Dystropepts	MWD (3 months)*
Makundu Series	Plinthic "Tropeptic" Umbriorthox	WD (2 months)*

These profiles are from the same sites described in Odell et al. (1974).

New surfaces were cut from the walls of the pits, then the depths and descriptions were checked. Both clod and bulk samples were collected from the pits. The clod samples were collected mainly in the B horizons and transitional horizons to the B. Metal cores were used to collect undisturbed samples from the gravelly profiles. Peds from the subsoils were collected for examination of clay skins and other morphological features (see Appendix A for profile descriptions). The bulk samples were collected in plastic bags and prepared

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*Drought period

according to standard procedures described in Soil Survey Investigation Report No. 1 (1972).

Physical Analyses

Particle Size Analyses

Procedures for particle size analyses, by the sieve and pipette methods, and soil moisture retention, are those outlined in Methods of Soil Analysis, edited by C. A. Black (1965).

Bulk density was done at Njala University College, Sierra Leone, by the clod method, outlined in Soil Survey Investigation Report No. 1 (1972).

Particle Size Analyses, After Fe Oxide Removal

Free iron oxides were removed by the dithionite-citrate-bicarbonate method of Mehra and Jackson (1960), after the removal of organic carbon with 30% hydrogen peroxide. The method of Kilmer and Alexander (1949) was employed for the size separations.

Chemical Analyses

Previously Reported by Odell et al. (1974)

Organic C was determined by the Walkley-Black wet oxidation method. Cation exchange capacity was by ammonium saturation, with normal ammonium acetate buffered at pH 7. The exchangeable bases were removed by leaching with neutral ammonium acetate. Exchangeable Ca and Mg were measured by EDTA titration, and K and Na by flame photometry. Exchangeable Al was removed by leaching with 1.0N KCl solution and then measured by emission spectroscopy.

Iron and Aluminum Extractions

Acid ammonium oxalate extraction for Al and Fe: The method of Tamm as modified by McKeague and Day (1966) was used. Four grams of fine earth (oven-dry basis) were shaken continuously in polyethylene bottles (in the dark) for four hours with 200ml of 0.2M ammonium oxalate solution adjusted to pH 3.0 with oxalic acid. Five drops of 0.4% superfloc was added to the mixture after the shaking to aid flocculation before centrifugation at 2,000 rpm (International type SB centrifuge).

Determinations of the Al and Fe in the extractant were by the Aluminon Colorimetry Method of Chenery (1948, cited in Soil Survey Report No. 1, 1972) with overnight color development, and by K-thiocyanate colorimetry, by Jackson (1956), respectively. The oxalate in the extractant was destroyed by successive oxidation with 30% hydrogen peroxide and concentrated HNO_3. The residue was taken up with 10ml of 1.0N HCl, and then made up to volume with distilled water. This treatment is necessary to prevent oxalate interfering with color development.

The free Fe oxides were precipitated with 25% NaOH solution (M. L. Jackson, Advance Chemical Analysis, 1956) before Al was determined in the extractant. High Fe in solution will affect the accuracy of the Aluminon method (Jackson, 1956).

Dithionite-citrate-bicarbonate extraction for Fe and Al: The method of Mehra and Jackson (1960), as outlined in Soil Survey Investigation Report No. 1 (1972) was followed.

Fe and Al in the extractant were determined by K-thiocyanate colorimetry and the Aluminon method, respectively. The extractant was digested with a H_2SO_4, HNO_3 mixture, and the residue taken up with 1.0N HCl. Fe was precipitated from the solution with 25% freshly prepared NaOH solution (Jackson, 1956) before the Al determination.

Sodium pyrophosphate extraction for Fe and Al: The method of Bascomb (1968), as outlined in Soil Survey Investigation Report No. 1, was adopted. Overnight shaking was for 8 hours. The determinations of Fe and Al in solution were by the methods described earlier under ammonium oxalate extraction.

Phosphorus Adsorption

Phosphorus adsorption studies on fine-earth: Phosphorus adsorption studies of the Langmuir type were made on the surface and subsurface horizons of four soil series, i.e., Makeni, Gbesebu, Masuba and Segbwema, and on the surface and subsurface ironstone gravels of the Njala and Makeni series.

For adsorption studies with the <2mm fraction, 50ml of 0.001M $CaCl_2$ solutions containing $Ca(H_2PO_4)_2 \cdot H_2O$ at concentrations of 0-150ppm P were added to 2gm of fine-earth in 250ml polyethylene bottles. Two drops of toluene were added to each bottle to inhibit microbial growth. The bottles were then shaken in a reciprocating shaker for 24 hours. The room temperature was $26°C \pm 1$. The samples were then centrifuged and the concentration of P in the supernatant liquid was determined by the method of Dickman and Bray (1940) as modified by Kurtz (1942). The quantity of P adsorbed was taken to be that lost from the solution during shaking.

P adsorption studies on the gravels: Ten grams of ironstone gravel, selected to represent the size distribution present in each horizon, were washed with a mixture of alcohol and water to remove loose soil particles on the surface of the gravel. Fifty milliliters of 0.001M $CaCl_2$ solution containing $Ca(H_2PO_4)_2 \cdot H_2O$ at concentrations of 0, 1, 2, 3, 4, and 5ppm of P were added to the gravel in 125ml pyrex flasks. Two drops of toluene were added to inhibit microbial growth and the flasks were shaken for 24 to 48 hours in a rotating shaker at a maximum of 150 rpm at room temperature. A rotating shaker was used because initial studies showed that shaking in the reciprocal shaker tended to cause slaking of the ironstone, as a result of possible grinding action.

P adsorbed was determined by the method described earlier for the fine-earth.

Mineralogical Analysis

The total clay fractions were separated by sedimentation (Black, 1965) after free Fe oxides had been removed. Fine clays were separated by centrifugation, using the method of Tanner and Jackson (1947). The International type SB centrifuge was used. The R/S of this centrifuge was calculated for use in the determination of the time of centrifugation, using the integrated form of Stokes' law as proposed by Svedberg and Nichols, and also given by Steele and Bradfield (1934). Corrections for temperature were also made.

X-ray analyses: Samples from the total ($<2\mu$) and fine clay ($<0.2\mu$) fractions were treated for x-ray diffraction using standard procedures (Grim, 1968). The Mg-glycerol saturated clays on ceramic tiles were dried over $CaCl_2$, and x-rayed using $CuK\alpha$ radiation. Scanning was between 2° and 29° 2θ in most cases.

Mineral grain counts: Grain counts were conducted on cleaned sand fractions of the 250-100μ and 100-50μ size range. No heavy mineral separation was made before the counting, which was done with the aid of a polarizing microscope (Black, 1965; Marshall and Jeffries, 1946). A total of 300 to 500 grains were counted per sample.

Micromorphology

Observations of peds by split and debris studies were conducted with the aid of a binocular microscope at various magnifications ranging from 9 to 54X. The main purpose of this was to identify any clay skins on the surfaces of peds from clod samples.

Thin sections of both soil and ironstone gravels were prepared by Gary Section Service, Tulsa, Oklahoma. The thin sections were studied under a Spencer polarizing microscope, at magnifications ranging from 20 to 400X, starting with the lowest magnification. The micromorphological characteristics were described and interpreted much as suggested by Brewer (1964).

RESULTS AND DISCUSSION

General Grouping of the Soils

Table 1 contains the grouping of the soils studied according to physiography, parent material, moisture regime, vegetation and climate.

Figure 2 shows the physiographic relationships of the soils in each of the three soil provinces. The soils of the Upland Surfaces may be very old and probably date to the late Tertiary (Odell et al., 1974). They are considered the oldest of the soils studied. The other three groups of soils are comparatively younger, and may be of Pleistocene or Holocene age. The alluvium on the river terraces is recent. These Alluvial soils may be derived, however, from highly weathered materials that have gone through several cycles of weathering and soil formation before they were deposited as parent materials for a new cycle of soil formation. In terms of years of development, the Alluvial soils are the youngest on the landscape, although their parent material may be very strongly weathered.

Physical Analyses

Table 2 contains the results of particle size analyses, with and without the removal of free Fe oxides, and also the percentage clay as estimated by the factor 2.5 x 15 bar moisture content.

Table 1. Grouping of the eleven profiles studied by physiography, parent material, rainfall, moisture regime and vegetation

Physiography and parent material	Soil province	Drainage and slope	Rainfall (mean annual)	Drought period*	Vegetation	Soil series
1. Upland Surfaces of Highly Weathered Material						
(a) Less gravelly** solum	L	WD gentle	225-275cm	4 months	Secondary bush/ coffee plantation	Baoma
(b) Very gravelly** solum and usually clayey reworked material	L	MWD-WD 5%	225-275cm	4 months	Secondary bush	Manowa
	G	WD 8%	250-275cm	5 months	Secondary bush	Njala
	J	WD 10-14%	275-300cm	5 months	Secondary bush	Makeni
2. Steep Hills and Slopes						
(a) Residium from granodiorite low in quartz and high in dark minerals	L	WD 42%	225-275cm	3 months	Secondary bush	Segbwema
(b) 60-120cm of gravelly** fine loamy material over residuum from granite	J	WD 6%	275-300cm	4 months	Secondary bush	Timbo

Table 1 (continued)

Physiography and parent material	Soil province	Drainage and slope	Rainfall (mean annual)	Drought period*	Vegetation	Soil series
3. Colluvial Footslopes and Upper River Tributary Terraces						
(a) Fine loamy colluvium/alluvium	L	Imperfect to MWD 2%	225-275cm	2 months†	Secondary bush/ cocoa plantation	Pendembu
gravel free	J	MWD 0-3%	275-300cm	3 months	Secondary bush	Masuba
4. Alluvial Terraces and Floodplains						
(a) Clayey alluvium	L	WD level	225-275cm	1 month***	Secondary bush	Moa
	G	WD; convex nearly level	250-275cm	2 months ***	Secondary bush	Gbesebu
	J	WD; concave 1%	275-300cm	2 months	Secondary bush	Makundu

*Drought period - the duration of moisture deficiency

**Ironstone gravels

***Soils may be flooded by river water from ½-1 month duration in rainy season

†Waterlogged for 1-2 months

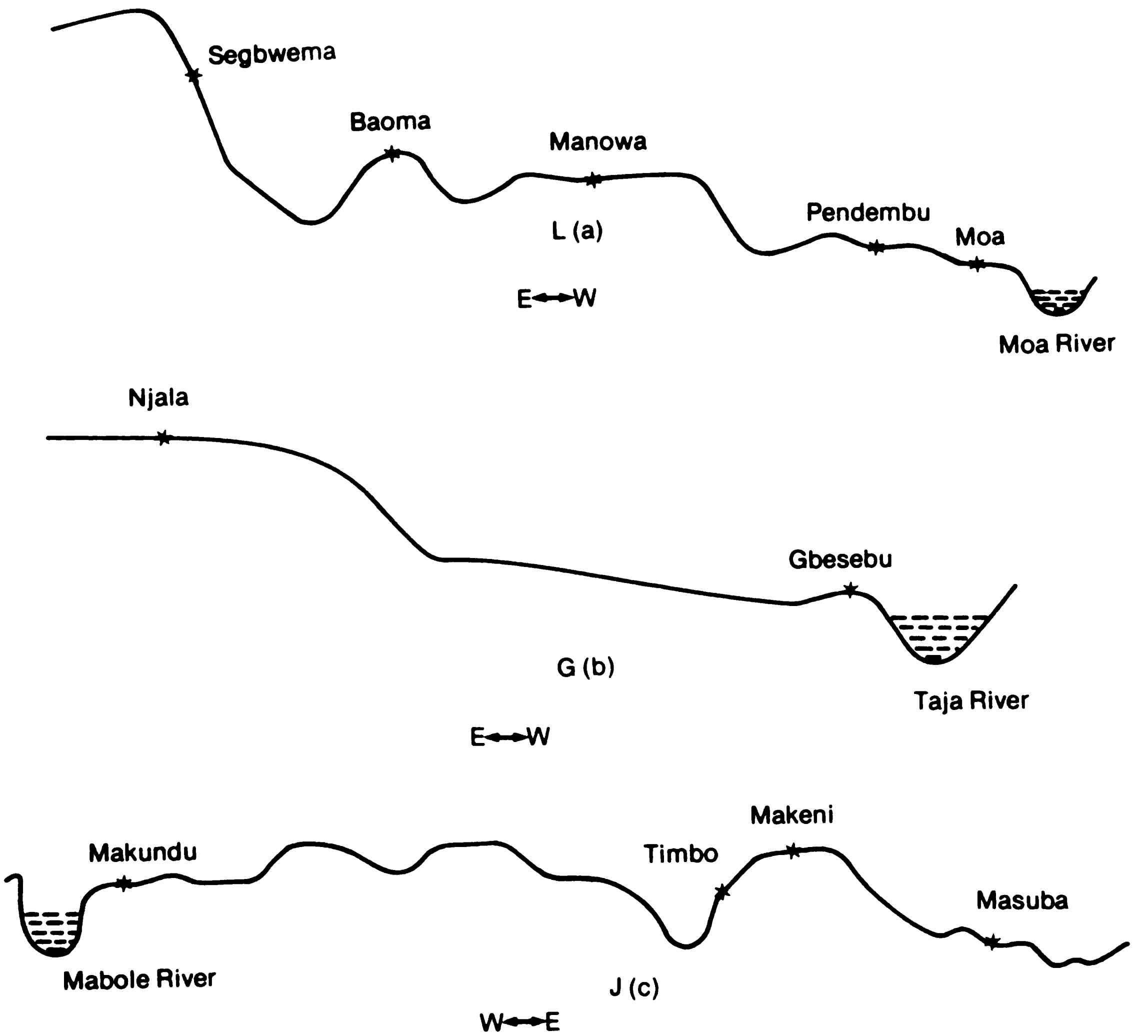

Figure 2. Relationship among the soils studied in each soil province with respect to the topography.

Table 2. Some physical properties: particle size analysis, bulk density, and 15 bar moisture content

Soil Series	% >2mm	% Sand	% Silt	% Total Clay (Fe Oxide Removed)	2µ-.2µ	<2µ	B/A Clay	Fine/Total	Texture	% Clay 2.5X 15 bar H_2O	% Sand (Fe Oxide Not Removed*)	% Silt	% Clay	B/A Clay	Texture	Bulk Density g/cc	15 bar* H_2O	15 bar* H_2O/$Clay_1$	15 bar H_2O/Clay+Fe	Silt/$Clay_1$	Silt/$Clay_2$
Baoma																					
(0-15cm)A_1	20	47.1	11.7	41.2	14.5	26.7		0.65	SC	48.0	52.5	13.4	34.1		SCL	1.2	19.2	0.34	0.31	0.28	0.39
(15-60cm)B_2	31	37.7	11.3	51.0	18.9	32.1	1.2	0.63	C	55.5	39.4	13.9	46.7	1.4	C	1.3	22.2	0.33	0.30	0.22	0.30
(60-110cm)IIB_{31}	52	34.1	9.5	56.4	20.1	36.3	1.4	0.64	C	62.3	28.6	15.0	56.4	1.7	C	1.5	24.9	0.35	0.32	0.17	0.27
(110-160cm)IIB_{32}	52	29.5	11.1	59.4	---	---	1.4	---	C	64.5	29.3	15.0	55.7	1.6	C	1.5	25.8	0.36	0.32	0.19	0.27
(160-180cm)IIB_{33}	45	29.5	10.9	59.6	---	---	1.5	---	C	---	---	---	---	---		---	---	---	---	0..8	---
Manowa																					
(0-25cm)A_1	8	52.9	9.5	37.6	10.2	27.4		0.73	SC	31.5	57.4	11.8	30.8		SCL	---	12.6	0.33	0.30	0.25	0.38
(25-52cm)A_3	61	50.9	9.0	40.1	11.0	29.1		0.73	SC	33.[illegible]	49.2	12.4	38.4		SL	1.4	13.3	0.33	0.30	0.22	0.32
(52-88cm)B_{21}	63	46.9	8.3	44.8	14.3	30.5	1.2	0.68	SC	---	48.6	11.2	40.2	1.3	SC	---	---	---	---	0.18	---
(88-175cm)B_{22}	65	40.0	9.1	50.9	16.3	34.6	1.4	0.68	C	44.0	38.9	13.3	47.8	1.6	C	1.5	17.6	0.35	0.31	0.18	0.28
Njala																					
(0-35cm)A_1	78	40.5	11.1	48.4	21.3	27.1		0.56	C	---	42.6	21.7	35.7		CL	---	---	---	---	0.23	0.60
(35-52cm)A_3	88	30.0	15.5	54.5	27.2	27.3		0.50	C	49.7	32.1	17.3	50.6		C	---	19.9	0.37	0.34	0.28	0.34
(52-122cm)B_{21}	83	20.4	12.8	66.8	35.3	31.5	1.4	0.47	C	53.5	24.2	15.3	60.5	1.7	C	1.5	21.4	0.32	0.30	0.19	0.25
(122-155cm)B_{22}	67	17.1	15.8	67.1	---	---	1.4	---	C	55.0	21.7	19.6	58.7	1.6	C	1.6	22.0	0.33	0.30	0.24	0.33
Makeni																					
(0-25cm)A_1	70	33.9	9.3	56.8	23.9	32.9		0.58	C	39.8	52.7	14.2	33.1 (44.2)		SCL	1.3	15.9	0.28	0.26	0.16	0.43
(25-50cm)B_{21}	76	26.3	9.0	64.7	29.2	35.5	1.1	0.55	C	54.3	30.6	13.2	56.2 (54.5)	1.7	C	1.4	21.7	0.33	0.31	0.14	0.23
(50-168cm)B_{22}	79	21.1	10.6	68.3	36.2	32.1	1.2	0.47	C	59.3	24.5	23.7	51.8 (55.3)	1.6	C	1.5	23.7	0.35	0.32	0.16	0.45
Segbwema																					
(0-32cm)A_1	22.8**	37.6	14.4	48.0	31.0	17.0		0.35	C	34.5	55.9	17.3	26.8 (42.3)		SCL	1.1	13.8	0.29	0.27	0.30	0.64
(32-70cm)B_{21t}	---	43.0	16.2	40.8	16.3	24.5	0.85 (1.6)†	0.60	C	---	---	---	--- (33.1)			---	---	---	---	0.40	0.6[illegible]
(70-150cm)B_{22t}	11.4**	45.7	22.0	32.3	16.9	15.4	0.67 (1.3)†	0.48	CL	41.5	41.1	25.1	32.8 (27.3)	1.3	CL	1.2	16.6	0.51	0.47	0.68	0.74
(150-235cm)C_1	8.5**	51.9	23.1	25.0	---	---			SCL	35.8	51.1	25.5	23.4 (20.0)		SCL	1.4	14.3	0.57	0.53	0.92	1.07
Timbo																					
(0-30cm)A_{11}	47	59.6	6.4	34.0	7.5	26.5		0.78	SCL	24.5	68.2	11.7	20.1		SCL	1.2	9.8	0.28	0.27	0.18	0.58
(30-47cm)A_{12}	59	51.7	7.1	41.2	12.7	28.5		0.69	SC	28.0	59.2	12.6	28.2		SCL	1.2	11.2	0.27	0.25	0.17	0.45
(47-70cm)AB	58	50.1	8.7	41.2	12.1	29.1	1.2	0.71	SC	31.0	57.6	11.7	30.7	1.5	SCL	1.2	12.4	0.30	0.28	0.21	0.38
(70-107cm)B_{21b}	54	49.3	12.5	37.7	10.[illegible]	27.5	1.1	0.73	SCL	32.0	55.7	13.6	30.7	1.5	SCL	1.[illegible]	12.8	0.34	0.30	0.33	0.44
(107-175cm)B_{22b}	46	55.5	12.7	31.8	12.4	19.4	0.9	0.61	SCL	32.8	51.7	14.6	33.7	1.7	SCL	1.3	13.1	0.40	0.37	0.40	0.43

Table 2 (continued)

Soil Series	Fe Oxide Removed % >2mm	% Sand	% Silt	% Total Clay	2µ-.2µ	<2µ	B/A Clay	Fine/Total	Texture	% Clay 2.5X 15 bar H_2O	Fe Oxide Not Removed* % Sand	% Silt	% Clay	B/A Clay	Texture	Bulk Density g/cc	15 bar* H_2O	15 bar* H_2O/$Clay_1$	15 bar H_2O/Clay+Fe	Silt/$Clay_1$	Silt/$Clay_2$
Pendembu																					
(0-18cm)A_1	15.5***	60.0	9.4	30.6	12.2	18.4		0.60	SCL	22.8	68.6	11.7	19.7		SL	0.9	9.1	0.30	0.28	0.31	0.59
(18-45cm)A_3	8.1***	[illegible]	10.1	31.5	8.2	23.3		0.74	SCL	21.8	63.0	13.2	23.8		SCL	0.9	8.7	0.28	0.26	0.32	0.55
(45-93cm)B_{21}	---	56.6	9.1	34.3	9.9	24.4	1.1	0.71	SCL	---	---	---	---	1.5		---	---	--	---	0.27	---
(93-135cm)B_{22}	2.4***	53.9	10.9	35.2	12.0	23.2	1.2	0.66	SCL	26.8	57.5	12.2	30.3		SCL	1.0	10.7	0.30	0.29	0.31	0.40
(135-165cm)B_{23}	---	50.8	10.0	39.2	17.3	21.9	1.3	0.56	SCL	---	---	---	---			---	---	---	---	0.26	---
(165-200cm)B_3	---	49.2	10.6	40.2	---	---	1.3	---	SC	---	---	---	---			---	---	---	---	0.26	---
Masuba																					
(0-18cm) Ap	---	64.8	10.8	24.4	---	---		---	SCL	25.3	64.0	12.6	23.4 (21.8)		SCL	1.1	10.1	0.41	0.40	0.44	0.54
(18-55cm)B_{21t}	---	54.4	12.5	33.1	---	---	1.4	---	SCL	25.3	59.6	13.6	26.8 (29.6)	1.2	SCL	1.3	10.1	0.31	0.30	0.38	0.51
(55-168cm)B_{22t}	---	56.2	11.2	32.6	---	---	1.3	---	SCL	25.8	60.4	13.9	25.7 (28.3)	1.1	SCL	1.3	10.3	0.32	0.30	0.35	0.54
Moa																					
(0-15cm)A_1	---	29.7	16.8	53.5	28.4	25.1		0.47	C	46.0	37.2	22.2	40.[illegible]		C	0.7	18.4	0.34	0.32	0.31	0.55
(15-53cm)B_{21}	---	28.4	14.9	56.7	25.5	31.2	1.1	0.55	C	48.3	31.1	20.7	48.[illegible]	1.2	C	0.8	19.3	0.34	0.32	0.26	0.43
(53-78cm)B_{22}	---	29.1	13.5	57.4	28.7	28.7	1.1	0.50	C	---	---	---	---			---	---	---	---	0.24	---
(78-148cm)B_3	---	28.9	13.6	57.5	27.0	30.5	1.1	0.53	C	51.0	31.3	19.8	48.9	1.2	C	1.3	20.4	0.36	0.33	0.24	0.40
(148-178cm)C	---	34.8	12.5	52.7	21.1	31.6	1.0	0.60	C	---	---	---	---			---	---	---	---	0.24	---
Gbesebu																					
(0-10cm)A_1	---	0.8	31.0	68.2	40.7	27.5		0.40	C	64.3	6.5	44.1	49.4 (61.2)		SiC	0.9	25.7	0.38	0.36	0.45	0.89
(10-18cm)A_3	---	0.4	30.5	69.1	39.7	29.4		0.43	C	66.0	[illegible]	38.1	59.7 (58.7)		C	1.0	[illegible]	0.38	0.36	0.44	0.64
(18-48cm)B_{21b}	---	0.1	32.7	67.2	40.3	26.9	1.0	0.40	C	67.5	0.8	38.0	61.2 (60.0)	1.2	C	1.1	27.0	0.40	0.37	0.45	0.62
(48-63cm)B_{22b}	---	0.1	29.1	70.8	42.5	28.3	1.0	0.40	C	68.3	1.6	37.8	60.6 (62.2)	1.2	C	1.1	27.3	0.39	0.36	0.41	0.62
(63-158cm)B_{23}	---	0.2	30.9	68.9	---	---	1.0	---	C	66.0	2.2	39.2	58.6 (60.2)	1.2	C	1.2	26.4	0.38	0.36	0.45	0.67
Makundu																					
(0-20cm)A_{11}	---	7.5	26.4	66.1	---	---		---	C	72.7	16.0	37.1	46.9		C	0.8	29.1	0.44	0.42	0.40	0.79
(20-40cm)A_{12}	---	5.6	26.2	68.2	---	---		---	C	72.3	17.6	35.6	46.8		C	[illegible]	28.9	0.42	0.40	0.38	0.76
(40-53cm)AB	---	5.3	27.5	67.2	---	---	1.0	---	C	67.8	8.1	42.1	49.8	1.1	SiC	1.0	27.1	0.40	0.38	0.41	0.84
(53-78cm)B_1	---	4.3	25.4	70.3	---	---	1.0	---	C	64.5	5.4	34.8	59.8	1.3	C	1.1	25.8	0.37	0.34	0.36	0.58
(78-115cm)B_{21}	---	3.2	25.7	71.1	---	---	1.1	---	C	64.5	4.7	34.0	61.3	1.3	C	1.2	25.8	0.36	0.34	0.36	0.55
(115-185cm)B_{22}	---	3.5	27.7	68.8	---	---	1.0	---	C	63.0	4.3	35.3	60.4	1.3	C	1.3	25.2	0.37	0.34	0.40	0.67

*Data taken from Odell et al., 1974. $Clay_1$ = Fe removed. $Clay_2$ = Fe not removed.

**Not ironstone nodule, but rock fragment.

***Soft-hard nodule (taken from Odell et al., 1974).

†B/C ratio. Clay + Fe = $Clay_1$ + dithionite Fe_2O_3.

( ) = Sutton's values of clay when Fe is not removed.

Data for the particle size analyses without the removal of free Fe oxide were obtained from Odell et al. (1974). A few of the samples were analyzed without the removal of free Fe oxide in the present study, to compare with the values obtained by Odell et al. (1974). These are listed in parentheses in Table 2, in the column for percent clay without Fe oxide removal. The difference between the values is usually not more than 3% in the subsoil. The greatest variation was in the surface soil samples.

In general, the percentage clay values, when free Fe oxide is removed before particle size analyses, are higher than those obtained when the free Fe oxide is not removed. The percentage clay values, obtained with free Fe oxide removed, are also commonly higher than the clay values estimated by the factor 2.5 x 15 bar moisture content. The exceptions to this latter relationship are the Baoma series, the subsoil of the Segbwema series and the A horizon of the Makundu series. In these situations the percentage clay estimated by the factor 2.5 x 15 bar moisture content is higher. The reason(s) for the deviation in the Baoma and Segbwema series is not fully known, and may need further investigation. One possibility is the nature of the Fe oxide present in these soils, and the ease of its removal by the dithionite-citrate-bicarbonate method. The high percentage organic matter in the surface horizon of the Makundu soil may be responsible for the difference there.

The increase in percent clay of the pedons, as a result of the treatment, varies from -2.4 to +23.7%. There is no significant relationship between these values and the general groupings of the soils. However, there is significant correlation (0.89) at the 1%

level between percent clay (Fe removed) and organic C for surface horizons. (The correlation value is 0.26 with the percent clay for the whole soil correlated with organic matter.) This value is significant at the 20% level.

In general, the values of percent sand and silt decrease in most of the soils when free Fe oxides are removed. However, the total loss in percent silt and sand is not reflected in the percentage increase in the clay fraction in most cases. Some of the Fe oxides in the form of discrete particles may have been removed from the soil. Desphande et al. (1968), in their studies on the changes in soil properties associated with the removal of Fe and Al oxides in soils, which included some laterite and lateritic soils, reported a decrease in the sand and silt fractions after the Fe oxide has been removed by the dithionite-citrate-bicarbonate method. They recorded not an increase in percent clay content, but a decrease. They suggested that the loss could be due to the iron oxides not present as cementing agents, but as discrete particles or that the amount of Fe initially present in the clay fraction and removed by the treatment was sufficiently large to offset any additions of clay resulting from removal of cements in the silt or sand fractions.

In the present study, the increase in percent clay, as a result of the removal of the free Fe oxides, suggests that some of the Fe oxides are in the soil as cementing agents binding clay particles together. However, the lack of correlation between the decrease in percent sand and silt with that of the increase in percent clay may indicate that some of the Fe oxide is present in discrete clay size particles.

In some of the pedons slight changes in the soil textures are observed as a result of the removal of free Fe oxides, towards a clayey texture.

Also, changes in the distribution of the percent clay are observed in some profiles after the removal of Fe oxide. In the soils of the Steep Hills and Slopes (Segbwema and Timbo series) (Table 1), a decrease in percent clay from the surface downward is observed in the Segbwema series, and a zone of clay accumulation is more clearly observed in the Timbo series with the removal of free Fe oxide. In the soils of the Upland Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni soils), there are gradual increases of clay with depth after the removal of Fe oxides. The Manowa profile also shows this gradual increase with depth, before removal of Fe oxides.

In the soils of the Colluvial Footslopes and Upper River Tributary Terraces, a zone of clay accumulation is more clearly observed with the removal of Fe oxide in the Masuba series, but in the Pendembu series only a gradual increase in clay with depth is evident after removal of Fe oxide.

A gradual increase in clay with depth, both before and after the removal of Fe oxides, is evident in the soils of the Alluvial Terraces and Floodplains. Only incipient illuvial horizons are observed in the Makundu and Moa series after the removal of Fe oxides, as opposed to an increase in percent clay with depth before removal. In the Gbesebu series the incipient nature of the illuvial horizon is recognized both before and after the removal of Fe oxides.

From the above discussion of the soils studied, the removal of the free Fe oxides, before particle size analyses, seems to aid in understanding the genetic processes that are taking place within these profiles.

Total Clay*

The lowest percent of total clay is observed (Table 2) in the soils of the Colluvial Footslopes and Upper River Tributary Terraces, i.e., the Pendembu and Masuba series. They are also lowest in total Fe oxides. They are closely followed by soils of the Steep Hills and Slopes, the Segbwema and Timbo series. The soils of both the Upland Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni series) and of the Alluvial Terraces and Floodplains (Moa, Gbesebu and Makundu series) have greater than 50% total clay throughout their sola. The highest percent clay is in the B horizons of the Makundu and Gbesebu series.

Clay accumulation in the subsurface horizon is a basic criterion for the identification of an argillic horizon, a major characteristic for Ultisols and Alfisols (Soil Taxonomy, 1975). The bulk of the accumulated clay in such soils is thought to have been eluviated from the overlying horizons. Recrystallization from solution and weathering of primary minerals in place account for the remainder of the accumulated clay in the subsurface horizons.

An increase of 3% more clay in the illuvial horizon if the total clay is <15%, or B/A ratio of 1.2 if the total clay is >15% but <40%, or an increase of 8% clay in the illuvial horizon if the

*Discussion is limited to clay after Fe has been removed.

total clay is >40%, constitute an argillic horizon. The main requirement is that there is evidence to show that the clay has moved. This is usually recognized by the presence of clay skins on the surfaces of natural peds. Clay skins are usually difficult to observe in the field in soils of the tropics high in free Fe oxides. Thin section studies are therefore commonly necessary to identify the oriented clays. Thin section studies on the eleven pedons in this study are discussed in the "Micromorphology" section.

The B/C ratio for the identification of argillic horizons has been suggested by Smith and Wilding (1972) as a better criterion for identifying the argillic horizons for soils with a lithologic discontinuity in the upper part of the solum.

The B/A ratio for most of the soils studied here are given in Table 2. The B/C ratio for Segbwema series is given in parentheses instead. The B/A ratio for the Segbwema soils is less than 1 throughout the profile. This is unlike the Timbo soil in which only the B22 horizon has a B/A ratio of less than 1. Both of these soils are developed from residuum of the parent rock. The Segbwema soil is on a Steep Slope of 42% as compared to 6% for the Timbo series. This will affect the depth of weathering in the Segbwema soil, with the deepest horizons being the least weathered. The B/A ratio in this situation may not be a good index for the recognition of an argillic horizon. The B/C ratio for this profile indicates the presence of an argillic horizon. This has been supported by thin section studies (see section on "Micromorphology").

In the soils of Upland Surfaces of Highly Weathered Material, the B/A ratio may not be useful for the identification of an argillic horizon, as they all have a total clay content of >40%. The requirement for an increase of 8% or more clay is diagnostic for these soils, if it occurs within 30cm depth. Both the Njala and Baoma profiles meet this requirement. The Makeni and Manowa soils have values of 7.9 and 7.2, respectively, which are only slightly less than this requirement.

In the soils of the Colluvial Footslopes and Upper River Tributary Terraces, the B/A ratio for the Masuba soil is greater than 1.2 and thus meets the requirement of an argillic horizon. The ratio is less than 1.2 for the Pendembu series, within 30cm depth, but shows a continual increase with depth.

The soils of the Alluvial Terraces and Floodplains do not meet any of the requirements for the argillic horizon discussed earlier.

<u>Fine Clay (<0.2μ)</u>

Data for the fine clays are also included in Table 2. In general, the percent of fine clay is higher than that of coarse clay (2μ-0.2μ) for most of the profiles.

Exceptions are the Gbesebu series (Alluvial Terraces and Floodplains) and the lowest horizons of the Njala, Makeni (soils of Upland Surfaces) and Segbwema series (soils of Steep Hills and Slopes). The higher values of the fine clays may be indicative of the intense weathering in these soils.

The ratio of fine clay to total clay is also a useful diagnostic criterion for an argillic horizon (Soil Survey Staff, 1975). A ratio of fine clay to total clay in the argillic horizon greater by one-third or more than the overlying eluvial horizon, and/or the underlying horizon, is required for soils with less than 15% total clay and 15-40% total clay. If the total clay is >40%, 8% more fine clay is required in the argillic horizon.

The Segbwema soil has a ratio of fine clay to total clay in the B horizon that is greater than one-third of that for the overlying horizon, which further confirms the presence of an argillic horizon. The Timbo series does not meet any of these requirements of an argillic horizon. The fine clay to total clay ratio for the soils of the Upland Surfaces of Highly Weathered Material show a clear decrease with depth, and meet none of the above criteria for an argillic horizon. In the soils of the Colluvial Footslopes and Upper River Terraces, the Pendembu series shows a general decrease with depth in the fine clay/total clay ratio. (Fine clay is not available for the Masuba profile.) This trend is similar to that of the soils of the Upland Surfaces of Highly Weathered Material. In the Gbesebu series the fine clay/total clay ratio is constant throughout the profile. A general increase with depth in the ratio is observed for the Moa series.

Silt/Clay Ratio

The values for the silt/clay ratios when Fe oxide is removed and not removed from the samples are also given in Table 2. The latter value is included only for comparison. Discussion will be limited to values obtained when the percent clay is that from which Fe oxide is removed.

In general, the ratio increases with depth in the Segbwema and Timbo series of Steep Hills and Slopes. The ratio shows a general trend of slight decrease with depth in the Baoma, Manowa, Njala and

Makeni series, all of which are soils of the Upland Surface of Highly Weathered Material. The Masuba and Pendembu soils, of the Colluvial Footslopes and Upper River Terraces, also show a gradual decrease with depth in the silt/clay ratio. The silt/clay values for the soils of Alluvial Terraces and Floodplains are irregularly distributed in the Gbesebu and Makundu profiles, and show a slight decrease with depth in the Moa profile.

van Wambeke (1962) suggests the use of silt/clay ratios for distinguishing tropical soils according to the age of their parent material, with certain limitations. These limitations include: (a) that the soil should be well drained, (b) that the clay fraction is dominated by kaolinite, and (c) that the textural B horizon should not be much richer in clay than the overlying and underlying horizons. He observed that tropical soil materials older than end-Tertiary have silt/clay ratios around 0.10, and that the critical value of 0.15 proved to correspond with a sharp distinction in their ages. Other researchers such as D'Hoore (1954) and Ashaye (1969) have also noted the usefulness of this ratio. Low silt/clay ratios have been suggested by these authors to indicate truly ferrallitic soils, or soils that have undergone ferrallitic pedogenesis.

In the soils studied, the silt/clay ratio decreases with removal of free Fe oxides in mechanical analysis, and none of the soils have ratios below 0.15. The silt/clay ratios are the lowest throughout the profile in soils of the Upland Surfaces of Highly Weathered Material. This suggests a more advanced stage of ferrallitic pedogenesis in these profiles (Ashaye, 1969).

Ratios for the other soils are comparatively higher with the exception of the Moa and the upper horizons of the Timbo series. The highest ratio is obtained for the Segbwema soils, followed by the Gbesebu, Makundu and Masuba series. The higher values are indicative of less ferrallitic weathering, suggesting younger soil profiles. This concept may not be true for the Alluvial Terrace and Floodplain soils, as they generally have high silt contents in their parent materials.

On the basis of the above discussion, the Segbwema series is the youngest of the soils studied.

Bulk Density and 15 Bar Moisture

The bulk density and 15 bar moisture content values are shown in Table 2.

In general, the bulk density increases with depth in all the profiles and tends to be constant in the lower B horizons in most of the soils. The lack of bulk density data for the upper horizons of the Manowa and Njala profiles is due to difficulties in getting either clod or core samples from these very gravelly horizons. Bulk density values reported for the gravelly soils may be subject to error, as a result of the difficulties in making the measurement with available methods. The bulk density values range from 0.8 to 1.6 g/cc. The highest values are obtained for soils of the Upland Surfaces of Highly Weathered Material. The lowest values are obtained in soils of the Alluvial Terraces and Floodplains. The very low values in the uppermost horizons of these soils may be attributed to high organic matter content and high percent porosity.

The 15 bar moisture content in most cases tends to follow the same distribution pattern as the clay content.* Correlation analyses between percent clay and 15 bar moisture content gave a correlation coefficient of 0.93 (significant at the 1% level). The same value of 0.93 was obtained when total clay was taken as the sum of percent clay when Fe oxide has been removed plus percent Fe_2O_3d** (Soil Survey Staff, 1975).

Values of the ratio of 15 bar H_2O/% clay and 15 bar H_2O/% clay + % Fe_2O_3d are given in Table 2. In some cases the values of the ratio are higher in the surface than in the subsoil. The averages of the ratios are 0.36 and 0.33 for 15 bar H_2O/% clay and 15 bar H_2O/% clay + % Fe_2O_3d, respectively.

In Soil Taxonomy (1975) the ratio of 15 atmosphere moisture content of clay has been suggested as a possible index for estimating percent clay in soils that have problems of clay dispersion. A value of 0.4 or less has been reported as the more common in oxic horizons when the percent total clay is taken to be the sum of percent clay with Fe removed plus percent Fe_2O_3d. In the soils studied, the ratios 15 bar H_2O/clay and 15 bar H_2O/clay + Fe_2O_3d are less than 0.4 for most of the profiles, with the exception of the Segbwema series, which has values >0.4 for the former. Ratios of less than 0.4 are obtained for soils with known cambic horizons, e.g., the Gbesebu series, average 0.39 or 0.36 for 15 bar H_2O/clay and 15 bar H_2O/clay + Fe_2O_3d, respectively.

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*Clay, when Fe oxide has been removed.

**Fe_2O_3d = Fe oxide extracted by sodium bicarbonate-citrate-dithionite.

Since percent clay increases with the removal of free Fe oxide, and the values obtained are also usually higher (in 28 of 41 comparisons) than those obtained by 2.50 x 15 bar H_2O, it would seem more logical to use 2.78 instead of 2.50 x 15 bar H_2O to estimate the clay contents of these soils after iron removal. The value of the sum of percent clay after Fe removed + Fe_2O_3d would require a factor of 3.0 x 15 bar H_2O to estimate clay content.

Chemical Analyses

The values of percent organic C, pH, C.E.C., percent base saturation, exchangeable cations and some ratios of these values to the clay contents (in Table 2) are given in Table 3.

Organic Carbon

In general, the percent organic C decreases with depth. The values range from 1.25-5.06 in the surface horizons, with the Gbesebu and Makundu soils having the highest percentage in their surface horizons. Comparatively higher percentages of organic C are also found in the lower horizons of these profiles. The presence of high percent organic C in the subsoil of Makeni series may be the result of dead roots or animal activity.

Within each of the four groups of profiles in Table 1 the percent organic C in the surface horizon increases with the moisture regime. The Masuba profile of the Colluvial Footslopes and Upper Terraces is the only exception.

Table 3. Chemical properties of the soils studied (% O.C., pH, C.E.C., % BS and exchangeable cations)

Soil Series	%* O.C.	pH* H_2O	pH* KCl	ΔpH	C.E.C. me/ 100g* soil	% Base Saturation (BS)	*Exchangeable Cations me/100g Soil Ca	Mg	K	Na	Al	$\frac{\text{C.E.C.} \times 100}{\text{Clay}_1}$	$\frac{\text{C.E.C.} \times 100}{\text{Clay}_2}$	Sum of Exchange Cations + $\frac{\text{Al} \times 100}{\text{Clay}_1}$	Sum of Exchange Cations + $\frac{\text{Al} \times 100}{\text{Clay}_2}$	(% Al saturation) $\frac{\text{Exchange Al} \times 100}{\text{Sum of Exchange Bases + Al}}$
Baoma																
A_1	2.43	4.6	3.8	0.8	11.93	4.4	0.21	0.23	0.06	0.02	1.33	28.9	33.6	4.5	5.2	71.9(11.1)
B_2	0.81	4.8	4.2	0.6	7.29	5.3	0.05	0.26	0.05	0.03	0.63	14.3**	15.6**	2.0**	2.2**	61.8(8.6)
IIB_{31}	0.53	5.0	4.6	0.4	6.50	9.4	0.23	0.26	0.05	0.07	0.12	11.6**	11.5**	1.3**	1.3**	16.4(1.8)
IIB_{32}	0.24	5.2	5.0	0.5	5.36	14.6	0.36	0.34	0.04	0.04	0.16	9.0**	9.6**	1.6**	1.7**	17.0(2.9)
IIB_{33}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Manowa																
A_1	2.69	4.3	3.8	0.5	11.79	2.1	0.01	0.10	0.10	0.04	3.06	31.4	37.4	8.8	10.0	92.4(26.0)
A_3	1.90	4.5	3.9	0.6	9.29	2.9	0.07	0.08	0.07	0.05	2.50	23.2	24.2	6.9**	7.2**	90.2(26.9)
B_{21}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B_{22}	0.71	4.8	4.2	0.6	6.00	3.0	0.00	0.08	0.06	0.04	0.67	11.8**	12.6**	1.7**	1.8**	78.8(11.2)
Njala																
A_1	2.78	4.5	3.8	0.7	13.22	5.7	0.36	0.28	0.06	0.06	3.00	27.3	37.0	7.8	10.5	79.8(22.7)
A_3	1.31	4.6	3.8	0.8	9.65	3.9	0.15	0.16	0.02	0.05	2.94	17.7	19.1	6.1**	6.6**	88.6(30.5)
B_{21}	0.68	4.8	3.7	1.1	7.72	7.6	0.28	0.23	0.04	0.04	1.72	11.6**	12.8**	3.5**	3.8**	74.5(22.3)
B_{22}	0.46	4.8	3.6	1.2	7.43	7.4	0.28	0.21	0.03	0.03	1.83	11.1**	12.7**	3.6**	4.1**	76.9(24.6)
Makeni																
A_1	4.19	5.2	4.4	0.8	14.14	35.9	2.63	2.10	0.25	0.10	0.27	24.9	35.5	9.4	13.4	5.0(1.9)
B_{21}	1.87	4.7	4.2	0.5	8.14	14.5	0.21	0.84	0.04	0.09	1.05	12.6**	14.5**	3.4**	4.0**	47.1(12.9)
B_{22}	1.13	5.2	4.6	0.6	5.28	29.5	0.68	0.79	0.03	0.06	0.16	7.8**	8.9**	2.6**	3.9**	9.3(3.0)
Segbwema																
A_1	2.01	4.7	3.8	0.9	10.65	17.0	0.96	0.44	0.35	0.06	0.93	22.1	30.9	5.7	7.9	33.9(8.7)
B_{21t}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B_{22t}	0.24	5.2	4.0	1.2	6.86	3.6	0.05	0.13	0.03	0.04	1.28	21.2	16.5	4.7**	3.7**	83.6(18.7)
C_1	0.10	5.5	4.0	1.5	6.00	5.0	0.05	0.10	0.08	0.07	1.11	24.0	16.8	5.6**	3.9**	78.7(18.5)

Table 3 (continued)

Soil Series	%* O.C.	pH* H_2O	pH* KCl	ΔpH	C.E.C. me/100g* soil	% Base Saturation (BS)	*Exchangeable Cations me/100g Soil Ca	Mg	K	Na	Al	C.E.C. x 100 / $Clay_1$	C.E.C. x 100 / $Clay_2$	Sum of Exchange Cations + Al x 100 / $Clay_1$	Sum of Exchange Cations + Al x 100 / $Clay_2$	(% Al saturation) Exchange Al x 100 / Sum of Exchange Bases + Al
Timbo																
A_{11}	2.34	4.6	4.2	0.4	7.64	13.6	0.47	0.27	0.15	0.15	0.82	22.4	31.2	5.5	7.6	44.1(10.7)
A_{12}	1.87	4.8	4.2	0.6	6.36	9.9	0.21	0.21	0.09	0.12	1.09	15.4**	22.6	4.2**	6.1**	63.4(17.1)
AB	1.05	4.8	4.2	0.6	4.57	12.7	0.16	0.21	0.09	0.12	0.43	11.1**	14.7**	2.5**	3.3**	42.6(9.4)
B_{21b}	0.70	4.8	4.4	0.4	3.79	12.7	0.21	0.11	0.06	0.10	0.31	10.1**	11.8**	2.1**	2.5**	39.2(5.2)
B_{22b}	0.51	4.9	4.6	0.3	3.79	21.4	0.38	0.15	0.13	0.15	0.24	11.9**	11.2**	3.3**	3.1**	22.8(6.3)
Pendembu																
A_1	2.25	4.1	3.6	0.5	9.44	2.4	0.00	0.08	0.10	0.05	3.56	30.8	41.4	12.3	16.6	93.9(37.7)
A_3	0.85	4.4	3.8	0.6	4.79	4.0	0.06	0.03	0.06	0.04	2.39	15.2*	20.1	8.2	10.8	92.6(49.9)
B_{21}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B_{22}	0.32	4.7	3.9	0.8	3.50	5.1	0.06	0.03	0.05	0.04	1.22	9.9**	11.6**	4.0**	4.6**	87.1(34.9)
B_{23}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B_3	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Masuba																
AP	1.25	4.7	4.1	0.6	5.71	16.6	0.47	0.37	0.03	0.08	0.99	23.4	22.7	7.9	7.7	51.0(17.3)
B_{21t}	0.62	4.6	4.0	0.6	3.79	11.1	0.16	0.16	0.02	0.08	1.09	11.5**	14.1**	4.6**	5.6**	72.2(28.8)
B_{22t}	0.51	4.8	4.0	0.8	3.14	14.6	0.21	0.16	0.01	0.08	1.05	9.6**	12.2**	4.6**	5.8**	69.5(33.4)
Moa																
A_1	2.98	4.5	3.8	0.7	13.78	7.5	0.61	0.23	0.14	0.05	2.78	25.8	34.0	7.1	9.3	72.9(20.2)
B_{21}	0.91	4.6	3.8	0.8	9.94	3.9	0.06	0.08	0.09	0.08	1.78	14.0**	16.4	3.7**	4.3**	85.2(17.9)
B_{22}	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B_3	0.41	5.1	4.0	1.1	6.50	6.0	0.06	0.21	0.07	0.05	1.17	11.3**	13.3**	2.7**	3.2**	75.1(18.0)
C	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

Table 3 (continued)

Soil Series	%* O.C.	pH* H_2O	pH* KCl	ΔpH	C.E.C. me/ 100g* soil	% Base Saturation (BS)	*Exchangeable Cations me/100g Soil: Ca	Mg	K	Na	Al	C.E.C. x 100 / $Clay_1$	C.E.C. x 100 / $Clay_2$	Sum of Exchange Cations + Al x 100 / $Clay_1$	Sum of Exchange Cation + Al x 100 / $Clay_2$	(% Al saturation) Exchange Al x 100 / Sum of Exchange Bases + Al
Gbesebu																
A_1	4.41	4.6	3.8	0.8	18.93	2.7	0.18	0.22	0.03	0.08	2.44	27.8	29.5	4.3	4.6	82.7(12.9)
A_3	2.43	4.6	3.8	0.8	12.65	3.1	0.13	0.18	0.02	0.06	2.00	18.3	19.2	3.5**	3.6**	83.7(15.8)
B_{21b}	1.00	4.8	3.8	1.0	9.29	3.3	0.08	0.15	0.02	0.06	1.78	13.8**	13.8**	3.1**	3.1**	85.2(19.2)
B_{22b}	0.87	4.8	3.7	1.0	9.57	5.0	0.10	0.33	0.01	0.04	1.94	13.5**	14.0**	3.4**	3.5**	80.2(20.3)
B_{23}	0.56	4.9	3.7	1.2	8.86	7.3	0.15	0.44	0.02	0.04	1.78	12.8**	13.4**	3.5**	3.7**	73.3(20.1)
Makundu																
A_{11}	5.06	5.3	4.5	0.8	23.62	22.9	3.20	1.16	0.53	0.53	0.41	35.7	32.4	8.8	8.0	7.0(1.7)
A_{12}	3.62	5.0	4.3	0.7	19.69	6.2	0.42	0.42	0.19	0.20	1.35	28.9	27.2	4.2**	3.6**	52.3(6.8)
AB	2.57	4.7	4.2	0.5	15.77	3.9	0.21	0.21	0.08	0.11	1.94	23.5	23.3	3.8**	3.8**	76.1(12.3)
B_1	1.40	4.9	4.1	0.8	9.70	4.6	0.21	0.11	0.05	0.08	1.69	13.8**	15.0**	3.0**	3.3**	78.9(17.4)
B_{21}	0.78	5.2	4.2	1.0	8.85	6.8	0.21	0.26	0.05	0.08	0.81	12.4**	13.7**	2.0**	2.2**	57.4(9.2)
B_{22}	0.04	5.4	4.2	1.2	3.79	12.9	0.21	0.11	0.07	0.10	1.04	5.5**	6.0**	2.3**	2.4**	68.0(27.4)

*Data taken from Odell et al., 1974.

**Diagnostic for oxic horizon.

$Clay_1 = Fe_2O_3$ removed.

$Clay_2 = Fe_2O_3$ not removed or 2.5 x 15 bar H_2O, whichever is higher.

( ) = % Al saturation calculated by $\frac{\text{exchange Al x 100}}{\text{C.E.C.}}$.

pH

The soils are generally low in pH, the range being 4.1 to 5.5 (1:1 H_2O). The values generally increase with depth in the profile. The ΔpH* values are positive, but low (<1.6).

Cation Exchange Capacity

The cation exchange capacity of the soil samples is typically low and decreases with depth. The values range from 3.14 to 23.6 me/100g of soil. The highest values are in the surface horizons where percent organic C is higher. The Makundu and Gbesebu soils of the Alluvial Terraces and Floodplains have comparatively higher cation exchange capacities than the other soil series. These latter soils have the highest percentage of clay in their profiles (Table 2) and the surface horizons are high in organic C. These factors may be responsible for their higher C.E.C. The surface horizon of the Makundu soil has the highest percentage of organic C and also the highest C.E.C.

Aside from the organic matter content and amount of clay influencing the cation exchange capacity, the types of clay and the size of the individual clay particles also influence the C.E.C. Clay mineralogy studies on the profiles (see discussion of "Mineralogical Analyses") show that the dominant clay mineral is kaolinite, which has a C.E.C. of 3.1 me/100g clay.

Grim (1968) and Calliere and Henin (1963) have shown that the size of the individual clay particles influences the amount of charge they carry. Small size particles have more electrically neutralizable charge per unit mass than larger particles. With this in mind, one would expect that horizons with higher percentages of

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*ΔpH = pH H_2O - pH KCl.

fine clay (Table 2) would have a comparatively higher C.E.C. than those with lower percent fine clays. This does not seem to be the case in the soils studied. One possible explanation is that the influence of the size of the clay particles on the C.E.C. is masked by the effect of the organic C.

One of the criteria used to identify an oxic horizon in Soil Taxonomy (1975) is the cation exchange capacity of the clay. The requirement is 16 me or less per 100g clay by the ammonium acetate determination (me C.E.C./100g soil x 100 ÷ % clay $\leq$ 16). The percent clay referred to here is as measured by the pipette method or 2.5 times the 15 bar water, whichever value is higher, but not more than 100. In the soils studied, the ratios C.E.C./% $clay_2$* and C.E.C./% $clay_1$ (Fe removed) were determined. The results are summarized in Table 3. Since there is an increase in percent clay after the removal of free Fe oxides, this value gives a better estimate of percent clay than without Fe oxide removal and lower C.E.C./% clay values. All but the Segbwema profile meet this criterion of oxic horizons. The 2.5 x 15 bar moisture values of $clay_1$ leave the Moa B_{21} and the Pendembu A_3 with values >16 but would reduce the Makundu B_1 to a value of <15.0. The soil that did not meet this requirement of an oxic horizon in its uppermost B horizon is the Segbwema series. Both the Gbesebu and Masuba series are known to have cambic horizons (Odell et al., 1974). Incipient argillans were also observed in the B horizon of the Masuba series in this study (see discussion on "Micromorphology").

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*$Clay_2$- Fe not removed or 2.50 x 15 bar H_2O, whichever is greater.

The value of percent clay, as determined by 2.5 x 15 bar moisture contents, or percent clay when Fe oxide is not removed (whichever is greater), was used by Odell et al. (1974) for the C.E.C./clay ratio. All the soils with the exception of the Moa and Segbwema series have this criterion of an oxic horizon (<16 me C.E.C./100g clay) in their uppermost B horizons. van Wambeke (1967) proposed a critical value of 12 me/100g clay, instead of 16, for older soils of the tropics, as this value seems to form a class which is characteristic for old stable landscapes in the tropics. He observed correlations between this criterion and soil structure, color, weatherable mineral content, the presence or absence of pressure faces, and clay skins on ped surfaces.

Could perhaps a group of soils studied here be better distinguished if this critical value is used? Using the value 12 instead of 16 with these pedons, the upper B horizon of Baoma series will be non-oxic according to this criterion. Similarly, the upper B horizons of the soils of the Alluvial Terraces and Floodplains (Gbesebu, Makundu and Moa series) will be non-oxic according to this limit. The Gbesebu and Makundu are eliminated from Oxisols by lack of an oxic horizon in the control section (25-100cm). On balance, the 16 me/100g of clay seems to give a clearer split of the oxic and non-oxic soils in this study if other criteria can be used for other important separations needed.

Percent Base Saturation

The percent base saturation of the eleven profiles is generally low, all samples being less than 36%. In most of the soils studied, such as the Njala, Makeni, Segbwema, Timbo, Masuba, Moa and Makundu series, the percent base saturation is higher at the surface, then decreases, followed by increases with depth. The other soils (Baoma, Manowa, Pendembu and Gbesebu series) all show increases in percent base saturation with depth. The general decrease with depth of percent base saturation, below the immediate surface, in the Segbwema and Timbo soils may be related in part to the topographic position of these profiles (Figure 2) and the circulation of bases to the surface by organisms. On this topographic position runoff is the predominant form of water movement. Infiltration is minimal. The increase of percent base saturation with depth may be in part a result of leaching to lower horizons of the exchangeable cations or continued release of bases from the less weathered deeper material.

The higher percent base saturation in the surface horizons of the Makundu, Makeni, Timbo and Masuba soils (all from soil province J) is the result of unusually high exchangeable Ca found in the surface horizon of these soils. The source is not certain, but may be from the organic additions to the land surface and a relatively long dry season with some dust additions. Finally, as the less leached parent material is approached with depth, the percent base saturation rises as the C.E.C. decreases, and with leaching to lower horizons of exchangeable cations or less leaching with depth and release of more bases from less leached subsoil layers.

Exchangeable Cations

Generally, the soils are low in exchangeable bases. The Makeni and Makundu soils have the highest amount of exchangeable Ca and Mg in their uppermost horizons. All the other profiles have low concentrations of these nutrients. These soils also have comparatively low exchangeable Al.

The exchangeable Al is highest in the Baoma, Manowa, Njala, Pendembu, Moa and Gbesebu soils. The percent Al saturation is highest in the Manowa, Njala, Pendembu, Masuba and Gbesebu series. The lowest values are in the subsoil of the Baoma series and in the Makeni profile (range = 5.0 in Makeni surface to 93.9 in Pendembu surface horizon). Decreases of percent Al saturation with depth were observed in the Baoma, Manowa, Pendembu and Gbesebu series, while Njala, Makeni, Segbwema, Timbo, Masuba, Moa and Makundu soils showed zones of high percent Al saturation in their profiles.

The high percent Al saturation of these soils poses toxicity problems, which will affect crop production. Lime application is therefore necessary in these soils to reduce percent Al saturation and increase pH.

The ratio of the sum of the exchangeable cations plus exchangeable Al to percent clay (clay as determined by pipette method or by 2.50 x 15 bar moisture, whichever is higher) is one of the criteria used in identifying an oxic horizon. A critical value of 10 me/100g clay or less is required.

In the soils studied, this ratio, if determined using percent clay with Fe oxide removed (Table 3), is less than 10 me/100g soils in the upper and lower B horizons of all the soils. A few surface horizons (Table 3) have values >10 me/100g clay, particularly if calculated with percent clay without Fe removal or as 2.5 x 15 bar moisture content. This means, then, that all the soils have this characteristic of oxic horizons in their B horizons. The Segbwema and Masuba or Gbesebu series have been shown to have argillic and cambic B horizons, respectively (see section on "Micromorphology"). On the basis of the criteria

$$\frac{\text{Sum of Exchangeable Cations + Al x 100}}{\text{\% Clay}} = \leq 10 \text{ and } \frac{\text{C.E.C. x 100}}{\text{\% Clay}} = \leq 16$$

for oxic horizons, the latter eliminates the Segbwema from the Oxisols.

Extractable Iron and Aluminum Oxides (Dithionite, Ammonium Oxalate and Na-Pyrophosphate, Fe and Al)

Fe and Al oxides are among the major components in tropical soils. Both physical and chemical behavior of these soils are affected in some ways by these components. Aggregate stability, the fixation of P (Udo and Uzu, 1972) and adsorption surface properties are among some of the soil properties affected by these oxides.

These oxides are known to exist as amorphous and crystalline inorganic forms (McKeague and Day, 1966) and as organic-oxide complexes (McKeague et al., 1971). The acid ammonium oxalate method of Tamm as modified by McKeague and Day (1966) is known to extract mainly amorphous Fe oxide. The dithionite-citrate-bicarbonate method of Mehra and Jackson (1960) is known to extract total free Fe oxides and also some organic complex forms. The Na-pyrophosphate extraction has been shown to be specific and extracts Fe and Al organic complexes (McKeague et al., 1971).

Dithionite-Citrate-Bicarbonate Extractable Fe Oxide

This method generally extracted more Fe oxides than did acid ammonium oxalate (Table 4). This compares favorably with observations

Table 4. Percent extractable Fe and Al oxides and their ratios with percent clay and organic C

Soil Series	Fe_2O_3			Al_2O_3			%*	Fe-Na-pyro-phosphate										
	Dithionite	Oxalate	Na-pyrophosphate	Dithionite	Oxalate	Na-pyrophosphate	Total Fe_2O_3	O.C.	$\frac{Fe_2O_3ox}{Fe_2O_3d}$	$\frac{Al_2O_3ox}{Al_2O_3d}$	$\frac{Fe_2O_3d}{Clay_1}$	$\frac{Fe_2O_3d}{Clay_2}$	$\frac{Fe_2O_3ox}{Clay_1}$	$\frac{Fe_2O_3ox}{Clay_2}$	$\frac{Fe_2O_3d-Fe_2O_3ox}{Clay_1}$	$\frac{Fe_2O_3d-Fe_2O_3ox}{Clay_2}$	$\frac{Al_2O_3d}{Clay_1}$	$\frac{Al_2O_3d}{Clay_2}$
Baoma																		
A_1	5.06	1.48	2.44	1.71	1.00	---	16.40	1.00	0.29	0.58	0.12	0.15	0.04	0.04	0.09	0.10	0.04	0.05
B_{21}	5.89	1.41	1.43	1.64	1.10	---	17.17	1.83	0.24	0.59	0.12	0.13	0.03	0.03	0.08	0.09	0.03	0.03
IIB_{31}	6.50	1.39	0.49	1.79	0.98	---	18.13	0.92	0.21	0.44	0.12	0.12	0.02	0.02	0.09	0.09	0.03	0.03
IIB_{32}	5.65	1.34	0.31	1.64	0.77	---	18.96	1.29	0.24	0.47	0.10	0.10	0.02	0.02	0.07	0.08	0.03	0.03
IIB_{32}	6.61	1.36	0.29	1.67	0.77	---	---	---	0.21	0.46	0.11	---	0.02	---	0.09	---	0.03	---
Manowa																		
A_1	3.46	0.41	2.57	1.63	1.10	---	8.10	0.96	0.12	0.67	0.09	0.11	0.01	0.01	0.08	0.10	0.04	0.05
A_3	3.65	0.34	2.89	1.60	1.35	---	---	1.52	0.09	0.84	0.09	0.10	0.01	0.01	0.08	0.08	0.04	0.04
B_{21}	3.99	0.26	2.59	1.48	1.17	---	8.99	---	0.07	0.79	0.09	0.11	0.01	0.01	0.08	0.09	0.03	0.04
B_{22}	4.89	0.20	1.18	1.52	1.30	---	11.19	1.66	0.04	0.86	0.10	0.10	0.004	0.004	0.09	0.10	0.03	0.03
Njala																		
A_1	2.46	0.59	1.81	0.26	0.77	1.13	5.09	0.65(0.41)+	0.24	2.96	0.05	0.07	0.01	0.02	0.04	0.05	0.01	0.02
A_3	3.48	0.50	2.35	0.38	0.80	1.33	5.86	1.79(1.01)+	0.14	2.10	0.06	0.07	0.01	0.01	0.05	0.01	0.03	0.04
B_{21}	4.49	0.46	2.10	0.44	0.58	1.26	6.80	3.09(1.85)+	0.10	1.30	0.07	0.07	0.01	0.01	0.06	0.01	0.04	0.04
B_{22}	5.26	0.38	0.75	0.27	0.27	0.61	6.90	1.63(1.32)+	0.07	1.00	0.08	0.09	0.01	0.01	0.08	0.01	0.02	0.01
Makeni																		
A_1	3.39	0.77	2.46	0.88	1.54	2.08	9.97	0.59(0.50)+	0.22	1.75	0.06	0.10	0.01	0.02	0.04	0.08	0.02	0.03
B_{21}	4.56	0.77	2.71	0.76	2.61	2.31	15.57	1.45(1.23)	0.17	3.43	0.07	0.08	0.01	0.01	0.06	0.07	0.01	0.01
B_{22}	5.10	0.67	0.67	0.61	1.59	0.17	16.60	0.59(0.15)+	0.13	2.61	0.07	0.10	0.01	0.01	0.07	0.09	0.01	0.01
Segbwema																		
A_1	3.79	1.86	0.47	1.09	0.56	0.10	5.50	0.23(0.05)	0.49	0.51	0.08	0.14	0.04	0.07	0.04	0.07	0.02	0.04
B_{21t}	3.57	1.52	0.06	1.07	0.48	0.02	---	---	0.42	0.45	0.09	---	0.04	---	0.05	---	0.03	---
B_{22t}	3.24	1.30	0.06	0.90	0.36	0.03	7.78	0.25(0.12)	0.40	0.40	0.10	0.09	0.04	0.04	0.06	0.06	0.03	0.03
C_1	1.69	0.82	0.05	0.73	0.22	0.08	4.85	0.55(0.8)	0.48	3.30	0.07	0.07	0.03	0.03	0.03	0.04	0.03	0.03

Table 4 (continued)

Soil Series	Fe_2O_3			Al_2O_3			%*	Fe-Na-pyrophosphate / O.C.	Fe_2O_3ox / Fe_2O_3d	Al_2O_3ox / Al_2O_3d	Fe_2O_3ox / $Clay_1$	Fe_2O_3d / $Clay_2$	Fe_2O_3ox / $Clay_1$	Fe_2O_3ox / $Clay_2$	Fe_2O_3d- Fe_2O_3ox / $Clay_1$	Fe_2O_3d- Fe_2O_3ox / $Clay_2$	Al_2O_3d / $Clay_1$	Al_2O_3d / $Clay_2$
	Dithionite	Oxalate	Na-pyrophosphate	Dithionite	Oxalate	Na-pyrophosphate	Total Fe_2O_3											
Timbo																		
A_{11}	2.68	0.58	1.39	1.20	1.45	---	10.36	0.59	0.22	1.21	0.08	0.13	0.01	0.02	0.06	0.10	0.04	0.06
A_{12}	3.63	0.50	2.09	1.37	1.54	---	11.45	1.12	0.14	1.22	0.09	0.13	0.01	0.02	0.08	0.11	0.03	0.05
AB	3.61	0.45	1.73	1.31	1.36	---	13.50	1.65	0.13	0.79	0.09	0.12	0.01	0.03	0.08	0.10	0.03	0.04
B_{21}	4.47	0.33	0.43	1.09	0.53	---	14.44	0.61	0.07	1.79	0.12	0.14	0.01	0.01	0.11	0.13	0.03	0.04
B_{22}	4.07	0.33	0.19	0.92	0.24	---	14.86	0.37	0.08	2.49	0.13	0.12	0.01	0.01	0.12	0.11	0.03	0.03
Pendembu																		
A_1	1.52	0.38	---	0.44	0.53	---	2.52	---	0.25	1.20	0.05	0.08	0.01	0.02	0.04	0.06	0.01	0.02
A_3	1.84	0.38	---	0.39	0.35	---	3.00	---	0.20	0.89	0.06	0.08	0.01	0.02	0.05	0.06	0.01	0.02
B_{21}	1.65	0.36	---	0.41	0.26	---	---	---	0.22	0.63	0.05	---	0.01	---	0.04	---	0.01	---
B_{22}	1.71	0.16	---	0.45	0.23	---	3.10	---	0.09	0.51	0.05	0.06	0.004	0.01	0.04	0.05	0.01	0.02
B_{23}	1.61	0.16	---	0.80	0.17	---	---	---	0.01	0.19	0.04	---	0.004	---	0.04	---	0.02	---
B_3	1.52	0.12	---	0.26	0.09	---	---	---	0.08	0.35	0.04	---	0.003	---	0.04	---	0.01	---
Masuba																		
A_{10}	0.59	0.18	---	0.20	0.11	---	2.67	---	0.30	0.53	0.02	0.03	0.01	0.01	0.02	0.02	0.01	0.01
B_{21t}	0.79	0.20	---	0.21	0.06	---	3.13	---	0.25	0.29	0.02	0.03	0.01	0.01	0.02	0.02	0.001	0.01
B_{22}	0.67	0.19	---	0.07	0.05	---	3.18	---	0.28	0.76	0.02	0.03	0.01	0.01	0.02	0.02	0.002	0.003
Moa																		
A_1	4.18	0.82	---	0.53	0.47	---	7.38	---	0.20	0.87	0.08	0.10	0.02	0.02	0.07	0.09	0.01	0.01
B_{21}	4.53	0.65	---	0.75	0.33	---	8.35	---	0.14	0.44	0.08	0.09	0.01	0.01	0.07	0.08	0.01	0.01
B_{22}	5.09	0.53	---	0.87	0.21	---	---	---	0.10	0.24	0.09	---	0.01	---	0.08	---	0.02	---
B_3	5.20	0.65	---	0.87	0.15	---	8.98	---	0.13	0.17	0.09	0.11	0.01	0.01	0.08	0.09	0.02	0.003
C	5.09	0.56	---	0.91	0.09	---	---	---	0.11	0.10	0.10	---	0.01	---	0.09	---	0.02	---

Table 4 (continued)

Soil Series	Fe_2O_3 Dithi-onite	Fe_2O_3 Oxa-late	Fe_2O_3 Na-pyro-phosphate	Al_2O_3 Dithi-onite	Al_2O_3 Oxa-late	Al_2O_3 Na-pyro-phosphate	%* Total Fe_2O_3	Fe-Na-pyro-phosphate / O.C.	Fe_2O_3ox / Fe_2O_3d	Al_2O_3ox / Al_2O_3d	Fe_2O_3ox / $Clay_1$	Fe_2O_3d / $Clay_2$	Fe_2O_3ox / $Clay_2$	Fe_2O_3ox / $Clay_2$	Fe_2O_3d-Fe_2O_3ox / $Clay_1$	Fe_2O_3d-Fe_2O_3ox / $Clay_2$	Al_2O_3d / $Clay_1$	Al_2O_3d / $Clay_2$
Gbesebu																		
A_1	4.10	1.32	1.21	0.56	1.45	0.66	5.84	0.27(0.15)+	0.32	2.60	0.06	0.08	0.01	0.03	0.04	0.06	0.01	0.01
A_3	4.97	2.11	1.57	0.69	1.38	0.44	6.20	0.65(0.18)+	0.42	2.00	0.07	0.08	0.03	0.04	0.04	0.05	0.01	0.01
B_{21}	5.41	2.04	1.09	0.43	1.39	0.44	7.53	1.09(0.44)+	0.40	3.20	0.08	0.09	0.03	0.03	0.05	0.06	0.01	0.01
B_{22b}	4.70	1.84	0.93	0.34	1.08	0.34	7.08	1.06(0.39)+	0.40	3.20	0.07	0.08	0.03	0.03	0.04	0.05	0.005	0.01
B_{23}	4.28	1.46	0.23	0.36	0.85	0.18	7.10	0.40(0.32)+	0.34	2.40	0.06	0.07	0.02	0.02	0.02	0.05	0.005	0.01
Makundu																		
A_{11}	3.74	0.43	1.68	1.68	0.65	1.84	10.39	0.33(0.36)+	0.11	0.15	0.07	0.08	0.01	0.01	0.05	0.07	0.03	0.04
A_{12}	4.47	1.39	2.12	1.33	2.95	1.80	10.94	0.51(0.50)+	0.31	2.25	0.07	0.09	0.02	0.03	0.05	0.07	0.02	0.03
AB	4.38	0.94	1.90	1.23	1.42	1.23	11.10	0.73(0.48)+	0.21	1.15	0.07	0.09	0.01	0.02	0.05	0.07	0.02	0.03
B_1	5.59	1.09	0.19	1.03	3.31	0.19	11.46	0.14(0.14)+	0.19	3.21	0.08	0.08	0.02	0.02	0.05	0.06	0.02	0.02
B_{21}	5.56	0.45	0.20	0.94	0.62	0.22	11.79	0.25(0.28)+	0.08	0.65	0.08	0.07	0.01	0.01	0.06	0.07	0.01	0.02
B_{22}	4.63	0.52	0.10	0.74	0.53	0.16	10.84	0.25(0.4)+	0.12	0.71	0.06	0.07	0.01	0.01	0.06	0.06	0.01	0.01

*Data from Odell et al., 1974.

$Clay_1$ = Fe removed.

$Clay_2$ = Fe not removed.

+ = Na-pyrophosphate Al/% O.C.

of other workers (Juo et al., 1974; McKeague and Day, 1966). The dithionite extracted Fe also exceeds the Na-pyrophosphate extracted Fe in these soils. Dithionite extractable Fe oxides increase with depth in the soils of the Upland Surfaces of Highly Weathered Material, i.e., Baoma, Manowa, Njala and Makeni series (Figure 3a). These soils are on more stable surfaces (Figure 2), interfluves and seepage slopes. Here, infiltration rather than runoff is the main process. Juo et al. (1974) observed a similar trend on six well-drained upland soils in Nigeria. Rhodes and Sutton (1978), in earlier studies on some Sierra Leone soils (some of which are included in this study), observed a similar trend of increase in percent Fe oxide with depth, a trend similar to that of total Fe.

In the soils of the Steep Hills and Slopes, there are marked decreases with depth of dithionite Fe oxide in the Segbwema series (Figure 3b). However, a zone of accumulation of Fe oxide is observed in the upper B horizon of the Timbo series. The decrease of Fe oxide with depth in the Segbwema profile is in sharp contrast to the distribution of Fe oxides in the soils of the Upland Surfaces of Highly Weathered Material (see discussion above). The Segbwema profile being located on a 42% slope, where runoff is the predominant process rather than infiltration, may account for this trend. This effect of slope is not evident in the Timbo* series, which is on a 6% slope. The distribution pattern of total Fe shows a zone of maximum in the Segbwema series, and increases with depth in the Timbo series.

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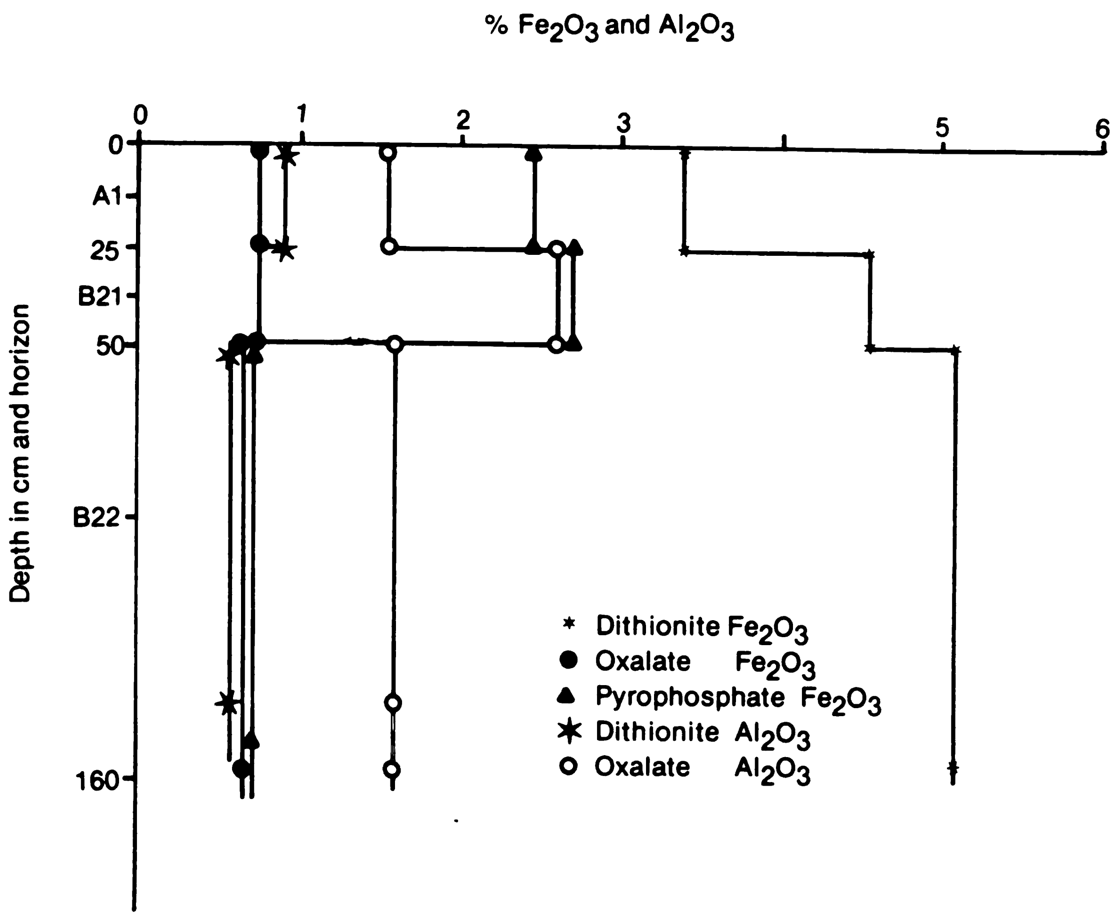
*Timbo series generally occurs on slopes steeper than 6%. This profile represents the less sloping members.

Figure 3a. Profile distribution of Fe_2O_3 and Al_2O_3 extracted by dithionite, oxalate and pyrophosphate solutions in Makeni series.



% Fe2O3 and Al2O3
0
1
2
3
5
6
Depth in cm and horizon
0
A1
25
B21
50
B22
160
* Dithionite Fe2O3
● Oxalate Fe2O3
▲ Pyrophosphate Fe2O3
✱ Dithionite Al2O3
○ Oxalate Al2O3

Figure 3a

Figure 3b. Profile distribution of Fe_2O_3 and Al_2O_3 extracted by dithionite, oxalate and pyrophosphate solutions in Segbwema series.

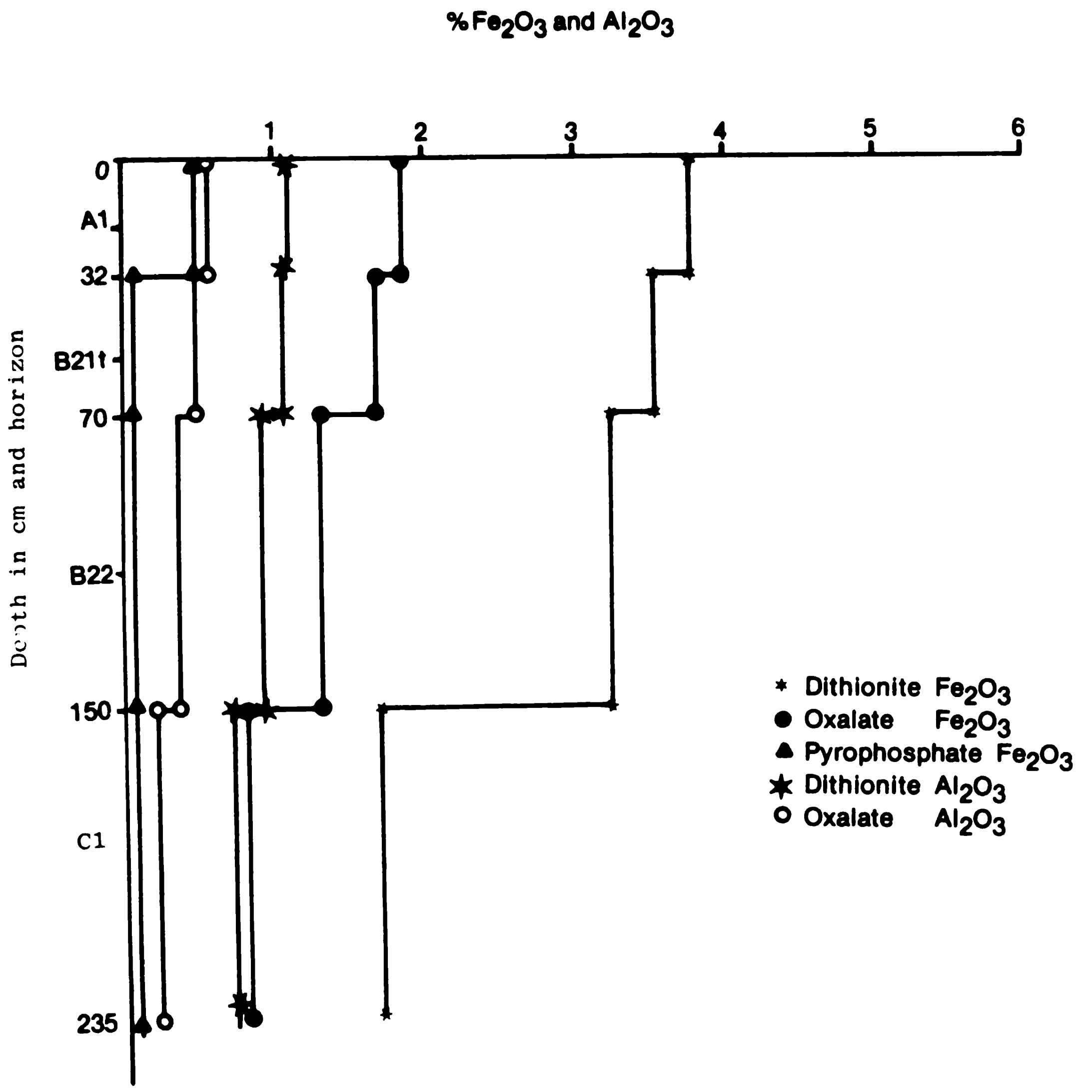

% Fe_2O_3 and Al_2O_3
1
2
3
4
5
6
0
A1
32
B21t
70
B22
150
C1
235
Depth in cm and horizon
Dithionite Fe_2O_3
Oxalate Fe_2O_3
Pyrophosphate Fe_2O_3
Dithionite Al_2O_3
Oxalate Al_2O_3

Figure 3b

Figure 3c. Profile distribution of Fe_2O_3 and Al_2O_3 extracted by dithionite and oxalate solutions in Masuba series.

Figure 3d. Profile distribution of Fe_2O_3 and Al_2O_3 extracted by dithionite, oxalate and pyrophosphate solutions in Gbesebu series.

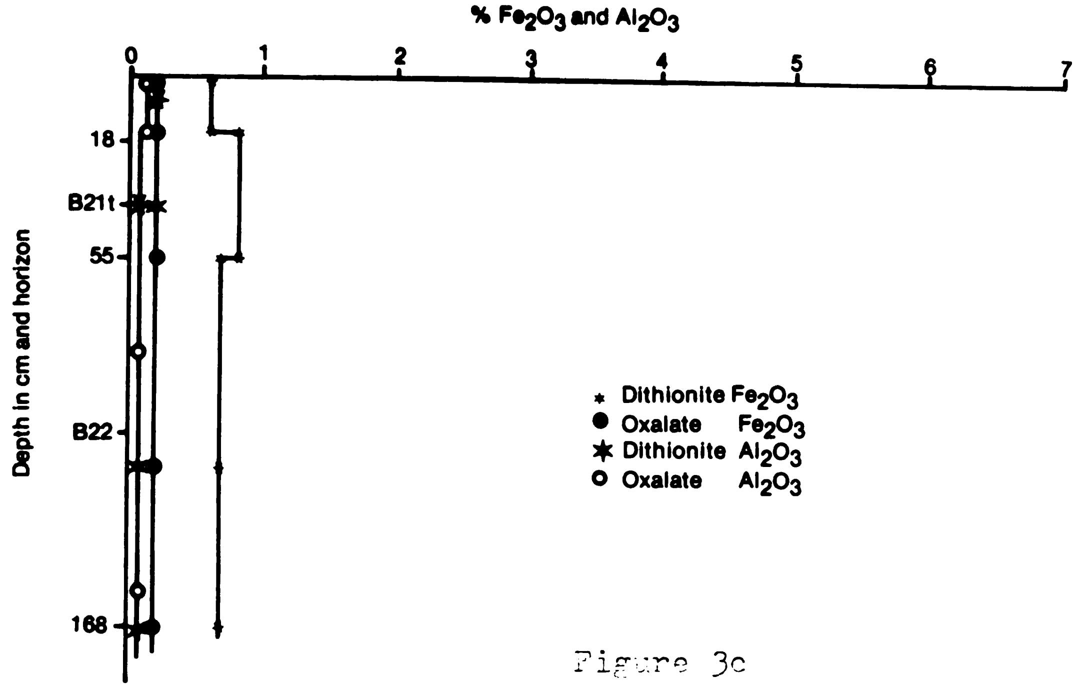


Figure 3c

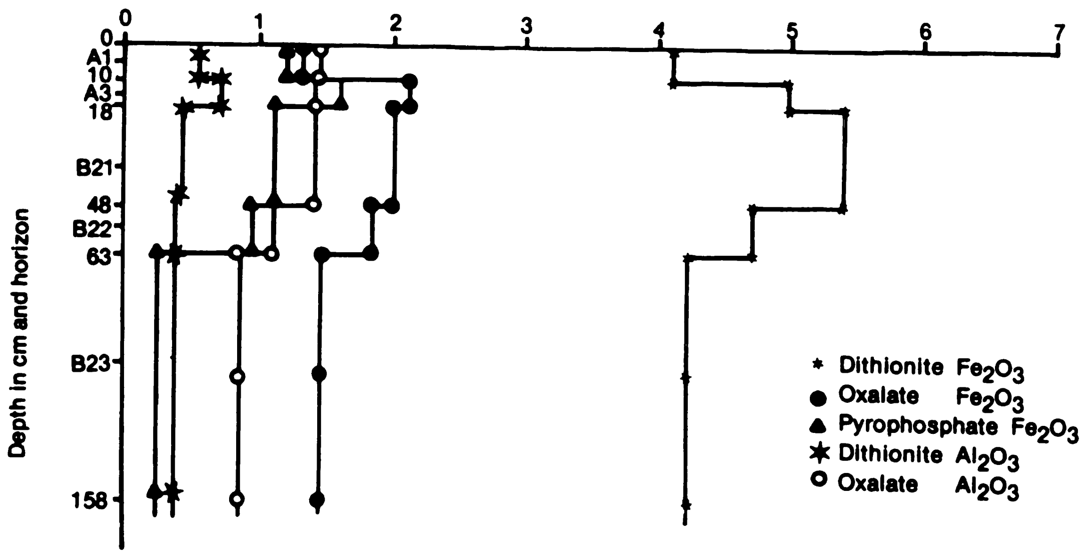


Figure 3d

Pendembu (Figure 3c) and Masuba soils of Colluvial Footslopes and Upper River Terraces have zones of Fe oxide accumulation within their profiles. The Pendembu profile has two zones of accumulation. Both these soils are on higher terraces than the soils of Alluvial Terraces and Floodplains (Figure 2). The unstable topographic positions of these soils may be responsible for the comparatively low amount of dithionite extractable Fe oxide, and the double maxima of oxides observed in the Pendembu series. The Timbo series resembles these soils more than the Segbwema or the preceding group. Total Fe increases with depth in both Pendembu and Masuba series.

The distribution of the dithionite extractable Fe oxide in the soils of Alluvial Terraces and Floodplains shows a zone of maximum within the profiles. The depth of the maximum varies slightly according to the profile, and it is the deepest and least pronounced in the Moa series. The presence of zones of maxima in the profiles suggests the movement of Fe within the profile or stratification of the materials. The maximum amounts of this form of Fe_2O_3 are similar in these soils to the amounts in the soils on the Upland Surfaces. The distribution pattern for total Fe_2O_3 is the same as the dithionite for Gbesebu and Makundu soils, but increases with depth in the Moa series.

<u>Ammonium Oxalate Extractable Fe Oxides</u>

The distribution pattern of Fe oxides extracted by this method, in the soils of the Upland Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni series), show a gradual decrease with depth in the profile. Similar trends of decrease with depth of the oxalate extractable Fe oxide are observed for soils of the

Steep Hills and Slopes (Segbwema and Timbo series). In the Segbwema profile, the distribution pattern is the same as in the case of the dithionite extractable Fe (Figure 3b). The possible reason for this trend has been discussed previously. The main difference between the distribution patterns for the two groups of soils is that the decrease in depth is less marked for soils of the Upland Surfaces.

In the soils of the Colluvial Footslopes and Upper River Tributary Terraces, decrease of oxalate extractable Fe with depth is also observed in the Pendembu series. The distribution is fairly constant in the Masuba profile.

The comparatively high surface values of the oxalate extracted Fe oxide may be explained by the extraction of some organic Fe complexes by the ammonium oxalate solution. McKeague and Day (1966) reported that ammonium oxalate solution extracts Fe and Al from amorphous inorganic substances as well as from horizons of Fe-Al organic matter complexes.

The Alluvial Terrace and Floodplain soils (Gbesebu, Moa and Makundu series) show zones of maxima, a trend similar to that of the dithionite extractable Fe oxide. The zone of maximum is less distinct in the Moa series.

Sodium Pyrophosphate (0.1M)
Extractable Fe

The distribution patterns of the Fe oxide extracted by this method for eight representative profiles are discussed. These profiles are selected from three* of the four groups of soils studied.

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*The soils of the Colluvial Footslopes and Upper River Tributary Terraces (Pendembu, Masuba) are low in Fe oxide.

In the soils of the Upland Surfaces of Highly Weathered Material, Na-pyrophosphate extractable Fe oxide decreased with depth in the Baoma series, but showed zones of maxima in the second and third horizons of the Manowa, Njala and Makeni (Figure 3a) series.

In the soils of the Steep Hills and Slopes, Na-pyrophosphate extractable Fe oxide decreased with depth in the Segbwema series (Figure 3b). A zone of maximum is observed in the Timbo series more like the Manowa, Njala and Makeni series.

The distribution pattern of the Na-pyrophosphate extractable Fe oxide in the soils of the Alluvial Terraces and Floodplains (Gbesebu and Makundu series) also shows zones of maxima in their second and third horizons, the highest values being in the second horizon (Figures 3b and 3d).

Decrease with depth of Na-pyrophoshate extractable Fe has been reported by Juo et al. (1974) in five out of six Nigerian soils studied (depth of study 110-150+cm). The soil with an accumulation in the second horizon is the Alagba/Benin series, located in an area of high rainfall. Bascomb (1968) also reported zones of higher K-pyrophosphate extractable Fe oxide in the B horizon of some soils.

One possible reason for the trend in the distribution of the Na-pyrophosphate Fe in the soils studied is that in the surface horizons the organic matter is in the less colloidal state, which is necessary for complexing the Fe compounds.

The fact that the highest value of Na-pyrophosphate extractable Fe is obtained on the surface horizon of the Segbwema profile could be explained by its topographic location. The organic matter in the surface horizon of the Baoma series may be in a more decomposed form.

The correlation between percent organic C and Na-pyrophosphate extractable Fe is low. Figure 4a is a plot of the ratio Fe_2O_3 Na-pyrophosphate/% organic C (as determined by Walkley and Black method, cited in Odell et al., 1974) with depth. A zone of maximum is evident for all of the eight representative soils studied, with the exception of the Segbwema series (Steep Hills and Slopes), which shows a gradual increase in the ratio from the B to the C horizon. The higher values of the ratio in the B horizons indicate a small relatively mobile colloidal organic matter that can carry a maximum of Fe oxide. In the surface horizons the organic matter, which is in a less colloidal state, is immobile. The small value of the ratio therefore indicates a large amount of immobile organic matter associated with a small amount of Fe oxide.

Similar trends were observed by Bascomb (1968) (Figure 4b), who worked with various kinds of soils, including a Ferritic Brown Earth. The values for organic C and Fe used in his study were those extracted by K-pyrophosphate. However, the graphs obtained in this study show a striking resemblance to those obtained by Bascomb (1968) (Figures 4a and 4b).

Total Fe Oxides

Total Fe oxides, as reported by Odell et al. (1974), is the highest in the soils of the Upland Surfaces of Highly Weathered Material, followed by the soils of the Alluvial Terraces and Floodplains. It is lowest in the soils of Colluvial Footslopes and Upper River Terraces. In soils of the Steep Hills and Slopes, total Fe is comparatively lower in the Segbwema series. The values for the Timbo series are within the same range as for soils of the Upland

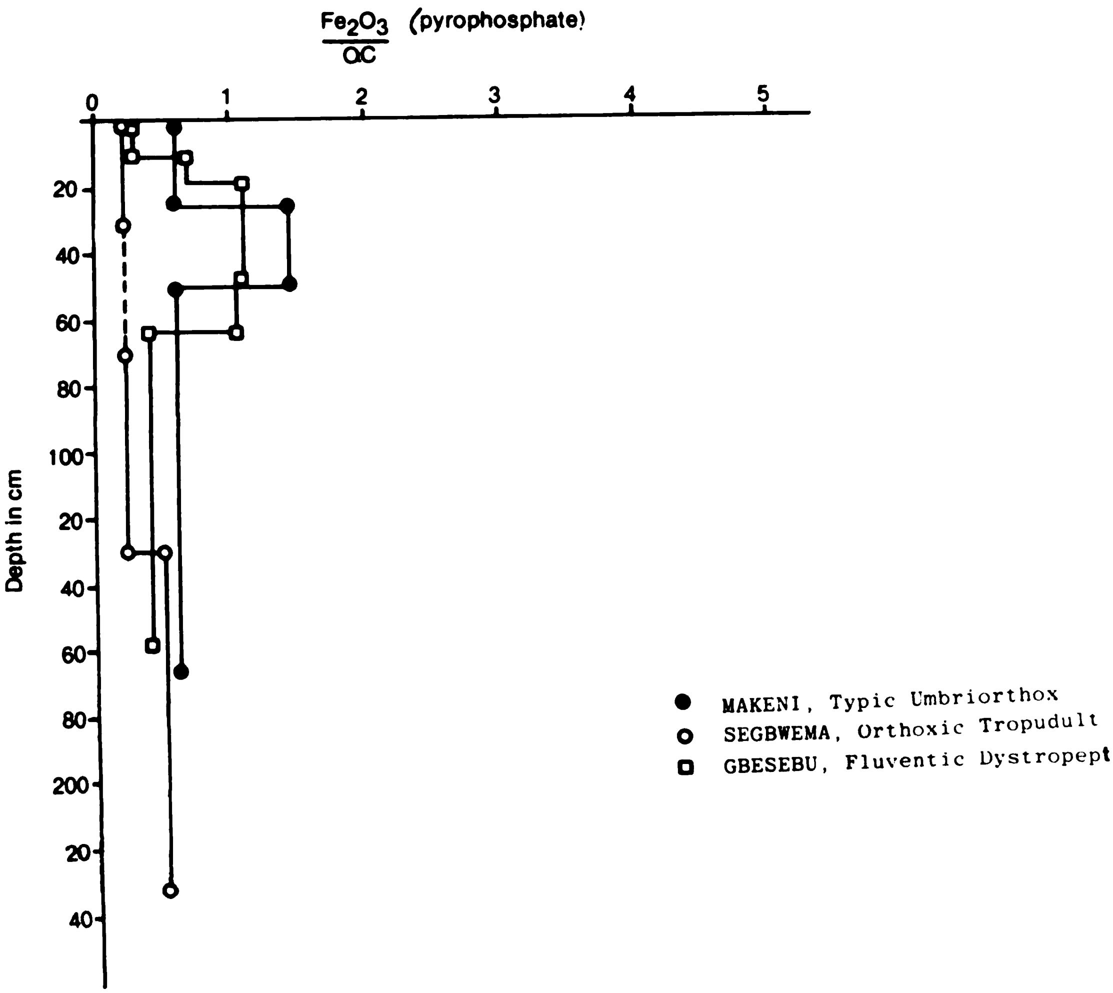

Figure 4a Ratio of pyrophosphate Fe_2O_3 to organic C. (Walkley-Black) with depth in Makeni, Segbwema and Gbesebu series.

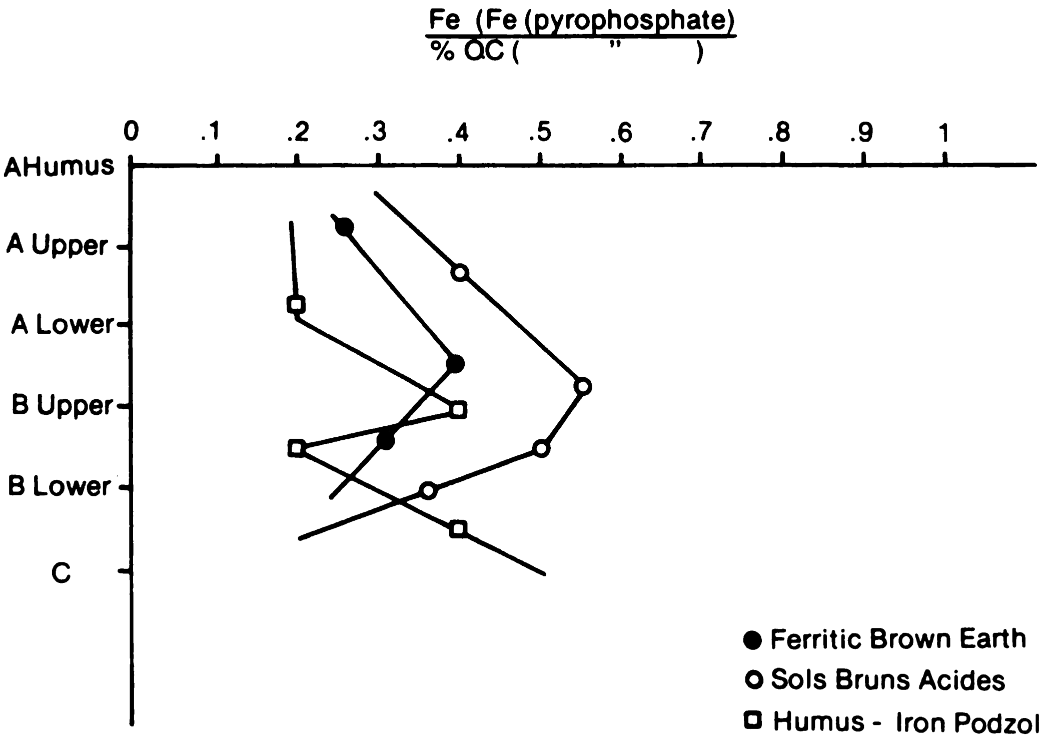

Figure 4b. Data from C. L. Bascomb (1968), showing ratio of $\frac{\text{Fe(Pyrophosphate)}}{\text{\% Organic C (Pyrophosphate)}}$ for comparison with Figure 4a.

Surfaces of Highly Weathered Material. The pattern of distribution is similar to that of the dithionite Fe, with the exception being the Segbwema series, which has a zone of maximum in the B horizon.

Amounts of Fe Oxides Removed by the Three Extractants

The amounts of free Fe oxides extracted by the three methods are highest, with dithionite-citrate-bicarbonate solution as the extractant.

This extractant has been shown to extract both crystalline and amorphous oxides by some workers (Blume and Schwertmann, 1969; McKeague and Day, 1966; Mehra and Jackson, 1960). The sum of the dithionite and oxalate extractable Fe oxide is the lowest in the soils of the Colluvial Footslopes (which are also lowest in total Fe); the highest values are obtained in the soils of the Alluvial Terraces and Floodplains.

In the soils of the Upland Surfaces of Highly Weathered Materials (the Manowa, Njala and Makeni series), Na-pyrophosphate extractable Fe oxide is usually higher than that of the acid ammonium oxalate extracted Fe oxides. The Baoma series, however, has higher values of Na-pyrophosphate Fe in its surface horizon than oxalate Fe. The trend reverses in the lower part of the profile, with a sharp decrease in the Na-pyrophosphate Fe. This change is above the control section for this soil.

In the soils of the Steep Hills and Slopes, oxalate extractable Fe oxide is consistently higher than Na-pyrophosphate Fe in the Segbwema series, as opposed to the Timbo series, in which Na-pyrophosphate extractable Fe oxide is usually higher than that of the acid ammonium oxalate extracted Fe oxide.

Both the Gbesebu and Makundu soils of the Alluvial Terraces and Floodplains have comparatively high values of oxalate extractable Fe oxide. This form of Fe oxide is consistently higher than Na-pyrophosphate extractable Fe in the Gbesebu series. Higher values of Na-pyrophosphate Fe are in the top three horizons of the Makundu series. The trend reverses in the lower part of the profile, with a sharp decrease in the Na-pyrophosphate Fe.

The higher values of Na-pyrophosphate Fe obtained in the Manowa, Njala, Makeni and Timbo series is in disagreement with results obtained by McKeague (1967) working with temperate soils, and Juo et al. (1974), who worked with some Nigerian soils. McKeague (1967) observed higher amounts of oxalate extracted Fe oxide than that extracted by Na-pyrophosphate. Juo et al. (1974) observed a similar trend for five of the six upland soils that they studied. In the Nkpologu/Nsukka series, the amount of Na-pyrophosphate Fe oxide was slightly higher than that of the oxalate Fe oxide throughout the profile. They suggested the presence of a moderate amount of gel-form (Fe-hydrous oxide) as the reason for the result which they obtained. This idea was supported by the studies of Bascomb (1968). While this may be true in the case of the upland soils they studied, it is also likely that some other factors are involved. High temperatures and a prolonged dry period have been shown to dehydrate amorphous Fe and Al and subsequently shift it to a system of greater crystallinity (Sherman et al., 1953).

It is believed that this is a contributing factor to the low amounts of oxalate Fe (amorphous Fe) extracted from the above-mentioned soils, as compared to the Na-pyrophosphate Fe.

The Manowa, Njala and Timbo soils, which experience a prolonged dry season of about 6* months, have been cultivated intermittently, and thus have had less continuous vegetative cover. The Baoma series, on the other hand (Plate 1b), has been under prolonged cultivation of cocoa and coffee trees (grown under shade) and thus have a much more moist surface over a longer period than the other profiles mentioned. It is also less gravelly. This local variation in moisture regime may explain the unusually high amorphous Fe oxide recorded for this soil. (However, all these soils have higher Na-pyrophosphate Fe than oxalate Fe contents in the A and upper B horizons.)

A moisture study conducted on the Njala, Makeni and Timbo soils for a period of about two years (van Vuure and Miediema, 1972) showed these soils to have less than 10% total moisture between January and early April. These soils also have a drought period of 4 to 5 months (Table 1), which tends to support the above explanation of the lower oxalate Fe than dithionite Fe.

The comparatively higher values of the oxalate Fe in the Baoma, Segbwema, Gbesebu and Makundu series are a possible reflection of both moisture regimes and degrees of development.

The ratio of oxalate Fe/dithionite Fe, the active Fe ratio, decreases with depth in the soils of the Upland Surfaces of the Highly Weathered Material (Baoma, Manowa, Njala and Makeni series). In the soils of the Steep Slopes and Hills, the ratio is fairly constant in the Segbwema series, but decreases with depth in the Timbo series. A decrease with depth of the ratio is observed in the

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*Duration of dry season. Soil is usually moist 1-2 months after the beginning of the dry season.

Pendembu series, while the ratio remains fairly constant in the Masuba series, both of which are soils of the Colluvial Footslopes and Upper River Tributary Terraces. In the soils of the Alluvial Terraces and Floodplains, the ratio shows zones of maxima in the Gbesebu and Makundu series. A decrease of the ratio with depth is observed in the Moa series.

The decrease in the ratio with increasing depth in the profiles clearly shows that higher proportions of crystalline Fe oxides are present in the lower horizons of the profiles.

In the Segbwema, Masuba, Gbesebu and Makundu profiles, the highest proportions of crystalline Fe oxides are in the upper parts of the profile.

Some workers (Alexander, 1974; McKeague and Day, 1966; McKeague et al., 1971; Juo et al., 1974) have used the active Fe ratio to indicate the degree of profile development or age trends in landscapes. The latter authors worked with tropical soils and the other three with temperate soils. McKeague and Day (1966) and McKeague et al. (1971) reported active Fe ratio of 30-60% for the soils they worked with, and Juo et al. (1974) reported values of about 8% for upland Nigerian soils. Alexander (1974) obtained a much higher ratio for lower terrace soils than for the older terrace soils which he studied. The range of active Fe ratios in the soils studied here is 0.07-0.42 (7-42%) for the upper B horizon. The lowest values, 0.07-0.17, are obtained for Manowa, Njala, Makeni (soil of Upland Surfaces of Highly Weathered Material) and the Timbo series of the Steep Hills and Slopes. The Baoma series, also of the soils of Upland Surfaces of Highly Weathered Material, has a ratio within the range of 0.21-0.27, which also includes the Pendembu and Masuba series (both of which are soils of the Colluvial Footslopes and Upper River Tributary Terraces, with low free and total Fe_2O_3).

From the foregoing discussion, the distribution pattern of the dithionite extractable Fe oxide appears to be useful in distinguishing the soils studied in relation to geomorphic surfaces. The ratio Fe_2O_3ox/Fe_2O_3d also appears to be useful in determining the degree of profile development.

Amounts of Dithionite, Oxalate and Na-Pyrophosphate Al

Data for aluminum oxides extracted by all three methods are given in Table 4. Figure 3 includes a plot of Al with depth for selected profiles. There is a general slight decrease with depth of Al oxide extracted by dithionite in ten of the eleven profiles studied. The Moa series, however, shows an increase with depth of dithionite Al oxide. Both decrease with depth and zones of Al maxima are observed in the profiles when ammonium oxalate is the extractant. The Makeni, Timbo and Makundu soils have the most prominent zones of Al oxide maxima.

Na-pyrophosphate soluble Al oxide was determined for five profiles. Both the Njala and Makeni profiles (soils of Upland Surfaces of Highly Weathered Material) have zones of maxima of Na-pyrophosphate Al, a trend similar to that of Na-pyrophosphate extractable Fe oxide. The Segbwema (soils of the Steep Hills and Slopes), Gbesebu and Makundu (soils of Alluvial Terraces and Floodplains) profiles show decreases with depth of Na-pyrophosphate

Al. The values of Na-pyrophosphate Al for the Segbwema profile are very low. The similarity in the distribution patterns of Na-pyrophosphate Al/% OC and Fe/% OC in the five profiles suggests that the Al and Fe are moved by the same organic matter colloidal fraction in these profiles.

The amounts of Al extracted by each of the three extractants show no consistent trend among the extractants. In the Njala, Makeni and Gbesebu series, ammonium oxalate extracted more Al than the dithionite solution throughout the profile. In the Baoma, Manowa, Segbwema, Moa and Makundu series, dithionite extractable Al is consistently higher than that extracted by ammonium oxalate. In the remaining three profiles the trend is less clear. Similar trends have been reported by other workers (Juo et al., 1974; McKeague and Day, 1966).

In the soils of Upland Surfaces of Highly Weathered Material, Njala and Makeni, Na-pyrophosphate Al is the predominant form of Al oxide in the A and upper B horizons. In the soils of the Alluvial Terraces and Floodplains, Al oxide forms are more varied.

The lack of consistency in the trend of the amounts of Al extracted by the different extractants makes interpretation of the results difficult, especially in distinguishing the forms of the Al oxides. This is particularly true for the oxalate and dithionite extractants.

Significance of the Study on Fe and Al Oxides

The oxides of Fe and Al are two of the major components of soils in the humid tropics. Their roles in the chemical and physical behavior of these soils include fixation of plant nutrients, influence on adsorption surface behavior, and influence on the aggregate stability (Kellerman and Isyurupa, 1966).

It was, therefore, thought that a study of these oxides could be important in understanding the genesis and properties of these soils and in their classification. In temperate regions some researchers have used the oxides and hydroxides of Fe and Al to identify diagnostic horizons, e.g., the spodic horizon; to separate some great soils groups (Franzmeier et al., 1965; McKeague and Day, 1966); and to estimate soil age (degree of development) along a toposequence (Alexander, 1974). Karmanova (1975) showed that some ratios of different forms of Fe oxides together with their distribution in the profile can serve as diagnostic criteria of the group and subgroup characteristics of some soils in the USSR.

In this study the distribution of various forms of extractable Fe oxides have been discussed. The distribution of the dithionite extractable Fe oxides has been shown to be more important than that of the other forms of extractable Fe, although the oxalate extractable Fe oxide seems to show Fe-movement within the profile. This is especially so in soils of the Alluvial Terrace and Floodplains, as well as those of the Colluvial Footslopes and Upper River Terraces. The distribution pattern of the dithionite extracted Fe oxide separates the young soils from the older soils (increase with depth in the older soils vs. concentration zones in the younger soils), but does not appear to separate an Oxisol from an Inceptisol or Ultisol.

The active Fe ratio Fe_2O_3ox/Fe_2O_3d* tends to indicate the degree of soil development, and may have a potential for separating the Oxisols from the younger soils, Inceptisols and Ultisols. However, its use may become limited by the fact that high temperatures and prolonged drying causes the amorphous oxides to dehydrate and shift to a system of greater crystallinity (Sherman and Alexander, 1959). This will have a reducing effect on the ratio and hence on any limits that may be set on this ratio.

Prolonged dry periods and high temperatures are common in Sierra Leone, where the dry season is about six months, and soil temperature during this period is over 21°C. Under the same environmental conditions a soil under prolonged vegetative cover will have less dehydrating effect on the oxides than a soil that is under continuous cultivation or subject to short fallow periods.

Several ratios are tested here. Table 4 contains some of them. The remainder are included in Appendix C. Among those studied are the Fe_{sil} values (silicate Fe) of Karmanova (1975). He considered the Fe_{sil} value to be equal to the difference between total Fe oxides and dithionite extractable Fe ($Fe_{sil} = Fe_t - Fe_d$). The results obtained in this study show no significant trends that can be used in separating these soils.

The ratios of different extractable Fe oxides and percent clay are also examined for their usefulness in separating the soils studied (Table 4). The most useful values among those examined are the Fe_2O_3d/clay, the $Fe_2O_3d-Fe_2O_3ox$/clay, and Fe_2O_3ox/clay.

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*ox = oxalate; d = dithionite, t = total.

These ratios are fairly constant with each profile, suggesting a possible co-migration of clay and the Fe oxides. This would indicate a mechanical migration of small mineral particles from the A to the B horizons of the soils, a process known as lessivage.

The most common values of the ratio of dithionite extractable Fe to percent clay in the literature (Soil Survey Staff, 1975) is 0.10 or more for highly weathered stable upland soils. This value is obtained when percent clay is that from which free Fe oxides have not been removed.

Values of 0.10 or more are obtained for the Baoma, Manowa, and Timbo series when Fe oxide was not removed from the clay fraction. These are soils that have been shown to have oxic horizons, by thin section (see section on "Micromorphology") and chemical analyses discussed earlier. The remainder of the profiles have values of less than 0.10. Three of these previously have been shown to have argillic or cambic horizons within the control section. When the ratio is calculated, with percent clay equal to that when free Fe oxide has been removed, the ratio decreases to 0.09 and the division is not so clearcut. Even Segbwema would then qualify.

The ratio of the difference between dithionite extractable and oxalate extractable Fe oxide (Table 4) relative to that of percent clay (with Fe removed) seems to have some promise in separating the soils studied. The mean ratio for the eleven profiles is 0.059 (0.06). If a critical value of 0.06 or more in the B horizon is used as one of the diagnostic properties of an oxic horizon in the soils studied, then Baoma, Manowa, Njala, Makeni, Timbo and Moa series will have this criterion on an oxic horizon, in their upper

B horizons, and the Segbwema, Pendembu, Masuba, Gbesebu and Makundu series would have non-oxic upper B horizons by this criterion. This division seems to support previous observations of argillic or cambic horizons in the Segbwema, Masuba and Gbesebu series, and oxic horizons for the Baoma, Manowa, Makeni, and Timbo series. This separation appears to be superior to that of the ratio of the sum of the exchangeable bases plus exchangeable Al, relative to percent clay for the soils studied.

The difference between dithionite extractable Fe and that of ammonium oxalate represents the crystalline form of Fe oxide (Karmanova, 1975; McKeague and Day, 1966). This is a more stable component in the older soils, where the distribution of oxalate extractable Fe is fairly constant throughout the profiles (except as affected by vegetative cover).

The ratio shows a general gradual increase with depth for soils with values of 0.06 or more and an irregular or a definite decrease with depth in soils with values less than 0.06, the Makundu soil representing a borderline situation.

Ratios of dithionite Al to that of percent clay are also included in Table 4. The ratio is constant for the Baoma, Manowa, Makeni and Timbo series, suggesting also a co-migration of Al and clay (Juo et al., 1974). They have ratios of 0.03 or more in the upper B horizon (except Makeni). In the soils of the Alluvial Terraces and Floodplains and the Colluvial Footslopes and Tributary Terraces (except Moa) there is a definite decrease with depth in the ratio and all are 0.02 or below. The Segbwema soil shows increases and decreases with depth, with and without the removal of Fe oxides from the clay.

Phosphorus Adsorption

Justification for these studies is: (a) to determine P adsorption isotherms for these soils since such data were not available; (b) to relate the amount of P adsorbed to other soil parameters already studied and evaluate their practical significance; (c) to study P adsorption on ironstone gravels (a major constituent of some of the soils studied) and to evaluate their practical significance.

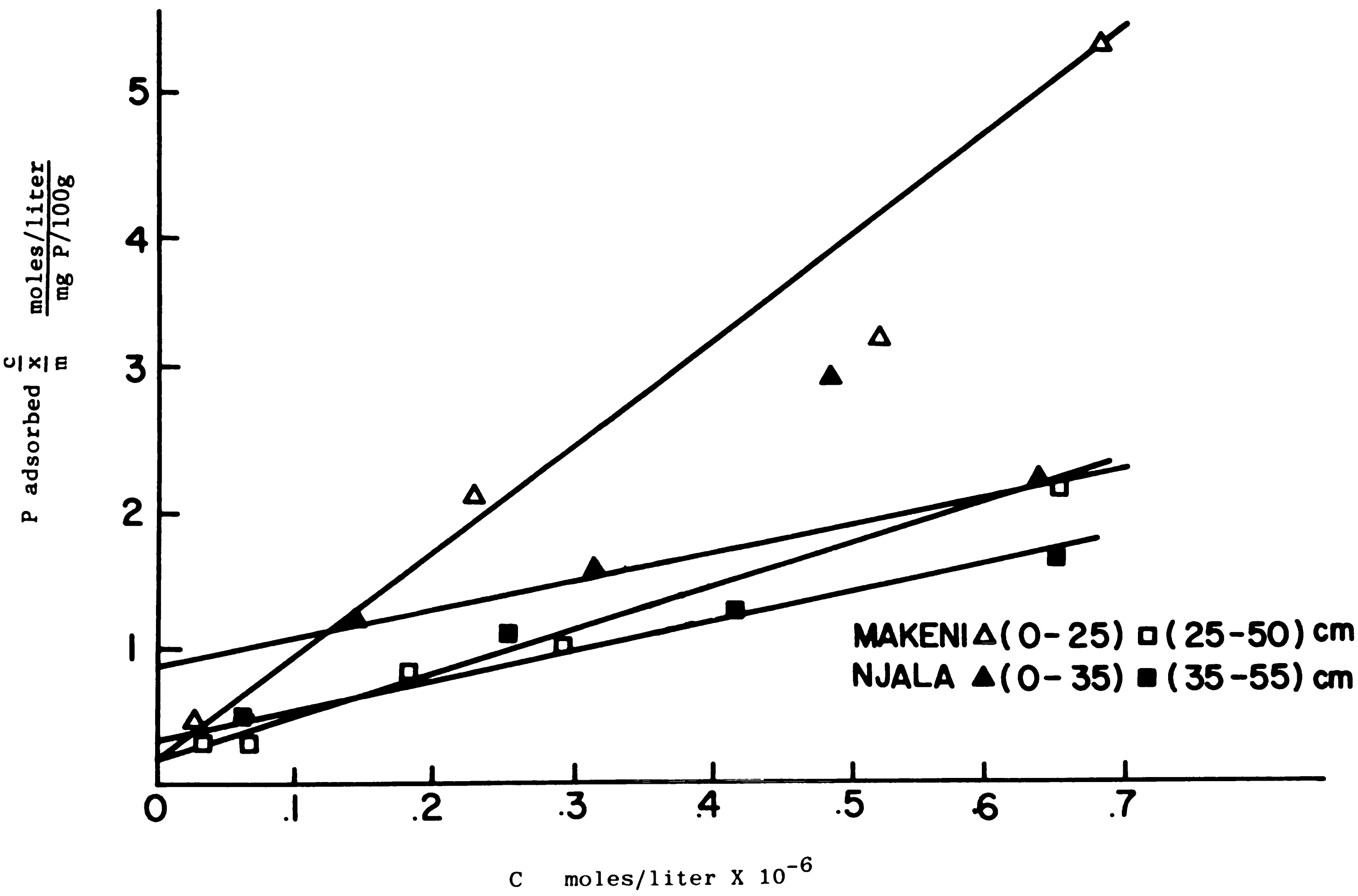
Adsorption studies were conducted on the A and upper B horizons of the Makeni, Segbwema, Masuba and Gbesebu series, representing the four physiographic units (Table 1 and Figure 2) and on the ironstone gravels of the surface and subsurface horizons of the Njala and Makeni series. The latter two profiles represent the gravelly soils and also the major types of ironstone gravels recognized in this study (see section on "Micromorphology").

Phosphorus Adsorption on Ironstone Gravels

Figure 5 shows plots of Langmuir adsorption isotherms for the surface and subsurface gravels of the Njala and Makeni series. Two main shaking times were employed for the gravels, 24 hrs and 48 hrs. The shaking was done on a rotating shaker at a maximum speed of 150 rpm. Higher rotation speeds caused the ironstone to slake, and so also did shaking with a reciprocating shaker. The percentage losses in weight of the ironstone gravels after shaking in distilled water for 6 hrs, with a reciprocating shaker, are given in Table 5.

After 24 hours shaking the adsorption maxima for the subsurface gravels of the two profiles are higher than those of the surface

Figure 5a. P adsorption isotherms, Makeni and Njala gravels; first 24 hr shaking.



P adsorbed c/(x/m) moles/liter / mg P/100g
5
4
3
2
1
0
.1
.2
.3
.4
.5
.6
.7
MAKENI △(0-25) □(25-50) cm
NJALA ▲(0-35) ■(35-55) cm
C moles/liter X 10^-6

Figure 5a

Figure 5b. P adsorption isotherms, Makeni and Njala gravels; 48 hr shaking.

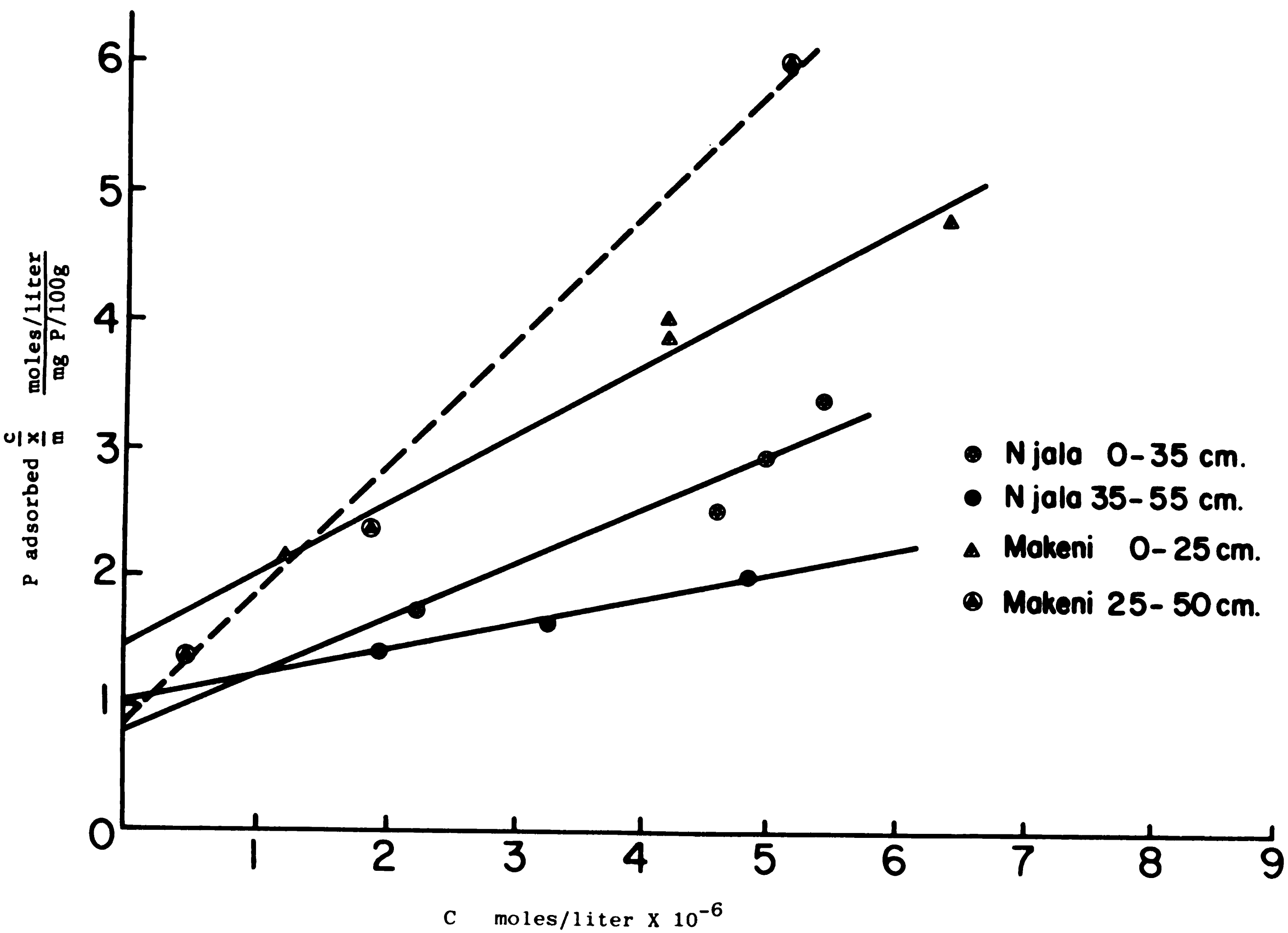
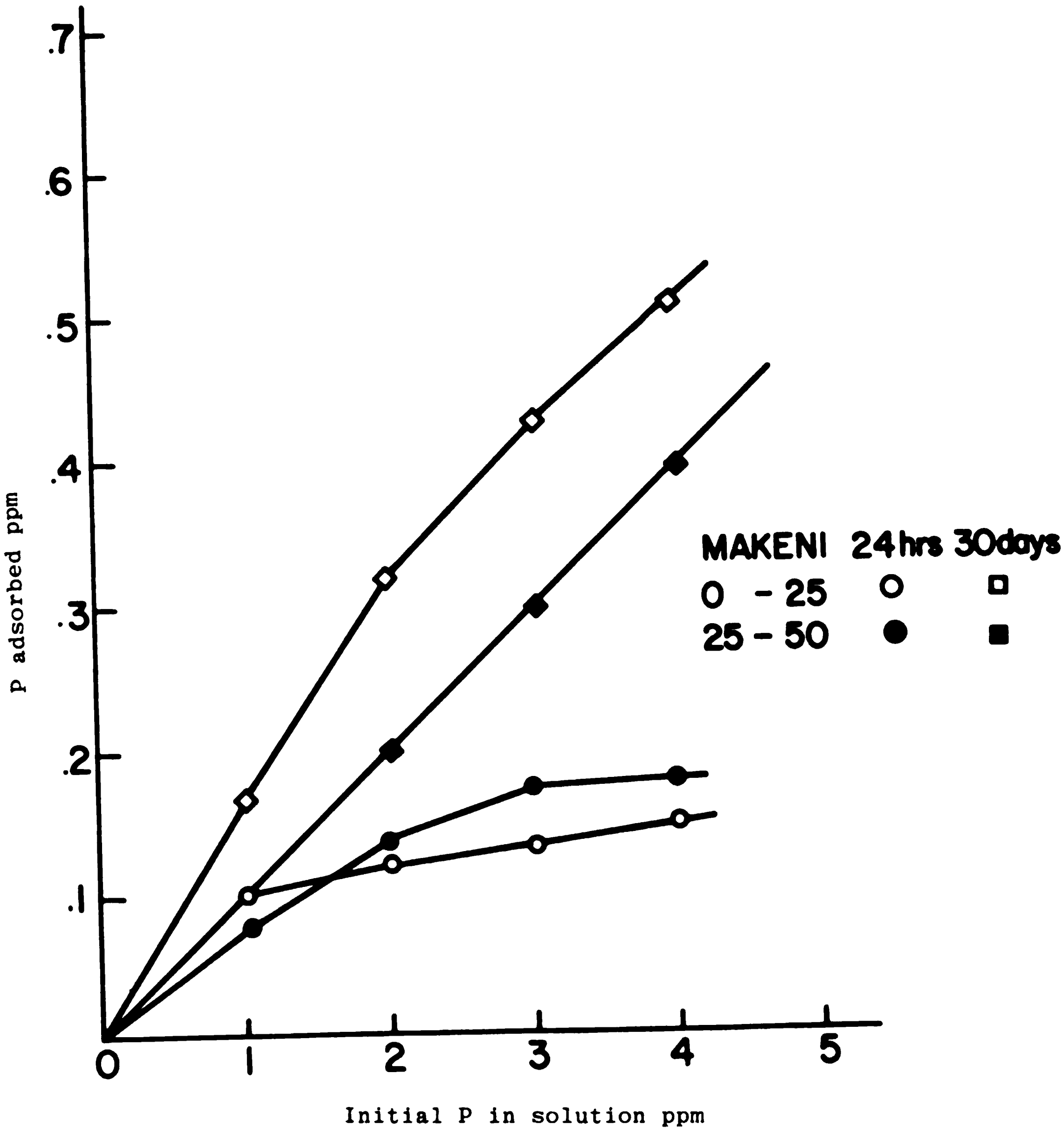

P adsorbed $\frac{C}{x/m}$ $\frac{\text{moles/liter}}{\text{mg P/100g}}$
0
1
2
3
4
5
6
7
8
9
C moles/liter X 10^{-6}
N jala 0-35 cm.
N jala 35-55 cm.
Makeni 0-25 cm.
Makeni 25-50 cm.

Figure 5b

Figure 5c. A plot of initial P concentration vs. P adsorbed by Makeni gravels, after second 24 hr shaking and 30 days equilibration.



.7
.6
.5
.4
.3
.2
.1
P adsorbed ppm
0
1
2
3
4
5
MAKENI 24hrs 30days
0 - 25
25 - 50
Initial P in solution ppm

Figure 5c

Figure 5d. P adsorption isotherms of Makeni gravels; second 24 hr shaking, followed by 30 days equilibration of the surface gravels.

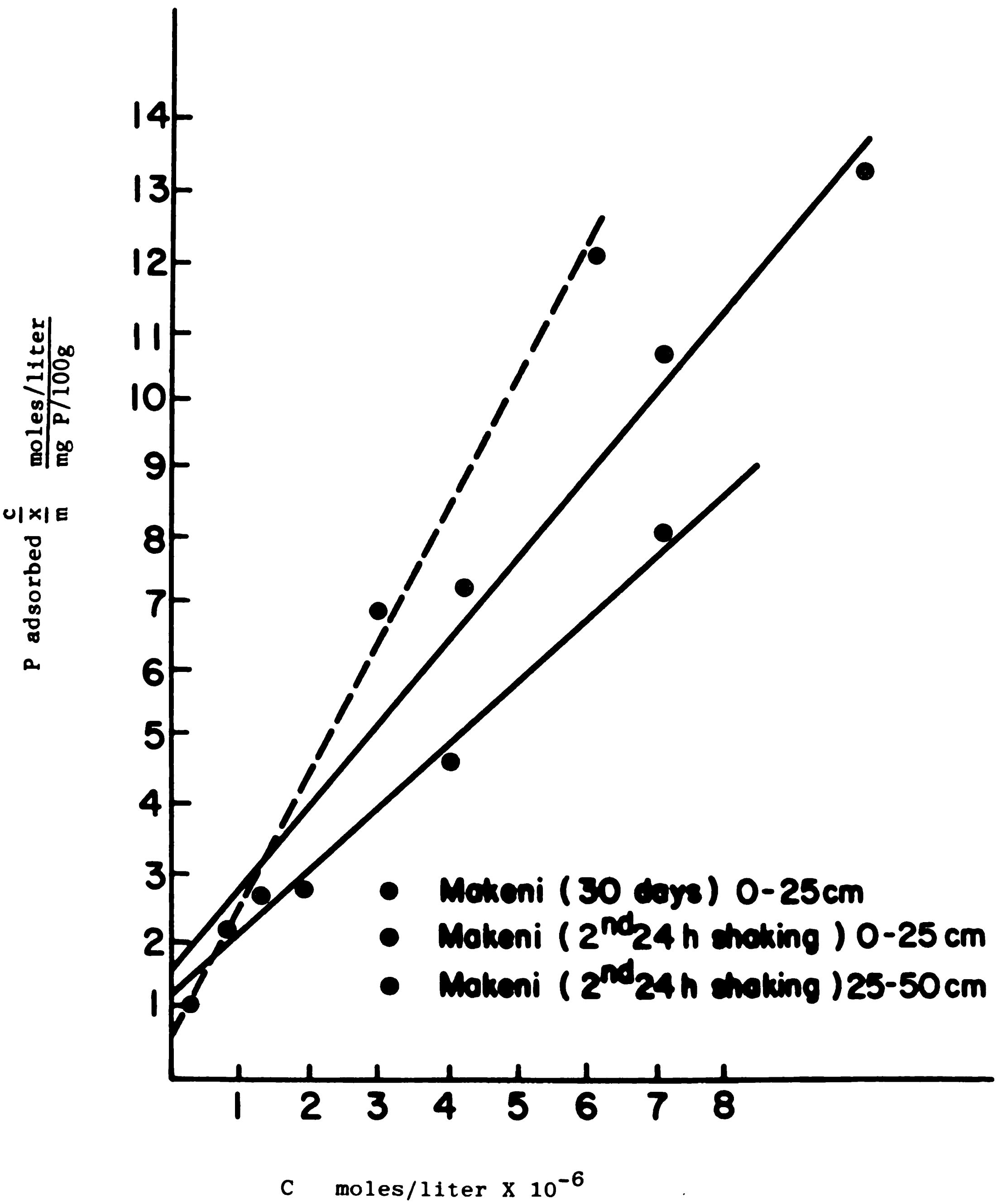

P adsorbed $\frac{c}{x/m}$ $\frac{\text{moles/liter}}{\text{mg P/100g}}$
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
Makeni (30 days) 0-25cm
Makeni (2nd 24 h shaking) 0-25 cm
Makeni (2nd 24 h shaking) 25-50 cm
C moles/liter X 10^{-6}

Figure 5d

Table 5. Loss in weight of gravels with 6 hours shaking in distilled water

Soil Series (gravels)	Initial Weight gms	Weight after 6 hours shaking gms	% Weight Loss
Njala 0-35cm	10.00	9.89	1.1
Njala 35-55cm	10.00	9.91	0.9
Makeni 0-25cm	10.00	9.81	1.9
Makeni 25-50cm	10.00	9.89	1.1

horizons (Table 6 and Figure 5). The adsorption maxima increased for both surface and subsurface horizons after 48 hours shaking.

In general, the subsurface gravels adsorbed slightly more P than the surface ones. This is particularly true for the 24 hr shaking and the 48 hr shaking of the Njala series (Table 6A). The subsurface gravels are less rounded (Westerveld, 1969) and have more loose Fe oxide coatings on the surface than the surface gravels (see section on Micromorphology). The more rounded nature of the surface gravels is possibly due to their solution* rather than transportation, as has been suggested by other authors (Odell et al., 1974; Westerveld, 1969).

The Njala gravels have higher adsorption maxima than those of the Makeni profile (Table 6A). Thin sections of the Njala gravels (Plate 6) reveal a concentration of Fe oxide as distinct bands on

*Detailed discussion under Micromorphology.

Table 6A. Adsorption maxima for Makeni and Njala gravels

Soil Series	1st 24 hr shaking		48 hr shaking		2nd 24 hr shaking		30 days	
	Surface	Subsurface	Surface	Subsurface	Surface	Subsurface	Surface	Subsurface
Njala	22mgP/kg	24mgP/kg	24mgP/kg	50mgP/kg	---	---	---	---
Makeni	14mgP/kg	17mgP/kg	38mgP/kg	21mgP/kg	8mgP/kg	9mgP/kg	27mgP/kg	

Table 6B. Adsorption maxima for fine-earth of A and upper B horizons of 4 soil series after 24 hrs shaking

Soil Series	A horizon	Upper B horizon
Makeni	1077mgP/kg	807mgP/kg
Segbwema	671mgP/kg	483mgP/kg
Masuba	434mgP/kg	552mgP/kg
Gbesebu	1217mgP/kg	1076mgP/kg

Table 6C. Linear correlation coefficients between P adsorption maxima of fine-earth fractions in Table 6B and percent organic C, exchangeable Al, or extractable Fe and/or Al oxides

Horizon	% O.C.	Exch. Al	Fe_2O_3d	Fe_2O_3ox	Fe_2O_3ox+ Al_2O_3ox	Fe_2O_3pp	Al_2O_3d	Al_2O_3ox	Al_2O_3pp	Fe_2O_3d- Fe_2O_3ox
Surface	.9918*	.3825	0.3402	-0.1865	.8110††	0.6915	-0.19837	0.8354††	0.5532	0.6184
Subsurface	.5715	.8541††	0.8608††	0.6812	.7544	0.4431	-0.1117	0.63828	0.1051	0.8137††
Surface + Subsurface	.7559**	.4662	0.5086††	0.5389††	.6988†	0.5088††	-0.1354	0.6266†	0.3417	0.6116††

*Significant at 1% level

**Significant at 5% level

†Significant at 10% level

††Significant at 20% level

the surfaces of these gravels, a pattern that is not observed in the Makeni gravels.

The Makeni gravels that were shaken for 24 hrs were washed several times with distilled water to remove water soluble P, and also to remove loose soil particles on the surface which may have been responsible for the adsorption of P. The washed samples were then shaken with P solutions containing 1-5ppm P for another 24 hrs (second 24 hrs). The P adsorbed after this treatment was determined, and the gravels were then allowed to equilibrate in the solutions for a further 30 days.

Figures 5c and 5d are plots of P adsorbed in relation to the initial P concentration in solution, and the Langmuir adsorption isotherms of Makeni gravels, respectively, with the above treatments. The P adsorption maxima after the 24 hour treatment are 8mgP/kg and 9.0mgP/kg for the surface and subsurface horizon gravels, respectively (Table 6A). These values may represent the amount of water soluble P that was originally adsorbed by these gravels. After the 30 days equilibrium the amount of P adsorbed per gram of gravel (Figure 5c) is much higher than that of the 24 hour shaking The maximum adsorption of the surface horizon increased to 27mgP/kg. This value may not represent only adsorption on the surface of the gravels, but possibly also P that diffused into the gravels.

The mechanism of adsorption on the gravel is not clear. The sizes of the gravels vary and only a small surface, compared to the weight of the gravels, is being presented for adsorption. This may explain the reason for the low adsorption values calculated, with respect to those of the fine-earth fractions (Table 6B), where a higher proportion of surface is exposed for the reaction, with respect to weight.

An important observation in this study is that the surface of the gravel is active with respect to P fixation. But, compared to the fine-earth fractions, they adsorb very little P. Thus, the gravels influence the amount of P that is actually fixed by the whole soil mainly by a dilution effect. Using the Makeni series as an example, the amount of P that can be fixed by the <2mm fraction per hectare of the surface soil is 5325 kg/hec, as compared to 203 kg/hec by the surface gravels (using 48 hr adsorption), assuming the surface is composed of only one fraction. However, the gravels account for 70% by weight of the surface soil and the <2mm fractions for 30% by weight. Based on these figures, the actual amounts of P that will be fixed by the fine-earth fraction in the surface soil is 1597kg/hec and 142kg/hec by the gravels. This gives a maximum fixation value of the whole surface soil of 1740kg/hec. The gravels in this case account for 8.2% of the amount of total P fixed in the surface horizon. In the subsurface horizon, 7.5% of the total P (1109kg/hec) that can be fixed by the soil is accounted for by the subsurface gravels (76% by weight).

This observation is very important if P fertilizer application is based on the P behavior of the fine-earth fraction, as otherwise more P will be applied than required. Also, it should be noted that the gravels perform a dual role in the soil, i.e., they dilute the amount of P fixed by the whole soil samples, and also contribute to P fixation.

Phosphorus Adsorption on the Fine-Earth (<2mm) Fractions

Figures 6a, 6b and 6c are plots of Langmuir adsorption isotherms for the fine-earth (<2mm) fractions of four soil series. Table 6B

Figure 6a. P adsorption isotherms, Makeni and Gbesebu series surface and subsurface horizons, fine-earth fractions.

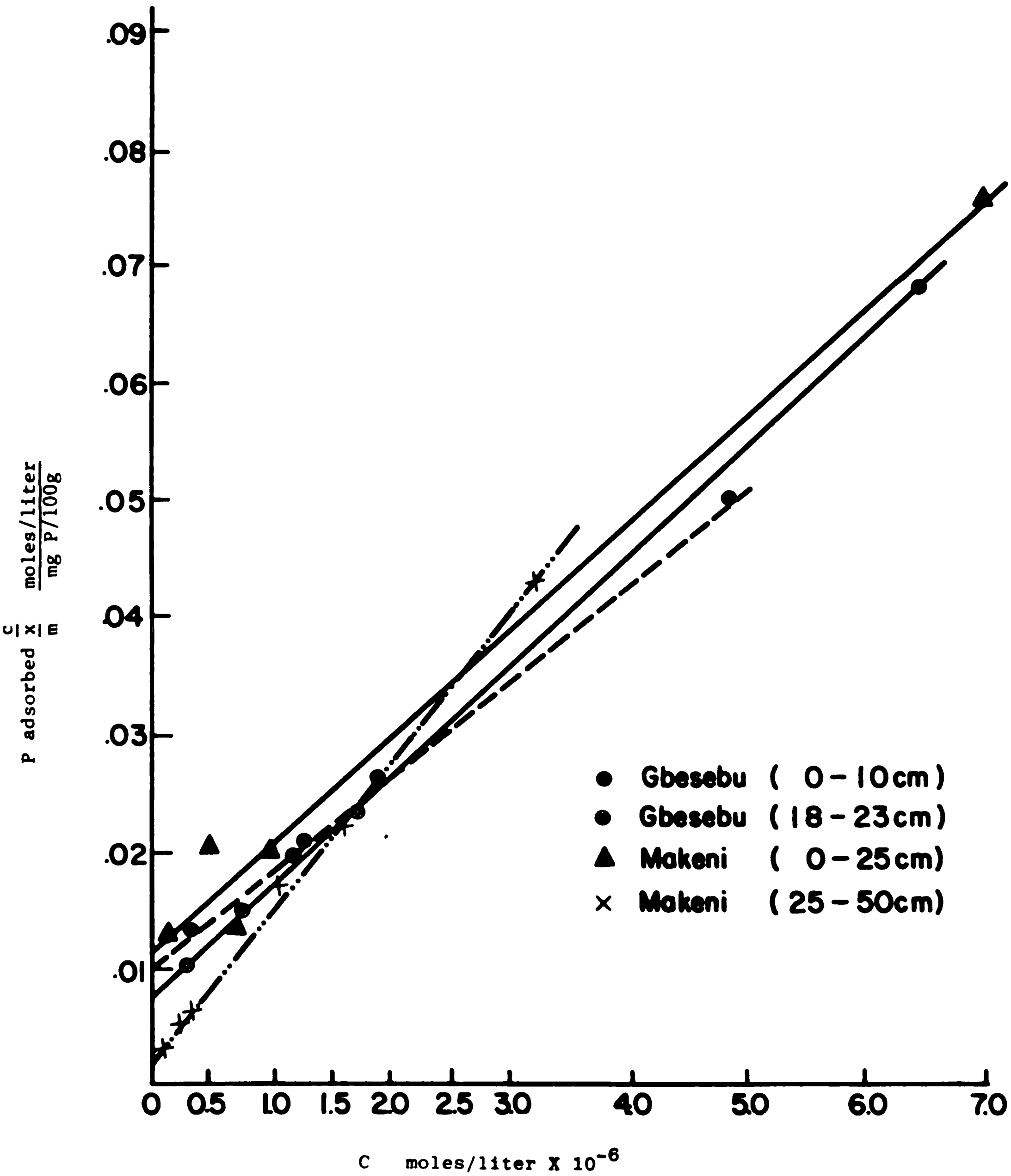
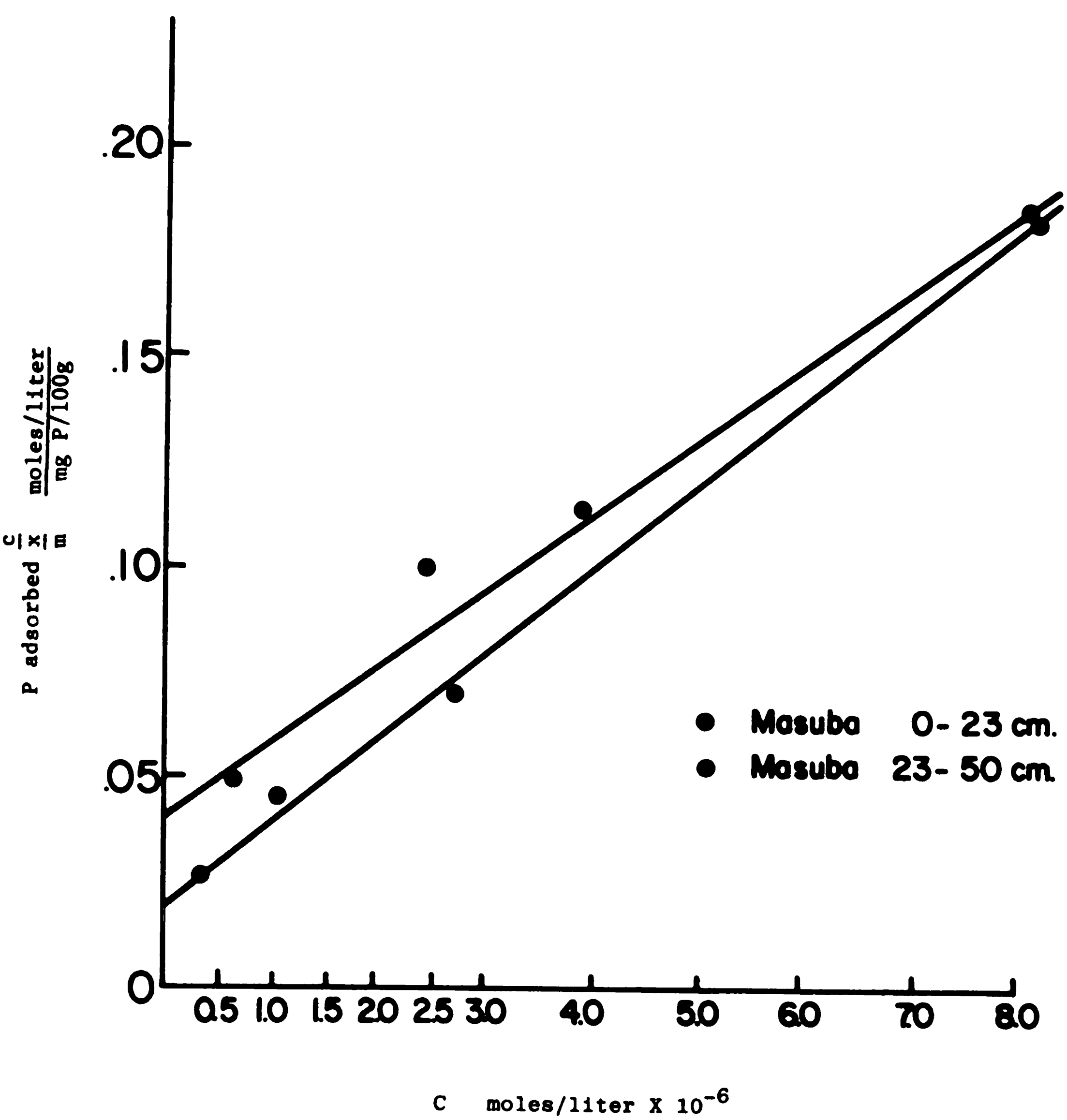

.09
.08
.07
.06
.05
.04
.03
.02
.01
P adsorbed c/(x/m) moles/liter / mg P/100g
0
0.5
1.0
1.5
2.0
2.5
3.0
4.0
5.0
6.0
7.0
C moles/liter X 10^-6
● Gbesebu (0-10cm)
● Gbesebu (18-23cm)
▲ Makeni (0-25cm)
× Makeni (25-50cm)

Figure 6a

Figure 6b. P adsorption isotherms, Masuba series, surface and subsurface horizons, fine-earth fractions.



P adsorbed $\frac{C}{\frac{x}{m}}$ $\frac{\text{moles/liter}}{\text{mg P/100g}}$
.20
.15
.10
.05
0
0.5 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 7.0 8.0
Masuba 0- 23 cm.
Masuba 23- 50 cm.
C moles/liter X 10^{-6}

Figure 6b

Figure 6c. P adsorption isotherms of Segbwema series, surface and subsurface horizons, fine-earth fraction.

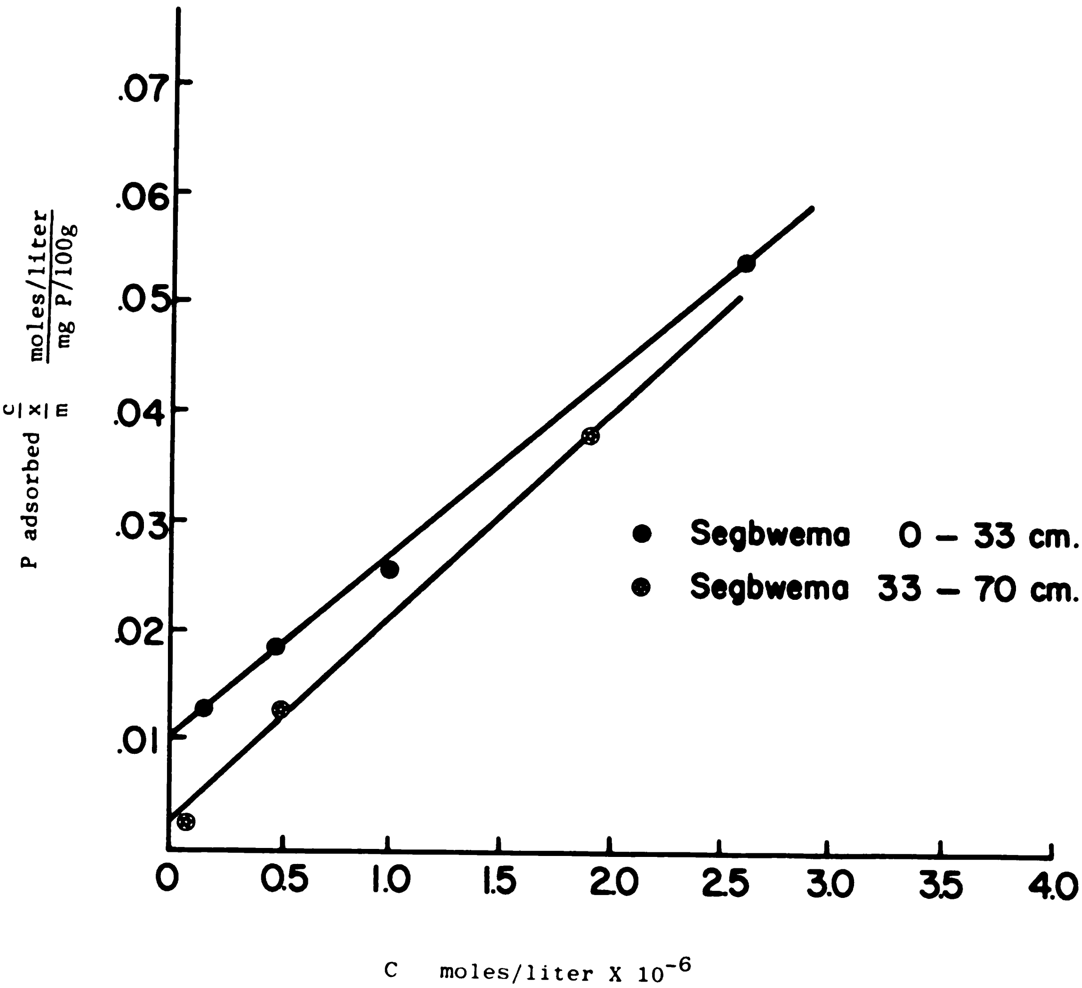

.07
.06
.05
.04
.03
.02
.01
P adsorbed $\frac{c}{x/m}$ $\frac{\text{moles/liter}}{\text{mg P/100g}}$
Segbwema 0 – 33 cm.
Segbwema 33 – 70 cm.
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
C moles/liter X 10^{-6}

Figure 6c

contains values of the adsorption maxima for these soils. The surface horizons (A) of the Makeni, Segbwema and Gbesebu series have higher adsorption maxima than the subsurface horizons. However, in the Masuba series the adsorption maximum is higher for the subsurface horizon. The maximum adsorption values vary from 434mgP/kg for the surface horizon of Masuba series to 1217mgP/kg for the surface horizon of Gbesebu series.

Other authors (Udo and Uzu, 1972), working with tropical soils, have reported higher values than those obtained in this study. Rhodes (1975) reported adsorption maxima of 2439 and 2137mgP/kg for the surface horizons of Njala and Makundu soils. Those values appear high and may have included P that was precipitated. In this study, any value of P left in solution greater than 2.5ppm (which is about the solubility product of the P compounds) was discarded.

The P adsorption maxima for the soils studied are correlated with percent organic C or Fe and Al oxides extracted by ammonium oxalate, ox, dithionite-citrate-bicarbonate, d, and Na-pyrophosphate solutions, pp. The linear correlation values are given in Table 6C. The highest correlation value (significant at 1% level) was obtained with organic C for the surface horizon, A. Similar correlations between percent organic C and P adsorption have been observed by other workers (Saunders, 1965; Udo and Uzu, 1972). Rhodes (1975) reported relationships between P adsorption maxima and organic matter for three Sierra Leone soils, i.e., Njala, Makundu and Bonjema series.

Although high correlation values were obtained for P adsorption maxima and organic C in subsurface, Fe_2O_3ox in subsurface, Fe_2O_3ox + Al_2O_3ox in the subsurface, Al_2O_3ox in the subsurface, and Fe_2O_3d-Fe_2O_3ox for the surface, Fe_2O_3-pp in the surface horizons, and

Al_2O_3-PP in the surface (Table 6c), the values are not significant at the 20% level, possibly due to the small sample sizes. All other values in Table 6c over 0.5 are significant at this or a higher confidence level. However, 74.1% (r^2) of the variation of the P adsorption maxima for the subsurface horizon can be explained by variation in dithionite extracted Fe oxide, compared to only 11.6% for the surface horizon. Forty-six and four-tenths percent of the variation of P adsorption maxima for the subsurface can be explained by oxalate extracted Fe oxide compared to only 3.4% for the surface horizon. Seventy percent of the variation in P adsorbed in the surface horizons can be explained by variation in oxalate extracted Al oxide, as compared to 63% for the subsoils. A higher percentage of the variation in P adsorbed in the surface horizons can be explained by variation in the sum of oxalate extracted Al plus Fe than by Na-pyrophosphate extracted Al or Fe.

In general, the influence of Fe_2O_3d-Fe_2O_3ox on the adsorption of P is greater in the subsurface horizon than in the surface horizon, where organic C, Al_2O_3ox and organic complexes of Fe_2O_3pp and Al_2O_3pp are more important.

Mineralogical Analyses

X-Ray Analyses of Total Clay Fractions

Interpretation of diffractograms for clay minerals present was done as follows. Kaolinite: The presence of this material is indicated by 7.18-7.3 A°(001) and 3.57-3.58 A°(002) basal spacing for the Mg saturated samples. These peaks are absent after heating to

550°C of K saturated samples. At this temperature kaolinite becomes amorphous.

Interstratified minerals: The (001) spacings of these minerals are intermediate between the normal (001) spacing of the individual members, depending on the relative amounts of the members in the mixture (Brown, 1961; Grim, 1968).

Gibbsite and goethite: These minerals are identified by the 4.85 A° (most intense peak) (020) or 3.18 A°(002) and the 4.18 A° (most intense peak) (110) or 3.38 A°(120) or 4.98 A°(020) reflections. The latter three are for goethite.

Quartz: The presence of this mineral is indicated by the 3.34-3.42 A°(101) most intense peak, or 4.26-4.43 A°(100).

Chlorite: Chlorite is identified by 14.0 A°(001), 7.00 A°(002), 4.7 A°(003) and 3.5 A°(004) peaks, for glycolated, and K saturated samples heated to 550° C.

Illite: Illite is identified by the 10.0 A°(001), 5.00 A°(002), and 3.33 A°(003) peaks, which persist throughout all the treatments.

Table 7 contains values for the total clay analyses of the soils studied (Odell et al., 1974) and Figure 7 contains x-ray diffractograms of representative total and fine clays of representative profiles.

Soils of the Upland Surfaces of Highly Weathered Material: The mineralogy of the total clay fraction of these soils (Table 7) is dominated by kaolinite. The smallest percentage of this mineral is in the Manowa series. Gibbsite is the second most abundant mineral. The Manowa series has the highest amount of gibbsite. Figure 7a shows x-ray diffractograms for A and upper B horizons of the Makeni series, with kaolinite and gibbsite peaks.

Table 7. Composition of total clay fractions of the eleven profiles studied (Odell et al., 1974)

Soil Series and Horizons	Quartz %	Goethite %	Gibbsite %	Kaolinite %	Illite %	Chlorite %	Interstratified %
Baoma							
A_1	6	6	8	66	3	11	---
B_2	4	6	9	70	3	8	---
$11B_{31}$	-	6	9	75	3	7	---
$11B_{32}$	-	7	10	72	3	8	---
Average	3	6	9	71	3	8	---
Manowa							
A_1	-	5	34	49	5	7	---
A_3	5	6	20	55	5	9	---
B_{22}	-	8	19	61	4	8	---
Average	2	6	24	55	55	8	---
Njala							
A_1	2	1	6	65	1	11	14
A_3	-	-	3	71	2	12	12
B_{21}	-	3	7	68	1	9	12
B_{22}	3	2	5	70	3	7	10
Average	1	2	5	68	2	10	12
Makeni							
A_1	-	-	11	84	-	5	---
B_{21}	3	-	14	71	3	6	3
B_{22}	4	7	14	71	2	2	---
Average	2	3	13	75	2	4	1

Table 7 (continued)

Soil Series and Horizons	Quartz %	Goethite %	Gibbsite %	Kaolinite %	Illite %	Chlorite %	Interstratified %
Segbwema							
A_1	3	2	4	80	4	2	5
B_{21t} and B_{22t}	6	4	2	82	4	2	---
C_1	2	7	5	82	4	-	---
Average	4	4	4	81	4	1	2
Timbo							
A_{11}	5	10	30	42	5	4	4
A_{12}	-	7	31	53	1	8	---
AB	-	9	38	46	3	4	---
B_{21t}	-	10	25	55	8	-	---
B_{22b}	-	11	28	61	-	-	---
Average	1	9	31	52	3	3	1
Pendembu							
A_1	-	-	14	73	6	7	---
A_3	-	-	15	75	5	5	---
B_2	1	-	16	74	5	4	---
Average	1	-	15	74	5	5	---
Masuba							
Ap	6	-	10	71	5	4	4
B_{1t}	5	-	9	77	4	3	2
B_{2t}	7	-	12	71	5	2	3
Average	6	-	10	73	5	3	3

Table 7 (continued)

Soil Series and Horizons	Quartz %	Goethite %	Gibbsite %	Kaolinite %	Illite %	Chlorite %	Interstratified %
Moa							
A_1	3	-	10	75	5	7	---
B_{21}	4	-	11	77	4	4	---
B_3	5	-	12	73	4	6	---
Average	3	-	11	75	4	6	---
Gbesebu							
A_1	-	-	14	76	4	6	---
A_3	5	-	12	71	3	5	4
B_{21b}	-	-	14	74	2	4	6
B_{22b}	4	-	13	73	2	4	4
B_{23}	4	-	12	75	2	4	3
Average	3	-	13	74	3	4	3
Makundu							
A_{11}	-	-	10	73	7	5	5
A_{12}	5	-	12	76	2	3	2
AB	3	-	11	75	3	4	4
B_1	7	2	11	73	3	1	3
B_{21}	5	-	12	76	3	2	2
B_{22}	5	3	10	77	3	-	2
Average	4	1	11	75	3	3	3

Figure 7a. X-ray diffractograms for total and fine clays of the A and upper B horizons of three representative profiles - Segbwema, Makeni and Gbesebu.

(1) Total clay
(2) Fine clay

Figure 7b. X-ray diffractograms for total clay fraction of Njala and Makeni gravels, A and B horizons.

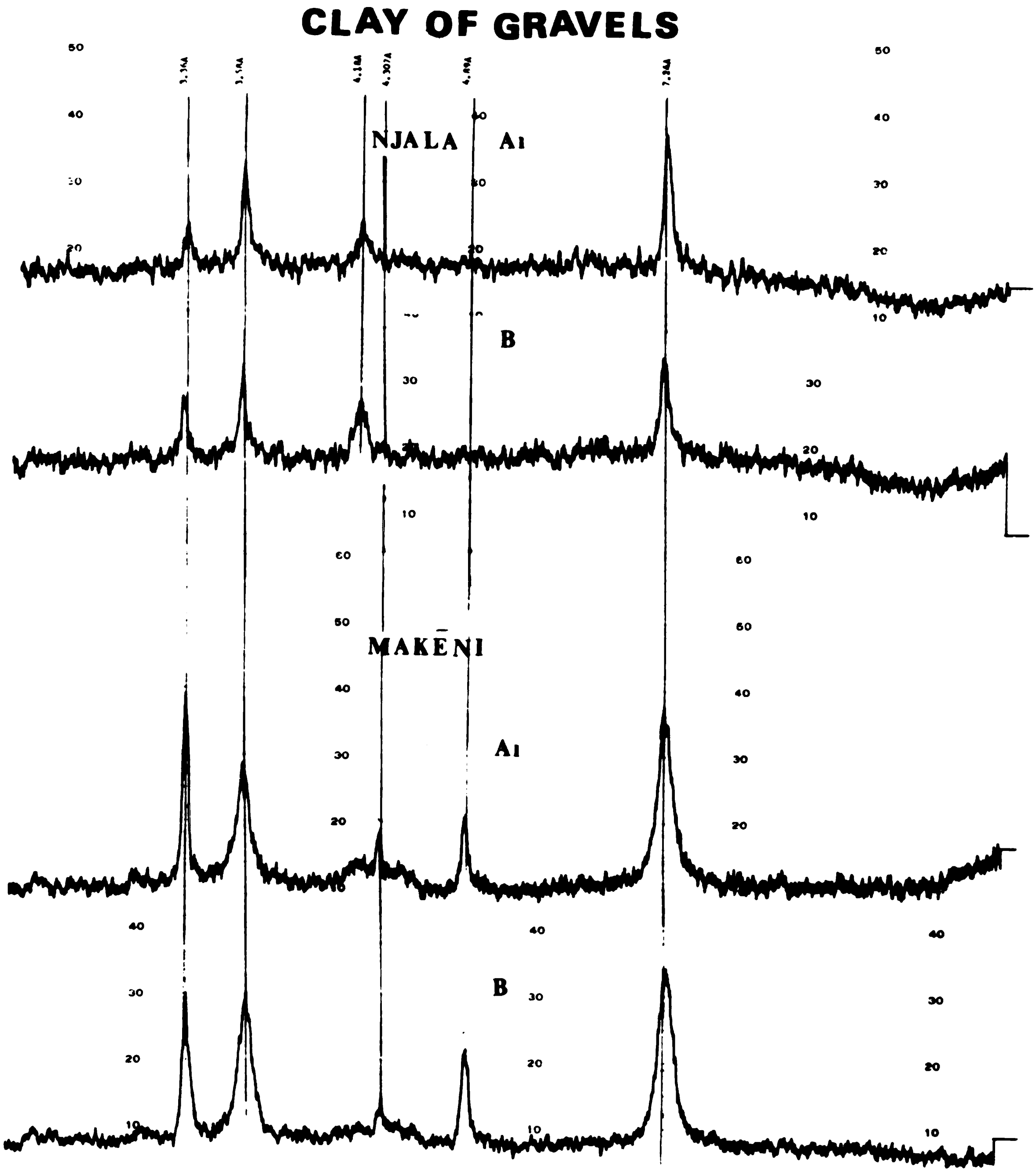


Figure 7b

Figure 7c. X-ray diffractograms for mica flakes in medium and fine sand fraction of the A, B and C horizons of the Segbwema series and B_{21} horizon of Timbo series.

(1) A_1, fine sand, Segbwema series
(2) A_1, medium sand, Segbwema series
(3) A_1, fine sand, K-saturated for one week and heat to 110°C, Segbwema series
(4) B_{21}, fine sand, Segbwema series
(5) B_{21}, fine sand, K-saturated for one week, Segbwema series
(6) B_{21}, fine sand, boiled with sodium citrate and K-saturated overnight, Segbwema series
(7) B_{22}, fine sand, Segbwema series
(8) C, fine sand, Segbwema series
(9) B_{21}, fine sand, Timbo series

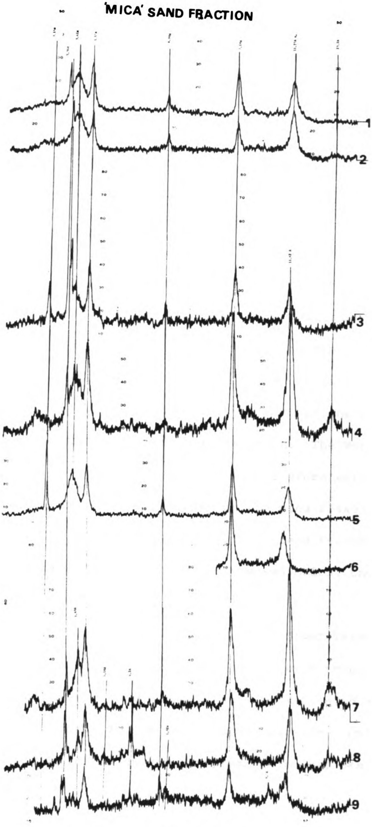


Figure 7c

Soils of the Steep Hills and Slopes: The predominant clay mineral in the Segbwema and Timbo series is kaolinite. Total clay analysis (Table 7) shows that the percentage of kaolinite is higher in the Segbwema than in the Timbo series, i.e., 81% compared to 52%, respectively. Gibbsite content is much higher in the Timbo (31%) than in the Segbwema series (4%). Both of these soils are derived from granite and acid gneiss. Intrusions of basic Kambui Schist are more common in soil provice L (Table 1), to which the Segbwema series belongs. Total analysis also shows traces of illite, chlorite and interstratified minerals in the profile. Goethite is also present in small amounts. X-ray diffractograms (Figure 7a) for total clay of the A and upper B horizons of the Segbwema series show mainly kaolinite with traces of gibbsite and quartz in the A and B horizon, respectively. Both of these samples have many mica-like flakes in their silt fraction. The very low content of illite in their clay fractions is therefore surprising. X-ray diffraction studies were conducted on the mica flakes of the sand fractions to aid in the explanation of the results obtained in the clay fraction. The findings are discussed below, under x-ray analyses of mica in sand fractions.

Soils of the Colluvial Footslopes and Upper River Terraces: In these soils, kaolinite is also the predominant clay mineral. Both Pendembu and Masuba series have greater than 70% kaolinite and 10-15% gibbsite. Illite accounts for 5% of the clay fraction. Chlorite, interstratified minerals and quartz are present in very small amounts.

Soils of the Alluvial Floodplains and Lower River Terraces: The predominant clay mineral is kaolinite, which accounts for 74-75% of the clay fractions of the three soils in this group. The soils have appreciable gibbsite content, 15-11%, which is higher than for some of the soils of the Upland Surfaces of Highly Weathered Materials (e.g., Baoma and Njala). The soils have very low illite content. Chlorite and interstratified minerals occur as traces. The low content of illite in the Gbesebu profile is interesting, as many mica-like flakes are present in the silt and fine sand fractions. X-ray diffractograms of clay from the A and B horizon of the Gbesebu series are shown in Figure 7a. The mineralogy of the two horizons is strikingly similar. Also, mica flakes from the sand fractions of the B21 horizon were x-rayed (see discussion on x-ray analyses of sand fractions).

X-Ray Analyses of Fine Clay Fractions

X-ray diffractograms of fine clays from the A and B horizons of the Makeni, Segbwema and Gbesebu series are included in Figure 7a. The mineralogy of both the fine clays and total clays of these soils is similar, with kaolinite being the dominant material. However, the amount of kaolinite is much smaller in the fine clay fraction. Peak intensity ratios between the fine and total clays varies between 0.34 and 0.56. The lowest is in the Makeni series and the highest is in the Gbesebu series.

The main difference between the diffractograms of the two clay fractions is that the peaks of the fine clays are broader and flatter, indicating the lower degree of crystallinity or more amorphous nature of the minerals.

In the A and B horizons of the Makeni series, the 3.38 A°(101) quartz peak is more intense in the fine clay, and the gibbsite peaks are much reduced. In the Gbesebu series the gibbsite and quartz peaks are noticeably reduced in the fine clay fractions.

X-Ray Analyses of Total Clay Fraction in Ironstone Gravels of Njala and Makeni Series

Figure 7b shows x-ray diffractograms of the total clay fractions of the A and B horizon gravels of the Njala and Makeni series.

In the Njala gravels, kaolinite and goethite are the main components of the clay fraction of the A and B horizons. Unlike the clay fraction of the fine earth fractions, gibbsite is absent. The Njala gravels are predominantly composed of Type la ironstone nodules (see discussion on Micromorphology), which are mainly fragments of mudstones and shales that have been impregnated by Fe oxide (Plate 6A, B and C). The intensities of the kaolinite peaks are much lower than those of the corresponding fine-earth clay fractions, possibly due to a lower degree of crystallinity or Fe oxide coatings.

The mineralogy of the clay fraction of the Makeni gravels is similar to that of the fine-earth components. Kaolinite is the dominant mineral and gibbsite is the second most abundant mineral. Quartz is also present as indicated by the 3.36 A°(101) and 4.30 A°(100) spacings. The quartz is assumed to be from the sample, as these peaks are absent for other samples, e.g., Segbwema A, for which the same mounting material was used. Most of the gravels of the Makeni series belong to Type 2a (see Micromorphology). The similarity between the clay mineralogy of the clay from the gravels and fine-earth in this soil seems to support the idea that these gravels were formed in place.

X-Ray Analyses of Mica Flakes in Sand Fractions of Segbwema and Timbo Series

The decision to conduct x-ray studies on the sand fraction was prompted by the occurrence of very small amounts of illite in their clay fraction, even though the sand fractions contain many micaceous flakes. Figure 7c shows x-ray diffractograms of the mica flakes, from the medium and fine sand fractions, of the Segbwema and Timbo series.

Interpretations of the air dried diffractograms show the presence of interstratified minerals, with peaks at about 11.8 A°, and 23.2 A°, kaolinite 7.18 A° and 3.57 A° peaks, and reflections of gibbsite 4.39 A° and quartz 3.34-3.42 A°(101) spacing, which account for a smaller percentage of the minerals present in the flakes. The lack of 9.9-10.1 A° peaks indicates that the flakes are not true mica, but weathered material. This tends to explain why there is very little or no illite content in the clay fractions of these soils. X-ray analysis of the mica flakes from the B21 horizon of Gbesebu series (diffractogram not shown) gave a 9.8 A° peak of illite, together with the peaks for kaolinite, but no inter-layer mineral occurred. This suggests differences between the mica-like flakes that are found in the Segbwema and Timbo series and those in the Gbesebu series (i.e., biotite in the Segbwema and Timbo series and muscovite in the Gbesebu series parent materials).

When mica-like flakes from the sand fractions of the A, B and C horizons of the Segbwema series and the B horizons of the Timbo series were compared (Figure 7c), the main difference that occurs between the A horizon and the B and C horizons is the presence of more highly ordered peaks of the interlayered material 22-24 A° in the B and C horizons. There is also some resemblance between the clay minerals present in the B horizon of the Timbo series and that of the Segbwema (Figure 7c).

To determine the interstratified material, the flakes were saturated with KCl, after which they were heated to 110°C. The time of K-saturation was varied, i.e., 8 hours, one week and two weeks. X-ray analyses after these periods showed no collapse of the peaks to the 10 A° of illite (mica) (Figure 7c, 3 and 5). The mica-like flakes were then boiled for five hours with Na-citrate, pH 7.3, before further K-saturation (Brown, 1961). This treatment is necessary to remove $Al(OH)_2^+$ occurring in the interlayer position. Tamura (1958) observed that the presence of $Al(OH)_2^+$ in interlayers position of interstratified Illite-Vermiculite will prevent the collapse of the peak to the 10 A°. Other workers (Rich and Obenshain, 1956; Brown, 1961) made similar observations. After the above treatment, the samples were x-rayed. Figure 7c, 6, includes the x-ray diffractogram for the treatment for the B horizon of the Segbwema series. The peaks for the interstratified mineral show a shift to the 11.3 A° for the B21 mica-like flakes. The higher order peaks disappeared with K-saturation. This suggests that the interstratified mineral is illite-chlorite. After one week of K-saturation and heating to 110°C, the 11.3 A° shifted to 10.6 A° (not shown).

The lack of shift in the peaks of the interstratified minerals to that of 10.1 A° after K-saturation and prior to the Na-citrate treatment indicates that K-fixation is not a serious problem in these soils.

Significance of the X-ray Analyses

The mineralogy of the clay fraction of soils of the Upland Surfaces of Highly Weathered Material and that of the Alluvial Terraces and Floodplains is strikingly similar (Table 7), indicating the common origin of the materials of the alluvium and the uplands. The main difference between the two groups of soils is the higher percentage of kaolinite in the alluvial floodplain soils. Also, in x-ray diffractograms of the Gbesebu and Makeni series, the kaolinite peaks are more intense in the Gbesebu than in the Makeni series, suggesting a higher degree of crystallinity of the minerals in Gbesebu.

The kaolinite peaks of the Segbwema series are of the lowest intensity and also broadest of the three representative profiles (Figure 7a). This tends to indicate a lower degree of crystallinity. The lack of gibbsite and goethite peaks in the diffractogram also points to a lesser degree of weathering in the Segbwema series.

The minerals in the fine clay fractions are poorly crystallized compared to those of the total clay components. This is supported by their broader, flatter, and lower intensity peaks (Figure 7a).

Grain Counts of the Fine Sand and Very Fine Sand Fractions

The fine and very fine sand fractions (Table 8A) of the five profiles (Timbo, Pendembu, Masuba, Moa and Makundu) are predominantly quartz (Table 8B). Mica (mostly muscovite) is the second most abundant mineral in these fractions. The highest amounts of mica

Table 8A. Sand size and coarse silt distribution in seven profiles expressed in percent of total soil (after Fe was removed)

Soil Series	VCS 2.0-1.0mm	CS 1.0-0.5mm	MS 0.5-0.25mm	FS 0.25-0.1mm	VFS 0.1-0.05mm	Coarse Silt 0.05-0.02mm	FS-Co.Si. Σ
Makeni							
A_1	4.2	2.8	7.2	14.8	4.8	1.7	
B_{21}	6.0	2.4	4.8	9.2	4.0	2.4	
B_{22}	5.9	3.1	2.4	6.0	3.7	2.1	
Timbo							
A_{11}	6.6	7.6	9.5	27.6	8.3	0.8	---
A_{12}	10.7	9.8	7.5	17.3	6.4	1.2	---
AB	12.2	10.7	6.4	14.5	6.2	2.8	23.5
B_{21b}	12.5	10.8	6.5	13.6	6.4	4.6	24.6
B_{22b}	10.5	12.0	7.6	16.3	9.0	3.9	29.2
Pendembu							
A_1	3.0	16.1	8.9	23.2	8.9	3.2	---
A_3	3.3	14.1	9.8	22.2	9.1	3.9	35.2
B_{21}	3.6	14.3	9.4	21.1	8.3	3.7	33.1
B_{22}	6.9	16.6	8.3	16.1	6.2	3.0	25.3
B_{23}	6.8	14.2	8.5	14.8	6.4	3.4	24.6
Masuba							
Ap	2.1	23.8	11.9	19.8	7.2	6.5	---
B21t	2.8	20.2	11.0	14.5	5.9	4.3	24.7
B_{22t}	3.2	20.8	12.3	14.1	5.8	4.4	24.3

Table 8A (continued)

Soil Series	VCS 2.0-1.0mm	CS 1.0-0.5mm	MS 0.5-0.25mm	FS 0.25-0.1mm	VFS 0.1-0.05mm	Coarse Silt 0.05-0.02mm	FS-Co.Si. Σ
Moa							
A_1	1.3	5.5	3.9	12.6	6.4	3.1	---
B_{21}	1.3	3.6	3.9	11.7	5.8	2.9	20.6
B_{22}	1.8	6.6	3.6	11.0	6.0	2.4	19.4
B_3	2.6	6.8	3.7	10.3	5.5	2.9	18.7
C	5.3	9.5	4.6	10.7	4.8	2.6	
Gbesebu							
A_1	0.00	0.04	0.03	0.20	0.54	3.2	
A_3	0.00	0.07	0.01	0.10	0.25	4.2	
B_{21b}	0.00	0.01	0.01	0.01	0.01	4.2	
B_{22b}	0.00	0.01	0.01	0.03	0.05	2.7	
B_{23}	0.00	0.02	0.02	0.10	0.14	2.3	
Makundu							
A_{11}	0.5	1.1	0.9	2.6	2.4	4.7	---
A_{12}	0.2	0.7	0.6	2.5	2.1	4.7	---
AB	0.2	0.6	0.4	1.8	2.2	4.5	8.5
B_1	0.1	0.4	0.3	1.6	1.8	4.5	7.9
B_{21}	0.2	0.4	0.3	1.0	1.3	4.2	6.5
B_{22}	0.3	0.7	0.3	0.9	1.2	3.8	5.9

Table 8A (continued)

Soil Series	VCS 2.0-1.0mm	CS 1.0-0.5mm	MS 0.5-0.25mm	FS 0.25-0.1mm	VFS 0.1-0.05mm	Coarse Silt 0.05-0.02mm	FS-Co.Si. Σ
Moa							
A_1	1.3	5.5	3.9	12.6	6.4	3.1	---
B_{21}	1.3	3.6	3.9	11.7	5.8	2.9	20.6
B_{22}	1.8	6.6	3.6	11.0	6.0	2.4	19.4
B_3	2.6	6.8	3.7	10.3	5.5	2.9	18.7
C	5.3	9.5	4.6	10.7	4.8	2.6	
Gbesebu							
A_1	0.00	0.04	0.03	0.20	0.54	3.2	
A_3	0.00	0.07	0.01	0.10	0.25	4.2	
B_{21b}	0.00	0.01	0.01	0.01	0.01	4.2	
B_{22b}	0.00	0.01	0.01	0.03	0.05	2.7	
B_{23}	0.00	0.02	0.02	0.10	0.14	2.3	
Makundu							
A_{11}	0.5	1.1	0.9	2.6	2.4	4.7	---
A_{12}	0.2	0.7	0.6	2.5	2.1	4.7	---
AB	0.2	0.6	0.4	1.8	2.2	4.5	8.5
B_1	0.1	0.4	0.3	1.6	1.8	4.5	7.9
B_{21}	0.2	0.4	0.3	1.0	1.3	4.2	6.5
B_{22}	0.3	0.7	0.3	0.9	1.2	3.8	5.9

Table 8B. Mineral grain count for fine sand and very fine sand fractions of five profiles

Soil Series	Fine Sand					Very Fine Sand					% 20-200μ approx.
	Quartz	'Mica'	Feldspar	Opaque*	Other minerals**	Quartz	'Mica'	Feldspar	Opaque*	Other minerals**	
Timbo											
A_{11}	72.7	15.5	1.5	3.4	6.9	70.6	16.4	3.7	5.3	4.0	---
A_{12}	72.3	18.0	1.3	1.6	6.8	74.3	13.5	4.6	2.4	5.2	---
AB	74.9	14.5	3.8	1.5	5.3	67.3	14.4	10.8	1.6	5.9	8.5
B_{21b}	72.3	18.4	3.9	0.5	4.9	52.8	25.6	13.4	3.6	5.6	11.1
B_{22b}	58.7	28.7	6.7	0.7	5.2	51.7	25.6	15.3	1.2	6.2	16.4
Pendembu											
A_1	80.4	2.6	0.0	10.0	7.0	77.9	4.1	0.7	12.4	5.5	---
A_3	80.9	2.5	0.5	9.3	6.8	78.6	4.8	0.8	12.7	3.1	2.2
B_{21}	78.6	5.8	0.6	9.2	5.8	74.4	8.3	0.0	11.1	6.2	3.6
B_{22}	82.0	3.1	0.0	9.7	5.2	71.1	4.4	0.9	14.9	8.7	1.6
B_{23}	84.9	2.9	0.0	5.9	6.3	70.4	9.4	1.4	11.6	7.2	2.7
B_3	---	---	---	---	---	---	---	---	---	---	---
Masuba											
AP	80.7	9.7	0.0	4.4	5.2	81.7	10.7	1.9	1.3	4.4	---
B_{21t}	78.6	15.1	1.3	0.0	5.0	70.0	18.8	4.6	1.2	5.4	6.9
B_{22t}	80.0	10.8	1.6	0.5	7.1	71.6	17.6	5.2	0.7	4.9	5.8
Moa											
A_1	76.5	9.6	0.5	7.2	6.2	70.1	9.4	0.7	14.1	5.7	---
B_{21}	72.2	7.9	0.7	11.5	7.7	67.6	11.6	0.6	16.0	4.2	6.2
B_{22}	70.0	10.0	0.0	11.5	8.5	67.1	11.8	0.6	16.3	4.2	6.0
B_3	69.9	9.9	0.0	10.8	9.4	67.4	12.5	0.0	16.0	4.1	5.6

Table 8B (continued)

Soil Series	Fine Sand					Very Fine Sand					% 20-200μ approx.
	Quartz	'Mica'	Feldspar	Opaque*	Other minerals**	Quartz	'Mica'	Feldspar	Opaque*	Other minerals**	
Makundu											
A_{11}	75.4	12.8	1.8	3.1	6.9	78.2	16.6	1.2	1.6	2.4	---
A_{12}	77.0	13.2	1.1	1.2	7.5	73.8	17.4	3.4	0.9	4.5	---
AB	76.1	15.2	2.1	0.0	6.6	69.8	22.4	3.9	0.0	3.9	8.9
B_1	77.7	12.0	2.5	1.2	6.6	68.8	22.6	2.9	0.7	5.0	7.8
B_{21}	67.6	22.6	3.5	0.0	6.3	67.6	22.2	5.4	0.0	4.8	8.3
B_{22}	62.9	26.8	2.8	0.8	6.7	62.8	25.9	4.2	1.2	4.9	8.7

*Mainly magnetite as confirmed by the use of magnet.

**Other resistant minerals.

are found in the subsoil horizons of Timbo and Makundu series. The mica in the B horizons of Timbo series is predominantly weathered biotite. X-ray analyses of this material (see section on x-ray analyses) show that it is a mixture of interstratified illite-chlorite and kaolinite. However, the 'mica' flakes in Pendembu, Masuba, Moa and Makundu series are predominantly muscovite.

The highest amounts of opaque minerals (composed mainly of magnetite) are in the Pendembu and Moa series, both of which are from soil province L (Table 1). High magnetite content is also recognized in the other soils studied in soil province L (see Table 1).

The Pendembu series appears to be the most intensely weathered of the five representative profiles.

Most of the five profiles have >6% weatherable minerals (mainly muscovite) in 20-200μ fractions of their upper B horizon and therefore do not meet this requirment of an oxic horizon (Soil Survey Staff, 1975). But the Pendembu series meets this requirement of an oxic horizon. However, it does not meet the free oxides/clay ratios expected of Oxisols.

Micromorphology

Soil morphology has been (restrictedly) defined as: (a) the physical constitution, particularly the structural properties of a soil profile as exhibited by the kinds, thickness, and arrangement of the horizons in the profile, and by the texture, structure, consistence and porosity of each horizon and (b) the structural characteristics of the soil or any of its parts (Brewer, 1964).

Soil micromorphology, then, is the study of soil morphology in the range where optical instruments (microscopes) are needed to aid the naked eye (Buol et al., 1973). It involves examination of the soil at a lower level than that required for field investigations. The emphasis is on the spatial arrangement of simple discrete grains and associated voids as well as the composition of the soil matrix.

There are two basic subdivisions of micromorphological studies: split and debris examination of the samples or profiles, after Kubiena (1938), and thin section observations, after Brewer (1964). The former were conducted here with aid of a binocular microscope, and the latter with a petrographic microscope.

The terms used in describing features observed in thin sections are adopted from Brewer (1964). Also, the description of the soils is divided into two groups: gravelly soils and non-gravelly soils. Each of the series descriptions will be divided into the whole soil and the gravels.

Split and Debris Analyses

Examination of samples from the horizons of the Segbwema series with the binocular microscope revealed the presence of clay skins on the surfaces of peds in the B horizon. This supported similar observations in the field study. Samples from the B horizons of Pendembu, Masuba, Moa, Gbesebu and Makundu series were also examined. However, the studies on these soils revealed no clay skins on the surfaces of the peds.

Descriptions of Thin Section of Gravelly* Soils Plus Their Ironstone Nodules (Baoma, Manowa, Njala, Makeni and Timbo)

Baoma series (Plate 2), 15-20cm, B2: The skeletal grains are randomly distributed, the predominant sizes being medium and fine sand. There are a few coarse sand grains. The fabric is intertextic to agglomeroplasmic and the plasma is composed mainly of a mixture of clay and Fe oxide. The clay is coated with Fe oxide; hence the undulic nature of the plasmic fabric at 200X. The horizon is porous. There are a number of channels and planes. The latter are mainly due to cracks in the soil matrix, possibly due to shrinking, evidence of craze planes. The channels are single and dendritic. Some are coated with sesquans, mainly Fe oxide, as confirmed with reflected light.

A patch of ferri-argillan was observed between the soil matrix and the nodule, possibly due to pressure of the nodule against the soil matrix.

Lithorelics are mainly small pieces of mica (muscovite) that weathered in place to clay. The clay shows preferred orientation. Pedological features are in the form of Fe oxide nodules; both Type 2a and 2b are recognized (Plates 2a, b and 15) (see definition of the different types in the discussion). The shape of the nodules is subrounded to subangular. The percent of nodules in the horizon is low.

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*Ironstone gravels

PLATE 2. Thin sections, Baoma series (whole soil).

(a)

15-20cm (B2), plain light, 40X. Soil matrix and a Type 2a nodule (round features). Note the similarity between the soil matrix and that of the nodule.

(b)

15-20cm (B2), plain light, 40X. Soil matrix and a Type 2b nodule (left half of photo). Note a small Type 2a nodule near the larger quartz grain in right half of photo.

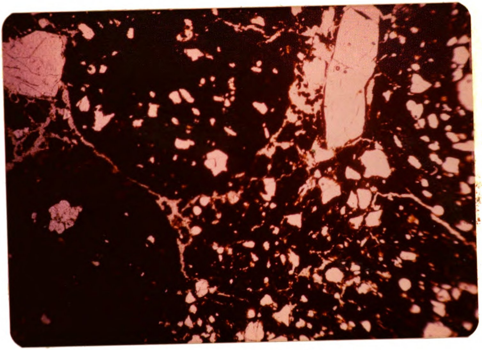


Plate 2a

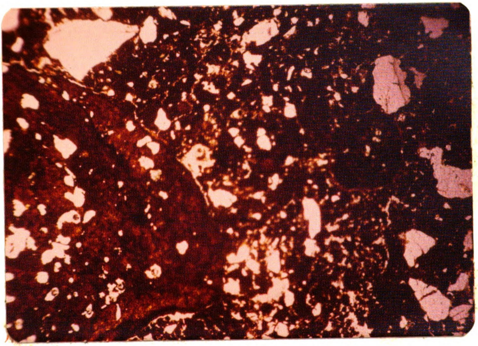


Plate 2b

PLATE 2 (continued)

(c)

30-38cm (B2), plain light, 40X. Type 2b nodule (lighter color) and soil matrix. Note the Fe oxide on the surface of the nodule. Also, note the cracks in the soil matrix.

(d)

30-38cm (B2), plain light, 40X. Oriented clay within a Type 2 nodule along an old channel.

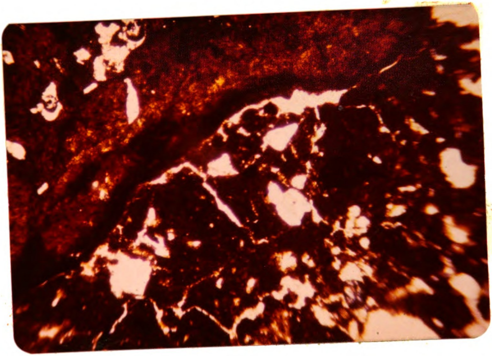


Plate 2c

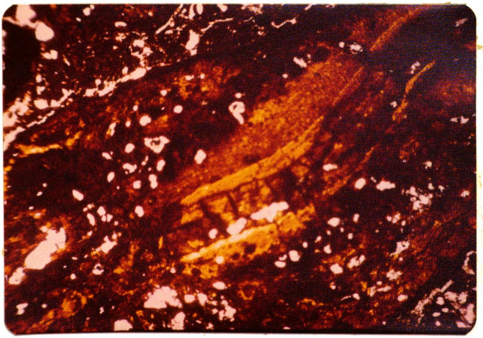


Plate 2d

PLATE 2 (continued)

(e)

30-38cm (B2), X nicol. Oriented clay within a Type 2 nodule along an old channel.

(f)

43-50cm (B2), plain light. Soil matrix and both Types 2a (north-east part of photo) and 2b (southwest part) nodules. Note the cracks in the soil matrix and the Fe oxide concentration on the surface.

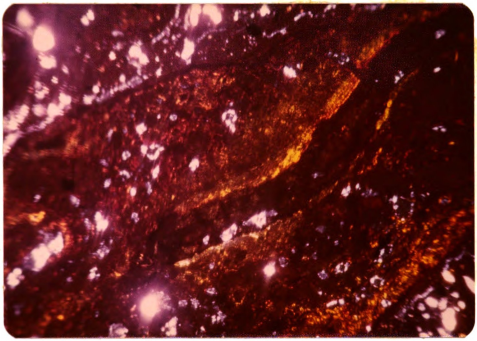


Plate 2e

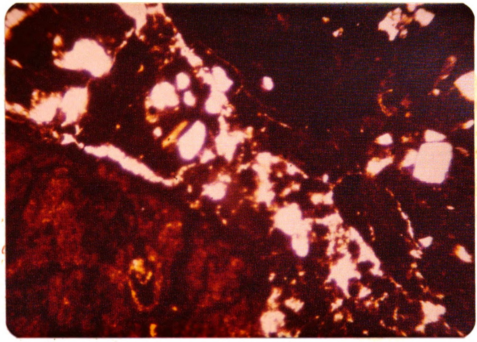


Plate 2f

30-38cm, B2: The skeletal grains are randomly distributed and they are composed mainly of medium and fine sand grains. The fabric is intertextic-agglomeroplasmic and the plasma is composed mainly of clay coated with sesquioxide, mainly Fe oxide. The plasmic fabric is inundulic to undulic at 200X. The horizon is porous. There are many cracks (Plate 2c). The channels are mainly single and dendritic. The vughs are mainly irregular orthovughs.

Pedological features occur in the form of nodules. Two types of nodules are recognized: Types 2a and 2b (Plate 2c), the plasma of which is composed of clay covered with Fe oxides, enclosing a few sand grains (mainly quartz grains). In both types, the perimeter (contact with the soil matrix) is coated with Fe oxides (Plate 2c). Some oriented clay minerals are evident within the matrix of the nodule (Plate 2d and e). Exfoliated, moderately weathered mica pieces (possibly muscovite) are also observed. The shape is subrounded to subangular. There is a slightly higher percentage of nodules than above.

43-50cm, B2: The skeletal grains are randomly distributed, as above. The fabric is agglomeroplasmic and the plasma is composed mainly of clay coated with Fe oxides. The plasmic fabric is inundulic-undulic at 200X and undulic at 400X. The horizon is very porous. There are numerous cracks and a craze plane is evident (Plate 2f). The plasma contains lithorelics, mainly small pieces of oriented clay, possibly derived from the weathering of mica *in situ*. Some of the channels are lined with sesquans, predominantly composed of Fe oxides. The vughs are mainly irregular orthovughs.

Orthic-pedological features include Mn concretions and both Types 2a and 2b nodules, which are elongated and mainly subangular in shape. The plasma of the nodules is similar to those described above.

60-68cm, IIB31(1): This horizon contains more nodules than the overlying one. The skeletal grains are randomly distributed and the size is predominantly medium and fine sand. The fabric is agglomeroplasmic and the plasma is composed mainly of clay and silt size material, with coatings of sesquioxides, mainly Fe. The plasmic fabric is undulic at 80X.

The horizon is porous; a craze plane is evident in the soil matrix between the nodules. The channels are single and dendritic.

Two kinds of orthic-pedological features are observed: Mn nodules and Fe oxide nodules. The two types of Fe oxide nodules described previously are also recognized. Some of the clays in the nodules show preferred orientation. In some cases the oriented clay appears to have been developed on the surface of the matrix of the nodules (i.e., plasma concentration of clay within the nodules). The present-day surface is coated with Fe oxides.

Type 2b nodules appear to have been developed, in this case, around a nucleus of plasma concentration of clay possibly derived from the weathering of primary minerals, feldspar or mica. The nodules are subangular to angular. Some of the nodules are less than 2mm in size.

60-68cm, IIB31(2): The soil matrix is similar to that of IIB31(1). There are a few elongated metavughs, with vugh sesquans.

Also, some of the nodules are 2mm or less in size. These appear as a plasma of clay that has been coated with Fe oxide (Type 2c). Some of the nodules appear as compound pedological features having both host and included sesquioxide nodules. Channel ferri-argillans are present within the concretions.

110-115cm, IIB32: The skeletal grains in the soil matrix are randomly distributed. The sizes of grains are predominantly medium and fine sand. A few coarse sand grains are also present.

The fabric is agglomeroplasmic and the plasmic fabric of the soil matrix is undulic-inundulic at 200X. The horizon is porous. Cracks are common, though fewer than those of the above-described horizon. A craze plane is evident.

Orthic-pedological features are of two kinds: Mn nodules and sesquioxide nodules. The perimeter of the nodules is coated with sesquans. Both Types 2a and 2b sesquioxidic nodules are recognized. There are a few old channels in the sesquioxidic nodules that are filled with Fe oxide and lined with strongly oriented ferri-argillans. Weathered grains of mica are present within the nodules; so also is chalcedony.

Baoma gravels (Plate 3), 0-15cm A_1: Subrounded in shape, Type 2a. The matrix contains randomly distributed skeletal sand grains similar to those of the soil matrix, and include pedological features such as Mn nodules.

There are a few old channels that are filled with sesquioxides. The plasma is predominantly clay coated with Fe oxide. The fabric is agglomeroplasmic. The plasmic fabric is undulic-inundulic at 200X.

PLATE 3. Thin sections, Baoma series, gravels.

(a)

Type 2a nodules: (a) 0-15cm (A1), plain light, 80X; (b) 160-180cm (B3), plain light, 80X. Note the similarity between the matrix; the lighter area in (a) is possibly a vugh that was filled with soil and organic material. Note the thick Fe oxide coatings on the edge of the vugh. Also, note fragments of weathered mica in both concretions.

(b)

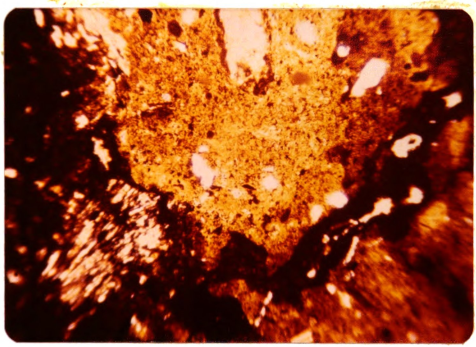


Plate 3a

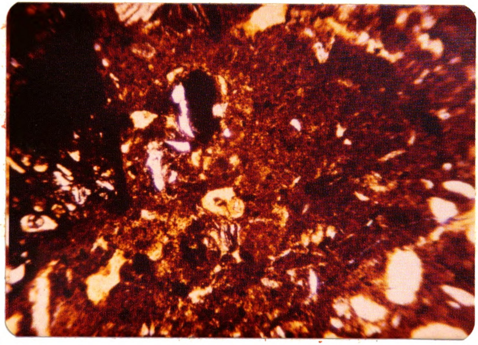


Plate 3b

The nodule is porous; some orthovughs are present. There are also a few metavughs. Some of the vughs have been filled by soil material and have their walls lined with Fe oxides (Plate 3a). Weathered grains of mica are present. The present-day surface is coated with Fe oxides.

15-30cm, B2: The skeletal grains are fewer in this nodule, which is similar to the Type 2a sesquioxide nodule described earlier. The shape is subrounded to subangular. The plasma is predominantly composed of clay coated with Fe oxides. The fabric is agglomeroplasmic-porphyroskelic and the plasmic fabric is undulic at 100X. There are old channels filled with ferri-argillans. The perimeter is coated in patches with sesquans.

30-60cm, B2: This nodule is similar to Type 2a described earlier. The skeletal grains are randomly distributed, and the size ranges between medium and fine sand. There are a few large sand grains. The matrix of this nodule is similar to that of the soil matrix. The nodule is porous. There are irregular orthovughs. The fabric is agglomeroplasmic. The composition is mainly clay, coated with Fe oxides. The plasma is undulic-inundulic at 200X. The outer surface of the concretion is coated with sesquans (Fe oxides). Plasma concentration of clay (partially coated with Fe oxides) with preferred orientation is present, possibly due to the weathering of primary minerals in place. '*In situ*' weathering of mica flakes is observable. Shape subangular.

60-110cm, IIB31: This appears as a compound pedorelic feature with the host pedorelic feature similar to that of the soil matrix.

The skeletal grains are randomly distributed, and the size of the grains is predominantly medium and fine sand. The included pedorelic is basically a concentration of clay coated with Fe oxide. The fabric of the host pedorelic feature is agglomeroplasmic and the plasmic fabric is undulic to inundulic at 200X.

The concretion is porous. There are a few irregular metavughs lined with ferri-argillans. The shape is subangular to angular. There are also a few channels that are coated with sesquioxides (Fe oxides). The perimeter is irregular. Examination at 400X depicts the rough nature of the surface, suggesting weathering (possibly by solution).

160-180cm, B33: The skeletal grains are randomly distributed, predominantly medium size sand grains. The fabric is agglomeroplasmic. The plasmic fabric is inundulic-insepic at 200X. Included pedological features are plasma concentrations of Fe oxides, or Mn nodules and clay. The clay has preferred orientation, due possibly to the weathering of feldspars and other primary minerals '*in situ*.' The vughs are mainly irregular orthovughs. Some vughs appear to be coated with a birefringent clay-like material. There are a few channels which are open to the outside which contain sesquans. Weathered mica grains are present. The shape is angular. The perimeter is rugged (Plate 3b).

Manowa series, 75-80cm, B21: The skeletal grains are randomly distributed, mostly of medium and fine sand size. The fabric is intertextic to agglomeroplasmic. The plasmic fabric is asepic to undulic at 80X. There are many cracks in the soil matrix, with some

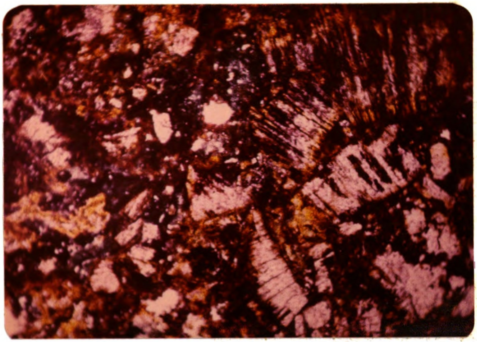
evidence of a craze plane. Channels are single. The plasma of the soil matrix is a mixture of clay and Fe oxides. Orthic pedological features are sesquioxide nodules, mainly Type 2a. In some of the nodules a center pore is observed. There is a great similarity between the matrix of the nodules and that of the soil. The perimeters of the nodules are coated with Fe oxides.

125-130cm, B22: The skeletal grains are randomly distributed and are of predominantly medium and fine sand size, with a few coarse sand grains. The fabric is intertextic to agglomeroplasmic and the plasmic fabric is asepic to undulic at 80X. The plasma is composed of clay coated with some Fe oxides. Channels are mainly single and a craze plane is also evident. Orthic pedological features are mainly sesquioxide nodules. Mainly Type 2a and 2b nodules are observed. Old channels and vughs are evident in some of the nodules. Some of them have patches of oriented clay coated with Fe oxides. In some of the nodules a single grain is observed in the center, which acts as a nucleus for the deposition of Fe oxides.

Manowa gravels (Plate 4), 0-25cm, Al:

Type 2a nodules. The skeletal grains are randomly distributed; there are some large sand grains. The fabric is intertextic. The plasma fabric is undulic at 160X. The plasma is a concentration of clay with preferred orientation and high birefringence. There are a few orthovughs which are coated with Fe oxides. There are also some channels that contain moderately to strongly oriented clay. The shape is subangular to subrounded.

PLATE 4. Thin section, Manowa series gravel.



25-53cm (A3), X nicol, 50X. Weathered mica pieces and other primary minerals that have been protected within a Type 2a nodule.

25-53cm, A3: The skeletal grains are randomly distributed and there are common sand grains. The fabric is intertextic and the plasmic fabric is masepic to insepic at 160X. There are plasma concentrations of oriented clay. Some irregular orthovughs have Fe oxide coatings and a few have patches of oriented clay. Weathered pieces of mica (possibly muscovite) are observable (Plate 4). Two zones are recognized in this nodule: a zone with very few skeletal grains in which the fabric is agglomeroplasmic to porphyroskelic, at left, and a zone with intertextic fabric. Similar kinds of nodules have been described for the Makeni series. It resembles a Type 1b gravel on which a Type 2b has been formed. Edge weathering is observed. Shape is angular to subangular.

53-88cm, B2: This is similar to that described in the A3. A few weathered primary minerals that have been protected by the nodule can be seen. The shape is angular and possible edge weathering is observed.

88-125cm, B22: This is similar to that described for 53-88cm. The main difference is that the Fe oxide concentration is higher. Weathered and weatherable materials, that have been protected within the nodule, are also present. The shape is angular. Possible edge weathering is observed. It is a Type 2a nodule.

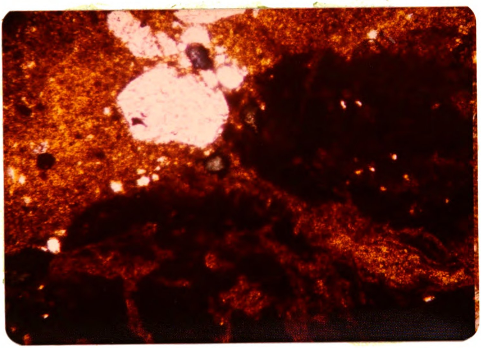
125-175cm, B22: It is similar to the nodule described above. Weathered and weathering primary minerals are observed. It is subrounded to subangular in shape. A Type 2a nodule.

Njala series (Plate 5), 123-128cm, B22 (Plate 5a, b, c): The skeletal grains are randomly distributed and the grain size is mainly medium and fine sand. The fabric is agglomeroplasmic. The plasma fabric is asepic to undulic at 80X and undulic at 200X. The horizon is very porous. There are a few irregular orthovughs. The plasma is mainly composed of clay coated with Fe. Orthic pedologic features are mainly sesquioxide concentrations. Two types of ironstone gravels are recognized, i.e., Type 1a and Type 2a (see later discussion on thin section of gravelly soils, and Plate 15).

The perimeter of some of the nodules is coated with ferri-argillan. The shape of the nodules is subangular to angular. The channels in some of the nodules contain argillans (Plate 5a and b). Also present are lithorelics which are mainly concentrations of oriented clay, possibly derived from the weathering of mica or feldspar *in situ*.

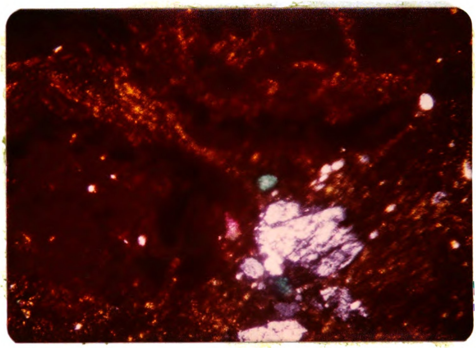
140-143cm, B22: This section has fewer nodules than that of 123-128cm. The skeletal grains are randomly distributed, the predominant sizes being medium and fine sand grains. There are also a few very coarse sand grains present. The fabric is agglomeroplasmic and the plasmic fabric is insepic at 80X. The horizon is porous. There are also many cracks and craze planes evident. The channels are single and dendritic and the vughs are mainly irregular orthovughs. Some vugh argillans (ferri-argillans) are observed in the soil matrix. Some channels within the soil matrix have sesquioxide coatings. Both types 1a and 2a nodules were recognized. Their shapes are subangular to angular.

PLATE 5. Thin sections, B2 horizon, Njala series



(a)

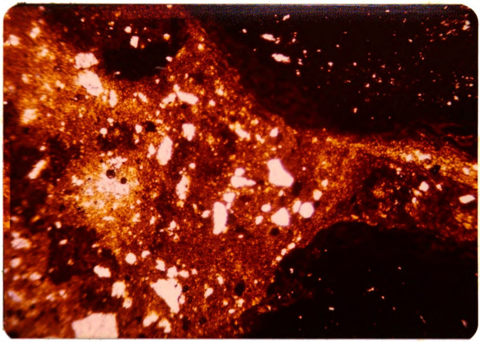
PLATE 5 (continued)



(b)

123-128cm (B22). (a) plain light, showing soil matrix (lighter portion) and Fe oxide nodule (dark portion). Note clay entry through pore in concretion; (b) X nicols, 50X. Note the flaky appearance of the oriented clay. Also, note patches of oriented clay as a result of weathering of mica within the concretion.

PLATE 5 (continued)



(c)

123-128cm (B22). (c) plain light, 50X. Soil matrix (lighter portion) between two ironstone nodules of Type la concretions. The white materials in the soil matrix and nodules are quartz grains. Some of the dark areas in the soil matrix are Fe and Mn concentrations.

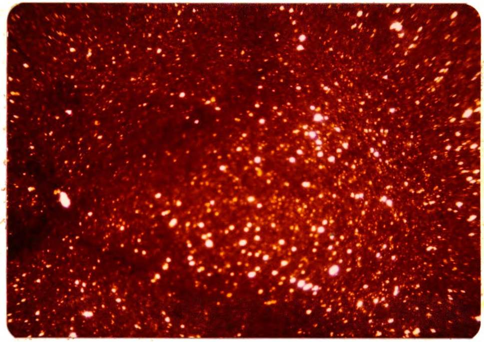
Njala gravels (Plate 6), 0-35cm, A1: This is a Type 1a nodule which is basically a rock fragment that has been impregnated and coated with Fe oxides (Plate 6a). The rock fragment in this case is shale or mudstone, which has been impregnated with bands of Fe oxide. It contains very fine sand grains. The fabric is porphyroskelic and the plasmic fabric is inundulic at 200X. The nodule is subrounded in shape. The perimeter is rugged. Possible edge weathering is evident at 400X.

35-53cm, A3: This is a section through a residual quartz grain. Thin bands of Fe oxide were observed between the joint planes.

53-95cm, B21(1): This resembles a Type 2b nodule with a higher percentage of skeletal grains. It is, however, possible that it is a Type 1a nodule derived from the weathering of sandstone (note both sandstone and shale are the common parent rocks found in this area). The fabric is intertextic and the plasmic fabric is undulic. The composition of the plasma is mainly clay coated with Fe oxide. The shape is subrounded to angular. A few metavughs are present which are lined with oriented clay. The edge is rugged in some places, and edge weathering is possible. Some oriented clay minerals were observed.

53-95cm, B21(2): The nodule is similar to that described in thin section of the A1 horizon (Plate 6a). It is a Type 1a nodule. The skeletal grains are randomly distributed and are of very fine sand grains. The fabric is porphyroskelic and the plasmic fabric is undulic at 200X. The plasma has a higher concentration of sesquioxide than that described in the A1. The Fe oxide bands are thick

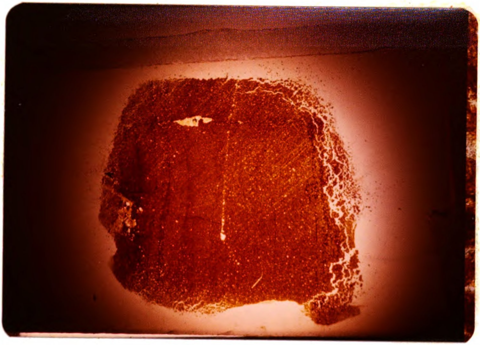
PLATE 6a, b, c. Thin sections, Njala series gravels, Type la nodules. These are the predominant form of Njala gravels.



(a)

0-35cm (Al), plain light, 100X.

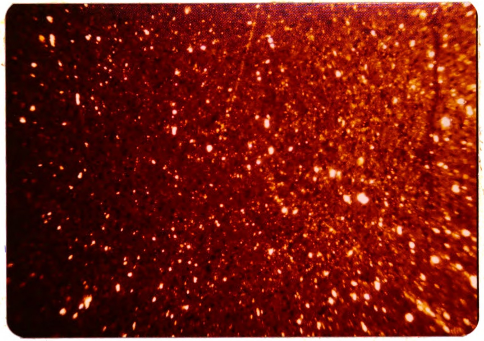
PLATE 6a, b, c (continued)



(b)

95-123cm (B21), plain light, 20X. This is basically shale or mudstone impregnated by Fe oxides. The Fe oxide bands are concentrated on the edge of the gravel.

PLATE 6a, b, c (continued)



(c)

95-123cm (B21), plain light, 100X. Note the similarity between this and (a). The dark areas or bands represent Fe oxide concentration, as do the dark red specks.

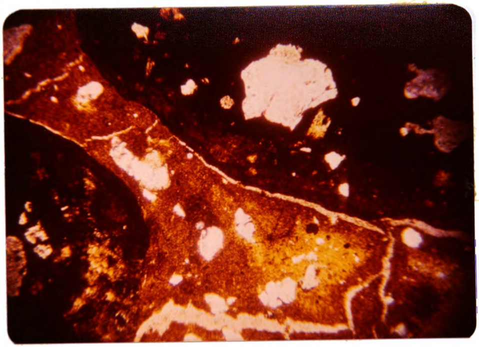
at the edges. A few pores lined with oriented clay were observed. The shape is angular; edges are rugged, indicating possible edge weathering.

95-123cm, B21: This nodule is similar to that described above, except that it has a lower percentage of Fe oxide concentration (Plate 6b, c). The edges have the highest percentage of the concentration. Within the matrix the Fe oxide concentration has a flecked appearance. The fabric is porphyroskelic and the plasmic fabric is undulic to inundulic at 100X. Possible edge weathering is taking place in this nodule also.

123-155cm, B22: This nodule is similar to that in the 95-123cm, B21 layer. There are fewer bands of Fe concentration and also a less flecked appearance of the Fe oxide coating of the soil plasma. The fabric is porphyroskelic and the plasmic fabric is inundulic to insepic at 100X. There is also evidence of possible edge weathering.

Makeni series (Plate 7), 35-38cm, B21: The skeletal grains in the soil matrix are randomly distributed, mostly medium to fine sand size. The fabric is agglomeroplasmic. The plasma is made of clay coated with Fe oxide. The soil matrix between the ironstone nodules shows high birefringence, possibly due to preferred orientation of the clay caused by the pressure of the nodules. The horizon is porous. The channels are single. There are also a few orthovughs. Orthic-pedological features are mainly sesquioxide concentrations in nodules. They vary in size. The distribution of the sesquioxide nodules is similar to that of the soil matrix. Old channels are recognized in some of the nodules.

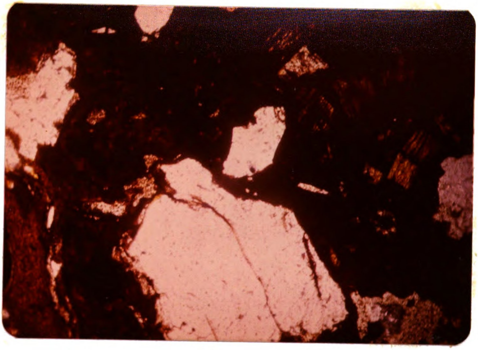
PLATE 7. Thin sections, Makeni series, B2 horizons.



(a)

75-78cm (B22), plain light, 40X. Soil matrix between two Type 2a ironstone nodules. The white areas around the nodules are channels. Note the similarity between the skeletal grain distribution in the soil matrix and nodule.

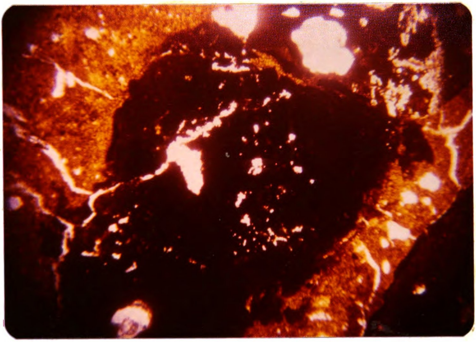
PLATE 7 (continued)



(b)

75-78cm (B22), plain light, 100X. Type 2a ironstone nodule. The black area is Fe oxide. The large grains are quartz grains. Note the weathered mica pieces that have been protected. Also, note the oriented clay coated with Fe on the southwest corner near an old channel.

PLATE 7 (continued)



(c)

115-118cm (B22), plain light, 40X. Soil matrix, lighter color, and ironstone nodule. Type 2b in the center. Note channels connecting nodule and matrix.

75-78cm, B22: The skeletal grains of the S-matrix are randomly distributed, predominantly medium to fine sand. The fabric is agglomeroplasmic to intertextic. The plasma is made up of clay coated with Fe oxides. The plasmic fabric is insepic to inundulic at 100X. The horizon is porous. The peds are easily recognized in the soil matrix, basically angular to subangular blocky. There are numerous cracks and craze planes. Channels are few and are mainly single channels, with a few bifurcating. Some channels between peds are coated with Fe oxides. Orthic-pedological features include Mn nodules and sesquioxidic nodules. These nodules vary in size. The distribution of the skeletal grains in the sesquioxide nodules is similar to that of the soil matrix (Plate 7a). No oriented clay is observed on the perimeter of the nodule; it is coated with sesquans. The shape of the nodule is subrounded to subangular. Some of the nodules have a few pores with a layer of clay and Fe oxides. Weathered pieces of mica and possibly feldspar are also observable in the nodules (Plate 7b). A few Type 2b nodules are observed, which are predominantly composed of Fe oxides.

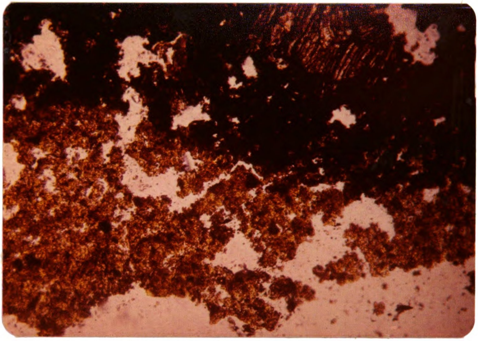
115-118cm, B22: The skeletal grains are randomly distributed in the soil matrix. They are fewer than those in the thin section of 75-78cm. There are also fewer cracks in this horizon (although a craze plane is also evident) than in the thin section of 75-78cm. The fabric is agglomeroplasmic. The plasmic fabric is inundulic to insepic at 200X. The horizon is porous. The channels follow the pattern of cracks. They are mainly single and dendritic. Orthic-pedological features are predominantly sesquioxide nodules. The plasma of the nodule is predominantly Fe oxide (Plate 7c). The Fe oxide concentration within the nodules is higher than that of the above layer. The shape of the nodules is subangular to angular and the perimeter is coated with Fe oxides. The plasmic fabric of the nodule is undulic.

Makeni gravels, (Plate 8) 0-25cm, A1: Two areas are recognized. Area 1 consists of randomly distributed skeletal grains. The fabric is intertextic and the plasmic fabric undulic at 200X. The plasma composition is mainly Fe oxides. Area 2 consists of basically alternate bands of Fe oxide and clay, with low birefringence. The skeletal grains are very few. Area 2 is probably sedimentary in nature. The shape of the nodule is subangular to subrounded.

25-55cm, B21: The skeletal grains are randomly distributed and the fabric is intertextic. They are predominantly medium and fine sand grains, with a few large grains. The plasmic fabric is insepic at 80X. It is porous. Included as pedological features are Mn nodules. Weathered and weathering grains include mica and feldspar. Chalcedony is also present. Some of the minerals have weathered to give clay minerals which show preferred orientation in the nodule. The shape is subrounded to subangular and the perimeter is coated with Fe oxides. The nodule appears to have a rock structure. This resembles a Type 1b nodule.

55-93cm, B22: Two areas are recognized. Area 1 is similar to the nodule described in the 25-55cm, B21, in terms of the distribution of skeletal grains. The fabric is intertextic. In area 2, there are

PLATE 8. Thin section, Makeni series gravel.



93-115cm (B22), plain light, 80X. Type 2a nodule, showing edge weathering and weathered mica pieces protected within the nodule. Most of the large irregular white areas are vughs.

fewer skeletal grains, which are mainly fine sand. The fabric is agglomeroplasmic to porphyroskelic. The plasma composition is mainly Fe oxide coated clay. It is undulic at 80X, as compared to area 1, which is insepic to inundulic at 80X. Area 1 is more porous than area 2. Weathered mica pieces (possibly biotite) are included in the nodule. This resembles a Type 1b nodule on which a Type 2b nodule has been formed. The shape is subangular to angular, with rugged edges.

93-115cm, B22: The skeletal grains are randomly distributed with the predominant size being fine sand. This concretion is Type 2b, and is similar to area 2 of 55-93cm. It contains a few channels that are single, some of which have Fe coatings, and metavughs coated with vugh sesquans. The fabric is agglomeroplasmic to porphyroskelic and the plasmic fabric is undulic at 200X. Weathered and weathering mica pieces (Plate 8) are evident and patches of oriented clay are seen within the matrix. The shape is angular. Edge weathering is possible.

115-168cm, B22: This is similar to the section described above in both skeletal grain distribution and the nature of the matrix within the nodule. However, there are more channels in this nodule. Vughs are irregular metavughs lined with Fe oxides. Some of the channels are filled with Fe oxides. The plasmic fabric is insepic to inundulic at 100X. A few weathered mica pieces are present. The shape is angular.

Timbo series, 35-65cm, AB_1: The skeletal grains are randomly distributed. The size is predominantly medium sand. There are a few large sand grains. The fabric is intertextic. The plasmic fabric is silasepic at 200X. The plasma composition is mainly clay and Fe oxides, plus organic material. The horizon is porous. The channels are few and are single and dendritic. Cracks are numerous in this horizon.

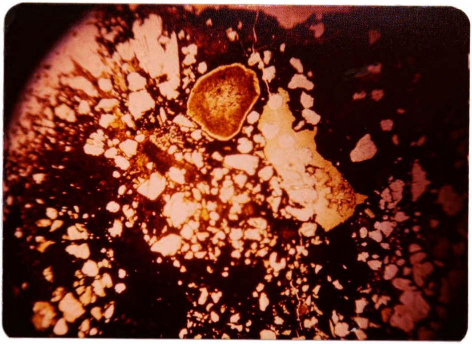
Lithorelics are mainly weathered pieces of mica and feldspar. Also observable are a few mica flakes and chalcedony. Orthic pedological features include Mn and Fe oxide nodules. The Fe oxide nodules, Type 1b, appear to have a rock structure, i.e., a piece of rock that was weathered in place with Fe oxide (Plate 9a, b).

95-100cm, B21(1): The skeletal grains are randomly distributed. There are many medium and fine sand grains, and a few coarse ones. The fabric is intertextic. The plasmic fabric is silasepic at 80X. The plasma is composed of clay and some Fe oxide. The voids are mostly of the simple packing type. The channels are single. This horizon appears dense and shows some evidence of rock structure. Lithorelics are mainly weathered pieces of mica and feldspar. Orthic pedological features are mainly Fe oxide nodules of Type 1b.

170-173cm, B22: This section is similar to that of the B21 horizon. The sesquioxide nodules are fewer and are of Type 1b. Also present are plasma concentrations of Fe oxides. Rock structure is also evident. Many weathering mica pieces are present, plus some weathered feldspar.

Timbo gravels (Plate 9), 0-30cm, A1: The skeletal grains are randomly distributed. The fabric is intertextic and undulic at 40X. The nodule is very porous and may be divided into two areas, one of

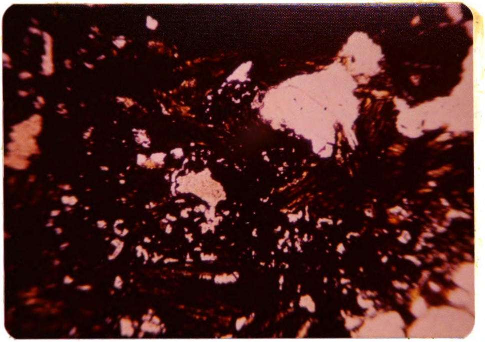
PLATE 9. Thin sections, Type 1b nodules, Timbo series.



(a)

0-15cm (A1), plain light, 40X. Note rock structure in nodule. The dark brown areas represent Fe oxides. The white areas are quartz grains.

PLATE 9 (continued)



(b)

70-115cm (B21), plain light, 40X. Dark areas are Fe oxide material. White areas are quartz grains. Also, note the weathered mica flakes (pseudomorphs of mica).

which resembles a rock structure and contains weathered pieces of mica and also chalcedony. The other has a higher concentration of Fe oxide, making the fabric of the matrix predominantly agglomeroplasmic rather than intertextic. In some places, the perimeter is coated with Fe oxide. The edge is rugged and there is evidence of weathering at the edge. There are a few vughs that are coated with clay and Fe oxides. Most of the clay appears to have been weathered in place. The shape is subrounded to subangular.

30-48cm, A12: It is basically a rock fragment that has been weathered in place, and impregnated by Fe oxides, Type 1b. It is subangular to angular in shape. There are a few areas with plasma concentrations of Fe oxides.

48-70cm, AB: It is predominantly a rock fragment that weathered in place and has been impregnated by Fe oxides, Type 1b. The fabric is intertextic. Weatherable minerals are observed. These include exfoliated, weakly weathered mica pieces and feldspar. A few papules (included pedorelic) are the result of mica pieces that have been weathered in place and coated with Fe oxide. The shape is angular. Some edge weathering is possible, as may be indicated by the rugged nature of the perimeter.

70-115cm, B21: It is basically a rock fragment that has weathered in place and then been impregnated by Fe oxides, Type 1b. The fabric is intertextic. It is porous and contains a few vughs lined with sesquioxide. The shape is angular and rugged, and edge weathering is observed. A patch of oriented clay is also observed at the perimeter of the nodule. Weathered or weathering minerals are also commonly present in this nodule. These include mica and possibly some feldspar (Plate 9b).

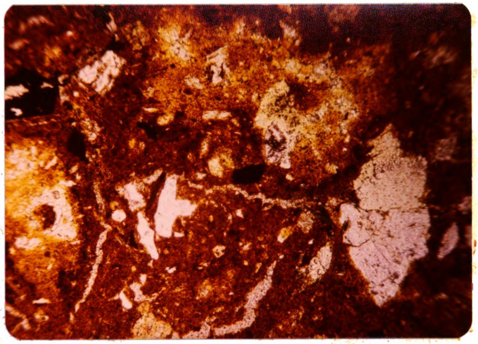
115-175cm, B22: Similar to the above nodule, this is basically a rock fragment that is being weathered in place and has been impregnated by Fe oxides, Type 1b. The fabric is intertextic to granular. The Fe concentration is lower than in the above-described horizon. Edge weathering is observable, but not as prominent as in the previous two nodules from the overlying horizons. Weatherable and weathered minerals include mica and feldspar.

Descriptions of Thin Sections of Non-Gravelly* Soils (Segbwema, Pendembu, Masuba, Moa, Gbesebu, and Makundu)

Segbwema series (Plate 10), 30-33cm, A1/B21 boundary: The skeletal grains are randomly distributed. They range from coarse to fine sand, with the medium and fine sand grains predominating. The fabric is porphyroskelic and the plasmic fabric is mainly skelinsepic (Plate 10a, b) at 100X. In some places, the plasmic fabric is mosepic. The horizon is porous. The plasma is composed of clay mixed with organic matter and Fe oxide. The channels are single, some of which are coated with a thin layer of ferri-argillans. The voids are of the compound packing type, and vughs are predominantly irregular orthovughs. A few of the pores and vughs have argillans. There are also embedded grain argillans (Plate 10a, b).

*Does not contain ironstone gravel.

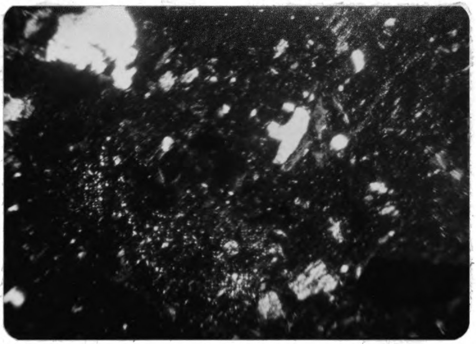
PLATE 10. Thin sections, Segbwema series, B horizon.



(a)

30-33cm (A1/B21 boundary), plain light, 50X. Note weathering rock fragments in the southeast corner. The plasma is high in Fe oxide as reddish brown coatings on the clay. The flaky rectangular materials in the matrix are weathered mica flakes. Also, note the distribution of the channels and the high amount of organic matter in the matrix. Some small channels are filled with mixtures of organic matter and Fe oxide.

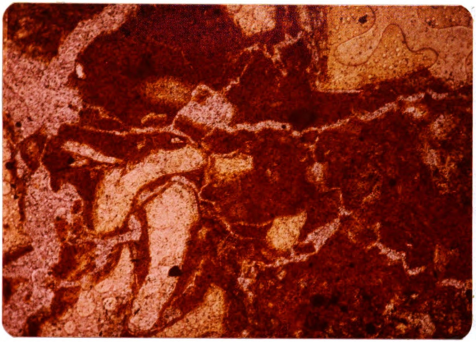
PLATE 10 (continued)



(b)

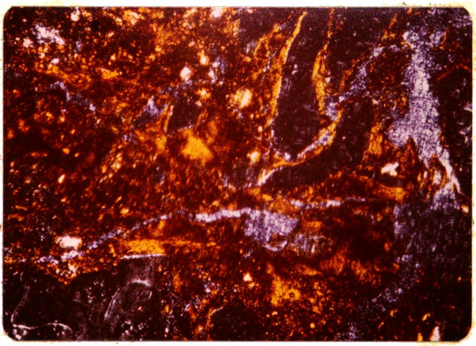
30-33cm (A1-B21), X-nicol, 50X of (a). Note the few embedded grain argillans and the insepic nature of the plasmic fabric. The darkened portion of the rock fragment, southeast corner, may be due to variations in orientation of that portion.

PLATE 10 (continued)



(c)

PLATE 10 (continued)



(d)

33-38cm (B21t): (c) plain light, (d) X-nicol, 50X. Insepic-mosepic, plasmic fabric. Channel and vugh argillans and also embedded grain argillans. Note the high concentration of Fe oxide in the matrix and plasma concentration of clay as a result of weathering of mica in place.

PLATE 10 (continued)

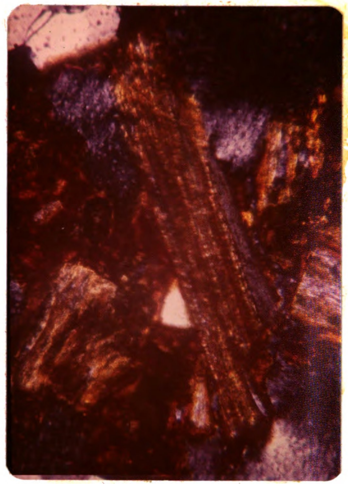
(e)

78-85cm (B22t), X-nicol, 150X. Mica flakes weathering in place. Note the different weathering zones and the stages of weathering. The piece in the southwest corner seems to be the most weathered. The reddish brown zone is clay coated with Fe; clay is predominantly kaolinite. The inner zones represent interlayer-illite-chlorite. The lighter speckled areas may represent gibbsite.

PLATE 10 (continued)

(f)

78-85cm (B22t), plain light, 200X. Mica flakes at various stages of weathering.



(g)

78-85cm (B22t), X-nicol, 200X.

Lithorelics included weathering primary minerals such as feldspars and mica, some of which have weathered in place to give a plasma concentration of oriented clay minerals. There are also plasma concentrations of Fe oxide. There are quite a few primary minerals in the sand fraction.

33-38cm, B21t: This section is similar to that of the 30-33cm layer. The fabric is agglomeroplasmic and the plasmic fabric is skel-insepic to mosepic at 100X. More channels, vughs and embedded grain argillans and ferri-argillans are present (Plate 10c, d). There are also a lot of weatherable minerals, mainly mica and feldspar.

40-55cm, B21t: The skeletal grains are randomly distributed. The fabric is agglomeroplasmic. The plasmic fabric is skel-insepic to insepic at 100X. The plasma is composed of clay mixed with Fe oxides. The channels are single and dendritic and there are both orthovughs and metavughs. Some of the vughs and channels contain strongly oriented clay and also pellets of organic matter and Mn pellets. There are embedded grain argillans and also plasma concentrations of Fe oxides. There are weathered primary minerals which produce clay minerals with preferred orientation. Weatherable minerals such as mica and feldspar are also present.

70-75cm, B22t: The skeletal grains are randomly distributed, and it is similar to the above horizons. The fabric is agglomeroplasmic and the plasmic fabric is vo-masepic. The horizon is porous. The channels are single and dendritic. There are both orthovughs and metavughs. Some of the channels and vughs have ferri-argillans lining the walls. Some vughs also contain Fe oxides. Some of the channel and vugh argillans show strong orientation. There are plasma concentrations of Fe oxides in the form of mottles. The Fe concentration in this horizon is higher than that of the above sections. There are weathered and weathering primary minerals, i.e., mica and feldspar, some of which have produced clay with preferred orientation in the soil matrix. There are also embedded grain argillans.

78-85cm, B22t: The skeletal grains are randomly distributed. This section is similar to that of the above. The fabric is agglomeroplasmic and the plasmic fabric is insepic to vo-mosepic. The plasma is composed of a mixture of clay and Fe oxides. There are plasma concentrations of Mn and Fe oxides. The Fe oxide concentration is in the form of mottles. The channels are single and bifurcating. There are some pores that are coated with strongly oriented clay. There are a few embedded grain argillans. There are weathered primary minerals which have produced clay with preferred orientation in the matrix. Also, some of the weathered mica pieces show various weathering bands (Plate 10e, f, g). Weatherable primary minerals are also present.

98-103cm, B22t: There are many to common skeletal grains which are randomly distributed. This section appears to be more compact than the previous ones and may be transitional to the C horizon. The fabric is agglomeroplasmic and the plasmic fabric is insepic to mosepic. There are plasma concentrations of Fe oxides and some Mn. The Fe oxide is in the form of mottles. The vughs are mainly irregular orthovughs and channels are single and bifurcating. There are a few embedded grain argillans. There are fewer oriented clays in the matrix. Weatherable minerals such as mica and feldspar are present, and weathered pieces of these minerals can also be seen.

Pendembu series, 45-48cm, A3/B2 boundary: The skeletal grains are randomly distributed. The size ranges from coarse to medium and fine, with the medium sand grains predominating. The fabric is intertextic and the plasmic fabric is silasepic at 200X. The voids are predominantly single packing voids. There are some vesicles. The channels are mostly single. There are Fe oxide concentrations in the form of mottles, and some Mn nodules are also present. Weathered mica pieces (possibly muscovite) are present.

75-78cm, B21 horizon: The skeletal grains are randomly distributed as in the A3/B2 boundary. The fabric is intertextic-agglomeroplasmic and the plasmic fabric is silasepic to undulic at 200X. The voids are of the single packing type. This layer is compact, and only a few vughs are present. These are mainly irregular metavughs. Also present are vesicles. There are a few Mn nodules and plasma concentrations of Fe in the form of mottles.

93-95cm, B22 horizon: The skeletal grains are randomly distributed as in the above horizons. The fabric is intertextic-agglomeroplasmic, and the plasmic fabric is silasepic to undulic at 200X. There are very few channels and vughs in this layer. It is dense and the packing voids are of the single type. The vughs are mainly irregular orthovughs. Lithorelics include weathered primary minerals, with resulting clay concentration, that shows preferred orientation.

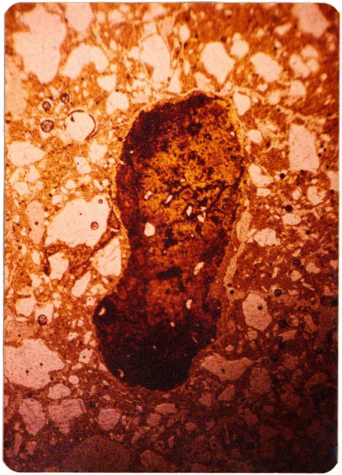
There are also plasma concentrations of Mn nodules and Fe oxides in the form of mottles.

108-110cm, B22 horizon: The skeletal grain distribution is random, with the most common size being that of medium sand grains. The fabric is intertextic to agglomeroplasmic, and the plasmic fabric is undulic at 200X. The voids are of the single packing type; vughs are mainly irregular orthovughs. The horizon is dense. There are plasma concentrations of clay showing preferred orientation. Possibly these are due to the weathering of primary minerals in place. There are also plasma concentrations of Fe oxides.

Masuba series (Plate 11), 23-25cm, boundary between Ap and B21t horizon: The skeletal grains are randomly distributed. The size varies from coarse to medium and fine sand, with medium and fine sand grains predominating. The fabric is intertextic and the plasmic fabric is inundulic to silasepic at 200X. The plasma is composed of a mixture of clay, with some Fe oxides and silt size organic matter. There are plasma concentrations of Mn and organic matter. The horizon is dense and pores are mostly micropores. There are a few irregular orthovughs. Lithorelics include chalcedony and weathered mica plates.

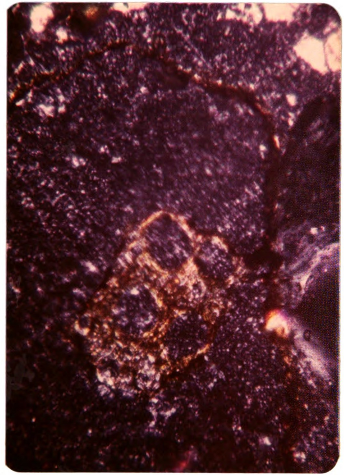
40-43cm, B21t horizon: The skeletal grains are randomly distributed. The predominant sizes are medium and fine sand. The fabric is porphyroskelic. In some places the skeletal grains show a clustered distribution. Some vugh ferri-argillans and embedded grain argillans are observed. The vughs are mostly orthovughs. The channels are small and single. The plasmic fabric is inundulic to

PLATE 11. Thin section of selected features of Masuba series, B horizon.



(a)

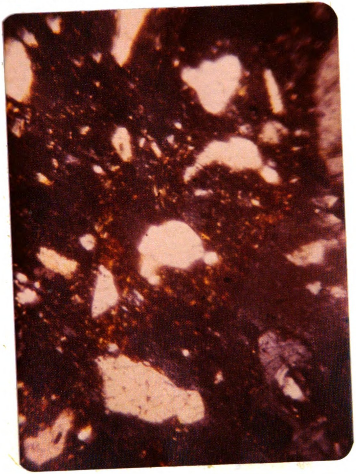
40-43cm (B21t), plain light, 40X. Isotubule (center) and surrounding matrix.



(b)

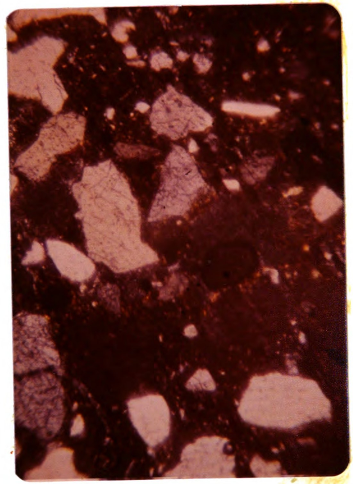
50-53cm (B21t), X-nicol, 40X. Incipient argillans and embedded grain argillans. Areas with few skeletal grains are common in this horizon.

PLATE 11 (continued)



(c)

63-65cm (B2), X-nicol, 40X. Few embedded grain argillans and incipient vugh argillan. Note the larger size of the skeletal grains.



(d)

100-103cm (B21), X-nicol, 40X. Vugh argillan.

silasepic at 200X, but undulic at 400X. A few plasma concentrations of Fe oxides and Mn are observed. A pedorelic is in the form of an isotubule, which is composed of a few skeletal grains and unoriented clay-like material plus organic matter (Plate 11a).

50-53cm, B21t horizon: The skeletal grains are randomly distributed within the soil matrix. However, clustering of fine grains is also evident. The grains are predominantly medium to fine sand. The fabric is agglomeroplasmic and is inundulic to silasepic at 200X. The horizon is compact and the pores are mainly micropores. Vughs are present, most of which are irregular orthovughs. A few vugh ferri-argillans are present. Also, there are both void argillans and embedded grain argillans (Plate 11b) in this horizon. Pedological features include plasma concentrations of sesquioxide (in the form of mottles) and oriented clay (possibly derived in part from the weathering of mica pieces in place, lithorelics). Manganese nodules and lithorelics of chalcedony.

63-66cm, B22t* horizon: The skeletal grain distribution is similar to that of the 50-53cm layer. Grains are randomly distributed with some clustering of smaller grains in some places. The fabric is agglomeroplasmic and plasmic fabric is insepic to inundulic at 200X. The horizon is porous and there are a few vughs, some of which are coated with ferri-argillans. There are also very few channels. The plasma is composed of silt and clay size material, which is more or less isotropic. Pedorelics include plasma concentrations of Fe

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*Two slides from the same depth were described.

oxides, Mn nodules and weathered mica and weathering mica and feldspar pieces. The Mn nodule is subrounded to subangular and it is coated with ferri-argillans. A few embedded grain argillans are observable. Also, vugh argillans are present.

63-65cm, B22t* horizon: It is similar to B22t above. Metavughs and a few channels are present. Also present are a few embedded grain argillans, vugh ferri-argillans and channel ferri-argillans. Some of the vughs contain small pieces of quartz grains. Chalcedony is present as lithorelic. Also present are nodules of organic matter.

80-83cm, B22t horizon: The skeletal grains are randomly distributed as described in the above sections. The fabric is agglomeroplasmic and plasmic fabric is undulic to insepic. There are few irregular orthovughs, some of which contain quartz crystals. The channels are few also. Some of the channels and vughs are lined with patches of oriented clay (vugh and channel argillan). There are also a few embedded grain argillans. In general, there is less illuvial clay in this layer than in the above layers. Pedorelics include Mn nodules and Fe oxide mottles.

100-103cm, B22t horizon: The skeletal grain distribution is as discussed in the pervious section. They are comparatively larger than those of the overlying B horizon. The fabric is agglomeroplasmic and the plasmic fabric is undulic to insepic. Also present in this layer are vugh argillans (Plate 11d).

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*Two slides from the same depth were described.

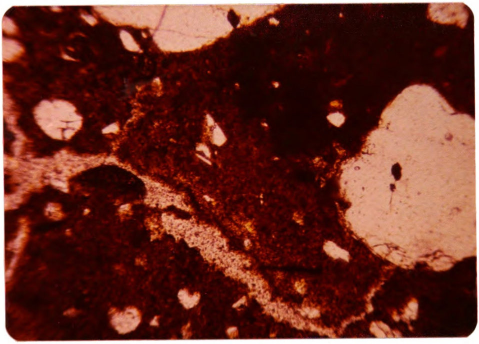
Moa series (Plate 12), 15-18cm, B21: The skeletal grains are randomly distributed. The size ranges from coarse to medium and fine sand, with the latter two predominating. The fabric is porphyroskelic (Plate 12), and the plasmic fabric silasepic-insepic at 200X. The plasma is a mixture of clay, Fe oxide and some organic matter. The horizon is porous. Voids are mainly compound packing voids. There are some irregular orthovughs and a few metavughs. The channels are mainly single with a few dendritic ones. There are plasma concentrations of Fe oxides and Mn oxides. Worm or insect castings are also observable.

Lithorelics include a few weathered mica pieces.

33-35cm, B21: The skeletal grains are randomly distributed and their predominant sizes are medium and fine sand. The fabric is agglomeroplasmic to porphyroskelic and the plasmic fabric is silasepic to insepic at 200X. The composition of the plasma is clay, coated with Fe oxides. The voids are compound packing voids. The channels are mainly single, with a few dendritic ones. Some of the channels are filled with Mn nodules and fine quartz grains and organic matter. The horizon is porous. The vughs are mainly irregular orthovughs. There are plasma concentrations of Mn and Fe oxides. Weathered or weathering pieces of mica are observable.

43-45cm, B21: The skeletal grains are comparatively fewer than in the overlying layers and are predominantly medium and fine sand. Some large grains are evident. The fabric is agglomeroplasmic to porphyroskelic. The plasma fabric is undulic to silasepic at 160X. The vughs are mostly metavughs, some of which contain Fe oxides. A

PLATE 12. Thin section, Moa series, B21 horizon.



15-18cm (B21), plain light, 80X. Showing Fe oxide coating on channel. Coarser and more sand grains than those in Plate 13, Gbesebu. Also, note plasma concentration of Fe oxides (northeast) and the porphyroskelic nature of the fabric.

thin layer of weakly oriented clay lines a metavugh. There are a few clay 'concentrations' with preferred orientation, probably due to the weather of mica '*in situ*.' Plasma concentrations of Fe oxides are also present in this horizon. The plasma is composed of clay coated with Fe oxide. This layer is less porous. The channels are predominantly single. A channel filled with weakly oriented clay is observable. The channel appears to be below the sesquioxide coating. Some other channels are filled with Mn nodules and organic matter. Pedological features include Mn nodules and some sesquioxides, mainly Fe oxide concentrations (mottles) with undifferentiated matrix. The external boundary of the mottles is irregular.

53-55cm, B22: This section is similar to that from 43-45cm. The skeletal grains are fewer than in the sections described for 33-35cm. It is also denser. The channels are few and are single and dendritic. Some of these channels contain Mn nodules. The vughs are fewer than the above horizon, and are mainly irregular metavughs. The fabric is agglomeroplasmic to porphyroskelic. The plasma is composed of clay coated with Fe oxides. A few weathered mica pieces are present.

65-68cm, B22: This section is similar to that of 53-55cm. The grains are randomly distributed. The fabric is agglomeroplasmic to porphyroskelic. The plasmic fabric is undulic to silasepic at 160X. Vughs are irregular orthovughs. The channels are few, single and dendritic. There are plasma concentrations of clay, Fe oxides and Mn. The clay is coated with Fe oxides.

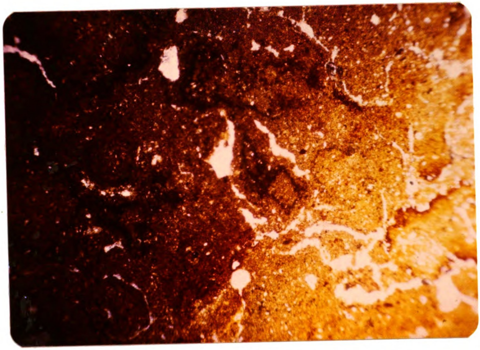
Gbesebu series (Plate 13), 18-28cm, B21b: The skeletal grains are randomly distributed and are few in number. The sizes vary, with the very fine sand grains being most common. The fabric is porphyroskelic and the plasmic fabric is silasepic to insepic at 200X. The plasma is composed of clay mixed with Fe oxides and organic matter. The channels are single and branching, some of which are filled with organic matter (Plate 13a) and others coated with Fe oxide. The vughs are predominantly orthovughs. The matrix is generally dense. Cracks, due to shrinking of the clay, occur in this horizon.

Lithorelics include weathered or weathering pieces of mica and plasma concentrations of Fe oxides and Mn oxides. The clay derived from weathered mica shows a preferred orientation.

35-43cm, B21b: The skeletal sand grains are few and randomly distributed, with very fine grains predominating. The fabric is porphyroskelic and the plasmic fabric is insepic at 200X. The plasma composition is clay coated with Fe oxides. The horizon is dense. There are a few channels and irregular orthovughs. Some of the channels are coated with Fe oxides or filled with organic matter. Lithorelics include plasma concentrations of Mn and Fe oxides (Plate 13b, c).

48-53cm, B22b: There are very few skeletal grains which are randomly distributed. The fabric is porphyroskelic and the plasmic fabric is insepic at 200X. Cracks are common and there is evidence of craze planes. The channels are single and dendritic and some metavughs are also present. A few of the vughs and channels are lined

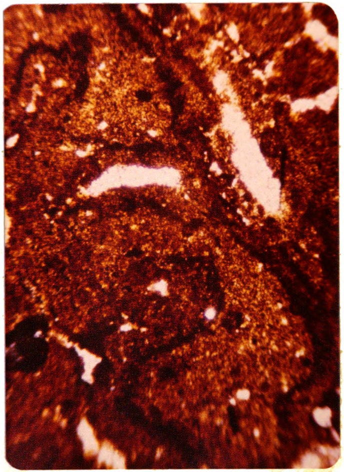
PLATE 13. Thin sections, B21 horizon of Gbesebu series.



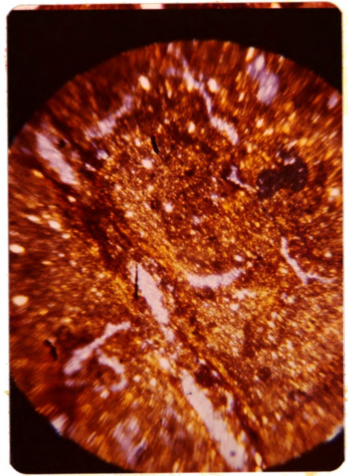
(a)

18-28cm (B21b), X-nicol, 80X. Note the filling of organic matter in the small channels and Fe oxide coatings on some of the ped surfaces. The reddish brown area represents Fe oxide concentrations. Also, note cracks or channels in the southeast corner.

PLATE 13 (continued)



35-43cm (B21b), plain light, 80X. Channels filled with organic matter and Fe oxides. Large white areas are vughs.



35-43cm (B21b), plain light, 40X. Showing Fe oxide lining of channels and silasepic to insepic nature of the plasma.

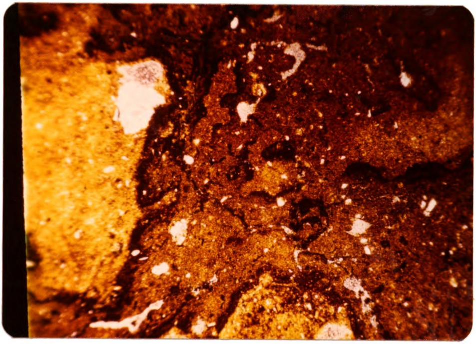
with Fe oxides. Pedological features include plasma concentrations of Mn and Fe oxides. Also weathered mica pieces are present, some of which appear like pieces of 'plasma concentration' of oriented clay.

55-60cm, B22b: This section is similar to the thin section described above. Some of the channels are coated with Fe oxides. Vughs are mostly irregular orthovughs. There are some cracks or channels. The section is comparatively denser. There are plasma concentrations of Mn and Fe oxides. Weathered and weathering mica pieces are evident.

125-130cm, B23 horizon: This section is dense with very few skeletal grains. The fabric is porphyroskelic and the plasmic fabric is insepic at 200X. There are few vughs and channels, and some of the channels contain Fe oxides and some organic material. Thin linings of weakly oriented clay are observed in a few pores. There are plasma concentrations of Fe oxides. Weathering mica pieces are also present.

Makundu series (Plate 14), 45-48cm, AB: The skeletal grains are randomly distributed and are predominantly medium and fine sand grains. The fabric is agglomeroplasmic to porphyroskelic and the plasmic fabric is inundulic to insepic at 100X. The plasma is composed of clay mixed with organic matter and Fe oxides. The horizon is not porous. The channels are single and bifurcating and the vughs are mostly irregular orthovughs. Pellets of organic matter occur in some of the channels and also as plasma concentrations. There are also plasma concentrations of Fe oxides and patches of

PLATE 14. Thin section of Makundu series, B21 horizon.



110-115cm (B21), plain light, 40X. Note the vughs and channels, some of which contain a mixture of organic matter and Fe oxides.

clay with preferred orientation, possibly due to the weathering of mica pieces '*in situ*.'

53-58cm, B1: Skeletal grains are randomly distributed, few, and predominantly fine sand grains. There are a few coarse grains, which were also observed in the AB horizon. The fabric is porphyroskelic and the plasmic fabric is inundulic to insepic at 100X. Channels are few; horizon is massive. There are predominantly metavughs, the lining material being mainly Fe oxides mixed with organic matter. Organic matter also occurs as a pedorelic. There are also Fe oxide concentrations in the form of mottles.

58-63cm, B1: The skeletal grains are few and are randomly distributed. The fabric is porphyroskelic and the plasmic fabric is insepic. The composition of the plasma is clay mixed with Fe oxide and organic matter. The horizon is dense but there are some cracks. The channels are single and bifurcating; some of them are coated with organic matter mixed with Fe oxide. There are both plasma concentrations of Fe oxides (which appear as mottles) and Mn nodules. Organic matter also occurs as pedorelics. There are a few grain argillans, and some channels have patches of weakly oriented clay.

77-82cm, B21: The skeletal grains are few and are randomly distributed. There are also a few coarse sand grains. The predominant grain size is fine sand. The fabric is porphyroskelic and plasmic fabric is insepic at 100X. There are some cracks, and numerous vughs, some of which are irregular orthovughs. There are a few metavughs. Some of these vughs have Fe oxide mixed with organic matter coating their walls. Some of these vughs also contain

Mn nodules and a few have soil material probably brought from overlying horizons as a result of termite or worm activities. There are plasma concentrations of Fe oxide in the form of mottles. Some fecal pellets occur in the plasma as fossil formations. Weatherable minerals are present, mainly mica and a few feldspars. The channels are mainly single and bifurcating. A very few of these channels have patches of weakly oriented clay. There are also 'clay concentrations', possibly due to the weathering of primary minerals in place, lithorelics.

110-115cm, B21 (Plate 14): The skeletal grains are few and are randomly distributed. The size is predominantly fine sand. The fabric is agglomeroplasmic to intertextic and the plasmic fabric is masepic to insepic. The plasma is composed of clay mixed with Fe and some organic matter. The horizon is less porous. The channels are predominantly single, some of which are coated with organic matter mixed with Fe oxides. The vughs are predominantly metavughs, some of which contain Mn and others are lined with Fe oxides. The clay of the plasma shows orientation in some places. There are plasma concentrations of both Mn and Fe oxides which are in the form of mottles. A thin layer of oriented clay was observed.

163-170cm, B22: The sand grains are randomly distributed and they are predominantly medium and fine in size. There are more coarse grains in this horizon than in the overlying ones. It is a dense horizon with predominantly single channels. The fabric is intertextic and the plasmic fabric is insepic. This layer resembles a B3 or C1 horizon. Also present are weatherable minerals and plasma concentrations of Fe oxide and Mn. The plasma also contains some organic matter.

Discussion of Thin Sections of Gravelly Soils (Baoma, Manowa, Njala, Makeni and Timbo

Both thin sections from the soils as a whole and individual ironstone nodules were studied. Nodule is used instead of concretions in this discussion. Nodules as defined by Brewer and Sleeman (1964) are glaebules with an undifferentiated initial fabric, which include recognizable rock and soil fabrics. The glaebules in the gravelly soils meet this definition.

The lack of illuvial clays in the B horizons of the soil matrix of Baoma, Manowa and Makeni series suggests that clay is not actively moving in these profiles (Plates 2, 5 and 7). The illuvial clays observed are within the ironstone nodules (Baoma, Manowa and Makeni) found in the B horizons (see detailed discussion below), indicating that active clay movement occurred at an earlier stage in the soil development. The presence of sesquioxide coatings in channels and on surfaces of nodules found in the sections studied suggests that some sesquioxides are moving within these profiles. Some structural development was observed in the matrix of the thin sections studied, as depicted by the presence of craze planes. The structure is not massive or similar to that of rock structure, as is diagnostic of cambic horizons. These observations, therefore, suggest the presence of an oxic horizon in the control sections of these profiles, a requirement for the order Oxisols. van Vuure and Miediema (1972) reported argillans in the B horizon of the same Makeni profile that was studied in this research, and suggested the order Ultisol. This study does not support this view, which is also not confirmed by clay analyses discussed earlier.

In the Njala series, degraded argillans were observed in a few channels (Plate 5a, b) and on the surface of some nodules. However, the bulk of the sections observed lack these degraded argillans and it is doubtful whether the percentage of illuvial clay required for an argillic horizon will be met in the control section. Fine clay analysis (previously discussed) did not indicate the presence of an argillic B horizon in this profile. The order Oxisol is, therefore, suggested for this series also.

Clearly evident in the thin section study of the Timbo profile is that clay movement is not an active process. Thin sections examined for the Timbo series were from the A and AB, B21 and B22 horizons. No illuvial clay was observed in channels or vughs. However, the structure is dense and shows some resemblance to rock structure. Also, quite a few weatherable minerals were observed in the soil matrix. Grain counts for the B horizon show enough weatherable minerals that it meets the requirement of a cambic horizon. The profile is believed to have a cambic horizon in the Upper B and, therefore, belongs in the order Inceptisol.

Discussion of Ironstone Nodules (Plate 15)

Thin sections of nodules from the five gravelly soil series discussed above were studied. The thin sections were made of representative nodules from each of the horizons described in these profiles.

Two main types of nodules were recognized. Type 1 nodules (Plates 5a, b, c; 6a, b, c; 9a, b) have basically a rock structure.

PLATE 15. Macromorphology of ironstone nodules: (a) Types 1a and b; (b) Type 2a.

(a)

Types 1a and 1b ironstone nodules. Left to right: first, subsurface and, second, surface horizon, Njala series (Type 1a); third, subsurface and, fourth, surface (A1), Timbo series (Type 1b).

PLATE 15 (continued)

(b)

Type 2a. Left to right: first, subsurface; second, surface; third, subsurface cut - Makeni series. Fourth, subsurface and, fifth, surface of Baoma series. Note the large pore on the top of the surface Baoma gravel.

Each is apparently a rock fragment which has been weathered in place to release Fe oxide that acts as a cementing agent or a rock fragment that is being weathered and impregnated by Fe oxide. In the latter situation, la, the Fe oxide tends to concentrate on the edges of the nodules, channels into the nodules and, in some cases, the Fe oxide appears as specks in the matrix of the nodules. The nodules from the Njala series are representative of Type la (Plates 5a, b, c and 12).

In the Type lb, the Fe oxide tends to concentrate within the matrix in places where primary minerals have been weathered to release Fe oxides. This nodule is porous, possibly as a result of minerals which have been weathered out in place. This kind of nodule tends to have a high concentration of weatherable minerals within them (Plate 9a, b). The nodules from the Timbo soils are representative of this kind of Type 1 nodule. Type lb nodules are what have been described as residual laterite (Alexander and Cady, 1962).

Type 2 nodule basically developed as a result of plasma concentration or separation of Fe oxides. Two kinds may be recognized in this type. In 2a, the matrix resembles that of the surrounding soil material (Plates 7a, b and 15). Basically, a concentration of Fe oxide has cemented the soil material together. In 2b (Plate 8c), there is basically a plasma concentration of clay or Fe oxide or clay coated with Fe oxide, with or without a few sand grains, which sometimes act as nuclei (Plate 2b, c, d, f). Type 2 may be considered as indurated plinthite (ironstone), derived from mottles or plasma concentrations of clay coated with Fe oxide. A third kind, 2c, shows preferred oriented clay derived from the weathering of primary minerals '*in situ*' and then coated with Fe oxide. These kinds of Type 2 nodules are usually smaller than the other types. It occurs mostly in the coarse sand fraction of gravelly profiles. This fraction in the gravelly profiles is usually made up of 50 to 60% ironstone nodules.

In some of the above profiles, at least two of the possible kinds suggested under Type 2 occur in the same horizon (Plate 2f), i.e., the Baoma and Makeni series. It should be noted at this point that other researchers, including Alexander and Cady (1962), have recognized the two *broad* types of nodules similar to Types 1 and 2 discussed above. Westerveld (1969) identified two types of ironstone nodules in the Njala series based on different criteria. His type distinction is based on the external appearance of the nodules, i.e., SLC (Smooth Laterite Concretions) and RLC (Rough Laterite Concretions).

The Type 1 nodules identified in this research predominate in the Njala and Timbo series. Smaller proportions of Types 2a and 2c are also present in the Njala series. Type 2 nodules predominate in the Baoma, Makeni and Manowa series.

For Fe oxide concentration, two major conditions are necessary: (1) an approximately equal length of wet and dry season, and (2) fluctuating water tables. It seems reasonable to assume that condition (1) plus intense weathering is more prone to produce the Type 1 nodule than condition (2) and that the Type 2 nodules (especially 2a and 2b) tend to be mainly the result of condition (2). This idea may be supported by the definition of plinthite and theories concerning its development (Soil Survey Staff, 1975). Type 2 nodules are here considered to be true ironstone, which is the hardened form of plinthite. Type 1 nodules are here considered as pseudo-ironstone. Sys (1968) suggested the name petroplinthite for ironstone nodules. In my view, this name should be applied to the Type 2 nodules discussed above. The term pseudo-petroplinthite is being suggested for the Type 1 nodules.

The presence of argillans (ferri-argillans) in the vughs and channels of some of the nodules studied in the Makeni, Manowa and Baoma soils and the absence of similar situations in the soil matrix proper (Plate 2d, e) may be due to one of the following reasons: (a) that the nodules are derived from an earlier soil material in which illuviation took place and have been transported and redeposited in their present location, or (b) that the nodules reflect illuviation processes which took place in the profiles in an earlier stage of development and have been preserved within the nodules.

The roundness of the gravels in the upper horizons (Appendix A) tends to support (a) that at least the surface gravels must have been transported from another source and redeposited in their present position. Westerveld (1969) and Odell et al. (1974) have suggested that the gravels of the upper horizons are colluvial in origin.

However, based on: the topographic location of the profiles; thin section studies conducted here, which show striking similarity between the surface gravels and those in the subsoil (see description of nodules, Plates 3, 6 and 7); the similarity in clay mineralogy of the A and B horizons of representative profiles (Westerveld [1969] also observed similarity in the mineralogy of the SLC and RLC gravels which he identified in an Njala profile and suggested that with passing of time the RLC would become SLC); and the slaking of the nodules (surface and subsurface) after shaking with distilled water for six hours in a reciprocating shaker (Table 5), the reason proposed in (b) is more likely than (a).

The appearance of the nodules in the surface horizon can be explained if the nodules (particularly Type 2) were formed below the soil surface at a time when the soil was wetter or at a zone of fluctuating water table, which became exposed at the surface, after uplift, followed by erosion.

The roundness of the surface nodules is probably a result of the action of intense rainfall which caused slaking by solution or abrasion between nearby nodules or external weathering of the nodules.

From the preceding discussion, the need for recognition of the ironstone nodules at some level of classification in the Soil Taxonomy (1975) arises. Recognition at the family level is hereby suggested. It is proposed that the term petroplinthic (Sys, 1968) be used in place of skeletal at the family level, if 35% or more of the coarse fragments in the upper 1.25m of the profile is composed of ironstone nodules (both Types 1 and 2), e.g., clayey-petroplinthic oxidic, etc.

The term petroplinthic will also reflect the genetic nature of the greater than 2mm fraction as opposed to skeletal, which refers mainly to primary rock or mineral fractions >2mm.

Discussion of Thin Sections of Non-Gravelly Soils (Segbwema, Pendembu, Masuba, Moa, Gbesebu and Makundu)

Both Segbwema and Masuba soils have illuvial clays in their B horizons. Taking the thickness of the horizons into consideration, their B horizons meet the requirements of an argillic horizon. Hence, the order Ultisols is suggested in view of their associated low base saturation. This observation is in agreement with the B/A and/or fine clay/total clay ratios of the two profiles. The thin section examinations of Segbwema series show many embedded grain argillans (Plate 10c, d).

Plate 10e, f and g shows thin sections across weathered mica pieces in the B horizon of Segbwema. Several weathering zones are observed that have high birefringence of oriented clays. Many of those mica-like flakes occur in the sand fractions, especially the very fine to medium sand of the horizons identified in Figure 9c. The profile x-ray analysis of the mica-like flakes in the sand fractions showed that these flakes are not true micas, but weathered material composed of interstratified clay minerals (illite-chlorite), kaolinite and gibbsite. The bands seen in the thin section represent layers of clay minerals. The outermost layer is assumed to be kaolinite, and the inner layers are believed to be the interstratified clay minerals and gibbsite.

Also, embedded grain argillans are present in the Masuba series, Plate 11b. The pedotubule shown in Plate 11a is the result of soil material from an overlying horizon filling a cavity created by the activities of soil organisms.

A few argillans were observed in the Pendembu and Makundu profiles. However, the amount of illuvial clay is very small and it is doubtful whether these soils have argillic horizons. The B/A and/or fine clay/total clay ratios of these soils do not indicate the presence of argillic horizons.

No argillans were observed in the Moa and Gbesebu series, confirming the absence of argillic horizons in these profiles. The dense appearance of the matrix of Pendembu, Moa, Gbesebu and Makundu suggest possible cambic horizons. Grain counts of the very fine and fine sands show the presence of a cambic horizon with weatherable minerals within the control section of the Moa, Gbesebu and Makundu profiles. Therefore, these three profiles meet the requirement of Inceptisols.

The occurrence of Fe oxide on ped surfaces and in channels in Moa, Gbesebu and Makundu profiles suggests that Fe oxide is actively moving in these profiles. This is in agreement with earlier observations for extractable Fe oxides in these profiles (Figure 3d).

Proposed Classification of the Soils

Diagnostic Horizons

The most important diagnostic horizons recognized in this study are umbric and ochric epipedons and argillic, oxic and cambic subsurface horizons. Detailed discussions of these horizons are given in Soil Taxonomy (1975).

Umbic epipedon: This is a surface horizon that is dark and has more than 0.6% organic C. It is usually 25cm or more thick and has a base saturation of <50% and less than 250ppm P_2O_5. Munsell colors for this horizon are values darker than 3.5 and chromas of less than 4 when moist. Five of the eleven profiles have umbric epipedons.

Ochric epipedons: This is a surface horizon that is too high in value and chroma, too low in organic C, or too thin to be an umbric epipedon or other related surface horizon. Six of the eleven profiles have ochric epipedons.

Argillic horizon: This is a subsurface horizon in which illuvial lattice silicate clays have accumulated to a significant extent. If an eluvial horizon remains and if there is no lithologic discontinuity between it and the argillic horizon, the argillic horizon contains more total clay and more fine clay than the eluvial horizon. The requirements for an argillic horizon are: If the eluvial horizon has <15% total clay, the argillic horizon should contain a minimum of 3% more clay. Ratio of fine clay to total clay is greater in the argillic horizon by one-third or more than that of the overlying and underlying horizons.

If the eluvial horizon contains 15-40% clay, the argillic horizon should have a minimum of 1.2 times more clay than the eluvial horizon or one-third more fine clay to total clay ratio than the overlying and underlying horizons.

If the total clay content of the eluvial horizon is 40% or more, the argillic horizon should have at least 8% more clay than the eluvial horizon, or meet the requirement as described above for fine clay to total clay. If the total clay in the eluvial horizon is >60%, 8% more fine clay is required in the argillic horizon.

These clay increases should occur within a vertical distance of 30cm or less, and the argillic horizon should be at least 15cm thick.

Since clay has moved, the presence of clay skins in pores and on ped faces is diagnostic of argillic horizons. Also, thin sections should show 1% or more of oriented clay.

In the soils studied, identification of clay skins in the field was extremely difficult, as they were poorly developed. Laboratory examination of thin sections from ten of the eleven profiles studied showed that only two profiles, Segbwema and Masuba series, have enough illuviated clays to meet the requirements of an argillic horizon in their B horizons. Other oriented clays observed are mainly within ironstone nodules (Baoma, Manowa and Makeni series).

If only the illuvial/eluvial clay* ratio of total clay is used to identify argillic horizons (Table 2), then Njala, Baoma and Manowa series will also have argillic horizons. However, the fine clay to total clay ratio together with thin section observations do not support the presence of argillic horizons in these profiles.

Oxic horizon: This is a mineral subsurface horizon in an advanced stage of weathering. It is an altered horizon that is at least 30cm thick. It consists of a mixture of hydrated oxides of Fe or Al or both with variable amounts of 1:1 lattice clay, and resistant minerals such as quartz + zircon. It contains more than 15% clay and the texture should be sandy loam or finer. The fine-earth fraction has a total of less than 10me per 100gm of clay of 1N NH_4OAC extractable bases plus Al extractable with 1N KCl. The C.E.C. of the fine-earth fraction is <16 me/100gm clay by NH_4OAC, unless there is appreciable content of Al interlayered chlorite. The horizon should have less than 3% weatherable mineral, or <6% muscovite, in the 20-200μ fraction and less than 5% by volume of

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*$Clay_1$.

rock structure. Boundaries between horizons are diffuse or gradual and clay skins are very few or absent.

The subhorizons of all the soils studied have one or more characteristics of an oxic horizon. Some of them, however, have other diagnostic characteristics that exclude them from the oxic horizon or do not have all the characteristics of an oxic horizon. Baoma, Manowa, Njala, Makeni and Pendembu series all meet the above criteria for oxic horizons. Moa, Gbesebu, Makundu and Timbo soils have diagnostic properties of oxic horizons in the subsoils but are excluded because they have too high a percentage of weatherable minerals. Moa, Gbesebu and Makundu soils have more than 6% mica, which is predominantly muscovite. Muscovite in the Makundu series is slightly weathered to give both the characteristic 10A° peak for mica and 7.2A° peak for kaolinite.

The Timbo series has >6% mica in subhorizons. However, x-ray analyses (see discussion on x-ray analyses) of the flakes from the sand fractions show that the material identified by optical methods as mica is not true mica but a mixture of interstratified illite-chlorite, kaolinite, and some gibbsite. If this material is accepted as mica (for classification purposes), then Timbo series will be excluded from the oxic horizon or otherwise it will be considered to have an oxic B horizon.

<u>Cambic horizon</u>: This is a slightly altered B horizon that lacks characteristics of an argillic horizon, and with no cementation or induration. Evidence of alteration includes strong chroma, redder hues or higher clay contents than the underlying horizons, gray colors associated with a regular decrease in organic matter with

increasing depth, lack of properties of umbric epipedons, textures of loamy fine sand or finer, soil structure or the absence of rock structure in at least half of the volume, and >3% weatherable minerals or >6% muscovite.

Gbesebu, Moa, Makundu and Timbo* series meet the mineralogical requirement. Also, the Timbo series has >5% rock fragments in its subsoil.

Classification of the Soils

Baoma and Manowa series: These soils are found in soil province L on summits and convex slopes. They are well drained. Manowa soils are very gravelly (Type 2a) from the surface to depths greater than 175cm. The gravel content in the Baoma series is comparatively low, especially in the surface 58cm.

Manowa has an umbric epipedon and Baoma an ochric epipedon. These soils have oxic B horizons. Manowa is classified in the clayey skeletal, oxidic, isohyperthermic family of Typic Umbriorthox. Baoma series is classified as clayey skeletal, oxidic, isohyperthermic family of Typic Haplorthox.

Njala series (P109): This soil is well drained and is found on stable upland surfaces of soil province G. It is gravelly from the surface to depths greater than 155cm. The gravel is predominantly Type 1a (see thin sections) - shale-like fragments that have been impregnated by Fe oxide. At lower depths (>155cm) the gravels are

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*Not true mica (see discussion on x-ray analyses).

softer. The percent gravel decreases with depth. The surface diagnostic horizon is umbric and the subsurface meets the requirements of an oxic horizon.

Thin sections show only relics of oriented clay. The percent total clay increases gradually with depth. The I/E horizon ratio of total clay increases with depth, and fine clay shows decreases with depth rather than a zone of accumulation, common in argillic horizons. The soil is classified as clayey-skeletal, kaolinitic, isohyperthermic, family of Typic Umbriorthox.

Makeni series: This soil is well drained and occupies a similar physiographic position to the Njala series. It accounts for a high percentage of the upland soils in soil province J. It is gravelly from the surface to >168cm. This is mainly Type 2a gravel. Some weathered bedrock gravels (Type 1b) are found in the deep layers.

The diagnostic surface horizon is umbric (0-25cm) and the subsurface horizon is oxic (25-168cm), as confirmed by thin sections and fine clay analyses. This soil is classified as clayey-skeletal, oxidic, isohyperthermic, family of Typic Umbriorthox.

Segbwema series: This soil is well drained and it occurs on steep slopes in soil province L. It has an ochric epipedon (0-33cm), comparatively high cation exchange capacity that is >16 mg/100g clay in the upper B horizon, high percentage of weatherable minerals, and an argillic horizon (33-150cm) that is identified by oriented clay in thin sections and a fine clay to total clay ratio in the argillic horizon of >1/3 that of the overlying and underlying horizons. It is classified as clayey, kaolinitic, isohyperthermic, family of

Orthoxic Tropudults (or may be placed in the great group Kandiudults [Moormann et al., 1977]).

Timbo series (P19): This soil is well drained and it occurs on moderate to steep slopes. It is very gravelly from the surface to >175cm. Most of the gravels are decomposed bedrock fragments, some of which occur at the surface. This soil is high in weatherable minerals, predominantly mica.* The diagnostic surface horizon is umbric (0-48cm) and the subsoil has a number of properties diagnostic for oxic horizons. However, the greater than 5% rock structure and the high percentage of mica (if accepted as one) exclude the Timbo series from the oxic horizon. It can be classified as clayey-skeletal, oxidic, isohyperthermic family of Ustoxic Dystropepts. Ustoxic is used because Timbo has about four months of drought period (as defined earlier). If the weathered flakes are not considered as mica and the rock fragments are disregarded, then the soil can be classified as Typic Umbriorthox.

Pendembu series: This imperfectly drained soil occurs on Foot-slopes and Upper Tributary Terraces. The surface horizon is ochric. Thin section studies of several layers of the B horizon did not show oriented clays.** Percent clay shows a gradual increase with depth, a pattern similar to that of Njala, Makeni, Baoma and Manowa soils. The I/E horizon clay ratio is less than 1.2 in the upper two B

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*Not true mica (see discussion on x-ray analyses).

**Clay coatings were reported observed in the field by Sivarajasingham (1968).

horizons. Also, the ratio of fine clay to total clay does not indicate the presence of an argillic horizon. Also, the percent of weatherable mineral in the 20-200μ fraction is less than that required for a cambic horizon. This soil is therefore classified in the fine-loamy, oxidic, isohyperthermic family of Epiaquic Haplorthox.

Masuba series (P9): This is a moderately well-drained soil that occurs on the lower part of tributary stream terraces. The texture is sandy clay loam throughout the profile, but there is higher percent clay in the B horizon that meets the requirement of I/E horizon ratio of 1.2 or greater in the illuvial horizon. Also, thin sections show oriented clays in the B horizon. The diagnostic surface horizon is ochric. This soil is classified in the fine-loamy, mixed, isohyperthermic family of Typic Paleudults. If there are >10% weatherable minerals in the 20-200μ fraction, this soil would be classified as Orthoxic Tropudults.

Moa series: This soil occurs on alluvial river terraces of large streams in the Moa basin of soil province L. It is moderately well to well drained. The surface horizon is ochric (0-15cm) and the subsoil has some properties of the oxic horizon. However, grain counts show >6% weatherable minerals in the 20-200μ fraction. The dominant mineral is muscovite mica. The soil is classified in the fine, kaolinitic, isohyperthermic family of Fluventic Oxic Dystropepts.

Gbesebu series (N125): This soil is found on Alluvial Floodplains and is moderately well drained. This soil has properties in the B horizons that are characteristic of an oxic horizon, but has >6% mica in the 20-200μ fraction, which excludes it from the oxic horizon. The mica is mainly muscovite that is slightly weathered. X-ray diffraction of the mica in the sand fraction gave the characteristic 10A° peak for mica and a 7.2A° peak for kaolinite, showing that part of the mica has been weathered to kaolinite. The mica observed here is different from that found in the Segbwema and Timbo series. Total clay analysis shows a slight accumulation in the B horizon. Fine clay analysis and thin section study did not support the presence of an argillic horizon. The surface epipedon is ochric and the classification is very fine, oxidic, isohyperthermic family of Fluventic Oxic Dystropepts.

Makundu series (P104): This soil occupies a physiographic position similar to that of the Gbesebu. It is found in soil province J. The drainage is moderately well to well drained. The diagnostic surface horizon is umbric. The B horizon has some properties diagnostic of an oxic horizon, as in the case of the Gbesebu series, but there are >6% weatherable minerals, predominantly muscovite mica, in the 20-200μ fraction. Total clay distribution is similar to that of Gbesebu series. Thin sections did not show significant amounts of oriented clay. This soil belongs to the very fine, kaolinitic, isohyperthermic family of Fluventic Oxic Dystropepts.

General Discussion

The above classifications for the gravelly soils do not take into account the presence of the ironstone nodules (petroplinthite and pseudo-petroplinthite) that are common in these soils. At the family level the term skeletal, however, indicates the presence of coarse fragments >2mm, in excess of 35% in the profile. The ironstones are different from the rock fragments found in temperate regions and in the U.S. in particular, where Soil Taxonomy (1975) was developed. These nodules are usually part of the 'soil system' as they are derived from it or reflect the genetic processes within the profile. Also, in this study it has been shown that these nodules have active surfaces (see phosphate adsorption) that can fix P. Therefore, there may be a need for the nodules to be considered in higher categories than family in Soil Taxonomy (1975). However, additional research is needed to justify their inclusion at a higher category of classification.

The proposed classifications of the eleven profiles studied and their previous classifications are given in Table 9.

If the proposal for modification at the family level is considered, the gravelly soils would be classified as follows:

Baoma series	Typic Haplorthox	clayey-petroplinthic, oxidic
Manowa series	Typic Umbriorthox	clayey-petroplinthic, oxidic
Njala series	Typic Umbriorthox	clayey-petroplinthic, kaolinitic
Makeni series	Typic Umbriorthox	clayey-petroplinthic, oxidic
Timbo series	Ustoxic Dystropepts	clayey-skeletal, oxidic

Table 9. Proposed classification of the eleven profiles according to the Soil Taxonomy (1975)

Soil Series	Diagnostic Surface Horizon	Diagnostic Subsurface Horizon	Order	Proposed Subgroup	Previous Subgroup (Odell et al., 1974)	Family*
Baoma 144801A	ochric	oxic	Oxisol	Typic Haplorthox	Typic Paleudults (or Tropeptic Haplorthox)	clayey-skeletal, oxidic
Manowa (Kpuabu 1)	umbric	oxic	Oxisol	Typic Umbriorthox	Orthoxic Palehumults (or Typic Umbriorthox)	clayey-skeletal, oxidic
Njala (P109)	umbric	oxic	Oxisol	Typic Umbriorthox	Orthoxic Palehumults	clayey-skeletal, kaolinitic
Makeni (P2)	umbric	oxic	Oxisol	Typic Umbriorthox	Typic Paleudults	clayey-skeletal, oxidic
Segbwema 145005	ochric	argillic	Ultisol	Orthoxic Tropudults	Tropeptic Haplorthox (or Udoxic Dystropepts)	clayey, kaolinitic
Timbo (P19)	umbric	cambic	Inceptisol	Ustoxic Dystropepts	Typic Umbriorthox (or Udoxic Dystropepts)	clayey-skeletal, oxidic
Pendembu (Kpuabu 2)	ochric	oxic	Oxisol	Epiaquic Haplorthox	Typic Paleudults	fine-loamy, oxidic

Table 9 (continued)

Soil Series	Diagnostic Surface Horizon	Diagnostic Subsurface Horizon	Order	Proposed Subgroup	Previous Subgroup (Odell et al., 1974)	Family*
Masuba (P9)	ochric	argillic	Ultisol	Typic Paleudults	"Plinthic" Udoxic Dys-tropepts	fine-loamy, mixed
Moa (Kpuabu 3)	ochric	cambic	Inceptisol	Fluventic, Oxic Dys-tropepts	Tropeptic Hap-lorthox (or Fluventic Udoxic Dystropepts)	fine, kaolinitic
Gbesebu (N125)	ochric	cambic	Inceptisol	Fluventic, Oxic Dys-tropepts	Fluventic Udoxic Dys-tropepts	Very fine, oxidic
Makundu (P104)	umbric	cambic	Inceptisol	Fluventic, Oxic Dys-tropepts	Plinthic "Tro-peptic" Umbri-orthox	Very fine, kaolinitic

*All isohyperthermic temperature regime, acidic reaction.

Proposed Hypothesis for the Genesis of the Soils

Differences in stages of development of the soils studied are the results of differences in kinds of parent materials and the rate and direction of physical, chemical and biological processes.

Three main stages in the development of the profiles are proposed. These are: (1) weathering of primary silicate minerals, (2) formation and illuviation of clay, and (3) accumulation of Fe and the formation of plinthite and ironstone nodules.

Weathering of Primary Silicate Minerals

The rate of weathering in Sierra Leone is very rapid. This is favored by the high temperatures and abundant rainfall. Primary silicates are rapidly weathered to release bases (mainly Ca and Mg), Si, Al, and Fe. The bases are easily lost from the soil, by leaching with excess moisture. The Si and Al combine to form 1:1 secondary clay minerals (mainly kaolinite). Kaolinite is the predominant clay mineral present in the soils studied.

The changes from primary silicate to kaolinite can take place within a short distance (Plate 10e, f, g). Two diagnostic soil horizons are related to the degree of weathering. These are the cambic and the oxic horizons. A cambic horizon represents a lesser degree of weathering and it is characterized by the presence of appreciable amounts of weatherable minerals. An oxic horizon represents a strongly weathered condition. It is characterized by the presence of few or no weatherable minerals and low cation exchange capacity.

The soils of the Upland Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni series) have oxic horizons. These soils are on stable landscapes, on which infiltration predominates. The abundant supply of moisture that moves through the profile, coupled with high temperatures, resulted in the strongly weathered profiles of these soils in which the released bases and Si have been depleted.

In the soils of the Steep Hills and Slopes (Segbwema and Timbo series), runoff predominates over infiltration. This resulted in less weathered and developed profiles, where appreciable amounts of weatherable minerals are still present. This explains the presence of a cambic horizon in the Timbo series. Weatherable minerals are also present in the Segbwema series. However, profile development has advanced to the stage at which illuvial clay is present in the B horizon.

Erosion is common on soils of the Steep Hills and Slopes. New surfaces are continuously exposed, which in some cases contain rock fragments, e.g., Timbo series. These exposed rock fragments are then subjected to the sequence of weathering and release of bases, Si, Al, and Fe . Under good vegetative cover, erosion is reduced and more moisture tends to move through the profile. This gives rise to a more advanced stage of profile development, similar to that of the Segbwema series.

The presence of an oxic horizon in the Pendembu series of the Colluvial Footslopes and Upper River Tributary Terraces is a reflection of the nature of the weathered material from which this soil is developed.

The soils of the Alluvial Terraces and Floodplains (Moa, Gbesebu and Makundu series) have cambic horizons. This reflects the nature of the eroded materials derived from the catchment area. They include weathered materials high in kaolinite and sesquioxides but also some weatherable minerals from soils on the steep slopes.

Illuviation of Clay

Two processes are involved in the formation of an illuvial clay horizon. These are: (1) eluviation of clay from the surface horizons and (2) accumulation of the eluviated clay (illuviation) in the subsoils.

Eluviation is favored by silica as a dispersing agent, or lack of excess Fe and excess infiltration over runoff and evaporation. This condition prevails during the rainy season. Illuviation (deposition from suspension) is favored by dry conditions. Both wet and dry conditions occur in Sierra Leone, giving rise to the development of eluvial and illuvial horizons. The illuvial horizon so formed is referred to as the argillic horizon. This horizon is characterized by the presence of argillans or clay skins on ped surfaces.

In the soils of the Steep Hills and Slopes, an argillic horizon is present in the Segbwema series. In the soils of the Colluvial Footslopes and Upper River Tributary Terraces, Masuba series also has an argillic horizon.

The presence of an argillic horizon represents an intermediate stage between the cambic and the oxic subsurface development of the profiles studied.

In the soils of the Upland Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni series), illuvial clays are believed to occur at depths greater than five feet. The possible reason is the result of deep movement of percolating water carrying eluvial clay, during the wet season.

Accumulation of Fe and the Formation of Plinthite and Ironstone Nodules

Intense weathering of silicate minerals releases, among other things, Fe. Mobilization of the released Fe is favored by low redox potential, and this condition can be achieved under fluctuating water table or waterlogged conditions. In the soils studied, mobilization of Fe is favored during the rainy season. The transportation of Fe occurs within relatively short distances in the profiles. During dry periods the mobilized Fe is oxidized (usually around large pores). This oxidized Fe subsequently accumulates to give bright mottles.

Plinthite is a more strongly developed mottled horizon which in addition to Fe oxides includes highly weathered mixtures of clay, quartz and other diluents. It is usually red in color. It becomes irreversibly hardened on exposure to wetting and drying. During the hardening process segregation and crystallization of Fe occurs. The hardened mottles are referred to as ironstone nodules. High rainfall and prolonged dry seasons, such as those in Sierra Leone, are favorable for the formation of plinthite and ironstone.

In the soils of the Upland Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni), ironstone nodules occur from the surface horizon to depths greater than five feet. Below this depth the nodules are soft.

The occurrence of ironstone nodules at the surface may be the result of: (1) transportation and deposition from another source or (2) erosion of surface gravel-free layers, to expose subsoil material.

The round shape of the surface gravels tends to support the idea of transportation from other sources (Sivarajasingham, 1968; Westerveld, 1969). Data obtained in this study and discussed earlier, however, support the idea of erosion and *in situ* development of the ironstone nodules.

Also, argillans described in old channels present in the ironstone nodules of Baoma, Manowa and Makeni series reflect the past genesis of the profiles. They also suggest that Fe accumulations in these profiles occurred at a later stage in the profile development, than illuviation of clay. The removal and accumulation of Fe represents an advanced stage in the profile development of the soils. At this stage, excess Si released by weathering of primary silicates has been removed from the profiles.

Fe movement seems to be an active process in the soils of the Alluvial Terraces and Floodplains (Plates 12 and 13).

The sequence in the genesis of the profiles studied can be summarized as follows:

(1) Parent material rich in primary silicates → cambic horizon (Inceptisol) → illuviation → argillic horizon (Ultisol)

——————————→ oxic horizon (Oxisols)
removal of Si, movement and accumulation of Fe. Extreme weathering, and breaking down of kaolinite to release gibbsite

(2) Parent material rich in kaolinite and sesquioxides → cambic horizon (Inceptisols) → oxic horizon (Oxisols)

The second sequence is proposed for soils of the Alluvial Terraces and Floodplains.

Significance to Land Use and Management

The usefulness of the research conducted here to characterize the soils depends on its applicability for crop production and other land use practices adopted by landowners and planners.

At the lower levels of classification, soil properties that significantly influence the use and management of the soils are taken into consideration. These properties include: slope (erosion hazard), surface texture (including gravels or stones), unfavorable layers such as gravel or rock, moisture holding capacity, nutrient status, and wetness. These may be used as phase separations at any category level with Soil Taxonomy (1975).

In the soils studied, the most important properties that require attention, aside from nutrient status, are erosion hazard, soil moisture holding capacity and unfavorable layers of gravels (including surfaces).

Erosion Hazard

This is a serious problem in Segbwema and Timbo series. These soils are well drained and are usually located on slopes >6%. This poses a moderate to severe erosion hazard, particularly if the land is cleared. The problem is more severe in Segbwema series, which is usually on steeper slopes than the Timbo series. Also, the high percentage of surface gravels in the Timbo series absorbs the impact of the intense rain characteristic of Sierra Leone, thereby reducing the detachability of the finer soil particles, hence minimizing soil loss. These soils preferably should be left under continuous vegetative cover, as they are too steep and erosive for cultivated crops.

Erosion hazard is not a serious problem in Baoma, Manowa, Njala and Makeni series, especially in those that occur on 0-3% slopes. However, on the sloping variants of these soils (3-15% slopes), continuous cultivation is not recommended as it will cause serious erosion problems, despite the surface gravels. A modified form of shifting cultivation, with longer fallow periods, will help to build a more stable soil structure and minimize erosion. Since a permanent vegetative cover is necessary to control erosion on these soils, forestry or permanent tree crops such as coffee, cocoa (Plate 1b) or citrus can be cultivated.

Pendembu, Masuba, Moa, Gbesebu and Makundu series all have little or no erosion problems. They are imperfectly to well drained soils and are found on fairly flat land surfaces (0-3% slopes). However, soil loss by erosion could be a serious problem if the surface soils are not properly managed, i.e., by correct timing of tillage operations. Destruction of surface structure and creation of a compact layer below the plow layer will reduce infiltration and cause surface runoff, particularly in Gbesebu, Makundu, and Moa series that have very fine textures.

Available Moisture Holding Capacity

This is an important factor that affects the use of the soils studied for agricultural production. Soil texture and organic matter content are soil properties that influence the amount of water that is retained against gravity and that will become available for utilization by plants. These properties have been discussed previously and are listed in Tables 2 and 3. Available moisture capacity is greatest in soils that contain much silt. The Segbwema series has a medium water holding capacity (Table 10) and experiences a drought period of three months. Timbo soil is very gravelly and has a more sandy surface horizon than Segbwema series. As a result of these two factors, it retains less water for utilization by crops. Timbo has a very low available moisture holding capacity and experiences four months of dry period. Manowa, Njala and Makeni series have clay to clay loam textures in their control sections but are also very gravelly (50-80% gravels by weight). The latter characteristic contributes to the fact that these soils have a low or very low available water holding capacity. They experience about four to five months of drought period. Cultivation of a second crop annually is possible in these soils with irrigation. This, however, is a very expensive operation and is not recommended, as these soils have low natural productivity. The Baoma soil is less gravelly, has a low moisture holding capacity and a drought period of about four months. The Pendembu and Masuba series have comparatively sandy profiles. They are imperfectly drained and moderately well drained, respectively. Masuba has medium water holding capacity and a drought period of three months. The water holding capacity of Pendembu series is slightly lower than that of Masuba. Also, Pendembu series is waterlogged for about one to two months during the rainy season, and only experiences a short drought period. Both of these soils are naturally poor in nutrients. With adequate fertilization they can be used for continuous crop production. A second crop is possible annually with irrigation.

The Moa, Gbesebu and Makundu series all have medium or high available moisture holding capacity and a short drought period of

Table 10. Groupings for available moisture capacities*

Designations	Units of available moisture capacity per unit of depth	Available moisture holding capacity to 1524mm (60 inches) (mm)	(inches)	Soil Series
Very low	0.01 - 0.03	15-51	0.6-2	Manowa, Makeni and Timbo
Low	0.03 - 0.06	51-102	2-4	Baoma, Pendembu and Njala
Medium	0.06 - 0.11	102-178	4-7	Makundu, Moa, Masuba and Segbwema
High	0.11 - 0.18	178-279	7-11	Gbesebu
Very high	0.18 - 0.25	279-381	11-15	

*Taken from Odell et al. (1974)

one to two months. The textures are clayey (very fine or fine), but their silt contents are moderate (15, 30 and 26%, respectively). Gbesebu and Makundu soils may be flooded for short periods during the rainy season, and Moa may be waterlogged for a short period. These soils are the most productive soils among the groups studied. Two crops can be grown in these soils annually with minimum irrigation.

Influences of Ironstone Gravel (Unfavorable Layer of Gravel)

This is of importance in Baoma, Manowa, Njala, Makeni and Timbo soils. The serious effects of the gravel on crop production are: (a) inhibit proper development of roots, (b) reduce the contact between roots and the finer soil particles, and (c) contribute to the reduction of the amount of available water that is retained by the soil per unit volume.

The gravels do not, however, pose serious problems to plowing, because of their comparatively small size (about 3cm or less in diameter). The above limitations affect the productivity of these soils and the amount of nutrients that can be retained for plant use. Since it has been shown in this study that the gravels retain very little soil P, phosphate fertilization rates should be adjusted to take the gravels into account. Since most of the fertilizer recommendations for these soils are based on analyses of the <2mm fraction, the diluting effect of the gravels should be taken into consideration.

A significant advantage of the gravels is their mulching effect on the surface soils, against intense rainfall. The gravels adsorb the impact of the rain, thereby reducing the severe effect on the erodability of the soils. They also increase infiltration and decrease runoff, as well as decrease erosion losses. Another possible advantage is the decrease in the amounts of PO_4 adsorption per unit volume of plow soil (see discussion on P fixation).

Suggested Crops and Their Management Needs

The most important single crop grown in Sierra Leone is rice. It is usually cultivated on uplands as well as in swamps.

Among the soils studied here, the best upland rice producing ones are the Gbesebu, Makundu, Moa, Masuba and Pendembu series. Continuous cropping can be practiced on these soils, and irrigation is not necessary during the rainy season. Since the soils are acid and poor in nutrients, a program of fertilization will be necessary for optimum yields. In situations where these soils are periodically flooded or waterlogged, bunding to control flood water may be necessary.

Njala, Makeni, Manowa and Baoma soils can also be used for rice production. However, since these soils are very poor in nutrients and there is also a higher risk of erosion hazard, organic matter management is very important. Continuous cultivation is not recommended. The traditional shifting cultivation with fallow periods is strongly recommended, as it will improve the organic matter and nutrient supply and also minimize erosion.

Timbo and Segbwema soils are the least suitable for rice production because of the high erosion risks.

Other crops, such as maize, coffee, cocoa, groundnuts and cassava, grow well under good management on Gbesebu, Moa, Makundu, Masuba and Pendembu soils. Cassava grows well on Baoma, Manowa, Njala and Makeni soils, but the size and shape of the tubers are sometimes adversely affected by the gravels.

A crop rotation system of rice followed by groundnuts, or rice followed by forage, may be useful for the above soils if they are to be continuously cultivated.

Permanent tree crops (such as oil palm, coffee or cocoa), pasture, or forestry are recommended for sloping phases of Baoma, Manowa, Njala and Makeni soils and also for Segbwema and Timbo soils.

Additional Research Needs

Insufficient information is presently available on the characteristics of soils in Sierra Leone to aid in their proper placement in the Soil Taxonomy. Some of the needed characterizations for selected soils have been looked into in this study, and some problems that need additional work have emerged.

It is shown in this study that removal of free Fe oxides from soils before particle size analyses is superior to not removing the Fe, and it also gives a better indication of the genesis of the profiles. This procedure is laborious. Therefore, working out a factor that can be used to multiply the moisture content at 15 bar to give an estimate of the percent clay can be meaningful. For testing that possibility, additional representative profiles would have to be studied.

The possible use of ratios of the difference between extractable dithionite Fe and oxalate Fe to total clay (Fe_2O_3 removed) in the separation of Oxisols from Inceptisols or Ultisols in Sierra Leone has been suggested. Additional work is required to study the extent to which this ratio is useful.

Ironstone nodules in the gravelly soils studied have been shown to adsorb P. However, the nature of the adsorption mechanism is not certain and additional research is needed to determine the nature of the adsorption process, whether it is a surface adsorption or diffusion of P into the nodules through micropores on the surface. If the latter mechanism is predominant, the gravels may result in much more P adsorption than this study indicates. It is important also to evaluate this relative to crop responses and fertilizer requirements for efficient production.

These ironstone nodules have been shown to slake on shaking in a reciprocating shaker. It would be interesting to know whether this same process takes place in the field under intense rainfall or whether certain management practices foster this slaking. Could this mechanism account for the lower percentage of gravels in the upper soil horizons? Or are they being diluted by concentrations of fine-earth in the plow layer by soil fauna, particularly termites, ants and earthworms? This may be important as some of these nodules have been shown to have primary minerals that have been protected from weathering.

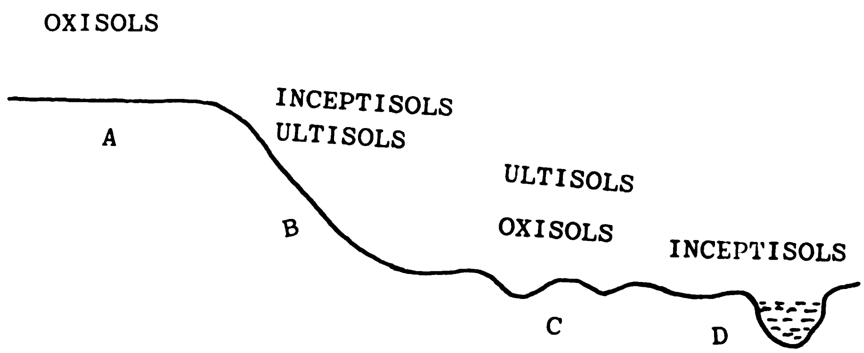
Finally, x-ray analyses of mica-like flakes in the sand fractions of some of the profiles have shown that these flakes are not true mica. It would be useful to know the state of mica-like flakes in other soils, and in which sand fractions true micas exist. This information would be useful for proper classification of the soils, and to assess their agricultural potential and management needs.

SUMMARY AND CONCLUSION

Eleven representative profiles from four physiographic groups in Sierra Leone were studied. Figure 8 shows the relationship between the physiography and the classification of the soils. The soils of the Upland Surfaces of Highly Weathered Material are all Oxisols. Segbwema and Timbo series of the Steep Hills and Slopes are Ultisols and Inceptisols, respectively. On the Colluvial Footslopes and Tributary Terraces, Pendembu soils belong to the order Oxisols and Masuba series to the order Ultisols. All the soils of the Alluvial Terraces and Floodplains belong to the order Inceptisols.

Other significant observations and relationships include the following. The percentage clay values are higher when free Fe oxide is removed before particle size analyses than when the free Fe oxide is not removed. The percentage clay values obtained with free Fe oxide removed are also commonly higher than the clay values estimated by the factor 2.5 x 15 bar moisture content. The value of the sum of percent clay (after Fe removed) + percent Fe_2O_3d would require a factor of 3.0 x 15 bar H_2O to estimate clay content in the soils studied.

Some differences in the vertical distribution pattern of percent clay with depth were observed after the removal of free Fe oxide. The percentage fine clay, <0.2μ, is usually higher than that of coarse clay. The ratio of fine clay to total clay for soils of the Upland



A Upland Surface of Highly Weathered Material
B Steep Hills and Slopes
C Colluvial Footslopes and Tributary Terraces
D Alluvial Terraces and Floodplains

Figure 8. Relationship between physiography and classification of soils.

Surfaces of Highly Weathered Material (Baoma, Manowa, Njala and Makeni) decreases with depth. A similar pattern is observed for the Pendembu series on the Colluvial Footslopes and Tributary Terraces. All of these soils belong to the order Oxisols.

The silt/clay ratio decreases with removal of free Fe oxide. The ratio is the lowest in the soils of the Upland Surfaces of Highly Weathered Material, suggesting a more advanced stage of ferrallitic-pedogenesis in these profiles. The highest ratio is obtained for the Segbwema series of the Steep Hills and Slopes, indicative of less ferrallitic weathering, suggesting it may be the youngest soil profile studied.

Percent sand and silt also tends to decrease with the removal of free Fe oxides. The 15 bar moisture content tends to follow the same distribution pattern as the clay content.

Within each of the four groups of soils studied, percent organic matter in the surface horizon increases with the moisture regime from ustic to udic. There is also a significant correlation (0.89) at the 1% level between percent clay (Fe oxide removed) and organic C for the surface horizon.

The critical value of ≤16 me C.E.C./100 g clay seems to give a clearer split of the oxic and non-oxic soils in this study than does a critical value of 12 me C.E.C./100 g clay. The critical value of ≤10 for the ratio of the sum of the exchangeable cations plus exchangeable Al to percent clay (also one of the criteria used to identify an oxic horizon) does not seem to be useful in the separation of the soils studied. Values of <10 are also obtained for soils with known argillic or cambic horizons, e.g., Segbwema and Masuba or Gbesebu series.

Dithionite-citrate-bicarbonate solution extracted more Fe oxide than did acid ammonium oxalate and Na-pyrophosphate solutions. Acid ammonium oxalate did not consistently extract more Fe oxide than Na-pyrophosphate solution.

In the soils of the Upland Surfaces of Highly Weathered Material, dithionite extracted Fe increased with depth in the profile. In the soils of the Steep Hills and Slopes, dithionite Fe decreased with depth in the Segbwema series and showed a subsoil maximum in the Timbo series. Zones of maxima of dithionite extracted Fe oxide are also present in the soils of the Colluvial Footslopes and Upper River Tributary Terraces and soils of the Alluvial Terraces and Floodplains.

The distribution pattern of oxalate extracted Fe oxide is a gradual decrease with depth in soils of the Upland Surfaces of Highly Weathered Material, and for soils of the Steep Hills and Slopes. In the soils of the Colluvial Footslopes and Upper River Tributary Terraces, oxalate extracted Fe oxide decreased with depth in the Pendembu series and remained fairly constant in the Masuba series. Zones of maxima are present in the soils of the Alluvial Terraces and Floodplains.

In general, the distribution pattern for Na-pyrophosphate extractable Fe oxide showed a subsoil maxima in all the soils studied except for the Segbwema and Baoma series. The correlation between percent organic C (Walkley-Black) and Na-pyrophosphate extracted Fe oxide is low.

The distribution pattern of dithionite extracted Fe oxide appears to be useful in distinguishing the soils studied in relation to geomorphic surfaces. The ratio of Fe_2O_3ox/Fe_2O_3d appears to be useful in determining the degree of profile development.

The ratio of the difference between dithionite extractable Fe oxide and oxalate extracted Fe oxide to that of percent clay (Fe removed) seems to have some promise as one of the criteria in separating the oxic and non-oxic soils. A critical value of 0.06 (6%) is suggested for the soils studied.

The amount of P adsorbed by the ironstone nodules of the Njala and Makeni series is comparatively much smaller than that adsorbed by the respective fine-earth fractions. The amount of P adsorbed by the nodules increased with time of equilibration. The ironstone nodules tend to have a diluting effect on the amount of P that is fixed by the whole soil, e.g., 5325kg/hec P can be fixed by the fine-earth of the surface horizon of the Makeni series and the gravels fixed 203kg/hec P in 48 hrs. The combined value is reduced to 1597kg/hec if the diluting effect of the ironstone nodules is taken into consideration. In the Makeni series, the ironstone nodules account for 8.2% of the P that can be fixed by the whole surface soil and 7.5% of the whole subsoil. The gravels are 70% and 76% of these soil layers.

In general, in the Makeni, Segbwema and Gbesebu series, P adsorbed by the surface soil is higher than that adsorbed by the subsurface soil. The reverse is true in the Masuba series. The influence of Fe oxide (by dithionite and oxalate) on the adsorption of P is greater in the subsurface horizon than in the surface horizon, where organic matter, Al oxide (oxalate) and organic complexes of Fe and Al are more important.

The predominant clay mineral in the total and fine clay fraction, as revealed by x-ray diffractograms, is kaolinite, which is less ordered in the fine clay. There is a striking similarity between the clay minerals of the ironstone nodules of the Makeni and Njala series and that of their respective fine-earth fractions. X-ray analyses of mica-like flakes in the medium and fine sand of the A, B and C horizons of the Segbwema series and fine sand of the B horizon of Timbo series show that the flakes are mainly interlayer 'illite-chlorite' and kaolinite. The interlayer material does not readily fix potassium.

Thin sections of the soil horizons sampled showed that most of them lack an argillic horizon. Thin sections of the ironstone nodules revealed two main types. Type 1 is derived from rock fragments and Type 2 is probably derived from plinthite. Subdivisions within the types are also recognized. The subdivisions in Type 1 represent nodules derived from granite and mudstones. In Type 2, the two main subdivisions represent nodules with similar matrix to that of the surrounding soil and nodules which are basically clay concentrations that have been coated with iron oxides. Argillans that have been protected in the nodules are observed along old channels, indicating past genetic processes in the profiles. Also, there is a striking similarity between the internal S-matrix of the surface and subsurface nodules of the gravelly soils studied. The roundness of the surface gravels is more likely the result of solution than of transportation.

The term petroplinthic is suggested in place of skeletal at the family level of classification, when the >2mm fraction is mainly **>35%**

ironstone nodules, to reflect the genetic nature of these nodules.

Soils of the Upland Surfaces of Highly Weathered Material are less suited for continuous cultivation than soils of the Colluvial Footslopes and Tributary Terraces and soils of the Alluvial Terraces and Floodplains. The soils of the Steep Hills and Slopes are the least suited for continuous cultivation, because of serious erosion hazards. Proper organic matter management is important for soils with oxidic mineralogy.

Percentage fine and total clay (when Fe oxide is removed), free Fe oxide/clay ratio (Fe removed), and thin section studies appear to be three of the most important bases for classifying the soils studied here within Soil Taxonomy (1975).

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APPENDICES

APPENDIX A

PROFILE DESCRIPTIONS (BAOMA, MANOWA, NJALA, MAKENI, SEGBWEMA, TIMBO, PENDEMBU, MASUBA, MOA, GBESEBU, MAKUNDU)

Profile 144801A, Baoma sandy clay loam
Description after Sivarajasingham (1968)

Location	On the right-hand side of the road from Daru Junction to Moa Barracks, about 150 feet (46m) past the Girl's School at the first bend of the road to the left.
Physiography	Undulating upland.
Relief	Upper gentle slope.
Vegetation	Cocoa 7 to 15 years old in very poor health, poor management, inadequate shade, open stand, and heavy weed growth; few tall trees of the former secondary forest remain.
Drainage	Well drained.
Parent material	A thick layer of locally transported material derived from laterite crust and partially weathered and fresh rock of a previous landscape.
A_1 0-5 inches 0-13 cm Lab. No. S28572	Dusky red (2.5YR 3/2); sandy clay loam; moderate fine subangular blocky; light and porous; soft, slightly sticky, slightly plastic; many fine and medium roots; clear, smooth boundary to horizon below.
B_{2t} 5-23 inches 13-58 cm Lab. No. S28571	Red (10R 4/6) to dark red (10R 3/6); clay; less than 5% hardened plinthite glaebules of the kind in the layer below; moderate medium and fine sub-angular blocky; porous; friable, slightly sticky, and slightly plastic; common fine and medium roots; abrupt, smooth boundary to horizon below.

IIB_{31} 23-43 inches 58-109 cm Lab. No. S28570	Main gravel layer; red (10R 4/6); gravelly clay; 40% black-coated and uncoated, medium, round, black, dense hardened plinthite glaebules, and 10% coarse, dense, very hard, fresh rock pebbles; moderate fine subangular blocky; porous; friable, slightly sticky, slightly plastic; few fine roots; diffuse, smooth boundary to horizon below.
IIB_{32} 43-67 inches 109-170 cm Lab. No. S28569	Red (10R 4/6); gravelly clay; 40% hardened plinthite glaebules as in IIB_{31} but finer in size; moderate fine subangular blocky; slightly porous; friable, slightly sticky, slightly plastic; no roots.

Profile Kpuabu 1, Manowa sandy clay loam
Description after Sivarajasingham (1968)

Location	Kpuabu Cocoa Experiment Station; about 450 feet (137m) from the Kenema-Joru road on the road to the Station Office, and about 150 feet (46m) on the right-hand side from the Station Office road.
Physiography	Accordant, flat-topped hill of the dissected lateritic upland.
Relief	Upper, convex 5% slope.
Vegetation	Cocoa plantation under many tall trees of original secondary vegetation; good grass cover.
Drainage	Moderately well drained.
Parent material	A thin layer of gravel-free material over a thick, very gravelly layer of locally transported material.
A_1 0-10 inches 0-25 cm Lab. No. S28558	Very dark grayish brown (10YR 3/2); sandy clay loam; moderate medium and fine subangular blocky; porous; friable, slightly sticky, slightly plastic; common fine, few medium, and very few coarse roots; clear, smooth boundary to horizon below.
A_3 10-21 inches 25-53 cm Lab. No. S28557	Dark brown (10YR 3/3); very gravelly sandy clay; 70% yellow-coated, nodular, coarse and medium, dense, red and yellow, hardened plinthite glaebules; weak, fine subangular blocky aggregates with no strong interface; friable, sticky, slightly plastic; few fine and very few medium roots; gradual, smooth boundary to horizon below.

B_{21} 21-35 inches 53-89 cm	Dark yellowish brown to yellowish brown (10YR 4/4-5/6); very gravelly sandy clay; 60% yellow-coated and uncoated, round, fine, dense, red and black, hardened plinthite glaebules; weak fine subangular blocky aggregates with no strong interface; friable, sticky, slightly plastic; very few fine and medium roots; gradual, smooth boundary to horizon below.
B_{22} 35-70 inches 89-178 cm Lab. No. S28556	Strong brown (7.5YR 5/8); very gravelly clay; 75% yellow-coated nodular, coarse, dense, red and yellow, hardened plinthite glaebules; weak fine subangular blocky aggregates with no strong interface; porous; friable, sticky, slightly plastic; very few fine and medium roots.
Remarks	This soil is very gravelly and droughty and would be expected to be unsuitable for cocoa. The cocoa planted in 1959 appears as stunted trees of very poor health, with many vacant patches because of low survival rate of the planted seedlings. Management is very good, but shade appears to be excessive.

Profile N109, Njala very gravelly clay loam
Described by H. Breteler on December 29, 1966

Location	Southwestern corner of the Oil Palm Station of Njala University College. From the junction of the Kania boundary road and the village path to Pujehun, 84 feet (26m) along the boundary line uphill towards the Taia River. Pit N109 is located between palms 1155 and 993.
Physiography	Dissected erosion surface; on the slope between the highest erosion surface and the upper river terrace.
Relief	Lower part of convex 8% slope, on mapping unit 3, Njala, sloping.
Vegetation	Oil palm plantation.
Drainage	Well drained.
Parent material	Colluvial material high in hardened plinthite glaebules.
A_1 0-14 inches 0-35 cm Lab. No. S29072	Dark brown (10YR 3/3); very gravelly (70% by volume) clay loam; gravels are mainly round and nodular, ¼" to ½" in diameter, hardened plinthite glaebules with outside colors of yellowish red

(5YR 4/6) and inside colors of yellowish red and very dusky red (5YR 4/6, 4/8, 5/8 and 10R 2/2); weak to moderate very fine and fine subangular blocky, breaking into very weak, very fine granular very friable; many fine, medium, and coarse pores; many fine, medium, and coarse roots; gradual, smooth boundary to horizon below. This A_1 horizon is thick enough and just dark enough to qualify as an umbric epipedon (see Section 4). Most profiles of Njala soils have thinner or lighter colored A_1 horizons, which are ochric rather than umbric.

A_3
14-21 inches
35-53 cm
Lab. No. S29074

Dark yellowish brown (10YR 4/4); very gravelly (80%) clay; gravels are mainly round and nodular, ¼" to 3" in diameter, hardened plinthite glaebules with outside colors of yellowish red and very dusky red (5YR 5/8 and 10R 2/2) and inside colors of dark red, red, and reddish yellow (10R 3/6, 4/8 and 7.5YR 6/8); weak very fine, fine, and medium subangular blocky, breaking into weak to moderate very fine, fine and medium granular; very friable; many fine, medium, and coarse pores; many fine, medium, and coarse roots; gradual, smooth boundary to horizon below.

B_{21}
21-49 inches
53-125 cm
Lab. No. S29076

Strong brown (7.5YR 5/8); very gravelly (70%) clay; gravels are mainly round and nodular, ¼" to 3" in diameter, hardened plinthite glaebules with outside colors of red (2.5YR 4/8-5/8) and inside colors of red and very dusky red (10R 4/6 and 2/2); very weak fine, medium, and coarse angular to subangular blocky, breaking into weak to moderate very fine and fine granular; friable; many fine, medium, and coarse pores; common fine, medium, and coarse roots; gradual, smooth boundary to horizon below.

B_{22}
49-62 inches
125-157 cm
Lab. No. S29076

Yellowish red (5YR 5/8); very gravelly (50%) clay; gravels are mainly round and nodular, ¼" to 1" in diameter, hardened plinthite glaebules with outside colors of yellowish red (5YR 5/8) and inside colors of red and very dusky red (10R 4/6 and 2/2); very weak fine, medium, and coarse angular to subangular blocky, breaking into weak to moderate very fine and fine granular; friable; common fine, medium, and coarse pores; common fine, medium, and coarse roots.

Profile P2, Makeni very gravelly sandy clay loam
Described by W. van Vuure and R. Miedema on
March 8, 1968

Location	Topographic map of Sierra Leone, scale 1:50,000, sheet 43, coordinates HE 27_4-86_5; on traverse A, near augerhole 4.
Physiography	Dissected erosion surface, sloping.
Relief	Slopes 14% to SSW and 10% to SE.
Vegetation	Secondary bush, 4 to 10 years old.
Drainage	Well drained.
Parent material	Gravelly to very gravelly weathering products of Precambrian granite and acid gneiss.
A_1 0-10 inches 0-25 cm Lab. No. S29804	Dark brown (10YR 3/3); very gravelly sandy clay loam; structure and consistence not observable because of gravel content; common macro- and many mesopores; few fine distinct charcoal mottles; common coarse, many medium and fine roots; common ant and termite activity; 74% uncoated, fine and medium, rounded, dense, red and yellow, hardened plinthite glaebules; clear, smooth boundary to horizon below.
B_{21} 10-20 inches 25-50 cm Lab. No. S29805	Yellowish red (5YR 4/8); very gravelly clay; very weak, very fine angular blocky; consistence is not observable because of high gravel content; common macro- and mesopores; common coarse many medium and fine roots; low biological activity; 77% uncoated fine and medium, rounded and nodular, dense, red and yellow, hardened plinthite glaebules; gradual, smooth boundary to horizon below.
B_{22} 20-67 inches 50-170 cm Lab. No. S29806	Yellowish red (5YR 5/8); very gravelly clay; very weak, very fine angular blocky; firm, slightly sticky and plastic; common macro- and mesopores; few medium, common fine roots; 80% yellow-coated, medium and coarse, nodular and angular, dense, red, hardened plinthite glaebules, and a few very fine quartz gravels.

Profile 145005, Segbwema gravelly sandy clay loam
Description after Sivarajasingham (1968)

Location	On a very high hill on the right-hand side of the road from Mano Junction to Segbwema Junction. The path leading to the pit starts from the village of Niahun and goes southwards.

Physiography	Very high hills.
Relief	The pit is on the middle part of a very steep (42%), straight slope of a very high hill.
Vegetation	The land was in upland rice during 1965; in 1966 it was under a low succulent to woody herbaceous vegetation with many wild oil palms.
Drainage	Well drained.
Parent material	Residual, presumably from rock of granodioritic composition.
A_1 0-13 inches 0-33 cm Lab. No. S28564	Strong brown (7.5YR 5/6); gravelly sandy clay loam; strong fine subangular blocky and granular; medium density and porosity; friable, slightly sticky, slightly plastic; common fine and medium roots; clear, smooth boundary to horizon below.
B_{21} 13-28 inches 33-71 cm	Red to weak red (10R 4/6-4/4); heavy sandy clay loam, slightly gritty; strong medium subangular blocky; porous; friable, slightly sticky, slightly plastic; few fine roots; gradual, smooth boundary to horizon below.
B_{22} 28-60 inches 71-153 cm Lab. No. S28563	Red (2.5YR 4/6) with few coarse red (10R-7.5R 4/6) mottles; clay loam with fine white specks of decomposing feldspar indicating its saprolitic nature; strong medium subangular blocky; porous friable, slightly sticky, slightly plastic; few fine roots; diffuse, smooth boundary to horizon below.
C_1 60-94 inches 153-239 cm Lab. No. S28562	Red (2.5YR 4/8 and 10R 4/8) in equal amounts present as coarse faint mottles; also contains white decomposing feldspar and black decomposing hornblende; sandy clay loam; weak fine subangular blocky; porous; nonsticky, slightly plastic; few fine roots.

Profile P19, Timbo gravelly sandy clay loam
Described by J. M. Cawray, A. A. Thomas and
R. Miedema on March 27, 1968

Location	Topographic map of Sierra Leone, scale 1:50,000, sheet 43, coordinates $HE26_1-85_2$; near Timbo along the motor road from Makeni to Panlap.
Physiography	Dissected erosion surface.

Relief	Slope 6% to south.
Vegetation	Cassava and short weeds and grasses.
Drainage	Well drained.
Parent material	Gravelly weathering products of Precambrian granite and acid gneiss.
A_{11} 0-12 inches 0-30 cm Lab. No. S29818	Very dark grayish brown (10YR 3/2); gravelly sandy clay loam; weak fine subangular blocky; slightly hard, friable, slightly stick, and slightly plastic; many macro- and mesospores; few fine distinct charcoal particles; common coarse and medium roots; 44% fine and medium, uncoated nodular, red, hardened plinthite glaebules, and a few decomposed rock fragments; clear, smooth boundary to horizon below.
A_{12} 12-19 inches 30-49 cm Lab. No. S29819	Dark brown (10YR 3/3); very gravelly sandy clay loam; weak fine subangular blocky; slightly hard, friable, slightly plastic; many macro- and mesopores; few fine distinct charcoal particles; common coarse, medium, and fine roots; 50% medium and fine, uncoated nodular, very hard, porous, yellow and red, decomposed rock fragments; clear, wavy boundary to horizon below.
AB 19-28 inches 49-70 cm Lab. No. S29820	Yellowish red (5YR 4/6); gravelly sandy clay loam; weak fine subangular blocky; friable, slightly sticky, and slightly plastic; many macro- and mesopores; few coarse, medium, and fine roots; 47% uncoated, very hard, porous, red and yellow, decomposed rock fragments; few feldspars and micas, especially in the decomposing rock pieces; gradual, wavy boundary to horizon below.
B_{21} 28-42 inches 70-100 cm Lab. No. S29821	Yellowish red (5YR 4/8); gravelly sandy clay loam; weak medium angular and subangular blocky; friable, slightly stick, and slightly plastic; many macro- and mesopores; few coarse, medium, and fine roots; 44% coarse, medium, and fine, uncoated, soft to hard, porous, red and yellow, decomposed rock fragments; few micas and feldspars; diffuse, smooth boundary to horizon below.
B_{22} 43-70 inches 110-179 cm Lab. No. S29822	Yellowish red (5YR 5/8); gravelly sandy clay loam; weak medium angular blocky; sticky and plastic; common macro- and mesopores; few coarse, medium, and fine roots; 20% coarse and medium, uncoated, soft to hard, porous, red and yellow, decomposed rock fragments, with feldspars and micas.

Profile Kpuabu 2, Pendembu fine sandy loam
Description after Sivarajasingham (1968)

Location	Kpuabu Cocoa Experiment Station, about halfway between the nursery buildings and the stream.
Physiography	Accordant, flat-topped hill of the dissected lateritic upland.
Relief	Long, gentle, concave slope of about 2%.
Vegetation	Cocoa plantation under adequate shade of many tall trees of original secondary forest. Although the soil is deep and gravel-free and would have been expected to be suitable, the cocoa planted in 1959 shows many large, vacant patches.
Drainage	Imperfectly drained.
Parent material	A thick layer of gravel-free, locally transported, leached parent material.
A_1 0-7 inches 0-18 cm Lab. No. S28552	Very dark gray (10YR 3/1); fine sandy loam; weak, medium, and fine, subangular blocky; friable, slightly sticky, nonplastic; very few fine pores; common fine and medium roots; clear, smooth boundary to horizon below.
A_3 7-18 inches 18-46 cm Lab. No. S28551	Dark grayish brown (2.5Y 4/2-10YR 4/2); sandy clay loam; dense clods breaking to weak fine subangular blocky aggregates with no characteristic interface; friable, slightly sticky, slightly plastic; very few pores and few large burrow holes; common fine and medium and few coarse roots in the first 5 inches, then decreasing gradually with depth; clear, smooth boundary to horizon below.
B_{1t} 18-37 inches 46-94 cm	Yellowish brown (10YR 5/4) to light olive brown (2.5Y 5/4); sandy clay loam; dense clods as in A_3 horizon; friable to firm, slightly sticky, slightly plastic; few pores with clay coatings along the pore walls; few fine and medium roots; gradual, smooth boundary to horizon below.
B_{2t} 37-54 inches 94-137 cm Lab. No. S28550	Yellow (2.5Y 7/6) to brownish yellow (10YR 6/6); sandy clay loam; massive clods breaking to weak very fine subangular blocky aggregates with no characteristic interface; friable to firm, slightly plastic, slightly sticky; few pores with clay coatings along the pore walls; very few fine and medium roots; gradual, smooth boundary to horizon below.

B_{3t} 54-72 inches 137-183 cm	Pale yellow to yellow (2.5Y 7/6) with common medium, faint yellowish brown (10YR 5/6) and few medium, prominent red (2.5YR 4/8) mottles; sandy clay loam; massive clods as in B_2 horizon; firm, slightly sticky, slightly plastic; many fine pores with clay coatings; very few very fine roots; gradual, smooth boundary to horizon below.
C_{1g} 72-80 inches 183-203 cm	White (2.5Y 8/2) with common medium, prominent yellowish brown (10YR 5/6) and strong brown (7.5YR 5/8) mottles; sandy clay; massive; wet; firm, sticky, slightly plastic; the strong brown mottles are firm to hard and may be considered as incipient plinthite glaebules; no roots.

Profile P9, Masuba sandy clay loam
Described by R. Miedema and A. A.
Thomas on March 20, 1968

Location	Topographic map of Sierra Leone, scale 1:50,000, sheet 43, coordinates $HE27_8$-87_2; on traverse E, 525 feet (160m) from profile P8.
Physiography	Lower part of stream terrace near valley edge.
Relief	Slope 0 to 3%.
Vegetation	Farm with cassava, Kandi trees and weeds, and many wild oil palms.
Drainage	Moderately well drained.
Parent material	Gravel-free, transported alluvial/colluvial material.
Ap 0-7 inches 0-19 cm Lab. No. S29810	Very dark grayish brown (10YR 3/2); sandy clay loam; weak fine to medium angular blocky; very hard; common macro- and many mesopores; few distinct fine charcoal mottles; many coarse, medium, and fine roots; many large and medium ant holes; clear, smooth boundary to horizon below.
B_1 7-22 inches 19-57 cm Lab. No. S29811	Pale brown (10YR 6/3); sandy clay loam; weak fine to medium angular blocky; very hard; many macro- and mesopores; few distinct fine charcoal mottles; common fine distinct reddish yellow to strong brown (7.5YR 5.5/8) to red (2.5YR 5/8) mottles; common coarse, many medium and fine roots; less than 10% uncoated, nodular, coarse, porous, red, hardened plinthite glaebules, with few quartz grains; many large and medium ant holes; gradual, smooth boundary to horizon below.

B_2 22-67 inches 57-170 cm Lab. No. S29812	Very pale brown (10YR 6.5/3); sandy clay loam; weak fine angular blocky; firm; many macro- and mesopores; many distinct fine and medium yellowish red (5YR 5/8) and reddish yellow (7.5YR 6/8) mottles; common distinct fine and medium charcoal mottles; few coarse, common medium, and many fine roots; less than 10% gravel, similar to B_1 horizon, and one quartz stone; common worm holes with dark coatings.

Profile Kpuabu 3, Moa clay
Description after Sivarajasingham (1968)

Location	Kpuabu Cocoa Experiment Station; near the path from the nursery buildings to the wooden bridge over the stream.
Physiography	Bottomland (river terrace).
Relief	Middle of a narrow, level terrace adjoining a stream whose bed has incised about 10 feet (3m) below the terrace surface.
Vegetation	A thick stand of cocoa planted in 1960, with dense foliage forming a close canopy adequate shade of many tall trees of the original secondary forest.
Drainage	Moderately good. The land may be flooded two or three times a year for durations of one or two weeks. Flood water drains rapidly from the surface layers, but even during the height of the dry season the water table is encountered within 6 or 7 feet (2m) below the surface.
Parent material	A thick layer of clayey river alluvium.
A_1 0-6 inches 0-15 cm Lab. No. S28555	Very dark grayish brown (10YR 3/2); clay; strong fine subangular blocky and fine granular; porous; friable, slightly sticky, slightly plastic; termites and earthworms present; many fine and medium roots; clear, smooth boundary to horizon below.
B_{21} 6-21 inches 15-53 cm Lab. No. S28554	Strong brown to dark brown and brown (7.5YR 5/6-4/4); clay; strong fine subangular blocky; porous; friable, sticky, slightly plastic; common fine and medium roots; gradual, smooth boundary to horizon below.

B_{22} 21-31 inches 53-79 cm	Strong brown (7.5YR 5/6-5/8) with few fine, distinct yellowish red (5YR 4/8) to red (2.5YR 4/8) mottles; clay; strong medium and fine subangular blocky; porous; friable, sticky, slightly plastic; common fine and medium roots; gradual, smooth boundary to horizon below.
B_3 31-59 inches 79-150 cm Lab. No. S28553	Brownish yellow (10YR 6/8) with few, medium distinct strong brown (7.5YR 5/8) and red (2.5YR 4/8) mottles; yellow (2.5Y 7/6) mottles are more numerous with increasing depth; clay; strong medium subangular blocky; porous; friable, sticky, slightly plastic; few fine and medium roots; gradual, smooth boundary to horizon below.
C_{1g} 59-71 inches 150-180 cm	Mottled white (N 8/), yellow (2.5Y 7/6), yellowish brown (10YR 5/8), and strong brown (7.5YR 5/6) in a variegated pattern; sandy clay; wet, massive clods; the strong brown mottles are firm to hard and may be considered as incipient plinthite glaebules.

Profile N125, Gbesebu silty clay
Described by H. Breteler on
January 18, 1967

Location	From the extreme southwestern corner of the Oil Palm Station of Njala University College, at the junction of the Kania boundary road and the path along the Taia River near surveyor stone No. PB-B 829, thence 322 feet (98m) down the steep slope towards the river to pit N125, near the river bank on a natural levee.
Physiography	Natural levee of the Taia River, on the present floodplain or first terrace.
Relief	Nearly level, convex slope.
Vegetation	Old secondary bush with much grass.
Drainage	Moderately well drained; may be flooded for several weeks during the wet season.
Parent material	Clayey alluvium.
A_1 0-4 inches 0-10 cm Lab. No. S29066	Dark brown (10YR 4/3); silty clay; weak very fine and fine subangular blocky, breaking to weak very fine granular; very friable; many fine, medium, and coarse pores; many fine, medium, and coarse roots; clear, smooth boundary to horizon below.

A_3 4-7 inches 10-18 cm Lab. No. S29067	Dark yellowish brown (10YR 4/4); clay; weak very fine and fine angular to subangular blocky, breaking to weak very fine granular; friable; many fine, medium and coarse pores; many fine, medium, and coarse roots; clear, smooth boundary to horizon below.
B_{21} 7-19 inches 18-48 cm Lab. No. S29068	Strong brown (7.5YR 5/6) with many fine and medium faint yellowish red (5YR 5/6) mottles; clay; weak very fine and fine blocky, breaking into weak very fine granular; friable; many fine, medium, and coarse pores; common fine, medium, and coarse roots; mica flakes; clear, smooth boundary to horizon below.
B_{22b} 19-25 inches 48-63 cm Lab. No. S29069	Strong brown to yellowish brown (7.5YR-10YR 5/6) with many fine, medium, and coarse faint yellowish red (5YR 5/6) mottles; this is a buried A horizon with common fine, medium, and coarse charcoal mottles; clay weak to moderate fine and medium blocky, breaking into weak to moderate very fine and fine granular; firm; many fine, medium, and coarse pores; common fine and medium roots; mica flakes; clear, smooth boundary to horizon below.
B_{23} 25-63 inches 63-160 cm Lab. No. S29070	Strong brown (7.5YR 5/6) with many fine, medium, and coarse faint yellowish red (5YR 5/6) mottles; clay; weak to moderate fine and medium blocky, breaking into weak to moderate fine granular; firm; many fine, medium, and coarse pores; few fine and medium roots; mica flakes.

<u>Profile P104, Makundu clay
Described by J. M. Cawray
and R. Miedema on June 18,
1968</u>

Location	Topographic map of Sierra Leone, scale 1:50,000, sheet 43, coordinates $HE12_4$-91_2; 300 feet (91m) from Mabole River, on the road from Makundu to the river.
Physiography	Nearly level river terrace.
Relief	Concave, very gentle 1% slope to the south.
Vegetation	Dense secondary bush, with many wild oil palms.
Drainage	Moderately well to well drained.
Parent material	Alluvium from the Mabole River.

A_{11} 0-8 inches 0-20 cm Lab. No. S29841	Very dark gray (10YR 3/1); clay; weak fine angular and subangular blocky; friable, slightly sticky, and slightly plastic; many macro- and mesopores; few medium distinct charcoal mottles; many coarse, medium, and fine roots; much ant, termite, and worm activity; clear, smooth boundary to horizon below.
A_{12} 8-16 inches 20-41 cm Lab. No. S29842	Very dark grayish brown to dark brown (10YR 3/2.5); clay; weak fine angular and subangular blocky; friable, slightly sticky, and slightly plastic; many macro- and mesopores; few medium distinct charcoal mottles; many coarse, medium, and fine roots; much ant, termite, and worm activity; clear, smooth boundary to horizon below.
AB 16-21 inches 41-53 cm Lab. No. S29843	Dark yellowish brown (10YR 4/4); silty clay; weak fine angular and subangular blocky; friable, sticky and plastic; many macro- and mesopores; few medium distinct charcoal mottles; many coarse, medium, and fine roots; much ant, termite and worm activity; clear, smooth boundary to horizon below.
B_1 21-28 inches 53-71 cm Lab. No. S29844	Yellowish brown (10YR 5/6); clay; moderate fine and medium angular and subangular blocky, firm, sticky, and plastic; many macro- and mesopores; few medium distinct charcoal mottles; few fine faint yellowish red (5YR 4/6) mottles; common coarse, many medium and fine roots; much ant, termite, and worm activity; gradual, smooth boundary to horizon below.
B_{21} 28-43 inches 71-108 cm Lab. No. S29845	Brownish yellow (10YR 6/6); clay; moderate fine and medium angular and subangular blocky; firm, sticky, and plastic; common macro- and mesopores; common medium distinct yellowish-red (5YR 4/8) mottles; few medium, common fine roots; much ant, termite and worm activity; gradual wavy boundary to horizon below.
B_{22} 43-74 inches 108-188 cm Lab. No. S29846	Brownish yellow (10YR 6/6); clay; moderate angular and subangular blocky; firm, sticky and plastic; common macro- and mesopores; many medium prominent yellowish red (5YR 5/6) mottles; common fine roots; common ant, termite, and worm activity.

APPENDIX B

MACROMORPHOLOGY OF IRONSTONE NODULES (BAOMA, MAKENI, MANOWA AND TIMBO)

Soil Series	Horizon Depth (cm)	Munsell Color (internal matrix)	Kind or Composition of Gravel	Size*	Shape
Baoma 144801A	0-15	2.5YR 4/4-5YR 5/8 Few 10YR 8/1 quartz	Ironstone gravel, few weathered rock and quartz gravel	Fine	Mainly round. Quartz angular
	15-30	5YR 5/6-5YR 2.5/1 Few 10YR 8/1 quartz	Ironstone gravel with few quartz	Fine and medium	Round and angular
	30-60	5YR 4/4-5YR 5/8	Ironstone gravel	Fine and medium	Round to angular
	60-110	2.5YR 3/4-10YR 3/4	Ironstone gravel, plus a few pieces of weathered rock gravel	Fine and medium	Angular to subrounded
	110-160	2.5YR 3/4	Ironstone gravel, few quartz	Fine and medium	Angular to subrounded
	160-180	5YR 5/8-2.5YR 4/6	Weathered rock gravel, ironstone gravel and quartz	Fine and medium and coarse	
Makeni P2	0-25	2.5YR 3/2-2.5YR 5/8	Ironstone gravel	Fine and medium	Round

APPENDIX B (continued)

Soil Series	Horizon Depth (cm)	Munsell Color (internal matrix)	Kind or Composition of Gravel	Size*	Shape
	25-55	2.5YR 3/2 & 2.5YR 3/6	Ironstone gravel	Fine and medium	Round and subrounded
	55-93	2.5YR 3/4 & 3/6	Ironstone gravel	Fine, medium and coarse	Subrounded to angular
	93-115	2.5YR 3/6	Ironstone gravel	Fine, medium to coarse	Angular
	115-168	2.5YR 3/4	Ironstone gravel	Fine, medium and coarse	Angular
Manowa	0-25	2.5YR 3/4-10R 3/3	Ironstone gravel	Fine and medium	Round and angular
	25-53	2.5YR 4/6 & 10R 3/6	Ironstone gravel	Fine and medium	Angular
	53-88	2.5YR 4/8, 2.5YR 3/4	Ironstone gravel	Fine, medium and coarse	Angular
	88-125	2.5YR 3/4-3/6	Ironstone gravel and few quartz	Fine, medium and coarse	Angular

APPENDIX B (continued)

Soil Series	Horizon Depth (cm)	Munsell Color (internal matrix)	Kind or Composition of Gravel	Size*	Shape
	125-180	2.5YR 4/6, 2.5YR 3/4	Ironstone gravel	Fine, medium and coarse	Angular
Timbo	0-30	2.5YR 4/4 & 7.5YR 5/6	Ironstone and a few rock gravel	Fine, medium and coarse	Angular
	30-48	2.5YR 4/8 & 10R 4/6	Rock gravel (weathering) plus few quartz gravel	Fine, medium and coarse	Angular
	48-70	5YR 5/8, 10R 4/6	Weathering rock fragments and gravel	Medium and coarse	Angular
	70-115	2.5YR 3/4, 2.5YR 5/8	Weathered rock fragments	Medium and coarse	Angular
	115-175	10R 4/8, 2.5YR 3/6	Weathered rock fragments	Medium and coarse	Angular

*Fine<1.25cm, medium 1.25-2.5cm, coarse >2.5cm.

APPENDIX C

RATIO OF EXTRACTABLE IRON AND ALUMINUM OXIDES TO OTHER VARIABLES

Soil Series	$\frac{Fe_2O_3d}{Md^*}$	$\frac{Fe_2O_3ox}{Md^*}$	$\frac{Fe_2O_3d - Fe_2O_3ox}{Md^*}$	$\frac{Al_2O_2ox}{Al_2O_3d}$	$\frac{Fe\ sil}{clay, Fe\ removed}$	Fe_{sil} = Total Fe - Fe_d**
Baoma						
A_1	1.33	0.39	0.90	0.58	0.27	11.34
B_2	1.55	0.36	1.20	0.59	0.22	11.28
IIB_{31}	1.70	0.36	1.30	0.44	0.21	11.60
IIB_{32}	1.50	0.35	1.20	0.47	0.22	13.06
IIB_{33}	---	---	---	---	---	---
Manowa						
A_1	0.11	0.75	1.10	0.67	0.12	4.64
A_3	0.09	0.82	1.35	0.84	0.13	5.34
B_{21}	0.07	0.92	1.17	0.79	---	---
B_{22}	0.05	1.16	1.30	0.86	0.13	6.30
Njala						
A_1	0.31	0.08	0.24	2.96	0.05	2.63
A_3	0.45	0.06	0.38	2.10	0.04	2.38
B_{21}	0.58	0.06	0.51	1.30	0.04	2.31
B_{22}	0.67	0.05	0.62	1.00	0.02	1.64
Makeni						
A_1	0.21	0.05	0.16	1.75	0.12	6.58
B_{21}	0.28	0.05	0.23	3.43	0.17	11.01
B_{22}	0.31	0.04	0.27	2.61	0.17	11.50
Segbwema						
A_1	0.68	0.33	0.35	0.51	0.03	1.7
B_{21t}	0.64	0.27	0.37	0.45	---	---
B_{22t}	0.58	0.23	0.35	0.40	0.14	4.56
C_1	0.30	0.12	0.16	3.30	0.13	31.10

Appendix C (continued)

Soil Series	Fe_2O_3d / Md*	Fe_2O_3ox / Md*	Fe_2O_3d - Fe_2O_3ox / Md*	Al_2O_2ox / Al_2O_3d	Fe sil / clay, Fe removed	Fe_{sil} = Total Fe - Fe_d**
Timbo						
A_{11}	0.31	0.07	0.25	1.45	0.23	7.68
A_{12}	0.43	0.06	0.37	1.54	0.19	8.02
AB	0.42	0.05	0.37	1.36	0.24	9.95
B_{21b}	0.53	0.04	0.49	0.53	0.26	9.97
B_{22b}	0.48	0.04	0.44	0.24	0.34	10.79
Pendembu						
A_1	0.19	0.05	0.15	1.20	0.03	1.00
A_3	0.24	0.05	0.19	0.89	0.04	1.16
B_{21}	---	---	---	0.63	---	---
B_{22}	0.21	0.02	0.20	0.51	0.04	1.34
B_{23}	---	---	---	0.19	---	---
B_3	---	---	---	0.35	---	---
Masuba						
AP	0.12	0.04	0.11	0.55	0.09	2.08
B_{21t}	0.17	0.04	0.16	0.29	0.09	2.34
B_{2t}	0.14	0.04	0.13	0.70	0.10	2.51
Moa						
A_1	0.42	0.08	0.34	0.87	0.06	3.20
B_{21}	0.45	0.07	0.39	0.44	0.07	3.85
B_{22}	0.51	0.05	0.46	0.24	---	---
B_3	0.52	0.07	0.45	0.17	0.07	3.78
C	0.51	0.06	0.45	0.10	---	---
Gbesebu						
A_1	0.37	0.12	0.25	2.60	0.02	1.74
A_3	0.45	0.19	0.26	2.00	0.02	1.23
B_{21b}	0.49	0.19	0.31	3.20	0.03	2.12
B_{22b}	0.43	0.18	0.26	3.20	0.03	2.38
B_{23}	0.39	0.13	0.26	2.40	0.04	2.82
Makundu						
A_{11}	0.26	0.03	0.23	0.15	0.10	6.65
A_{12}	0.31	0.10	0.22	2.24	0.09	6.47
AB	0.31	0.07	0.24	1.15	0.10	6.72
B_1	0.32	0.08	0.25	3.21	0.10	6.87
B_{21}	0.32	0.03	0.29	0.65	0.10	7.23
B_{22}	0.30	0.04	0.27	0.71	1.09	6.48

*Mean difference of percent clay after Fe removed and before Fe removal.

**Total iron - Fe dithionite = Silicate Fe, Fe_{sil}.