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PEDOGENIC CHANGES AND PHOSPHORUS AVAILABILITY IN SOME SOILS OF NORTHERN GHANA

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Legon

By

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INTEGRI PROCEDAMUS

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DEDICATION

Dedicated to the glory of God, and to my parents whose sweat and toil have made possible my education up to this level.

AND TO

She

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DECLARATION

I hereby declare that this thesis, "Pedogenic Changes and Phosphorus Availability in Soils of Northern Ghana", has been written by me and that it is the record of my own research work. It has neither in whole nor in part been presented for another degree elsewhere. Works of other researchers have been duly cited by references to the authors and all assistance received also acknowledged.

....

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The above declaration is affirmed:

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ABSTRACT

Pedogenic changes and P saturations in five ferruginous soils (Lixisols or Alfisols) and their associated nodules on two different landscape positions in northern Ghana were investigated. Tingoli, Tolon and Kumayili series are well drained upland soils which occur on one landscape (toposequence 1). Kpelesawgu series which is imperfectly drained and Changnalili series which is poorly drained occur on a relatively lower landscape (toposequence 2). Chemical, physical and mineralogical properties of the soils and their associated nodules were determined including factors which tend to affect the P saturation levels.

The amounts of dithionite-citrate-bicarbonate (DCB) extractable Fe and Al are higher than the oxalate Fe and Al indicating that the Fe and Al oxides are very crystalline. Both DCB and oxalate forms of Mn are very low. The DCB- Fe and -Al generally increase with depth in all the soils. On toposequence 1, the content of free Fe and Al follows the order Tingoli series > Tolon series > Kumayili series. In the low lying soils on toposequence 2, the order is Kpelesawgu series > Changnalili series. The oxalate Fe and Al are, however, higher in the low lying soils than in the well drained soils due to the low oxidising conditions in the soil environments of toposequence 2.

Crystallinity is higher in the well drained soils than in the imperfectly and poorly drained soils. Crystallinity which reflects the stage of maturity is found to be in the order of nodules (> 2mm) > nodules (< 2mm) > clay > total fine earth > silt. The sequence of maturity in the well drained soils also follows the trend Tingoli series > Tolon series > Kumayili series. In the soils of the low lying areas, Kpelesawgu series is more matured than the Changnalili series. The sand and silt fractions in all the soils generally lack weatherable minerals indicating advanced stage of weathering in the soils. The clay fraction of the well drained soils is dominated by kaolinite and quartz with traces of goethite and haematite, while the low lying soils have illite in addition to the kaolinite and quartz. The major minerals in the nodules are goethite, haematite and quartz. The CEC is generally

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low in all the soils (< 10 cmol (+)/kg) due to the nature and activity of clay minerals. This is also supported by the very low specific surface area of the clay fraction.

In each respective soil, total phosphorus (TP) concentration follows the sequence nodule (< 2mm) ≈ clay > nodule (> 2mm) > total fine earth > silt. The phosphorus saturation levels in the well drained soils on toposequence 1 correspond to the stage of profile maturity. In the Tingoli series where the highest TP levels are found, only DCB-Al and oxalate forms of Fe and Al appear to exert any influence on phosphorus saturation. The TP saturation in the Tolon and Kumayili series is greatly affected by the clay content, oxalate-Fe and -Al and DCB-Fe. In the low lying area soils, total phosphorus content is higher in the Changnalili series than in the Kpelesawgu series probably due to translocation. In the Kpelesawgu series TP saturation is influenced by the silt content, DCB -Fe and -Al and oxalate-Al whereas in the Changnalili series, DCB and the oxalate forms of Al and Fe enhance total phosphorus saturation.

The Tingoli and Tolon series can be classified as Plinthic Lixisols (FAO-UNESCO) or Plinthustalfs (USDA Soil Taxonomy) while the Kumayili series is placed under Ferric Lixisols or Haplustalfs. Both the Kpelesawgu and Changnalili series are classified as Plinthic Lixisols or Plinthaqualfs.

It also appears that poorly crystalline forms of Fe and Al oxides and oxyhydroxides control the P saturation and distribution in the soils. However, as nodules are formed the P saturation tends to be controlled by both crystalline and poorly crystalline forms of the iron and aluminium oxide minerals. This would imply that the nature and properties of the clay fraction are very important in controlling the P saturation levels in the soils studied. It is suggested that for sustainable agricultural production the factors which affect phosphorus saturation in soils should be addressed.

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CHAPTER ONE

INTRODUCTION

The soils of northern Ghana are characterised by fertility constraints and low moisture contents resulting from inadequate rainfall. The organic matter content is very low because of the predominantly grass vegetation. Removal of bases leaves only the sesquioxide minerals of iron and aluminium which in turn result in a low cation exchange capacity (Obeng, 1975). The fertility problem also includes low clay content, intense weathering, low natural phosphorus saturation in the parent material and high phosphorus fixation (Halm, 1968; Kanabo et al., 1978). The soils in addition contain many to abundant nodules and concretions.

Ferruginous concretions, nodules and ferricretes represent a more extreme case of heterogeneity within the soils. They not only affect root penetration and water movement, but also have substantially higher iron and aluminium oxide contents than the surrounding soil (Taylor and Schwertmann, 1974; Nahon et al., 1977; Tiessen et al., 1987; Obeng, 1970). The concretions, which contain large quantities of iron oxides act as an effective "sink" for added phosphorus (Tiessen et al., 1991b). Phosphorus deficiency has thus become widespread in the majority of soils of northern Ghana.

About 50% of the soils in the savanna zone is made up of Groundwater Laterites (Ahn, 1970; Obeng, 1970), which with the notable exception of some relatively deep variants, are highly concretionary and have a very high sorption capacity for phosphorus. This, therefore, imposes a severe limitation to their use and management.

In the recent past, the soils of northern Ghana have been cultivated without the use of fertilizers. Consequently, their fertility was maintained by prolonged fallow periods. However, with the increasing population pressure and demands for food production, the fallow periods are becoming shorter. Furthermore, permanent land cultivation is being introduced increasingly to replace the traditional bush fallow system (Schmidt and Frey, 1988). The situation has, therefore, led to a serious decline in soil productivity. The high

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phosphorus sorption capacity has not brought about the desired benefits from fertilizer application. The poor fertility of these soils thus still remains a problem for sustainable agricultural production.

The majority of research on soils of northern Ghana have focused on reactions of phosphorus with soils, which sought to predict more accurately the availability of applied phosphorus for plant growth (Kanabo et al.,1978; Abekoe, 1989; Tiessen et al.,1991b). Some other studies have focused also on phosphorus sorption and desorption in surface soils (Ahenkorah, 1968; Kanabo et al., 1978; Owusu-Bennoah and Acquaye, 1989; Tiessen et al., 1991b). However, phosphorus saturation in soils at different landscape positions and factors which tend to influence these saturation levels have received very little attention. The continuous use of the lateritic or concretionary soils in northern Ghana for crop production, therefore, requires an indepth understanding of the pedogenic processes that affect their natural P saturation. A detailed understanding of the pedogenic changes in soils on the landscape and the natural differences existing among them is also important.

The objectives of this study are, therefore, to determine the:

(i) pedogenic changes in soils at different landscape positions including their respective associated concretions or nodules; and

(ii) natural phosphorus contents and the factors that affect the P saturation levels in these soils.

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CHAPTER TWO

LITERATURE REVIEW

2.1 Nature of soils in northern Ghana

The soils of the interior savanna zone of Ghana have developed through the influence of climate and vegetation on the local geology (parent materials) (Obeng,1975). Among the factors which contribute to the formation of the soils climate, especially temperature and rainfall distribution, geology and relief seem to be the most important. The rainfall in northern Ghana is not well distributed because most of it occurs within about six months. The rest of the year is very dry and hot with practically no rains at all. These prevailing climatic conditions, coupled with the general gentle relief, result in the formation of very shallow soils overlying impermeable ironpan (Obeng, 1975).

In Ghana, the ironpan soils occur commonly within the Guinea savanna zone (locally referred to as the Interior savanna zone). They cover about 76 000 km^2 and may occur at different elevations in the landscape (Kanabo et al., 1978). These soils, including other ferruginous tropical soils of West Africa, are fairly shallow and the profiles of the majority of them are less than 150 cm deep (Jones and Wild, 1975).

Among the dominant groups of soils in northern Ghana are also the lateritic soils with various amounts of iron-bearing nodules. These soils are highly weathered, sesquioxide-rich, low in organic matter and mainly kaolinitic (Obeng, 1975). The soils which are typical of the 'middle' belt of West Africa also contain small amounts of illite (Adu, 1957; Ahn, 1970). In the surface horizon, clay contents are generally low because of the downward movement of clay within the profile.

The lateritic soils are inherently infertile except for the limited, non-gravelly upland soils developed from basic rocks and those developed in medium to moderately heavy textured alluvial materials within the extensive valley flats (Obeng, 1975). The genesis of these soils including the iron rich nodules needs, therefore, to be studied in greater detail.

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2.2 Plinthite and associated forms

Various names have been used to describe the iron-containing entities embedded or occurring in tropical soils. These include concretions (Ho, 1960; Gallaher et al., 1973), iron concretions (Hamilton, 1964; Fiskell and Perkins, 1970), laterite (Weaver et al., 1992) plinthite (Daugherty and Arnold, 1982; Eswaran et al., 1990), glaebules (Gallaher et al., 1973) and ferricrete (Ollier, 1991).

Plinthites are unique to the tropics and they are associated with low relief (McFarlane, 1976). It has been suggested by many workers (Winters, 1938; Drosdoff and Nikiforoff, 1940) that a fluctuating groundwater table is necessary to concentrate iron in plinthite. Strong weathering is particularly significant in the formation of plinthite. The parent material can also strongly influence the rate of iron release. Perkins and Lawrence (1982) noted that parent materials of soils with plinthite contain more iron than those of non-plinthic soils within the same locality. Lithology, therefore, has stronger influence on the plinthite formation process than age or stratigraphy (Oti, 1987).

Iron has been found to be the major element in plinthite, nodule and concretion formation; consequently there must be a mechanism by which iron moves to be concentrated in these products of pedogenesis. Among the various processes proposed for plinthite formation, ferrolysis, which is a hydromorphic process (Brinkman, 1970), may be especially important. The mechanism depicts the disintegration and solution of iron oxides in water by a process based upon the alternating reduction and oxidation of iron.

The next and most important stage of plinthite formation is the local accumulation or segregation of sesquioxides which follows the release of iron from primary minerals. Ollier (1991) suggested lateral movement of iron in solution as a major process in the segregation and subsequent accumulation of iron. In the Fe^{2+} form, iron is mobile and is transported to sites where accumulation takes place through accretion. According to Stoops (1970), the localised redistribution of iron results in mottles. Thus, there are bleached zones depicting areas of Fe and Mn removal and enriched zones where there is Fe and Mn accumulation.

The final stage in plinthite formation is its induration into petroplinthite. According to Schwertmann (1985), the cementation of petroplinthite results from a close packing of goethite and / or haematite crystals.

2.3 Sesquioxide distribution in soils

Iron, Al and Mn distribution in soils is greatly affected by pedogenesis. The distribution of pedogenic oxides and oxyhydroxides of these elements in soils also characterises the type, direction and extent of pedogenic processes (Schlichting and Blume, 1966). The distribution of oxides of Fe, Al and Mn is also used to interpret soil formation processes in the temperate regions (McKeague and Day, 1966; Blume and Schwertmann, 1969). These oxides and oxyhydroxides of Fe and Al are dominant in highly weathered tropical soils and occur in both poorly crystalline and / or crystalline forms . A small portion of Fe and Al is also present in the form of organic complexes (Juo et al.,1974).

2.3.1 Forms of extractable Fe and Al

The differentiation among the various forms of Fe and Al in soils can be made by selective extraction methods. The acid ammonium oxalate method extracts mainly the poorly crystalline amorphous forms of inorganic and organic-complexed Fe and Al from soils (Mehra and Jackson, 1960). The alkali sodium-pyrophosphate extraction method extracts organic-complexed fraction of Fe and Al. Total free oxides including the major portions of organic complexes can be determined by reductive dissolution with dithionite-citrate-bicarbonate solution. This solution also extracts goethite and haematite and silicate minerals only slightly including silicate Fe and Al (Mehra and Jackson, 1960). The dithionite-citrate-bicarbonate solution, therefore, provides an estimate of 'free' (non-silicate) forms. However, these procedures have proved more successful in differentiating Fe than Al in soils (Bascomb, 1968; McKeague et al., 1971).

The oxalate extractable Fe (Feo) and Al (Alo) give an approximation of the degree of accumulation of amorphous products of recent weathering. This is especially true for

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soils formed from materials varying widely in texture, colour, pH, organic matter and total oxides (McKeague and Day, 1966). Large amounts of oxalate extractable Fe and Al are also associated with soils of high pH-dependent charges and high phosphorus fixing capacity (Saunders, 1965).

The dithionite extractable iron (Fed) mostly accounts for the combined content of amorphous and crystalline iron oxides. According to Blume and Schwertmann (1969), dithionite extractable iron is not a useful quantitative measure of the extent of release of iron from primary minerals because of passive iron migration in profiles. For this reason, the oxalate extractable iron (Feo) tends to be more suitable for that purpose. On the other hand, the amount of Fed in the B horizon can serve as a basis for assessing the relative degree of development of normal soil profile from the same kind of parent material.

The Feo contents are generally greater in surface horizons than in the subsurface horizons (Moniz et al., 1982). This is the result of decreasing organic matter content with depth. Moreover, organic matter is known to inhibit crystallization of iron in soils (Schwertmann, 1966; Huang and Violante, 1986). Juo et al. (1974) found the Feo in well drained savanna soils to be low and attributed this to the high temperature and prolonged dry season associated with the environment. However, de Endredy (1963) observed the content of iron oxides extracted by acid ammonium oxalate from some Ghanaian soils to be as high as 25%. Sherman et al. (1964) noted that drying at elevated temperatures causes amorphous Fe and Al oxides to dehydrate and subsequently lead to greater degree of crystallinity. The loss of amorphous nature of oxides as a result of high temperature also leads to decrease in cation exchange capacity in tropical soils.

The amount of Feo is usually less than the total free iron (Alexander, 1970). The relative distribution of (Feo) to (Fed) in soils (Feo/Fed) is commonly expressed as "active Fe ratio". This ratio is used as a relative measure of the degree of aging or crystallinity of free iron oxides (Schwertmann and Taylor, 1977). The active ratio is normally less than one, because acid oxalate extracts less iron from mineral soils than does dithionite-citrate.

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It approaches zero in old tropical soils (Alexander, 1974). This active iron ratio is valid only when comparing or characterising soils with similar parent material or where all significant amounts of primary iron have been removed (Blume and Schwertmann, 1969). The active iron ratio is also generally found to be higher in surface soils than in subsoils (Gamble and Daniels, 1972; Juo et al., 1974). Daugherty and Arnold (1982) found this trend to be more prevalent in well-drained soils than in soils where iron is concentrated by a fluctuating water table.

During the initial stages of weathering and soil development, the release of iron from primary minerals may exceed the rate of crystallisation into secondary compounds, causing the active Fe ratio to increase, but thereafter the ratio decreases with increasing age. High ratios of Fed to total iron (Fet) of soils suggest strong weathering in the landscape. As soil development continues, the ratio of Fed to Fet increases further (Schwertmann, 1985; Bigham et al., 1991).

2.3.2 Sesquioxide distribution and particle size

Free iron oxides are often closely associated with clay size particles in soils. They occur as discrete particles or coatings on the clay particles and act as cementing agents (Mitchell et al., 1964). The oxide-clay relationship may not be significant, especially if particulate oxides are extracted (Ashaye, 1969).

Juo et al. (1974) found that the free Fe oxides in some Nigerian soils followed the same distribution as the clay content within the same profile. They also noted that the clay/Fed ratio in some soils may be fairly constant with increasing depth, indicating a combined movement of Fe and clay into the subsoil. However, soils in dry environments tend to show a clay/Fed ratio which decrease with increasing depth suggesting that Fe movement can also be partially independent of clay movement.

Asamoa (1973) found a close similarity between free iron, especially Feo and clay in soils of the humid forest zone of Ghana. These soils show minimum free Fe content in

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the A horizons and a maximum in the B horizon which suggest that clay migrates with Fe in these soils. The same study showed that the distribution of Fe in the semi-arid savanna zone are, however, more closely related to silt than clay.

2.4 Geochemical aspects of phosphorus

It has been estimated that the total amount of phosphorus on earth is of the order of about 10^{19} t. About 10^{15} t of this total amount are in the earth's crust, which on the average contains 0.12% phosphorus (van Wazer, 1961). Nearly 200 phosphorus-bearing minerals have been found in nature but of these only one group is of agronomic significance, namely the apatites. The apatites have a general chemical formula as $M_{10}(PO_4)_6X_2$ and most frequently the metal ion (M) is calcium and the anion (X) is fluorine. Fluoroapatite is classified among the most easily weathered minerals (Mitchell et al., 1964) and hence rarely occurs as a primary mineral in sediments. The P content of sediments is on the average lower than in igneous rock (Larsen, 1967).

In virgin soils, the total P content varies widely and is obvious that significant quantities are lost during soil formation, probably by leaching and erosion (Larsen, 1967). Soils, on a global scale, do not receive P from any source other than from parent materials. Some redistribution is, however, brought by wind, water, animals and plants which cause depletion in some areas and enrichment in others. In modern times, this redistribution has been accelerated by the activity of man; enrichment is caused by manufacturing and applying fertilizers containing P on one hand, and depletion through cropping on the other.

2.5 Mobility of soil phosphorus

Although P is considered to be immobile in soils, considering the long time spans involved in soil profile development, the element can undergo significant changes in form and location. Nevertheless, movement of soil P may occur in three ways namely; (a) by the action of soil organisms, (b) with flowing water (mass flow) and (c) by thermal movement along a concentration gradient (diffusion). For each process, the magnitude of the movement will depend upon the fraction of soil P that is involved and the rate of movement of that fraction.

The phosphate anion has a low solubility and strong affinity to soil mineral components and readily moves within the profile and landscape segments even in semi arid climates (Tiessen et al.,1991b) . The fixation of 145 kg ha^{-1} of fertilizer P into discrete nodules in a fertilizer trial in northern Ghana implies mobility of P within the top soil. It has been suggested that P often moves from the bulk of the soil fines into the nodules (Tiessen et al., 1991b). There is also a growing realisation that P can move within soils in significant amounts particularly in some sandy soils (Frossard et al.,1989).

The movement of P in soils along the landscape often produces differences in P status of pedons of the same soil series or association. Smeck and Runge (1971) showed that the P status of some Mollisols varied widely, because of differences in landscape positions. Pedons at the foot of the slopes showed more P contents than soils in upland positions.

The redistribution of phosphorus in a landscape has been attributed to surface and subsurface flow of water (Ryden et al.,1973). The extent of run-off and erosion dictates the overland movement and redistribution of P in the landscape. Using a mass balance (pedogenic index) approach, Smeck and Runge (1971) showed that the loss of P from upland soils leads to gains in soils in lower slope positions. Phosphorus is also lost from soils either by surface flow or by leaching (Frossard et al., 1989).

Horizontal movement of P by subsurface flow is considered minimal due to sorption of phosphate anions by hydrous oxides of Al and Fe, which have strong affinity for P ions (Larsen,1967). The mobility of P anions in soils, therefore, tends to depend on the nature of the mineral surfaces and oxide coatings. This is because P anions are strongly adsorbed by mineral constituents such as clays and sesquioxides (Parfitt, 1978; Jones, 1981).

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Considering the various mechanisms of P movement, the activity of the larger soil animals will only cause a random redistribution whereas higher plants will bring about a unidirectional movement (Larsen,1967). The whole of the labile soil P is involved in this latter process and its rate will also depend on the quantity of P which is taken up by the roots through the plants and released to the topsoil by subsequent decay. This process may result in a very uneven distribution of P in an undisturbed profile.

Movement by mass flow may be important in bringing soil P to the plant roots and in causing leaching. The amount of P moved by mass flow is a product of concentration of P in the soil solution and the extent of liquid flow. Since the concentration of P in the soil is generally low, the amount of movement will normally be insignificant . It is noted that phosphorus is not normally considered to be lost by leaching. Nevertheless, some losses may occur over geological time because the total soil P contents are generally low in the parent materials (Larsen, 1967).

Diffusion is the process by which matter is transported from one part of a system to another as a result of the thermal movement of molecules or ions (Larsen, 1967). This movement is continuous, but where the system is at equilibrium there is no net transport. However, where differences in concentration exist, transport will occur, which moves the system to equilibrium. The rate of diffusion is related to the degree of saturation of the P adsorption capacity (Gunnary and Sutton, 1965) Thus, addition or removal of P or treatments which bring about changes in the P adsorption capacity of a given system also influence changes in the rate of diffusion. A strong heterogeneity of the distribution of P and sorption potential in concretionary soils often promote P movement by diffusion (Tiessen et al., 1991b).

2.6 Soil phosphorus and pedogenic weathering

Phosphorus is perhaps the key element in pedogenesis because of its great ecological significance (Walker, 1964). In unfertilised native soils, the source of phosphorus in organic matter is almost entirely supplied by parent materials because of low atmospheric returns. Parent materials are, thus, the only sources of P in soils other than the minimal amount contained in precipitation.

Phosphorus undergoes both pedological and short term biological transformation in soils on landscapes (Smeck,1985). The biological transformation may be crucial to the short term availability of P (Hedley et al., 1982). However, availability on long term basis is governed by pedological transformation. In unweathered parent material, the P is generally present as apatite. Consequently, the quantity of P in solution is governed by the weathering of apatite. The P in inorganic form, released from the parent material, may be immobilised by plants and soil microbes. It may also be leached or enter into the labile pool (Racz and Soper, 1967; Smeck, 1973). The P in the labile pool is also governed by the solubility of calcium, aluminium and iron bearing minerals to form secondary minerals especially Ca, Al and Fe phosphates (Racz and Soper, 1967; Smeck, 1973).

Phosphorus is most susceptible to translocation or utilisation and incorporation into the organic cycle at pH 7.0. The soil pH must, therefore, drop below 7.0 before significant quantities of P are released. At pH values below 7.0, the solubility of P is governed by Al and Fe activity and decreases rapidly as pH decreases. At pH values above 7.0, the solubility is governed by calcium phosphates and decreases rapidly as pH increases (Smeck, 1973). As weathering progresses, and basic cations are leached (with lowering in pH), accumulation of Fe and Al oxides occurs. These oxides then tend to fix P in solution. There is, therefore, a shift from Ca-P minerals to Al-P and Fe-P forms which become occluded in character with time (Walker and Syers, 1976; Tiessen et al., 1984; Sharpley et al., 1987).

The total P content of soils is of no direct practical importance but has often been used as a weathering index (Sanchez, 1976). It decreases in the topsoil with increasing weathering intensity. The relative abundance of primary, secondary and occluded P serves as a useful index of soil weathering intensity and profile development (Smeck and Runge,

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1971; Smeck, 1973; Walker and Syers, 1976). The quantities of total and organic P of some soils decrease with increasing profile development.

At the onset of weathering, the build up of organic P is controlled by the availability of inorganic P in the parent material. As weathering progresses and inorganic P (Pi) is released into the soil solution, part of the Pi is immobilised by plants and microbes leading to a build up of organic P with time. With further soil development, the quantities of primary P minerals decline and organic P increases until equilibrium is established between occluded P minerals and organic P (Walker and Syers, 1976). When this occurs, P availability is dictated by organic P (P_o) mineralisation (Tiessen et al., 1984; Stewart and Tiessen, 1987).

St. Arnaud et al. (1988) used a mass balance approach to compare grassland and forest soils and noted that 32-55% of the Ca-P (apatite P), which originally accounted for over 90% of total P in the parent material, had disappeared from the sola of forest soils. This was, in part, through leaching and conversion to organic forms during P cycling processes.

2.7 Phosphorus redistribution in landscapes

Soil P can be considered to be essentially immobile over a short time span. Nevertheless, it is mobile enough to provide a useful index of flow patterns in a landscape during the long time span in soil development (Smeck, 1973). Many researchers (e.g. Smeck, 1973; Walker and Syers, 1976) have shown that P is translocated within soil profiles and landscapes within a pedologic time frame. Smeck and Runge (1971) calculated that a minimum of 945 kg of P may be translocated laterally within a landscape; some pedons may gain up to 493 g m^{-2} while others lose up to 151 g m^{-2}.

Distribution of P within soil profiles formed in downslope or run-on sites is largely different from those formed in upland positions or runoff sites (Smeck, 1973; Day et al., 1987). Total P tends to increase downslope. On the contrary, Agbenin (1992) observed

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that total P contents of soils on a toposequence from N.E. Brazil decrease down the slope. According to Nye and Bertheux (1957), total P is greatest in surface forest soils but in savanna soils there is no consistent change in total P with depth.

2.8 Particle size

Many researchers (Allanway and Rhoades, 1951; Godfrey and Riecken 1954; Smeck and Runge 1971; Runge et. al., 1974; Ridley 1984) have shown that soils exhibit eluvial-illuvial horizons with respect to P redistribution. This creates a distinct minimum and maximum P distribution pattern within the soils. The total P in eluviated zones is more marked in soils with greater textural differentiation (Ridley, 1984). Studies have also shown that the highest total P concentration exist in clay size particles and suggest that P movement is positively correlated with clay movement and texture (Syers et. al., 1969; Hanley and Murphy, 1970; Lekwa and Whiteside, 1986; Day et al., 1987). The maximum and minimum total P accumulations, therefore coincide with maximum and minimum clay content, respectively (Ovalles and Collins, 1986). Acquaye and Oteng (1972) observed similar trends in alluvial and sandstone soils of Ghana.

The high concentration of apatite minerals in the sand and silt fractions of soils constitute a major source of total P in upland soils (Agbenin, 1992). The uniform distribution of total P with depth in soils also indicates a relatively homogeneous parent material. It appears, therefore, that clay is not an effective immobilizer of P in some soils (Godfrey and Riecken, 1954; Smeck and Runge, 1971).

The fixation of P by Fe oxide, indicates that a clay-Fe oxide-P relationship exists rather than a direct clay-P interaction (Smeck and Runge, 1971; Lekwa and Whiteside, 1986; Day et al., 1987). In non-concretionary soils, majority of the inorganic P is associated with the clay fraction (Nye and Bertheux, 1957). In sandy soils, some P is found in the iron oxide coating the same grains. In the subsoil, however, the P may be associated with any concretionary iron gravel or pan present.

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Surface reactions involving ligand exchange and non-specific retention could be the mechanisms of P association with clay (Parfitt, 1978; Jones, 1981). The sand and silt, more closely, reflect the P composition of the original parent material. It is also probable that where P is mainly concentrated in the sand and silt fractions, soil development tends to be at its early stages. Erosion selectively removes silt and clay size particles to which a large portion of the P is bound (Syers et al., 1969). During movement of fine particles a high proportion of P redistribution occurs in landscapes. This removal and deposition of P -rich fine particles might be responsible for the different P status of pedons of the same soil series or association (Syers et al., 1969).

2.9 Profile development and drainage

Landscapes are characterised by soils at various stages of profile development. Weathering intensity is the major factor affecting the transformation of soil P and a definite relationship exists between the quantity and form of P and the stage of profile development of soils in a landscape (Godfrey and Riecken, 1954). Often, the most highly developed profiles accumulate more phosphorus. Consequently, total P is likely to be lower in Entisols than in Oxisols. Contrary to this view, however, total P was noted to decrease from Entisols to Oxisols due to the combined effects of weathering and leaching (Agbenin, 1992).

The concentration of total and inorganic P decreases in the subsoils of low lying soils and this is attributed to higher increase in moisture content (Roberts et al., 1985). As soil moisture increases, leaching intensity and plant growth increase. Consequently, more inorganic P is removed from the subsoil by both plant uptake and leaching losses. The drainage status of soils also affects the nature of P and its distribution. As relief or slope decreases and drainage improves, there is a lowering in calcium phosphate contents which results in an increase in non-occluded, occluded and total phosphorus (Hsu and Jackson, 1960).

2.10 Phosphorus status and availability in West African savanna soils

Tropical soils in general and West African Savanna soils in particular have been known to suffer from multiple nutrient deficiencies, particularly P (Akinola et al., 1983; Ibia and Udo, 1993). According to Pieri (1985), P is one of the most limiting nutrients to crop growth in the Sahel. The response of millet to N fertilization is generally non-existent until the P requirement is met (Bationo et al., 1989). The total amounts of P in non-concretionary, light textured savanna soils are generally low (Jones and Wild,1975) and may range from 25 to 349 mg kg^{-1} (Manu et al., 1991). The available phosphorus levels are correspondingly low, ranging from 1 to 30 mg kg^{-1} with an average of 6 mg kg^{-1}.

The average total P contents of soils of West Africa are worthy of note. Enwezor and Moore (1966) observed that some savanna soils in Nigeria have an average total P content of 110 mg kg^{-1}. Goldsworthy and Heathcote (1963) reported an average total P content of 107 mg kg^{-1} for some 54 unfertilised topsoils from northern Nigeria. The average for 67 top soils from the sub-humid savanna of Ghana is 134 mg kg^{-1} (Nye and Bertheux, 1957). Recent studies by Tiessen et al. (1987) and Abekoe (1989) on selected savanna soils of northern Ghana have confirmed these findings.

2.11 Factors affecting P status in soils of northern Ghana

2.11.1 Parent Material

The parent materials of soils of northern Ghana are low in P. Available data on rock samples show an average of 700 mg kg^{-1} total P for 15 granitic rocks and 750 - 2440 mg kg^{-1} total P for rocks of intermediate and basic composition (Nye and Bertheux, 1957). Little is known about the age of the soil materials but the land surfaces are believed to date from the mid-Tertiary. Although the soils are not necessarily of the same age, there is evidence that they have been exposed to climatic periods, which were more humid than at present. The extensive occurrence of plinthite implies that the iron was mobile, probably as ferrous iron (Jones and Wild, 1975) resulting in an increased solubility of P. The present

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low content of soil P may, therefore be a consequence of the age of the parent materials and the pedogenic processes which had taken place in the soils. A high proportion of total P in these soils is often in the occluded form and is not available to plants.

2.11.2 Leaching and Erosion

Nye and Bertheux (1957) suggested that leaching is an important mechanism of soil P loss. The annual movement out of the profile is probably small except where the soil is sandy because surface reactions with silicate clay minerals and free iron and aluminum oxides tend to maintain a low soil solution P concentration. However, large amounts of P may be lost from the zone of rock weathering (Wild, 1961) where P solubility appears to be higher.

The loss of topsoils through erosion involves substantial loss of P. In northern Ghana where the terrain is fairly flat, erosion by wind and water could remove substantial amount of P. Elsewhere, wind-blown sand may give a surface deposit low in P (Jones and Wild, 1975).

2.11.3 Vegetation

In general, soil total P contents are higher in the forest zone than in the savanna. These differences follow the same pattern as those of organic carbon and total N (Nye and Bertheux, 1957; Acquaye and Oteng, 1972) and appear to reflect the extent to which the natural vegetation returns P to the soil surface through litter and dead roots. The available P content is independent on the vegetation or litter which is returned to the soil (organic P).

Recent studies in northern Ghana have shown that the role of organic phosphorus (P_O) is usually negligible because of the effect of too frequent fires which eliminate the release of P from recent organic residues (plant materials) added to the soil (Tiessen et al., 1993). In addition to mineralization, the competition by organic ligand for Fe and Al oxides surfaces lowers the fixation of applied and native P (Bhat and Bouyer, 1968).

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However, the vegetation is usually destroyed through burning and most of the benefits from organic matter are lost.

2.11.4 Sesquioxides

The majority of soils in northern Ghana are highly weathered and contain iron and aluminium oxides and oxyhydroxides (sesquioxides). These minerals have the capacity to sorb very large added P or native P thereby transforming them into Fe- and Al-bound forms (Dabin, 1974). In many cases, P sorption by sesquioxides appears to be a process of limited reversibility. Normally, the specific surface area of sesquioxides is more important in determining the sorptive properties of soils than the total amount of the sesquioxides present (Juo and Fox, 1977).

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CHAPTER THREE

MATERIALS AND METHODS

3.1. Site characteristics

The soils used for the study were collected from the Savanna Agricultural Research Institute (SARI) (formerly, Nyankpala Agricultural Research Station), which lies 16 km west of Tamale on the road leading to Daboya in the Northern Region of Ghana. The study site (Fig. 3.1), which is on latitude 9° 25' N and longitude 1° 00' W approximately, falls within the Interior Savanna zone of Ghana . The study site is typical of the general ecology and geomorphology of the Interior Savanna Zone. The soils cover more than 50% of the zone.

3.1.1. Physiography of area.

The general relief of the study site varies from about 165 m to about 200 m above sea level. The area is predominantly level to gently undulating. The local geology comprises clay-shale with lenses of sandstone, siltstone and mudstone (Adu, 1957) which belong to the Obosum beds of the lower Voltaian formation. These rocks are of early Carboniferous age (Junner and Hirst, 1946) and have weathered to secondary rocks which contain ironstone or ironstone gravels. The weathering of these secondary rocks produced the parent materials from which the soils have formed.

The climate of the area is typically hot and dry most of the year with low humidity. Mean monthly temperatures vary from 31 °C in March to about 26 °C in August. The area has a single rainy season from May to October, followed by a prolonged dry season (Walker, 1962). The monthly rainfall and temperature distributions are given in Table 3.1. The rainy season starts in April with about 82.5 mm of rain. The peak of the rainy season is in the months of August and September with September having the highest rainfall of 231.6 mm during a cumulative period of 18 rainy days. The relative humidities are high

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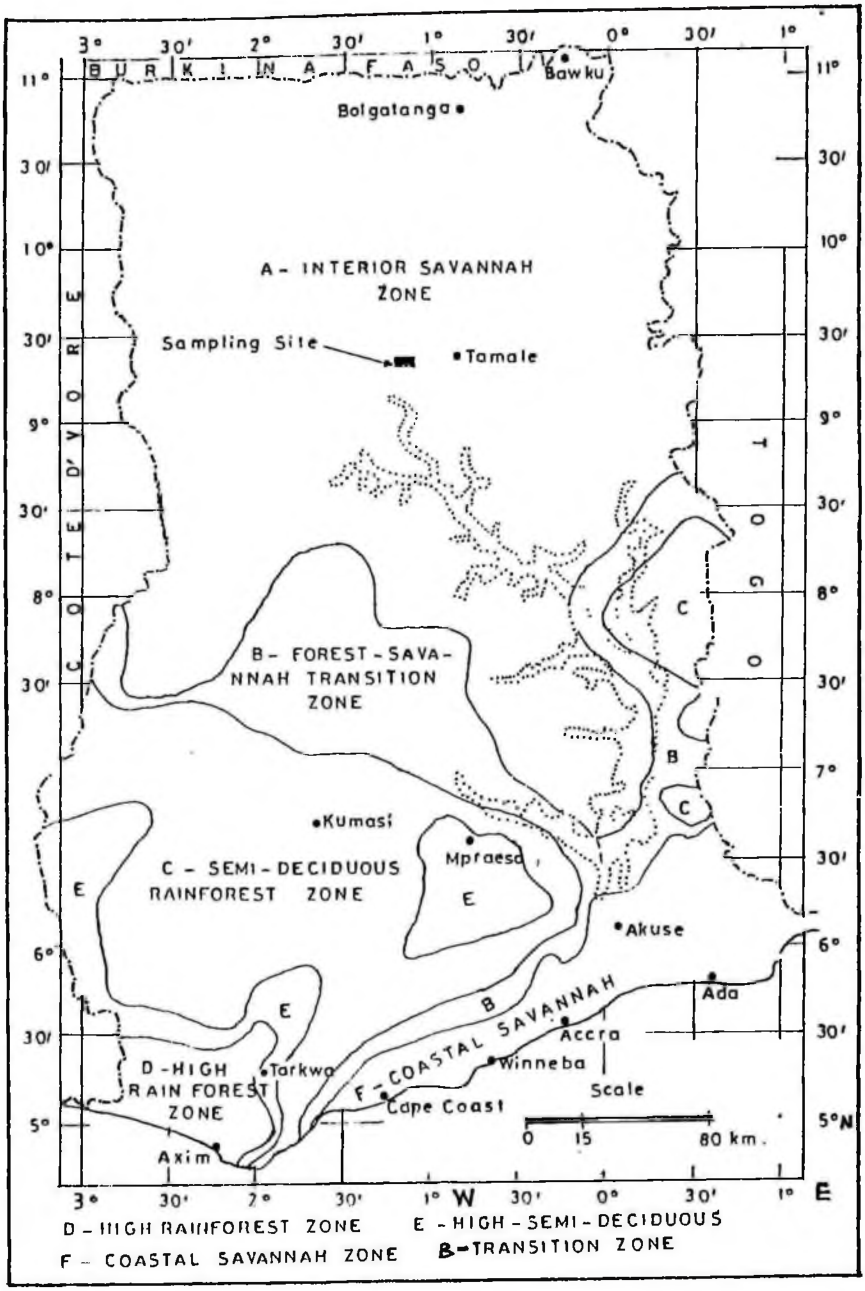

Figure 3.1 Map of Ghana showing the study site.

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Table 3.1 Climatic data of the study site*

	Major rainy season							Major dry season					
	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Annual total
Rainfall (mm)	82.5	115.2	91.6	157.1	203.6	231.6	75.7	11.5	2.8	2.1	8.6	50.4	1032.7
Rainy days	7	9	11	12	14	18	10	2	1	1	1	4	80
													Annual av.
Temp. (^oC)	30.5	29.1	27.1	26.3	26.0	26.1	27.6	28.1	26.9	27.5	30.2	31.4	28.1

*Computed from Ghana Meteorological Annual Records (1960 - 1990); (30 years average).

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during the rainy season (70-90%) but may fall to as low as 20% during the dry season, especially, in the month of January.

The natural vegetation consists of savanna grassland which is interspersed by fire resistant trees. The dominant grass species are *Andropogon gayanus* (elephant grass), *Imperata cylindrica* (spear grass) and *Sporobulus pyramidalis*. Prominent among the few scattered trees are *Butyrosperum parkii* (shea butter tree).

3.2 Soils and sampling

Soils on two different landscapes were used in this study. Tingoli, Tolon and Kumayili series occur on one landscape (toposequence 1) at elevations of approximately 186m, 178m and 171m above sea level, respectively. The soils on the other landscape (toposequence 2) are dominantly made up of the Kpelesawgu and Changnalili series, which are found at approximately 170m and 167m above sea level, respectively.

Tingoli, Tolon and Kumayili series are well drained soils and have been classified as Savanna Ochrosols (Brammer, 1962). The two upland members (Tingoli and Tolon series) contain various amounts of ironstone nodules. These two soils have developed from ironstone gravel and ferruginized brash (Adu, 1957). The Tingoli series are noticeably redder and occupy the summit and upper slopes of a low hill at the southwestern portion of the Research Institute. The Tolon series are orange to mid-brown in colour and occupy the shoulder position of the toposequence, downslope of the Tingoli series. The Kumayili series,which is next to the Tolon series has developed from local colluvium or hill wash. The soils occupy the mid-slope of the toposequence and have very few amounts of ironstone concretions.

The low lying soils of the station are the Kpelesawgu and Changnalili series which may be classified as Groundwater Laterites (Brammer, 1962). The Kpelesawgu series are yellow-brown in colour and have developed from local colluvium and alluvium. They are found on the lower slopes to the flat valley bottoms and are imperfectly drained. The

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Changnalili series are grey and brown in colour and occupy the edges of the valley bottom. They are developed from massive ironstone, deepened by soil wash (Adu, 1957) and are also shallow and poorly drained.

Each profile was described after which disturbed and undisturbed core samples were collected from each genetic horizon . The undisturbed samples (for bulk density determination) were taken with core samplers of 5.0 cm (internal diameter) by 5.0 cm (height). Summary of the morphological description of each profile is provided in Table 4.1 (see Chapter 4).

3.2.1 Sample preparation

The disturbed soil samples were air dried, ground and sieved to pass through a 2 mm sieve to obtain the fine earth fraction. The nodules were isolated by physical picking, washed and dried in an oven at 105 ^{o}C for analyses.

3.3 Laboratory analyses

3.3.1 Physical properties

3.3.1.1 Bulk density and particle size distribution

Bulk density was determined using the core method (Blake, 1965). The undisturbed core samples were weighed, dried in an oven at 105 ^{o}C for 24 hours and reweighed. The overall density, D_b (g/cm^3) of each core sample was calculated from the dry mass of the core and its volume. Particle size distribution was determined by the conventional hydrometer method (Day, 1965) after dispersion in sodium hexametaphosphate.

3.3.1.2 Available moisture content

The moisture content of the < 2 mm fraction of the soils was measured at field capacity (1/3 bar or 33 kPa) and at wilting point (15 bar or 1500 kPa) using the pressure plate extraction method (Eilers, 1978). The difference in moisture content of the soil at wilting point and at field capacity was then calculated as a measure of available moisture content of the soil.

3.3.1.3 Specific surface area

Specific surface area (SSA) of the clay fraction was determined using the multiple point Brunauer-Emmett-Teller (BET) (1938) method with the help of a Quantachrome autosorb gas adsorption system machine. The BET specific area of the clay was determined by nitrogen adsorption at -196 ^{o}C. The samples were degassed prior to nitrogen adsorption by passing helium at 80 ^{o}C through the samples for 12 hours.

3.3.2 Chemical analyses

3.3.2.1 Soil pH and organic carbon

Soil pH was determined in both distilled water and 1N potassium chloride solution using a 1:2 (soil to solution) ratio on a Pye-Unicam pH meter. Similar measurements were done for the ground nodules. Organic carbon was determined on both the fine earth and ground nodules using a Lec Carbonator equipment. Hundred milligrammes each of the < 2 mm soil and nodules (all ground to pass through a 100 mesh sieve) were weighed and placed inside the furnace of the Carbonator. The percent organic carbon was then read on the carbonator after 2 minutes of combustion.

3.3.2.2. Exchangeable bases

Exchangeable bases determination was done also on both the fine earth and the nodules. Five grammes of the samples were weighed into separate extraction bottles. Twenty-five millilitres of 1M NH_4Cl were added and shaken end-over-end for 30 minutes. The solution was centrifuged at 10,000 revolutions per minute (rpm) and the supernatant decanted into vials. A further 25 ml of 1M NH_4Cl was added to the samples and shaken for another 30 minutes The contents in each bottle were centrifuged and the supernatant added to the original extracts. The extracts were then filtered using a Millipore filter paper and the exchangeable Ca and Mg determined on an atomic absorption spectrometer. Potassium and sodium were determined using a flame emission photometer.

3.3.2.3 Exchange acidity, Effective CEC and Base saturation

Aluminium and hydrogen ions were extracted from the samples with 1N KCl according to the method of Thomas (1982). Ten grammes of the fine earth and the ground nodules were weighed into separate beakers. Twenty-five ml of 1N KCl was added and the contents mixed thoroughly. The suspension was left to stand for 30 minutes after which it was transferred into a buchner funnel fitted with a filter paper and mounted on a 250 ml vacuum flask. The sample was then leached with additional 125 ml of 1N KCl in increments of 25 ml. Exchange acidity was then determined by titrating the extracts with 0.1M NaOH using phenolphthalein as an indicator.

Effective CEC was calculated by cation summation and base saturation calculated as the sum of bases (Ca, K, Mg and Na) expressed as a percentage of effective CEC.

3.3.2.4. Dithionite-citrate-bicarbonate extractable Fe, Al and Mn

Extractable iron, aluminium and manganese were determined using the method of Mehra and Jackson (1960). Dithionite-citrate-bicarbonate (DCB) Fe, Al and Mn were extracted from the fine earth, silt and clay fractions and the ground nodules. Five hundred milligrammes of the fine earth (ground to pass through a 100 mesh sieve) and 200 mg each of the silt and clay and ground nodules were weighed into separate 15 ml graduated test tubes. A citrate-bicarbonate buffer solution was added up to the 5 ml mark. Using a calibrated scoop, 0.2 g of $Na_2S_2O_4$ was added to the samples, vortexed and placed in a water bath at 80 ^oC for 15 minutes. One ml of saturated NaCl solution was added. The sample in each tube was then vortexed again for thorough mixing, centrifuged and the supernatant poured off into a 100 ml volumetric flask. The extraction process was repeated on the soil residue. The residue was then washed once with 5 ml of citrate bicarbonate buffer solution and then washed again with 1 ml of saturated NaCl. After each washing,

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the sample was centrifuged and the supernatant added to the contents of the flask. The contents in the flask were made up to the 100 ml mark with deionised water. The flask was then shaken for thorough mixing and the concentration of Fe, Al and Mn in the extracts was estimated using the Perkin Elmer 3100 Atomic Absorption Spectrometer (AAS).

3.3.2.5 Tamm's oxalate extractable iron, aluminium and manganese

The oxalate extractable Fe, Al and Mn were determined on the fine earth, silt, clay and nodules using the method of McKeague and Day (1966). Two hundred and fifty milligrammes of each sample (the total fine earth and nodules ground to pass through a 100 mesh sieve) were weighed into 15 ml test tubes. Ten ml of ammonium oxalate solution (buffered at pH 3) was added. The tubes were placed horizontally in a covered box and shaken for 4 hours in the dark. After shaking, the contents in the tubes were centrifuged and the clear supernatant decanted into vials for analyses. The oxalate extractable Fe, Al and Mn were determined on the Perkin Elmer 3100 AAS.

3.3.2.6 Available phosphorus

Available phosphorus in the samples was determined using the method of Olsen et al. (1954). Two and a half grammes of each sample was weighed into a 250 ml conical flask. Fifty ml of 0.5 M $NaHCO_3$ was added and the suspension shaken on a reciprocating shaker for 30 minutes. The suspension was then filtered into vials through a number 40 Whatman filter paper. The extract was then analysed for available P using the Murphy and Riley (1962) method. All the inorganic P concentrations were read using the Beckman DU-64 Spectrophotometer at a wavelength of 710 nm.

3.3.2.7 Total phosphorus

Total phosphorus was determined using a modified method of Thomas et al. (1967). Two hundred and fifty grammes of oven dried (65 ^{o}C) soil samples were weighed into 75 ml digestion tubes. Two boiling chips and 5 ml of deionised water were added and

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the contents vortexed and later allowed to stand overnight. The tubes were then put on a heating rack and heated for 30 minutes at a temperature of 110 °C. After 30 minutes of heating, the temperature was increased to 125 °C. Heating was continued at temperatures of 150 °C, 175 °C, 200 °C, 250 °C, 300 °C and 360 °C and on each occasion heating was done for 30 minutes. On the following day, five millilitres of H_2SO_4 and 0.5 ml of H_2O_2 were added to the contents in each tube, vortexed and put back onto the rack at 360 °C. After 30 minutes of heating, the tubes were taken off, allowed to cool for approximately 30 minutes and another 0.5 ml of H_2O_2 added. The tubes were vortexed and heated again at 360 °C for 30 minutes. This heating procedure was repeated ten times until the solution in each tube became clear. On the tenth time, the heating was done for one hour to remove excess H_2O_2. The tubes were then taken off the rack and allowed to cool completely for about 4 hours. The contents in each tube was brought to the 75 ml mark with deionised water, shaken thoroughly and poured into vials. The total P in each digest was then determined using an auto-analyzer.

3.3.2.8 Dithionite-citrate-bicarbonate extractable phosphorus

Dithionite-citrate-bicarbonate extractable phosphorus was determined using a modified method of McLeod and Clarke (1973). Five millilitres of the DCB extracts (see section 3.3.2.4) were pipetted into 50 ml flasks. Five millilitres of concentrated HNO_3 and 1.0 ml of concentrated (16 N) H_2SO_4 were added. The contents of each flask were then heated at about 360 °C until white fumes of H_2SO_4 were seen. The samples were then taken off, cooled and deionised water added up to the 25 ml mark. The samples were then boiled for about 5 minutes and then taken off to cool completely. The DCB extractable P was then determined using the Murphy and Riley (1962) solution. The concentrations of DCB-P in the extracts were read using the Beckman DU-64 Spectrophotometer at a wavelength of 710 nm.

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3.3.2.9. Total elemental analysis

Total elemental analysis was done on the fine earth, nodules and clays using the closed vessel microwave technique (CEM Sample Preparation System Manual, 1992). Hundred milligrammes each of the oven dried finely ground samples were weighed into separate digestion vessels and wetted with few drops of water. Five millilitres of concentrated HNO_3, 4 ml of 48% HF and 1.0 ml of HCl were added. The vessels were then sealed tightly and placed in the microwave and digested at pressures of up to 80 psi. At the end of the digestion the pressure was allowed to fall to zero. The vessels were then removed from the microwave and a 200 mg boric acid powder was added to the samples. The vessels were then quickly covered and shaken on a reciprocating shaker for 15 minutes. They were later removed and the contents decanted carefully into 100 ml flasks. The digestion vessels were rinsed thoroughly with deionised water and the water added to the contents of the flasks. The extracts in the flasks were made up to the 100 ml mark and shaken thoroughly. The concentration of total Si, Fe, Al, Mn, Ti, Ca, and Mg in the extracts was determined using the AAS. Sodium and potassium in the extracts were determined by flame emission photometry.

3.3.3 Mineralogical analyses

3.3.3.1 Fractionation of samples

Fifty grammes of the fine earth sample were weighed into 500 ml beakers and 300 ml of deionised water added. The suspension was stirred vigorously and sonified with a Brausonic ultra sonifier at 300 watts for 8 minutes. The sonified suspension was poured through a 0.05 mm sieve (300 mesh) to separate the sand fraction from the silt and clay fractions. The sand was washed several times with deionised water and later poured into 150 ml plastic beakers. Undecomposed organic residues were separated by flotation. The collected sand fraction was freeze-dried and stored for analysis. The silt and clay fractions were separated by repeated centrifugation and resuspension. After each centrifugation, the clay in the suspension was decanted carefully into 5 L bottles and saved. The sample in each bottle was then resuspended in 500 ml centrifuge bottles to a 10 cm height and recentrifuged. This was done for eight times to make sure that all the clay was separated from the silt. The silt fraction residue was carefully transferred into plastic beakers, freeze-dried and stored for analysis.

The clay suspension was flocculated by adding NaCl and allowed to stand overnight. The flocculated clay samples were later washed free of the NaCl. The washing was done several times with deionised water and then methanol. The total clay was then freeze-dried and stored for further preparation.

3.3.3.2 Saturation of clay samples

Each clay sample was saturated with potassium by repeated (3 times) addition of 1N KCl. After each KCl addition, the suspension was centrifuged and the centrifugate discarded. Excess salts were removed from the clay by repeated washings with deionised water and methanol.

3.3.3.3 Specimen preparation

A few millilitres of a suspension containing about 20 mg of K-saturated clay per 1ml of deionised water was prepared. About 1 ml of each suspension was spread uniformly on separate petrographic slides with the help of a dispensing pipette. The slides were then allowed to dry at room temperature. Heating of each sample above room temperature was done after the initial x-ray analysis.

3.3.3.4 X-ray diffraction

A Rigaku X-ray diffractometer was used for the x-ray analysis. A Cu K-α radiation with a Ni filter was produced using 50 kV and 150 mA power source. The samples were scanned at a rate of 5 ^{o} per minute between 3 ^{o} and 60 ^{o}. The K-saturated slides were exposed for x-ray analysis at room temperature, after two hours of heating at 350 ^{o}C, and again after two hours of heating at 550 ^{o}C.

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The silt and sand fraction were ground and mounted on glass slides with the help of acetone for parallel orientation. Diffraction patterns of the oriented samples were obtained to determine if weatherable minerals were present. Random powder analysis of the ground nodules was done on a Philips X-ray diffractometer fitted with an iron target and scanned at a speed of 1^{o} per minute between 5^{o} and 60^{o} to determine the type of iron oxide present.

3.3.3.5 Quartz determination

Quantitative analysis of quartz in the fine earth and silt fractions was done using the method of John et al. (1954). Mixtures (w/w) of pure quartz and pure kaolinite i.e. quartz:kaolinite ratios of 100 : 0; 90 : 10; 80 : 20; 60 : 40; 50 : 50; 40 : 60; 20 : 80; 10 : 90 and 0 : 100) were prepared.

The mixtures in the various proportions were mounted on aluminium stubs and exposed to x-rays using a Cu K-α radiation with a Ni filter. The intensities of quartz at 0.426 nm were taken by measuring the diffraction peak heights of the mixtures. A standard curve was then constructed from the intensity and weight data.

The intensity of quartz at 0.426 nm in the finely-ground samples was determined and amounts of quartz estimated by extrapolation from the standard curve.

3.4 Data analyses

Correlation coefficients were computed between various properties to find out if there is any association between the tested properties.

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CHAPTER FOUR

RESULTS

4.1 Macromorphological description of the soils

The macromorphological description of the soils is given in Table 4.1. The Tingoli, Tolon and Kumayili series on toposequence 1 are well drained soils with fine subangular blocky structure which changes to medium and then to coarse subangular blocky with increasing depth. The Kpelesawgu series and Changnalili series on toposequence 2 have granular to subangular blocky structure which changes to medium subangular blocky and then becomes massive with depth.

The soils on toposequence 1 generally have slightly sticky, friable and slightly hard consistence which becomes sticky, firm to very hard with depth. In the Kpelesawgu and Changnalili series, the consistence is slightly sticky, friable and slightly hard becoming sticky, firm and hard and then to coarse indurated ironpan with depth. The horizon boundaries of the soils are generally gradual and smooth. The soils on toposequence 1 are reddish in colour and their redness rating follow the sequence Tingoli series > Tolon series > Kumayili series. The Kpelesawgu and Changnalili series on toposequence 2 are, however, yellow in colour.

4.2 Physical properties

4.2.1 Nodule and particle size distribution

The analytical results of the physical properties of the soils are given in Table 4.2. The nodule content generally increases with depth. The accumulation of the nodules is more marked in the well drained, upland soils on toposequence 1. The Tingoli series has the highest amount of nodules which vary from 11% (w/w) in the surface to > 80% in the subsurface. In the Tolon series, the distribution changes from 4.2% in the surface horizon to 91% at depths below 76 cm. The moderately well drained Kumayili series at

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Table 4.1. Macromorphological description of the soils.

Depth (cm)	Colour (dry)	Texture†	Structure‡	Consistency*	Boundary¶	Special features
			Tingoli series			
0-16	5YR 4/6	scl	2f-m gr-sbk	wss, mfr dsh	cs	Fe-oxide nodules
16-32	2.5YR 3/6	scl	2f-m sbk	wss, mfr, dsh	gs	Fe-oxide nodules
32-48	2.5 YR 3/6	sc	2m sbk	wss, mfi, dh	cs	Fe-oxide nodules
48-67	2.5 YR 4/6	scl	2m sbk	wss, mfi. dh	cs	Fe-oxide nodules
67-98	2.5 YR 3/6	sc	2c sbk	ws, mfi, dh	cs	Fe-oxide nodules
98+	2.5 YR 3/6	sc	2c sbk	ws, mfi, dvh	-	Fe-oxide nodules
			Tolon series			
0-14	5YR 5/6	scl	2f-m gr-sbk	wss,mfr, dsh	cs	Fe-oxide nodules
14-30	5YR 5/6	scl	2f-m sbk	wss,mfr, dsh	gs	Fe-oxide nodules
30-54	7.5YR 5/4	scl	2m sbk	wss,mfi, dh	cs	Fe-oxide nodules
54-76	5YR 5/4	sc	2c sbk	ws,mfr, dh	cs	Fe-oxide nodules
76-100	5YR 5/6	scl	3m sbk	wss, mfi, dvh	-	Fe-oxide nodules
			Kumayili series			
0-18	5YR 5/6	scl	1f gr	wss, mfr, dsh	cs	-
18-36	5YR 5/6	scl	2f-m sbk	wss, mfr, dsh	cs	-
36-57	7.5YR 6/6	scl	2m sbk	wss, mfi, dh	gs	-
57-90	7.5YR 5/6	scl	2m sbk	wss, mfi, dh	gs	-
90+	7.5YR 5/6	cl	3c sbk	wss, mfi, dvh	-	Fe-oxide nodules

† scl = sandy clay loam; sc = sandy clay.
‡ c = coarse; f = fine; m = medium; gr = granular; sbk = subangular blocky.
* ws = wet sticky; wss wet slightly sticky; mfr = moist friable; mfi = moist firm; dsh = dry slightly hard; dh = dry hard; dvh = dry very hard.
¶ cs = clear smooth; gs = gradual smooth.

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Table 4.1. cont'd.

Depth (cm)	Colour (dry)	Texture†	Structure‡	Consistency*	Boundary¶	Special features
Kpelesawgu series						
0-15	7.5YR 7/4	scl	1f-m gr-sbk	wss, mfr, dsh	cs	-
15-34	7.5YR 7/4	scl	1m sbk	wss, mfr, dsh	gs	-
34-64	7.5YR 7/4	sc	2m sbk	ws, mfi, dh	gs	common mottling
64-100+	7.5YR 7/4	cl	massive	ci	-	ironstone induration
Changnalili series						
0-12	10YR 6/4	scl	1f-m gr-sbk	wss, mfr, dsh	cs	-
12-24	7.5YR 6/2	scl	2f-m sbk	wss, mfr, dsh	gs	-
24-37	7.5YR 6/2	scl	2m sbk	wss, mfi, dh	gs	common mottling
37-57	7.5YR 6/2	cl	3c sbk	wss mfi, dh	gs	Fe-oxide nodules
57-100+	7.5YR 6/4	cl	massive	ci	-	ironstone induration

† scl = sandy clay loam; sc = sandy clay; cl = clayey..

‡ c = coarse; f = fine; m = medium; gr = granular; sbk = subangular blocky.

* ws = wet sticky; wss wet slightly sticky; mfr = moist friable; mfi = moist firm; dsh = dry slightly hard; dh = dry hard; dvh = dry very hard; ci = coarse indurated.

¶ cs = clear smooth; gs = gradual smooth

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Table 4.2. Physical properties of the soils.

Depth	Particle size (%)			BD†	Nodule content †	SSA(clay)†	Moisture content †		
(cm)	sand	silt	clay	(g/cm^3)	(%)	(m^2/g)	1/3 bar	15 bar	A MC
					Tingoli series				
0-16	70.0	8.1	21.9	1.56	11.0	43.3	0.97	0.63	0.35
16-32	59.9	7.9	32.2	1.62	9.3	54.6	1.61	1.12	0.49
32-48	43.3	7.7	49.1	1.76	43.5	58.0	2.37	1.85	0.52
48-67	52.7	10.6	36.7	1.74	84.0	60.7	1.82	1.52	0.31
67-98	46.2	8.9	44.9	1.88	82.8	62.9	1.79	1.51	0.28
98$^+$	40.6	8.8	50.6	1.51	17.5	62.3	2.46	1.73	0.73
					Tolon series				
0-14	70.5	7.9	21.5	1.58	4.2	25.1	1.47	0.65	0.83
14-30	62.4	12.4	25.2	1.64	12.2	nd	1.48	0.66	0.82
30-54	48.4	15.4	36.3	1.70	70.0	33.5	2.22	1.10	1.13
54-76	46.4	6.3	47.2	1.70	80.3	nd	2.54	1.19	1.35
76-100	60.8	7.3	31.9	1.95	91.3	45.1	2.00	1.54	0.46
					Kumayili series				
0-18	72.8	8.0	19.2	1.52	0.5	25.7	0.82	0.38	0.44
18-36	64.3	11.8	23.9	1.63	0.3	nd	1.13	0.61	0.52
36-57	54.7	15.9	29.5	1.59	1.4	30.5	1.67	0.87	0.81
57-90	45.5	15.5	39.0	1.60	0.2	nd	1.84	1.30	0.55
90$^+$	36.9	13.8	49.3	1.80	65.8	59.6	2.33	1.42	0.91
					Kpelesawgu series				
0-15	63.4	15.0	21.5	1.48	0.7	20.4	1.42	0.51	0.92
15-34	51.2	18.5	30.3	1.46	0.1	nd	1.92	1.01	0.91
34-64	34.6	22.6	42.9	1.52	0.6	nd	2.15	1.09	1.06
64-100$^+$	42.0	25.9	32.1	1.99	61.1	30.4	2.25	1.68	0.57
					Changnalili series				
0-12	57.0	22.7	20.3	1.41	0.7	23.6	1.46	0.59	0.87
12-24	50.9	20.9	28.2	1.65	0.5	nd	1.72	0.89	0.83
24-37	44.6	22.0	33.4	1.62	0.9	31.3	1.86	1.08	0.79
27-57	34.9	24.6	40.5	2.03	76.3	nd	2.29	1.21	1.09
57-100$^+$	26.4	12.6	61.0	1.69	51.5	59.4	3.22	2.00	1.22

† BD=Bulk density; nd=Not determined; SSA=Specific Surface Area ; AMC = Available moisture content.

midslope positions on the same toposequence, however, has nodule content which is less than 1% except at depths below 90 cm. The poorly to imperfectly drained Kpelesawgu and Changnalili series on toposequence 2 also have nodule content distribution similar to the Kumayili series.

The soils are generally sandy clay loam in texture in the surface horizon of the solum and clayey in the subsoil. There is a slight increase in clay content and decrease in sand content with depth in all the soils studied. The sand content is higher in the soils on toposequence 1 than in the soils on toposequence 2. The surface horizons of soils on toposequence 1 have on the average 70% sand content as against 60% in the toposequence 2 soils.

The silt content is higher in the low lying soils than in the upland soils. On toposequence 1, the Kumayili series has the highest silt content whereas on toposequence 2 the Changnalili series has a higher silt content than the Kpelesawgu series.

4.2.2 Bulk density

The bulk density values increase, generally, with depth in all the soils and tend to be higher in the soils on toposequence 1. In all the soils, the horizon of maximum nodule concentration also has the highest bulk density. On toposequence 1, Kumayili series has the lowest range in bulk density values. On toposequence 2, Kpelesawgu series has bulk density values which range from 1.48 g/cm^3 at the surface to 1.99 g/cm^3 at the indurated layer.

4.2.3 Surface area (SSA)

Specific surface area (SSA) of the soils is generally low (< 63 m^2/g). The surface area generally increases with increasing depth in all the soils studied. The well drained Tingoli series has the highest SSA whilst the Kpelesawgu series has the lowest SSA. The Tolon and Kumayili series on toposequence 1 and Changnalili series on toposequence 2 appear to have similar SSA values.

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4.2.4 Moisture content.

The moisture content at 1/3 bar (33 kPa) and 15 bar (1500 kPa) is higher in the toposequence 2 soils than in the soils on toposequence 1. With the notable exception of the Tingoli series, there is an increase in moisture content with depth both at field capacity (1/3 bar) and wilting point (15 bar) in all the soils. There is, however, no consistent trend in the amount of available moisture with depth. Nevertheless, available moisture content is higher in the imperfectly drained Kpelesawgu series and poorly drained Changnalili series on toposequence 2 than the relatively well drained soils on toposequence 1.

4.3 Mineralogy

The x-ray diffraction pattern of the sand fraction shows quartz as the dominant mineral. Peaks referable to other minerals are absent (Table 4.3). The sand fraction mineralogy is similar in all the profiles. In the silt fraction, quartz also constitutes the dominant mineral and there are minor quantities of feldspar and kaolinite. The imperfectly and poorly drained soils on toposequence 2 contain mica (illite) in addition to quartz and feldspar.

The clay fraction of all the soils is dominated by kaolinite and quartz except the Changnalili and the Kpelesawgu series which are dominated by illite. There are also traces of feldspars, goethite and haematite in the clay fraction of all the soils. The amounts of illite seem to be higher in the soils on toposequence 2 than in those on toposequence 1. The nodules contain mainly quartz, goethite, haematite and traces of kaolinite.

4.4 Quartz contents

The quartz contents (%) in the total fine earth and the silt fraction are given in Table 4.4. In each profile, the amount of quartz in the silt fraction is higher than those in the fine earth fraction. With the notable exception of the Tingoli series, the quartz contents in both fractions generally decrease with depth.

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Table 4.3. Mineralogical composition of the soils†.

Profile	Sand	Silt	Clay	Nodules
		Tingoli series		
0-16	Q	Q, f, k, i	K, Q, f, i	Q, G, H, k
16-32	Q	Q, F	K, q, i, g, h	Q, G, H, k
32-48	Q	Q, f	K, q, i, g, h	Q, G, H, k
48-67	Q	Q, k	K, q, i, g, h	Q, G, H, k
67-98	Q	Q, k, f	K, q, i, g, h	Q, K, G,H
		Tolon series		
0-16	Q	Q, f, k	K, Q, i, f, g, h	Q, G, H, k
14-30	Q	Q, f	K, Q, i, f, g, h	Q, G, H, k
30-54	Q	Q, f, k	K, Q, i, g, h	Q, G, H, k
54-76	Q	Q, f, k	K, Q, i, g, h	Q, G, H, k
76-100	Q	Q, f, k	K, Q,i, f, g, h	Q, G, H, k
		Kumayili series		
0-18	Q	Q, f	K, Q, i, f, g	nd
18-36	Q	Q, f	K, Q, i, f, g	nd
36-57	Q	Q, f	K, Q, i, f, g	nd
57-90	Q	Q, f	K, Q, i, f, g	Q, G, H, k
90+	Q	Q, f	K, Q, i, f, g	Q, G, H, k
		Kpelesawgu series		
0-15	Q	Q, f	Q, k, i, f, g	nd
15-34	Q	Q, F, i	Q, I, f, k, g, h	nd
34-64	Q	Q, F, i	Q, I, f, k, g, h	nd
64-100$^+$	Q	Q, f, i	Q, I, F, k, g, h	Q, G, H, k
		Changnalili series		
0-12	Q	Q, f, i	K, I, Q, f, g, h	nd
12-24	Q	Q, F, i, k	K, I, Q, f, g, h	nd
24-37	Q	Q, f, i, k	K, I, Q, f, g, h	Q, G, H,k
37-57	Q	Q, f, i, k	K, I, Q, f, g, h	Q, G, H,k
57-100$^+$	Q	Q, f, i, k	K, I, Q, f	Q, g, h,k

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† Q = Quartz; K = Kaolinite; F = Feldspar; I = illite; G = Goethite; H = Haematite; nd = Not determined; Lower case = minor component.

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Table 4.4. Quartz contents in the soils.

Depth (cm)	Quartz content % (w/w) total fine earth	 silt
	Tingoli series	
0-16	85.4	80.8
16-32	49.3	76.5
32-48	52.8	85.8
48-67	11.8	28.5
67-98	14.4	24.5
98+	20.4	45.6
	Tolon series	
0-14	87.1	98.4
14-30	82.8	88.5
30-54	60.3	86.9
54-76	31.6	57.7
76-100	28.4	37.3
	Kumayili series	
0-18	88.3	73.7
18-36	83.1	82.0
36-57	74.4	79.1
57-90	65.2	79.7
90+	39.1	52.6
	Kplesawgu series	
0-15	92.1	80.2
15-34	76.8	69.5
34-64	68.7	70.8
64-100+	52.5	67.8
	Changnalili series	
0-12	84.1	82.6
12-24	78.5	88.1
24-37	70.5	82.5
37-57	55.7	71.9
57-100+	83.1	66.5

Regarding the fine earth fraction of the soils on toposequence 1, Kumayili series has the highest amount of quartz with (average of 70%) followed by Tolon series (average of 58%) and then Tingoli series (average of 39.0%). In the toposequence 2 soils, the Changnalili series has an average quartz content of 74% whilst the Kpelesawgu series has an average of 72%.

The average quartz content in the silt fraction are as follows: Tingoli series = 57%, Tolon series = 73%, Kumayili series = 73%, Kpelesawgu series 72% and Changnalili series = 78%.

4.5 Total elemental analyses

The results of the total elemental analyses are given in Table 4.5. Silicon is the dominant element in the fine earth fraction of all the soils. The relative abundance of the elements in the fine earth fraction of Tingoli series is in the order Si > Fe > Al > Ti > K > Mg > Ca >Mn > Na. The sequence in the Tolon and Kumayili series follows the order Si > Al > Fe > K > Ti > Mg > Ca >Mn > Na. The abundance of elements in the Kpelesawgu and Changnalili series on toposequence 2 follows the order Si > Al > Fe > K > Ti > Mg > Na >Ca > Mn.

In all the soils, Si in the fine earth tends to decrease with depth whilst the other elements increase with increasing depth in the profiles. Iron and Al in the total fine earth are higher in the toposequence 1 soils than in the toposequence 2 soils. The amount of Mn, unlike Si and Al, is very low in all fractions of the soils. The concentrations of Ca, Mg, K and Na in the total fine earth are generally low . The imperfectly drained Kpelesawgu series and poorly drained Changnalili series, however, have higher K contents than the soils on toposequence 1.

The relative abundance of elements in the clay fraction of the Tingoli series is in the order Si > Fe = Al > Ti > K > Na > Mg >Mn > Ca whilst the sequence in the Tolon and Kumayili series is Si > Al > Fe > Ti > K > Na > Mg >Mn > Ca. In the Kpelesawgu series

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Table 4.5. Total elemental composition of the soils.

Depth (cm)	SiO_2	Fe_2O_3	Al_2O_3	MnO	TiO_2	CaO	K_2O	MgO	Na_2O
					%				
					Tingoli series				
					Total fine earth				
0-16	89.54	4.30	4.12	0.04	0.20	0.07	0.41	0.24	0.05
16-32	73.25	10.81	12.58	0.05	0.84	0.12	0.69	0.27	0.15
32-48	71.05	12.28	13.53	0.05	0.90	0.11	0.65	0.27	0.04
48-67	58.91	22.84	15.42	0.13	0.69	0.07	0.48	0.19	0.04
67-98	54.53	28.04	13.91	0.07	0.98	0.04	0.77	0.24	0.13
98+	55.85	20.71	20.11	0.06	0.91	0.11	0.68	0.30	0.06
					Clay fraction				
0-16	68.86	11.75	12.98	0.13	2.76	0.03	1.76	0.17	0.44
16-32	54.51	22.56	17.49	0.14	2.21	0.04	1.15	0.36	0.32
32-48	51.74	21.23	21.67	0.11	1.98	0.04	1.06	0.42	0.54
48-67	46.97	24.80	23.25	0.16	1.67	0.08	0.99	0.32	0.51
67-98	52.26	22.02	21.26	0.08	1.41	0.04	0.95	0.22	0.53
98+	54.58	18.01	23.10	0.07	1.35	0.07	0.83	0.25	0.47
					Nodules (< 2mm)				
0-16	31.21	52.21	13.53	0.08	0.53	0.08	0.60	0.20	0.03
16-32	26.56	56.81	13.60	0.06	0.56	0.06	0.54	0.19	0.03
32-48	30.18	52.98	13.86	0.06	0.56	0.06	0.55	0.17	0.04
48-67	31.01	50.41	15.44	0.09	0.70	0.05	0.54	0.20	0.03
67-98	40.23	39.63	17.11	0.04	0.69	0.07	0.58	0.20	0.04
98+	44.92	36.04	15.97	0.05	0.76	0.07	0.54	0.23	0.04
					Nodules (> 2mm)				
0-16	49.59	37.28	10.23	0.06	0.57	0.06	0.48	0.19	0.10
16-32	40.95	42.97	13.19	0.06	0.60	0.07	0.48	0.22	0.02
32-48	33.04	49.28	14.76	0.05	0.55	0.06	0.52	0.19	0.04
48-67	32.06	49.99	14.86	0.10	0.58	0.05	0.58	0.23	0.05
67-98	37.32	43.56	16.18	0.04	0.52	0.08	0.57	0.23	0.05
98+	32.44	48.56	15.91	0.04	0.51	0.07	0.66	0.26	0.05

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Table 4.5. cont'd.

Depth (cm)	SiO_2	Fe_2O_3	Al_2O_3	MnO	TiO_2	CaO	K_2O	MgO	Na_2O
					%				
				Tolon series					
				Total fine earth					
0-14	90.77	2.03	4.29	0.04	0.58	0.12	0.93	0.18	0.05
14-30	88.69	2.96	5.20	0.04	0.73	0.08	1.02	0.21	0.05
30-54	80.11	7.10	8.85	0.06	1.01	0.13	1.32	0.30	0.05
54-76	65.02	17.56	12.91	0.08	1.28	0.15	1.45	0.30	0.07
76-100	61.07	22.19	12.88	0.14	0.91	0.09	1.20	0.25	0.03
				Clay fraction					
0-14	68.09	9.18	16.41	0.19	2.10	0.24	1.72	0.20	0.78
14-30	69.30	10.43	13.10	1.15	2.79	0.09	2.04	0.27	0.72
30-54	66.44	12.14	14.11	0.15	2.73	0.06	2.13	0.14	0.98
54-76	65.31	13.78	14.03	0.10	2.12	0.03	1.98	0.60	0.91
76-100	61.48	17.40	14.78	0.15	1.88	0.04	1.97	0.21	0.92
				Nodules (< 2mm)					
0-14	43.89	41.82	10.96	0.08	0.58	0.16	0.81	0.23	0.03
14-30	47.43	38.73	10.62	0.11	0.56	0.11	0.80	0.22	0.03
30-54	35.63	48.33	12.83	0.06	0.55	0.10	0.77	0.22	0.03
54-76	49.23	31.52	15.58	0.07	0.83	0.12	1.00	0.27	0.06
76-100	46.48	37.23	13.05	0.13	0.70	0.10	0.71	0.18	0.03
				Nodules (> 2mm)					
0-14	61.91	26.28	8.67	0.06	0.55	0.11	0.84	0.25	0.06
14-30	47.07	38.73	11.34	0.05	0.46	0.07	0.61	0.24	0.05
30-54	37.97	45.82	13.29	0.04	0.42	0.12	0.61	0.23	0.03
54-76	40.98	41.74	14.55	0.05	0.44	0.08	0.45	0.26	0.04
76-100	39.06	45.27	12.54	0.06	0.57	0.06	0.72	0.23	0.03

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Table 4.5. cont'd.†

Depth (cm)	SiO_2	Fe_2O_3	Al_2O_3	MnO	TiO_2	CaO	K_2O	MgO	Na_2O
					%				
					Kumayili series				
					Total fine earth				
0-18	94.17	1.11	2.53	0.02	0.40	0.04	0.58	0.10	0.03
18-36	90.32	2.42	4.49	0.03	0.62	0.07	0.84	0.16	0.02
36-57	88.70	2.52	5.88	0.02	0.68	0.08	0.88	0.19	0.02
57-90	84.50	3.95	8.28	0.03	0.80	0.09	1.01	0.29	0.02
90+	72.79	10.51	12.87	0.08	0.93	0.14	1.17	0.35	0.05
					Clay fraction				
0-18	72.04	7.47	13.71	0.17	2.16	0.20	1.89	0.76	0.53
18-36	69.88	10.07	13.45	0.07	2.68	0.04	1.96	0.32	0.41
36-57	66.65	11.83	15.11	0.05	2.55	0.01	1.95	0.12	0.62
57-90	59.81	15.80	18.43	0.07	1.85	0.03	2.00	0.09	0.77
90+	73.93	10.92	9.65	0.08	1.29	0.04	2.33	0.07	0.57
					Nodules (< 2mm)				
0-18	nd	nd	nd	nd	nd	nd	nd	nd	nd
18-36	nd	nd	nd	nd	nd	nd	nd	nd	nd
36-57	nd	nd	nd	nd	nd	nd	nd	nd	nd
57-90	39.65	43.77	12.93	0.06	0.76	0.15	0.93	0.26	0.04
90+	50.93	33.74	11.76	0.21	0.71	0.10	0.92	0.24	0.05
					Nodules (> 2mm)				
0-18	nd	nd	nd	nd	nd	nd	nd	nd	nd
18-36	nd	nd	nd	nd	nd	nd	nd	nd	nd
36-57	nd	nd	nd	nd	nd	nd	nd	nd	nd
57-90	75.35	11.71	9.30	0.05	0.99	0.11	1.05	0.29	0.04
90+	44.42	41.19	11.00	0.07	0.46	0.09	1.07	0.27	0.02

† nd = not determined.

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Table 4.5. cont'd.†

Depth (cm)	SiO_2	Fe_2O_3	Al_2O_3	MnO	TiO_2	CaO	K_2O	MgO	Na_2O
					%				
Kpelesawgu series									
Total fine earth									
0-15	91.97	1.19	3.78	0.02	0.45	0.07	1.12	0.21	0.19
15-34	88.27	1.91	5.90	0.02	0.67	0.07	1.60	0.33	0.21
34-64	87.04	2.34	6.43	0.02	0.70	0.12	1.73	0.37	0.23
64-100$^+$	80.67	5.75	8.64	0.10	1.08	0.03	2.08	0.38	0.19
Clay fraction									
0-15	72.56	7.14	13.99	0.07	1.59	0.03	2.67	0.10	0.76
15-34	74.18	8.39	10.19	0.05	1.97	0.00	3.13	0.09	0.92
34-64	71.58	10.19	10.89	0.10	2.13	0.00	3.27	0.10	0.63
64-100$^+$	76.67	7.29	9.74	0.19	1.68	0.04	2.58	0.05	0.70
Nodules (< 2mm)									
0-15	nd	nd	nd	nd	nd	nd	nd	nd	nd
15-34	nd	nd	nd	nd	nd	nd	nd	nd	nd
34-64	nd	nd	nd	nd	nd	nd	nd	nd	nd
64-100$^+$	48.71	36.76	10.91	0.16	0.54	0.07	1.08	0.32	0.06
Nodules (> 2mm)									
0-15	nd	nd	nd	nd	nd	nd	nd	nd	nd
15-34	nd	nd	nd	nd	nd	nd	nd	nd	nd
34-64	nd	nd	nd	nd	nd	nd	nd	nd	nd
64-100$^+$	53.80	31.13	10.81	0.25	0.64	0.14	1.45	0.38	0.09

† nd = not determined.

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Table 4.5. cont'd.†

Depth (cm)	SiO_2	Fe_2O_3	Al_2O_3	MnO	TiO_2	CaO	K_2O	MgO	Na_2O
	%								
				Changnalili series					
				Total fine earth					
0-12	92.18	1.13	3.58	0.03	0.45	0.10	1.11	0.20	0.20
12-24	88.61	2.04	5.46	0.04	0.60	0.14	1.51	0.33	0.25
24-37	87.85	2.03	6.32	0.03	0.60	0.11	1.53	0.32	0.19
37-57	81.51	4.66	8.70	0.16	1.14	0.14	2.05	0.36	0.23
57-100$^+$	93.48	1.54	2.47	0.05	0.40	0.07	0.72	0.17	0.08
				Clay fraction					
0-12	71.12	8.90	12.80	0.16	2.03	0.07	2.97	0.09	0.77
12-24	72.67	8.61	11.73	0.14	2.02	0.01	2.96	0.10	0.67
24-37	68.45	9.45	14.31	0.16	2.26	0.01	3.23	0.12	0.92
37-57	52.84	20.45	21.14	0.21	2.43	0.04	1.24	0.07	0.39
57-100$^+$	56.83	9.82	26.01	0.05	1.28	0.04	3.48	0.28	1.11
				Nodules (< 2mm)					
0-12	nd	nd	nd	nd	nd	nd	nd	nd	nd
12-24	nd	nd	nd	nd	nd	nd	nd	nd	nd
24-37	50.99	36.95	8.69	0.08	0.48	0.12	1.00	0.28	0.03
37-57	48.63	36.09	11.24	0.26	0.72	0.11	1.15	0.38	0.04
57-100$^+$	59.43	25.85	10.35	0.23	0.62	0.14	1.61	0.45	0.06
				Nodules (> 2mm)					
0-12	nd	nd	nd	nd	nd	nd	nd	nd	nd
12-24	nd	nd	nd	nd	nd	nd	nd	nd	nd
24-37	67.55	19.96	8.54	0.10	0.67	0.14	1.37	0.36	0.10
37-57	60.06	26.79	9.24	0.39	0.48	0.08	1.29	0.34	0.06
57-100$^+$	66.74	13.63	14.33	0.21	0.72	0.20	2.18	0.69	0.14

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† nd = not determined.

on toposequence 2, the sequence is Si > Al > Fe > K > Ti > Na > Mg >Mn > Ca whereas in the Changnalili series it is Si > Al > Fe > Ti > K > Na > Mn >Mg > Ca.

The Si in the clay fraction of the soils on toposequence 1 decreases with depth whilst the Fe content increases with depth. In the soils on toposequence 2 the Fe content decreases with depth but there is no consistent trend in the Si content. The Ca, Mg, K and Na in the clay fraction are higher than their respective concentrations in the fine earth. The amount of K content in the clay fraction is higher than in the fine earth and also higher in the toposequence 2 soils than in the toposequence 1 soils. The K content in the clay fraction of the toposequence 1 soils is in the order Kumayili series > Tolon series > Tingoli series. In the toposequence 2 soils, the K content is generally the same. There is an average of over 10% more Ti in the clay fraction of the soils on toposequence 1 than in the corresponding fraction of the soils on toposequence 2.

The analytical data show that there is little difference in the elemental composition of the <2 mm and >2 mm nodules in each profile. Unlike the fine earth and clay fractions, the Fe content in the nodules is higher than the Si content. The Fe content is higher in the nodules than in the clay and in the total fine earth. The order of relative elemental composition in both sizes of nodules follows the order Si > Fe > Al >K > Ti > Mg > Ca > Na except in the Tingoli series where Fe > Si.

4.6 Chemical properties

4.6.1 pH and organic carbon

Results of the analyses on the chemical properties of the soils are given in Table 4.6. The soils and their respective associated nodules are slightly acidic. The pH values of the nodules are nearly similar to those of the associated soil matrix. The pH variations within and between profiles are narrow. The pH (H_2O) values of the nodules range from 5.6 to 6.3 whilst those of the fine earth range from 5.6 to 6.6.

Organic carbon accumulation in the soils is very low ranging from 2.8 to 7.0 g/kg. The Changnalili series has the highest organic carbon content throughout the profile whilst

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Table 4.6. Chemical properties of the soils.

Depth (cm)	pH (total fine earth)†		pH (nodule)†		Organic carbon (g/kg)	
	H_2O	KCl	H_2O	KCl	total fine earth	nodule
			Tingoli series			
0-16	6.0	4.4	5.8	5.4	6.5	4.7
16-32	6.1	4.5	5.9	5.5	5.4	5.1
32-48	6.2	4.6	5.8	5.6	6.1	5.7
48-67	5.9	4.9	6.3	6.0	6.7	4.6
67-98	5.6	4.4	5.5	5.6	4.4	4.0
98+	5.9	4.3	6.1	5.4	2.8	4.4
			Tolon series			
0-14	6.6	5.1	6.3	5.5	6.3	7.5
14-30	6.3	4.6	6.3	5.4	3.4	4.6
30-54	6.3	4.7	6.1	5.6	6.4	5.5
54-76	6.3	4.6	6.0	5.5	7.0	3.4
76-100	6.3	5.0	6.2	5.6	4.9	5.0
			Kumayili series			
0-18	5.8	4.1	nd	nd	3.6	nd
18-36	6.0	4.5	nd	nd	3.3	nd
36-57	6.2	4.5	nd	nd	3.4	nd
57-90	6.1	4.4	6.0	5.2	3.6	4.2
90^+	6.3	4.9	6.1	5.4	2.9	4.2
			Kpelesawgu series			
0-15	5.7	4.0	nd	nd	4.3	nd
15-34	5.8	4.0	nd	nd	4.5	nd
34-64	6.0	4.0	nd	nd	5.2	nd
$64\text{-}100^+$	6.2	4.1	6.0	4.8	4.0	3.7
			Changnalili series			
0-12	5.9	4.7	nd	nd	6.4	nd
12-24	6.0	4.3	nd	nd	6.2	nd
24-37	6.1	4.4	6.1	5.6	6.1	4.47
37-57	6.4	4.6	6.2	5.5	6.8	3.54
$57\text{-}100^+$	6.0	3.6	5.7	4.3	5.3	2.39

† pH in H_2O and KCl was in a 1:2 soil to liquid suspension.

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the Kumayili series has the lowest. On the whole organic carbon content in the fine earth fraction is higher than in the associated nodules.

4.6.2 Exchangeable bases, exchange acidity and CEC

The exchangeable bases of the soils and their associated nodules are generally very low (Table 4.7). In each profile, the amounts of exchangeable bases follow a decreasing order of Ca > Mg > K > Na. Exchangeable Ca and Mg in the soils generally tend to increase with increasing depth in all the soils. Exchangeable Ca and Mg are highest in the Changnalili series and lowest in the Kpelesawgu series. In general, these two bases are higher in the soils than their respective associated nodules. Exchangeable K and Na in both the fine earth and nodules are extremely low. There is no difference in the exchangeable K and Na values between the fine earth and associated nodules.

Exchange acidity is generally very low in all the soils. The imperfectly drained Kpelesawgu series has the highest exchange acidity. There is no apparent difference in exchange acidity between the soils and their respective associated nodules.

The effective cation exchange capacity (ECEC) falls within the expected range for highly weathered ferruginous tropical soils. All the soils including their respective nodules have ECEC values less than 16 cmol(+)/kg. The poorly drained Changnalili series has the highest ECEC ranging from 3.38 cmol(+)/kg in the surface to 13.45 cmol(+)/kg down the profile. The ECEC in the upland Tingoli and Tolon series on toposequence 1 is not strikingly different but seems to be higher than in their midslope counterpart, Kumayili series. The base saturation (BS) in all the soils and accompanying nodules is very high (> 60%).

4.6.3 Extractable Fe, Al and Mn

The contents of the various forms of extractable Fe, Al and Mn in the total fine earth , silt and clay fractions and the nodules are given in Table 4.8. Generally, DCB extractable

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Table 4.7. Exchangeable bases, exchange acidity and effective cation exchange capacity.

Depth (cm)	Ca	Mg	K	Na	Ex Ac.†	ECEC	BS† (%)
	cmol (+) / kg						
			Tingoli series				
			Total fine earth				
0-16	1.47	0.64	0.39	0.28	0.15	2.78	94.9
16-32	1.94	1.24	0.09	0.02	0.10	3.29	97.1
32-48	2.35	1.94	0.19	0.03	0.25	4.34	94.8
48-67	2.09	1.39	0.21	0.01	0.15	3.70	96.1
67-98	2.40	1.37	0.16	0.02	0.55	3.95	87.8
98+	2.85	1.54	0.17	0.01	0.70	4.57	86.7
			Nodules				
0-16	1.49	0.68	0.17	0.04	0.15	2.38	94.1
16-32	1.43	0.03	0.13	0.02	0.25	1.61	86.6
32-48	1.25	0.99	0.15	0.03	0.25	2.42	90.1
48-67	1.27	0.71	0.19	0.04	0.20	2.21	91.7
67-98	1.44	0.72	0.15	0.02	0.15	2.33	93.9
98+	1.64	0.78	0.16	0.03	0.15	2.61	94.6
			Tolon series				
			Total fine earth				
0-14	2.60	0.92	0.19	0.00	0.15	3.71	96.1
14-30	2.01	0.73	0.10	0.01	0.20	2.85	93.4
30-54	2.73	1.18	0.19	0.01	0.20	4.11	95.4
54-76	3.52	1.97	0.29	0.01	0.20	5.49	96.7
76-100	2.62	1.58	0.28	0.02	0.20	4.49	95.7
			Nodules				
0-14	2.06	0.74	0.22	0.01	0.15	3.03	95.3
14-30	1.35	0.56	0.17	0.01	0.20	2.14	91.3
30-54	1.10	0.56	0.22	0.01	0.20	1.89	90.4
54-76	1.44	0.84	0.24	0.07	0.15	2.59	94.5
76-100	1.37	0.91	0.29	0.19	0.20	2.76	93.2
			Kumayili series				
			Total fine earth				
0-18	0.87	0.24	0.08	0.00	0.40	1.19	74.8
18-36	1.44	0.39	0.07	0.00	0.20	1.90	90.5
36-57	1.68	0.68	0.08	0.01	0.20	2.45	92.5
57-90	2.18	1.37	0.11	0.02	0.25	3.68	93.6
90+	3.36	2.67	0.19	0.07	0.20	6.29	96.9
			Nodules				
0-18	nd	nd	nd	nd	nd	nd	nd
18-36	nd	nd	nd	nd	nd	nd	nd
36-57	nd	nd	nd	nd	nd	nd	nd
57-90	2.14	1.42	0.17	0.19	0.15	3.92	96.3
90+	1.15	0.92	0.20	0.11	0.15	2.38	94.1

† Ex Ac = Exchange acidity ; BS = Base saturation; nd = not determined.

Table 4.7. cont'd.

Depth (cm)	Ca	Mg	K	Na	Ex Ac.†	ECEC	BS† (%)
	cmol (+) / kg						
			Kpelesawgu series				
			Total fine earth				
0-15	0.93	0.64	0.13	0.00	0.45	1.70	79.1
15-34	1.23	0.81	0.09	0.04	1.00	2.17	68.5
34-64	1.01	1.02	0.14	0.09	1.30	2.26	63.5
64-100+	1.16	1.58	0.18	0.09	1.05	3.01	74.1
			Nodules				
0-15	nd	nd	nd	nd	nd	nd	nd
15-34	nd	nd	nd	nd	nd	nd	nd
34-64	nd	nd	nd	nd	nd	nd	nd
64-100+	0.89	1.23	0.28	0.12	0.31	2.52	89.4
			Changnalili series				
			Total fine earth				
0-12	1.98	1.14	0.26	0.00	0.10	3.38	97.1
12-24	2.78	1.31	0.09	0.02	0.35	4.20	92.3
24-37	2.98	1.51	0.12	0.02	0.25	4.63	94.9
37-57	3.71	2.22	0.29	0.02	0.20	6.23	96.9
57-100+	5.99	6.87	0.31	0.28	2.00	13.45	87.1
			Nodules				
0-12	nd	nd	nd	nd	nd	nd	nd
12-24	nd	nd	nd	nd	nd	nd	nd
24-37	2.41	1.26	0.20	0.06	0.15	3.93	96.3
37-57	1.84	1.22	0.27	0.04	0.20	3.37	94.4
57-100+	4.70	5.46	0.39	0.36	0.60	10.90	94.7

† Ex Ac = Exchange acidity ; BS = Base saturation; nd = not determined.

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Fe and Al are higher than the oxalate extractable forms in all the particle size fractions of the soils studied. For both DCB and oxalate extractable forms, the concentration of the sesquioxides follow the order Fe > Al > Mn.

Regarding the fine earth fraction, the upland Tingoli and Tolon series have the largest accumulation of Fed. This ranges from 21.26 to 95.20 g/kg in the Tingoli series and from 10.46 to 74.64 g/kg in the Tolon series. The Fed in the fine earth of the Kumayili series, the midslope soil on toposequence 1, is relatively low and ranges from 5.84 to 52.47 g/kg. The Fed in the fine earth of the Kpelesawgu series on toposequence 2 ranges from 5.43 to 24.70 g/kg whilst in the Changnalili series the range is from 5.28 to 14.36 g/kg.

The Feo, however, is higher in the soils on toposequence 2 than in those on toposequence 1. The distribution of Feo within and between Kpelesawgu and Changnalili profiles is fairly constant. However, regarding the soils on toposequence 1, the Feo content follows a decreasing order of Tingoli series > Tolon series > Kumayili series. The Feo is fairly uniform throughout the Tingoli profile but in the Tolon and Kumayili series, this increases with depth.

The Fed content in the silt fraction varies between 12.94 and 87.07 g/kg for the Tingoli series and 4.96 and 45.24 g/kg for the Tolon series. The Fed (silt) of the Kumayili series, the other member on toposequence 1, ranges from 3.84 to 34.72 g/kg. Unlike the Fed content in the fine earth fraction of the soils on toposequence 2, the Fed in the silt fraction is higher in the Changnalili series (3.25 to 24.54 g/kg) than in the Kpelesawgu series (2.39 to 15.84 g/kg). The distribution of Feo in the silt fraction is similar to the trend in the total fine earth.

The Fed content in the clay fraction is higher than in the fine earth and silt fractions and increases with increasing depth. The Fed (clay) is also higher in the toposequence 1 soils than in the toposequence 2 soils. The general trend in Fed accumulation follows the order Tingoli series > Tolon series > Kumayili series (toposequence 1), which is similar to

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Table 4.8. DCB and oxalate extractable Fe, Al and Mn content.

Depth (cm)	Fe_o	Fe_d	Al_o	Al_d	Mn_o	Mn_d
	(g/kg)					
			Tingoli			
			Total fine earth			
0-16	0.60	21.26	0.37	0.80	0.18	0.16
16-32	1.27	53.05	0.82	2.76	0.09	0.18
32-48	1.19	55.05	0.73	3.24	0.10	0.18
48-67	1.30	55.02	1.02	4.09	0.58	0.50
67-98	1.09	95.20	0.90	4.23	0.11	0.19
98^{+}	1.17	87.83	0.80	4.25	0.08	0.24
			Silt fraction			
0-16	0.65	12.94	0.37	0.85	0.30	0.33
16-32	0.50	17.82	0.28	0.96	0.15	0.27
32-48	0.38	13.29	0.12	1.01	0.05	0.08
48-67	1.18	87.07	0.59	6.83	0.49	0.68
67-98	0.84	78.53	0.46	5.33	0.05	0.22
98+	0.82	62.47	0.32	4.60	0.04	0.19
			Clay fraction			
0-16	4.60	79.81	3.20	4.62	0.92	0.81
16-32	3.91	97.01	2.52	5.24	0.51	0.82
32-48	4.92	78.62	3.02	4.51	0.34	0.40
48-67	6.10	89.54	2.71	5.90	0.52	0.71
67-98	3.92	87.62	2.11	5.02	0.11	0.30
98^{+}	3.93	83.81	2.33	4.71	0.10	0.42
			Nodules (< 2mm)			
0-16	2.71	155.62	1.21	7.38	0.20	0.33
16-32	2.32	156.93	1.03	6.60	0.11	0.19
32-48	2.04	166.01	1.04	7.42	0.11	0.15
48-67	1.72	155.23	1.32	8.23	0.23	0.30
67-98	1.42	135.72	1.11	6.94	0.04	0.13
98^{+}	1.43	133.51	1.10	6.01	0.05	0.15
			Nodules (> 2mm)			
0-16	0.89	124.40	0.71	7.01	0.30	0.20
16-33	0.82	131.41	0.62	8.32	0.12	0.21
32-48	1.12	144.43	0.74	8.84	0.11	0.11
48-67	0.91	146.22	0.73	8.90	0.41	0.31
67-98	0.72	148.81	0.61	8.11	0.04	0.12
98^{+}	0.91	133.20	0.50	6.42	0.10	0.11

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Table 4.8. cont'd.

Depth	Fe_o	Fe_d	Al_o	Al_d	Mn_o	Mn_d
(cm)	(g/kg)					
			Tolon series			
			Total fine earth			
0-14	0.44	10.46	0.26	0.53	0.15	0.16
14-30	0.42	12.46	0.28	0.90	0.23	0.14
30-54	0.65	29.44	0.50	1.54	0.31	0.22
54-76	0.98	65.33	0.83	3.10	0.57	0.31
76-100	0.81	74.64	0.80	3.60	0.08	0.45
			Silt fraction			
0-14	0.35	4.96	0.11	0.59	0.16	0.15
14-30	0.35	5.01	0.12	0.74	0.13	0.11
30-54	0.39	9.76	0.12	0.66	0.11	0.16
54-76	0.63	29.65	0.24	1.87	0.12	0.21
76-100	0.80	45.24	0.41	3.10	0.31	0.51
			Clay fraction			
0-14	4.11	28.31	1.81	2.30	0.91	1.21
14-30	4.12	32.02	1.74	2.31	0.70	0.82
30-54	4.02	41.14	2.22	3.41	0.64	0.91
54-76	3.34	49.30	2.31	4.03	0.32	0.60
76-100	3.81	68.03	2.22	5.11	0.51	0.92
			Nodules (< 2mm)			
0-14	1.81	101.70	1.03	4.35	0.20	0.21
14-30	1.72	126.62	0.91	4.77	0.32	0.38
30-54	1.83	145.72	1.01	6.47	0.12	0.16
54-76	1.20	131.21	1.12	6.55	0.11	0.27
76-100	1.31	137.83	1.02	7.27	0.31	0.58
			Nodules (>2mm)			
0-14	0.90	85.05	0.44	4.67	0.29	0.25
14-30	0.69	114.83	0.29	4.33	0.10	0.15
30-54	0.79	162.94	0.33	7.36	0.08	0.12
54-76	0.89	156.92	0.38	7.55	0.02	0.14
76-100	1.06	154.12	0.45	5.32	0.13	0.19

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Table 4.8. cont'd.†

Depth (cm)	Fe_o	Fe_d	Al_o	Al_d	Mn_o	Mn_d
	(g/kg)					
			Kumayili series			
			Total fine earth			
0-18	0.39	5.84	0.26	0.23	0.05	0.07
18-36	0.47	8.19	0.24	0.27	0.03	0.08
36-57	0.52	11.27	0.31	1.08	0.04	0.05
57-90	0.59	17.80	0.48	1.65	0.19	0.05
90+	0.76	52.47	0.71	4.08	0.06	0.38
			Silt fraction			
0-18	0.29	3.84	0.06	0.53	0.05	0.06
18-36	0.37	4.21	0.08	0.74	0.12	0.13
36-57	0.28	4.15	0.06	0.54	0.03	0.04
57-90	0.24	5.78	0.08	0.89	0.03	0.05
90+	0.82	34.72	0.34	3.06	0.23	0.31
			Clay fraction			
0-18	4.31	22.91	1.12	2.61	0.82	1.19
18-36	5.22	29.23	1.33	3.13	0.61	0.92
36-57	3.01	27.81	1.01	3.14	0.21	0.41
57-90	3.00	35.73	1.92	4.12	0.22	0.31
90+	2.03	40.20	2.13	4.83	0.21	0.52
			Nodules (< 2mm)			
0-18	nd	nd	nd	nd	nd	nd
18-36	nd	nd	nd	nd	nd	nd
36-57	nd	nd	nd	nd	nd	nd
57-90	1.81	134.62	1.54	8.05	0.10	0.17
90+	2.02	126.93	1.62	7.36	0.94	1.15
			Nodules (> 2mm)			
0-18	nd	nd	nd	nd	nd	nd
18-36	nd	nd	nd	nd	nd	nd
36-57	nd	nd	nd	nd	nd	nd
57-90	1.17	44.69	0.46	2.41	0.24	0.20
90+	1.28	143.06	0.38	6.58	1.37	0.23

† nd = not determined.

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Table 4.8. cont'd.†

Depth (cm)	Fe_o	Fe_d	Al_o	Al_d	Mn_o	Mn_d
	(g/kg)					
			Kpelesawgu series			
			Total fine earth			
0-15	1.14	5.43	0.38	0.53	0.03	0.05
15-34	1.08	7.50	0.46	0.93	0.02	0.06
34-64	0.95	8.50	0.50	1.36	0.03	0.04
64-100$^+$	1.14	24.70	0.57	2.90	0.24	0.50
			Silt fraction			
0-15	0.62	2.39	0.11	0.81	0.03	0.03
15-34	0.94	3.48	0.15	0.59	0.05	0.02
34-64	0.48	4.33	0.09	0.75	0.01	0.02
64-100$^+$	1.28	15.84	0.27	1.90	0.42	0.38
			Clay fraction			
0-15	9.21	14.20	1.11	1.41	0.42	0.61
15-34	5.70	12.92	1.42	1.63	0.23	0.33
34-64	3.82	17.63	1.52	2.62	0.13	0.34
64-100$^+$	3.21	26.61	1.44	3.43	0.44	0.61
			Nodules (< 2mm)			
0-15	nd	nd	nd	nd	nd	nd
15-34	nd	nd	nd	nd	nd	nd
34-64	nd	nd	nd	nd	nd	nd
64-100$^+$	2.51	113.02	1.43	7.13	0.70	0.88
			Nodules (> 2mm)			
0-15	nd	nd	nd	nd	nd	nd
15-34	nd	nd	nd	nd	nd	nd
34-64	nd	nd	nd	nd	nd	nd
64-100$^+$	2.39	107.39	0.70	7.75	9.06	1.25

† nd = not determined.

Table 4.8. cont'd.†

Depth (cm)	Fe_o	Fe_d	Al_o	Al_d	Mn_o	Mn_d
	-----------	-----------	(g/kg)	-----------	-----------	-----------
			Changnalili series			
			Total fine earth			
0-12	0.97	5.28	0.30	0.59	0.08	0.11
12-24	1.07	5.98	0.46	0.86	0.14	0.14
24-37	1.18	7.39	0.49	1.08	0.74	0.14
37-57	1.49	14.36	0.80	1.69	0.38	0.77
57-100	0.54	7.58	0.29	0.43	0.19	0.17
			Silt fraction			
0-12	0.56	3.25	0.07	0.36	0.07	0.06
12-24	0.82	3.36	0.13	0.47	0.15	0.15
24-37	0.93	6.94	0.18	0.86	0.60	0.56
37-57	1.60	5.34	0.29	0.82	0.56	0.39
57-100	1.25	24.54	0.16	0.95	0.43	0.38
			Clay fraction			
0-12	8.31	14.52	1.41	1.61	0.11	1.24
12-24	6.43	12.51	1.51	1.62	0.73	0.83
24-37	5.52	15.82	1.73	2.23	0.74	0.94
37-57	4.94	17.21	1.81	2.62	0.81	1.03
57-100	2.10	17.54	1.43	1.81	0.14	0.23
			Nodules (< 2mm)			
0-12	nd	nd	nd	nd	nd	nd
12-24	nd	nd	nd	nd	nd	nd
24-37	3.01	132.71	1.43	9.38	0.20	0.36
37-54	2.63	111.24	1.24	6.81	1.11	1.27
57-100	2.34	100.24	1.34	4.35	0.90	1.15
			Nodules (> 2mm)			
0-12	nd	nd	nd	nd	nd	nd
12-24	nd	nd	nd	nd	nd	nd
24-37	1.96	67.84	0.46	4.47	1.67	0.59
37-57	2.27	102.13	0.50	6.21	5.60	2.32
57-100	1.77	60.01	0.50	3.55	5.14	1.03

† nd = not determined.

Feo, and Kpelesawgu series > Changnalili series (toposequence 2). Consistent with the Feo contents in the other fractions the Fed (clay) is higher in the toposequence 2 soils than in the soils on toposequence 1. However, unlike the total fine earth and the silt fraction where the Feo contents in the two toposequence 2 soils are similar, the Feo content in the clay fraction is higher in the Changnalili series than in the Kpelesawgu series but tends to decrease with depth in these two profiles. The Feo content in the clay fraction of the toposequence 1 soils follows the pattern of distribution for the silt and fine earth fraction.

The nodules (< 2mm and > 2mm sizes) show greater accumulation of Fed than all their respective other fractions. The Fed of the < 2 mm nodules in the Tingoli series varies from 133.51 to 166.01 g/kg whilst in the Tolon series it is from 101.70 to 145.72 g/kg. However, in the >2 mm nodules, the Fed content in the Tolon series is higher than the Tingoli series. The Feo concentration is generally higher in the < 2mm size nodules than in the >2mm size nodules for both the Tingoli and Tolon series. For the <2mm size nodules, the Feo content decreases with depth in the two soils. The amounts of Feo in the >2mm size nodules are similar in both upland soils on toposequence 1.

The Ald content (Table 4.8) in the fine earth is higher in the toposequence 1 soils than in the toposequence 2 soils. In the toposequence 1 soils, the Tingoli series has the highest Ald content (0.80 to 4.33 g/kg) followed by the Tolon series (0.53 to 3.60 g/kg) and then the Kumayili series (0.23 to 4.08 g/kg). There is no apparent difference in Ald contents of the soils on toposequence 2. The Alo concentration is low and hardly exceeds 1 g/kg in all the soils.

In the silt fraction, Ald is concentrated more in the toposequence 1 soils than in the toposequence 2 soils. In the toposequence 1 soils, Tingoli series has the highest amounts which range from 0.85 to 4.60 g/kg, followed by Tolon series (0.59 to 3.10 g/kg) and then Kumayili series (0.53 to 3.06 g/kg). The Ald content in the Kpelesawgu series on toposequence 2 is higher (0.81 to 1.90 g/kg) than its Changnalili series counterpart (0.36 to

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0.95 g/kg). The Alo content in the silt fraction is lower than in the total fine earth and generally increases with depth except in the Tingoli series.

The DCB and oxalate extractable Al in the clay fraction follow a similar pattern as for the Fed and Feo. The Ald and Alo are higher in the soils on toposequence 1 than in the soils on toposequence 2. On toposequence 1, Tingoli series has the highest concentration of Ald (4.51 to 5.90 g/kg) and Alo (2.11 to 3.20 g/kg). The Kpelesawgu and Changnalili series on toposequence 2 have Ald and Alo concentrations which fall below 3.4 g/kg and 1.8 g/kg, respectively.

In both nodule sizes, Ald and Alo concentrations are greater than in the other size fractions of each respective soil profile. The difference in Ald content between the two forms of nodules is not striking. However, the Alo of the <2 mm size nodules is ≥ 1 g/kg in the Tingoli and Tolon series whilst Alo content of the > 2mm size nodules is ≤ 0.7 g/kg. The imperfectly and poorly drained soils on toposequence 2 show relatively low levels of Ald and Alo in the nodules which are confined to the subsurface.

The Mnd and Mno forms are extremely low (Table 4.8) and do not exceed 1.5 g/kg in the soils with the notable exception of the imperfectly and poorly drained soils on toposequence 2 where Mno and Mnd in the nodules exceed 9 g/kg and 2 g/kg, respectively. The clay fraction appears to accumulate more Mno and Mnd in all the three soils on toposequence 1.

4.6.4 Forms and distribution of phosphorus

4.6.4.1 Total phosphorus

The total P (TP) saturation in the various size fractions are given in Table 4.9 and Figure 4.1. In all the soil profiles, TP saturation levels follow the general trend nodule ≈ clay > soil fines (fine earth) > silt.

The total P concentration of the fine earth in all the soils is very low, ranging from 78 to 282 μg/g. The upland Tingoli series and Tolon series, developed from ironstone

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Table 4.9. Phosphorus contents (μg/g) in the various fractions.

Depth (cm)	Total P					Available P	
	soil	silt	clay	nodule (>2mm)	nodule (<2mm)	soil	nodule (>2mm)
	(μg/g)						
				Tingoli series			
0-16	132.2	91.9	744.6	192.0	700.3	2.8	3.1
16-32	276.2	95.5	588.8	405.1	777.6	2.2	2.7
32-48	252.0	66.7	491.4	540.1	675.6	1.8	2.8
48-67	282.1	203.5	464.3	588.2	425.2	1.3	2.5
67-98	228.3	163.1	332.3	408.0	281.8	1.6	1.5
98+	216.0	131.4	398.5	264.1	286.6	1.7	3.6
				Tolon series			
0-14	105.2	66.0	457.0	291.0	510.4	2.9	2.9
14-30	114.1	58.6	469.1	279.2	419.0	2.4	2.1
30-54	198.3	92.5	454.2	318.2	482.5	2.9	1.9
54-76	231.1	107.9	431.0	360.1	268.2	1.4	4.1
76-100	204.4	139.3	373.5	294.2	257.2	2.1	4.3
				Kumayili series			
0-18	84.2	61.9	380.9	nd	nd	2.4	nd
18-36	81.3	53.0	363.0	nd	nd	2.5	nd
36-57	96.1	53.9	315.9	nd	nd	1.6	nd
57-90	126.0	58.0	323.5	294.0	392.1	2.1	4.1
90$^+$	156.2	100.2	264.0	246.2	314.0	2.1	4.6

nd = not determined.

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Table 4.9. cont'd.

Depth (cm)	Total P					Available P	
	soil	silt	clay	nodule (>2mm)	nodule (<2mm)	soil	nodule (>2mm)
	(μg/g)						
			Kpelesawgu series				
0-15	78.2	50.4	259.2	nd	nd	2.3	nd
15-34	96.1	46.9	287.2	nd	nd	2.1	nd
34-64	99.3	52.9	268.5	nd	nd	1.7	nd
64-100$^+$	138.2	74.4	268.1	210.1	359.4	1.6	3.9
			Changnalili series				
0-12	102.2	58.2	432.46	nd	nd	3.8	nd
12-24	102.1	64.5	348.51	nd	nd	3.8	nd
24-37	114.3	101.8	344.0	390.3	374.1	2.4	5.0
37-57	180.1	87.2	371.7	270.2	290.7	2.3	4.4
57-100$^+$	90.4	63.7	198.2	198.0	136.8	1.9	3.4

nd = not determined.

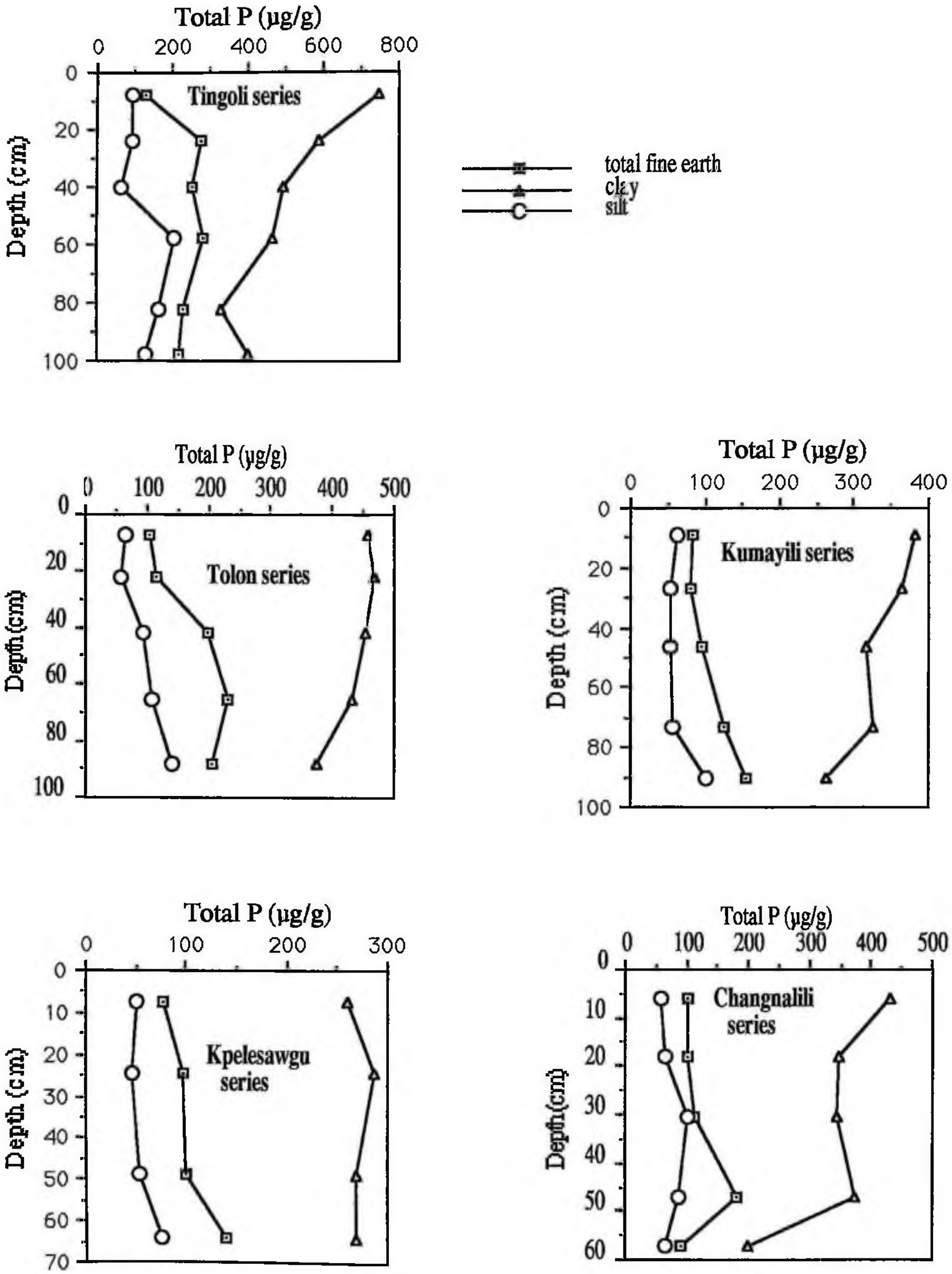

Fig. 4.1. Total P distribution in the total fine earth and the silt and clay fractions.

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gravel and ferruginized brash, have higher fine earth total P contents than their midslope counterpart, Kumayili series (toposequence 1) and the low-lying Kpelesawgu series and Changnalili series (toposequence 2). The TP varies from 132 to 282 µg/g in the Tingoli series, 105 to 231 µg/g in the Tolon series and 81 to 156 µg/g in the Kumayili series which has developed from local colluvium or hill wash. On toposequence 2, the Kpelesawgu series has TP between 78 and 138 µg/g whilst the Changnalili series has slightly higher TP values but comparable to the Kumayili series. The total P tends to increase gradually with depth in all the five profiles studied (Fig 4.1).

In the silt fraction, the TP saturation varies between 50 and 204 µg/g. The TP saturation in the soil profiles follows a decreasing order of Tingoli series > Tolon series > Kumayili series (toposequence 1) > Changnalili series > Kpelesawgu series (toposequence 2). The TP distribution in each profile follows a similar pattern as in the fine earth.

The TP concentrations in the clay fraction are generally higher than in the silt fraction and in the total fine earth (Fig 4.1) and range from 198.2 to 744.6 µg/g. The clay fraction TP content varies from 398.5 to 744.6 µg/g for the Tingoli series, 373.5 to 469.1 µg/g for the Tolon series and 264.0 to 380.9 µg/g for the Kumayili series. For the Changnalili series, the TP concentration ranges from 198.0 to 432.0 µg/g. The Kpelesawgu series has the least TP saturation with values ranging from 259 to 287 µg/g. There is a decrease in TP levels in the clay fraction with depth.

For the > 2mm size nodules, the TP saturation varies from 192.0 to 588.2 µg/g in the Tingoli series and 291.0 to 360.1 µg/g in the Tolon series. The corresponding ranges of TP saturation in the < 2 mm size nodules for the two soils are 286.6 to 777.6 µg/g and 257.2 to 510.4 µg/g, respectively. For the two nodule sizes, therefore, TP saturation is higher in the Tingoli series than in the Tolon series. The TP content in the nodules (> 2 mm) generally increases with depth in the concretionary Tingoli series and Tolon series. The TP content in the nodules (< 2 mm), on the other hand decreases with depth. In general, the TP in the clay fraction in the two upland soils is higher than in the nodules (> 2 mm) but comparable to the contents of the < 2 mm nodules .

4.6.4.2 Available phosphorus

The $NaHCO_3$ extractable P (available P) levels are extremely low in comparison with the total P (Table 4.9). The available P concentration ranges from 1.3 to 3.8 µg/g in the fine earth fraction and 1.5 to 4.3 µg/g in the nodules. The Changnalili series has the highest levels of available P which range from 1.9 µg/g in the subsurface to 3.8 µg/g at the surface. The fine earth concentration appears to follow a decreasing order of Changnalili series > Tolon series >Kumayili series > Tolon series > Kpelesawgu series. Available P concentration shows a general decrease with depth in all the profiles on the two landscapes with the least concentration occurring between 60-70 cm depth (Fig 4.2).

4.6.4.3 Dithionite-citrate-bicarbonate extractable phosphorus (DCB-P)

The DCB-P is the P attached to Fe and Al extracted by dithionite-citrate-bicarbonate. The concentrations of DCB-P in the various size fractions are given in Table 4.10. The DCB-P levels in all the size fractions are higher in the soils on toposequence 1 than in the toposequence 2 soils.

The DCB-P content in the fine earth is highest in the Tingoli (115.9 µg/g) and lowest in the Kpelesawgu series (27.4 µg/g). Also in both the silt and clay fractions, the Tingoli series has the highest concentrations of DCB-P which are 118.8 µg/g and 316.7 µg/g, respectively. The lowest DCB-P concentration in the silt fraction (18.2 µg/g) is found in the Kpelesawgu series. In the clay fraction the least concentration of 46 µg/g is in the Changnalili series. The DCB-P contents in the total fine earth and the silt fraction follow similar pattern of distribution within all the profiles.

In the clay fraction of the toposequence 1 soils, DCB-P is highest in the Tingoli

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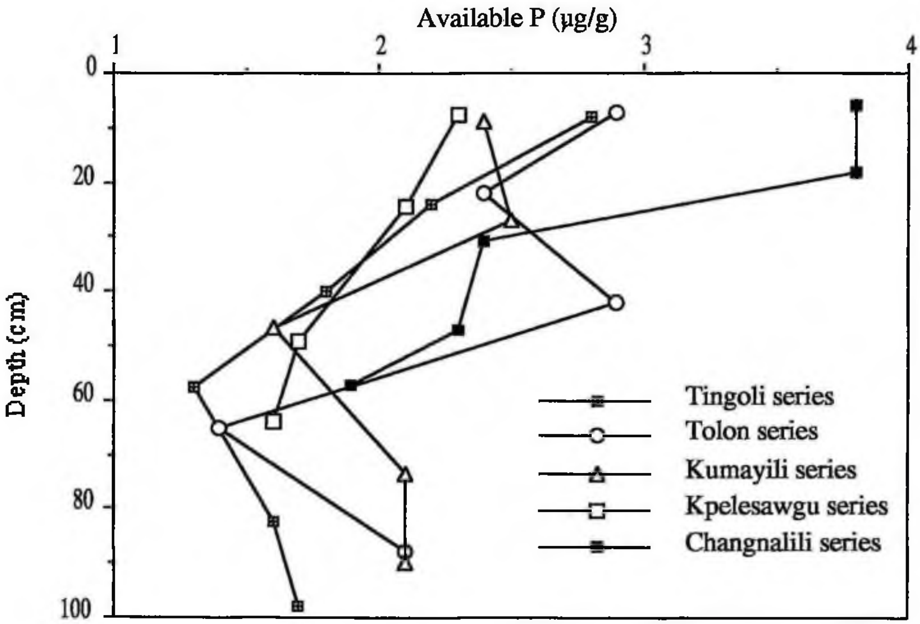

Fig.4.2. Variations in available phosphorus in the soil profiles.

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Table 4.10. DCB extractable phosphorus in the soils.

Depth (cm)	total fine earth	silt	clay	nodule (> 2mm)	nodule (< 2mm)
	--------	--------	DCB-P (μg/g)	--------	--------
			Tingoli series		
0-16	68.6	85.3	302.8	198.0	253.9
16-32	115.9	67.5	316.7	172.3	259.8
32-48	108.1	40.7	195.2	184.0	234.0
48-67	73.3	118.8	186.7	108.5	120.5
67-98	58.7	78.1	137.8	69.9	70.7
98^+	79.6	77.8	139.8	68.9	101.0
			Tolon series		
0-14	44.4	28.3	185.2	112.1	124.7
14-30	44.1	26.2	177.0	101.9	143.3
30-54	74.2	44.2	198.2	116.0	146.0
54-76	66.2	41.2	191.9	98.6	108.8
76-100	55.8	53.7	149.0	64.4	86.4
			Kumayili series		
0-18	45.9	29.7	180.5	nd	nd
18-36	35.9	24.5	154.5	nd	nd
36-57	36.5	22.0	118.5	nd	nd
57-90	43.2	18.3	117.9	65.0	173.5
90^+	51.6	48.2	87.7	141.4	122.9
			Kpelesawgu series		
0-15	31.0	18.2	123.0	nd	nd
15-30	27.4	21.3	54.2	nd	nd
30-64	23.5	18.3	88.0	nd	nd
$64\text{-}100^+$	33.0	38.9	80.7	110.4	118.1
			Changnalili series		
0-12	42.8	31.0	146.2	nd	nd
12-24	33.1	36.6	122.5	nd	nd
24-37	32.8	37.4	46.4	69.6	161.6
37-57	46.1	43.9	105.0	77.1	105.0
$57\text{-}100^+$	45.0	24.3	47.1	20.7	30.6

nd = not determined.

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series followed by the Tolon series and then the Kumayili series. In the toposequence 2 soils, DCB-P is higher in the Changnalili series than in the Kpelesawgu series. The DCB-P in the clay fraction generally decreases with depth (Fig. 4.3).

The DCB-P concentration in the <2mm size nodules is higher than in the >2 mm size nodules. For both forms of nodules, the Tingoli series shows greater saturation levels of DCB-P than the Tolon series. In each respective profile, the DCB-P follows the order clay > nodules (< 2mm) > nodules (> 2 mm) > fine earth > silt.

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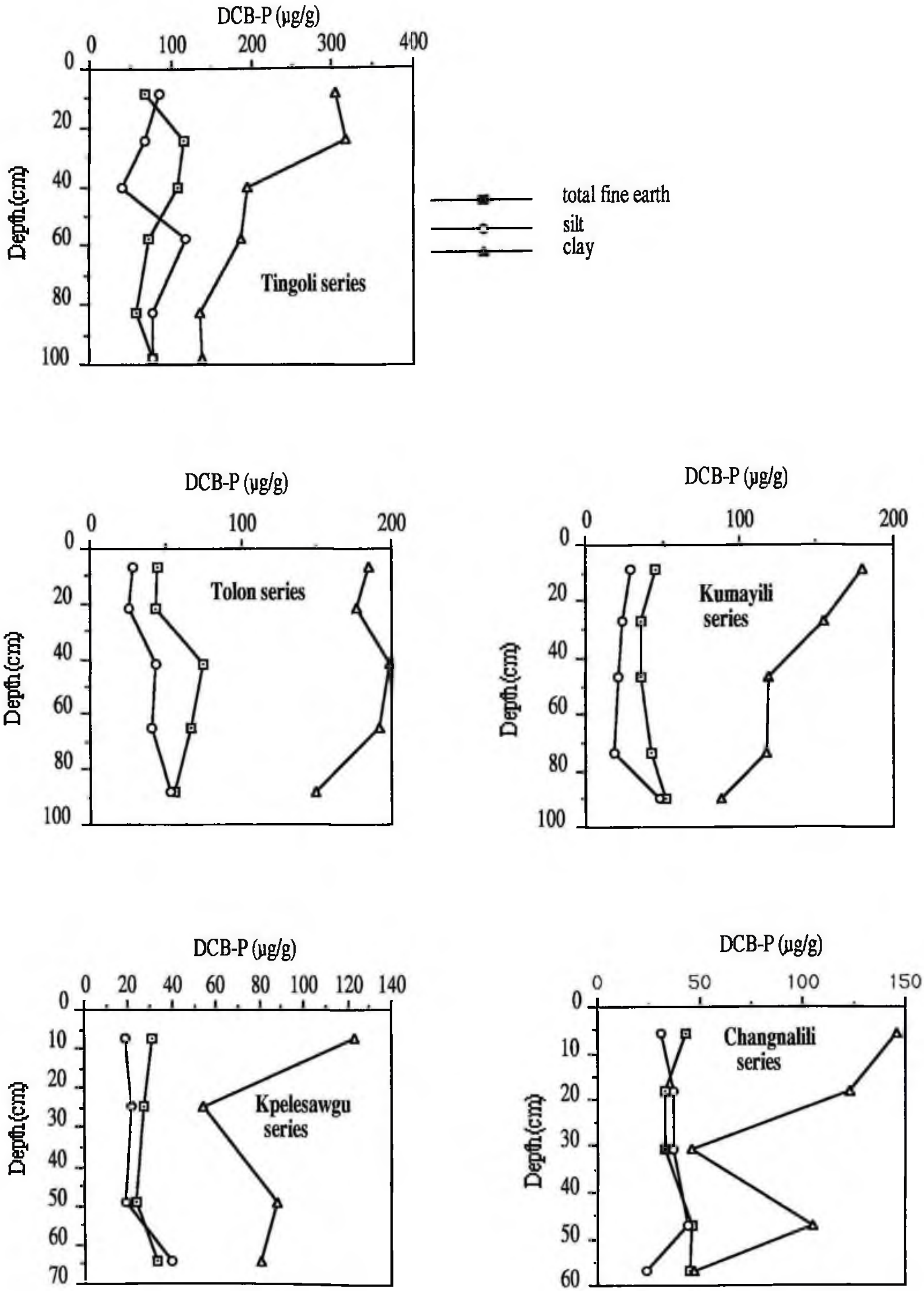

Fig. 4.3. Changes in DCB-P concentration in the soil profiles.

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CHAPTER FIVE

DISCUSSION

5.1 Physical properties

5.1.1 Nodule distribution and particle size

In the Tingoli and Tolon series which have nodules throughout their profiles, there is a general increase in nodule content with depth. The nodule content is related to the total Fe content in the fine earth fractions. There is a highly significant correlation between the nodule content and total Fe content in the fine earth fraction (Fig. 5.1). The accumulation of nodules in the soils has a sequence of Tingoli series ≈ Tolon series > Changnalili series > Kumayili series > Kpelesawgu series. For plinthite and nodule formation, there is a supply of iron which usually comes from the weathering zone (Gallaher et al., 1974). In the soils developed from the iron rich parent materials on toposequence 1, the higher amounts of nodules at the subsurface are consistent with the nature of the parent material.

In the poorly drained Changnalili series and the imperfectly drained Kpelesawgu series, the nodule content is very low in the upper portions of the profiles. Maximum nodule content occurs in the subsurface in both profiles. The subsurface is characterised by abundant mottles which give an indication of redoximorphic conditions. According to Schwertmann and Fanning (1976) these conditions are conducive for plinthite and subsequently nodule or concretion formation. This may account for the accumulation of nodules in the two profiles.

The amount of nodules and concretions in lateritic soils increases with increasing drainage (Schwertmann and Fanning, 1976) and may also be controlled by the nature of the parent material. It is known that nodules in the soils of northern Ghana are derived from the ironstone parent materials (Obeng, 1975). The Tingoli series and Tolon series, which have been developed from ironstone gravel and ferruginised brash parent materials, and the Changnalili series (developed from a massive ironstone) are, therefore, expected to have

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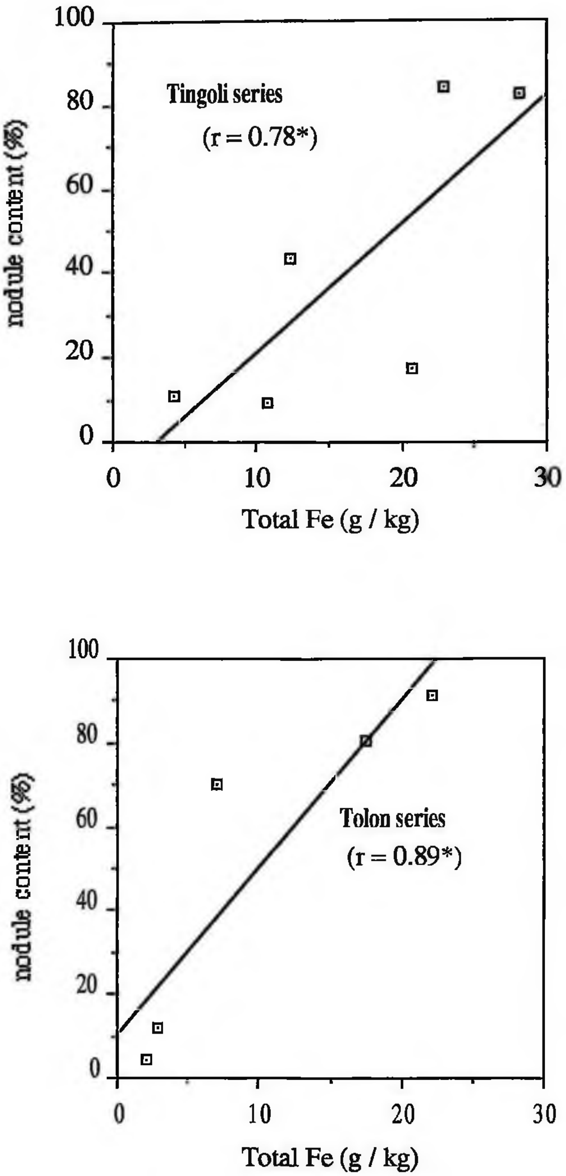

Fig. 5.1. Relationship between nodule content and total iron in the soils (* = Significant at P=0.05).

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higher amounts of nodules than the Kpelesawgu series and Kumayili series which have been developed from local colluvium and alluvium, respectively.

The clay content in all the soils tends to increase with decreasing sand content down the profiles. This inverse relation shows that there is weathering of sand size particles into clay size fractions. The increasing clay content with depth may also be due to vertical translocation of clay from the surface horizons to the subsurface.

The sand content is higher while the silt content is lower in the toposequence 1 soils than in their counterparts on toposequence 2. This could be due to the relative elevation of the two landscapes and also due to the influence of the different parent materials. The soils on toposequence 2 are at a lower elevation and occur in low lying areas and may have accumulated silt from adjacent landscapes which occur at higher elevations. The Kpelesawgu series has developed from local colluvium and the Changnalili from massive ironstone deepened by soil wash (Adu, 1957). These soils may, therefore, have accumulated more silt from their respective parent materials.

5.1.2 Profile uniformity

The usual method of determining profile uniformity is to calculate the ratios of concentration of minerals resistant to weathering (e.g. quartz) in different size fractions (Chittleborough and Oades, 1979). A constant ratio throughout the profile indicates profile uniformity, whilst a variable ratio points to a variable parent material. The quartz ratios (silt:fine earth) in each profile are given in Table 5.1. Figure 5.2 also shows the distribution of quartz ratios in the profiles of the soils studied. It can be inferred from the data that all the soils have varying quartz ratios with depth which suggest that they have parent materials that are not uniform. The study site falls within the Interior Savanna zone which has a history of series of past erosion cycles (Brash, 1962). The non-uniformity of the parent materials from which the soils have developed is, therefore, consistent with the local geomorphology.

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Table 5.1. Quartz ratios in the soils.

Depth (cm)	Quartz ratio
Tingoli series	
0-16	0.95
16-32	1.55
32-48	1.62
48-67	2.42
67-98	1.70
98+	2.23
Tolon series	
0-14	1.13
14-30	1.07
30-54	1.44
54-76	1.83
76-100	1.31
Kumayili series	
0-18	0.83
18-36	0.89
36-57	1.06
57-90	1.22
90+	1.35
Kpelesawgu series	
0-15	0.87
15-34	0.90
34-64	1.03
64-100+	1.29
Changnalili series	
0-12	0.98
12-24	1.12
24-37	1.17
37-57	1.29
57-100+	0.80

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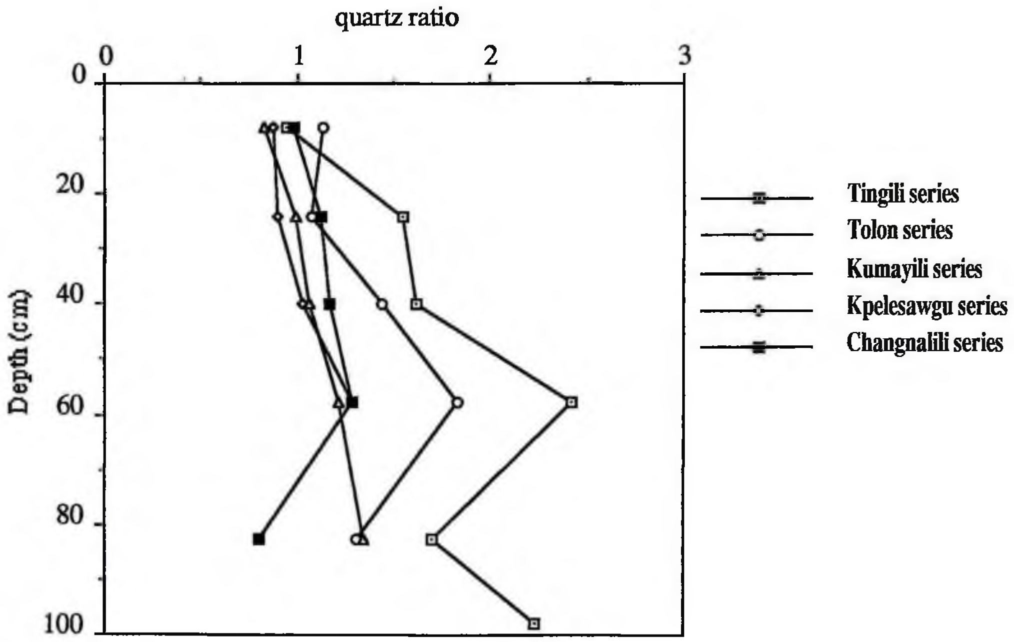

Fig. 5.2. Variations in quartz ratios in the soils.

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5.1.3 Bulk density

The increase in bulk density with depth is related to the variations in nodule content in the soils. This is supported by the significant correlation between bulk density and nodule content in the soils (r = 0.85* for Tingoli series, r = 0.79* for Tolon, r = 0.92* for Kumayili series, r = 0.99* for Kpelesawgu series and r = 0.84* for the Changnalili series). The higher bulk density in the toposequence 1 soils is due to the higher amounts of nodules in the soils. A high percentage of nodules would lead to a lower proportion of pore space which would in turn result in high bulk density.

5.1.4 Surface area and moisture content

The very low specific surface area (63 m^2/g) shows the dominance of low activity clays which are mainly kaolinites and illites. The SSA appears to be influenced by the clay content as suggested by the significant correlation value (Fig 5.3).

The moisture contents at 1/3 bar (33 kPa) and 15 bar (1500 kPa) and available moisture content (AMC) in the toposequence 2 soils are generally higher than in the toposequence 1 soils. This is because the soils on toposequence 2, which occur at low-lying sites, are predisposed to poor internal drainage. In the Changnalili series, AMC is controlled by clay content (Fig 5.4). The significant correlation between AMC and clay content (r = 0.86*) in this soil is worthy of note. The greatest accumulations of nodules in the Changnalili series are at depths which also have high clay and AMC contents. This implies that enrichment of iron and subsequent formation of nodules are facilitated by high moisture content and clay accumulation. This trend is not necessarily true for the Kpelesawgu series, the other member of toposequence 2, where a poor correlation (r = 0.26) between AMC and clay content exists.

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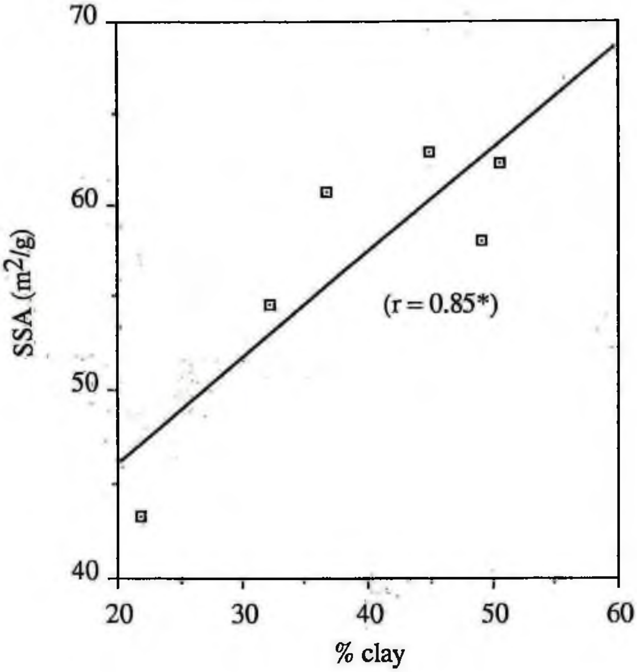

Fig. 5.3. Relationship between SSA and clay content in the Tingoli series.
(* = Significant at P = 0.05).

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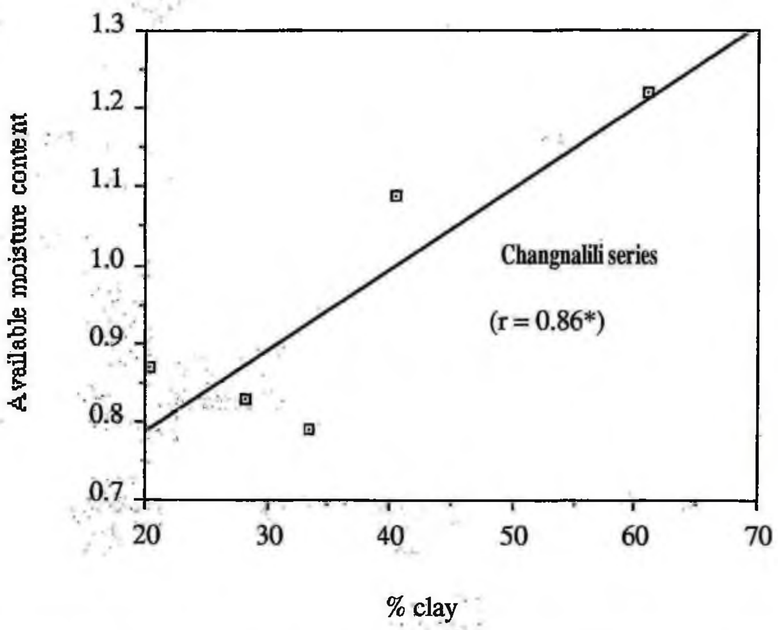

Fig. 5.4. Relationship between available moisture and clay content in the Changnalili series. (* = Significant at P = 0.05).

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5.2 Mineralogy

The mineralogical composition of the sand and silt fractions often provides quantitative data on the nature and properties of the parent materials, the extent of pedogenic weathering and lithologic discontinuity in profiles (Buol et al., 1980; Yoshinaga et al., 1986). The absence of weatherable minerals in the profiles studied shows that the soils are highly weathered and agrees with the assertion by Daugherty and Arnold (1982) that soils containing plinthite are often at an advanced stage of weathering. The absence of illite in the silt fraction of the soils on toposequence 1 supports the view that the well drained soils are at a more advanced stage of weathering than the poorly drained soils on toposequence 2 (Stumm and Morgan, 1981). The low amounts of illite in the Tingoli, Tolon and Kumayili series on toposequence 1 are supported by the low K_2O levels in these soils which also conform to the absence of illite in the sand and silt fractions.

The dominance of kaolinite and illite in these soils agrees with the observation by Obeng (1975) that these minerals are the dominant clay minerals in soils of northern Ghana. The formation of kaolinite in the soils might be related to the weathering of the feldspars, the main primary mineral in the silt fraction. Dowuona et al. (1994) noted diminution in feldspar contents with increases in kaolinite in similar soils of northern Ghana. The nodules also show dominance of quartz, goethite and haematite with moderate to minor amounts of kaolinite. The dominance of goethite and haematite in the nodules is consistent with the mineralogical composition of similar lateritic soils elsewhere (Soileau and McCracken, 1967; Shadfan et al., 1985).

The very weak peaks referable to kaolinite coupled with the high levels of goethite and haematite may be attributed to the hardening process during nodule formation. This is because hardening of nodules has been found to be accompanied by loss of kaolinite and dominance of goethite and haematite (Alexander and Cady, 1962). In the hardening process during nodule formation close packing of goethite crystals, which is necessary for

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the rigidity of the nodule crust, often slows down the formation of kaolinite (Schwertmann, 1985).

5.3 Elemental composition

The high concentration of Si may be due to the high levels of quartz in the soils. The decrease in the concentration of Si in the fine earth and clay fractions as well as the increase in Fe and Al with depth in each profile, is the result of desilication. It is likely that silica is being removed from the various profiles with the consequent accumulation of sesquioxides in the profiles. The high temperatures and leaching which occur in northern Ghana tend to favour this process.

The desilication process is more intense in the soils on toposequence 1 than in the soils on toposequence 2. This suggests that the Tingoli, Tolon and Kumayili series are more weathered than the Kpelesawgu and Changnalili series on toposequence 2. The higher nodule contents in the Tingoli and Tolon series further show that these two soils are at a more advanced stage of weathering than the rest. These soils also have greater concentrations of total Fe and Al.

The concentrations of Ca, Mg, K and Na can be used to infer the relative abundance of primary minerals and weathering intensity in soils (Parker, 1970). The low levels of these elements confirm the absence of weatherable minerals in the soils studied. The relatively high levels of K in the imperfectly and poorly drained soils on toposequence 2 are consistent with the greater accumulation of illite.

The relatively low levels of Si, Ca, Mg and K in the nodules in each profile is the result of higher degree of desilication. This confirms that the nodules reflect a more advanced stage of weathering than the rest of the soil matrix. The concentration of Fe in the < 2mm size nodules is greater than that in the > 2mm size nodules. This relation agrees with the observation by Drosdoff and Nikiforoff (1940) and Taylor and Schwertmann (1974) that Fe concentration of nodules is inversely related to size. The concentration of Si is higher in the fine earth and clay fractions than in their respective associated nodules. The concentration of Fe, however, is higher in the nodules than in the fine earth and clay fractions. A similar observation was made in other ferruginous tropical soils elsewhere (Redden and Parker, 1962; Brooks, 1965; Sokoleva and Polteva, 1968).

5.4 Chemical properties

5.4.1 pH and organic carbon

There is no apparent difference in pH values of the soils and their respective associated nodules. It is, therefore, likely that the nodules have been formed *in situ*. The change in pH values, that is, $\Delta pH = pH\ KCl - pH\ H_2O$ are negative for both the fine earth fraction and the nodules. This negative ΔpH values indicate that the soil colloids possess net negative charges (Juo et al., 1974; Tan, 1982).

The very low organic carbon content is similar to values obtained by Tiessen et al. (1991b). This low level is due to the low biomass turnover from the predominantly grass vegetation and frequent destructive bush fires characteristic of the the savanna environment where the study site is located. Consequently, organic matter returned to the soil from the vegetation is low. The Changnalili series has relatively high organic carbon accumulation due to the poor drainage which retards decomposition of litter. Characteristically, the nodules have lower organic carbon content than their respective associated soils. This may be explained by the fact that at sites where nodule formation takes place organic carbon content is generally low (Eswaran et al., 1990).

5.4.2 Exchangeable bases and effective cation exchange capacity (ECEC)

In general, the exchangeable bases are low and hence the ECEC also very low. The exchangeable bases and ECEC values are consistent with values obtained by Obeng (1975), Tiessen et al. (1987) and Tiessen et al. (1991b) on similar soils of northern Ghana. The increase in exchangeable Ca and Mg with depth suggests that there is vertical leaching

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of the two bases. Exchangeable Ca and Mg are also highest in the Changnalili series and this could be due to the relatively high amount of organic carbon in that soil.

The very low ECEC in all the soils is the result of near complete removal of weatherable primary minerals under the prevailing tropical environment. The low ECEC is consistent with the dominance of the low activity kaolinitic clays and low specific surface areas. The comparatively higher ECEC values in the Changnalili series is reflected by the minor to moderate amounts of non-expandable 2 : 1 illite clays in this soil.

The base saturation in the soils and associated nodules is very high (> 60%) which is due to the very low exchangeable acidity. Soils in the savanna areas of West Africa have been known to have very low exchangeable acidity because of their very low free aluminium content (Ahn, 1970). The high base saturation in the soils can also be explained by a constant replenishment of bases from annual harmattan dust storms, which have been found to increase the CEC (Tiessen et al., 1991a).

5.4.3 Free iron oxides and particle size

The distribution of Fed in the various size fractions is given in Fig 5.5. The distribution of Fed in the Kpelesawgu and Changnalili series is more closely related to the distribution of silt (Fig. 5.5) in these soils. The highest and lowest silt contents in these two soils closely match the maximum and minimum Fed content, respectively. A similar trend in distribution pattern between silt and rather oxalate extractable Fe was observed for some highly weathered savanna soils of Ghana by Asamoa (1973).

For the Tingoli, Tolon and Kumayili series, the pattern of Fed distribution is, however, closely related to the clay content. The increasing Fed and clay contents may, in part, be due to the concentration of iron oxide in the clay fraction. The clay / Fed ratios in the Tingoli , Tolon and Kumayili series show decreasing trends with depth (Fig. 5.6) thus corroborating the suggestion that iron movement is, however, partially independent of clay movement (Juo et al., 1974).

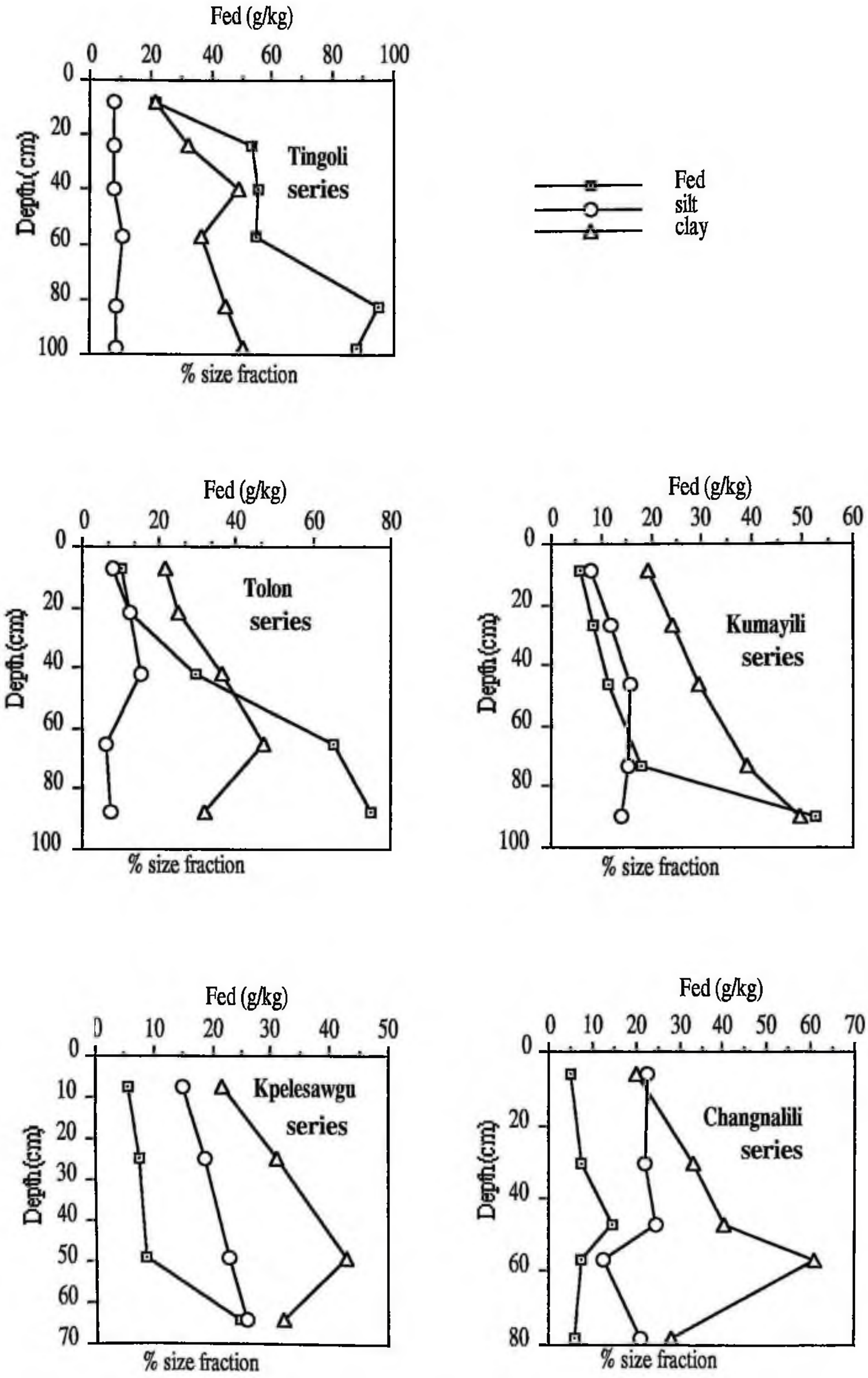

Fig. 5.5. Changes in Fed, silt and clay contents with depth.

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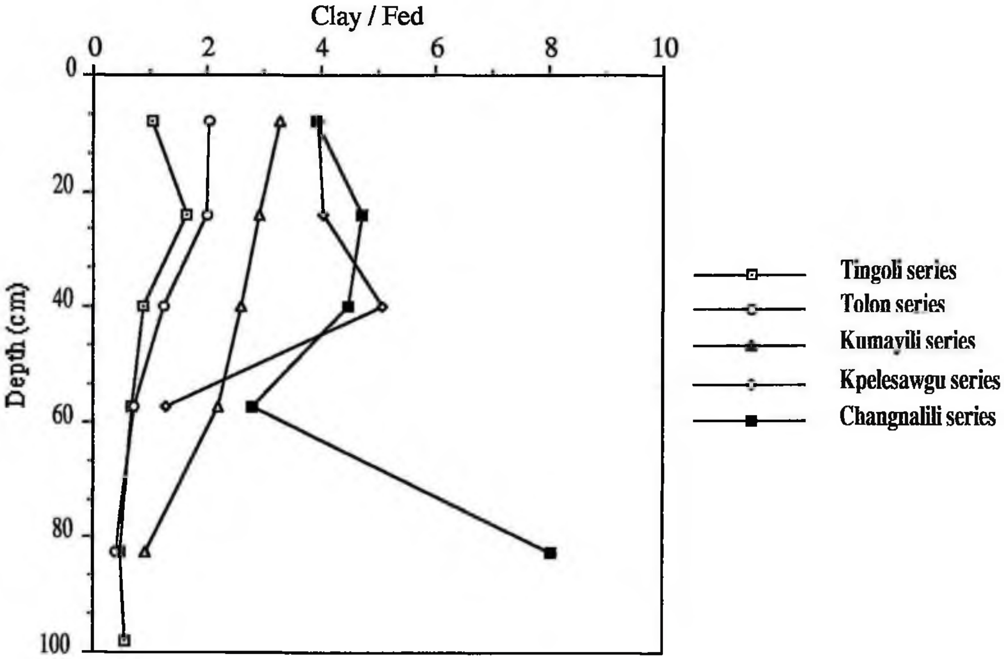

Fig. 5.6. Variations in clay : Fed ratios with depth.

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5.4.4 Active iron ratio

The crystallization of Fe oxides in soils is an important process in soil genesis (Schwertmann and Taylor, 1977). This is because the ratio of Feo to Fed is used in determining the degree of aging of Fe released from silicate-Fe weathering. The relative contribution of Feo to Fed is expressed as the active iron ratio. The active ratio is normally less than one, because acid oxalate extracts less iron from mineral soils than does dithionite-citrate. It approaches zero in old tropical soils (Alexander, 1974).

The active Fe ratios are generally very low and less than 0.1 in the well drained soils on toposequence 1 and greater than 0.1 in the soils on toposequence 2 (Table 5.2). A comparison of the Feo/Fed ratios indicates that the degree of crystallinity (Feo/Fed) of Fe is lower in all size fractions of the toposequence 2 soils than their corresponding toposequence 1 soils. The sequence of crystallinity of soils on toposequence 1 follow the sequence Tingoli series > Tolon series > Kumayili series. On toposequence 2, the order is Changnalili series > Kpelesawgu series.

The low ratios in the toposequence 1 soils reveal that these soils are at an advanced stage of weathering, relative to the toposequence 2 soils. The very low ratios (≈ zero) are also indicative of old tropical soils as noted by Alexander (1974). The active Fe ratios of the nodules are similar to ratios found in nodules in northern Ghana by Tiessen et al. (1993). All the nodules have lower Feo / Fed ratios than their respective associated soils suggesting a higher degree of maturity for the nodules. There is no apparent difference in crystallinity between the different nodules sizes.

5.4.5 Feo, Alo and crystallinity

The very low Feo and Alo contents are similar to values reported for related soils by Tiessen et al. (1993). The Feo and Alo in the soils studied are, however, lower than values obtained for many temperate soils where Feo contributed 30 to 60% of Fed (McKeague and Day, 1966; McKeague et al., 1971). The very low Feo and Alo values in all the fractions

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Table 5.2. The Feo / Fed (active) ratios.

Depth (cm)	total fine earth	clay	silt	nodules (>2mm)	nodules (<2mm)
	Fe_o / Fe_d				
			Tingoli series		
0-16	0.03	0.06	0.05	0.01	0.02
16-32	0.02	0.04	0.03	0.01	0.02
32-48	0.02	0.06	0.03	0.01	0.01
48-67	0.02	0.07	0.01	0.01	0.01
67-98	0.01	0.05	0.01	0.01	0.01
98^+	0.01	0.05	0.01	0.01	0.01
			Tolon series		
0-14	0.04	0.15	0.07	0.01	0.02
14-30	0.03	0.13	0.07	0.01	0.01
30-54	0.02	0.1	0.04	0.01	0.01
54-76	0.02	0.07	0.02	0.01	0.01
76-100	0.01	0.06	0.02	0.01	0.01
			Kumayili series		
0-18	0.07	0.19	0.08	nd	nd
18-36	0.06	0.18	0.09	nd	nd
36-57	0.05	0.11	0.07	nd	nd
57-90	0.03	0.08	0.04	0.03	0.01
90+	0.01	0.05	0.02	0.01	0.02
			Kpelesawgu series		
0-15	0.21	0.65	0.26	nd	nd
15-34	0.14	0.44	0.27	nd	nd
34-64	0.11	0.22	0.11	nd	nd
64-100+	0.05	0.12	0.08	0.02	0.02
			Changnalili series		
0-12	0.18	0.57	0.17	nd	nd
12-24	0.18	0.51	0.24	nd	nd
24-37	0.16	0.35	0.13	0.03	0.02
37-57	0.10	0.29	0.30	0.02	0.02
57-100	0.07	0.12	0.05	0.03	0.02

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in each profile reflect the trend in the very low organic carbon contents in the soils. The low build up of organic matter causes the low levels of Feo and Alo in the soils as postulated by Juo et al. (1974).

Organic matter is known to inhibit crystallization of Fe and Al in soils (Schwertmann, 1966; Schwertmann et al. 1968; Huang and Violante, 1986). The low organic carbon content of the soils coupled with the high temperatures existing in northern Ghana is likely to promote formation of crystalline Fe and Al oxides. At elevated temperatures, a shift from amorphous to crystalline forms of oxides is likely to occur (Juo et al., 1974). The relatively high environmental temperatures of the study site might explain the low content of Feo and Alo and the abundance of crystalline forms of iron oxides in all the soils.

5.4.6 Free iron and soil colour

There is an obvious relationship between soil colour and concentration of free Fe-oxide in the soils at the different landscape positions. There is also an increase in redness of colour as the active Fe ratio (Feo / Fed) decreases (Table 5.3). This trend is found both within and between profiles. Samples with more yellowish hues (7.5 YR and 10 YR) generally have higher Feo/Fed ratios than those with reddish hues (2.5 YR). Ibanga et al. (1983) found a similar trend in some old tropical soils of Nigeria and Brazil. The Tingoli series, which is the most well-drained and matured soil among the soils studied, has the highest redness rating followed by the Tolon series, Kumayili series, Changnalili series and then Kpelesawgu series.

Red colouration in soils is due to the influence of Fe^{3+} and free iron oxides (Buol et al., 1980). On the contrary, Fe^{2+} contributes to yellowish colouration. The well-drained soils on toposequence 1 would, therefore, contain much more Fe^{3+} and free iron oxides and hence more reddish colouration and higher oxidation state than the poorly and imperfectly drained soils on toposequence 2. The toposequence 2 soils have hues on the

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Table 5.3. DCB extractable Fe, active iron ratios and soil colour.

Depth (cm)	Fed (g / kg)	Feo/Fed (total fine earth)	Colour (dry)
		Tingoli series	
0-16	21.3	0.03	5YR 4/6
16-32	53.1	0.02	2.5YR 3/6
32-48	55.1	0.02	2.5YR 3/6
48-67	55.0	0.02	2.5YR 4/6
67-98	95.2	0.01	2.5YR 3/6
98+	87.8	0.01	2.5YR 3/6
		Tolon series	
0-14	10.5	0.04	5YR 5/6
14-30	12.5	0.03	5YR 5/6
30-54	29.4	0.02	7.5YR 5/4
54-76	65.3	0.02	5YR 5/4
76-100	74.6	0.01	5YR 5/6
		Kumayili series	
0-18	5.8	0.07	5YR 5/6
18-36	8.2	0.06	5YR 5/6
36-57	11.3	0.05	7.5YR 6/6
57-90	17.8	0.03	7.5YR 5/6
90+	52.5	0.01	7.5YR 5/6
		Kpelesawgu series	
0-15	5.4	0.21	7.5YR 7/4
15-34	7.5	0.12	7.5YR 7/4
34-64	8.5	0.11	7.5YR 7/4
64-100$^+$	24.7	0.05	7.5YR 7/4
		Changnalili series	
0-12	5.3	0.18	10YR 6/4
12-24	6.0	0.18	7.5YR 6/2
24-37	7.4	0.16	7.5YR 6/2
37-57	14.4	0.10	7.5YR 6/2
57-100$^+$	7.6	0.07	7.5YR 6/4

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yellow side because of their poor drainage which promote the formation of Fe^{2+} and less free iron oxides.

5.4.7 DCB and oxalate forms of Mn

The DCB and oxalate extractable Mn in the soils are lower than both extractable forms of Fe and Al. This low Mn concentration is consistent with the very low Mn-bearing mineral contents in the soils. The low Mno and Mnd may also be due to the generally higher mobility of Mn in soils which may have caused the Mn to be leached.

In spite of the general low levels, Mno and Mnd concentrations in the clay fraction of the well drained soils are higher than in the low lying soils. This could be alluded to the better drainage in the well drained soils which inhibits migration of Mn (in clay size fractions) out of the profiles. The Mno and Mnd in the nodules, however, are higher in the toposequence 2 soils than in the toposequence 1 soils. The Mn which is mobile may have accumulated in the soils on toposequence 2 from adjacent higher elevated landscapes. This is in accord with the view that there are higher quantities of Mn in nodules of poorly drained soils than in well drained soils of West Africa (Ahn, 1970).

5.4.8 Maturity of soils

The amount of Fed in the solum has been used as a basis for assessing the degree of development of soils formed from similar of parent materials (Blume and Schwertmann, 1969). The amount of Fed in soils is also used to depict the weathering intensity of soils. High amounts of Fed indicate advanced weathering. This is in accord with the view that the intensity of soil development can be determined by the amount of sesquioxides and their distribution in soil profiles (Gorbunov et al., 1961). On the basis of the Fed distribution, therefore, the weathering intensity of the soils on toposequence 1 follows a maturity sequence of Tingoli series > Tolon series > Kumayili series. For the toposequence 2, Kpelesawgu series is more matured than Changnalili series.

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The Fed : Fet ratio has also been used to predict soil maturity. As soil development continues, the ratio of Fed to Fet usually increases (Schwertmann,1985; Bigham et al., 1991). From Table 5.4 it can be inferred that soils on toposequence 1 have higher Fed : Fet ratios and thus are more developed than soils on toposequence 2. This ratio also confirms the Tingoli series to be the most matured soil among all the soils studied.

Within each profile, the Fed : Fet ratio in the fine earth decreases with depth suggesting that the intensity of weathering decreases down the profiles. The decreasing Fed : Fet ratios may relate to drainage or moisture content. It has been established that presence of water inhibits crystallization of Fe and thus maturity of soils (Schwertmann, 1985). Consequently for the Kpelesawgu and Changnalili series with poor internal drainage, the Fed : Fet ratios are low and point to relatively immature profiles.

During prolonged and intense weathering, losses of silica are proportionally greater than those of the sesquioxides of Fe and Al. The silica : sesquioxide molar ratio can, therefore, be used as an index of weathering (Jones and Wild, 1975) and ratios < 2 indicate greater weathering intensity. The ratios of the various fractions in each respective profile (Table 5.5) confirm the observed sequence of soil maturity in the soils studied. All the nodules have lower values (mostly < 2) than their respective associated soils. This suggests that the nodules are at an advanced stage of weathering and, therefore pedogenically more matured than the soils in which they formed.

The silt / clay ratio in soils has also been used to indicate the extent of weathering. According to Jamagne (1963), a silt / clay ratio of less than 0.2 in a soil indicates that the soil is a ferrallitic one whereas a ratio greater than 0.2 indicates a ferruginous soil. D'Hoore (1964), however, used a silt / clay ratio of more than 0.25 to depict ferruginisation. The silt / clay ratios in the soils are generally higher than 0.25 (Table 5.5) indicating that all the five soils are ferruginous. This is further supported by the presence of kaolinite and some amount of 2 : 1 micaceous clays (illite) as well as some resistant minerals e.g. titanium in the clay fraction of the soils (Duchaufour, 1982). The higher

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Table 5.4. The Fed:Fet ratios in the soils.

Depth (cm)	total fine earth	clay	silt	nodules (>2mm)	nodules (<2mm)
	Fed/Fet				
Tingoli series					
0-16	0.81	0.74	nd	0.53	0.47
16-32	0.76	0.72	nd	0.49	0.44
32-48	0.73	0.60	nd	0.48	0.45
48-67	0.33	0.57	nd	0.48	0.49
67-98	0.58	0.63	nd	0.53	0.52
98^+	0.72	0.67	nd	0.44	0.59
Tolon series					
0-14	0.88	0.48	nd	0.54	0.38
14-30	0.70	0.51	nd	0.45	0.52
30-54	0.64	0.57	nd	0.56	0.47
54-76	0.65	0.52	nd	0.60	0.67
76-100	0.58	0.66	nd	0.53	0.59
Kumayili series					
0-18	0.82	0.50	nd	nd	nd
18-36	0.56	0.50	nd	nd	nd
36-57	0.70	0.39	nd	nd	nd
57-90	0.68	0.38	nd	0.62	0.50
90^+	0.74	0.60	nd	0.55	0.61
Kpelesawgu series					
0-15	0.68	0.31	nd	nd	nd
15-34	0.58	0.24	nd	nd	nd
34-64	0.54	0.27	nd	nd	nd
64-100+	0.64	0.62	nd	0.54	0.50
Changnalili series					
0-12	0.68	0.28	nd	nd	nd
12-24	0.47	0.24	nd	nd	nd
24-37	0.51	0.28	nd	0.54	0.58
37-57	0.50	0.13	nd	0.59	0.49
57-100+	0.78	0.30	nd	0.75	0.64

nd = not determined.

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Table 5.5. Silt : clay and silica to sesquioxide molar ratios.

Depth (cm)	silt : clay	molar SiO_2 / (Fe_2O_3 + $Al2O_3$)			
		total fine earth	clay	nodules (>2mm)	nodules (<2mm)
		Tingoli series			
0-16	0.37	13.88	3.55	1.69	0.77
16-32	0.25	3.95	1.84	1.16	0.62
32-48	0.16	3.51	1.56	0.82	0.73
48-67	0.29	2.14	1.28	0.79	0.75
67-98	0.20	1.91	1.57	0.96	1.07
98+	0.17	1.78	1.65	0.79	1.29
		Tolon series			
0-14	0.37	16.54	3.14	2.78	1.35
14-30	0.49	12.85	3.67	1.50	1.55
30-54	0.42	6.27	3.19	1.03	0.95
54-76	0.13	2.92	3.03	1.13	1.53
76-100	0.23	2.49	2.55	1.09	1.44
		Kumayili series			
0-18	0.42	29.50	4.00	nd	nd
18-36	0.49	15.33	3.66	nd	nd
36-57	0.54	12.00	3.07	nd	nd
57-90	0.40	7.97	2.20	4.84	1.12
90^+	0.28	3.90	4.76	1.38	1.74
		Kpelesawgu series			
0-15	0.70	20.28	4.00	nd	nd
15-34	0.61	12.43	5.00	nd	nd
34-64	0.53	11.06	4.35	nd	nd
64-100^+	0.81	6.79	5.55	2.00	1.63
		Changnalili series			
0-12	1.12	21.46	3.99	nd	nd
12-24	0.74	13.20	4.39	nd	nd
24-37	0.66	11.56	3.48	3.57	5.64
37-57	0.61	7.15	1.64	2.60	4.16
57-100^+	0.21	27.94	1.77	3.07	5.52

nd = not determined.

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TiO_2 contents in the clay fraction (Table 4.5) and the lower silt/clay ratios of the soils on toposequence 1 also confirm the fact that these soils are at a more advanced stage of weathering than the toposequence 2 soils.

5.5 Forms and distribution of Phosphorus

5.5.1 Total P and Available P

The total phosphorus (TP) concentrations in the soils (fine earth fraction) are generally within the limits reported for some other studies in West Africa (Jones and Wild, 1975; Nye and Bertheux, 1957; Tiessen et al., 1993). The available P levels are very low. The TP and available P levels can be ascribed to the nature of the parent materials from which the soils developed. These materials contain very low phosphorus bearing mineral reserves and lack primary weatherable minerals necessary for nutrient recharge (Jones and Wild, 1975; Nye and Bertheux, 1957).

It has been noted that the most highly developed soils in a landscape tend to accumulate more total P (Godfrey and Riecken, 1954). Consistent with this view, it stands to reason that the Tingoli series has the highest TP concentrations in any fraction considering the advanced stage of maturity of this soil. For toposequence 1, therefore, the order of decreasing TP accumulation in the soils is Tingoli series > Tolon series > Kumayili series. Kaolinite plays an active role in P sorption (Juo and Fox, 1977; Fageria and Filho, 1987) and soils generally high in kaolinite such as the Tingoli series may have high P sorption.

The TP contents in the imperfectly and poorly drained soils on toposequence 2, on the contrary, decreases with increasing profile maturity. A similar observation in other poorly drained soils was reported by Walker and Syers (1976). For soils on low-lying landscapes, the distribution does not normally follow the sequence of maturity. The higher P accumulation in the Changnalili series may be the result of translocation of material from upslope (Smeck and Runge, 1971). Furthermore, silt contents more closely reflect the P

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composition of parent materials and where the TP is mainly concentrated in the silt fraction, soil development is often at its early stages (Syers et al., 1969) as in the Changnalili series. Nevertheless, in all the soils TP accumulation in the silt fraction is far lower than in the clay fractions. This, therefore,tends to further confirm that the soils, especially those on toposequence 1 are at advanced stages of weathering.

The uniform distribution of total P with depth in soils indicates a relatively homogeneous parent material (Godfrey and Riecken, 1954; Smeck and Runge, 1971). In the soils studied, however, the TP contents of all fractions are not uniformly distributed in each respective profile. This trend is in accord with the non-uniformity of the parent materials from which the soils have developed.

Within each profile, the total P levels in the clay fraction and nodules are nearly similar and tend to decrease with depth and weathering intensity. The silt fraction accumulates less amounts of total P suggesting that the clay and the nodules are more effective in controlling the total P saturation levels in all the soils (Dowuona et al. 1994). The nodules in the sola of the Tingoli and Tolon series show marked differences in total P saturation compared to those nodules at depths in the profiles. At the surface soils, the nodules (< 2mm) may immobilize more P (through fertilizer application or ash inputs) added to the soils because of their greater sesquioxide contents. This immobilisation may have agronomic implications considering that the concretionary Tingoli and Tolon series are widely cultivated and are also subjected to annual dry season burning.

The total P saturation especially in the solum of the < 2mm size nodules is higher than in the > 2mm size nodules suggesting greater sorption capacity for the smaller size nodules. The higher P concentration in the < 2mm nodules can be attributed to their higher surface area which exposes larger external surface for sorption in comparison with the >2mm size nodules. This difference in and causes for the total P saturation of the two forms of nodules are consistent with the findings by Weaver et al. (1992) for similar ferruginous soils in the semi arid areas of Southwestern Australia.

The significance of these observations relate to their implications for fertilizer application. Soils with greater accumulation of nodules will sorb more phosphorus in applied P-fertilizer. Furthermore, soils with smaller size nodules (e.g. <2mm size nodules) will also sorb more phosphorus. In the management of the soils on the two landscapes, therefore, careful note should be taken of the properties which affect P saturation and sorption.

The available P in the soils and their respective associated nodules is very low probably because of the poor P content of the parent material (Adu, 1957). There is also little concentration of P through vegetative cycling in the savanna zone and therefore organic phosphate which contributes to available P levels are low (Halm and Bampoe-Addo, 1972). Organic matter has a favourable effect on P dynamics in soils. In addition to mineralisation to release P, the competition of organic ligands for Fe and Al oxide surfaces can result in decrease in sorption of applied and native P and, therefore, make P more available (Bhat and Bouyer, 1968). However, considering the low organic matter status and high Fed and Ald contents in the soils studied, the very low available P is not unexpected.

The available P content is generally higher in the upper portions of each profile. This is consistent with the low concentrations of DCB and oxalate-extractable Fe and Al in the surface horizons. The Tingoli series, which has the highest TP content, recorded the lowest profile average of available P concentration. This suggests very low P availability in the Tingoli series despite its high TP content. The Changnalili series, on the other hand, has the highest available P content probably due to its lower sesquioxide and higher organic carbon contents.

The lowest available P in all the soils is at depths where the greatest accumulation of nodules occurs, thus suggesting that phosphorus availability may be controlled by Fe and Al oxides (Nye and Bertheux, 1957). This is more pronounced in the upland and more matured Tingoli and Tolon series on toposequence 1 than in all the other soils. Figure 5.7

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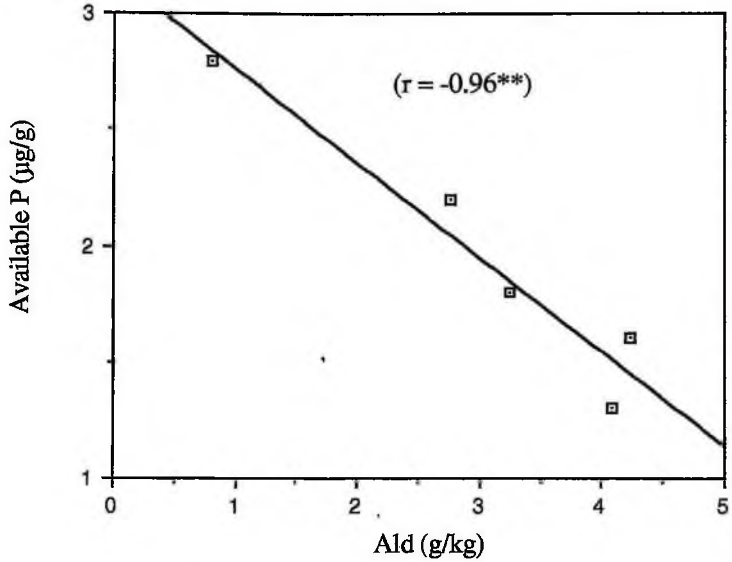

Fig. 5.7. Relationship between available P and Ald in the Tingoli series (** =Significant at P = 0.01).

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shows that the available P concentration in the soils is largely influenced by the levels of Ald. The negative coefficient of correlation implies that soils with high sesquioxide contents would have low available P. This, in part, explains why the Tingoli series has a very low available P concentration. The very low available P (< 3% of total P) also suggests a higher sorption capacity for all the soils studied.

5.5.2 Dithionite-citrate-bicarbonate extractable phosphorus (DCB-P)

Considering that the nodules (< 2mm) have higher amount of sesquioxides, one would expect them to contain the highest amount of DCB-P. On the contrary, the clay fraction has the highest content of DCB-P. This then shows that the attachment of P to the DCB extractable Fe and Al is dependent on some other factors apart from sesquioxide content. It is probable that the nature and quantity of clay minerals (e.g. kaolinite) and surface area also have some interactive roles to play.

Dithionite-citrate-bicarbonate extractable phosphorus (DCB-P) is higher in the soils on toposequence 1 than in the soils on toposequence 2 and this is in agreement with the observation by Schwertmann and Fanning (1976) that DCB-P clearly decreases with increasing soil wetness. The Tingoli and Tolon series on toposequence 1 and the Changnalili series on toposequence 2 show similar DCB-P distribution pattern which is consistent with the particle size distribution in each of these respective profiles (see section 4.4.3). These soils have formed from ironstone and the distribution pattern suggests that DCB-P is closely related to the sesquioxide concentration in each fraction.

Notwithstanding the increase in sesquioxide contents with depth, the decrease in the DCB-P concentrations in the clays and nodules is consistent with the observation by Schwertmann and Fanning (1976). It may be attributed to a more readily available P supply in the zone of bio-accumulation in the topsoils. In the toposequence 1 soils, the DCB-P decreases from the Tingoli series to the Kumayili series which also reflects the stage of soil maturity and crystallinity in these soils. This trend, which is consistent with

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the total phosphorus concentration sequence in the toposequence 1 soils, implies that the DCB-P may be responsible for the degree of total P saturation in these soils. The significant correlation between the DCB-P and the total phosphorus concentrations in the Tolon series on toposequence 1 soils ($r = 0.8^*$) adds credence to this observation. In the toposequence 2 soils, DCB-P concentration is higher in the Changnalili series than in the Kpelesawgu series reflecting the trend in the TP concentrations of the two soils. The higher DCB-P in the relatively low-lying Changnalili series could also be due to translocation of material from upslope.

5.6 Factors affecting P saturation

5.6.1 DCB and oxalate extractable Fe and Al, and P saturation

The availability of P to plants in highly weathered soils is low because of the transformation of most of the native and / or added P into Fe- and Al- bound forms (Dabin, 1974). The relationship between total P and Fed and Ald are shown in Figures 5.8 and 5.9, respectively.

Total P appears to be closely bound to free iron in all the soils (Fig 5.8), except in the Tingoli series. This confirms the view that highly weathered soils may have high total P and Fed contents and that not all the phosphorus is bound to the iron (Taylor and Schwertmann, 1974). The highly significant correlation for the total P versus Fed and Ald plots (Figs. 5.8 and 5.9) suggests that total P saturation is controlled by Ald in all the soil, except in the Tingoli series.

Poorly crystalline forms of iron (Feo) and aluminium (Alo) are also influential in phosphorus saturation, especially in the Tingoli series ($TP = 199Feo + 8.8$; $r = 0.96^{**}$) and the Tolon series ($TP = 222Alo + 61$; $r = 0.83^*$). This implies that in the highly weathered environments, it is the oxalate extractable Fe and Al which control the saturation of P in the soils (e.g. Tingoli series). In the Tolon, Kumayili and Changnalili series, however, both DCB and oxalate extractable Fe and Al are influential in controlling the P

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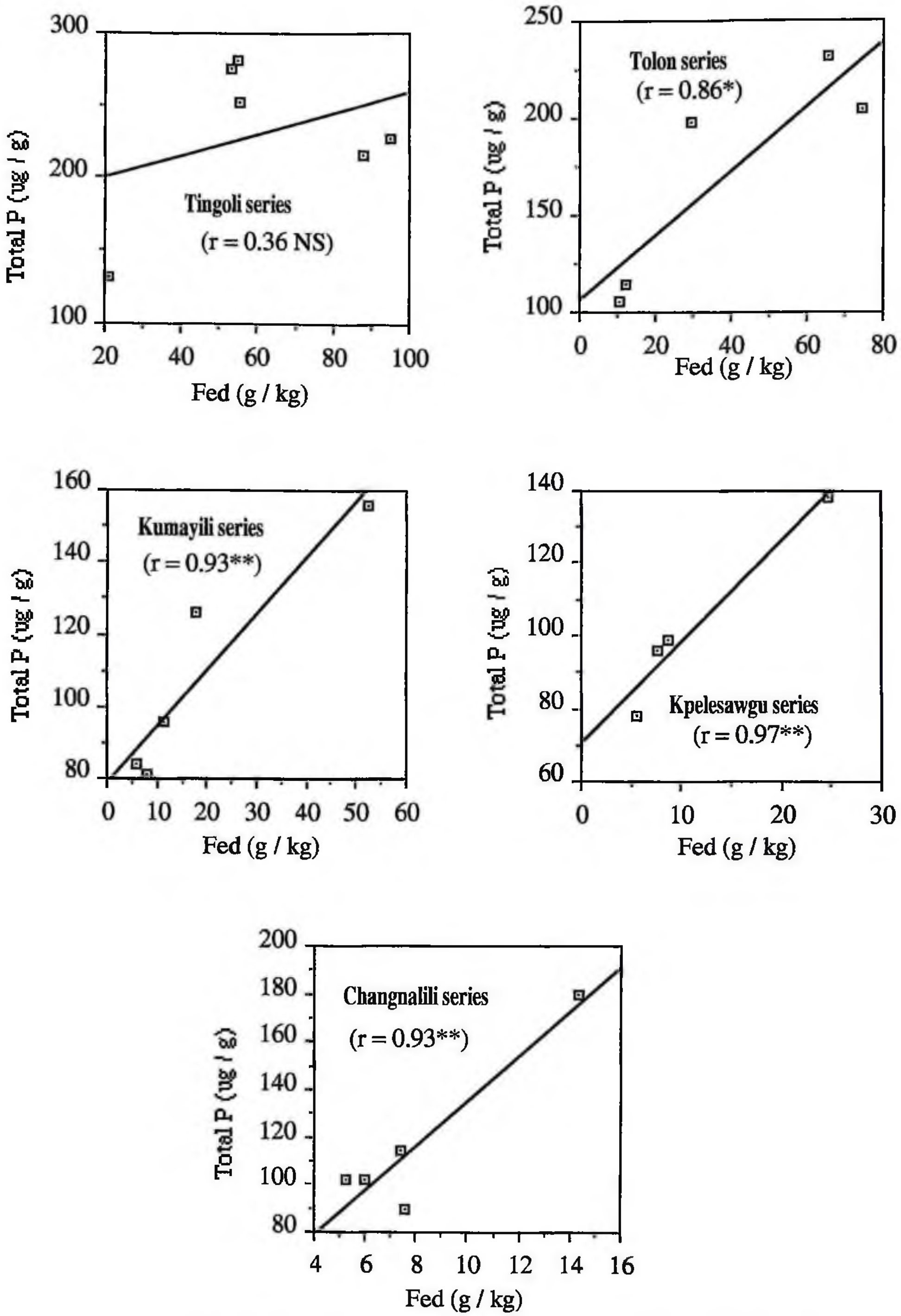

Fig. 5.8. Relationship between total P and Fed. (* and ** denote significance at P = 0.05 and 0.01, respectively; NS = not significant).

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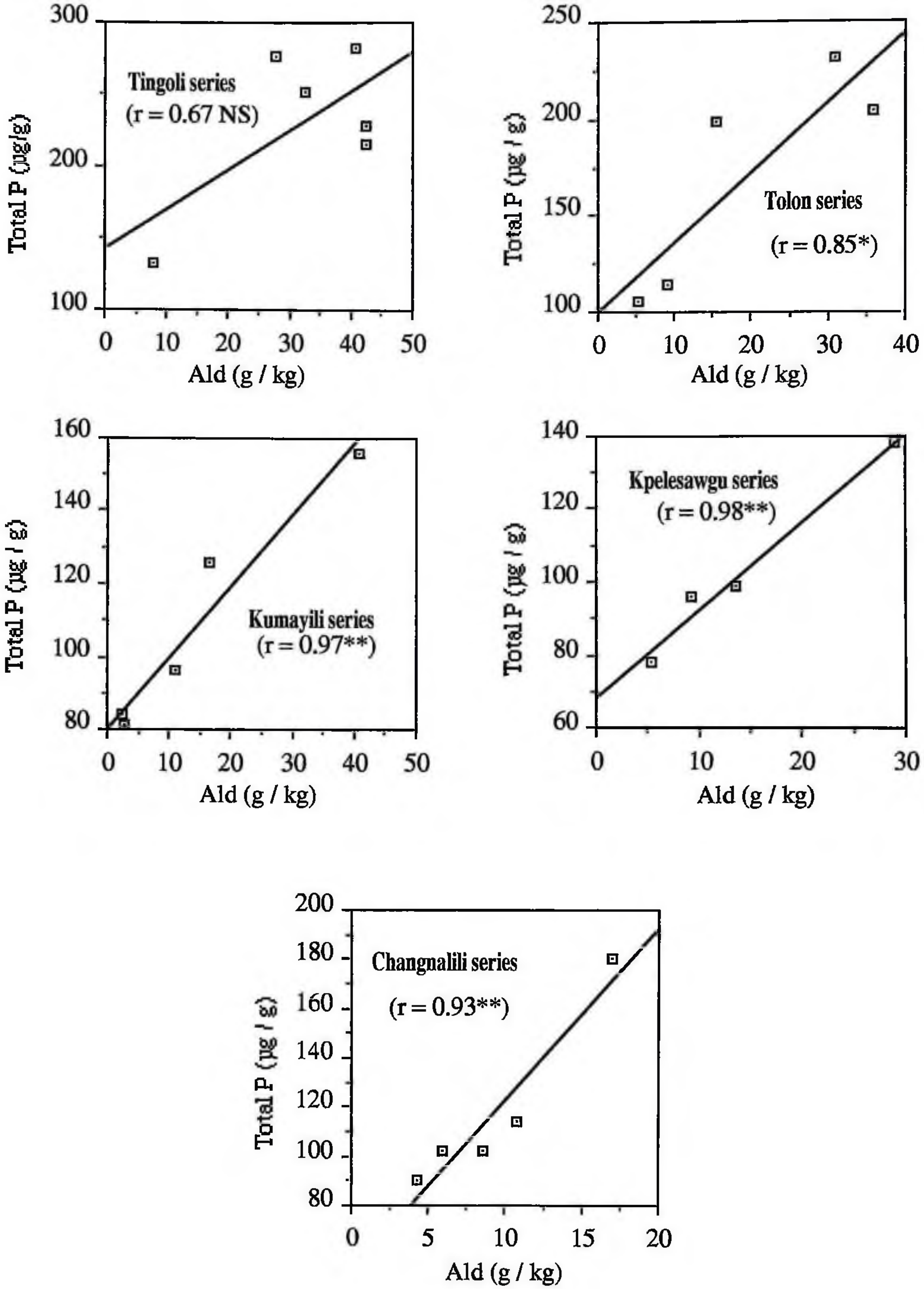

Fig. 5.9. Relationship between total P and Ald. (* and ** denote significance at P = 0.05 and 0.01, respectively; NS = not significant).

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saturation. In the Kpelesawgu series on toposequence 2, total P saturation is also controlled by oxalate extractable Al.

The total P saturation in the nodules of the two concretionary soils on toposequence 1 seems to be controlled by both the crystalline and poorly crystalline forms of Fe and Al. In these soils, the iron and aluminium oxides serve as more efficient sink for P, probably because of their low moisture relationship. The good aeration in the well drained soils provide oxidising conditions which promote the formation of Fe and Al oxides. These oxides then serve as suites for P sorption. In the poorly drained soils on toposequence 2, oxide formation is not enhanced because of wetter conditions, hence total P saturation remains low as noted by Schwertmann and Fanning (1976) in some concretionary soils elsewhere.

5.6.2 Total P and particle size

In all the soils, TP accumulation in the clay fraction is greater than in the silt fraction. This is in agreement with previous reports on the relationship between TP and particle size (Lekwa and Whiteside, 1986; Day et al., 1987). Hanley and Murphy (1970) suggested that a meaningful way to determine the role of particle size on TP saturation is by comparing the contribution by silt and clay size separates to the TP status of soils. The calculated values are given in Table 5.6.

The data show that clay is a more important contributor to the soil TP pool. The clay fraction contributes over 90% of the TP in all the well drained soils on toposequence 1. In the imperfectly drained and poorly drained soils on toposequence 2, the contribution by clay is still high (about 88% on the average). This trend can be explained by the fact that the Fe and Al oxides, which act as sites for phosphorus sorption, are concentrated more in the clay fraction.

The contribution by silt is far less in all the soils (< 20%). The Changnalili series shows the highest contribution to total P by the silt fraction. This relatively high

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Table 5.6. Relative contribution to total P by the silt and clay fractions.

Depth (cm)	Particle size distribution		Total P		Proportion of Total P*	
	silt	clay	silt	clay	silt	clay
	-----------%	-----------	-------µg/g	-------	---------%	------------
			Tingoli series			
0-16	8.1	21.9	91.9	744.6	4.4	95.6
16-32	7.9	32.2	95.5	588.8	3.9	96.1
32-48	7.7	49.1	66.7	491.4	2.1	97.9
48-67	10.6	36.7	203.5	464.3	11.2	88.8
67-98	8.9	44.9	163.1	332.3	8.9	91.1
98+	8.8	50.6	131.4	398.5	5.4	94.6
			Tolon series			
0-14	7.9	21.5	66.0	457.0	5.1	94.9
14-30	12.4	25.2	58.0	469.1	5.8	94.2
30-54	15.4	36.3	92.5	454.2	8.0	92.0
54-76	6.3	47.2	107.9	431.0	3.3	96.7
76-100	7.3	31.9	139.3	373.5	7.8	92.2
			Kumayili series			
0-18	8.0	19.2	61.9	380.9	6.4	93.6
18-36	11.8	23.9	53.0	363.0	6.7	93.3
36-57	15.9	29.5	53.9	315.9	8.4	91.6
57-90	15.5	39.0	58.0	323.5	6.6	93.4
90+	13.8	49.3	100.2	264.0	9.6	90.4
			Kpelesawgu series			
0-15	15.0	21.5	50.4	259.2	12.0	88.0
15-34	18.5	30.3	46.9	287.2	9.1	90.9
34-64	22.6	42.9	52.9	268.5	9.4	90.6
64-100$^+$	25.9	32.1	74.4	268.1	18.3	81.7
			Changnalili series			
0-12	22.7	20.3	58.2	432.5	13.1	86.9
12-24	20.9	28.2	64.5	348.5	12.0	88.0
24-37	22.0	33.4	101.8	343.9	16.3	83.7
37-57	24.6	40.5	87.2	371.7	12.5	87.5
57-100$^+$	12.6	61.0	63.7	198.2	6.2	93.8

* calculated as: $\frac{\text{total P in silt or clay x \%silt or clay.}}{(\text{total P in silt x \%silt}) + (\text{total P in clay x \%clay})} \times 100\%$

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contribution is the result of greater accumulation of silt in this soil. This agrees with the observation in other low lying soils elsewhere (Syers et al., 1969).

It has been noted that the total P saturation in soils increases with increasing clay content (William and Saunders, 1956; Acquaye and Oteng, 1972) which suggests co-migration of clay with phosphorus. Figures 5.10 and 5.11 show that the clay and silt translocation can be used to assess the relative accumulation of total phosphorus in soils on different landscape positions. The significance of this relation may lie in the ease with which the total phosphorus saturation of soils can be predicted from routine particle size distribution data. The accumulation of clay may be used to predict total P levels in well drained soils whilst silt content can be used for poorly drained low lying soils.

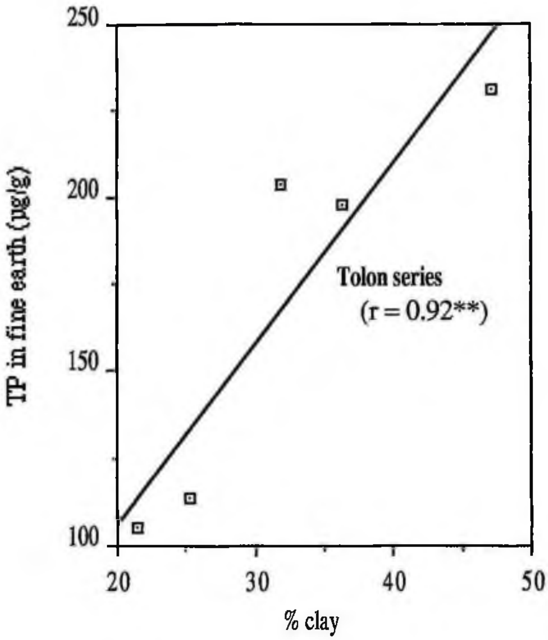
5.6.3 Total phosphorus and drainage

The total phosphorus content is generally lower in the soils on toposequence 2 than in those on toposequence 1. The poorly drained soils on toposequence 2, which occur in low lying areas, become waterlogged especially during the wet season. This predisposes them to leaching losses of phosphorus especially inorganic P. There is evidence of leaching of P from soils associated with oxidising and reducing conditions brought about by a fluctuating water table (Glenworth, 1947).

As slope or relief increases, drainage improves which leads to a decrease in calcium phosphates concentrations. This subsequently results in an increase in both occluded and non-occluded P and, therefore, TP (Hsu and Jackson, 1960). This may, in part, account for the different levels of P saturation in the soils on toposequence 1. The midslope Kumayili series has the least amount of TP compared to the upland end member, Tingoli series, which has the greatest total P saturation.

5.7 Classification of the soils

Soils classified in different great soil groups have been shown to vary in total phosphorus distribution with depth (Pearson and Parker, 1949). It is, therefore, important



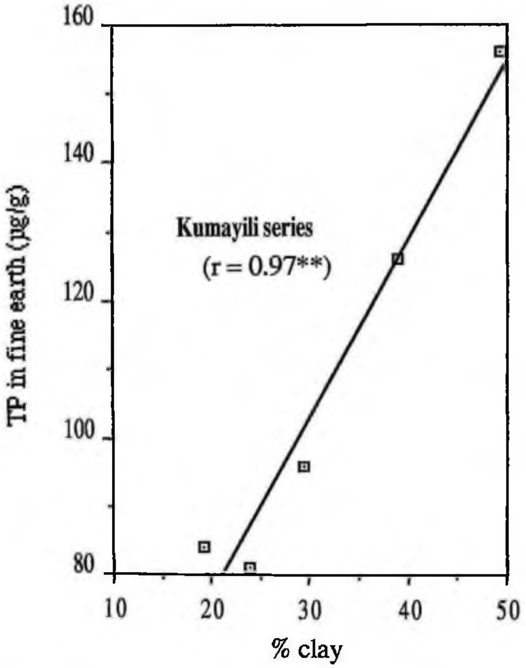


Fig. 5.10. Relationship between total P in the total fine earth and clay content. (** = Significant at P = 0.01).

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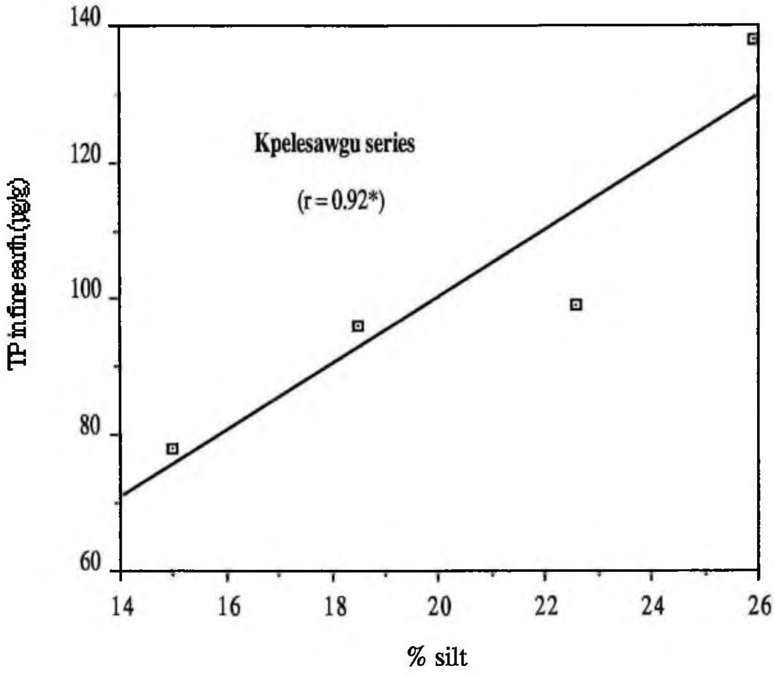

Fig. 5.11. Relationship between total P in the total fine earth and silt content. (* = Significant at P = 0.05).

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to classify soils to help in monitoring the distribution of P.

The FAO-UNESCO (1990) Legend defines Lixisols as follows "Soils having an argic B horizon with a cation exchange capacity (clay) of less than 24 cmol (+) kg^{-1} at least in some parts of the B horizon and a base saturation of 50 % or more throughout the B horizon; absence of a mollic A horizon; absence of an E horizon which abruptly overlie a strongly permeable horizon and which lack the distribution pattern of the clay and the tonguing diagnostic for Planosols, Nitisols and Podzoluvisols".

When the morphological characteristics and the physical and chemical properties (Table 5.7) are considered, the soils studied can be classified as Lixisols. The upland Tingoli and Tolon series have common nodules within 125 cm of their surface. They also lack an albic, gleyic and stagnic properties within 100 cm of the surface. These soils can, therefore, be classified as Plinthic Lixisols. The Kumayili series has few nodules which are confined below 90 cm of the profile. The exteriors of these nodules are indurated with iron and have redder hues than the interior. The Kumayili series also lacks gleyic and stagnic properties within 125 cm of its surface. The Kumayili series can thus be classified as a Ferric Lixisol.

The Kpelesawgu and Changnalili series have appreciable amounts of nodules within 125 cm of their profiles. The profiles of these two soils lack albic E horizons and in addition do not have both gleyic and stagnic properties within 100 cm of their surface. Based on these properties, the Kpelesawgu and Changnalili soils can be classified according to FAO-UNESCO (1990) as Plinthic Lixisols.

Soils which have either an argillic, kandic or a natric horizon or a fragipan that has clay films 1 mm or more thick in some part of the profile have been generally classified as Alfisols (Soil Survey Staff, 1994). All the soils in this study have argillic properties and can, therefore, be classified as Alfisols. The Tingoli, Tolon and Kumayili series have ustic moisture regimes and are therefore Ustalfs. The Kpelesawgu and Changnalili series have aquic moisture regimes and are thus Aqualfs.

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Table 5.7. Clay content, ECEC and base saturation.

Depth (cm)	clay (%)	ECEC (total soil) (cmol (+) / kg)	ECEC (clay) (cmol (+) / kg)	BS† (%)
		Tingoli series		
0-16	21.9	2.78	12.69	94.9
16-32	32.2	3.29	10.23	97.1
32-48	49.1	4.34	8.85	94.8
48-67	36.7	3.70	10.08	96.1
67-98	44.9	3.95	8.79	87.8
98+	50.6	4.57	9.03	86.7
		Tolon series		
0-14	21.5	3.71	17.23	96.1
14-30	25.2	2.85	11.23	93.4
30-54	36.3	4.11	11.34	95.4
54-76	47.2	5.49	11.62	96.7
76-100	31.9	4.49	14.08	95.7
		Kumayili series		
0-18	19.2	1.19	6.21	74.8
18-36	23.9	1.90	7.93	90.5
36-57	29.5	2.45	8.31	92.5
57-90	39.0	3.68	9.42	93.6
90+	49.3	6.29	12.76	96.9
		Kpelesawgu series		
0-15	21.5	1.70	7.9	79.1
15-34	30.3	2.17	7.16	68.5
34-64	42.9	2.26	5.27	63.5
64-100+	32.1	3.01	9.38	74.1
		Changnalili series		
0-12	20.3	3.38	16.66	97.1
12-24	28.2	4.20	14.88	92.3
24-37	33.4	4.63	13.85	94.9
37-57	40.5	6.23	15.37	96.9
57-100+	61.0	13.45	22.05	87.1

† BS = Base saturation (in total soils).

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Ustalfs which have one or more horizons within 150 cm of the mineral surface, in which plinthite either forms a continuous phase or constitutes one half or more of the volume, are classified as Plinthustalfs. The Tingoli and Tolon series have these properties and may be placed under the Plinthustalfs Great Group. The Kumayili series qualifies to be a Haplustalf as it has few nodules in its profile and does not pass for a Natrustalf, Kandiustalf, Paleustalf, Kanhaplustalf or a Rhodustalf. The Changnalili and Kpelesawgu series have plinthite between 30 and 150 cm from their mineral surface and, therefore, qualify as Plinthaqualfs.

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CHAPTER SIX

SUMMARY AND CONCLUSIONS

The study has shown that the well-drained upland soils have greater accumulation of nodules because of prevailing favourable environmental conditions. There is a higher clay content in the soils on toposequence 1 than in the soils on toposequence 2. The parent materials from which the soils developed are not uniform across the two landscapes due to the previous erosion cycles in the area.

The soils on toposequence 1 generally lack weatherable minerals due to intense weathering. The clay mineralogy of the toposequence 1 soils is dominated by kaolinite whilst the poorly drained soils on toposequence 2 have illite in addition to kaolinite. Haematite and goethite are the major minerals in the nodules. There is no apparent difference in pH and in cation exchange capacity of the soils and their respective associated nodules indicating that the nodules may have been formed *in situ.*

It is apparent from the study that distinct differences exist in the two landscapes particularly in the Fed, Ald and P contents. The Fed and Ald contents are higher in the soils on toposequence 1 than in those on toposequence 2. The pattern of Fed distribution is closely similar to clay distribution in the toposequence 1 soils whilst the Fed is related to the silt contents in the low-lying soils. Crystallinity of the free metal oxides and oxyhydroxides is also higher in the soils on toposequence 1 than in those on toposequence 2. In the toposequence 1 soils, crystallinity is in an order of Tingoli series > Tolon series > Kumayili series whereas in the soils on toposequence 2 Kpelesawgu series has a higher crystallinity than the Changnalili series. Crystallinity in the various fractions studied follows the order nodules > clay > total fine earth > silt.

Weathering is more intense in the toposequence 1 soils than in the toposequence 2 soils and is highest in the Tingoli and Tolon series. Maturity of the soils, as indicated by the high Fed/Fet, low silica/sesquioxide and low silt/clay ratios and higher TiO_2 contents in the clay fraction, is also higher in the well-drained soils than in the low-lying soils.

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Total phosphorus in the soils follows a profile concentration sequence of Tingoli series > Tolon series > Kumayili series > Changnalili series > Kpelesawgu series. The available P content is highest in the Changnalili series because of its relatively low Fed and Ald contents. Total P and DCB-P are related to maturity in the soils on toposequence 1. However, in the soils on toposequence 2, TP and DCB-P are related to drainage. Total P and DCB-P in all the soils are highest in the clay fraction and the <2mm size nodules.

The Fed contents in the nodules (> 2mm size) and nodules (< 2 mm size) are higher than those in the clay fraction. However, the TP concentrations in the clay fraction is higher than those in the > 2mm size nodules but comparable with the values in < 2mm size nodules. The <2mm size nodules show higher levels of P saturation because of their larger surface area. Total P saturation in the well-drained Tolon and Kumayili series is controlled by clay content as well as the DCB and oxalate-extractable forms of Fe and Al. In the Tingoli series, TP is controlled by only Feo and Alo. In the Kpelesawgu series on toposequence 2, TP saturation is controlled by the silt, Fed, Ald and Alo contents. In the Changnalili series the TP saturation is controlled by both DCB and oxalate extractable forms of Fe and Al.

The data also indicate that oxalate Fe and Al control the saturation of P in the fine earth fraction of the soils. It also appears that poorly crystalline forms of Fe and Al oxides and oxyhydroxides control the P saturation and distribution in all the soils. However, as nodules are formed the P saturation tends to be controlled by both crystalline and poorly forms of the iron and aluminium oxide minerals.

The Tingoli series, Tolon series, Kpelesawgu series and Changnalili series can be classified as Plinthic Lixisols whilst the Kumayili series falls under Ferric Lixisol in the FAO-UNESCO system. With Soil Taxonomy, the well-drained Tingoli and Tolon series are Plinthustalfs whereas the Kumayili series can be classified as Haplustalf. On the other hand, the low-lying soils on toposequence 2 all qualify as Plinthaqualfs.

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It has become evident from the study that P saturation in the soils is controlled by a combination of factors. These include the clay content in the well-drained soils and silt in the low-lying soils as well as nodule concentration. It is, therefore, suggested that future studies on P availability should also focus on clay and silt translocation as well as accumulation of nodules within and across landscapes. The factors which affect phosphorus saturation should also be considered when devising strategies for the use and management of these ferruginous soils for sustainable agricultural production.

CHAPTER SEVEN

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