CHARACTERISATION OF THE SOILS OF MASHURU AREA WITH RESPECT TO THEIR GENESIS AND CLASSIFICATION

BY

FENDO M. SHITAKHA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

FmShitakha 3/4/2000

FENDO M. SHITAKHA

This thesis has been submitted for examination with our approval as university supervisors.

Signature: 4/4/2000

Prof. J.P. Mbuvi

Signature: 17/11/2000

Dr. Kithome Musolini

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ABSTRACT

Soils are a component of the ecosystem vital for the maintenance of the land-based life-support systems and hence, reliable soil information is essential in planning for sustainable development and environmental conservation. Nevertheless, reliable soil information required for development planning is scarce. A semi- detailed soil survey of an area in Mashuru division, Kajiado district was conducted with the principal objective of mapping and characterizing the soils. Specifically, the morphology, mineralogy, physical and chemical properties of the soils were studied. The soils were classified according to FAO/UNESCO (1994) and SOIL SURVEY STAFF (1992) versions. The survey provides information on the area's major soil types and their distribution. A physiographic soil map at scale 1:50,000 is presented while interpretative soil information is presented in Tables.

The soils mapped in the area include Ferralsols, Vertisols, Cambisols, Leptosols, Acrisols, Luvisols and Lixisols. Ferralsols are found on uplands and erosional plains. Shallow Leptosols occur on the hills and scarps while brownish sandy clay to clay Acrisols occur on the footslopes. Luvisols are found on uplands and on volcanic plains while Lixisols are found on erosional plains. The saline-sodic Vertisols are found in the bottomlands whereas Cambisols occur on the piedmont plains and volcanic plains. Based on parent material, relief, climate and soil characteristics, four genetical groups of soils have been identified in the area. The Vertisols with high sodium contents and unique physical properties constitute the first group. Ferralsols and Cambisols with an irregular clay distribution in the profile form the second group. The Acrisols, Luvisols and Lixisols constitute the third group because of the higher clay contents in the subsoils. The last group consists of the shallow Leptosols. These soils are developed on various volcanic rocks and basement system rocks and occur in agro-climatic zone V.

The soil forming factors of parent material (geology), climate (past and present) and relief have played a significant role in the morphology, chemical and physical properties of the soils of the area.

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CHAPTER ONE: INTRODUCTION

1.1 General introduction

The Arid and Semi-arid Lands (ASAL) in Kenya comprise about 455,408 km^2 which is more than four-fifths of the country's total land surface and support over 35% of the total human population (Darkoh, 1990). Rainfall reliability in these semi-arid areas is very low, sporadic and always punctuated with constant failures and continued drought.

The study area is located in Mashuru Division of Kajiado District. The area is an ASAL and is approximately 15km from Emali town along the Emali-Loitokitok Road. The area lies between longitudes $37^0 25^1$ and $37^0 30^1$E and latitudes $2^0 05^1$ and $2^0 15^1$S. The project area has a ratio of mean annual rainfall to mean annual evaporation (r/E_o) of 0.25-0.40 placing it in agro-climatic zone V. The average annual rainfall is in the range of 500-600 mm and mean annual temperature is 18-20^{0}C (Sombroek *et al.*, 1982). Major limitations to crop production include rainfall, husbandry techniques and soil fertility.

Due to a limited acreage of farmland and a high population increase rate of 3.4% (National Development Plan, 1997-2001), Kenya is currently facing land scarcity. The high rate of population increase is causing pressure on land especially in the high rainfall areas. As a result, there has been a recent acceleration of migration into the ASAL. This often leads to land degradation and crop failure due to unreliable rainfall and unfavourable soil conditions. To keep up with a population growth rate of 3.4%, food production must increase at the same rate or higher. It is becoming increasingly difficult to maintain such food production rate because the rainfed areas are already overpopulated and overused. In order to attain self-sufficiency in national food requirement, the Kenya Government drew up a national food policy in the session paper No 1 of 1996, outlining the objectives, constraints and strategies of maintaining a position of broad self-sufficiency in production of the main foodstuffs so as to enable the nation to be fed without using scarce foreign exchange on food imports. A feasible alternative is to open up semi-arid areas for agricultural production. Unfortunately, these are the areas that have the so called "problem soils" (Muchena, 1982). The problems in these regions include crusting, impeded drainage, salinisation, sodification and low rainfall. These areas were formally designated as ranching zones with very fragile ecosystem. An alternative use of such an environment requires careful planning and proper management.

Soils should be considered at all levels of land related planning. No meaningful agricultural development can take place without proper knowledge of soils. Soil survey can provide information on soil characteristics and their distribution. It involves the description and characterization of soils as they occur naturally in the environment, their classification and location on a map. The soil data, maps and classification enable the environment to be characterized so that an interpretation can be made from the data about the suitability, capabilities and limitations of areas of land for various uses. Using soil maps, soil and land resources can be managed properly in order to achieve optimum yields of specified crops. Soil losses through erosion can also be predicted and control measures established where losses are excessive. Soil data gathered from soil surveys can also be used for correlation purposes with other areas of similar environment.

Kenya Soil Survey section of the Kenya Agricultural Research Institute carries out soil surveys in the country both for national planning and for land utilization. Among the many duties assigned to the Kenya Soil Survey is soils research with a view to the identification of constraints for optimal agricultural production which is currently a matter of national importance. Constraints include soil parameters such as acidity, toxicity, salinity, sodicity, erodibility, lack of foot hold, unavailability of moisture and soil nutrients and unfavourable soil mechanical characteristics.

As part of the Kenya Soil Survey work programme, Kajiado District was selected for a reconnaissance soil survey starting in Mashuru Division. The area has been under group ranches and is currently being converted to small scale farming involving growing of maize, beans, potatoes, onions and tomatoes. Because this is done without proper knowledge of soils, there is an urgent need for soil information in this low rainfall area in order to assess the hazard of land degradation and at the same time introduce appropriate technologies and management practices for sustained agricultural production.

1.2 Background to the study area

The study area is confined within agro-climatic zone V which is semi-arid (Sombroek *et al.*, 1982). Analysis of rainfall data for the two wet seasons indicate that the study area receives about 50% of the total annual rainfall during the March-May seasons and 30% during October to December season (Kajiado District Development Plan, 1997-2001). The general topography is characterized by plains and volcanic hills. The plains are dissected by several valleys. Group ranching has been the main land use until recently. The semi-arid climate does not only affect the type of agriculture that can successfully be practiced in the area but also poses a problem on soil conditions. The high temperature favour rapid decomposition of organic matter when the soil is ploughed. Removal of vegetative cover exposes the soil to high evapotranspiration rates removing some of the water that would have been used by plants. The solution to these problems is management methods appropriately designed for them e.g. mulching.

Severe water shortages pose a major constraint to agricultural production. The area is served by Noilturesh water pipeline and supplemented by boreholes, shallow wells and water pans. Most of the boreholes are non operational due to poor maintenance and management. The water sources available are not protected and as a consequence, water for domestic use is fetched at the same source where livestock is watered.

Except for the Emali-Simba tarmac road, the study area is poorly accessed. The Emali-Loitokitok road is in a poor state and hence more access roads are required in the newly sub-divided group ranches to allow access of farm produce to the market.

The existing soil map of the area is of a small scale (1:250,000), Touber (1983). This scale of mapping is not adequate for proper land use planning at the farming level, hence the reason for the current study at a large scale 1:50,000.

1.3 The study objectives

The broad objective of the current study was to map and characterize the soils of Mashuru area of Kajiado District. The underlying principle is that soil is a component of the ecosystem vital for the maintenance of the land-based life-support systems and hence, reliable soil information is essential in planning for sustainable development and environmental conservation.

The specific objectives are:

1. To identify and map the soils and other terrain features of the area
2. To characterize the soils in terms of their physical and chemical properties and mineralogical composition
3. To classify the soils according to the two international systems used in East Africa i.e. FAO/UNESCO and USDA soil classification systems

To achieve these objectives, a semi-detailed soil survey was conducted in the study area. A physiographic soil map at scale 1:50,000 (appendix 2) was produced and interpretative soil information is presented in Tables. This information is intended to contribute to long-term understanding and planning for sustainable management in the project area.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The term 'pedology' is used widely throughout the world but in different contexts. In the European sense, pedology has been used synonymously with 'soil science' (Buol *et al.*, 1989). The same author defined pedology as 'a phase of soil science that deals with factors and processes of soil formation including description and interpretation of soil profiles, soil bodies and patterns of soil on earth's surface. The concept of pedology as used in this review is the science of soil development (Sposito & Reginato, 1992). More specifically pedology is defined herein as 'that component of earth science that quantifies the factors and processes of soil formation including the quality, extent, distribution, spatial variability and interpretation of soils from microscopic to megascopic scales".

Pedology is both an interpolative and extrapolative science (Wilding, 1986; Sposito & Reginato, 1992). The discipline provides a hierarchical framework to integrate components of soils (e.g., mineral structures, mineral-organic complexes, soil aggregates, and soil horizons) into basic soil individuals called pedons. Pedons are assembled into toposequences, which in turn comprise regional physiographic units that collectively represent the pedosphere or global soil cover. Pedology provides the basic framework to examine soils at various scales of resolution using different methodologies so that the system can be viewed in holistic terms for component integration and system extrapolation (Arnold, 1991).

Dokuchaev (1883) established that soils develop as a result of the interplay of the five factors i.e. parent material, climate, organisms, topography and time. The first four are the tangible factors reacting through time to create a number of specific processes leading to horizon differentiation and soil formation. The pioneering work of Jenny (1941, 1980) demonstrated methods by which the soil system could be quantitatively investigated. It gave forth to a more scientific approach by synthesizing conceptual ideas into a mathematical syllogism - a more scientific grounding to pedology.

Smeck *et al.* (1983) comprehensively evaluated the strengths and weaknesses of pedogenic models including the factorial analysis model of Jenny (1941). The factorial model states that soil (S) is a function of climate (cl), organisms (o), topography (r), parent material (p) and time (t). It is expressed as

$$S = f(cl, o, r, p, t, \ldots)$$

where the dots indicate additional unspecified factors. Accordingly, the factors define the soil in terms of controls on pedogenesis and soil distribution factors.

Jenny (1941) originally hoped that the equation could be reformulated into quantitative expressions which could be solved to predict soil types and properties on the basis of state factors. This has proved to be difficult, and likely impossible, because of difficulties in quantifying the broadly-defined factors, the interdependence of all but the time factor (Yaalon, 1975), and because in its most general formulation the system is undetermined (Phillips, 1989). An inability to 'solve' this equation does not diminish the utility of the state factor model as a conceptual framework (Birkeland, 1984; Phillips, 1989; Amundson and Jenny, 1991).

Perhaps one of the major limitations of the state factor model as viewed from breakthroughs in modern pedology is the recognition and general acceptance that soils are developed along polygenetic pathways, on dynamically evolving landforms under the influence of paleoclimates, in non-uniform parent materials and through combinations of processes (Simonson, 1978; Wilding, 1986). This has enhanced the morphogenetic model of soil and moved us farther from purely genetic concepts. This backdrop serves as a yardstick in evaluating possible constraints of Jenny's factorial model. The following should be considered as limitations to the model:

1. Independence of state factors.
2. Extension to older landforms.

3. Polygenetic pathways of soil genesis.
4. Factor interchangeability.
5. Anthropogenic influences.
6. Knowledge of precise processes.
7. Difficulty in testing and validating models.

Application of factorial model to recent or late Quarternary landforms probably has the best opportunity for success. Extension to older landforms are more risky because of greater probability of factor interactions and multiple polygenetic pathways of soil genesis (Simonson, 1978). Examples of this have been reported by Wilding and Flach (1985) for many properties and diagnostic horizons in soils including: albic, spodic, cambic, argillic and calcic.

The human influence confounds factor variables - liming, drastically disturbed lands, drainage of wetlands, compaction, irrigation, salinity/sodicity (Fanning & Fanning, 1989). Anthropogenic influences on pedogenesis were not outside the scope of the first text by Jenny (1941) but were given more prominent consideration in his last text (Jenny, 1980).

It is not easy to rigorously reconstruct the time effects on pedogenesis (Van Cleave *et al.*, 1991). Numerous chronosequences have been offered in literature (e.g. Birkeland, 1984), but establishing such effects on resultant soil attributes are still open to question.

2.2 Geographical location and communication

The study area is situated between longitudes 37^0 25' and 37^0 30'E and latitudes 2^0 05' and 2^0 15'S. It covers an area of about 216 km^2 within Mashuru division of Kajiado district. The area lies between Simba and Emali and is about 15 km from Emali along the Emali - Loitokitok road. The area is found on topographical map sheet Nos 174/1 (Simba) and 173/2(Sultan Hamud) scale 1: 50,000 (Survey of Kenya, 1974).

The area can be accessed using the Emali - Simba tarmac road. Also, the Emali - Loitokitok road traverses the area in a North - South direction. The Mombasa rail line passes through Simba and Emali on its way to Nairobi. The access roads are suiTable only for four wheel drive vehicles. Figure 1 shows the location of the study area.

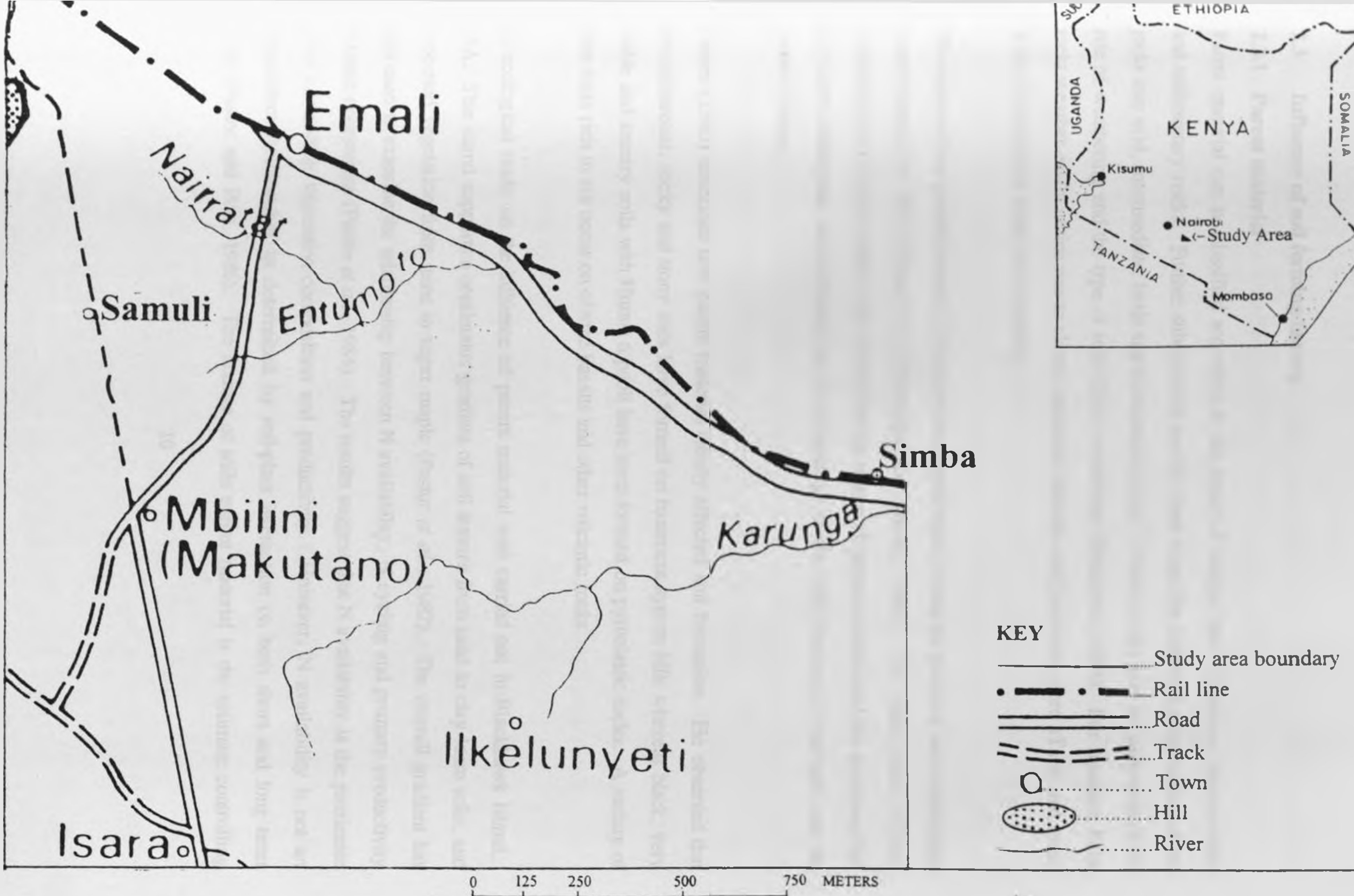

Fig. 1: Location Map of the Study Area

2.3 Influence of soil forming factors

2.3.1 Parent material

Parent material can be classified according to the mode of origin, that is igneous, metamorphic and sedimentary rocks. Further subdivisions can be done using the chemical composition of the rocks into acid, intermediate, basic and ultra-basic groups. These groups give an indication of the rate of weathering and the type of soils likely to develop (Birkeland, 1984). For instance, basic rocks weather easily giving rise to clayey materials whereas acid rocks are more sTable and result in the formation of sands on weathering.

The nature of the parent material influences the morphologic, chemical, physical and mineralogic characteristics of the resultant soils (Wanjogu and Mbuvi, 1995). In their study of two catchments in Laikipia district, they found that the nature of parent material and the processes that they have undergone were reflected in the mineralogy of the sand fraction of the soils and the textural breaks.

Touber (1983) described how parent material clearly affected soil formation. He observed that non-calcareous, rocky and stony soils have formed on basement system hills whereas black, very friable and smeary soils with Humic topsoil have been formed on pyroclastic rocks. A variety of other soils rich in silt occur on olivine basalts and other volcanic rocks.

An ecological study on the influence of parent material was carried out in Blackhawk Island, USA. The island supports a continuous gradient of soil texture from sand to clay loam soils, and associated vegetation from pine to sugar maple (Pastor *et al.*, 1982). The overall gradient has been used to examine the relationship between N availability, N cycling and primary productivity in forest ecosystems (Pastor *et al.*, 1984). The results suggest that N availability is the proximate factor controlling vegetation composition and productivity. However, N availability is not an independent factor-rather its determined by soil-plant interaction on both short and long term scales (Pastor and Post, 1986). The texture of soils parent material is the ultimate controlling factor; its effect on N availability is mediated through the effects of soil texture on moisture availability and of clay content on the stabilization of soil organic matter (Parton *et al*; 1987).

Soils developed from volcanic materials are known to have morphological, chemical and physical properties different from those of other mineral soils developed under similar climatic conditions (Wada, 1985). In addition to a low bulk density, these soils are often characterized by surface areas as high as 600 m^2g^{-1} and are capable of retaining 40 to 142% water expressed on an oven-dry weight (Maeda *et al.* 1977). They have high phosphate retention and organic C (Shoji and Ono, 1978). These unique properties are commonly associated with the presence and abundance of amorphous constituents and/or metal-humus complexes (Wada, 1980). Mohr *et al.* (1972) describes volcanic ash deposits (ash, pumice, tuff) as parent materials that probably control soil formation more than any other parent materials. Although they develop into Andosols, other soils such as Ferralsols form on old volcanic ash. An important but often undetected effect of parent material is the effect of volcanic eruptions on soils downwind of the eruptive centres. The effect was studied in the Kisii area (Wielmaker, 1979; Wielmaker and Boxem, 1982) where it was found to be very extensive and very important for soil formation. In Kiboko area (Michieka and Van der Pouw (eds.), 1977) reported a very limited volcanic ash influence north of the Chyulu Hills. Under conditions of relatively flat topography without free drainage, volcanic ash enrichment may contribute to the formation of fine textured soils with Vertic properties.

Birkeland (1984) observed that parent material influenced many soil properties to varying degrees. It's influence is greatest in drier regions and in the initial stages of soil development. In wetter regions, and with time, other factors may overshadow the influence of parent material. Parent material, whether mineral or rock, exerts some control on the clay minerals that form because weathering releases constituents essential to the formation of the various clays (Sposito and Regnato, 1992). Parent material act on soil formation via its texture and chemical composition. Parent materials with a fine texture, and consequently low permeability, give rise generally to shallow soils. Permeable parent material are favourable for the formation of deep soils. Materials consisting of resistant minerals such as quartz, orthoclase, microline, biotite and muscovite resist soil formation considerably and give rise to shallow soils (van Reeuwijk, 1994). In the opposite direction act materials with easily weatherable minerals, such as plagioclases, olivine, leucite, augite, hypersthene and volcanic glass.

According to geological surveys carried out between 1953 and 1956 (Searle, 1954 and Saggerson, 1963) the rocks of the area can be subdivided into Basement System rocks and Quaternary volcanics.

The Precambrian Basement System rocks consist of gneiss which can be sub-divided into gneisses that are poor in ferro-magnesian minerals and gneisses rich in ferro-magnesian minerals (Searle, 1954 and Saggerson, 1963). The former are composed of mainly quartz-feldspar and granitoid gneiss, chemically poor Basement system rocks. Due to their relative hardness they form most of the hill masses in the project area. The gneisses rich in ferro-magnesian minerals include mainly biotite-hornblende, biotite and hornblende-garnet gneisses together with amphibolites. These chemically richer Basement System rocks occur in the eastern part of the project area (Searle, 1954 and Saggerson, 1963).

Volcanic activity has significantly enriched large areas of Basement System rocks with volcanic material. This enrichment coincided with major volcanic activities during the pleistocene time. It took place either directly, through deposition, or indirectly through redeposition (e.g. colluvia) of volcanic materials (Searle, 1954 and Saggerson, 1963). The volcanic cones and associated lavas of the Sultan Hamud - Simba area are considered as the north-westerly representatives of, and contemporaneous in age with, the Chyulu basalt range which lies to the south-east of the project area. Various olivine basalts of pleistocene age occur together with breccias, agglomerates and ashes in the Simba-Emali area.

2.3.2 Weathering and clay formation

Weathering is the process of disintegration and decomposition of rocks and minerals under atmospheric conditions (Niewenhuyse and Van Bremen, 1997). It transforms the original rock into soil parent material. Knowledge about mineral weathering and neoformation in soils is important for estimating (i) nutrient supply by weathering (Stoorvogel, 1993) (ii) accepTable annual soil loss by erosion (Wischmeier and Smith, 1978) and (iii) the rate of buffering of soils by acid rain (Van Grinsen, 1988). There are two forms of weathering: physical and chemical.

2.3.2.1 Physical weathering

Physical weathering is the process whereby rocks and minerals are cracked, crumbled, crushed and mellowed (Niewenhuyse and van Bremen, 1997). The result is a material that varies in size from boulders to very fine particles. The chemical composition of the rocks and minerals is not changed, hence, physical weathering is a mechanical disintegration of the solid mass that causes a change in shape, form and size of the rock and mineral debris (van Reeuwijk, 1994). Physical weathering is favoured by temperature variations, alternating heating and freezing, erosion agents such as moving water and wind, and by the activities of man and other living organisms. This kind of weathering is dominant in cold or desert climates.

2.3.2.2 Chemical weathering

Chemical weathering is the decomposition of the complex substances of rocks and minerals into compounds with a lower energy content (Niewenhuyse and Van Bremen, 1997). Some of these decomposition products dissolve and others are emitted as gases. The bulk of them, however, remain in place.

Chemical weathering gives rise to: (i) soluble material that are generally salts able to release ions which either become exchangeable or are leached; (ii) colloidal gels by hydration and polymerization of the heavy cations of aluminium and/iron (Bruijnzeel, 1990). The insolubilisation of these heavy cations, which is rapid in most soils, decreases in acid conditions rich in soluble organic matter, which favours complex formation; (iii) microcystalline entities with sheet structure (clays) which fix to their surface iron and aluminium hydroxides.

2.3.2.3 General processes of rock weathering

Hydrolysis is the result of the dissociation of water into H^+ and OH^- ions and consists of the separation of salts containing the union of a weak acid and or the cation of a weak base into the corresponding base and acid (Birkeland, 1992). This is the most important process of rock weathering. Other processes, which can be important in particular cases include: dissolution of saline rocks; hydration, which is the combination of solids with water to form hydrates; oxidation which causes the release of ferrous ions (Fe^{2+}) contained in certain primary minerals, so disrupting their crystal lattices (Jongmans, *et al.*, 1993). The process of reduction occurs more rarely but, under hydromorphic and badly aerated conditions, it is responsible for the solution of ferruginous sandstone cements and hence for their breakdown (Jongmans, 1994).

2.3.2.4 Weathering stability

Weatherability of the various minerals is very different. Some are very stable e.g. quartz, others offer only slight resistance, e.g. limestone. Differentiating the classes of weatherability in very unstable, unstable, moderately stable, stable, and very stable, it is possible to arrange the minerals in the following order (van Reeuwijk, 1994):

Very unstable	:	gypsum, limestone, dolomite
Unstable	:	olivine, anorthite
Moderately stable	:	augite, hormblende, plagioclase, albite, biotite
Stable	:	Orthoclase, Muscovite
Very stable	:	quartz, magnetite, titanite, ilmenite, tourmaline, clay minerals.

Weatherability depends on several factors:

a) The higher the silica content the higher the weathering stability.

b) The weaker the base (Na-->NaOH) the more unstable.

c) The higher the Fe^{2+} content the more unstable.

It is evident that weathering is a destructive process. However, parallel with this destruction, a building up process or synthesis may take place. It is possible that certain constituents, set free during weathering, react with each other, giving rise to secondary minerals (van Seeters, 1993). In this way, very important group of silicates, the clay minerals, are formed.

2.3.2.5 Clay formation

According to Van Seeters (1993) clay minerals are formed in two ways:

a) By rearrangement of the layer silicates (Phyllosilicates) muscovite and chlorite; the original structure of the silicate remains unaltered, while the ions between the elemental layers are dissolved and removed.

b) By decomposition of the silicates, such as feldspars, augite and hornblende into ions or colloidal substances, from which clay minerals may be synthesized.

Formation from layer-silicates

According to Van Reeuwijk (1994) the micas muscovite, biotite and chlorite are of importance with respect to clay formation. In the case of the micas, the K-ions are gradually replaced by H_30^+-ions and hydro-muscovite is formed. By further loss of K, illite is formed and if K is completely removed, a swelling illite results. At the same time, the particles decrease in size, however, structure is maintained. If the Mg-content in the weathering-solution is relatively high, which may happen during the weathering of biotite, vermiculite can be formed. According to Van Seeters (1993), in acid medium, vermiculite can take up Al or Fe-ions and form secondary chlorite. Chlorite loses Mg-ions upon weathering and forms vermiculte. Upon further removal of Mg, a swelling chlorite is formed. By uptake of Al, the process leads to the formation of secondary chlorite. The end-members are swelling minerals and resemble with respect to this property the montmorrilonite minerals. In the presence of K- and Mg-ions the minerals with swelling lattices can be transformed into illite, vermiculite and chlorite (Van Reeuwijk, 1994). The weathering of illite, vermiculite and chlorite is through a reversible process.

Formation from decomposition products of silicates

Feldspar and other silicates decompose completely upon weathering into ions or molecules. From these ions or molecules clay minerals can be synthesized, if conditions are favourable. This is especially probable under alkaline conditions, because then the silicate-ion and aluminate-ion can occur simultaneously. This alkaline reaction can be found during the hydrolysis of the silicates if the alkali- and alkali-earth metals are not removed rapidly. Under neutral conditions the silicate-ions polymerize into colloidal poly-silicic acid, while the aluminate-ions form colloidal $Al\ (OH)_3$. This latter substance can exchange OH-ions against silicate-ions, thus forming in first instance allophane. Upon frequent dessication and wetting and with the cooperation of other cations, such as Mg and K, a layer-lattice of the clay minerals can be formed (Bruijnzeel, 1990).

It is very difficult to trace these reactions in nature, because the transformations require a long time to occur. Therefore, they were studied in the laboratory, thereby imitating most of the natural conditions as much as possible (van Reeuwijk, 1994).

2.3.3 Movement of materials within soils

The water circulating in the soil pores (gravitational water) carries with it certain substances either in solution or suspension, and is responsible for their general movement. A great amount of the material thus mobilized can be removed completely from the profile. In contrast, another portion of the mobilized material is deposited at lower levels in the profile, i.e. is redistributed enabling two main horizons to be differentiated: (a) A horizons that are in general impoverished-eluvial horizons: (b) B horizons that are in general enriched-illuvial horizons. Duchaufour (1982) identifies four ways in which materials move within the soil.

2.3.3.1 Pervection (lessivage): movement of particles in suspension

According to Duchaufour (1982), lessivage is the washing in suspension of fine clay and lesser amounts of coarse clay and fine silt down cracks and other voids in a soil body reflected by (1) depletion of A horizon in clay, (2) enrichment of the B horizon in clay content relative to the C and/or A horizon, (3) higher fine clay: total clay ratio in the B horizon than in the A horizon, and (4) presence of argillans in the B and C horizons. The mobile clay involved may be a product of weathering in the A horizon or may be of eolian origin added to the soil during development.

2.3.3.2 Lixiviation: migration of soluble salts

Lixiviation is concerned mainly with most mobile cations, those capable of forming soluble salts at the pH of the soil: essentially the alkali and alkaline earth cations (Na^+, K^+, Mg^{2+} , Ca^{2+}) which occur in soil solutions in equilibrium with the exchangeable cations retained by the adsorbent complex (Duchaufour, 1982). The anions that migrate may be in the inorganic form for example nitrates or carbonates, or organic such as lactates. The heavy polyvalent cations rarely migrate as salts, except Mn^{2+} and Fe^{2+} ions in reducing conditions and sometimes Al^{3+} in very acid conditions.

The gradual movement of alkali and alkaline earth cations generally leads to their replacement on the adsorption complex by H^+ or Al^{3+} ions, which result in desaturation of the complex and soil acidification. The loss of cations by lixiviation affects not only the upper part of the profile (A horizon) but often the profile as a whole. Re-adsorption of cations in the B horizon can occur, but the general balance indicates a deficit, particularly in humid climates with a strong element of climatically controlled drainage.

Soils containing carbonates are subject to a particular kind of lixiviation - decarbonation which generally occurs as a result of the action of dissolved carbon dioxide.

$$CO_3 + CO_2 + H_2O = Ca(HCO_3)_2$$

The loss by deep drainage occurs in humid climate. Translocation also occur in drier climates where precipitation of the calcium bicarbonate occurs at a certain depth as a particular kind of illuvial horizon (calcic horizon). More rarely, in rather more acid areas the loss of calcium from the A-horizon occurs as gypsum ($CaSO_4$); then a gypsic horizon can form at a certain depth.

2.3.3.3 Cheluviation: movement of organometal complexes

Soluble organic substances produced by microbial (mainly fungal) attack on plant litter, move downward with the soil solution and form complexes with Al^{3+} and Fe^{3+} ions. There's little known of the rates at which such reactions proceed in natural soil systems; they seem to depend on the nature and concentration of the organic compounds in solution, the pH, the mineral surface area that is susceptible to attack, and the nature of the minerals (Duchaufour, 1982).

Fulvic acids are the dominant complexing organic compounds; their carboxylic and phenolic groups act as 'claws' which preferably grab polyvalent metal ions such as Al^{3+} and Fe^{3+}. Chelation continues as long as the fulvic acids are not saturated with metal ions. Fulvic acids are comparatively abundant where low temperatures, low chemical soil fertility and/or periodic water saturation retard the microbial decomposition of organic matter.

Fulvic acids are soluble in water, however, as more reaction sites become occupied by Al^{3+}, the solubility product decreases: fully saturated fulvic acids are practically insoluble in water. If the soil supplies Al^{3+} and or Fe^{3+} at low rates compared with the rate of fulvic acid production, fulvic acids can migrate over considerable distances northern the profile. Normally, the bulk of all fulvic acids is saturated with Al^{3+} and/or Fe^{3+} after migration over only a few decimeters so that an illuvial B-horizon (spodic B-horizon) forms in the profile. In sandy soils that are very low in Fe^{3+} and Al^{3+}, the spodic B-horizon may occur at a depth of several metres or, in the extreme case, a spodic B-horizon may not form at all and (the bulk of) the fulvic acid is discharged in effluent 'black water'.

2.3.3.4. Movement of silica within the soil

According to Duchaufour (1982), silica migrates in the soluble form (monosilicic acid). It's maximum solubility is low (about 100 mg/kg) and relatively independent of the pH; any considerable increase in soil solution concentration, as a result of the drying out. causes silica precipitation as a polymerized gel. However, when the profile is well provided with water, the silica concentration is less and variations in this concentration are to a large extent related to environmental factors, particularly the pH. In addition, it depends also on the source of the silica which may be either biological (litter) or geochemical (weathering of silicates or even very slow dissolution of quartz). It should be mentioned that, as yet there is little information on the forms of silica present in litter and the causes of its mobilization.

2.4 Climate

The effect of climate on soil formation is direct and indirect. The direct effect is that of precipitation (moisture), temperature, evaporation and wind. The indirect effect is in its effect on flora and fauna (the biosphere). The climate factor accounts for the largest amount of variation in soil properties (Vitousek, 1994). Indeed, moisture and temperature (independently) probably account for more of that variation than any other single factor.

These variations in the soils originate from such processes as organic matter influx and decomposition, presence or absence of chelating agents, soil-water chemistry and the depth and rate of leaching of water through the soil. The main soil morphological and mineralogical properties that correlate with climate are organic matter content, clay content, kind of clay and iron minerals, colour, various chemical extracts, the presence or absence of $CaCO_3$ and more soluble salts, and depth to the top of salt-bearing horizons (Holiday, 1989b).

For a full appreciation of the role of climate in soil formation it is necessary to discuss temperature and moisture separately.

2.4.1 Temperature

According to Retallack (1994), the higher the temperature, the greater the evaporation and transpiration and the lower the effective precipitation that percolates through the soil. The result is that, with the same precipitation in two different isothermal belts, different types of soil profiles will develop. In the cold temperate regions, and in the high mountain country long and severe winters occur; hence, percolation is hindered with the result that many lakes, swamps and peats are formed. The conditions for peat formation are favourable in spite of the scarce vegetation because the microbial activity responsible for the rapid destruction of the organic material is restricted during the long winters. Prolonged freezing and consequent drying favours the stabilization of humus, rendering it more resistant to decomposition by micro-organisms. The O-horizon is therefore very thick, 30cm or more. Below the O-horizon there is generally no soil formation because the decomposition products formed in the O-horizon cannot percolate into the mineral mass and, consequently, cannot react with it.

In the humid tropics and subtropics, on the contrary, a very dense vegetation occurs, but at the same time an intense activity of micro-organisms. The plant residues are therefore rapidly mineralized. The result is that very little organic matter accumulates in O-layer, except in areas of poor drainage where anaerobic conditions prevail. Peat formations can therefore also occur in the humid tropics.

Based on the difference between the mean maximum temperature, Soil Survey Staff (1975) came up with various soil temperature regimes. These include pergellic (<0°C), cryic (0°C-8°C), frigid (5°C-8°C), mesic (8°C-15°C), thermic (15°C-22°C), hypothermic (>22°C). The iso prefix is used for the last four temperature regimes if the mean summer and winter soil temperature differ by less than 5°C at a depth of 50cm or at a lithic or paralithic contact, whichever is shallower.

2.4.2 Rainfall

When rain falls onto the earth's surface, it may penetrate into the soil flow along the surface if topography allows, or evaporate. It is generally accepted that 15-50% of the total rainfall percolates and reaches groundwater (Fitzpatrick, 1986). The part that penetrates and percolates is very important with respect to soil formation. This water reacts with mineral particles of the parent material, dissolves some constituents of it, removes this dissolved material from the surface and deposits it at a lower part of the solum. In this way the mass is differentiated into horizons and the soil body is formed. This process is only effective, if there is established vegetation. Roots protect the material from being eroded, leaves protect the soil against the impact of raindrops, and decomposition products of the organic material become increasingly important as they contribute effectively in the reactions between the percolating waters and the materials with which they come in contact.

The effective rainfall (actual rainfall-surface runoff-evaporation-transpiration) depends on the total actual rainfall and determines the rate of profile development (Retallak, 1990). In the deserts there is no profile differentiation, because there is no water for percolation. Some soil profiles are however found in deserts which is an indication of earlier more humid climates. Precipitation varies from place to place but the actual total amount entering the soil is determined by rainfall intensity, vegetation cover, inflitration capacity, permeability and slope, speed of snow melting and original moisture content of the soil (Fitzpatrick, 1986).

Soil moisture regimes are classified by Soil Survey Staff (1975) based on ground water and the presence or absence of water held at a tension of less than 15 bars in the middle of the pedo units. These soil moisture regimes are aquic, aridic, torric, udic, ustic and xeric.

The climate data available in the project area is on rainfall for a period of 45 years upto 1976, obtained at Simba Railway Station (Met. Sta. No. 9237003). The station is located at the eastern end of the study area. The monthly and annual average rainfall is given in Table 1.

Table 1: Average Monthly Rainfall at Simba Railway Station (in mm)

No. and altitude	Years of rec	Ann. Rainf. mm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
9237003 1036 m	45	636	43	39	76	128	40	5	0	2	5	27	163	108

The average annual rainfall is about 600 mm and the area shows a bimodal rainfall pattern. The long rains extend from March through May followed by a long dry season from June to October. The short rains appear in November and December. The short dry season usually begin in January and ends in February.

2.5 Relief

Topography or local relief influences the distribution of soils in the landscape to such an extent that soils of markedly contrasting morphologies and properties can merge laterally with one another and yet be in equilibrium under existing local conditions (Mbuvi *et al.*, 1997). The nature of the topography can influence soils in many ways, for example, the thickness of the pedo unit is often determined by the nature of the relief (Fitzpatrick, 1986). Topographic features fall into three main categories, mountains and hills, those formed by erosion and those formed by deposition.

Macrotopographical (hilly or mountainous topography) conditions favour the formation of intrazonal soils (Birkeland, 1984). The continuous geologic erosion hinders the development and formation of distinct soil profiles, because some of the products of weathering are removed from the slopes. Consequently, the soils remain immature and young. Such soils are called skeletal or Leptosols (Entisols) and consist of fresh rock fragments, large stones and boulders imbedded within the mass of the young soil body. Soil formation is also affected by the effect of exposure. Southern exposures are generally warmer (and therefore drier) and subject to strong fluctuation in temperature and moisture. The reverse is true for northern exposures. As a consequence of this difference entirely different soils can be formed on both slopes, even if the parent material is similar.

Nearly all landscapes show evidence of erosion and deposition as well as areas of relative stability, thus within any one area there may be soils of widely differing ages and degree of development (Swahney *et al.*, 1992). In areas of rolling terrain, soil properties vary because lower areas are likely to be areas of accumulation of water runoff and sediment derived from surrounding higher-lying areas. Also, low areas might be influenced by a high water Table, which could have considerable effect on the soil. In these areas of rolling topography, it is common to find well drained soils on the uplands whereas those in the depressions are poorly drained and rich in clay and organic matter, with signs of various degrees of gleying. In dry climates, saline and alkaline soils occupy the depressions, better-leached soils the slopes, and the less-leached soils the summits (Holiday, 1989b). The differences in soil properties with position could be due to pedogenesis in place, resulting from differences in moisture, leaching, and vegetation over the rolling landscape. In this case, the various parts of the landscape are assumed to be approximately the same age, and soil differences are attributed to the relief factor. Position with respect to groundwater is an important aspect of microtopography. An example is the formation of ground-water-laterites in small depressions of an area occupied by Oxisols.

Numerous studies have shown that many soil properties are related to the gradient of the slope as well as to the particular position of the soil on a slope. Milne (quoted in Birkeland (1984) proposed the term catena to describe this lateral variability on a hillslope and emphasized that each soil along a slope bears a distinct relationship to the soils above and below it, for a variety of geomorphological and pedologic reasons.

It can be concluded that topography is of great importance as a site factor in pedogenesis both in temperate climates, where it either prevents the complete development of the profile by slowing down processes or modifies the climatically controlled development as a whole by affecting lateral movement, and in the tropics, where it can completely reverse the climatically controlled processes of weathering.

2.6 Living organisms

The biotic factor is a logical topic in the study of soil formation - but as Jenny (1941) made clear, the biotic factor provides conceptual difficulties more severe than those for other factors. Jenny (1980) wrote; 'The real bugbear was the biotic factor. Like everybody else, I could see that vegetation affects the soil and that soil affects the vegetation, the very *circulus vitiosis* that I was trying to avoid'. Jenny's solution was to identify the regional flora (and fauna), the potential occupants of a site, as the factor of interest. This definition avoids the problem of trying to determine cause and effect in the feedback system that characterizes plant-soil interaction.

The biosphere is composed of two elements, viz, the plant kingdom (phytosphere) and the animal kingdom (the zoosphere). The two elements have opposing effects on soil formation (ITC Notes, 1986). Whereas the phytosphere promotes soil horizon formation, the zoosphere retards the differentiation of the soil into horizons.

2.6.1 The phytosphere

According to Fitzpatrick (1986), plant roots penetrate into rock and parent material and open channels for the movement of water and air. As the roots and other subterranean parts of plants die and decompose, many organic and inorganic acids are released. These acids react with the minerals or the weathering products of minerals and the reaction products can be transported with the percolating waters and can be either accumulated at one place in the profile or completely removed with the draining waters. In this way, a differentiation of the soil into horizons starts. In this reaction mechanism, complex-formation (or chelation), hydrolysis, oxidation and reduction play the most important roles in humid and semi-humid climates. The results of these processes are a redistribution of iron, aluminium, silica, clay, calcium and magnesium in the profile. In arid and semi-arid climates, where the effect of organic matter is negligible, solublization and precipitation of soluble salts are the most important phenomena (van Reeuwijk, 1994). In the humid hot climates hydrolysis and oxidation are very intensive leading to the formation of typical soils (Ultisols and Oxisols).

Plants act as soil binders and prevent soil erosion from taking place. Plant roots, especially of grasses, bind soil particles together to form crumb and granular structures. The roots also cause redistribution of minerals. Plant roots exude various substances on which many microorganisms thrive so that the soil in immediate proximity to the root or rhizophere is an area of prodigious microbiological activity and frequently, the concentration of iron immediately next to the live root is reduced imparting a bleached appearance to the soil (Metting, 1993).

The vegetation in the study area falls under wooded bushed grassland (Touber, 1983). Except for seasonal burning, vegetation has little been disturbed by man. Vegetation species are quite heterogenous and have been described extensively by Touber (1983).

On the hills and piedmont plains, are found grasslands and bushed grasslands of *Digitaria macroblephara* and *Aristida keniensis* with *Combretum zeyheri* and *Balanites aegyptiaca.*

Uplands consist of grasslands and wooded bushed grasslands of *Digitaria macroblephara* and *Sporobolus fimbriatus* with *Acacia totilis*. Other grasses are *Pennisetum mezianum* and *Lintonia nutans*.

Various grasses and bushes are found on erosional plains. Examples are *Chloris roxburghiana* and *Sporobolus angustifolia* with *Commiphora schimperi* and *Acacia mellifera*.
Bottomlands support grasses such as *Pennisetum mezianum*, *Lintonia nutans* and *Echinochloa haploclada*.

2.6.2 The zoosphere

The contribution of the animal kingdom to the processes of soil formation is primarily mechanical in nature. Metting (1993) says that whereas the phytosphere causes a differentiation of the soil, the zoosphere has the tendency to hamper and even to nullify this. They homogenize the soil more or less. In reality, they disturb the profile. Rodents carry down much materials from the A down into their nests (mostly located in the B-horizon) and bring up B-material to the A-horizon. This animal effect is important from the viewpoint of agriculture, because plant roots frequently follow the abandoned channel borings of rodents, worms, and insects.

According to Coleman and Crossley (1996) worms appear to be capable of bringing every year about 10 tons of soil material per acre to the surface, being about 2.5 cm in five years. They drag down leaves and grasses from the surface into their burrows. The depth to which worms penetrate the soil varies from a few centimeters to 7.5 meters. In 10 months they consume about 1.0% of the plant residues of the forest floor and they prefer a neutral to an alkaline medium. However worms can also be found in moderately and even strongly acid medium.

Ants and termites carry material form lower to higher levels, build galleries and underground passageways, throw out a great deal of material to the surface and frequently form hills and mounds.

Wielemaker and Boxem(1982), found that the construction of termite mounds, nests and galleries from soil or mixtures of soil and other materials or within soil horizons affect the physical and chemical characteristics of both the soil used for construction and the soil of the surrounding areas from which the materials are derived. This is because soil particles are selected, transported, rearranged, cemented together and mixed with organic matter.

Mice and rodents, found mainly in treeless regions, are very active in transporting material. They can throw out 50 tons of materials per year per hectare (Coleman and Crossley, 1996). The formation of crotovinas in the chernozems is an essential feature of these soils and is the result of the activity of rodents.

It can be stated that the activity of the zoosphere is strongly influenced by the amount of food present in and on the soil and of the composition of the food. It is frequently found that the dressing of pastures with fertilizers increase the worm-population strongly, giving rise to the formation of agric horizons.

Termites are found all over in the study area. Termite mounds as tall as 2-3 meters were sighted and sometimes they are as close as 50 m apart. These insects are adapted to a wide range of semi-arid ecosystems where earthworms are not found. They feed on wood and humus. Termites influence soil structure by:

1) Mixing organic and mineral particles
2) Redistribution of organic matter
3) Creation of biopores
4) Promoting humification process.

Farmers in the project area consider them pests and a hazard to farm structures.

2.7 Time

It must be stressed that time means the stage of development of the soils or in other words, the grade of maturity. According to Buol (1989) terms such as youth, maturity and old age (senile) have been applied to soils. Entisols and some Inceptisols may be considered youthful while mature soils are thought to be in equilibrium with the environment. Senile soils are pedogenic accumulations of inert material - sesquioxides and heavy minerals. Mature soils have fully developed profiles and young soils have only indications of horizon development, independent of the geological age of the land. Acid rocks will resist weathering and soil formation stronger than basic rocks. Soils developed over acid rocks will therefore possess less well developed profiles than those of basic rocks under the same climatic conditions. Therefore, soils on acid parent materials need more time for full development than those on basic materials.

Soils pass through a number of stages as they develop, culminating in deep pedo units with many well differentiated horizons. Most soils are not developed by a single set of processes but undergo successive waves of pedogenesis (Fitzpatrick, 1986). Soils are thus regarded as having developmental sequences which manifest not only the present factors and processes of soil formation but also a varying number of preceding phases. The various progressive changes in soils are known as soil evolution.

The relationship of soils to time can be discussed with respect to (1) relative stage of development, (2) absolute dating of horizons and profiles, (3) rate of formation, (4) relation to age of slope and land form and associated weathering complexes. The time of formation for a particular soil is determined by its stratigraphic position relative to adjacent deposits and soils (Birkeland, 1984). It is important to understand landscape evolution and its strong effect on the time factor in soil formation. Although a given landscape may appear quite uniform and simple from a casual glance, chances are that it has a complex geomorphic history and that some soils differ on this landscape because of differences in their time of soil formation related to the landform they occupy. In a single toposequence, the dynamics within the soil mantle can assist in deducing which soil unit is older than the other (Okoth, 1988).

The effect of time is frequently obscured because of past climates that are different from present - day climate. In such cases it is difficult to establish whether the soils are different as a consequence of time or of climate.

CHAPTER THREE: SOIL SURVEY AND RESEARCH METHODS

3.1 Previous soil studies in the area

The area is covered by the general countrywide Exploratory Soil map at a scale of 1:1 million (Sombroek et al., 1982) and the "Soils and Vegetation of the Amboseli-Kibwezi area" by Touber (1983) at a scale of 1:250,000. The above reports are based on photo-interpretation and extrapolation with very limited fieldwork. The soil units identified in these reports describe the soils in general and lack detailed soil characterization in terms of laboratory analysis and fieldwork. In the above maps, the study area is shown to fall under Luvisols, Regosols, Nitisols and Vertisols as the major soils. According to Touber (1983), in the study area, hills, scarps and ridges have shallow, stony and rocky soils. Undulating uplands have moderately deep to deep soils, whereas all the plains have in general deep soils. Chemical soil fertility is reported to be high in the area due to the presence of many weatherable primary minerals. CEC figures are moderately low while base saturation figures are above 50%. The topsoils are reported to be weakly developed and low in organic matter content due to truncation by sheet erosion. This study was aimed at characterizing soils of the area in detail to provide soil information in a standard format.

Some soil information exists for isolated areas in the region but outside the study area. Three major soil units were mapped in Kiboko area by Michieka and van der Pouw (1977). The three soil units comprised of shallow soils (Leptosols) of the volcanic area; well drained, deep soils (Ferralsols and Luvisols) of the Basement plains, and moderately well drained calcareous soils (Chernozems, Fluvisols, Vertisols) of the floddplains, bottomlands and swamps.

Van Wijngaarden and van Engelen (1985) distinguished the following soil mapping units in Tsavo area:

- Mountains, hills, low ridges and minor scarps (Leptosols)
- Footslopes, piedmont plains and plateaus (Ferralsols, Luvisols, Cambisols)
- Uplands (Acrisols, luvisols, Cambisols)

- Erosional plains (Ferralsols, Luvisols, Acrisols)
- Sedimentary plains (Luvisols, Planosols, Ferralsols, Solonetz)
- Floodplains, alluvial valleys and bottomlands (Luvisols, Solonetz, Vertisols, Cambisols, Fluvisols)
- Volcanic plains and lava flows (Andosols, Chernozems)

In the soils of Makueni (Njoroge, 1996) several major groups of soils were mapped. Leptosols were mapped on mountains, hills and major scarps. Ferralsols were mapped on footslopes and plateaus. Uplands had Arenosols, Ferralsols, Luvisols and Cambisols. Fluvisols and Vertisols were mapped on river terraces and bottomlands, respectively. Vertisols were mapped in minor valleys. These reports give information that is useful to the present study.

3.2 The present study

3.2.1 Office methods

This involved the acquisition of aerial photographs at a scale of 1:50,000 and a review of any literature on the study area like geological reports, soil survey reports and topographical maps at scale 1:50,000 (Survey of Kenya, 1974). The aerial photographs were systematically interpreted using a mirror stereoscope. A combined physiographic and element analysis method was used (FAO/UNESCO, 1967a; Mulder, 1987; Vink, 1968). Photo interpretation was based on the recognition of visible features on the photos which are assumed to correlate with soil differences (FAO/UNESCO, 1967). The features include landform, surface drainage, natural vegetation, slope gradient and form, photo-tone and photo-texture. The aim of the interpretation was to arrive at a classification of the land units which through subsequent fieldwork and laboratory analysis would be transformed into soil mapping units.

Photo-interpretation boundaries were transferred to the 1:50,000 topographical maps, resulting in a photo interpretation map covering the study area. The units delineated on the photo interpretation map were classified and analyzed resulting in characterizing each by a combination of elements. The units were given preliminary symbols and described in the provisional legend.

3.2.2 Field methods

Fieldwork was carried out between October and December 1998. The field survey begun with a general orientation of the area to get a broad view of the geology, landforms and vegetation in relation to the soils.

Field observations were carried out in a grid system of 500 m by 500 m thus making one observation per 25 hectares. Some free survey was exercised where surface features indicated soil differences not necessarily on the traverse. Augerings were made to a depth of 120 cm and mini pits upto 50 cm deep if soil depth permitted. Augerings and mini pits were described and recorded on the standard Kenya Soil Survey forms which are based on the FAO/UNESCO guidelines for soil profile description (FAO/UNESCO, 1977).

At each observation site, information was described and recorded on: landform, relief, geology, slope, drainage conditions, vegetation, rock outcrops, surface stoniness and geographic location. Soil material from the auger and the mini-pit was described for colour, texture, consistency, occurence of lime, characteristics and thickness of soil horizons and soil depth. Differences in these characteristics from the top to the bottom of the hole enabled the sub-division of the soil into horizons. Soil colours were determined using soil colour charts (Munsell, 1990).
The boundaries on the photo interpretation map were checked and changed where necessary during fieldwork. The augerings and mini-pits helped in the identification of landscape-geology-soil relationship and the different soil mapping units on the basis of soil depth, colour, texture, mottling, consistence, concretions and drainage.

All augerings were numbered and their positions recorded on the photo interpretation map. Representative profile pits were dug for each mapping unit and the profiles were fully described and sampled for chemical, physical and mineralogical analysis at the National Agricultural Research Laboratories. The method of genetic horizon sampling was followed in order to characterize A, E, B or Bt, and C horizons separately. For each horizon, soil samples were taken from various positions and mixed well, before being put into sealed and labelled plastic bags. Around every profile pit, composite sample were taken for mass analysis of available nutrients. This was done at three different locations around the pit and mixed well. In addition, undisturbed samples for bulk density and pF determinations were collected. Three cores were taken from well distributed points from previously wetted horizons. Also, rock samples were taken for geo-chemical analysis.

3.2.3 Laboratory methods

Soil samples collected from the field were analyzed in the laboratory using the standard procedures followed at the National Agricultural Research Laboratories in Nairobi. All the detailed procedures are described by Hinga *et al.* (1980); Black (1965) and van Reeuwijk (1986). All the disturbed samples were first air-dried and ground into fine particles to pass through 2 mm sieve. The following methods were used:

Mechanical analysis: Soil texture was determined by the hydrometer method. The samples were shaken overnight with calgon (sodium hexametaphosphate and sodium carbonate) solution in an end-over-end shaker at 40 revolutions per minute. The measurement of silt plus clay was done after 40 seconds and clay after 2 hours, all with a soil hydrometer. Sand fraction was obtained by the difference. Texture classes were then read directly from textural triangle.

Bulk density: This was obtained using undisturbed core ring samples after oven drying for 24 hours at 105°C. The mass of the oven-dry soil was divided by the volume to obtain the bulk density.

Soil reaction (pH) and electrical conductivity (EC): The pH was measured with a glass electrode pH meter on 1:2.5 suspension of soil in water, and on 1N KCL solution, in all cases after shaking for 1 hour. The electrical conductivity was also measured on the 1:2.5 soil water suspension using direct reading conductivity meter using electrodes and the results reported in dS/m.

Cation exchange capacity (CEC) and exchangeable bases: 2.5g soil was leached with 100 ml 95% ethanol and percolated with 100 ml 1N NH_4OAc at pH 7; Na and K were determined directly on the flame photometer; Mg and Ca were then determined by automatic absorption spectroscopy (AAS) after dilution with lanthanum chloride. The samples were subsequently leached with 1N sodium chloride and the leachate used for the determination of CEC.

Mass Analysis for available nutrients: This was performed for the composite topsoil samples only. The soil was extracted by shaking for 1 hour at 1:5 ratio with 0.1N HCL and 0.025 N H_2SO_4. The Ca, K and Na were determined by flamephotometer after an anion resin treatment for Ca, for Mg the same procedure as for exchangeable Mg. For phosphorus, soil was extracted with 0.5M sodium hydrogen carbonate solution at pH 8.5, a reagent which controlled the removal of calcium phosphate (Olsen *et al.*, 1954). Manganese was measured colorimetrically using phosphoric acid-potassium periodate for colour development.

Total nutrients (K, Mg and P): The samples were digested with 1N Hcl and 30% H_2O_2 and then filtered. The amounts of K, Mg and P in filtrate were then determined (Hinga et al., 1980).

Organic carbon (C%) and total nitrogen (N%): Organic carbon was determined colorimetrically by mixing concentrated sulphuric acid and aqeous potassium dichromate ($K_2Cr_2O_7$). 0.5g of the soil sample and the mixture were heated at 150°C for 30 minutes. After cooling, 0.4% barium chloride solution was added to the mixture. Organic carbon was then determined on the colorimeter (Anderson and Ingram, 1993). Nitrogen was determined by semi-micro Kjedahl method (Anderson and Ingram, 1993). To 0.2g of soil, 4.4 ml of digestion mixture of 30% hydrogen peroxide, selenium powder and lithium sulphate were added. Digestion was done for 2 hours at 360°C. Total N was then determined on the colorimeter.

Standard calculations

$$\text{Base saturation} = \frac{\text{Sum of exchangeable cations}}{\text{Cation Exchange Capacity}} \times 100$$

$$\text{Porosity (\%)} = \left\{1 - \left(\frac{\text{bulk density}}{\text{Particle density}}\right)\right\} \times 100$$ where particle density is assumed to be 2.65 g/cm^3 for most mineral soils.

Soil moisture characteristics

This was determined by moisture percentages at sunctions of 0.001, 0.2 and 0.5 bars and pressures of 5.0 and 16.0 atmospheres (pF 0, 2.3, 2.7, 3.7 and 4.2, respectively). Undisturbed core samples for the three lowest pF-values were subjected to sunction (Kaolin box apparatus) to remove water. Disturbed samples for the two highest pF-values were subjected to positive external gas pressure until the soil water and the external gas pressure came into equilibrium. To transfer the weight/weight data of the disturbed samples to weight/volume, they were multiplied by the bulk density (Hinga *et al.*, 1980).

Sand mineralogy: Selected soil samples were sieved and the sand fraction between 50 and 250 microns were retained on a 300-micron mesh. The samples were cleared with 2N Hcl and boiled with 30% H_2O_2 until no frothing occurred at boiling point. The sand fraction was mounted on glass slides ("1X3") with Canada balsam and covered with a thin glass (1" x 1"). The mineralogical indentification was done with a standard polarizing petrographic microscope (Hinga *et al.*, 1980).

Iron oxides: Selected soil samples were analyzed for three forms of iron oxides. Soil samples were shaken with a complexing and reducing buffer of sodium citrate and sodium dithionate to extract both active and sTable iron oxides. To extract active iron, soil samples were shaken with a mixture of oxalic acid and ammonium oxalate. Soil samples were shaken with sodium pyrophosphate solution to extract iron complexed to organic matter. The iron was measured in the extracts by AAS (van Reeuwijk, 1986).

Geochemical analysis of soils: Selected soil samples were digested by the hydrofluoric acid – Boric acid dissolution method. The oxides of the various elements were determined by the atomic absorption spectrometer (Laboratory Manual for Geochemical Analysis, 1989).

3.2.4 Cartographic methods

The boundaries on the photo-interpretation map at scale 1:50,000 were transferred onto the translucent base maps at the same scale using an optical pantograph and a Vertical sketch master. Observation points were also transferred onto the base map. The base map was then used for printing of the soil map.

The soil survey approach used related the soils to the landforms and the type of parent material on which they occur, resulting in a physiographic soil map. In the construction of the legend of the soil map, the physiographic classification provided the framework of the soil map units. A three level hierarchical system of legend construction has been used (KSS, 1987; Van de Weg, 1978). The landform sub-division is at the highest level, a geological sub-division at the second level, and soil characteristics separated within each physiographic-geological unit at the third level.

Areas delineated on the map are identified by codes which represent physiography, geology and soil characteristics. The first code refers to the landform while the second refers to geology. The third entry in the legend describes the soil units and refers mainly to characteristics of the subsoil, usually to a depth of 100 cm. All soil descriptions follow the FAO/UNESCO guidelines for soil profile description (FAO/UNESCO, 1977).

In addition, each soil map unit is characterized by the dominant slope class for which a code is written under the soil map unit code. The map unit description in the legend is followed by the taxonomic classification of the soil using FAO/UNESCO (1994) system. The following codes are used:-

Physiography:

H = Hills and minor scarps
F = Footslopes
Y = Piedmont plains
U = Uplands
P = Volcanic and erosional plains
B = Bottomlands

Geology:

B = olivine basalts
F = gneisses rich in ferromagnessian minerals
U = colluvium from various rocks
V = various volcanic rocks

X = various parent materials

Soil:

r = red colour pre-dominant

1,2 = general sub-division of the soil units

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 General properties of the soils

Parent material and relief largely determine the distribution of soil types in the project area. Hills and scarps have shallow, stony and rocky soils. Undulating uplands have deep to very deep soils whereas all the plains have in general very deep soils. Most of the soils are well drained and the imperfectly drained soils are found in the bottomlands.

Soil textures vary according to parent material and physiography. Soils developed on volcanic material have textures with low sand percentages, mainly clays and clay loams. The soils on basement system rocks have in general sandy clay loams to sandy clays, with sandy loam to sandy clay loam topsoils, especially in the more undulating and hilly areas. Red sandy clays dominate on Basement system rocks rich in ferro-magnesian minerals (biotite-hornblende gneisses) while brown coloured sandy clay loams prevail on the undifferentiated Basement System rocks (mainly quartz feldspar gneisses).

Most of the top soils are weakly developed (ochric A-horizon), thin, light coloured and low in organic matter content, owing to truncation by sheet erosion. The workability of the soils is good except the imperfectly drained soils of the bottomlands. Sealing of the topsoil is a widespread unfavourable characteristic, most pronounced on soils on Basement Systems rocks. On volcanic soils, sealing of the topsoil is much less pronounced but in many cases still an important factor with regard to erosion hazard (for complete profile description and chemical data see appendix 1).

The natural soil fertility is generally high in the project area. This could be due to the presence of many weatherable primary minerals, which either occur in the weathering material from Basement System rocks rich in ferro-magnesian minerals or were added later by volcanic ash enrichment of chemically poor soils. Base saturation figures vary from medium to high. CEC figures of the topsoils range from low to very high

4.1.1 Soils of the hills

Mapping Unit HVP

1) Environment

The total area of the unit is 1853.02 ha. The parent material is various volcanic rocks, which are predominantly olivine basalt's in the form of boulders, breccia and agglomerates. The vegetation is bushed grasslands *Digitaria macroblephara* and *Aristida keniensis* with *Combretum Zeyheri* and *Balanites aegyptiaca.* The unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is small rounded singular hills with convex to straight slopes of 16-30%.

2) Soil properties and classification

The soils are excessively drained, shallow, bouldery and gravelly with a weakly developed horizon differentiation. The soils are classified as Humic Cambisols (FAO/UNESCO, 1994) or Dystric Ustochrepts (Soil Survey Staff, 1992).

Profile 174/1-9

a) Morphology

The profile is located on the apex of the hill. The A-horizon is 25 cm thick, dark reddish brown (5YR 3/4), clay, sub-angular blocky structure and friable. The B-horizon is 22 cm thick, dark reddish brown (5YR 3/4), clay loam, sub-angular blocky structure and friable. Below this is a hard layer of weathering material. Soil horizon boundary is abrupt and wavy.

b) **Chemical**

The pH-H_2O increased with depth from 6.3 to 6.5. Electrical conductivity (EC) increased with depth from 0.29 dS/m in topsoil to 0.34 dS/m in subsoil. Cation exchange capacity (CEC) decreased with depth from 21.12 cmol(+)/kg in the topsoil to 18.36 cmol(+)/kg soil in the B-horizon. There is a general decrease with depth in the exchangeable cations. Base saturation is between 81% and 88% in the profile.

c) **Physical**

The sand content decreased from 42% in the topsoil to 29% in the subsoil. The silt content increased with depth from 15% in the topsoil to 42% in the subsoil. Clay content decreased from 43% in the topsoil to 29% in the subsoil.

d) **Interpretation**

The thick A-horizon is due to a sTable condition with Vertical processes exceeding lateral ones. Climate has played a role by letting exchangeable cations be concentrated in the topsoil. This means that the drainage water has not been enough to leach the soil. A similar argument can be made for the distribution of clay in the profile. The higher clay content in the topsoil than the subsoil is due to limited drainage water.

Mapping Unit HUP

1) Environment

The total area of the unit is 322.74 ha. Parent material is Basement System rocks that consist of gneisses poor in ferro-magnesian minerals, predominantly quartz-feldspar and granitoid gneisses. Vegetation is wooded bushland and grassland of *Commiphora schimperi, Acacia tortilis, Chloris roxburghiana* and *Pennisetum mezianum*. The unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is variable and irregular slopes that are generally over 16%.

2) Soil properties and classification

The soils are somewhat excessively drained, shallow to deep, rocky and stony. The soils are classified as Eutric Regosols (FAO/UNESCO, 1994) or typic Ustorthents (Soil Survey Staff, 1992).

Profile 173/2-3

a) Morphology

The profile is located on the shoulder of the hill. The A-horizon is 14 cm thick, dark yellowish brown (7.5YR 3/6) to dark reddish brown (5YR 3/2), silty clay loam, sub-angular blocky structure and friable. Below this is weathering material. Soil horizon boundary is abrupt and wavy.

b) Chemical

The pH-H_2O increased from 6.3 in the topsoil to 6.4 in the weathering material. EC increased with depth from 0.32 dS/m to 0.35 dS/m. Organic carbon is 1.13% in the profile. CEC is 17.60 cmol(+)/kg soil in the A-horizon and 16.0 cmol(+)/kg soil in the weathering material. Ca and Mg are about 7.0 cmol(+)/kg soil and 3.0 cmol(+)/kg soil, respectively in the profile. K and Na are 0.96 cmol(+)/kg soil and 0.57 cmol(+)/kg soil, respectively. Base saturation increases with depth from 67% in the topsoil to 75% in the weathering material.

c) Physical

The sand content increased from 13% in the A-horizon to 33% in the weathering material. Silt and clay contents decreased with depth.

d) Interpretation

The thin A-horizon is evidence of limited soil formation occasioned by lateral truncation that dominates Vertical soil forming processes. The abrupt change from an A-horizon to a C-horizon is typical of Leptosols. Parent material may have played a role as can be observed by the high content of sand immediately below the A-horizon.

4.1.2 Soils of the footslopes

Mapping Unit FUr

1) Environment

The total area of the unit is 522.49 ha. Parent material is collovium derived from various gneisses, predominantly quartz-feldspar gneisses and in places gneisses rich in ferro-magnessian minerals (biotite and horn-blende-biotite gneisses). The vegetation is bushed grassland of *Acacia tortilis, Combretum apiculatum, Themeda triandra* and *Chloris roxburghiana.* The unit falls within agro-climatic zone V with rainfall of approximately 600 mm. Relief is composed of uniform, slightly concave to straight slopes ranging from 4% to 16%.

2) Soil properties and classification

The soils are well drained, very deep, dark reddish brown to dark red, friable sandy clay to clay. The soils are classified as Haplic Acrisols (FAO/UNESCO, 1994) or Typic Rhodustults (Soil Survey Staff, 1992).

Profile 173/2-4

a) Morphology

The profile is located on the upper part of the footslope. The A-horizon is 18 cm thick, dark reddish brown (5YR 2.5/2), sandy loam, sub-angular blocky structure and friable. The Bt1 horizon is 40 cm thick, dark reddish brown (2.5YR 3/4), sandy clay loam, weak angular blocky and friable. The Bt2 horizon is 50 cm thick, dark red (2.5YR 3/6), sandy clay, weak angular blocky and friable. The Bt3 horizon is 42 cm thick, dark red (2.5YR 3/6), clay, weak angular blocky and friable. All the horizon boundaries are gradual and wavy.

b) Chemical

The pH-H_2O decreased with depth from 5.3 in the top soil to 4.4 in the sub-soil. EC decreased with depth from 0.06 dS/m in the topsoil to 0.03 dS/m in the sub-soil. Organic carbon decreased with depth from 0.49% in the topsoil to 0.19% in the sub-soil. Topsoil CEC is 9.80 cmol(+)/kg soil while that of sub-soil is between 7.40 and 10.80 cmol(+)/kg soil . Ca ranges between 0.09 cmol(+)/kg soil to 1.47 cmol(+)/kg soil in the profile. Mg increased with depth from 0.67 cmol(+)/kg soil in the top soil to 2.36 cmol(+)/kg soil in the sub-soil. Na and K decreased with depth in the profile. Base saturation is less than 50% in all horizons.

c) Physical

The sand content decreased with depth from 83% in the top soil to 46% in the subsoil. The clay content increased with depth from 14% to 52%. Silt content is approximately uniform in the profile.

d) Interpretation

The low exchangeable cations and CEC are indications of poor chemical characteristics of these soils. The increase in clay with depth is an indication of Vertical soil processes that have taken place. The dark red sub-surface colours and the thin, brown ochric A-horizon are characteristics typical of Acrisols.

4.1.3 Soils of the uplands

Mapping unit UVr1

1) Environment

Total area of the unit is 75070.10 ha. Parent material comprises pleistocene volcanics that are mainly olivine basalts in the form of agglomerates and breccias. Vegetation is wooded bushed-grassland of *Digitaria macroblephara, Acacia tortilis, Pennisetum mezianum* and *Lintonica nutans*. The unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is uplands with smooth, slightly concave and convex slopes surrounding the hills of unit HVP. Slopes range from 3-7%.

2) Soil properties and classification

The soils are well drained, very deep, dark reddish brown to dark red, friable clay. The soils are classified as Rhodic Ferralsols (FAO/UNESCO, 1994) or Rhodic Halpustox (Soil Survey Staff, 1992).

Profile No. 174/1-3

a) Morphology

The profile is located on a flat terrain in the uplands. The A-horizon is 24 cm thick, dark reddish brown (2.5YR 3/4), loam, sub-angular blocky structure and friable. The AB-horizon is 21 cm thick, dark reddish brown (2.5YR 3/4), clay loam to loam, sub-angular blocky structure and friable. The B-horizon is 145 cm thick, dark red (2.5YR 3/6), clay loam to silty clay, porous massive to weak, very fine angular blocky and friable. Soil horizon boundaries are gradual and wavy. There are active biological activities throughout the profile.

b) Chemical

The pH-H_2O increases with depth from 6.0 to 7.10. EC decreases with depth from 0.19 dS/m to 0.11 dS/m. Percent carbon decreases with depth from 0.42% to 0.23%. CEC of the topsoil is 12.0 cmol(+)/kg soil while that of the sub-soil ranges between 12.52 to 18.71 cmol(+)/kg soil. There is a general increase of Ca and Mg with depth in the profile. K decreases with depth whereas Na ranges between 0.60 to 0.85 cmol(+)/kg soil. The base saturation ranges from 67% in the topsoil to 98% in the sub-soil.

c) Physical

The sand content decreased from 42% in the topsoil to 24% in the sub-soil. Silt content increased with depth from 36% to 56%. Clay content increased with depth from 22% to 34%.

d) Interpretation

These soils have a deep solum, diffuse boundaries and lack well developed blocky structures, characteristics that are typical for Ferralsols. The distinct red colours in the B-horizon are indicative of high iron content. The sTable micro-aggregates, porous structure and many biopores account for excellent porosity, good permeability and high infiltration in these soils. The low CECs are an indication that these soils are chemically poor.

Mapping Unit UVr2

1) **Environment**

The total area of the unit is 197.34 ha. Parent material is pleistocene volcanics, mainly olivine basalts in the form of agglomerates and breccias. Vegetation is wooded bushed grassland of *Digitaria macroblephara, Aristida keniensis with Combretum zeyheri* and *Balanites aegyptiaca*. The mapping unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is characterized by slightly concave and convex slopes surrounding the hills of unit HVP. Slope percentages range from 3-8%.

2) **Soil properties and classification**

The soils are well drained, deep, dark reddish brown, friable clay loams with a stony phase. The soils are classified as Rhodic Ferralsols (FAO/UNESCO, 1994) or Rhodic Haplustox (Soil Survey Staff, 1992).

Profile No. 174/1-12

a) **Morphology**

The profile is located on gently undulating slopes within the soil mapping unit. The A-horizon is 20 cm thick, dark reddish brown (2.5YR 3/4), clay, sub-angular blocky structure and friable. The B-horizon is 97 cm thick, dark reddish brown (2.5YR 3/4), silt loam, porous massive to weak, very fine angular blocky structure and friable. Soil horizon boundaries are gradual and wavy.

b) Chemical

The pH-H_2O increases with depth from 5.8 in the topsoil to 6.5 in the sub-soil. EC decreases wi depth from 0.11 dS/m in the topsoil to 0.06 dS/m in the sub-soil. The topsoil has organic carbo content of 0.48%. CEC decreases with depth from 13.20 cmol(+)/kg soil in the topsoil to 10.9 cmol(+)/kg soil in the subsoil. Ca, K and Na decrease with depth. Mg increases with depth fro 2.24 cmol(+)/kg soil in the topsoil to 3.76 cmol(+)/kg soil in the sub-soil. Base saturation between 52% and 60% throughout the profile.

c) Physical

There was an increase in sand content with depth with a maximum of 28% in the B-horizon. Si content increased with depth from 22% in the topsoil to 59% in the sub-soil. Clay conte decreased from 74% in the topsoil to 17% in the subsoil.

d) Interpretation

This unit has similar characteristics to unit UVr1. It is important to note that the Vertic distribution of the exchangeable cations suggest that percolating water is limited. Due to littl relief intensity and limited soil moisture most processes of the soil formation take place Verticall and the lateral dynamics are minimal.

Mapping Unit UVd

1) Environment

The total area of the unit is 37.84 ha. The parent material is pleistocene volcanics, mainly olivine basalts in the form of agglomerates and breccias. Vegetation is composed of wooded bushed grassland of *Digitaria macroblephara* and *Aristida keniensis* with *Combretum zeyheri* and *Balanites aegyptiaca*. The mapping unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is made up of undulating slopes of 4-8%.

2) Soil properties and classification

The soils are well drained, deep, dark brown, firm, stony and bouldery clay showing Vertic properties. The soils are classified as Vertic Luvisols (FAO/UNESCO, 1994) or Vertic Haplustalfs (Soil Survey Staff, 1992).

Profile No. 174/1-2

a) Morphology

The profile is located on an undulating position on the upland. The A-horizon is 25 cm thick, clay, dark brown (7.5YR 3/2), sub-angular blocky structure and friable. The Bt horizon is 88 cm thick, silty clay to clay, dark brown (7.5YR 3/2), sub-angular blocky structure and firm. There are pieces of weathering rock in the Bt3 horizon. Below the Bt3 horizon is a layer of weathering material. Soil horizon boundaries are clear and smooth.

b) **Chemical**

Organic carbon in the A-horizon is 0.86%. pH-H_2O increases with depth from 7.3 in the top soil to 7.9 in the sub-soil. EC of the topsoil is 0.57 dS/m while that of the subsoil ranges from 0.52 dS/m to 0.55 dS/m. CEC decreases with depth from 66.61 cmol(+)/kg soil in the topsoil to 65.52 cmol(+)/kg soil in the sub-soil. Ca and K decreased with depth while Mg and Na increased with depth. Base saturation is approximately 100% in the profile.

c) **Physical**

There was a slight increase with depth in the sand content (9% to 12%). Silt content increased from 31% in the A-horizon to 45% in the Bt2 horizon and then decreased to 32% in the Bt3 horizon. Clay distribution in the profile is irregular with Bt1 horizon of 50%, Bt2 horizon 48% and Bt3 horizon 56%.

d) **Interpretation**

The argillic horizon in these soils was most likely formed by transport of peptized clay particles percolated through the cracks. Clay translocation is particularly prominent in soils, which crack in the dry season but become wet during occasional downpours. The soils have favourable physical properties as indicated by the sTable blocky structures. It should be pointed out that the high silt contents pose a risk to slaking and erosion. The high base saturation indicates that these soils are chemically fertile.

Mapping Unit UFr

1) Environment

The total area of the unit is 352.80 ha. Parent material comprises gneisses rich in ferro-magnesian minerals, mainly biotite and hornblende-biotite gneisses. The vegetation is bushed grassland of *Chloris roxburghiana* and *Cenchrus ciliaris* with *Combretum apiculatum* and *Combretum collinum*. The mapping unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is undulating to gently undulating uplands with rather uniform convex slopes ranging from 4-8%.

2) Soil properties and classification

The soils are well drained, deep to very deep strongly weathered friable sandy clays. The soils are classified as Rhodic Ferralsols (FAO/UNESCO, 1994) or Rhodic Haplustox (Soil Survey Staff, 1992).

Profile No. 174/1-5

a) Morphology

The profile is located on an undulating position on the upland. The A-horizon is 26 cm thick, dark reddish brown (2.5YR 3/4), sandy clay, sub-angular blocky structure and friable. The B-horizon is 119 cm thick, dark reddish brown (2.5YR 3/4), sandy clay, porous massive to weak, medium angular blocky and friable. There are common small pores in all the horizons. Soil horizon boundaries are gradual and wavy.

b) Chemical

pH-H_2O increased with depth from 5.8 in the topsoil to 6.7 in the sub-soil. EC increased with depth from 0.09 dS/m in the topsoil to 0.26 dS/m in the sub-soil. Organic carbon in the A-horizon is 0.34%. CEC increased with depth from 13.08 cmol(+)/kg soil in the topsoil to 16.45 cmol(+)/kg soil in the sub-soil. Ca and Mg increased with depth while K and Na decreased with depth. Base saturation ranges from 92% to 103% in the profile.

c) Physical

The sand content decreased with depth from 55% in the topsoil to 40% in the sub-soil. Silt content increased slightly with depth from 9% in the topsoil to 13% in the sub-soil. Clay content increased with depth from 36% in the A-horizon to 47% in the BU3 horizon.

d) Interpretation

The deep solum and diffuse boundaries are characteristics that are typical of Ferralsols. The porous massive structure gives good permeability and high infiltration rates. The low CECs indicate that the soils are chemically poor.

4.1.4 Soils of the piedmont plains

Mapping unit YUd

1) Environment

The unit lies on a total area of 523.92 ha. Parent material comprises of colluvia and alluvia derived from various gneisses, mainly quartz-feldspar gneisses, which are poor in ferro-magnessian minerals. The vegetation is bushed grassland of *Themeda triandra, Digitaria macroblephara* with *Combretum* species, *Acacia Senegalensis* and other shrubs/trees. The soil mapping unit falls within agro-climatic zone V with rainfall of about 600 mm. Relief is composed of gently sloping area with slopes of about 3% and upto 4 km long.

2) Soil properties and classification

The soils are well drained, very deep, dark greyish brown to dark brown, friable, sandy clays. The soils are classified as Humic Cambisols (FAO/UNESCO, 1994) or Dystric Ustochrepts (Soil Survey Staff, 1992).

Profile No. 173/1-5

a) Morphology

The profile is located in the middle of the slope. The A-horizon is 22 cm thick, very dark grey (5YR 3/1), sandy clay loam to sandy clay, sub-angular blocky structure and friable. The B-horizon is 128 cm thick, dark reddish brown (5YR 3/3), sandy clay, sub-angular blocky structure and friable. There are very many small pores throughout the profile. The soil horizon boundaries are gradual and wavy.

b) Chemical

Organic carbon content of the topsoil is 0.56%. pH-H_2O increased from 4.60 in the topsoil to 4.90 in the sub-soil. The EC decreased with depth from 0.06 dS/m in the topsoil to 0.03 dS/m in the subsoil. CEC increases with depth from 12.60 cmol(+)/kg soil in the topsoil to 22.18 cmol(+)/kg soil in the subsoil. There is a general decrease with depth in the amounts of Ca, K and Na. Mg increased with depth from 1.58 cmol(+)/kg soil in the topsoil to 2.01 cmol(+)/kg soil in the B-horizon. Base saturation ranges from 23% to 28% in the profile.

c) Physical

The sand content decreased from 61% in the topsoil to 52% in the subsoil. Silt content was approximately 5% in the profile. Clay content increased from 35% in the A-horizon to 42% in the B-horizon.

d) Interpretation

These soils have medium texture, good structural stability, high porosity and good internal drainage, characteristics that are common in Cambisols. The strongly acid soil reaction and low base status may pose restriction on the use of these soils. The thick, dark grey A-horizon may be as a result of the influx of colluvium on the piedmont plain.

4.1.5 Soils of erosional plains

Mapping unit PU1

1) Environment

The total area of the unit is 938.87 ha. Parent material is composed of undifferentiated gneisses that are poor in ferro-magnessian minerals. Vegetation is wooded bushland and *Chloris roxburghiana* and *Sporobolus angustifolia* with *Commiphora schimperi* and *Acacia mellifera*. The unit falls within the agro-climatic zone V with rainfall of about 600 mm. Relief comprises flat to gently undulating uniform convex-concave slopes of upto 5%.

2) Soil properties and classification

The soils are well drained, very deep, dark brown to dark reddish brown, friable to firm, sandy clay to clay. They are classified as Haplic Lixisols (FAO/UNESCO, 1994) or Typic Haplustalfs (Soil Survey Staff, 1992).

Profile No. 173/2-6

a) Morphology

The profile is located on a flat area within the erosional plains. The A-horizon is 20 cm thick, dark brown (7.5YR 4/4), sandy clay loam, sub-angular to porous massive structure and friable. The Bt horizon is 180 cm thick, dark reddish brown (2.5YR 3/4), sandy clay to clay, porous massive to angular blocky structure and friable to firm. There are many fine pores throughout the profile. Soil horizon boundaries are gradual and wavy.

b) Chemical

Organic carbon in A-horizon is 0.74%. pH-H_2O increased with depth from 6.3 in the topsoil to 7.2 in the sub-soil. EC is approximately 0.05 dS/m in the profile. CEC increased with depth from 11.6 cmol(+)/kg soil in the topsoil to 15.2 cmol(+)/kg soil in the subsoil. Ca increased with depth from 5.6 cmol(+)/kg soil in the A-horizon to 8.6 cmol(+)/kg soil in the Bt4 horizon. Mg increased with depth from 2.3 cmol(+)/kg soil in the topsoil to 4.8 cmol(+)/kg soil in the subsoil. K decreased with depth from 1.4 cmol(+)/kg soil in the A-horizon to 0.3 cmol(+)/kg soil in the B-horizon. Na ranges from 0.1 cmol(+)/kg soil to 1.0 cmol(+)/kg in the profile. Base saturation ranges from 64% to 97% in the profile.

c) Physical

The sand content decreased from 61% in the topsoil to 49% in the subsoil. Silt content ranges between 6% to 12% in the profile. There was an increase in clay content with depth with a maximum of 47% in the Btl and Bt2 horizons.

d) Interpretation

The porous massive surface structure poses a problem of structure stability and hence there is a risk of slaking and cracking of the surface soil. The higher soil pH and absence of serious Al-toxicity makes these soils better than the Ferralsols and Acrisols.

Mapping unit PU2

1) Environment

The size of the unit is 2209.50 ha and the parent material comprise of undifferentiated gneisses that are predominantly quartz-feldspar gneisses poor in ferro-magnessian minerals. Vegetation is bushed grassland of *Chloris roxburghiana* and *Sporobolus angustifolia* with *Commiphora schimperi, Acacia ancistroclada* and *Acacia mellifera*. The unit is in agro-climatic zone V with rainfall of about 600 mm. Relief is gently undulating to undulating with convex-concave uniform slopes of upto 5%.

2) Soil properties and classification

The soils are well drained, deep to very deep, dark reddish brown to dark red, friable clays. They are classified as Rhodic Ferralsols (FAO/UNESCO, 1994) or Rhodic Haplustox (Soil Survey Staff, 1992).

Profile No. 173/2-2

a) Morphology

The profile is located in the middle of a slope on the erosional plains. The A-horizon is 23 cm thick, dark reddish brown (2.5YR 2.5/4), sand clay loam, sub-angular blocky to porous massive structure and friable. The B-horizon is 105 cm thick, dark reddish brown (2.5YR 3/4) to dark red (2.5YR 3/6), sandy clay to clay loam, porous massive to very weak angular blocky structure and friable. There are many fine pores in the profile. Soil horizon boundaries are gradual and wavy.

b) Chemical

pH-H_2O increased with depth from 5.3 in the topsoil to 5.9 in the subsoil. EC decreased with depth from 0.07 dS/m in the topsoil to 0.03 dS/m in the B-horizon. Organic carbon in the A-horizon is 0.57%. CEC is approximately 12 cmol(+)/kg soil in the profile. Exchangeable cations decrease with soil depth. Base saturation is between 39% and 62% in the profile.

c) Physical

The sand content decreased from 54% in the topsoil to 39% in the subsoil. Silt content increased with depth from 12% in the A-horizon to 23% in the BU3-horizon. Clay content increased from 34% in the topsoil to a maximum of 42% in the sub-soil.

d) **Interpretation**

These soils exhibit characteristic morphological features of Ferralsols i.e. deep solum, gradual horizon boundaries, good internal drainage, distinct red colours and absence of well developed blocky structures. The many biopores and sTable micro-aggregates account for good porosity, permeability and high infiltration rates in these soils. The low base saturation account for poor chemical fertility in these soils.

4.1.6 Soils of volcanic plains

Mapping Unit PBr

1) **Environment**

The total area of the unit is 4803.95 ha and parent material is olivine basalts. The unit is mainly flat and falls within agro-climatic zone V with rainfall of about 600 mm. Vegetation is grassland of *Digitaria spp., Sporobolus spp, Cenchrus ciliaris* and *Themeda triandra.*

2) **Soil properties and classification**

The soils are well drained, very deep, dark reddish brown to dark red, friable clays. They are classified as Eutric Cambisols (FAO/UNESCO, 1994) or Typic Ustochrepts (Soil Survey Staff, 1992).

Profile No. 174/1-1

a) Morphology

The profile is located in a flat area on the volcanic plains. The A-horizon is 22 cm thick, dark reddish brown (5YR 3/4), clay loam, sub-angular blocky structure and friable. The B-horizon is 178 cm thick, dark reddish brown (2.5YR 3/4) to dark red (2.5YR 3/6), clay loam angular blocky structure and friable. There are many fine pores throughout the profile. Soil horizon boundaries are gradual and wavy and there are weatherable minerals in the profile.

b) Chemical

Organic carbon is 0.59% in the A-horizon. pH-H_2O increased with depth from 6.0 in the topsoil to 6.5 in the subsoil. EC decreased with depth from 0.16 dS/m in the topsoil to 0.09 dS/m in the subsoil. Topsoil CEC is 20 cmol(+)/kg soil while that of the subsoil ranges from 15.20 cmol(+)/kg soil to 18.93 cmol(+)/kg soil. There is a general decrease with depth of the exchangeable cations. Base saturation ranges from 71% to 81% in the profile.

c) Physical

The sand content is highest in the Ap2-horizon with 43% and lowest in the BU2-horizon with 29%. Silt content distribution is irregular with 29% in the topsoil and a maximum of 44% in the B-horizon. Clay content is also irregularly distributed with 34% in the topsoil and a maximum of 35% in the subsoil.

d) **Interpretation**

These soils are best described by the following characteristics that are common in Cambisols.

- The presence of weatherable minerals in the profile
- The medium texture that makes them have a good structural stability, a high porosity and good water holding capacity.
- The near neutral to weakly acid soil reaction and a satisfactory chemical fertility

Mapping unit PBd

1) **Environment**

The unit occupies an area of 48.15 ha and the parent material is olivine basalts. Vegetation is grassland of *Digitaria spp.*, *Cenchrus cilliaris*, *Sporobolus spp* and *Themeda triandra*. The unit is on flat land and falls within agro-climatic zone V with rainfall of about 600 mm.

2) **Soil properties and classification**

The soils are well drained, deep, black, friable calcareous clays. The soils are classified as Haplic Luvisols (FAO/UNESCO, 1994) or Typic Haplustalfs (Soil Survey Staff, 1992).

Profile No. 174/1-4

a) Morphology

The profile is located in the middle of the plains. The A-horizon is 25 cm thick, black (2.5YR 2/0), clay. sub-angular blocky structure and friable. The B-horizon is 67 cm thick, black (2.5YR 2/0), clay, sub-angular blocky structure and friable. There are fragments of weathering rock in Bt_1 horizon. Below the Bt3 horizon is weathering rock. There are may fine pores in the profile. Soil horizon boundaries are clear and wavy.

b) Chemical

Organic carbon is 1.37% in the topsoil and decreased to 0.69% in the subsoil. pH-H_2O increased with depth from 6.5 in the A-horizon to 8.0 in the lower B-horizon. EC increased with depth from 0.34 dS/m in the topsoil to 0.52 dS/m in the subsoil. CEC increases with depth from 46.59 cmol(+)/kg soil in the topsoil to 61.15 cmol(+)/kg soil in the subsoil. Exchangeable cations increased with depth with Ca showing the most increase. Base saturation is 46% in the topsoil and increases to over 100% in the subsoil.

c) Physical

Sand content decreased from 37% in the topsoil to 18% in the subsoil. Silt content is approximately 12% in the profile. Clay content is 49% in the topsoil and increased to 68% in the B-horizon.

d) **Interpretation**

The thick black A-horizon is an indication of sTable conditions that allowed Vertical processes instead of lateral ones. Drainage waters have led to pervection resulting in the formation of an argic horizon. The Vertical processes have also resulted in the relative accumulation of exchangeable cations in the subsoil. The high base status is an indication that the soils are fertile. With sTable blocky structures and a porous well aerated profile, these soils have favourable physical properties.

4.1.7 Soils of bottomlands

Mapping unit BXC

1) **Environment**

The unit occupies an area of 5892.4 ha and the parent material is alluvial and colluvial clay deposits mainly derived from volcanic rocks and ashes. Vegetation is grassland of *Pennisetum mezianum*, *Lintonia nutans* and *Enchinochloa hapoclada*. The landscape is flat to very gently undulating with slopes of less than 2%. The unit falls within agro-climatic zone V with rainfall of about 600 mm.

2) **Soil properties and classification**

The soils are a complex of imperfectly drained, very deep, very dark brown to dark grey, firm cracking clays of varying calcareousness. They are classified as Eutric Vertisols, saline-sodic phase (FAO/UNESCO, 1994) or Typic Haplusterts (Soil Survey Staff, 1992).

Profile No. 174/1-7

a) Morphology

The profile is located in the middle of the bottomland. The A-horizon is 24 cm thick, very dark brown (10YR 3/3), clay, crumb structure and firm. The C-horizon is 81 cm thick, very dark brown (10YR 3/3), clay, angular blocky structure and firm. There are many thick slickensides throughout the profile. Soil horizon boundaries are generally gradual and the profile is cracked up to a depth of 50 cm.

b) Chemical

Organic carbon is about 0.74% in the profile. pH-H_2O increased with depth from 7.6 in the topsoil to 8.4 in the subsoil. EC of the topsoil is 0.67 dS/m while that of the subsoil is 0.87 dS/m. CEC is approximately 64 cmol(+)/kg soil in the profile. There is a general increase with depth of the exchangeable cations. Base saturation is more than 100% throughout the profile.

c) Physical

Sand content decreased with depth from 36% in the topsoil to 22% in the subsoil. Silt content also decreased with depth from 17% in the topsoil to 12% in the subsoil. Clay increased with depth from 47% in the topsoil to 66% in the subsoil.

d) Interpretation

The thick and dark A-horizon may have resulted from an influx of material from higher positions to the bottomlands. The relatively low moisture in the depressions and the material (organic matter) mix resulting into thick and dark A-horizon. The deep cracks and slickensides are as a result of swelling and shrinking of these soils. The very hard consistence when dry and very sticky and plastic when wet are unfavourable physical characteristics. The fine texture and poor internal drainage account for poor workability of these soils. These soils are fertile as shown by high CEC and high base saturation. The saline/sodic phase occurs in these soils because they are located in depressions without an outlet.

4.2 SOIL CLASSIFICATION, CORRELATION AND GENESIS

The soils of the study area are classified according to FAO/UNESCO-UNESCO (1994) system and the Soil Survey Staff (1992) system. The classification systems define a soil unit in terms of diagnostic horizons and diagnostic properties. Diagnostic horizons are soil horizons that combine a set of properties that are used in identifying soil units. These characteristics are expressed in terms of quantitatively defined morphological, chemical and physical properties that were developed during the process of soil formation. Most of the properties refer to permanent soil characteristics that are not easily altered.

The current FAO/UNESCO system of classification comprises 28 major soil groupings, sub-divided at the second level into 153 soil units. The Revised Legend (FAO/UNESCO, 1990) introduced a third level of soil sub-units, devised in support of soil mapping at larger scales (> 1:5,000). Phases are specific none taxonomic mapping units. They mark surface or sub-surface features of the land, limiting the agricultural use and often cutting across the boundaries of soil units or soil sub-units. This system is used as a framework for classification in Kenya.

Soil Taxonomy and FAO/UNESCO systems have a similar structure, but in line with its wider application in both large scale and small-scale soil mapping, Soil Taxonomy uses more hierarchical levels (categories) than the FAO/UNESCO system. The definitions of both diagnostics criteria (horizons) and properties of the FAO/UNESCO system were copied largely from the Soil Survey Staff Soil Taxonomy. This has the advantage that it is relatively easy to correlate the soils of both systems.

In this section, the description of the main soil classification units identified in the project area is given. Each of the identified classification units are described with respect to diagnostic horizons and diagnostic properties as far as they are relevant in the survey area.

4.2.1 Major classification units

Ferralsols

The essential diagnostic feature of ferralsols is the presence of a ferralic B-horizon. A ferralic B-horizon is at least 30 cm thick with a texture that is sandy loam or finer and has at least 8 per cent clay in the fine earth fraction. It has a CEC of $\leq$ 16 cmol(+)/kg^{-1} clay and less than 10% weatherable minerals in the 50-200 μm fraction. It has less than 10% water-dispensable clay and silt-clay ratio of 0.2 or less (FAO/UNESCO, 1994). The horizon does not show andic properties and has less than 5% by volume showing rock structure. Rhodic Ferralsols have been mapped in the study area.

Rhodic ferralsols have a red to dusky red ferralic B horizon which are not strongly Humic and lack geric properties. They also lack plinthite within 125 cm of the surface. In the study area, ferralsols are found on volcanic plains, footslopes and the uplands. They are developed from volcanic rocks and have good physical properties but are chemically poor. Ferralsols occupy nearly half of the project area. Their low natural fertility, virtual absence of weatherable minerals, and very low cation retention capacity are serious limitations.

Vertisols

These soils consist of the dark cracking clays that expand and contract with changes in moisture content resulting in the formation of polished and grooved surfaces called slickensides. The clays are dominantly montmorillonite, which is characteristically sticky and plastic when, wet and very hard when dry. These soils have an AC profile, the A horizon consisting of both the surface mulch (or crust) and the underlying structure profile that changes only gradually with depth (FAO/UNESCO, 1994). When dry, the cracks extend from the surface to depths of more than 50 cm and the cracks are at least 1 cm wide. Eutric Vertisols with a saline-sodic phase are found in the study area. Eutric Vertisols have a base saturation of 50% or more at least between 20 and 50 cm from the surface and lack calcic or gypsic horizon.

In the study area, Vertisols are found in bottomlands and are developed on various parent materials. Vertisols occupy nearly one fifth of the project area. The fine texture and poor internal drainage account for the often poor workability of Vertisols, both in wet and dry conditions.

Leptosols

Leptosols are soils, which are limited in depth by continuous bedrock or continuous cemented layer within 30 cm of the surface (FAO/UNESCO, 1994). In the project area, these soils are found on hills and scarps and are classified as eutric Leptosols. Eutric Leptosols have an ochric A-horizon and base saturation of 50% or more and lack hard rock and continuous cemented layer within 10 cm. The surface is stony and bouldery and the steep scarps have prominent rock outcrops. These shallow soils have developed due to steep eroded slopes.

Luvisols

Luvisols have an ochric or umbric epidedon and base saturation by ammonium acetate of 50% or more throughout the B-horizon and a cation exchange capacity equal to or more than 24 cmol(+)/kg soil in the argic B-horizon (FAO/UNESCO, 1994). Evidence of argic B-horizon includes a sufficient increase in clay content between A and B horizons and the presence of clay cutans on ped faces and in pores in part of the B-horizon. In the study area, Luvisols are found on the uplands and on plains. They have developed on volcanic rocks and have favourable physical properties and are generally fertile.

Cambisols

The cambic B-horizon is the only diagnostic feature that all Cambisols have in common. A cambic B-horizon can also occur in other major soil groupings but it is not a differentiating characteristic there because other properties are given a higher priority (salic properties in Solonchaks, gleyic properties in Gleysols and andic properties in Andosols).

The fact that Cambisols key out last in the taxonomic hierarchy of major soil groupings implies that Cambisols include many soils that just missed out on one or more requirements for other soil groupings. In other words, many Cambisols are in a transitional stage of development from a young soil to a mature soil with an argic, natric, spodic or ferralic B-horizon. Nonetheless, a cambic B-horizon can be quite sTable, viz: where the environment counteracts pedogenetic change, e.g. by low temperatures or even permafrost, or by low precipitation, or impeded drainage or weathering-resistant parent materials, or by a continuous supply of ions to relinquish ions lost by leaching. (i) recognizable soil structure (ii) greyish reduction colours and/or (iii) a stronger chroma, redder hue or higher clay content than the underlying horizon mark a cambic B-horizon (FAO/UNESCO, 1994). Eutric Cambisols have an ochric A-horzizon and a base saturation of 50 per cent or more at least between 20 and 50 cm from the surface but which are not calcareous within this depth. Humic cambisols have an umbric A-horizon or a mollic A-horizon overlying a cambic B-horizon with a base saturation of less than 50 per cent. In the study area the cambisols are found on the plains.

Acrisols

Acrisols are characterized by the presence of an argic B-horizon, a dominance of sTable low activity clays and a general paucity of bases. The argic B-horizon forms through (i) clay dispersion (ii) clay transport and (iii) clay accumulation in a Bt-horizon.

Most Acrisols have a thin, brown. ochric A-horizon; darker colours occur where (periodic) water-logging, augmented perhaps by oligotrophy hinders mineralization of soil organic matter. Most Acrisols have bright red and yellow sub-surface colours. Gleyic soil properties and/or plinthite are common in Acrisols in low terrain positions. Eluviation of the surface horizons of Acrisols has lowered their sesquioxide content. The soil structure is weak and individual elements collapse readily under the impact of tropical rains showers, particularly where the E-horizon has become exposed by erosion. The structure of the Bt-horizon is more sTable. Haplic Acrisols are strongly Humic, lack ferric properties, lack plinthite within 125 cm of the surface and lack gleyic properties within 100 cm of the surface (FAO/UNESCO, 1994). The Acrisols in the study area are found on the footslopes.

Lixisols

Most Lixisols have a brown ochric A-horizon (not seldom shallow as a result of erosion) over a brown or reddish brown argic B-horizon. The sub-surface soil may show signs of iron redistribution. The horizon of eluviation of clay and free iron oxides may be sufficiently developed to qualify as an albic E-horizon. Lixisols have an argic B-horizon which has a cation exchange capacity of less than 24 cmol (+)/kg clay at least in some part of the B-horizon and a base saturation of 50 percent or more throughout the B-horizon (FAO/UNESCO, 1994). Haplic Lixisols lack an albic E-horizon, lack ferric properties and plinthite within 125 cm of the surface and lack gleyic and stagnic properties within 100 cm of the surface. Lixisols are found on the plains in the study area.

Correlation of the units found in the project area

FAO/UNESCO-UNESCO system	SOIL SURVEY STAFF Taxonomy
Leptosols	Entisols
Ferralsols	Oxisols
Luvisols	Alfisols
Vertisols	Vertisols
Cambisols	Inceptisols
Acrisols	Ultisols
Lixisols	Alfisols

4.2.2 Soil genesis

Soil forming factors of parent material, topography (relief), climate, organisms and time determine development of soils. Understanding of the influence of these factors helps greatly in the mapping and classification of soils. In order to understand better the pattern of soils in the survey area, an overview on soil genesis is presented in relation to the soil forming factors.

4.2.2.1 Influence of parent material

The soils of the survey area have developed on basement system rocks and various volcanic rocks. The mineralogy of five rock samples was examined and the analysis revealed that the rocks were predominated by iron oxides, vesicles, clays, feldspars, rutile and pyroxenes (Table 2).

Table 2: Petrographic analysis of rock samples of Mashuru area

Rock sample No **Mineralogy**	**173/3-3**	**174/1-12**	**74/1-6**	**174/1-8**	**174/1-5**
Vesicles %	50	35	10	7	-
Iron oxides (Fe_3O_4	35	30	15	14	2
%)	2	5	-	-	-
Silica (%)	5	9	10	5	10
Clays (%)	3	3	22	30	15
Feldspar (%)	2	5	5	2	2
Rutile (%)	2	9	10	2	-
Pyroxenes (%)	-	-	25	30	-
Augite (%)	-	-	-	-	28
Amphibole (%)	-	-	-	10	-
Olivine (%)	-	-	-	-	3
Biotite (%)	-	-	-	-	40
Quartz (%)	1	5	3	-	-
Others (%)					
Name of rock	Pumice	Tuff	Basalt	Basalt	Hornblende-Gneiss

The feldspars exhibited multiple lamellae that showed good cleavage parallel to the basal planes. This high angle of extinction indicated that the plagioclase feldspar were calcic. The high percentage of vesicles in samples 173/3-3 and 174/1-12 is an indication of the enrichment of this area with volcanic lava. Pumice is the lava that contains abundant vesicles while tuff is the consolidated lava. The ferro-magnessian minerals (olivine, augite, biotite and amphiboles) are generally in low to moderate amounts in the rocks. Two rock samples (173/3-3 and 174/1-12) are rich in iron oxides (Fe_3O_4) while the other samples indicate low to moderate amounts of the oxides. The amount of silica in the rocks is low.

Sand fraction mineralogy was obtained for soils developed on various volcanic rocks and those developed on Basement System rocks. The results are presented in Table 3 below.

Table 3: ***Sand mineral composition of the samples***

Profile No.	Geology	Depth	Quartz	Calc feldspar (%)	Magnetite (%)	Haematite (%)	Biotite (%)	Allanite (%)	Orthoclase (%)	Hornblende (%)	Iron ores (%)	Calcite (%)	Ilmenite (%)
174/1-1	VV	0-10	40	20	5	5	10	-	-	10	-	-	-
		10-22	40	20	10	5	10	10	-	5	5	-	-
		72-117	40	20	10	10	10	10	-	-	-	-	-
		117-200	40	20	5	5	10	10	-	10	10	-	-
174/1-3	VV	24-45	40	-	20	5	10	15	-	5	5	5	-
		45-77	30	20	10	-	20	7	-	10	10	-	-
		77-106	40	30	10	-	10	10	-	-	-	-	-
		106-190	40	20	5	5	-	10	-	10	-	-	-
173/2-2	BS	0-23	40	-	15	2	3	-	30	-	9	1	-
		23-47	30	-	20	5	2	-	40	-	1	1	-
		34-128	40	-	10	3	15	-	20	-	10	-	2
173/2-4	BS	0-18	50	-	-	-	15	-	30	-	-	-	-
		18-58	50	10	5	20	-	2	5	5	3	-	-
		58-108	50	25	5	5	3	2	-	5	5	-	-
		108-150	50	5	-	-	-	5	-	-	20	-	-

- = mineral not detected

VV = various volcanic rocks

BS = Basement System rocks

In the above Table it is evident that the samples have high amounts of quartz. Two samples (174/1-1 and 174/1-3) from an area on various volcanic rocks show moderate levels of calc-feldspars. The samples from Basement System rocks indicate relatively high amounts of orthoclase (K-feldspars). There are moderate amounts of magnetite, haematite and biotite in samples from both various volcanic rocks and Basement system rocks.

Geo-chemical composition of selected soil samples indicated that the soils are rich in the oxides of Si, Al, Fe, Ti and K (Table 4).

Table 4: Geo-chemical composition of selected soil samples

Profile No.	Horizon	Depth (cm)	CaO %	MgO %	SiO_2	Al_2O_3	Fe_2O_3	MnO	K_2O	Na_2O	TiO_2	SiO_2/Al_2O_3	Soil Class
	Ap1	0-10	0.30	0.48	40.50	25.50	16.60	0.13	1.12	0.66	4.39	1.6	
	Ap2	10-22	0.23	0.45	40.20	27.30	16.90	0.12	1.07	0.68	4.54	1.5	Eutric
174/1-1	Bu1	22-72	0.17	0.41	38.60	26.20	15.70	0.10	0.89	0.66	4.24	1.4	Cambisols
	Bu2	72-117	0.17	0.41	38.10	27.00	16.00	0.10	0.83	0.66	4.46	1.4	
	Bu3	117-200	0.23	0.42	37.50	26.10	15.70	0.10	0.74	0.66	4.29	1.4	
	Ap1	0-23	0.24	0.44	45.50	24.20	10.20	0.09	1.44	0.70	2.93	1.8	Rhodic
173/2-2	Bu1	23-47	0.15	0.38	49.00	26.60	10.30	0.06	1.23	0.66	2.86	1.8	Ferralsols
	Bu3	74-128	0.11	0.34	46.00	30.20	11.40	0.05	1.08	0.65	3.07	1.5	
	AB	25-45	0.26	0.50	45.50	25.00	19.60	0.15	0.72	0.67	4.27	1.8	
	Bu1	45-77	0.27	0.50	38.10	25.90	20.20	0.16	0.68	0.67	4.54	1.5	Rhodic
174/1-3	Bu2	77-106	0.26	0.47	38.00	26.10	20.60	0.15	0.61	0.66	4.41	1.5	Ferralsols
	Bu3	106-150	0.28	0.49	35.50	26.30	20.50	0.15	0.61	0.67	4.61	1.4	
	A	0-25	0.25	0.55	36.90	24.00	10.10	0.13	0.95	0.68	4.96	1.5	
173/2-4	Bt2	58-103	0.13	0.41	48.80	27.90	8.30	0.04	0.65	0.62	4.45	1.7	Haplic
	Bt3	103-150	0.12	0.39	42.90	26.00	8.20	0.03	0.62	0.63	4.47	1.7	Acrisols

The high silica and aluminium oxide contents of the soils resulted from the weathering of calc-feldspars and the orthoclases (K-felspars). According to Allen and Hajek (1989), calc-feldspars have a higher weathering potential than the orthoclases. The weathering of K-feldspars resulted in relatively high levels of K^+ while that of plagioclases gave rise to Ca^{2+} (Table 4). Although these soils show low levels of Ca^{2+}, it should be noted that the weathering of plagioclase feldspars has a direct bearing on the presence of Ca^{2+} in soils.

According to Longwell *et al.*(1969), ferro-magnesian minerals (pyroxenes in the study area) weather to give Fe^{2+} and Mg^{2+} as metallic ions and silica and aluminium as colloids. Pyroxenes are considered unsTable in pedogenic environments (Allen and Hajek, 1989). They weather easily giving cations of Fe^{2+}, Mg^{2+} and Ca^{2+}.

The sand fraction of the soils (Table 3) was dominated by quartz, calcic-feldspars, magnetite, biotite and haematite. The assemblage of the minerals reflected the nature of the parent material i.e. volcanic rocks are typified by basic plagioclase feldspar and pyroxenes whereas the basement system is characterised by orthoclases (K-feldspars). Since calcic feldspars weather fairly rapidly, their presence indicated a relatively short period of pedogenesis. The presence of magnetite in both the rocks and the soils indicated that its presence in the soils was geo-genetic i.e. as a result of rock weathering. Haematite was present in most of the soil samples but was not observed in the rocks. This indicated that the mineral was a secondary product of the weathering of magnetite. Biotite was present in the soils but absent in the rocks. This indicated that the biotite in soils was of pedogenetic origin.

According to Longwell *et al.*(1969), magnetite upon weathering produce Fe^{2+} as metallic ions and iron oxides as colloids while haematite and limonite are the secondary minerals. The high amounts of Fe_2O_3 in the soils explains the red colours on the hills, footslopes, uplands and plains. The red colours are due to the presence of haematite as confirmed by the sand mineralogy. According to Allen and Hajek (1989), haematite is an effective soil-pigmenting agent. It has colours of 5YR to 2.5YR and forms extremely small crystallites. Schwertmann and Taylor (1989) noted that even at low concentrations in soil, haematite has a high pigmenting power and determine the red colour in soils.

The SiO_2:Al_2O_3 ratios (Table 4) were nearly constant throughout the profiles. This reflected an environment devoid of the leaching typical of the semi-arid conditions in the survey area. Mohr *at al.* (1972) suggested that SiO_2:Al_2O_3 ratios greater than 2 indicates fersiallitic weathering. Higher ratios reflect intense chemical activity in the soil. In the survey area, the ratio for the soils was less than 2, implying little chemical activity. This is confirmed by the low cation exchange capacities. According to Allen and Fanning (1983), rutile weathers to give titanium oxides. The high levels of TiO_2 in the soils resulted from the weathering of rutile.

As indicated and confirmed by chemical, mineralogical and geo-chemical analyses, it can be concluded that parent material has greatly influenced chemical and mineralogical properties of soils in the study area. The mineralogy of the sand fraction reflected the processes that the parent materials have undergone. The presence of calcic-feldspars and haematite indicated incomplete weathering and that there is a high nutrient reserve potential.

Iron oxides

With the high amounts of iron oxides in these soils, it is appropriate to illustrate the manifold significance of the oxides in the soils so as to better understand the genesis of the soils and their behaviour as plant growth mediums. The iron oxides (a term used to embody oxides, oxyhydroxides and hydrated oxides) are the most abundant of the metallic oxides in soils (Schwertmann and Taylor, 1989). They are present in most soils of the different climatic regions as very fine particles in one or more of their mineral forms and at variable levels of concentration. They may occur evenly dispersed throughout the soil in horizons or in friable or loose consistency, or concentrated in discrete horizons or in particular morphological features as in ferricretes, mottles, nodules or pipestems (Aniku and Singer, 1990).

The many different mineral phases previously have been referred to as "free iron oxides" in an attempt to differentiate between true oxides and the Fe bound in other minerals such as the silicates (Torrent *et al.*, 1980). This distinction is unnecessary, since Fe in other minerals is not really present as an oxide; therefore, it will be more meaningful to refer to the minerals collectively as "iron oxides", and subsequently distinguish primary and secondary or pedogenic forms (Schwertmann and Taylor, 1989).

Pedogenic Fe-oxide minerals form under the influence of the common soil-forming factors (climate, relief, parent material, organisms and time) and therefore reflect the pedo-environmental conditions under which they have formed (Schwertmann, 1988). Once formed, the mineral phases, composition and distribution of Fe oxides may be subject to continual modification in an approach towards equilibrium with the changing soil environment (Newman, 1987). Even at low concentrations in soils, Fe oxides have a high pigmenting power and determine the colour of many soils. Thus, yellow, brown and red soil colours as determined by the type and distribution of Fe oxides within a profile, help explain soil genesis and are used in all languages for naming and classifying soils (e.g. Red-Yellow Podzolic, Braunerde, sols rouges tropicaux, terra rossa and Kransnozem).

According to Schwertmann and Taylor (1989), the chemical nature and high specific surface area of sub-microscopic Fe-oxide particles make them efficient sorbents and therefore sinks for (i) inorganic anions such as silicate, phosphate and molybdate; (ii) organic anions and molecules such as citrate, fulvic and Humic acids and biocides; and (iii) cations such as Al, Cu, Pb, V, Zn, Co, Cr and Ni, some of which are essential for plant growth. The cations can be adsorbed on the surface or incorporated into the oxide structure. Barberis *et al* (1991) found that Fe-oxides affect soil structure often including the formation of aggregates and the cementation of other major soil components giving rise to nodules, pipestems, plinthites, ortsteins and bog iron ores.

Of the crystalline pedogenic Fe-oxides, geothite and haematite are the most common (Aniku and Singer, 1990). Lepidocrosite has occasionally been found in well drained soils and in some buried paleo-soils. Maghemite, also rare, has been reported by Abreu and Robert (1985). This mineral, when present in the A-horizon, usually results from the transformation of other Fe-oxides by forest fires. However, it has also been found in B-horizon, where it seems to be neoformed.

Geothite occurs in almost every soil type and climatic region and is responsible for the yellowish-brown colour of many soils and weathered materials (Schwertmann, 1993). Rubification (i.e. reddening due to pedogenic haematite formation) is favoured by a pedo-environment where soils are warm, dry for long periods and low in organic matter (Schwertmann *et al.*, 1982). Haematite refers to the bright red colour of this mineral in a finely dispersed state. This colour makes haematitic soils red (5YR and redder) and because of its greater pigmenting power, can mask the yellow colour of higher concentrations of geothite. The redness of various soils has been found to be significantly correlated with their haematite content (Torrent *et al*, 1983).

The distribution of three forms of iron oxides developed from various volcanic rocks and Basement system rocks was carried out. Table 5 gives the results of the three forms of iron oxides.

Table 5: Percentages of pyrophosphate (Fe_p), Oxalate (Fe_{ox}) and dithionite (Fe_d) extracTable iron oxide and active-Fe and Fed clay ratios in the soils.

Horizon	Depth (cm)	Colour	Fe_p (%)	Fe_{ox}(%)	Fe_d (%)	Fe_{ox}/Fe_d	Fe_d/Clay	Classification
Profile No. 174/1-1								
Ap1	0-10	d.r.b	0.10	1.67	5.88	0.28	0.17	
Ap2	10-22	d.r.b	0.13	0.42	4.96	0.08	0.17	Eutric Cambisols
Bu2	72-117	d.r.	0.07	0.99	6.31	0.16	0.23	
Bu3	117-200+	d.r	0.06	0.14	6.29	0.02	0.18	
Profile No. 174/1-3								Rhodic Ferralsols
AB	24-45	d.r.b	0.02	2.80	5.94	0.47	0.22	
Bu1	45-77	d.r	0.03	0.01	7.86	0.001	0.23	
Bu2	77-106	d.r	0.01	1.06	2.54	0.42	0.09	
Bu3	106-150+	d.r	0.02	1.21	5.86	0.21	0.29	
Profile No. 173/2-2								Rhodic Ferralsol
A	0-23	d,r.b	0.15	1.67	2.46	0.68	0.07	
Bu1	23-47	d.r.b	0.16	1.86	2.87	0.65	0.07	
Bu3	74-128+	d.r	0.14	1.68	2.95	0.57	0.08	
Profile No. 173/2-4								Haplic Acrisols
A	0-18	d.r.b	0.16	0.44	0.77	0.57	0.06	
Bt1	18-58	d.r.b	0.09	0.99	1.20	0.83	0.05	
Bt2	58-108	d.r	0.09	0.34	2.09	0.16	0.06	
Bt3	108-150+	d.r	0.23	1.02	1.33	0.77	0.03	

In the above Table, nearly all of the pyrophosphate-extracTable Fe values were lower than the corresponding oxalate values. The organic bound iron (Fe_p) in the soils ranges from 0.01 to 0.23%, indicating that Fe_p contributes a negligible proportion of total iron oxides in the soils. Low values of Fe_p in soils may be attributed to low organic carbon contents. There is irregular variation in the Fe_p content in the soils within profiles.

Profiles Nos. 174/1-3 and 173/2-2 have each nearly uniform contents of Fe_p due to almost similar values of organic carbon contents. Profile No. 174/1-1 has relatively high values of organic carbon contents in the topsoil, which is consequently reflected by the relatively high

Fe_p contents. The high organic carbon content in the topsoil is probably due to an accumulation of vegetative materials. Profile No. 173/2-4 shows the highest Fe_p content in the sub-soil. This profile has a coarse topsoil texture and the subsoil is clay. The relatively high Fe_p content in the subsoil may be due to the migration of the iron oxides, bound as organic complexes, from the coarse-textured surface soil to the finer textured subsoil.

Oxalate extracTable iron oxide (Fe_{ox}) content is higher in the surface soils of profile pits Nos. 174/1-1 and 174-1-3 than in the subsoils. Fe_{ox} values in the surface soil range between 1.67% and 2.80% whereas values for the sub-soils range between 0.01% and 1.21. Profile pit no. 173/2-2- has an average Fe_{ox} value of 1.74% whereas Fe_{ox} values for profile pit no. 173/2-4 ranges between 0.34% and 1.02%. The degree of crystallinity of Fe oxides is determined by the pedo-environment (Schwertmann and Taylor, 1989). Excessive temperatures and relatively low contents of inhibitors of crystallization (organic matter and silicate) determine that the ferrihydrite formed when Fe is released from the primary Fe-bearing minerals be converted into crystalline Fe-oxides (Schwertmann, 1985). The prolonged high temperatures and low organic matter in the project area may serve to explain the low content of Fe_{ox} in the soils.

The total iron oxides (Fe_d) content of the soils ranged from approximately 1% to 8%. This is high when compared with values of soils developed on volcanic ash. Okoth (1988) presented values of dithionite extracTable iron of soils developed on volcanic ash that were approximately 1.0%. The high values in the Fe_d in the project area are probably because the soils are rich in ferro-magnesian minerals.

Except for profile pit no. 174/1-3, there is a general increase with depth in the contents of Fe_d in the soils of the other profiles. Profile pit no. 174/1-1 and 174/1-3 contain the highest amounts of the total iron oxides (Fe_d) throughout the profile (4.96 to 6.31% and 2.54 to 7.86%, respectively). In well drained soils, Fe-oxides occur as isolated crystals or in small aggregates concentrated in the clay-fraction (Torrent *et al.*, 1980). Consequently, *Fed* is correlated to the clay content of the soil. In the study area, however, there is no correlation between the clay content and the distribution of the Fe_d in the profiles. The Fe_d/clay ratio generally ranged from 0.03 to 0.29 (Table 5), which means that on a weight basis, about 3-29% of the clay fraction corresponds to Fe oxides.

The distribution of oxalate extracTable Fe to dithionite extracTable Fe within each pedon can be conveniently expressed as "active Fe ratio" (Lekwa and Whiteside, 1986). The Fe_{ox}/Fe_d ratio measures the degree of activity of the Fe-oxides and has often been used in pedogenic studies where it generally decreases with soil age (Aniku and Singer, 1990). The active Fe ratios are generally higher in the topsoil than the subsoil in the profile nos. 174/1-1, 174/1-3 and 173/2-2. The decrease in the active Fe ratio with depth indicated that higher proportions of Fe are present in more crystalline forms in the lower horizons of the profiles. In profile no. 173/2-4,

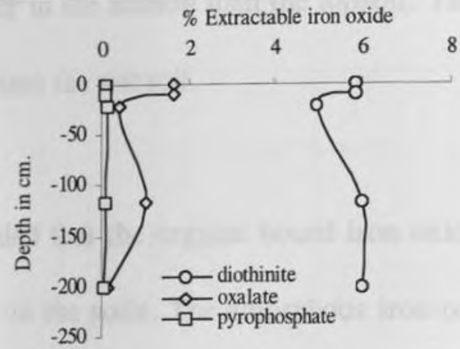

Figure 3. Depth functions of extractable iron oxide in profile 174/1-1

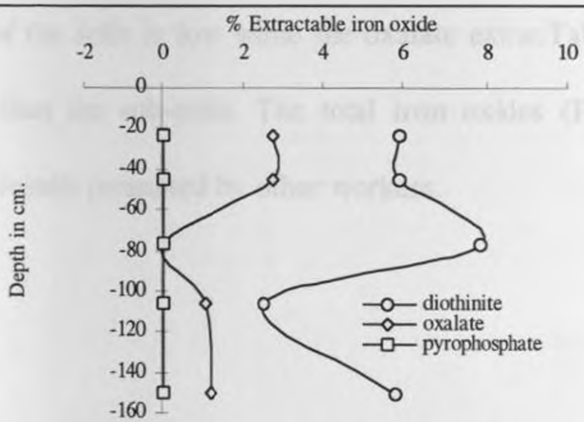

Figure 4. Depth functions of extractable iron oxides in profile 174/1-3

the ratio is higher in the subsoil than the topsoil. This indicates illuviation and accumulation of Fe from topsoil into the subsoil.

It can be concluded that the organic bound iron oxides constitute a negligible proportion of the total iron oxides in the soils. The amorphous iron oxides are generally low as compared to the total iron oxides. It should be pointed out that there is a high correlation between the P adsorbed by a soil and the level of oxalate-soluble Fe and also between P adsorption and the more crystalline Fe oxides (Borgaard, 1988a).

Figures 3-6 show graphical representations of the distribution of iron oxides in the soils. The Fe_p content of the soils is low while the oxalate extracTable iron content is generally high in the topsoils than the sub-soils. The total iron oxides (Fe_d) content of the soils is high as compared to results presented by other workers.

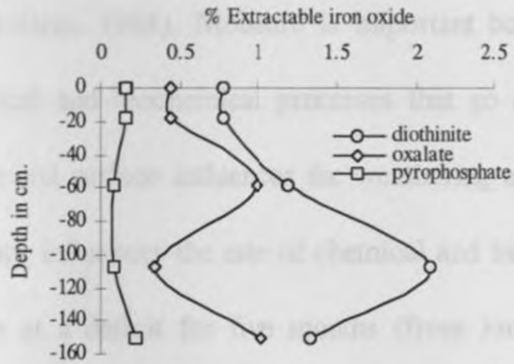

Figure 6 Depth functions of extractable iron oxide in proile 173/2-4

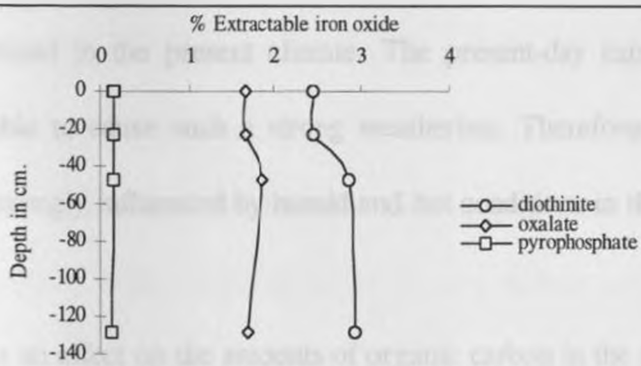

Figure 5. Depth functions of exractable iron oxide in profile 174/2-2

4.2.2.2 Influence of climate

Moisture and temperature are the two aspects of climate most important in controlling soil properties (Birkeland, 1984). Moisture is important because water is involved in most of the physical, chemical and biochemical processes that go on in soil, and the amount of moisture delivered to the soil surface influences the weathering and leaching conditions with depth in the soil. Temperature influences the rate of chemical and biochemical processes. In the project area, soil moisture is at a deficit for five months (from June to October). The probability that the rainfall exceeds 600 mm in any one year is about 40% (Table 1).

A considerable part of the soils in the survey area are deep, reddish, non-calcareous and predominantly kaolinite in their clay mineral composition. They have few weatherable primary minerals left and show a weak or non-argic horizons (Ferralsols). These strongly weathered soils cannot be attributed to the present climate. The present-day rainfall and seasonal distribution would not be able to cause such a strong weathering. Therefore it must be assumed that soil formation was strongly influenced by humid and hot conditions in the past.

Temperature has an effect on the amounts of organic carbon in the soil. High temperatures lead to high decomposition rates of organic carbon (Sanchez, 1976) and this explains the low topsoil carbon contents (<1%). Though the soil to some extent has a stabilizing effect on the decomposition of organic carbon (Duchaufour, 1982) the influence of temperature seems to outweigh the chemical and mineralogical soil components. The result is lower organic carbon contents than would be found under cooler, more humid conditions (Mizota, 1987).

4.2.2.3 Influence of relief

According to Daniels and Hammer (1992), topography influences soil formation by controlling the dynamics within and above the soil mantle. Generally, the higher parts are better drained than the lower parts giving different environments for clay formation. The migration of silica, calcium and magnesium salts is normally downslope resulting in neo-formation of montmorillonitic clays on foot slope positions. Aluminium is normally less mobile and its concentration reduces downslope.

Topography influences soil formation in terms of spatial redistribution within the soil mantle of the bases, aluminium, iron and silica. The better drained summits have higher concentrations of Al than the slopes. The more mobile basic cations like sodium migrate to the downslope positions accompanied by calcium. Clay and silica are also translocated in the same way. The steeper midslope positions sometimes have shallower soils than the summit and footslope positions. This is caused by truncation of the steeper slopes by flowing surface water (Birkeland *et al.*, 1991).

Within the study area, the influence of topography is seen by the systematic arrangement of different soil units from the hill summits down to the bottomlands. Soil variations occur from Entisols on the relief summits, Alfisols on footslopes and Inceptisols in the Swale positions. Within the uplands, Oxisols occupy the summits and middle positions while Vertic Alfisols occupy the lowest positions. The drainage is generally better on the higher parts than on the lower parts. Soil depth increases downslope.

On the piedmonts, the higher slopes are normally well drained, the middle moderately well drained and the lower ones somewhat imperfectly drained. Soil units vary from Dystric Ustochrepts on upslope and midslope positions to Typic Ustochrepts on downslope position. The thickness of B-horizon is highest on the downslope position.

In the study area, Rhodic Ferralsols are mainly found on uplands and on plains. It is significant to note that these soils occur on old landscapes i.e. landscapes of gentle relief not or little affected by erosion.

Under conditions of a relatively flat topography without free drainage, volcanic ash enrichment may contribute to the formation of fine textured soils with Vertic properties (Daniels and Hammer, 1992). In combination with certain base rich parent materials, imperfect drainage may also lead to the formation of fine-textured soils with Vertic properties. An example is the Eutric Vertisols of unit BXC. As they are formed under imperfect drainage conditions, the Vertisols have saline-sodic subsoil. With increasing relief intensity and erosion, younger and shallower soils may be expected. Such a sequence has been observed in the project area on those basement system rocks, which are not affected by more recent ash enrichment.:

- Ferralsols on plains (mapping unit PU2)
- Acrisols on footslopes (mapping unit FUr)
- Leptosols on hills and scarps (mapping unit HUP).

Figures 7a and 7b are N-S cross sections showing the influence of topography in relation to soil development.

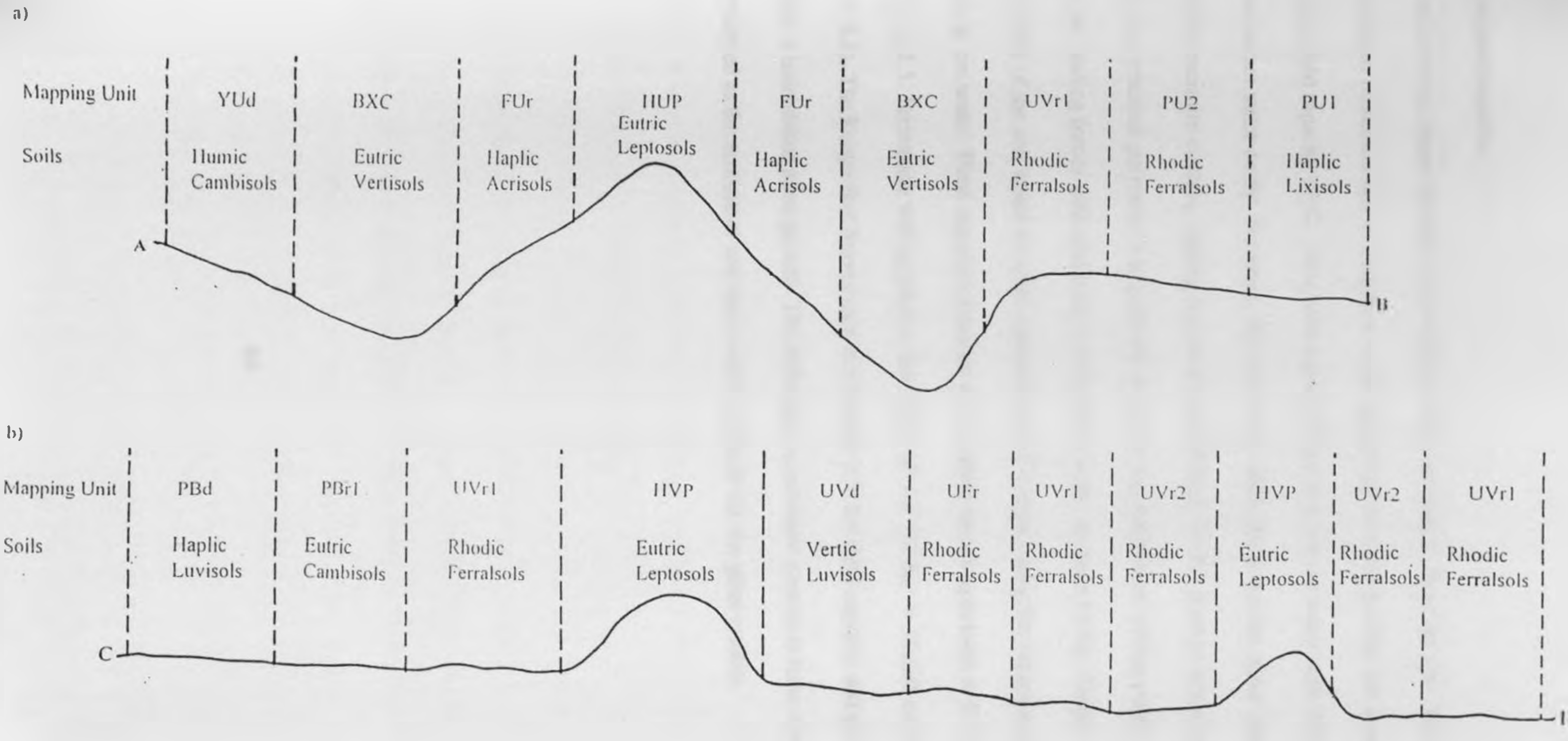

Fig 7. Schematic cross sections showing influence of relief on soil development

4.3 Soil physical aspects

For growth and survival, plants depend on the moisture they can extract from the soil. The soils retain moisture from infiltrated rain or irrigation water against the force of gravity; the amount retained is called field capacity (F.C). Near field capacity the soil holds the water with little force and plants can extract water easily. However, the force with which the soil holds water increases with a decreasing moisture content, making it increasingly difficult for the plant to extract water from the soil. For practical purposes, it is generally accepted that permanent wilting point (W.P), occurs when the binding forces with which the soil holds the water exceeds 15 bar (Hillel, 1982). The binding forces of the soil water are often expressed as pF-values, being the logarithm of the binding forces in cm water. Field capacity coincides with binding forces equivalent to 0.1 to 0.33 bar, or pF 2.0 to 2.5. Permanent wilting point is reached at pF 4.2 (15 bar = 15,000 cm water; log 15,000 = 4.2). The Kenya Soil Survey uses 0.2 bar (pF 2.3) for field capacity and pF 3.7 for the upper limit of uninhibited plant growth. The difference in moisture content at these two pF values is considered as the amount of soil water easily available for the plant growth.

Table 6: ***Results of pF-analyses***

Soil Classification	Depth (cm)	Moisture content (vol. %) at pF								Available* moisture	% silt + Caly
		0	1.0	1.5	2.0	2.3	2.7	3.7	4.2		
Rhodic Ferralsol	0-5	31.45	29.96	27.24	24.30	21.14	19.61	10.00	13.0	11.14	56
	50-55	43.57	42.22	38.86	34.02	23.89	22.00	12.65	14.0	11.24	69
	98-103	40.18	38.04	33.96	31.59	24.81	22.85	12.0	13.0	11.81	73
Vertic Luvisol	2-7	38.89	37.47	35.28	32.52	24.81	22.63	11.0	11.0	13.81	91
	34-39	40.80	39.79	36.93	32.94	25.14	24.72	12.0	14.0	13.14	92
	103-108	43.49	41.95	38.50	32.30	28.16	25.50	14.0	15.0	14.16	88
Rhodic Ferralsol	0-5	32.84	25.94	25.06	20.46	16.12	6.79	4.76	5.0	11.36	17
	24-29	27.03	25.94	18.36	14.56	11.00	8.84	7.0	8.0	4.0	26
	82-87	32.84	31.11	25.09	22.96	21.23	19.93	11.0	11.0	10.23	37
Humic Cambisol	0-5	52.60	40.23	37.44	33.10	31.20	27.80	23.90	21.30	7.3	39
	50-55	48.70	42.61	38.27	36.70	34.50	31.50	26.10	24.20	8.40	48

* Available moisture = moisture content at pF 2.3 - moisture content at pF 3.7

Table 6 presents average results of the pF analyses from A and B horizons of four profile pits. The Table shows a difference in moisture between the Rhodic Ferralsols and the other two soils (Vertic Luvisols and Humic Cambisols). The Rhodic Ferralsols (units UVR1, UVR2, PU2) have about 11 volume % available moisture in their A and B horizons while the Luvisols (unit Uvd) and Cambisols (unit YUd) have about 13% and 8% respectively.

The very high silt+clay % of the Vertic Luvisols can account for the high moisture retention of the soils. The Rhodic Ferralsols have a somewhat limited available water holding capacity because of low silt content. The relatively less favourable water retaining capacity of the Humic Cambisols may have been influenced by their topographic position. Other physical aspects on which data are available are porosity and bulk density. The data given in Table 7 are for the soils listed in Table 6, averaged per soil classification unit.

Table 7: Porosity and bulk density

Soil classification	Porosity (%)		Bulk density (g/cm^3)	
	A-horizon	B-Horizon	A-horizon	B-Horizon
Rhodic Ferralsol	31	42	1.37	1.20
Vertic Luvisols	38	42	1.28	1.23
Rhodic Ferralsols	33	30	1.38	1.39
Humic Cambisols	52	48	1.18	1.26

The porosity (%) is that proportion of the volume of an undisturbed soil, which is not occupied by solid soil material. Theoretically, the volume of water in a completely saturated, undisturbed soil equals the porosity. As this condition is supposed to occur at pF 0, the % water (vol.) at this pF was taken as a measure for the porosity. The relevant data are presented in Table 7.

Bulk density is expressed in g/cm^3 and is a measure for the weight of undisturbed, air-dry soil. Average data are given in Table 7 for the listed soils. The combined data of Table 7 does not allow for detailed conclusions. However, the Cambisols have a higher porosity and a lower bulk density than the Ferralsols and the Luvisols. This means that there is less root penetration impedence in the Cambisols than in the Ferralsols and the Luvisols.

4.4 Soil fertility status

For the soil fertility appraisal of the survey area, composite topsoil (0-20 cm) samples were taken at the sites of representative profile pits and analyzed according to a "mass analysis' method for soil fertility evaluation (Chapter 3.2.3). Total nitrogen in the soil was obtained empirically from the content of organic carbon in the soil. The C:N ratio in a soil is approximately 10:1 (Landon, 1984). From this relationship, total nitrogen was thus calculated. Total nitrogen is considered deficient if less than 0.2%. Based on Landon (1984) and Okalebo et al., (1993). Table 8 presents classes for available P, K, Ca and Mg. The Table shows general tendencies since fertilizer response depends on soil chemical characteristics and the various crops under consideration. The analytical data on the available nutrients are presented in Table 9.

Table 8: Available nutrient classification

Nutrient	Deficiency level	Adequate level	Excessive or reactionary level
Phosphorus mg/kg	Less than 20	20-80	greater than 80
Potassium cmol(+)/kg	Less than 0.2	0.2-1.5	greater than 1.5
Calcium cmol(+)/kg	Less than 2.0	2.0-15.0	greater than 15
Magnesium cmol(+)/kg	Less than 1.0	1.0-3.0	greater than 3.0

Table 9: Available nutrients (0-20 cm)

Mapping Unit	PBr	Uvd	UVr1	UFr	UVr2	HVP	HUP	PU1	YUd	BXC
Observation	174/1-1	174/1-2	174/1-3	174/1-5	174/1-12	173/1-9	173/2-3	173/2-2	173/2-5	174/1-7
Laboratory No.	1	02	03	05	12	09	15	14	17	07
PH-H_2O	6.85	7.30	6.58	6.83	6.40	6.85	6.32	6.13	5.88	7.84
Na (cmol(+)/kg)	0.18	0.15	0.13	0.13	0.15	0.15	0.18	0.13	0.15	0.28
K (cmol(+)/kg)	1.20	0.65	0.78	0.75	0.63	0.43	0.70	0.38	0.90	0.20
Ca (cmol(+)/kg)	5.00	36.00	5.00	6.58	3.5	37.50	23.00	1.50	6.00	4.50
Mg (cmol(+)/kg)	1.65	5.44	1.85	1.49	2.59	5.31	4.17	1.55	3.61	2.85
Mn (cmol(+)/kg)	2.05	2.07	2.58	1.92	1.02	1.36	1.18	2.00	1.29	1.51
P (mg/kg)	19	55	22	94	27	295	113	12	60	22
N (%)	0.05	0.12	0.06	0.06	0.04	0.16	0.13	0.06	0.09	0.06
C (%)	0.46	1.06	0.61	0.56	0.37	0.57	1.31	0.64	0.99	0.59

Apart from soils of mapping unit BXC that are moderately alkaline, the soils of the other mapping units are moderately acid to near neutral. Except soil mapping units Uvd and HUP where organic carbon is in moderate amounts, the other units have registered low amounts. Na, K, Ca, Mg and Mn are adequate to excessive in all the soil mapping units.

Mapping unit PU1 and PBr are deficient in P while the other mapping units show adequate to excessive levels of the nutrient. According to Sanchez (1976), highly weathered Oxisols, Ultisols and slightly weathered Andepts and Vertisols have a common problem of phosphorus deficiency. This is due to fixation and immobilization of phosphorus by aluminium oxides, iron oxides, calcium and magnesium ions when present in large quantities. Given that the soils in the survey area are highly weathered, it is strange that they contain adequate to excessive amounts of phosphorus. Even with the high levels of phosphorus, these soils are characteristically low in the portion utilizable for crop growth. This condition is aggravated by unfavourable environmental conditions such as low soil moisture and high temperatures when crops are heading and ripening.

The project area has recorded less than 0.2% N and hence there is a deficiency of total nitrogen. Nitrogen occurs in soils as organic compounds, nitrate and nitrite anions and ammonium ions (Tisdale *et al.*, 1985). Nitrates are the main forms of N used by plants. Mineralization of organic N compounds takes place through aminization, ammonification and nitrification. These processes are influenced by soil and climatic conditions (Matson and Vitousek, 1981). Therefore, the amount of nitrogen that will be mineralized depends a lot on the soil mineral and chemical properties. The low levels of N in these soils could be attributed to both the soil and climatic conditions. Application of nitrogenous fertilizers to these soils is recommended.

It can be concluded that these soils have got adequate to excessive levels of Na, K, Ca, Mg and Mn. Mapping units PU1 and PBr are deficient in P while the other mapping units have sufficient supplies of the nutrient. Level of %N is low in all the soils.

Total nutrient reserve

For optimum growth of most agricultural crops, the total as well as the proportion of nutrients play a major role. The proportions of Ca, K and Mg in relation to one another is important in that over-supply of one may hinder the uptake of the other resulting in deficiency although the element exist in adequate amounts in the soil (Medina and Cuevas, 1989). For proper growth the optimum ratios of Ca:K and Ca:Mg are 10:1 and 4-2:1, respectively (Landon, 1984). The following key (Braun and Van de Weg, 1977) was used in the appraisal of the total nutrient reserve.

Nutrient reserve	P (mg/kg)	K (cmol(+)/kg)	Mg (cmol(+)/kg)
Low	<250	<5	<10
Moderate	250-500	5-25	10-40
high	>500	>25	>40

Soil samples from a selected few soil profiles were analyzed for total nutrient reserve of P, K and Mg and the results are presented in Table 10.

Table 10: Total nutrient reserve of selected soil profiles

Soil mapping unit	Classification	Profile No.	Total nutrient reserve		
			P	K	Mg
PU1	Haplic Lixisols	173/2-6	44	3.2	2.8
UVr1	Rhodic Ferralsols	173/1-3	120	2	15
PBr	Eutric Cambisols	174/1-1	210	2	33
BXC	Eutric Vertisols	174/1-7	65	3	135
YUd	Humic Cambisols	173/2-5	650	14	180

In Table 10, except for soil mapping unit Yud that has high levels of total P, the other units registered low amounts of the nutrient. Similarly, total K content is low in the same units except YUd where it is moderate. Soil mapping units BXC and YUd are high in total Mg, unit PBr has moderate amounts and units PU1 and UVr1 registered low amounts of the nutrient.

The group of soils with the lowest nutrient reserve are the Haplic Lixisols and Rhodic Ferralsols of mapping units PU1 and UVr1 (Table 10). The second group of soils are the Eutric Cambisols and Eutric Vertisols of mapping units PBr and BXC. This group has low nutrient reserve of P and K but moderate to high reserves of Mg. The last group of soils are the Humic Cambisols of unit YUd. This group has high amounts of P, K and Mg.

The total nutrient reserve correlates in general with the pattern discussed on available nutrients both for individual elements as well as for the general fertility status. In terms of fertility, mapping unit PU1 has the poorest soils while unit YUd has the richest soils. The other soil mapping units have moderately fertile soils.

CHAPTER FIVE: SUMMARY AND CONCLUSIONS

The physical, morphological, chemical and mineralogical properties of the soils in the study area can be summarized as follows:

Physical

The Rhodic Ferralsols have a somewhat limited available water holding capacity because of low silt content. The Vertic Luvisols retain more available moisture relative to their high silt+clay % due to the high silt content in these soils. The Humic Cambisols have a relatively less favourable water retaining capacity. The Cambisols have a higher porosity and lower bulk density than the Ferralsols and the Luvisols. The Leptosols have silty clay loam textures while the Acrisols tend to be sandy clay. The texture of Ferralsols vary from clay loams to sandy clays while the Lixisols have silty loam to sandy clay texture. The Cambisols have texture that varies from clay loam to sandy clays. The Vertisols and Luvisols have clay texture.

Morphological

The Ferralsols and Lixisols have sub-angular blocky topsoil structures with porous massive subsoil that break into angular blocks. The other soils have in general subangular blocky structures in the topsoil and angular blocks in the subsoil. Most of the soils have dark reddish brown topsoils and dark red subsoils. The Vertisols are very dark brown. Soil horizon boundaries tend to be gradual and wavy.

Chemical

The carbon contents range from very low to moderate (0.31-1.63%). There is an increase of carbon contents down the topo-sequences, a fact conditioned by higher soil moisture in the lower slope positions or accretion by downslope translocation. Most of the project area has adequate (20-80 mg/kg) to excessive (80 mg/kg) levels of P while most soils have adequate (0.2-1.5 cmol(+)/kg) amounts of K. The soils recorded adequate (2.0-15 cmol(+)/kg) to excessive (>15 cmol(+)/kg) levels of calcium. Magnesium levels are also adequate (1.0-3.0 cmol(+)/kg) to excessive (>3.0 cmol(+)/kg). The CECs are generally high (mean 25.2 cmol(+)/kg soil) and the base saturation is high except in a few cases when values below 50% were obtained.

Mineralogical

The soils are rich in iron (Fe^{3+}), aluminium, titinium, silica but low in manganese. The high amount of Fe^{3+} is due to the presence of iron oxide (magnetite). High amount of silica (SiO_2) in the soils is due to the predominance of feldspars and quartz. The pyroxenes weathered resulting in cations of Fe^{2+}, Mg^{2+} and Ca^{2+}. The high levels of TiO_2 in the soils resulted from weathering of rutile. Augites and amphiboles were detected in three rock samples and are probably responsible for the high amounts of Al_2O_3 in the soils. The organic bound iron oxides constitute a negligible proportion of the total iron oxides in the soils and the amorphous iron oxides are generally low as compared to the total iron oxides. Low values of organic bound iron oxides may be attributed to low organic carbon contents. The prolonged high temperatures and low organic matter in the study area are responsible for the low values of amorphous iron oxides. The sand mineralogy analysis shows two things: (i) the presence of quartz, orthoclase, biotite and hornblende are indications of the Basement system rocks (ii) the volcanic assemblage is characterized by calc-feldspars and alterites.

Genesis and classification

Parent material, topography and climate have influenced soil formation in the area. Most soils have been classified as Ferralsols according to the FAO/UNESCO (1994) classification and Oxisols according to Soil Survey Staff (1992). Other soils include Vertisols, Cambisols, Leptosols, Acrisols, Luvisols and Lixisols. Vertisols are found in the bottomlands whereas Cambisols are found on the piedmont plains and volcanic plains. Leptosols are found on hills and Acrisols on footslopes. Luvisols are found on uplands and on volcanic plains. Lixisols are found on erosional plains. Four genetical groups, separated according to parent material, relief, climatic conditions and soil characteristics are identified in the area.

The first group consists of the Leptosols. This group has higher clay contents in the topsoil than the subsoil. Found on hills, soil formation of these soils is slow and as a result, they are poorly developed. The second group consists of Acrisols, Luvisols and Lixisols. The group has higher clay content in the Bt-horizon when compared to the other groups. Found on flat to slopping land, the soils are strongly weathered. The third group consists of Ferralsols and Cambisols. The group has an irregular distribution of clay in the profile. The soils are found on level to undulating land. The last group consists of Vertisols that are found in bottomlands.

The group is separated from the rest because of its physical characteristics and the relatively high sodium contents.

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APPENDIX 1: DESCRIPTION AND CLASSIFICATION OF THE REPRESENTATIVE SOIL PROFILE PITS WITH ANALYTICAL DATA

Mapping Unit HVP

Total area	:	1853.02 ha
Parent material	:	Various volcanic rocks, which are predominantly olivine basalts in the form of boulders, breccia and agglomerates.
Relief	:	Small rounded singular hills with convex to straight slopes of >16%.
Vegetation and land use	:	Bushed grassland/grazing.
Soils general	:	Somewhat excessively drained, shallow, bouldery and gravelly soils with a weakly developed horizon differentiation.
Colour	:	The colour is dark reddish brown (5YR 3/4) throughout.
Texture	:	Gravelly clay loam, with stones and gravel increasing with depth.
Structure	:	Weak, medium, sub-angular blocky throughout.
Consistence	:	Slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet throughout the profile.
Chemical properties	:	The organic carbon (OC) in the A-horizon is 1.25%. The pH-H_2O is 6.3 in the top soil and 6.5 in the sub-soil respectively.

Electrical conductivity (EC) is between 0.29 and 0.34 dS/m in the topsoil and subsoil respectively. The cation exchange capacity (CEC) of top soil is 21.12 cmol(+)/kg soil while that of the B-horizon is 18.36 cmol(+)/kg soil. Calcium (Ca) is 12.20 cmol(+)/kg in the top soil and 9.4 cmol(+)/kg B horizon. Magnesium (Mg) ranges between 4.32 cmol(+)/kg in the topsoil to 6.2 cmol(+)/kg in the sub-soil. Potassium (K) is 0.39 cmol(+)/kg throughout the profile. Sodium (Na) is 0.30 cmol(+)/kg in the topsoil and 0.1 cmol(+)/kg in the B-horizon. Base saturation (BS) is between 81% and 88% in the profile.

Representative profile pit No. 174/1-9

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-25	a	aw	5 YR/3/4 d.r.b	sb	42	15	43	C	12.20	4.32	0.39	0.30	21.12	1.25	81	5.2	6.31	0.29	
B	25-47			5 YR 3/4 d.r.b	sb	29	42	29	CL	9.4	6.2	0.39	0.1	18.36	0.92	88	5.3	6.5	0.34	

a = abrupt
w = wavy
d.r.b = dark reddish brown
sb = sub-angular blocky
Top = Topography

Soil classification: FAO/UNESCO (1994) : Humic Cambisols
Soil Survey Staff (1992) : Dystric Ustrochrepts

Mapping unit HUP

Total area	:	322.74 ha
Parent material	:	Basement system rocks: gneisses poor in ferro-magnesian minerals, predominantly quartz-feldspar and granitoid gneisses.
Relief	:	Variable and irregular slopes, in general over 16%
Vegetation and land use	:	Wooded dense bushland and grassland/semi-nomadic and sedentary grazing.
Soils general	:	Somewhat excessively drained, shallow to deep, rocky and stony.
Colour	:	Colours range from dark yellowish brown (7.5YR 3/6) to dark reddish brown (5YR 3/2).
Texture	:	Gravelly sandy clay loam.
Structure	:	Weak, medium, sub-angular blocky throughout.
Consistence	:	Slightly hard when dry and friable to firm when moist, slightly sticky and slightly plastic when wet.
Chemical properties	:	Organic carbon is 1.13% in the profile. pH-H_2O and EC are 6.31 and 0.31 dS/m respectively. CEC is 17.60 cmol(+)/kg soil in the top soil and 16.0 cmol(+)/kg in the subsoil. Ca and Mg are about 7.0 cmol(+)/kg and 3.0 cmol(+)/kg respectively in the profile. K and Na are 0.96 cmol(+)/kg and 0.57 cmol(+)/kg respectively. Base saturation is 67% in the topsoil and 75% in the subsoil.

Representative profile pit No. 173/2-3

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-14	A	A	7YR/3/2 d.r.b	Sb	13	57	30	SiCL	7.11	3.17	0.96	0.57	17.60	1.13	67	5.5	6.31	0.32	
C	14-66				Sb	33	38	27	CL	7.30	3.24	0.84	0.61	16.00	1.02	75	5.6	6.40	0.35	

a = abrupt
w = wavy
d.r.b = dark reddish brown
sb = sub-angular blocky
Top = Topography

Soil classification: FAO/UNESCO (1994) : Eutric Regosols
USDA (1992) : Typic Ustorthents

Mapping unit FUr

Total area	:	522.49 ha
Parent material	:	Colluvium derived from various gneisses, predominantly quartz-feldspar gneisses and in places gneisses rich in ferro-magnesian minerals (biotite and hornblende-biotite gneisses).
Relief	:	Uniform, slightly concave to straight slopes ranging from 4 to 16%.
Vegetation and land use	:	Bushed grassland/rainfed fallow cultivation and semi-nomadic grazing.
Soils general	:	Well drained, very deep, strongly weathered soils.
Colour	:	Topsoil is dark reddish brown (5YR 2.5/2) and the subsoil is dark red (2.5YR 3/6).
Texture	:	The top soil is sandy whereas the sub-soil is sandy clay.
Structure	:	Weak, medium sub-angular blocky structure in the topsoil and weak, angular blocky in the subsoil.
Consistence	:	Slightly hard when dry, friable when moist and slightly sticky and non-plastic when wet.
Chemical properties	:	The pH-H_2O decreases with depth from 5.3 in the top soil to 4.4 in the sub-soil. EC decreases with depth from 0.06 dS/m in the topsoil to 0.03 dS/m in the sub-soil. The topsoil has 0.49 and the sub-soil has between 0.19 and 0.30% organic carbon. CEC of the topsoil is 9.80 cmol(+)/kg soil while that of the subsoil is between 7.40 and 10.80 cmol(+)/kg soil. Ca in the topsoil ranges between 0.09 and 1.47 cmol(+)/kg soil. Mg increases with depth from 0.67 cmol(+)/kg soil in the topsoil to 2.36 cmol(+)/kg soil. K decreases with depth from 0.84 cmol(+)/kg soil in topsoil to 0.08 cmol(+)/kg soil in the subsoil. Na decreases with depth from 0.32 cmol(+)/kg soil in the topsoil to 0.07 cmol(+)/kg soil in the sub-soil. Base saturation is less than 50% in all horizons.

Representative profile pit No. 173/2-4

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-18	g	w	5 YR2.5/2 d.r.b	sb	83	3	14	SL	1.21	0.67	0.84	0.32	9.80	0.49	31	4.7	5.26	0.06	Free iron oxides
Bt1	18-58	g	w	2.5YR3/4 d.r.b	ab	74	3	23	SCL	0.09	0.98	0.64	0.22	10.80	0.30	18	4.2	4.75	0.05	"
Bt2	58-108	g	w	2.5YR3/6 d.r	ab	63	1	36	SC	1.47	1.62	0.34	0.17	7.40	0.19	49	4.0	4.44	0.03	"
Bt3	108-150+			2.5YR 3/6 d.r	ab	46	2	52	C	1.35	2.36	0.08	0.07	10.00	0.27	39	4.0	4.39	0.03	"

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification: FAO/UNESCO (1994) : Haplic Acrisols

Soil Survey Staff (1992) : Typic Rhodustults

Mapping unit UVr1

Total area	:	75070.10 ha
Parent material	:	Pleistocene volcanics, mainly olivine balsalts in the form of agglomerates and breccias.
Relief	:	Uplands with smooth, slightly concave and convex slopes surrounding the hills of unit HVP. Slope percentage ranges from 3-7%.
Vegetation and land use	:	Wooded bushed grassland/semi-nomadic grazing.
Soils general	:	Well drained, very deep soils that surround the hills.
Colour	:	Topsoil is dark reddish brown (2.5YR 3/4) and the sub-soil is dark red (2.5YR 3/6).
Texture	:	Clay throughout the profile.
Structure	:	Weak, medium sub-angular blocky structure in the topsoil and porous massive to weak, very fine, angular blocky in the subsoil.
Consistence	:	Slightly hard when dry, friable when moist, sticky and plastic when wet.
Chemical properties	:	The topsoil has organic carbon content of between 0.36 and 0.42%. The topsoil has a pH-H_2O range of 5.97 to 6.37 while that of the subsoil ranges from 6.10 to 7.08. The EC of the topsoil ranges from 0.17 to 0.19 dS/m while that of the subsoil ranges from 0.10 to 0.17 dS/m. CEC of the topsoil ranges between 12.0 and 18.71 cmol(+)/kg soil while that of the sub-soil ranges between 12.52 to 18.70 cmol(+)/kg soil. Ca increases with depth from 3.9 cmol(+)/kg in the topsoil to 12.3 cmol(+)/kg in the subsoil. Mg ranges between 2.66 cmol(+)/kg to 3.70 cmol(+)/kg in the topsoil to 3.01 cmol(+)/kg in the B-horizons. K decreases with depth from 1.45 cmol(+)/kg in the top soil to 0.79 cmol(+)/kg in the subsoil. Na ranges between 0.60 to 0.65 cmol(+)/kg in the topsoil while the subsoil has a range of 0.55 to 0.60 cmol(+)/kg. The base saturation ranges from 67% in the topsoil to 98% in the subsoil.

Representative profile pit No. 174/1-3

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-24	g	w	2.5YR/3/4 d.r.b	sb	42	36	22	L	3.90	2.66	1.45	0.60	12.0	0.42	71	5.5	5.97	0.19	Free iron oxides
AB	24-45	g	w	2.5YR ¾ d.r.b	sb	34	39	27	CL/L	6.6	3.7	1.38	0.85	18.71	0.36	67	5.4	6.37	0.17	"
Bu1	45-78	g	w	2.5YR 3/6 d.r	pm - ab	31	35	34	CL	5.92	2.87	1.05	0.55	12.52	0.39	83	5.3	6.10	0.10	"
Bu2	77-106	G	w	2.5YR 3/6 d.r	pm - ab	27	46	27	CL/L	6.20	2.99	0.89	0.55	14.32	0.31	74	5.7	6.44	0.17	"
Bu3	106-150+			2.5YR 3/6 d.r	pm - ab	24	56	20	SiC	12.3	3.01	0.79	0.60	17.00	0.23	98	6.1	7.08	0.11	"

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification: FAO/UNESCO (1994) : Rhodic Ferralsols

Soil Survey Staff (1992) : Rhodic Haplustox

Mapping Unit UVr2

Total area	:	197.34 ha
Parent material	:	Pleistocene volcanics, mainly olivine basalts in the form of agglomerates and breccias.
Relief	:	Slightly concave and convex slopes surrounding the hills of unit HVP. Slope percentages range from 3-8%.
Vegetation and land use	:	Wooded bushed grassland/semi-nomadic grazing.
Soils general	:	Well drained, deep soils that are shallower and have a stony phase as compared to unit UVr1.
Colour	:	Dark reddish brown throughout the profile.
Texture	:	Silty clay throughout the profile.
Structure	:	Moderate, fine to medium sub-angular blocky structure in the topsoil and porous massive to weak, very fine, angular blocky in the subsoil.
Consistence	:	Slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet.
Chemical properties	:	The top soil has organic carbon content of 0.48%. Topsoil pH-H_2O is 5.8 while that of the subsoil ranges from 6.4 to 6.5. The EC of the topsoil is 0.11 dS/m while that of the subsoil ranges from 0.06 to 0.09 dS/m. CEC of the topsoil is 13.20 cmol(+)/kg soil while that of the subsoil decreases from 12.60 cmol(+)/kg soil to 10.92 cmol(+)/kg soil. Ca is 3.31 cmol(+)/kg in the topsoil and decreases to 1.20 cmol(+)/kg soil in the B-horizon. Mg increases with depth from 2.24 cmol(+)/kg in the topsoil to 3.76 cmol(+)/kg in the subsoil. K decreases with depth from 1.52 cmol(+)/kg in the topsoil to 0.38 cmol(+)/kg in the B-horizon. Na decreases with depth from 0.82 cmol(+)/kg in the topsoil to 0.42 in the subsoil. Base saturation is between 52% and 60% throughout the profile.

Representative profile pit No. 174/1-12

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-20	g	w	2.5YR3/4 d.r.b	sb	4	22	74	C	3.31	2.24	1.52	0.82	13.20	0.48	60	5.3	5.77	0.11	
Bu1	20-47	g	w	2.5YR3/4 d.r.b	pm-ab	28	52	20	SiL	2.11	3.14	1.04	0.52	11.60	0.39	59	5.7	6.42	0.08	
Bu2	47-79	g	w	2.5YR3/4 d.r.b	pm-ab	26	56	18	SiL	2.21	2.80	1.04	0.72	12.60	0.37	54	5.8	6.47	0.06	
Bu3	79-119			2.5YR3/4 d.r.b	Pm-ab	24	59	17	SiL	1.20	3.76	0.38	0.42	10.92	0.26	52	5.8	6.51	0.09	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography
pm = porous massive

Soil classification FAO/UNESCO (1994) : Rhodic Ferralsols
Soil Survey Staff (1992) : Rhodic Haplustox

Mapping unit UVd

Total area	:	37.84 ha
Parent material	:	Pleistocene volcanics, mainly olivine basalts in the form of agglomerates and breccias.
Relief	:	Undulating with slopes of 4-8%
Vegetation and land use	:	Wooded bushed grassland/semi nomadic grazing.
Soils general	:	Well drained, deep, bouldery and stony soils showing Vertic properties.
Colour	:	Dark brown (7.5YR 3/2) throughout.
Texture	:	Clay throughout with pieces of weathering rock in the lower part of the subsoil.
Structure	:	Moderately strong, medium sub-angular blocky structure throughout.
Consistence	:	Slightly hard when dry, friable when moist, sticky and plastic when wet.
Chemical properties	:	Organic carbon in the A-horizon is 0.86%. The pH-H_2O increases with depth from 7.3 in the topsoil to 7.9 in the subsoil. EC of the topsoil is 0.57 dS/m while that of the subsoil ranges from 0.52 dS/m to 0.55 dS/m. CEC of the topsoil is 66.61 cmol(+)/kg soil and decreases in the subsoil to 65.52 cmol(+)/kg soil. Ca decreases with depth from 59 cmol(+)/kg in the topsoil to 46.8 cmol(+)/kg in the subsoil. Mg is low in the topsoil (1.04 cmol(+)/kg) while the subsoil has approximately 18.00 cmol(+)/kg. K decreases from topsoil with 1.10 cmol(+)/kg to 0.65 cmol(+)/kg in the subsoil. Na increases with depth from 0.55 cmol(+)/kg in the topsoil to 1.25 cmol(+)/kg in the subsoil. Base saturation is approximately 100% throughout the profile.

Representative profile pit No. 174/1-2

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH H_2O	EC (dS/m)	
A	0-25	C	S	7.5YR3/2 d.b	sb	9	31	60	C	59	1.04	1.10	0.55	66.61	0.86	93	5.8	7.24	0.57	
Bt1	25-55	C	S	7.5YR3/2 d.b	sb	8	42	50	SiC	55	18.64	0.80	0.80	66.61	0.81	113	6.0	7.27	0.52	
Bt2	55-102	C	S	7.5YR3/2 d.b	sb	9	45	48	SiC	48.8	18.76	1.04	0.95	65.88	0.78	106	6.0	7 86	0 53	
Bt3	102-113			7.5YR3/2 d.b	sb	12	32	56	C	46.8	17.88	0.65	1.05	65.52	0.80	101	5 9	7 94	0.55	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography
C = clear
S = smooth

Soil classification: FAO/UNESCO (1994) : Vertic Luvisols

Soil Survey Staff (1992) : Vertic Haplustalfs

Mapping unit UFr

Total area	:	352.80 ha
Parent material	:	Gneisses rich in ferro-magnesian minerals: biotite and hornblende-biotite gneisses.
Relief	:	Undulating to gently undulating uplands with rather uniform convex slopes ranging from 4-8% up to 500 m long.
Vegetation and land use	:	Bushed grassland/semi nomadic grazing
Soils general	:	Well drained, deep to very deep, strongly weathered friable soils.
Colour	:	Dark reddish brown (2.5YR 3/4) throughout.
Texture	:	Sandy clay throughout
Structure	:	Weak, medium, sub-angular blocky structure in the A-horizon and porous massive to weak, medium, angular blocky structure in B-horizon.
Consistence	:	Slightly hard when dry, friable when moist, sticky and plastic when wet.
Chemical properties	:	Organic carbon in the A horizon is 0.34%. The pH-H_2O increases with depth from 5.75 in the topsoil to 6.72 in the subsoil. EC increases with depth from 0.09 dS/m in the topsoil to 0.26 dS/m in the subsoil. CEC increases with depth from 13.08 cmol(+)/kg soil in the topsoil to 16.45 cmol(+)/kg soil in the subsoil. Ca increases with depth from 8.1 cmol(+)/kg in the topsoil to approximately 10 cmol(+)/kg in the subsoil. Mg increases with depth from 2.96 cmol(+)/kg in the topsoil to 6.17 cmol(+)/kg in the subsoil. K decreases with depth from 1.08 cmol(+)/kg in the topsoil to 0.63 cmol(+)/kg in the subsoil. Na decreases with depth from 0.45 cmol(+)/kg in the topsoil to 0.20 cmol(+)/kg in the subsoil. Base saturation ranges from 92% to 103% in the profile.

Representative profile pit No. 174/1-5

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	% C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-26	g	w	2.5YR3/2 d.r.b	sb	55	9	36	SC	8.1	2.96	1.08	0.45	13.08	0.34	96	5.5	5.75	0.09	
Bu1	26-45	g	w	2.5YR3/4 d.r.b	pm-ab	50	9	41	SC	10.0	3.83	0.62	0.25	15.90	0.36	92	5.1	5.83	0.11	
Bu2	55-120	g	w	2.5YR3/4 d.r.b	pm-ab	47	7	46	SC	9.72	4.32	0.35	0.20	16.45	0.29	89	5.8	6.29	0.13	
Bu3	120-145			2.5YR3/4 d.r.b	pm-ab	40	13	47	SC	8.64	6.17	0.63	0.55	15.45	0.25	103	5.7	6.72	0.26	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification FAO/UNESCO (1994) : Rhodic Ferralsols
Soil Survey Staff (1992) : Rhodic Haplustox

Mapping unit YUd

Total	:	523.92 ha
Parent material	:	Colluvia and alluvia derived from various gneisses, mainly quartz-feldspar gneisses, which are poor in ferro-magnesian minerals.
Relief	:	Very gently sloping area with slopes of less than 3% and upto 4 km long.
Vegetation and land use	:	Bushed grassland/semi-nomadic grazing and ranching.
Soils general	:	Well drained, very deep sandy clays.
Colour	:	The topsoil is very dark grey (5YR 3/1) while the subsoil is dark greyish brown (10YR 3/2).
Texture	:	Topsoils are in general of a much sandier texture than the subsoils, which are sandy clay loams or sandy clays.
Structure	:	Moderate, medium to coarse sub-angular blocky structure throughout the profile.
Consistence	:	The A-horizon is slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet. The B-horizon is hard when dry, friable when moist, slightly sticky and slightly plastic when wet.
Chemical properties	:	The topsoil has organic carbon content of 0.56%. pH-H_2O of the topsoil is 4.66 while that of the subsoil ranges from 4.60 to 4.90. The EC decreases with depth from 0.06 dS/m in the topsoil to 0.03 dS/m in the subsoil. CEC of the topsoil is 12.60 cmol(+)/kg soil and that of the subsoil ranges from 10.80 cmol(+)/kg soil to 22.18 cmol(+)/kg soil. Ca decreases with depth from 1.23 cmol(+)/kg in the topsoil to 0.46 cmol(+)/kg in the subsoil. Mg increases with depth from 1.58 cmol(+)/kg in the topsoil to 2.01 cmol(+)/kg in the subsoil. K decreases with depth from 0.30 cmol(+)/kg in the topsoil to 0.08 cmol(+)/kg in the subsoil. Na is 0.17 cmol(+)/kg in the topsoil and nil in the subsoil. The base saturation ranges from 23% to 28% in the profile.

Representative profile pit No. 173/2-5

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-22	g	w	5YR3/1 v.d.g	sb	61	4	35	SCL/SC	1.23	1.58	0.30	0.17	12.60	0.56	26	4.0	4.66	0.06	
Bu1	22-50	g	w	5YR3/3 d.r.b	sb	54	5	41	SC	0.63	1.81	0.25	0.0	10.80	0.42	23	3.9	4.60	0.03	
Bu2	50-103	g	w	5YR3/3 d.r,b	sb	52	6	42	SC	0.55	1.96	0.16	0.0	22.18	0.34	20	3.8	4.72	0.04	
Bu3	103-150+			5YR3/3 d.r.b	sb	53	5	42	SC	0.46	2.01	0.08	0.0	20.16	0.23	28	3.8	4 90	0.04	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification FAO/UNESCO (1994) : Humic Cambisols

Soil Survey Staff (1992) : Dystric Ustochrepts

Mapping unit PU1

Total area	:	938.87 ha
Parent material	:	Undifferentiated gneisses, poor in ferro-magnesian minerals
Relief	:	Flat to very gently and gently undulating with uniform convex-concave slope of maximally 5% and about 2 km long.
Vegetation and land use	:	Wooded bushland/rainfed fallow cultivation and semi-nomadic grazing
Soils general	:	Well drained, very deep, weakly developed soils.
Colour	:	Top soil is dark brown (7.5YR 4/4) to dark reddish brown (5YR 3/2). The subsoil is dark reddish brown (2.5YR 2/4) to yellowish and (7.5YR 4/4).
Texture	:	The topsoil is sandy loam to sandy clay and there is always less clay than in the B-horizon.
Structure	:	The A-horizon is weak, medium, sub-angular blocky to moderately coherent porous massive. The subsoil is moderately coherent porous massive to weak, medium and coarse, angular blocky.
Consistence	:	Slightly hard when dry, friable to firm when moist, and sticky and plastic when wet throughout the profile.
Chemical properties	:	Organic carbon in A-horizon is 0.74%. The pH-H_2O increases with depth from 6.3 in the topsoil to 7.2 in the subsoil. EC in the topsoil is 0.05 dS/m and decreases to 0.04 dS/m in the subsoil. CEC increases with depth from 11.6 cmol(+)/kg soil in the topsoil to 15.2 cmol(+)/kg soil in the subsoil. Ca increases with depth from, 5.6 cmol(+)/kg in the topsoil in the topsoil to 8.6 cmol(+)/kg in the subsoil. Mg increases with depth from 2.3 cmol(+)/kg in the topsoil to 4.8 cmol(+)/kg in the subsoil. K decreases with depth from 1.4 cmol(+)/kg in the A-horizon to 0.3 cmol(+)/kg in the B-horizon. Na ranges from 0.1 cmol(+)/kg to 1.0 cmol(+)/kg in the profile. Base saturation ranges from 64% to 97% in the profile.

Representative profile pit No. 173/2-6

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H.O	EC (dS/m)	
A	0-20	g	w	7.5YR4/4 d.b	sb-ab	61	12	27	SCL	5.6	2.3	1.4	0.1	11.6	0.74	81	5.5	6.3	0.05	
Bt1	20-46	g	w	7.5YR3/4 d.r.b	pm-ab	47	6	47	C	/6.4	2.5	1.0	0.1	14.8	0.38	68	5.4	6.2	0.04	
Bt2	4690	g	w	2.5YR3/4 d.r.b	pm-ab	45	8	47	C	6.2	2.2	0.7	0.2	14.6	0.38	64	5.6	6.3	0.05	
Bt3	90 140	g	w	2.5YR3/4 d.r.b	pm-ab	49	12	39	SC	6.8	2.8	0.5	0.7	12.4	0.0	87	5.8	7.2	0.03	
Bt4	140-200			2.5YR3/4 d.r.b	pm-ab	49	11	40	SC	8.6	4.8	0.3	1.0	15.2	0.0	97	5.8	7.2	0.04	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification: FAO/UNESCO (1994) : Haplic Lixisols

Soil Survey Staff (1992) : Typic Haplustalfs

Mapping unit PU2

Total area	:	2209.50 ha
Parent material	:	Undifferentiated gneisses, predominantly quartz-feldspar gneisses, poor in ferro-magnesian minerals.
Relief	:	Gently undulating to undulating with convex-concave uniform slopes of upto 5% and 1 km long.
Vegetation and land use	:	Bushed grassland/semi-nomadic grazing.
Soils general	:	Well drained, deep to very deep clays with a weakly developed A-horizon.
Colour	:	The A-horizon is dark reddish brown (2.5YR 3/4) while the subsoil is dark red (2.5YR 3/6).
Texture	:	Clay throughout the profile
Structure	:	The topsoil has weak, medium sub-angular blocky to moderately porous massive. The subsoil is moderately coherent porous massive to very weak, medium to coarse angular blocky.
Consistence	:	Slightly hard when dry, friable when moist, sticky and plastic when wet throughout the profile.
Chemical properties	:	Organic carbon in the A-horizon is 0.57%. The pH-H_2O is 5.32 in the topsoil and increases with depth to 5.86 in the subsoil. EC decreases with depth from 0.07 dS/m in the topsoil to 0.03 dS/m in the B-horizon. CEC is approximately 12 cmol(+)/kg soil in the profile. Ca is 3.53 cmol(+)/kg in the A-horizon and ranges between 1.66 cmol(+)/kg to 2.27 cmol(+)/kg in the B-horizon. Mg is 1.91 cmol(+)/kg in the subsoil. K decreases with depth from 1.20 cmol(+)/kg to 0.62 cmol(+)/kg in the subsoil. Na also decreases with depth from 0.67 cmol(+)/kg in the topsoil to 0.42 in the subsoil. Base saturation is between 39% and 62% in the profile.

Representative profile pit No. 173/2-2

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-23	g	w	2.5YR2.54 d.r.b	sb-pm	54	12	34	SCL	3.53	1.91	1.20	0.67	11.80	0.57	62	4.7	5.32	0.07	
Bu1	23-47	g	w	2.5YR3/4 d.r.b	pm-ab	44	16	40	CL	1.66	1.49	0.98	0.52	12.00	0.45	39	5.2	5.48	0.06	
Bu2	47-74	g	w	2.5YR3/6 d.r	pm-ab	43	15	42	SC	1.99	1.49	0.74	0.42	11.60	0.33	40	5.3	5.54	0.04	
Bu3	74-128			2.5YR3/6 d.r	pm-ab	39	23	38	CL	2.27	1.69	0.62	0.42	11.40	0.25	43	5.3	5.86	0.03	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification FAO/UNESCO (1994) : Rhodic Ferralsols

Soil Survey Staff (1992) : Rhodic Haplustox

Mapping unit PBr

Total area	:	4803.95 ha
Parent material	:	Olivine basalts.
Relief	:	Nearly flat.
Vegetation and land use	:	Grassland/Ranching and fallow cultivation
Soils general	:	Well drained, very deep well developed soils that cover the flat plains.
Colour	:	Dark reddish brown (5YR 3/4) topsoil that changes to dark red (2.5YR 3/6) deep down the profile.
Texture	:	Clay loam throughout the profile.
Structure	:	Moderate, medium, sub-angular blocky in the A-horizon. The subsoil has weak, medium to coarse, angular blocky structure.
Consistence	:	Slightly hard when dry, friable when moist, sticky and plastic when wet throughout the profile.
Chemical properties	:	Organic carbon decreases with depth from 0.59% in the A-horizon to 0.22% in the subsoil. EC decreases with depth from 0.16 dS/m in the topsoil to 0.09 dS/m in the subsoil. CEC of topsoil is 20.57 cmol(+)/kg soil while that of the subsoil ranges from 15.20 to 18.93 cmol(+)/kg soil. Ca decreases with depth from 10.70 cmol(+)/kg in the topsoil to 8.63 cmol(+)/kg in the subsoil. Mg is 2.05 cmol(+)/kg in the topsoil and varies from 1.89 cmol(+)/kg to 2.74 cmol(+)/kg in the subsoil. K decreases with depth from 1.96 cmol(+)/kg in the A-horizon to 0.22 cmol(+)/kg in the B-horizon. Na decreases with depth from 0.80 cmol(+)/kg in the topsoil to 0.20 cmol(+)/kg in the subsoil. Base saturation ranges from 71% to 81% in the profile.

Representative profile pit No. 174/1-1

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H$_2$O	EC (dS/m)	
Ap1	0-10	g	w	5YR3/4 d.b	sb	37	29	34	CL	10.70	2.05	1.96	0.80	20.57	0.59	75	5.2	5.96	0.16	
Ap2	10-22	g	w	2.5YR3/4 d.r.b	sb	43	28	29	CL	10.53	1.89	1.53	0.60	18.02	0.54	81	5.0	5.57	0.12	
Bu1	22-72	g	w	2.5YR3/4 d.r.b	ab	38	30	32	CL	8.50	2.21	1.12	0.60	15.20	0.45	81	5.1	6.20	0.10	
Bu2	72-117	g	w	2.5YR3/6 d.r	ab	29	44	27	CL/C	8.63	2.51	0.36	0.25	16.15	0.31	71	5.5	6.03	0.08	
Bu3	117-200			2.5YR3/6 d.r	ab	36	29	35	CL	10.37	2.74	0.22	0.20	18.93	0.22	72	5.5	6.47	0.09	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography

Soil classification: FAO/UNESCO (1994) : Eutric Cambisols

Soil Survey Staff (1992) : Typic Ustochrepts

Mapping unit PBd

Total area	:	48.15 ha
Parent material	:	Olivine basalts.
Relief	:	Nearly flat.
Vegetation and land use	:	Grassland/semi nomadic grazing
Soils general	:	Well drained deep, calcareous clays showing Vertic properties
Colour	:	Black (2.5YR 2/0) throughout the profile.
Texture	:	Clay throughout the profile.
Structure	:	Weak, medium, sub-angular blocky in the topsoil and moderate, medium to coarse sub-angular blocky in the subsoil.
Consistence	:	Friable, sticky and plastic throughout the profile.
Chemical properties	:	Organic carbon is 1.37% in the topsoil and decreases to 0.69% in the subsoil. pH-H_2O increases with depth from 6.5 in A-horizon to 8.0 in the lower B-horizon. EC increases with depth from 0.34 dS/m in the topsoil to 0.52 dS/m in the subsoil. CEC increases with depth from 46.59 cmol(+)/kg soil to 61.15 cmol(+)/kg soil in the subsoil. Ca increases with depth from 16.8 cmol(+)/kg in the topsoil to 62.55 cmol(+)/kg in the subsoil. Mg increases with depth from 3.01 cmol(+)/kg in the topsoil to 17.15 cmol(+)/kg in the subsoil. K is 0.79 cmol(+)/kg in the topsoil and varies between 4.20 cmol(+)/kg to 4.40 cmol(+)/kg in the subsoil. Na increases with depth from 0.60 cmol(+)/kg in the topsoil to approximately 2.0 cmol(+)/kg in the subsoil. Base saturation is 46% in the topsoil and it is over 100% in the subsoil throughout the profile.

Representative profile pit No. 174/1-4

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-Kcl	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-25	c	w	2.5YR2/0 bl	sb	37	14	49	C	16.8	3.01	0.79	0.60	46.59	1.37	46	5.9	6.52	0.34	
Bt1	25-45	c	w	2.5YR2/0 bl	sb	22	10	68	C	32.5	10.85	6.40	2.10	55.15	0.84	94	6.0	7.01	0.43	
Bt2	45-67	c	w	2.5YR2/0 bl	sb	22	10	68	C	44.4	12.99	5.20	1.90	49.69	0.82	130	6.2	7.54	0.53	
Bt3	67-92			2.5YR2/0 bl	sb	18	14	68	C	62.55	17.15	4.20	1.85	6.15	0.69	140	6.2	8.06	0.52	

g = gradual
w = wavy
ab = angular blocky
d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography
Bl = Black

Soil classification FAO/UNESCO (1994) : Vertic Luvisols

Soil Survey Staff (1992) : Vertic Haplustalfs

Mapping unit BXC

Total area	:	5892.49 ha
Parent material	:	Alluvial and colluvial clay deposits, mainly derived from volcanic rocks and ashes.
Relief	:	Flat to very gently undulating with slopes of less than 2%.
Vegetation and land use	:	Grassland/semi-nomadic grazing
Soils general	:	Complex of imperfectly drained, very deep, cracking clays of varying calcareousness, salinity and sodicity.
Colour	:	Very dark brown (10YR 3/3) throughout the profile.
Texture	:	Clay throughout the profile.
Structure	:	Moderate to strong, medium, angular blocky in the topsoil and strong, medium to coarse, angular blocky in the subsoil.
Consistence	:	Very hard when dry, firm when moist, sticky and plastic when wet throughout the profile.
Chemical properties	:	Organic carbon is approximately 0.72% in the profile. pH-H_2O increases with depth from 7.6 in the topsoil to 8.4 in the subsoil. EC of the topsoil is 0.67 dS/m while that of the subsoil is 0.87 dS/m. CEC is approximately 64 cmol(+)/kg soil in the profile. Ca is 47 cmol(+)/kg in the topsoil and ranges between 43 cmol(+)/kg soil to 48 cmol(+)/kg soil in the subsoil. Mg increases with depth from 17.8 cmol(+)/kg in the topsoil to 23.0 cmol(+)/kg in the subsoil. K is 0.2 cmol(+)/kg in the profile. Na increases with depth from 1.8 cmol(+)/kg in the topsoil to 3.9 cmol(+)/kg in the subsoil. Base saturation is more than 100% throughout the profile.

Representative profile pit No. 174/1-7

Horizon	Depth (cm)	Boundary		Colour (Moist)	Structure	Texture %			Textural class	Exchangeable bases (cmol(+)/kg)				CEC (cmol(+)/kg) pH 7.0	%C	% BS	pH-KCL	Suspension		Remarks
		Width	Top			Sand	Silt	Clay		Ca	Mg	K	Na					pH-H_2O	EC (dS/m)	
A	0-24	g	w	10YR3/3 v.d.b	Cr	36	17	47	C	47	17.8	0.20	1.8	64	0.72	104	4.7	7.60	0.67	Slickensides
C1	24-57	g	w	10YR3/3 v.d.b	Ab	23	10	67	C	43	17.3	0.20	2.9	63	0.74	101	6.1	7.82	0.63	Slickensides
C2	57-105+			10YR3/3 v.d.b	Ab	22	12	66	C	48	23	0.2	3.9	64	0.74	117	6.2	8.37	0.87	Slickensides

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d.r.b = dark reddish brown
d.r = dark red
sb = sub-angular blocky
Top = Topography
Cr = Crumb

Soil classification: FAO/UNESCO (1994) : Eutric Vertisols, saline-sodic phase

Soil Survey Staff (1992) : sodic Haplusterts