SOIL SURVEY, GENESIS AND CLASSIFICATION ALONG A TRANSECT UNDERLAIN BY QUATERNARY SEDIMENTS IN KILIFI COUNTY, KENYA.

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DECLARATION

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

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DEDICATION

In hopes that this work may in some way contribute to their better understanding of the soil, I dedicate this dissertation to all soil scientist of the present and future generations.

A special dedication goes to my lovely family whose words of encouragement and push for tenacity contributed a great deal of success towards completion of my studies.

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LIST OF ACRONYMS AND ABBREVIATIONS

FAO	Food and Agriculture Organization
ISSS	International Soil Science Society
MoA	Ministry of Agriculture
NGO’S	Non-governmental Organizations
USDA	United State Department of Agriculture
UNESCO	United States Education Science and Cultural Organization
RSGs	Reference Soil Groups
SMU	Soil Mapping Unit
WRB	World Reference Base
CEC	Cation Exchange Capacity
ESP	Exchangeable Sodium Percentage

ABSTRACT

Soil resource data is at an increasing demand to provide efficient information on soil properties that we rely on for crop production, grassland and forest sustenance. A pedogenesis study was conducted in Kilifi County, Kenya, for the purpose of generating soil information and map of the area. Five representative pedons were identified on various sedimentary parent materials and landscape positions. These included Mavueni pedon located on the coastal lowland underlain by Magarini sand, Ngombeni pedon on a valley bottom underlain by Upper Jurassic shales, Vyambani and Ngamani pedons located on the coastal uplands also underlain by Upper Jurassic shales and Kitsoeni pedon located on the coastal uplands underlain by Kambe Limestone. These representative pedons were opened and described following the FAO guidelines for soil description. Soil samples were collected horizon wise for laboratory analysis for the purpose of soil classification. Representative rock samples were also collected from each pedon for petrography and geochemical analysis to determine the influence of parent material on soils. Variations in soil properties were observed across the pedons and within some pedons. The soil depth ranged from shallow in Vyambani, moderately deep in Ngamani and very deep in Ngombeni, Mavueni and Kitsoeni. Drainage ranged from poorly drained in Ngombeni to well drained in Kitsoeni. Variation in soil colour was also observed. Soils in Kitsoeni were observed to have dark reddish brown colour throughout the profile, brown to dark reddish brown colour in Mavueni, dark reddish brown to reddish brown in Vyambani, very dark grayish to olive brown in Ngamani and brown, gray and black in Ngombeni. The soil texture was clay in Ngombeni, Vyambani and Ngamani, sandy clay to sandy clay loam in Mavueni and sand clay loam in Kitsoeni. Sand content ranged between 31- 73%, clay 21- 47%, and silt 2- 28%. Bulk density ranged between 1.3 to 1.7g/cm^3 and porosity was slightly low (39- 41%) in Mavueni and Kitsoeni and slightly high Ngombeni, Vyambani and Ngamani (39- 47%). Saturated hydraulic conductivity was moderately rapid to rapid (5- 7-5cm/h) in Kitsoeni, slow to moderate (1- 2cm/h) in Mavueni and very slow (<1g/cm) in Ngombeni, Vyambani and Ngamani. pH_{water} was observed to be moderately acidic to moderately alkaline (5.3- 8.6). The CEC was low to medium (2- 10cmolkg^{-1}) in Mavueni and Kitsoeni and relatively high (19- 24cmolkg^{-1}) in Ngombeni, Vyambani and Ngamani. The soils were non-sodic (ESP <15%) except for Ap and Bt1 in Mavueni and B and BC in Ngamani pedons. The soils were also free from salts since the EC was <0.5dS/m. The Kambe limestone in Kitsoeni was dominated by calcite while the Upper Jurassic shales were dominated by feldspars in Vyambani and olivine in Ngombeni. Brucite, biotite, magnetite, magnesite, spinel and quartz were also identified in these parent materials. The parent materials in the study area influenced some soil properties. High sand content was as a result of weathering of quartz while the upper jurrasic shales were a major source of clay. Iron oxides caused the reddish colour in Kitsoeni, Mavueni and Ngamani. Feldspars, olivines, biotite, brucite, spinel present in the parent materials were the source of basic cations. Regression analysis of primary minerals in the rock and soil showed a significant correlation for SiO_2 and K having R values of 0.99 and 0.98 respectively. These soils were then classified according to the WRB, 2014 based on the morphological, chemical and physical properties as Protoargic Sideralic Chromic Arenosol (Endostagnic) in Mavueni, Pontofluvic Fluvisol (Clayic, Oxyaquic, Protovertic, Magnesic) in Ngombeni, Leptic Lixisol (Hypereutric, Magnesic, Clayic) in Vyambani, Ferritic Lixic Ferralsol (Loamic) in Kitsoeni and Eutric Sodic Cambisol (Clayic, Magnesic, Densic) in Ngamani.

CHAPTER ONE

1.0 Background Information

Soil is an evolutionary body operating independent that can be subdivided into compartments and that has formed under the five forming factors (Bockheim et al., 2004). The study of soils has emerged in two approaches. The first approach is pedological which involves the study of soil in its original environment as a natural body and the second approach is edaphological whereby soil properties that directly or indirectly influence plants' growth, development and production are studied. The pedological study of soil gives an understanding of soil formation since it takes into account the analysis of rocks, parent materials and soil forming minerals, soil forming factors and processes, soil survey, soil description and soil classification (Sighn and Chandra, 2015).

Soil formation is an interplay between parent material, climate, relief, organisms taking place over a period of time (Kalala et al., 2017; Bockheim et al., 2004). These pedogenic factors set conditions for internal pedogenic processes (Joffe, 1936) that in turn cause soil formation with their respective properties (Marbut, 1927). The key soil forming factor is Parent material (Jenny, 1941) mainly at a regional scale (Dokuchaev, 1883). Parent materials originate from weathering of rocks which accounts for about 45% of the soil mass. The parent material is therefore at zero state of soil formation. Parent materials are composed of minerals whose chemical structure and composition are best described using their physical properties. Minerals are important to the soil as they influence several soil properties. For instance red or brown soil colour is caused by oxidized iron, gray and blue are caused by reduced iron while Manganese oxide is responsible for black colour (Brady and Weil, 2008). Minerals are also a source of plants nutrients after weathering from their original parent material (Agricultural Research Council, 2009). Ferromagmesium minerals (pyroxene, olivine, amphiboles, muscovite and biotite) produce of Fe^{2+} and Mg^{2+} ions while non ferromagnesium minerals such as feldspars are a source of Ca^{2+}, Na^{+} and K^{+} ions (Longwell et al., 1969). These minerals also produce clay minerals which influence the CEC through the attraction and retention of cations by their negatively charged surfaces. Weathering of parent material that has a high content of quartz mineral produce soils of high sand content hence sandy texture (Wanjogu and Mbuvi, 1995). High sand content can also be derived from weathering of both the ferromagnesium and non ferromagnesium minerals that produce silica as colloids (Longwell et al., 1969). The minerals therefore account for the mineralogical and chemical similarity between soil and the parent material (Sighn and Chandra, 2015).

Pedogenic processes on the other hand are extremely complex and dynamic processes whereby the original parent material is transformed into mature soils (Bockheim and Gennadiyev, 2000). The basic processes involved are addition, loss, transformation and transfer of mineral and organic matter present in the soil (Simonson, 1959). Ultimately these processes promote formation of different horizons accompanied by production of clay minerals, soluble salts, Sesquioxides, carbonates and organic acids which are later removed by percolating water and deposited at different depths within the soil (Sighn and Chandra, 2015). Pedogenic processes that are found in all soils are humification, elluviation and illuviation while there are those which are specific include calcification, decalcification, podsolization, laterization, salinization, alikanization, gleization and pedoturbation. A state of equilibrium between the extent of weathering and leaching subsequently results into soil properties that may slowly or rapidly attain stability and that when buried they may persistent or irreversible (Bockheim et al., 2004).

Naturally all soils differ with their characteristics varying laterally across landscapes and down soil profiles, following a systematic order (Fikre, 2003; Brubaker et al., 1993; Wilding and Dress, 1983). The spatial distribution of soils calls for soil survey and subsequently classification in order to increase efficiency of their utilization to benefit human beings. Soil survey draws heavily from geomorphology, soil genesis, physical geography and analysis of vegetation and land use (USDA, 2017). It provides a systematic examination, description, classification and mapping of soil in a given area. The purpose of soil survey is to investigate the geographical distribution of soils, establish characteristics that are vital to soils and define mapping units and explain them logically in a legend. Soil maps are important in showing the geographical distribution of soil, including individual characteristics. Valuable information on soil properties generated from soil survey form a basis for soil classification. It aids in understanding soil genesis and characterization better and this a necessity to sustainable utilization of the soil for crop production, grasslands and forests sustenance (Ogunkunle, 2005).

Agriculture is the backbone of most economies as it provides livelihood for almost every human being and a contributor to most Gross Domestic Product (World Food Summit, 1996) is based on soil. Although efforts are made to improve on agricultural production great challenges are being experienced especially in poor and low yields which fail to satisfy the food demands hence increased food insecurity. Improving agricultural productivity greatly depend on efficient management and utilization of the soil (Waddington et al., 1998). Furthermore sustainable use of soil resource requires an understanding of soil genesis and important soil properties that affect nutrient reserves (Msanya et al., 2003). Thus, pedological characterization gives appreciated knowledge and information on soil properties that enable people clearly understand soil morphology, genesis, classification and their spatial distribution in a given place (Kabeney et al., 2015).

1.2 Statement of the problem

Soil information is at an increasing demand because it provides means for food production (Fasina et al., 2007). However, there is a great challenge in acquisition of this information due to inadequate data on soil genesis and soil properties, as seen in different parts of Kenya (NAAIAP, 2014). In areas where agriculture production and research is mostly done soils are not identified and characterized (Fawole, 2016). Generally soil data is very scanty in relation to the size of the country. Futhermore the few available soil resource data inventories are generated from small scale surveys (reconnaissance) that are overgeneralized on basis of very few observations spread over a large area (Mbaga et al., 2017).

Soils exhibit a range of potentials and limitations that influence their sustainable use. Limitations present in a soil type have unique challenges towards agricultural production. Some of the challenges are manageable but others require special treatment. Apart from inherent soil challenges, inappropriate agricultural practices are detrimental to soil resources. Use of soil resource without proper understanding of its properties may result in degradation of the resource that consequently threatens sustainability of agricultural production (Sheldrick et al., 2002).

Soils can naturally sustain crop production through nutrient reserves. However, to some extent this is not well understood. Fertilizer application without proper understanding of soil properties is commonly practiced by many farmers. The impact of this practice is excessive fertilization for those soils with good nutrient availability or nutrient deficiency for the nutrient poor soils. This potential then need to be explored and sustainably used for agriculture. Agricultural activities therefore require pedological information of nutrients available in the soil so as to ensure nutrients are not depleted from the soil (Chukwu et al., 2013).

Soil information is limited in the study site since only one reconnaissance soil survey has been done on small scale that failed to critically assess the influence of underlying parent materials on soil types. Hence this study has been conducted with aim of establishing the genesis of the soils, characterize them and develop a classification map for use in assessing the potential of the soils and appropriate management strategies.

1.3 Justification of study.

Soils of Kilifi area vary widely with their characteristics changing across the region. Boxem et al. (1983) reported that these soils are influenced by the parent material, more so the geology of the area as surveyed by Caswel (1952) showed that the area is underlain by sedimentary rock with parent materials differing across the area. These parent materials are differentiated by the times when sediments were deposited having recent from the ocean, Pleistocene, Pliocene, jurrasic and triassic to the right all aligned almost parallel to each other. Composition of Parent materials differ physically, chemically and mineralogically and upon weathering soils with different properties are produced. Therefore there is need to study into details how these parent materials influence their respective soils.

Pedological characterization of soils is vital in guiding decisions especially on the best use of these resources and enhance their conservation. It is equally essential to users such as farmers who require soil data when deciding the type of crops to grow while considering the best management strategies suitable for enhancing optimum and sustainable crop production (Halima et al., 2017). Evaluation of the potential and value of land resource to sustainable production of food, fiber and fodder requires detailed information on soil properties (Tosheme, 2016). In addition sufficient knowledge on soil type and its properties is vital in making proper decision for improving crop production (Demiss et al., 2010). Intensification of crop yields will benefit from comprehensive understanding of the nature and properties of soils as well as proper management of the nutrient and moisture requirements (Msanye et al., 2003).

Proper characterization of soils is a prerequisite of informative soil fertility studies (Kebeney et al., 2015). Information on soil's chemical and physical properties together with climatic condition of the sites will assist experts in determination of amounts and types of fertilizers appropriate for the area for enhancement of soil fertility and optimum agricultural production (Msanya et al., 2003). Findings generated from trials conducted on characterized site will easily be transferred and applied to areas with similar soils and conditions (Kebeney et al., 2015; Msanya et al., 2003). Alternatively in cases where funds are limited access to pedological information on properly classified soils will be crucial in adopting well tested management technologies and landscape positions without going through the whole process of time consuming and expensive technology selection trials as this will provide the basic information for sustainable agricultural planning (Fikre, 2003).

Detailed soil information will assist current and future land users in assessing limitations and potential of the soil for a variety of uses to provide grounds to formulate appropriate land management practices targeting soil and water conservation and improve agricultural production (Muya et al., 2011). It is therefore inevitable to have sufficient pedological information in order to use soil in the best possible way. It also simplify communication and sharing of knowledge regarding soils to land users and stakeholders (Zone et al., 2018).

1.3 Objectives

1.3.1 General objective

To undertake a pedogenesis study with the aim of generating soil data and map of the coastal lowland Kenya.

1.3.2 Specific objectives

1) To map and characterize the soils of the study area

2) To classify the soils of the study area on the basis of their physical, chemical and morphological characteristics using the revised WRB.
3) To determine the relationship between parent material and the soils primary mineral constituents.

1.3.3 Study questions

1) How are the soils of the study area distributed?
2) Do the soil types vary according to their pedogenic characteristics as influenced by their underlying parent material?
3) Is there a relationship between the parent material and the primary mineral constituents?

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil formation

Soil arises from interaction between climate, parent material, topography and organisms over a period of time (Dokuchaev 1879a, 1883, 1893, 1899b). The role of these soil forming factors resulting to soil formation were recognized since the beginning of pedological studies. Parent material is the key factor of soil pedogenesis particularly in a given area (Hilgard, 1906; Dokuchaev, 1883; Coffey, 1912). Animals are important in soil formation through the process of pedoturbation that shows a localized recurrent motion of soil (Johnson et al., 1987; Hole, 1961) while vegetation gives an indication of climate which is important in development of soil. Topography is a significant factor for vertical arrangement of soil. Organisms (Quideau et al., 2001) and climate (Maynard et al., 2004) directly influence soil formation while relief indirectly influence formation and distribution of soil (Wang et al., 2001). There is a considerable variation in chemical, physical and mineralogical properties of a soil (Fawole, 2016) which is attributed to different soil forming factors and processes.

2.2 Topography

Topography where soil is developed influences the process of pedogenesis which determines how soils are distributed and used along the terrain (Esu et al. 2008; Hoosebeek et al., 2000). This role of topography in soil formation has been recognized for long (Pregitzer et al., 2000) and showed that it results to soil variation from the surface to the rock following systematic change. (Wilding and Dress, 1983). Landscape position influence surface water movement, drainage and soil depth that result to soil formation (Ewulo, 2015; Demiss et al., 2010). As water moves downslope, its velocity on the slope influence how materials in suspension will be deposited. The first materials to be deposited are those with the largest size particles (sand) followed by fine sized particles (clay) which are moved further down away towards the slope base before undergoing deposition (Glassman et al. 1980). Sand and clay content have been seen to highly correlate with the position of landscape (Wang et al., 2000). In cases where there is high clay content which increase with depth such a scenario may be caused by either two or more in combination of translocation of clay into the Bt horizon, pedogenic clay formation in the subsurface horizons, clay destruction of the topsoil clay, selective removal of clay by erosion at the surface, shrink and swell processes causing coarser particles moving upwards leaving the fine clay biotic activities (Yitbarek et al., 2016). Slope orientation on the other hand affect the microclimate of an area, whereby flat areas positioned away from sun have a tendency of becoming cooler and wetter than slope angles looking towards the direction of the sun (Ewulo, 2015).

Soil morphological properties vary along the topography. For example a soil pedon along a topography have been reported to show differences in sequence of horizons, variation in soil depth and colour even from the surface to the subsurface horizons (Yitbarek et al., 2016). This variation is attributed to the slope which contribute to drainage (Fawole, 2016) and greater translocation of materials on the surface down the slope through soil movement and surface erosion (Karuma et al., 2015). Soil colour variation can be especially from the surface to the subsurface horizons caused by other factors which directly relate to the slope. Accumulation of organic materials makes the topsoils to be darker colors than subsequent subsoils (Yitbarek et al., 2016), oxidized iron which is attributed by drainage condition of the soil (Fawole, 2016; Yitbarek et al., 2016) . Amount of organic matter vary on soils along the slope (Miller et al., 1998). Topography influence growth and production of plants, production of litter and hence decomposition process that definitely have an effects on soil nitrogen (N) and carbon (C) contents (Demiss et al., 2010). Soil pH also has proven to highly associate with topography (Wang et al., 2000). Low pH tend to dominated upper positions of the topography and high pH at the lower position due to movement of basic cations in solution downslope (Abate et al., 2014).

The influence of topography in terms of depth is such that soils found on abrupt high slopes vary from shallow to moderately deep, having good drainage with sandy to silt loam texture normally related to rock outcrops. In the mid-slope and toe, soils tend to be generally deep with good drainage but gravelly silt loam texture. (www.fs.fed.us/r8/boone /resources/soil/index.shtml 03/08/2009). At the foot and toe of slopes, regolith may be saturated with water to an extent of limiting water and air movement in the soil. This results to retardation of weathering of certain parent materials and breaking down of organic materials, whereas iron and manganese are being lost at a faster rate. Flat areas on a landscape with such processes may result to formation of unusual soil profile morphologies which are distinguished as wetland soils. (Brady and Weil, 2002).

2.3 Parent material

Soil parent material has been defined as the material from which soil has apparently been derived (Jenny, 1941; FAO, 2006). According to Brandy and Weil (2002) the process of soil formation can either be through on site weathering of parent material (residual), saprolite (chemically weathered rock) or materials being transported from one place and deposited on another place by water (alluvial), wind (eolin) gravity (colluvial) and ice (moraine). The upper 5km of the surface of the earth is made up of sedimentary rocks (74%), igneous rocks (18%) and other rocks (8%). Igneous rocks are prolific on the earth occupying about 95% on the crust however they are located in the deeper layers while igneous occupies only 5% of the total earth's crust but abundant at the earth's upper layers. During weathering these rocks produce minerals that significantly determine mineralogical composition of soil (Righi, 1995). Minerals are significant in releasing exchangeable ions that influence soil fertility. Minerals are categorized into primary, secondary and accessory. Primary minerals are derived are inherited from metamorphic and igneous rocks through the process of cooling and crystallization of magma. Their chemical nature remains unchanged. When primary minerals weather they form Secondary minerals and the most common are clay minerals. Some secondary minerals are inherited from weathering of sedimentary rock. Accessory minerals on the other hand are non-essential occurring only in small quantities in the rocks (Sighn and Chandra, 2015).

Soil parent materials are responsible for soil formation, irrespective of the state of weathering (Lacoste et al., 2011). The soil chemical, morphological, mineralogical and physical characteristics are influenced by nature of the parent material (Wanjogu and Mbuvi, 1995). Parent materials influence different soil properties for instance texture, colour, structure, porosity and degree of saturation (Gökbulak & Özcan, 2008; Bockheim et al., 2005). The study area is underlain by parent materials that originate from sedimentary rocks (Boxem et al., 1987). It is for this reason that emphasis has been made in this review on sedimentary rocks.

2.4 Sedimentary Rock

Sedimentary parent rock is a dominant rock at or near the surface approximately within the upper

5km. it is an important rock however it occupies only about 5% of the total earth's crust (Sighn and Chandra, 2015). They are from pre-existing living organisms or rocks. These materials are removed and deposited by to another place by means of water, wind and ice. Upon deposition of these materials they buried while young materials accumulate successively showing distinctive layers (Boggs, 2009). Ultimately sedimentary process generates four constituents; biochemical/chemical, carbonaceous, terrigeneous silicates and authigenic all in different proportions that generally make up the sedimentary rocks (University of Arizona, 2017).

2.4.1 Chemical and biochemical

These are formed when soluble elements are extracted from a water basin caused by chemical/biochemical processes occurring in basins where sediments deposit. These processes results to formation of minerals such limestone, apatite, gypsum and calcite. Other minerals such as evaporates, limestone, phosporites and cherts are intrabasinal that aggregate into sand or silt sized grains upon precipitation and moved by waves and currents within their depositional basin (Boggs, 2009).

2.4.2 Terrigenous silicaclastic

These are seen as true sedimentary rocks because rock fragments (clasts) are directly from other igneous, sedimentary and metamorphic rocks. Constituents here are generated by rocks that are dominantly made of silicate minerals like micas, quartz and feldspars. Additionally chemical elements during weathering of parent rock may undergo recombination and crystallization processes generate secondary fine sized grains mostly clay minerals and iron oxides. These rock fragments and minerals derived from the land surface are transported in solid form to depositional basins. These silicaclastic constituents are dominant in shale, sandstones and conglomerates (University of Arizona, 2017).

2.4.3 Carbonaceous

These originate from carbon residues of marine organisms and terrestrial plants in combination with petroleum bitumen. Humic carbonaceous materials from woody residues of plant tissue are the chief components of most coals (University of Arizona, 2017).

2.4.4 Authigenic

These are secondary sedimentary rock whose constituents comprise of silicate minerals like feldspars, quartz, glauconite and clay minerals also non-silicate minerals like gypsum, calcite, hematite and barite. These can be added in the course of burial of any kind of sedimentary rock nonetheless they are not even the main make up of sedimentary rocks (University of Arizona, 2017).

2.5 Soil survey

It is a process that defines characteristics of soils of a specified area then classifies those soils in accordance to a standard taxonomy system, map the soils, organize soil information in a database as well as making predictions regarding to limitations, suitability and possibly management strategies of each soil. This information greatly assists in evaluation and prediction of land use effects affecting the environment (USDA, 2017). There are five types of soil surveys done in Kenya: Exploratory soil survey whose scale ranges between 1:500,000 to 1: 1,000,000 for the purpose of establishment of major soil regions for agricultural research and planning, international correlation and exchange of soil of data; Reconnaissance soil survey whose scale ranges between 1: 100,000 to 1:250,000 for the purpose of systematic land and soil resource inventory for multipurpose land-use planning; Semi-detailed soil survey at a scale of 1:20,000 to 1:50,000 for particular purpose; Detailed soil survey at a scale of 1:10,000 or large which is mainly used for farm planning, characterization of trial research site and final irrigation layout and; Site evaluation whose scale is variable depending on the purpose (KSS, 1979). Site evaluation type of soil survey was adopted in this study for the purpose of achieving its objective of evaluating soil genesis of the study area particularly how the parent materials influence soils properties.

2.6 Soil Classification

Soil classification systematically organizes soils according to groups or classes which have similar characteristics (chemical, physical and biological) and possibly the same behaviour (Yitbarek et al., 2016; Msanya et al., 2003). Soil classification was initially based on geological and geomorphological concepts such as chemical and mineralogical characteristics (Bockheim et al., 2005). These diagnostic properties gives a reflection of the important soil forming processes occurring either at the present or in the past the different soil profiles (Yitbarek et al., 2016). However, the process of soil classification has evolved which now use diagnostic horizons, properties and material. Physical and chemical properties that cannot be identified in the field are best determined during soil classification alongside with characterization (Boul et al., 2003).

Soil classification and characterization gives information which is required for soil management purposes and land use planning (Mukungurutse et al., 2018). Such information is significant for determining potential and limitations for agriculture with possible options for management of soils in a given area and in doing so it helps in identification of the agricultural practice appropriate for such an area (Karuma et al., 2015; Kebeney et al., 2015). Planning and development of irrigation projects are established on data gained after classification and characterization of soil. Management systems on soil fertility for specific areas that are intended to increase crop production can be established for such specific areas with the use of soil survey data in replacement for fertilizer recommendations. Classification and characterization data might be exploited extensively by agriculture researchers, farmers and extension officers for the purpose of increasing agriculture production sustainably (Mukungurutse et al., 2018). There are several soil classification systems that are used. The mostly applied ones are FAO- UNESCO and WRB systems.

2.6.3 The USDA Soil Taxonomy

It is a system where soils are classified in a hierarchical system at six levels, from highest to lowest: orders, suborders, great groups, subgroups, families, and series (Soil Survey Staff, 1999). Soils at the order level are separated on the basis of properties resulting from major processes and pathways of soil formation. Twelve classes are recognized and defined. At the suborder level (8) soils are separated within each other on the basis of soil properties that are major controls, or reflect such controls on the current set of soil forming processes. Soil in great groups are separated within each suborder on the basis of properties that constitute subordinate or additional control, or reflect such controls (static properties) on the current set of soil forming processes (Sumner, 2000). Subgroups are subdivided according to the central concept of the great group vs. intergradations to other taxa or extra-gradations to ‘‘not soil”. Families are differentiated into mineralogy, particle-size and soil temperature class (Bockheim et al., 2005). The lowest category in Soil Taxonomy (Soil Survey Staff, 1999) is the series, which is based on the kind and arrangement of horizons. Soil series are divided into phases on the basis of surface stoniness, slope steepness, amount of previous erosion or other attributes that are not diagnostic in Soil Taxonomy, but which are important to land use (Bockheim et al., 2005).

2.6.1 The FAO-UNESCO Soil Classification System

The United Nation Education Scientific and Agricultural Organization (UNESCO) and the Food and Agriculture Organization (FAO), in association with the International Society of Soil Science (ISSS) jointly took up the recommendation made during the sixth and seventh ISSS Congress in 1956 and 1960 to prepare a soil map of the world at a scale 1:5, 000,000. The objectives of this map were to: (a) Make the first appraisal of world's soil resources, (b) supply scientific basis for the transfer of experience between areas with similar environments, (c) promote establishment of a generally acceptable soil classification and nomenclature, (d) establish a common framework for more detailed investigation in developing areas, (e) serve a basic document for educational, research and development activities and (f) strengthen international contacts in the field of soil science (FAO- UNESCO, 1974).

The soil units which form the basis of the FAO-UNESCO Legend are defined in terms of measurable and observable properties of the soil identified. These units form a monocategorical and not a taxonomic system with different levels of generalization. Based on soil development status, materials and major geographical zones, 24 major soils and 106 soil unit are distinguished. Soil units are characterized by the presence or absence of diagnostic horizons and properties (FAO-UNESCO, 1974). Most of the old soil survey publications in Kenya have used this system.

2.6.2 Revised Legend of FAO-UNESCO

The Revised Legend of FAO-UNESCO was revised in 1988 to assess the extent to which the objectives of the original Legend of the soil map of the world were met and analyzed its present function (Sumner, 2000). The amendment made was the monocategorical character of the 1974 legend which was transformed to multicategory system with Major Soil Grouping (28) for example Luvisol, soil units (153) for example Chromic Luvisol and soil subunits for example

Gleyi-chromic Luvisol.

2.6.4 World Reference Base for soil resources

The World Reference Base (WRB) is a soil classification system for naming soils and creating soil map legends (FAO -WRB, 2015). It is based on the Legend (FAO-UNESCO, 1974) and the Revised Legend (FAO, 1988) of the Soil Map of the World (FAO-UNESCO, 1971-1981). In 1980, the International Society of Soil Science (ISSS, since 2002 the International Union of Soil Sciences, IUSS) formed a Working Group ‘International Reference Base for Soil Classification’ for further elaboration of a science based international soil classification system.

The main objectives of WRB are to: (1) Develop an internationally acceptable framework for delineating soil resources to which national classification can be attached and related, using the FAO Revised Legend as a guideline. (2) Provide this framework with a sound scientific base so that it can also serve different applications in related fields such as agriculture, hydrology geology and ecology. (3) Acknowledge in the framework important lateral aspects of soil and soil horizons as characterized by topo- and chronosequencs. (4) Emphasize the morphological characterization of soils rather than to follow a purely analytical approach ((ISSS FAO- ISRIC, 1994)). It is the international standard for soil classification system endorsed by the International Union of Soil Sciences (http://www.fao.org/soils-portal/soil-survey/soil-classification/world-referencebase/en/).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study area

The study was conducted in Kilifi County at the coastal region of Kenya with five representative pedons located at Mavueni, Ngombeni, Ngamani, Vyambani and Kistoeni. The area lies on coordinates UTM9593248, 37M0590420 and UTM9590374, 37M0581774 covering an area of 132.52 km^2. It is located on the coastal lowlands in agro- ecological zone III (Jaetzold et al., 2006). The temperature ranges from 24^{0}C to 31^{0}C annually with a bimodal type of rainfall received at an annual average of 1000mm to 1250mm occurring from March to June for the long rains and October to December for the short rains. The amount of rainfall received in this area ranges from 1000mm to 1250mm annually.

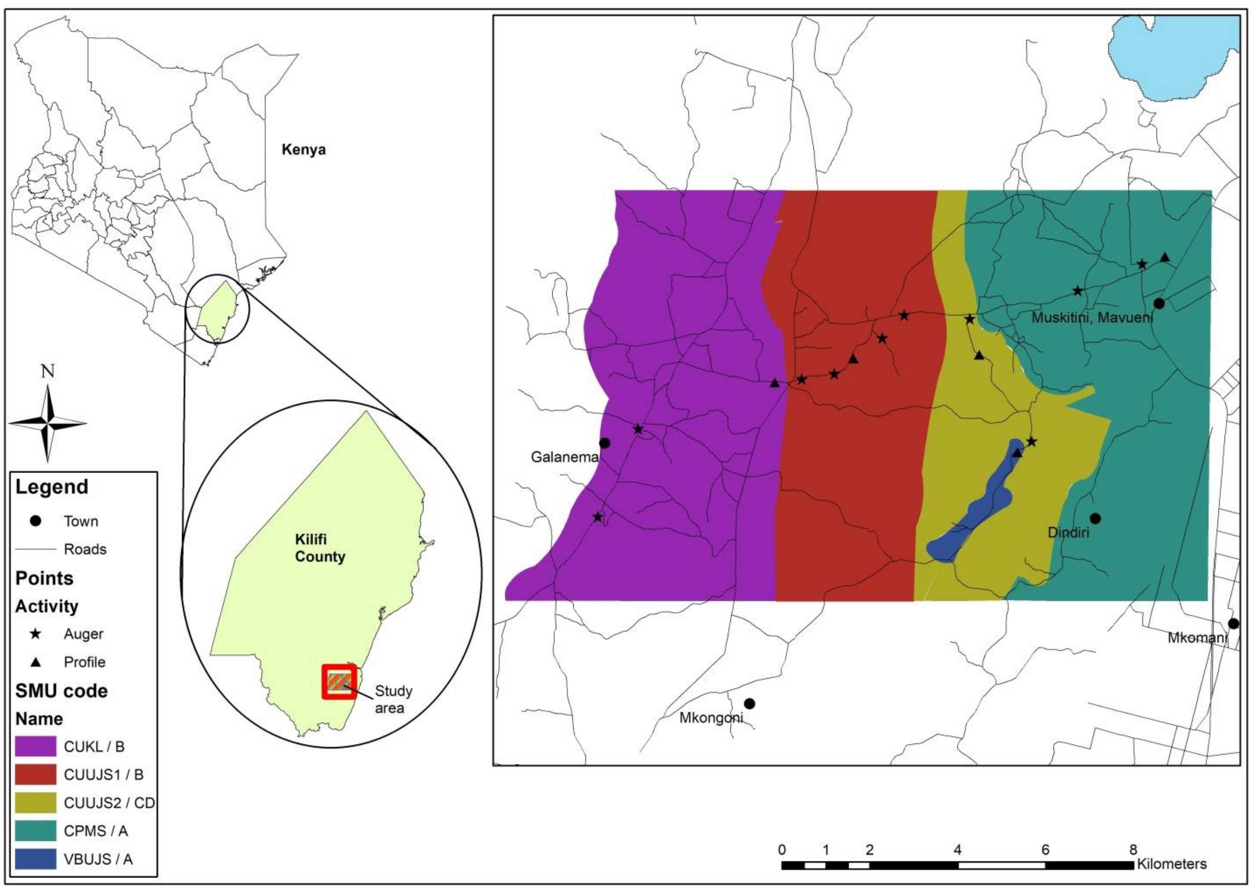


Figure 1: Map of study area. CULK=Coastal Upland Kambe Limestone; CUUJS=Coastal Upland Upper Jurassic Shales; CPMS=Coastal Plain Magarini

Sands; VBUJUS=Valley Bottom Upper Jurasic Shales.

3.2 Geology

Kilifi area is underlain by Quaternary system of sedimentary rocks with different formations (Caswell, 1953) including recent alluvium developed on recent alluvial and marine deposits. These are made of fine grained sands, silts and clays that are exposed in valleys throughout the studied area. Wind-blown and superficial sand, lagoonal sands and coral and coral breccia form the next strip of formations. On the right of these formations are Magarini sands comprising of medium grained sand which contain fine sands, silts and clay. The next strip is made of the Upper Jurassic shales followed by a narrow strip of Kambe limestone towards the west. Mazeras and Mariakani formations are at the extreme end of Kilifi area. These are made of coarse and medium grained sandstones respectively (Boxem et al., 1987). The formations that were identified during the study were magarini sands in Mavueni, Upper Jurassic shales in Ngombeni, Vyambani and Ngamani and Kambe limestone in Kitsoeni

3.3 Landform, land cover and land use

The selected area of study constituted of three distinct major landforms; coastal plain, coastal upland and bottomland. The coastal plain is adjacent to the shore on a flat to very gently undulating topography (< 5% slope). The altitude ranges from 0- 75m above sea level. The coastal upland is made up of slopes of up to 16% with both erosional and depositional surfaces. The topography ranges from gentle undulating to rolling. Unlike the upland, the bottomland is made up of depositional surfaces in valleys and depressions on a flat to gentle undulating topography. The bottomland is majorly formed on unconsolidated deposits of recent alluvium.

The area is endowed with both natural and planted vegetation. The natural vegetation includes vast areas covered by grassland, neem trees and baobab. The planted vegetation include coconut (Cocos *nucifera*) trees, cashew nuts (Anacardium *occidentale*), mango (Mangifera *indica*), oranges (Citrus *sinensis*), maize (Zea *mays*) and cassava (Manihot *esculenta*), and cowpeas (Vigna *unguculata*). Vegetables like tomatoes (Solanum *lycopersicum*), chilies (Capsicum f*rutescens*), brinjals (Solonum *melongena*) and okra (Abelmoschus *esculentus*) which are grown on small holder farms. Land in the studied area is mostly used for cultivation and free range grazing. Both rain fed and irrigated agriculture is practiced. Vegetables are mostly irrigated using water from existing rivers and boreholes. Quarrying is also done in this area because the rock undelying the Upper Jurassic shales is an importance raw material for making cement.

3.4 Field methodology

A site evaluation soil survey was conducted in the study areas using a 21km transect. The length of the transect was determined by the underlying geological formations to avoid the survey area falling under one geological formation. Soil Mapping Units (SMUs) were identified using Google Earth. Once identified, auger hole observations were done to confirm the SMU boundaries. Five soil profile pits were located based on the identified five SMUs which also coincided with different geological formations. The profiles were dug in each SMU to represent each soil type identified. General information about the area where the profile pits were located was recorded. These included coordinates, parent material, slope, land use, elevation, regional vegetation, meso and micro relief, erosion and flooding. The profiles were fully described according to the FAO Guidelines for soil profile description (FAO, 2006). Soil samples were collected horizon-wise from each profile for laboratory analysis which the results were used for soil classification purposes. Rock samples from each pedon were collected for both petrographic and mineralogical analysis. These samples were easily collected from the bedrock of Ngamani and Vyambani profiles because these profiles relatively shallow. Kistoeni and Ngamani rock samples were collected from the surrounding because the profiles were very deep and presence shallow water table respectively. Unfortunately it was not possible to get rock samples for Mavueni profile because it was very deep and there was no rock sample around the profile.

3.6 Laboratory analysis

3.6.1 Soil sample preparation

Disturbed soil samples were air-dried, crushed gently using a pestle and motor and then passed through 2-mm mesh sieve to obtain fine soil particles for chemical and physical analysis.

3.6.2 Physical analysis

Soil texture was determined using Bouyoucos hydrometer method (Day, 1965). Undisturbed (core) samples collected were used for determination of bulk density and saturated hydraulic conductivity. Bulk density was determined using core sample method (Black and Hartge, 1986) and saturated hydraulic conductivity was analyzed using the constant head method (Klute and Dirksen, 1982). Total porosity was calculated from the bulk density using the equation of ($1-\rho b/\rho s$) where ρb is the bulk density and ρs is the average particle density (2.65Mg/m3).

3.6.3 Chemical analysis

Soil reaction (pH) was measured potentiometrically in water and in 1M $CaCl_2$ at the ratio 1:2.5 soil-water and soil - $CaCl_2$ (Mclean, 1986). Electrical conductivity (EC) was measured on a 1:2.5 ratio extract with an EC meter. The Cation Exchange Capacity (CEC) and exchangeable bases were determined by buffered neutral 1M NH_4OAc (ammonium acetate) (Sumner and Miller, 1996). The bases which were displaced by NH_4^+ ions were measured by atomic absorption spectrophotometer (AAS) for Ca and Mg, while K and Na were measured by flame photometer. Base saturation (%) was calculated by dividing the sum of exchangeable bases by the CEC and multiplied by 100. The exchangeable sodium percentage (ESP) was calculated by dividing the exchangeable Na by CEC (× 100), which is a measure of the sodicity of the soil. All the above data was important in soil classification.

3.6.4 Primary minerals analysis

The minerals were analyzed in rock samples using petrography techniques (Bullock et al., 1985; Fitzpatrick, 1980). These rocks were cut, sliced and thin sections generated that were mounted with on microscopic slides and examined using a petrographic microscope. Both soils and rock samples were analyzed for Oxides of Al. Fe, Si. Ca, Mg, K, Na, Mn and Ti using X-ray Diffraction (Wilson, 1987) and X- ray Florescence. This provided information on the relationship of the parent material and soils and potential nutrient reserve. These analyses were carried out at the Department of Mines and Geology, Ministry of mining and petroleum. The primary minerals identified in both the soils and rocks were subjected to regression analysis to determine the relationship between the parent material and soil.

3.7 Classification of the soils

Soils of the study area were classified using the World Reference Base for Soil Resources, 2014.

The process of soil classification was based on soil properties that were defined in terms of diagnostic horizons, diagnostic properties and diagnostic materials and to the greatest extent the measurable and observable in the field. The WRB is a two-tier soil classification system with the first level being 32 Reference Soil Groups (RSGs) and second level being RSGs with qualifiers. The RSGs were allocated to soils on the basis of dominant identifiers, i.e. the soil-forming factors or processes that most clearly condition the soil. The soils were then allocated the principal qualifiers that are regarded as being most significant for a further characterization of soils of the particular RSG and finally the supplementary qualifiers to give some further details about the soils (WRB, 2014).

3.8 Systematics and Nomenclature

Creation of map legend followed guidelines as outlined under the WRB (2014). A physiographic approach was adopted which involved the following steps.

3.8.1 Physiography

Physiographic units were arranged in order of decreasing relief as presented in Table 1.

Table 1: Physiography of the studied area

Physiographic unit	Code
Coastal Upland	CU
Coastal Plain	CP
Valley Bottom	VB

Source: Soils of Kilifi Area, 1987

3.8.2 Geology

The soils of the study area are derived from a variety of parent materials developed from sedimentary rock. Table 2 show the parent material identified in order of the physiography with their codes.

Table 2: Geology of the studied area

Parent material	Code
Kambe Limestone	KL

Upper Jurassic shale	UJS
Magarini sand	MS

Source: Geological map of the Kilifi- Mazeras area, 1953

3.8.3 Soil description

Soils identified from each SMU were described in the following criteria; drainage class, depth, color, consistence, textural class, diagnostic horizon or property or material and finally the soil class.

3.9 Creating soil map

A map of the Geology of the Kilifi-Mazeras area was generated from samsamwater.com that was georeferenced and digitized in ArcGIS. The easily distinguishable geological formations were traced on Google earth, saved and used to make a comparison with already existing digitized geological formations. One shapefile was developed from this comparison and a final one was developed based on expert opinions.

Table 3: Site characterization and land use

Location	Coordinates	Altitude	Landform	Geology	Slope	Land use
Mavueni	UTM9593248,37 M0590420	65m	Coastal plain	Magarini sands	1%	Cultivation
Ngombeni	UTM9588888,37 M0587270	50m	Valley bottom	Upper Jurassic shales	12%	Cultivation
Vyambani	UTM9590945,37 M0583329	109m	Coastal upland	Upper Jurassic shales	5%	Grazing
Ngamani	UTM9591025,37 M0586193	61m	Coastal upland	Upper Jurassic shales	10%	Grazing
Kistoeni	UTM9590374,37 M0581774	144m	Coastal upland	Kambe limestone	6%	Cultivation

CHAPTER FOUR

4.0 RESULTS

4.1 Morphological characteristics of the soils

Soils of the study area showed variation in their morphological properties as shown in Table 4. Pedon CPMS was located in Mavueni area on UTM9593248 37M0590420 coordinates. The area is found on the coastal plain at an altitude of 65m above sea level. The parent material underlying this SMU is Magarini sands. The macro relief of this area is flat to very gently undulating on a slope of 1%. Five horizons were identified from this profile as Ap, Bt1, Bt2, Bt3 and Bt4 from the topsoil to the subsoil respectively. The horizon boundary between Ap and Bt1 was gradual and smooth while Bt2, Bt3 and Bt4 horizons showed clear and smooth boundaries. The soils were very deep (>120 cm) with moderate to well drainage. The texture was sandy clay loam having a moderate medium subangular blocky structure throughout the profile. The consistence under moist condition was friable and under wet condition was slightly sticky and slightly plastic throughout the profile. The colour of soil on Ap and Bt1 horizon was dark brown (10YR 3/3) and brown (7.5YR 4/4) on Bt2, Bt3 and Bt4. Common, distinct and medium sized light red (2.5YR 6/6) iron mottles were identified on the Bt3 horizon.

Pedon VBUJS was located in Ngombeni area which lies on UTM9588888,37M0587270. The profile was positioned on a valley bottom at an altitude of 50 m above sea level. The area is flat to very gently undulating on slope of 2%. The area is underlain by Upper Jurassic shales parent material. The soils of this area were poorly drained with an effective depth of 60 during the wet season. Four horizons were identified as Ap, Bu1, Bu2 and Bu3 respectively from the surface. The horizon boundary between Ap and Bt1 was gradual and smooth while for the continuing horizons it was abrupt and smooth. The soil colour was observed to be distinct under each horizon. Soil on horizons Ap and Bu1 was gray (5YR 4/1), brown (10YR 4/6) on Bu2 and black (5YR 4/1) on Bu3. The structure was weak medium subangular blocky structure throughout the profile. Soil consistence ranged from hard to extremely hard when dry, firm to extremely firm when moist and sticky to very sticky and plastic to very plastic when wet. Bu3 horizon was submerged in water and showed traces of slinkensides.

Pedon CUUJS1 was located in Vyambani area on coordinates UTM9590945,37M0583329. The area is found on the coastal upland with an altitude of 109m above sea level. Like pedon VBUJS the area is underlain by Upper Jurassic shales. The area is gently undulating with a slope of 5%. Shallow soils were observed in this area whereby by only two horizons were identified from the profile as A and BC. Horizon boundaries were clear and irregular throughout the profile. The soils were well drained with an effective depth of 42 cm. The colour of the soil ranged from dark reddish brown (5YR 3/3) in A horizon to reddish brown (5YR 4/6) in BC horizon having a clay texture, weak medium subangular blocky structure and very hard (dry), very firm (moist), sticky and plastic (wet) consistence throughout the profile.

Pedon CULK was located in Kitsoeni area which lies on UTM9590374, 37M0581774. The area is found on the coastal upland at an altitude of 144m above sea level. The area is undulating on a slope gradient of 7% and underlain by Kambe limestone parent material. The soils of this SMU were very deep (>120), well drained and very deep ground water table. Four horizons were identified from the profile as Ap, Bu1, Bu2 and Bu3. Gradual and smooth horizon boundary was observed throughout the profile. The pedon showed the same morphological properties throughout the soil depth. Dark reddish brown (5YR 3/4) colour, moderate fine to medium subangular blocky structure and friable (moist), slightly sticky and slightly (wet) plastic consistence.

Pedon CUUJS2 was located in Ngamani area which lies on UTM9590374, 37M0581774. The area is found on the coastal upland at an altitude of 60m above sea level. The macro relief of the area is rolling on a slope of 10%. The soils were moderate to poorly drained with an effective depth of 80cm. Four horizons were identified as A, BA, B and BC respectively from the surface. Gradual and clear horizon was observed throughout the profile. The texture is clay, weak medium subangular blocky structure and very hard (dry), very firm (moist), sticky and plastic (wet) consistence throughout the profile. The colour was observed to be very dark grayish (2.5Y 3/2) in A and BA horizons, dark grayish brown (2.5Y 4/2) in B horizon and olive brown (2.5Y 4/3) in BC horizon.

Table 4: Key soils morphological properties

Location	Horizon	Depth (cm)	Textural class	Colour (moist)	Structure	Consistence	Horizon boundary
Mavueni	Ap	0-30	SCL	dbr 10YR3/3	mo &me, sab	fr,sst & sp	g & s
	Bt1	30-46	SCL	dbr 10YR3/4	mo & fi, sab	fr,sst & sp	c & s
	Bt2	46-60	SC	br 7.5YR4/4	mo & fi, sab	fr,sst & sp	c & s
	Bt3	60-83	SC	br 7.5YR4/6	mo & fi, sab	fr,sst & sp	c & s
	Bt4	83-115+	SC	br 7.5YR4/6	mo & fi, sab	fr,sst & sp	N/A
Ngombeni	Ap	0-03	C	g 5Y4/1	wk & me, sab	vh, vf, st & p	g & s
	Bu1	30-46	C	g 5Y4/1	wk & me, sab	vh, vf, st & p	ab & s
	Bu2	46-62	SC	br 10YR4/6	wk & me, sab	vh, vf, st & p	ab & s
	Bu3	62+	C	bl 5Y2/1	wk & me, sab	eh, ef, st & p	N/A
Vyambani	A	0-25	C	drbr 5YR3/3	wk & me, sab	vh, vf, st & p	c & irr
	BC	25-40	C	rbr 5YR4/6	wk & me, sab	vh, vf, st & p	c & irr
Kitsoeni	Ap	0-30	SCL	drbr 5YR3/3	mo & fi, sab	fr,sst & sp	g & s
	Bu1	30-50	SCL	drbr 5YR3/4	mo & fi, sab	fr,sst & sp	g & s
	Bu2	50-80	SCL	drbr 5YR3/4	mo & fi, sab	fr,sst & sp	g & s
	Bu3	80-150+	SCL	drbr 5YR3/4	mo & fi, sab	fr,sst & sp	N/A
Ngamani	A	0-15	C	brbl 2.5Y3/2	wk & me, sab	vh, vf, st & p	g & s
	BA	15-40	C	dg 2.5Y4/2	wk & me, sab	vh, vf, st & p	g & s
	B	40-61	C	obr 2.5Y4/3	wk & me, sab	vh, vf, st & p	g & s
	BC	61-88	C	obr 2.5Y5/3	wk & me, sab	vh, vf, st & p	N/A

t=textural difference; u=undifferentiated; C=clay; SC=sandy clay; SCL=sandy clay loam; drb= dark brown; br= brown; g= gray; bl= black; rbr=reddish brown; drbr= dark brown; brbl= brownish black; dg= dark grayish; obr= olive brown; mo= moderate; me= medium; fi= fine; wk= weak; sab= subangular blocky; fr= friable; vr= very hard; vf= very firm; eh= extremely hard; ef= extremely firm; st= sticky; sst= slightly sticky; p= plastic; sp= slightly plastic; g= gradual; c= clear; ab= abrupt; s= smooth; irr= irregular; N/A= not applicable

4.2 Soil physical characteristic

Selected physical properties of the studied soils are presented in Table 5. The texture of soils in the study area showed variation within the pedons. Mavueni and Kitsoeni pedons were observed to have high sand content ranging between 57- 71% which declined with depth. Bu2 horizon of

Ngombeni pedon also recorded high sand content (59%). Clay content ranged between 21- 47% with values being high in profile Ngombeni (31- 59%), Vyambani (41-43%) and Ngamani (37-39%) which irregularly increased or decreased with depth. Silt content was generally low (4-20%) in all the pedons. Mavueni and Kitsoeni pedons recorded the lowest silt content (2- 8%). Textural class for soils in Kitsoeni was sandy clay loam throughout the profile. In Mavueni, soils on Ap and Bt1 horizons had a sandy clay loam texture whereas Bt2, Bt3 and Bt4 horizons had sandy clay texture. Clay texture was observed to be high (41- 47%) in Ngombeni, Vyambani and Ngamani throughout the soil depth with the exception of Ngombeni pedon which had a sandy clay texture on Bu2 horizon.

Saturated hydraulic conductivity (ksat) of the soils showed distinct values as shown in Table 5. Kitsoeni recorded the highest ksat values ranging from 5-7.5cm/h, followed by Mavueni, 1.5-2.2cm/h. Ksat values of Ngombeni, Vyambani and Ngamani pedons were generally low <1 cm/h.

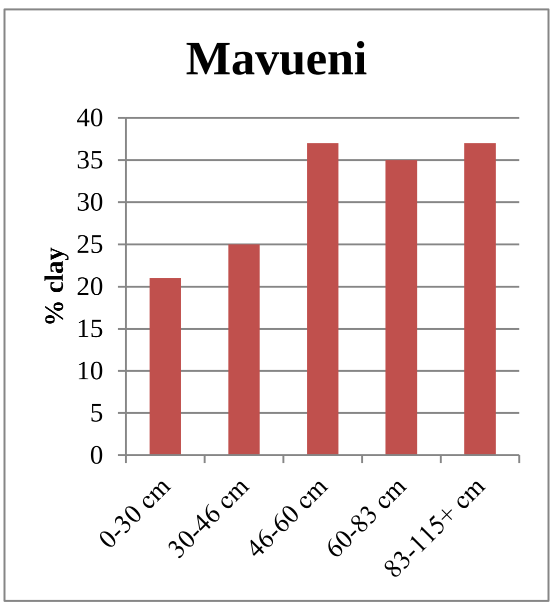
Bulk density was observed to be high in Mavueni and Kitsoeni whose value ranged between 1.5-1.6 and 1.4- 1.7 gcm^{-3} respectively. The bulk density for these pedons decreased with depth. In Ngombeni, Vyambani and Ngamani the bulk density values were <1.5 except in Bu2 horizon of profile 3 that was observed to be 1.7 gcm^{-3}.

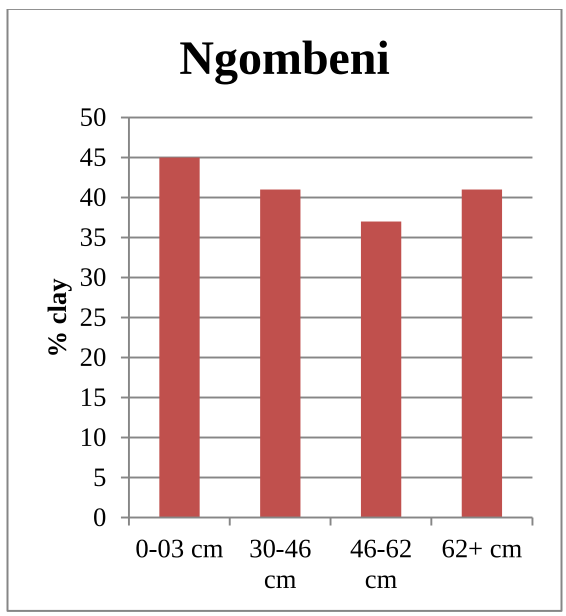
Total void space (porosity) showed a unique trend with respect to the soils. Porosity in Mavueni and Kitsoeni increased with depth with values ranging from 38.8- 41.6% and 35.8- 45.8% respectively (Table 5). In Ngombeni the values ranged from 45.5- 47% which decreased with depth except for the Bu2 horizon which recorded the lowest (34.6%). Vyambani and Ngamani pedons showed the same trend of porosity that was decreasing with increase in depth with values of 45.4 and 38.7- 43.1% respectively.

Table 5: Soils physical properties

Profile	Horizon	% Sand	%Clay	% Silt	Textural Class	BD (g/cm3)	Porosity (%)	Ksat (cm/h)
Mavueni	Ap	73	21	6	SCL	1.6	38.80	1.600
	Bt1	73	25	2	SCL	1.6	39.30	2.200
	Bt2	59	37	4	SC	1.5	40.07	1.500

	Bt3	57	35	8	SC	1.5	41.57	1.030
	Bt4	59	37	4	SC	1.5	39.87	0.900
Ngombeni	Ap	41	45	14	C	1.4	45.50	0.100
	Bu1	39	41	20	C	1.4	46.50	0.080
	Bu2	59	37	4	SC	1.7	34.57	0.160
	Bu3	31	41	28	C	1.3	47.00	0.041
Vyambani	A	41	43	16	C	1.4	45.40	0.024
	BC	43	47	10	C	1.4	45.40	0.030
Kitsoeni	Ap	63	31	6	SCL	1.7	35.80	6.900
	Bu1	65	31	4	SCL	1.5	42.60	4.960
	Bu2	65	29	6	SCL	1.4	45.83	7.500
	Bu3	63	31	6	SCL	15	42.60	7.200
Ngamani	A	37	45	18	C	1.5	43.10	0.006
	BA	35	45	20	C	1.6	39.43	0.007
	B	39	43	18	C	1.6	38.70	0.006
	BC	35	47	18	C	1.5	40.90	0.063





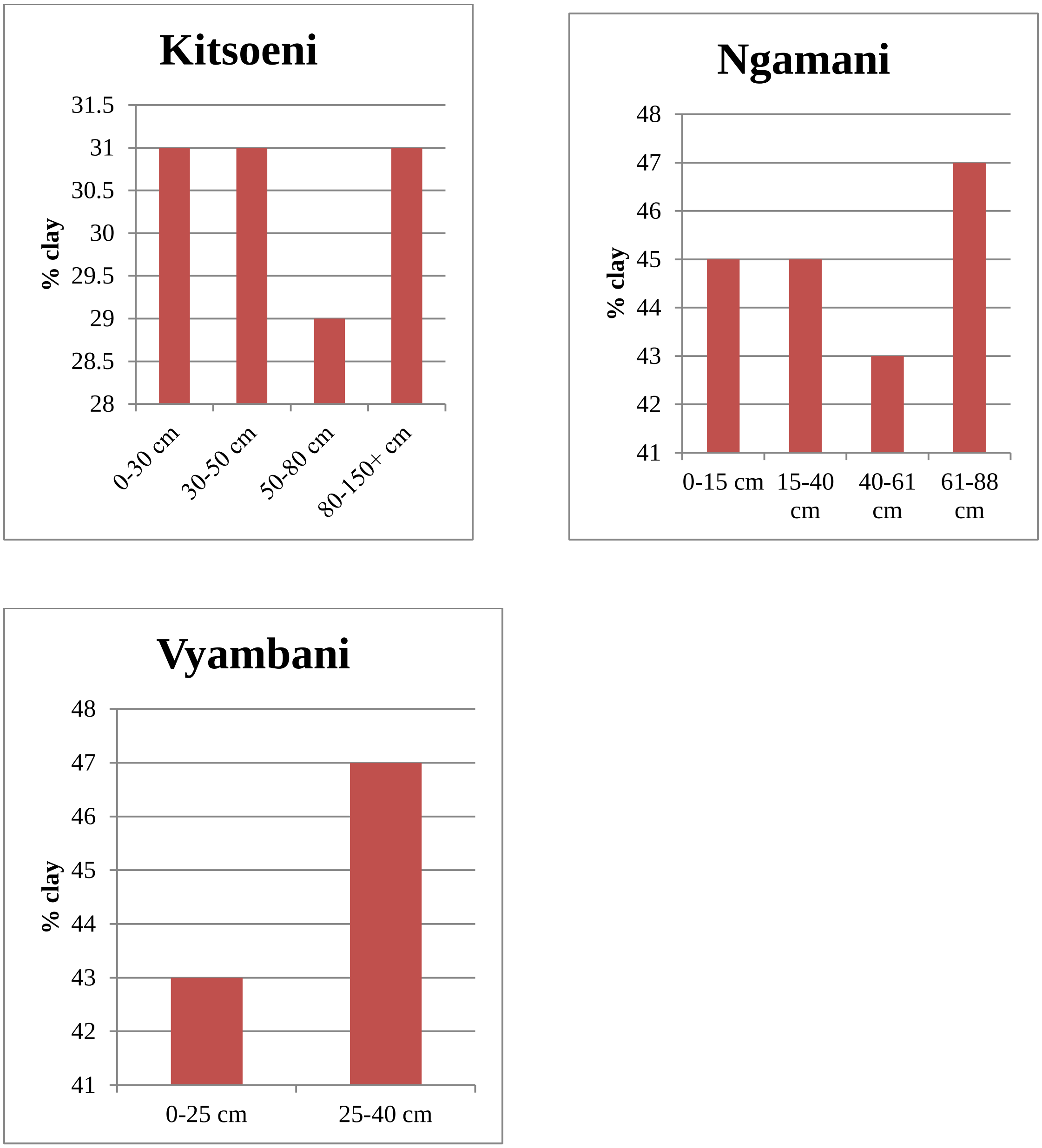
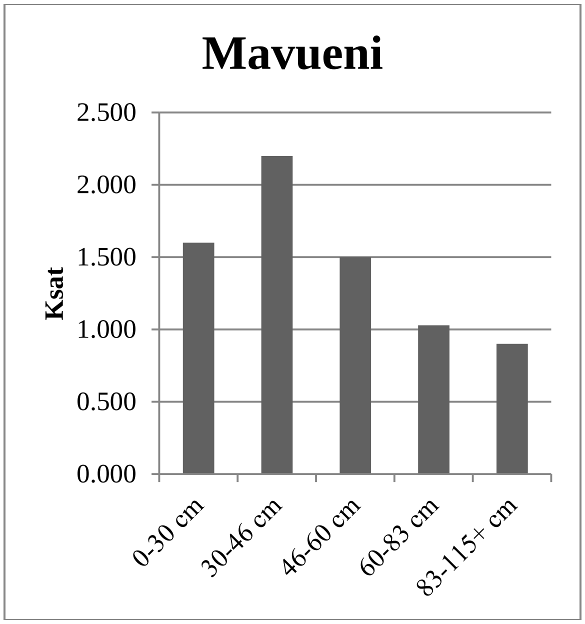
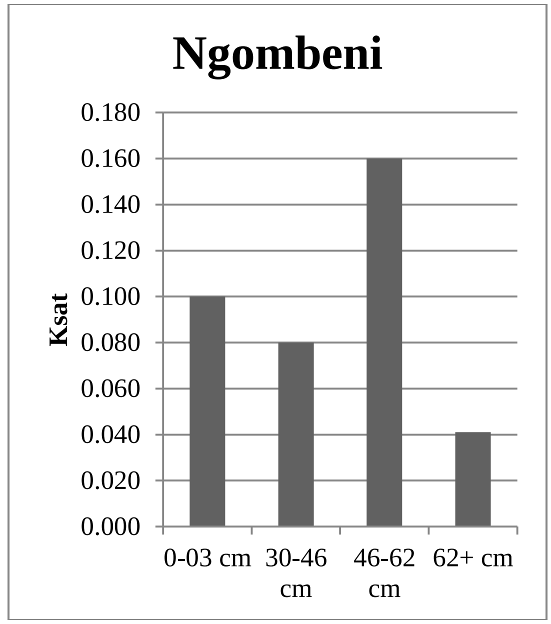
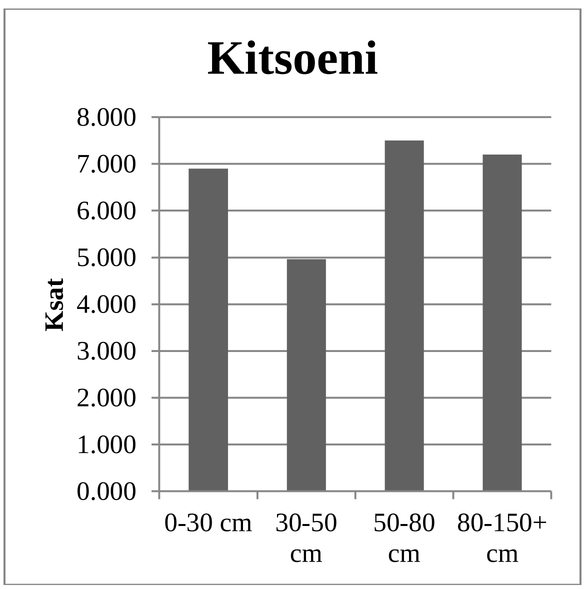
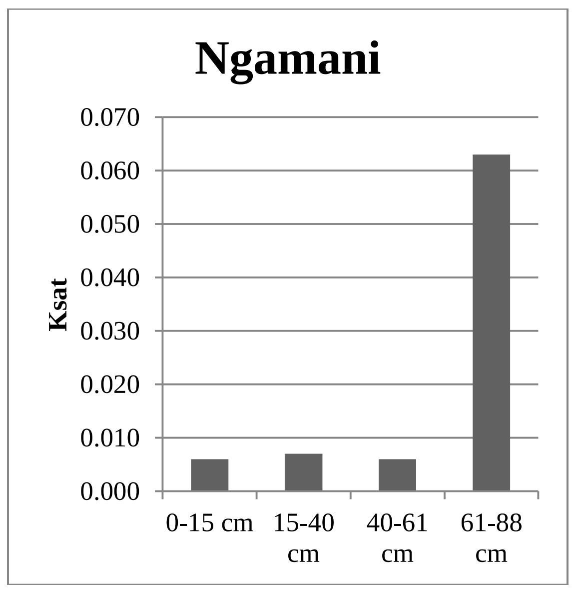


Figure 2: Graphs showing clay distribution with depth


Mavueni
2.500
2.000
1.500
1.000
0.500
0.000
Ksat
0-30 cm
30-46 cm
46-60 cm
60-83 cm
83-115+ cm


Ngombeni
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
Ksat
0-03 cm
30-46 cm
46-62 cm
62+ cm


Kitsoeni
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
Ksat
0-30 cm
30-50 cm
50-80 cm
80-150+ cm


Ngamani
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
Ksat
0-15 cm
15-40 cm
40-61 cm
61-88 cm

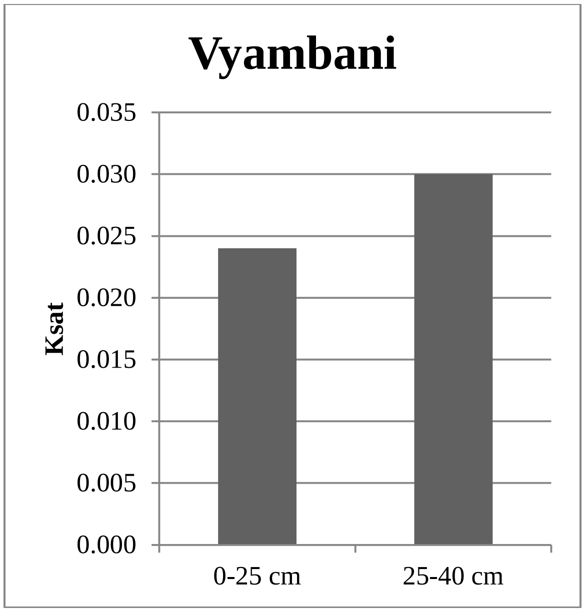


Figure 3: Graphs showing saturated hydraulic conductivity of the studied soils

4.3 Soil chemical properties

4.3.1 Soil reaction and Electrical Conductivity (EC)

The pH and EC values of the studied pedon are presented in Table 6. In Mavueni the pH in water ranged from 5.3- 6.1, Ngombeni 8.2- 8.3, Vyambani 6.5- 7.3, Kitsoeni 6.6- 7.8, Ngamani 7.8- 8.5. pH in Ngombeni and Ngamani was low in the surface horizons and increased with depth while in Mavueni, Vyambani and Kitsoeni the pH was high in the surface horizons and decreased with depth. Electrical Conductivity (EC) values generally ranged from 0.01 to 1.4 dS/m with Mavueni pedon recording the lowest EC while Ngamani had the highest. There was no clear trend of EC with soil depth except for Vyambani and Ngamani, with Ngamani pedon having its BC horizon recording the highest value (1.4dS/m).

4.3.2 CEC, Exchangeable bases, Base saturation and Exchangeable Sodium Percentage

The values of CEC were observed to vary across the pedons as presented in Table 6. In Mavueni it ranged from 1- 5 cmol/kg showing irregular distribution with depth. In Ngombeni it ranged from 11- 26 cmol/kg increasing with depth except for horizon Bu2. In Vyambani the results showed that the CEC was the same throughout the profile. In Kitsoeni it ranged from 4-10 cmol/kg decreasing the depth. In Ngamani it ranged from 19- 24 cmol/kg showing irregular distribution with depth. Unlike the other pedons Mavueni showed an increase of exchangeable bases with depth. In Ngombeni the exchangeable bases followed a pattern of irregular increase and decrease with depth. Exchangeable Ca^{2+} and K^{+} and Na^{+} (except for BC horizon in Ngamani which was observed to be 10cmol/kg) was low (<4 cmol/kg) as compared to Mg^{2+} which recorded values of even > 10cmol/kg. Horizons which had high exchangeable Mg^{2+} were BC in Ngamani and A and BC in Vyambani. ESP values were <15% in all soils except for the Ap and Bt1 horizons of Mavueni pedon and in the B and BC horizons of Ngamani.

Table 6: Chemical properties of studied soils

Profile	Horizon	pH water	EC	K cmol/kg	Na cmol/kg	Ca cmol/kg	Mg cmol/kg	CEC cmol/kg	% BS
Mavueni	Ap	6.1	0.1	0.00	0.45	0.88	0.77	2.2	95.32
	Bt1	6.3	0.11	0.45	0.45	0.88	1.97	1.4	267.57
	Bt2	6.1	0.11	1.34	0.00	1.33	4.27	3.4	203.76
	Bt3	5.5	0.08	2.67	0.45	1.77	4.00	5.0	177.71
	Bt4	5.3	0.15	1.34	0.45	0.44	1.40	4.0	90.58
Ngombeni	Ap	8.2	0.45	1.78	3.12	3.54	6.95	23.6	65.18
	Bu1	8.2	0.4	1.34	1.34	2.65	4.74	26.0	38.70
	Bu2	8.3	0.5	0.89	1.34	1.33	5.05	11.8	72.91
	Bu3	8.2	0.4	0.45	3.12	2.65	8.40	31.0	47.17
Vyambani	A	7.3	0.17	3.56	0.45	3.54	13.03	22.2	92.67
	BC	6.5	0.12	1.34	0.89	1.77	16.45	22.2	92.08
Kitsoeni	Ap	7.8	0.2	2.67	0.45	2.65	3.36	10.4	87.80
	Bu1	7.2	0.3	2.67	0.00	1.77	3.04	7.4	101.04
	Bu2	6.8	0.2	0.45	0.45	0.88	3.10	6.6	73.80
	Bu3	6.6	0.01	0.45	0.45	0.44	3.46	4.4	108.90
Ngamani	A	7.8	0.8	0.45	0.89	1.77	9.99	24.2	54.10
	BA	8.1	0.21	0.45	1.34	1.77	9.86	24.2	55.43
	B	8.6	0.4	0.87	4.01	0.88	9.20	19.4	77.12
	BC	8.0	1.4	1.34	10.25	1.77	13.41	21.6	123.89

4.4 Geochemistry of rock and soil

4.4.1 Geochemistry of rock

XRF analysis of rock samples is presented in Table 7a. The analysis indicated that rock from

Vyambani was rich in oxides of Silicon (42.14%), Calcium (44.87%), Aluminium (7.21%) and Iron (4.41%), Potassium and Manganese were only traces (>1%) while Magnesium was absent. In Ngamani results indicated that the rock was also highly rich in SiO_2 (63.28%), followed quite far by Aluminium (16.35%). Oxides of Iron, Calcium and Magnesium were present at almost the same percentage (5- 6%) with traces of Manganese (0.06%). Rock from Kistoeni on the other hand was very rich in CaO (95.66%) with traces of oxides of Aluminium, Iron and Manganese (>2%) while Silicon and Magnesium were absent.

4.4.2 Geochemistry of soil

The XRF results of soil samples from selected horizons from each soil mapping unit are presented in Table 7b. The analysis indicated that SiO_2 occupies the highest percentage (52-78%) in all soils of the studied area. This trend is followed by AL_2O_3 (10- 23%). Fe_2O_3 follows after with soil from Kitsoeni having the highest percentage (17%). The other Oxides of Ca, Mg, Mn and K are present in smaller percentages (> 10%) in all soils except for Magnesium which was totally absent in soils of Kitsoeni.

Regression analysis of selected geochemical properties as presented in Table 7c shows that there is a positive significant correlation at 0.01 level between $SiO_{2,}$ in the rock and in the soil whereas AL_2O_3 and Fe_2O_3 are negatively correlated at the same significant level. At level 0.05 K is significantly correlated while Ca and Mg are not significantly correlated at the same level.

Table 7: Selected geochemical properties of rocks

Location	%SiO_2	%Al_2O_3	%Fe_2O_3	%Mg	%Ca	%K	%Mn
Vyambani	42.14	7.21	4.41	0	44.87	0.56	0.13
Kitsoeni	0	2.08	1	0	95.66	0	0.28
Ngamani	63.28	16.35	5.41	5.09	6.06	2.77	0.06

Table 8: Selected geochemical properties of soil

Location	Horizon	%SiO_2	%Al_2O_3	%Fe_2O_3	%Mg	%Ca	%K	%Mn
Kitsoeni	50-80	52.04	22.83	17.05	0	0.55	0.36	5.55
Vyambani	0-25	63.58	19.98	8.48	2.87	1.07	2.65	0.19
Ngamani	41-60	66.17	15.78	5.65	6.18	3.37	1.9	0.12
Ngombeni	46-62	79.32	10.54	3.49	2.01	2.8	1.1	0.08

Ngombeni	62+	67.26	17.05	5.16	3.07	3.89	2.48	0.12
Mavueni	41-60	78.82	14	2.52	3.04	0.25	0.63	0.09

Table 9: Regression analysis values for selected geochemical properties

Primary Mineral	R
SiO_2	0.99**
Al_2O_3	-0.99**
Fe_2O_3	-0.99**
Mg	0.89*
Ca	-0.91*
K	0.98*

** and * correlation is significant at 0.01 and 0.05 levels respectively

4.5 Petrography of the rock

Examination of thin slides under petrography microscope revealed minerals present in each of the rock samples. The slide with rock from Kitsoeni revealed white to colourless minerals (Fig 2). This colourless mineral was calcite which had a perfect cleavage with relief which varied from low to moderate. The calcite ($CaCO_3$) showed simple twinning among other inclusion minerals which constituted the rock matrix. The inclusion minerals were olivine- $(Mg^{2+}, Fe^{2+})_2SiO_4$, magnetite- Fe_3O_4 and spinel- $MgAl_2O_4$. Other minerals identified from the sample were brucite- $Mg(OH)_2$, biotite- $K(Mg, Fe)_3(AlSi_3O_{10})$ and quartz- SiO_4 which are in traces.

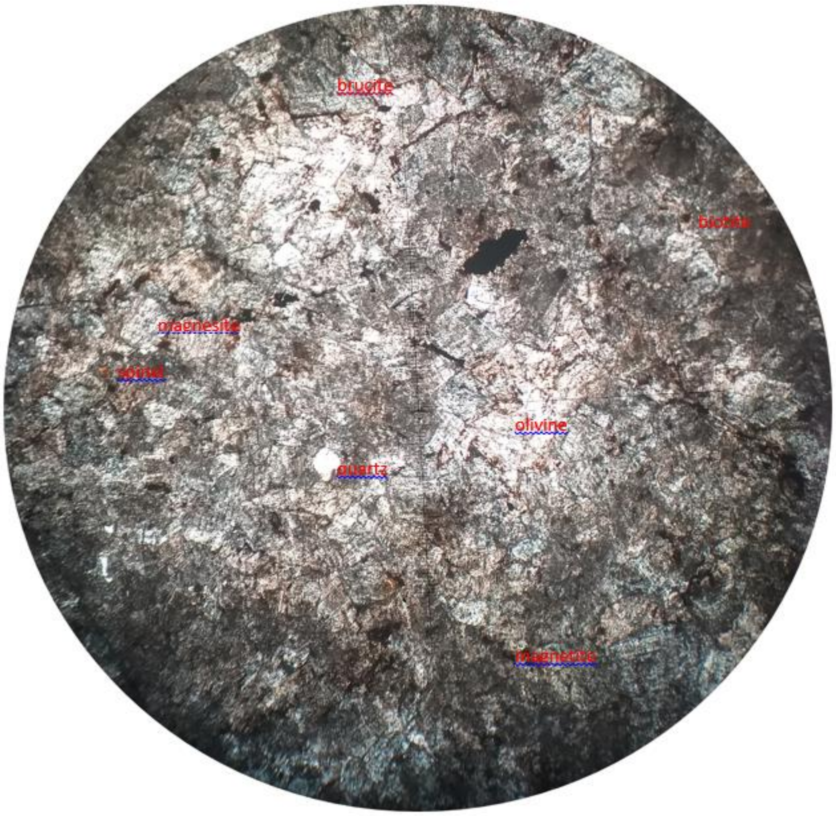


Figure 4: Thin rock section of Kambe Limestone

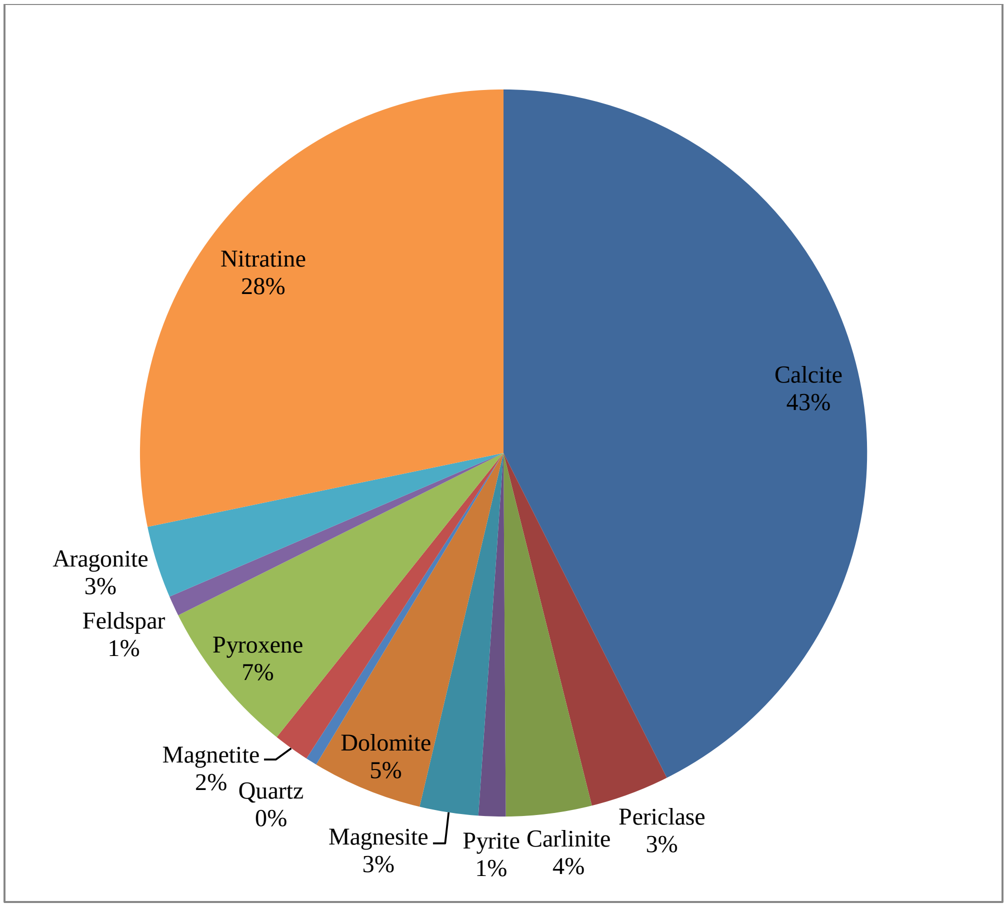


Figure 5: Mineral composition of Kambe Limestone

In Vyambani the slide revealed colored minerals which changed to colourless upon rotation of the stage (Fig 4). The rock sample was dominated by feldspar minerals. Olivine- $(Mg^{2+},Fe^{2+})_2SiO_4$ appeared weathered and zoned. A few isotropic minerals appear as inclusions. Quartz- SiO_4, biotite- $K(Mg, Fe)_3(AlSi_3O_{10})$ and magnetite- Fe_3O_4 minerals were also identified.

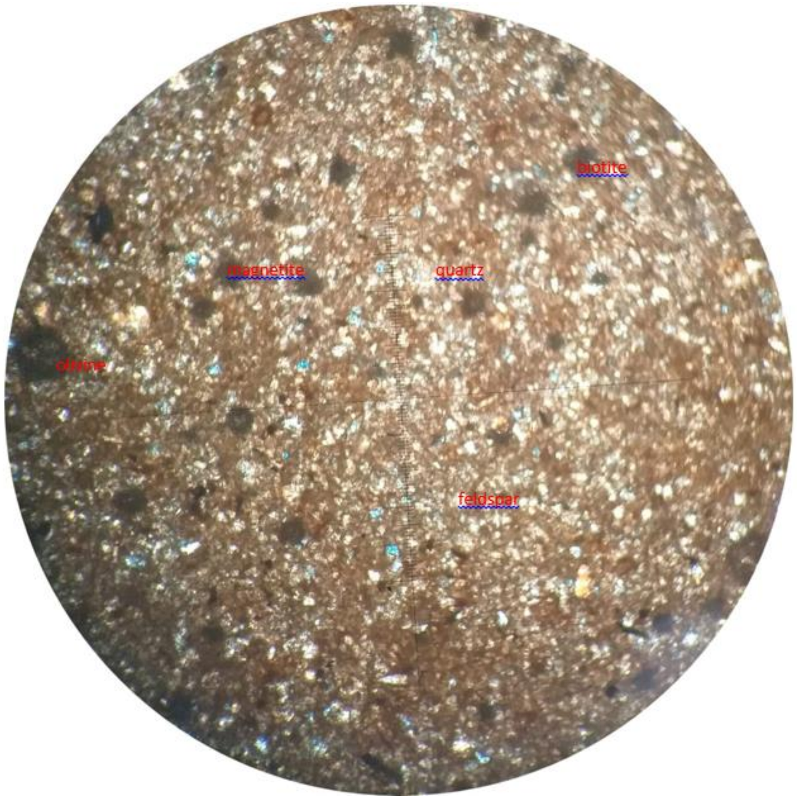


Figure 6: Thin rock section of Vyambani Upper Jurrasic shale

In Ngamani the minerals on the slide appeared white to colorless and were not altered (Fig 5). Inclusions identified include olivine- $(Mg^{2+},Fe^{2+})_2SiO_4$ and spinel- $MgAl_2O_4$. Compositional twinning was seen for olivine. Other minerals identified are biotite- $K(Mg, Fe)_3(AlSi_3O_{10})$, quartz- SiO_4, feldspars, magnetite- Fe_3O_4 and brucite- $Mg(OH)_2$.

Figure 7: Thin rock section of Ngamani Upper Jurrasic shale

4.5 Soil classification

Soils were classified according to WRB (2014) on the basis of their diagnostic horizons, properties or materials (Table 8).

Table 10: Soil classification according to WRB, 2014

Location	Diagnostic horizon	Other diagnostic features/ materials	Reference soil group	Principal qualifiers	Supplementary qualifiers	Soil name
Mavueni	Argic B	Sandy texture, Iron mottles	Arenosol	Protoargic, sideralic, chromic	Stagnic	Protoargic Sideralic Chromic Arenosol (endostagnic)
Ngombeni		Fluvic material, Vertic properties	Fluvisol	Pontofluvic	Claycic, Oxyaquic, petrovertic, Magnesic	Pontofluvic Fluvisol (Clayic, Oxyaquic, Protovertic, Magnesic)
Vyambani	Argic B	Leptic	Lixisol	Leptic,	Hypereutric, Magnesic, Differentiatic, Clayic	Leptic Lixisol (Hypereutric,Magnesic, Clayic)

Kistoeni	Ferralic B, Argic B	Sandy texture	Ferralsol	Ferritic, Lixic	Loamic	Ferritic Lixic Ferralsol (Loamic)
Ngamani	Cambic B	Sodic phase	Cambisol	Eutric, Sodic	Clayic, Magnesic, Densic	Eutric Sodic Cambisol (clayic, Magnesic, Densic)

Soils in Mavueni were developed on Magarini sandstones that are rich in quartz mineral. They are very deep with a sandy texture meeting the requirement of Arenosol. Clay content increase with depth in Bt1 and Bt2 horizons giving rise to argic B horizons. The CEC is relatively low throughout the soil depth which qualifies for sideralic properties. The colour when moist is 7.5YR4/4- 7.5YR4/6 at a depth of more than 40 cm which meets the requirement for chromic qualifier. The soil has stagnic properties at a depth of more than 80cm with light red iron mottles indicating reducing condition. These soils are thus classified as Protoargic Sideralic Chromic Arenosol (Endostagnic).

Soils in Ngombeni are developed on Upper Jurassic shales. These soils are developed on alluvial deposits. Stratification is evidently seen by the alteration of colour and texture within the horizons. Bu2 horizon has a sandy texture unlike the other horizons which are clayey. These properties meet the requirements for Fluvisol. Bu3 horizon is submerged in oxygen rich water and does not show any stagnic or gleyic properties (oxyacquic). Bu3 horizon is influenced by shrinking and swelling clays because of traces of slinkenisides (protovertic). The ratio of exchangeable Ca to Mg is less than 1 hence magnesic. These soils are thus classified as Pontofluvic Fluvisol (Clayic, Oxyaquic, Protovertic, Magnesic)

Soils in Vyambani are developed on Upper Jurassic shales. These soils are shallow with an effective depth of only 40 cm having a continuous rock at less than 100 cm (leptic). Has a clay texture throughout the profile. There is pedogenetic increase of clay into the Argic B horizon. The base saturation is >50cmol+/kg with moderately high CEC hence meet the requirements for Lixisols. The ratio of exchangeable Ca to Mg is less than 1 (Magnesic). These soils are there therefore classified as Leptic Lixisol (Hypereutric,Magnesic, Clayic)

In Kitsoeni soils are developed on Kambe limestone parent material. The soils are highly weathered with Ferralic B being the major diagnostic horizon. The soils also have dark reddish brown color and sandy clay loam texture (loamic) throughout the profile. These properties meet the requirements for Ferralsols. There is pedogenic movement in clay content into Bt horizon. Base saturation was more than 50% but CEC less than 24cmol+/kg hence lixic. The soils are thus classified as Ferritic Lixic Ferralsol (Loamic)

Soils in Ngamani are also developed on Upper Jurrasic shales having Cambic B horizon as the main diagnostic horizon. The CEC of these soil is 24cmol+/kg and a base saturation of >50% hence eutric qualifier. The texture is clay throughout the soil depth (clayic) and the ratio of exchangeable Mg to Ca is less than 1 (Magnesic). The soil has more than 15% exchangeable Sodium (sodic) and evidence of compaction in the B horizon where roots were developing horizontally (Densic). These soils are thus classified as Eutric Sodic Cambisol (Clayic, Magnesic, Densic).

CHAPTER FIVE

5.0 DISCUSSION

5.1 Morphological characteristics

The depth varied from shallow in Vyambani to moderately deep in Ngamani and very deep in Mavueni, Ngombeni and Kitsoeni (Table 4). Soils in Mavueni are developed on Magarini sands. This parent material is rich in quartz which is a resistant mineral to weathering (Brady and Weil, 2008). Its presence therefore imply that the parent material is highly weathered which coupled with the physiography of the area (plain) results to very deep soils. Kambe limestone in Kitsoeni weathers to calcite as a secondary mineral. Calcite is less resistant to weathering because in the presence of water it undergoes hydrolysis and weathers easily (Singh and Chandra, 2015; Sumner, 2002; Rowell, 1994). This may have contributed to the deep Ferralsols soils of Kitsoeni. Ngamani, Vyambani and Ngombeni soils are developed from the same parent material (Upper Jurassic Shales) but their depths vary. Topographic positions of these areas may have influenced the soil depth (Moore et al, 1993). Ngamani and Vyambani are found on the upper slope while Ngombeni is found at the bottom according to the FAO Guidelines for soil description, 2006. The rate of soil removal by erosion tends to dominate on upper slopes while deposition and accumulation occurs on the lower positions of slopes resulting to shallow and deep soils respectively (Schoeneberger et al., 2002). Similar observations were reported by Abate et al. (2014).

Each SMU had a distinct soil colour except for Ngombeni and Vyambani pedons (Table 4) which are found on the same parent material (Upper Jurassic shales). However each horizon in Ngombeni pedon had different colour and this is due to the fluvic nature of the soil. Soils in Kitsoeni have the same colour (dark reddish brown) throughout the soil depth. XRF analysis (Table 8) of both soil and rock sample and petrographic results of rock revealed presence of iron rich minerals. Vyambani soils also showed presence Fe in both the rock and soil. Fe present coupled with good drained which facilitate it oxidation is responsible for the reddish colour of these soils (Brady and Weil, 2008; Foth, 1990; Allen and Fanning, 1983).

All soils of the studied area had subangular blocky structure which is a stable structure and suitable for crop production because their continuous elongated pores facilitate root growth and more so water movement in the soil is greatly enhanced (Pagliai, 2010). However, Ngombeni, Vyambani and Mavueni soil exhibited weak soil structure and this may be due to their clay texture. Under natural conditions of wetting and drying these soils undergo shrinking and swelling which in the absence of cementing agents weakens the soil structure (Sequi, 1978). Soil consistence varied considerably due to the difference in soil texture. Ngombeni, Vyambani and Ngamani pedons that are clayey were hard to extremely hard when dry, firm to extremely firm when moist and sticky and plastic when wet. Mavueni and Kistoeni pedons which had sandy texture were friable when moist and none sticky to slightly sticky and none plastic to slightly plastic when wet. The textural difference results to difference in soil consistence (Moradi, 2013). Clay content distribution in the soil has also been proven to affect and cause variation in consistence (Thangasamy et al., 2005; Singh and Agarwal 2003).

5.2 Soil physical Properties

Ngombeni, Vyambani and Ngamani soils were observed to have clay texture while Mavueni and Kitsoeni had sandy throughout the soil depths. The sand texture in Mavueni arises from weathering of the Magarini sandstone which is majorly composed of quartz (Boxem et al., 1987). The sand content in Mavueni and Kitsoeni pedons decrease with depth which may be attributed to removal of fine materials in suspension from the surface horizons to the subsurface horizon, leaving the coarse materials behind (Karuma, 2019; Mbaga et al., 2017). The Upper Jurrasic shales in Ngombeni, Vyambani and Ngamani are formed from consolidation of clay, silt or mud that upon weathering give rise to fine textured soils (Bates and Jackson, 1980). According to Haung (1962) shales are made up of clay minerals, quartz and other miscellaneous substances in about equal proportions. This explains the distribution of sand (31- 43%), clay (41- 47%) and silt (10-20%) in the soils of Ngombeni, Vyambani and Ngamani. In Mavueni and Ngombeni the clay content increased with increase in soil depth. This trend may be partially attributed to pedogenetiic translocation of clay or in situ formation of secondary clay in the B horizon (Brandy & Weil, 2008; Sumner, 2002).

Bulk density is influenced by soil texture such that sandy soils like for the case in Mavueni, Kitsoeni and Bu2 horizon in Ngombeni are less porous than clay soils hence relatively high bulk densities (McKenzie et al., 2004). Bulk density in Ngombeni varied within the horizons which is attributed to the fluvic nature of the soil. Bulk density was high in the topsoils than in the subsoils of Mavueni and Kitsoeni pedons. The topsoils especially the Ap horizons had high bulk density due to excessive tillage which destroy the soil structure, reduce porosity and increase bulk density. Continuous tillage every season at the same depth in the plough layer causes soil compaction which in turn results in higher bulk density (Karuma et al., 2014).

Porosity is indirectly affected by bulk density ($1\text{-}\rho b/\rho s$) such that porous soils have low bulk. Particle density is not affected mostly by agriculture hence it does not affect porosity (Karuma et al., 2014). Mavueni and Kitsoeni pedons are observed to have slightly lower porosity which increased with depth. This may be partially due to high sand content and bulk density. Ngombeni, Vyambani and Ngamani pedons have slightly higher porosity and this may be due to the clay texture of the soil and slightly lower bulk density. Ngombeni pedon had an exception in the Bu2 horizon whose porosity value was much lower than in the other horizons. This is due to the higher sand content than the other horizons. Generally porosity values of these soils are suitable for crop growth and development according to Brandy and Weil (2008) who concluded that 50% is optimum for crops.

Saturated hydraulic conductivity of the soils showed distinct values, Table 5. In Mavueni, permeability was moderate Bt1 and slow in Ap, Bt2, Bt3 and Bt4. Unlike normal Arenosals which are highly permeable these soils show an increase in clay with depth which hinders water movement down the profile. Bt4 had stagnic condition that justifies the challenges with regard to water movement. Pedons in Ngombeni, Vyambani and Ngamani had very slow Ksat which is caused by the clay texture. Soils in Kitsoeni had Ksat values ranging from moderate to moderately rapid and this is due to the sandy texture. Soil texture significantly influences saturated hydraulic conductivity following sand= loam= clay texture trend in the soil (Brady and Weil, 2008).

5.3 Soil chemical characteristics

5.3.1 Soil reaction and electrical conductivity

The pH (H_2O) of the soils was moderately acidic in Mavueni, moderately alkaline in Ngombeni, neutral in Vyambani, slightly alkaline in Kitsoeni and moderately alkaline in Ngamani. The pH in Ngombeni increased down the profile except for Bu2 horizon which had the highest pH, indicating fluvic properties. This pedon and that from Ngamani had a pH which increased with depth which may be due to movement of bases from the top soil to the subsoil. Mavueni, Vyambani and Kitsoeni pedon had pH which decreased with increase in soil depth and this could be attributed to leaching of anions (Al and/or H) from the surface to the subsurface horizons. According to Motsara and Roy (2008) the pH for these soils are suitable for growing of most crops.

Electrical conductivity results were observed to be generally very low (<1 dS/m) in all soils of the studied area except for BC horizon of Ngamani pedon which recorded 1.4 dS/m. Generally the EC values were high in Ngamani and low in Mavueni. EC of these studied are low may be due to combined effect of pH and parent material (Abate et al., 2014) Naturally soil mineral influence the EC and for the case of the studied the values are low because the rock and soil mineral do not contribute any salts in the soil. EC normally gives a measure of salt concentration in a soil (Mostara and Roy, 2008) and according to Richards (1954) these soils are non-saline since the values are <4 dS/m.

5.3.2 CEC, Exchangeable bases, Base saturation and Exchangeable Sodium Percentage.

CEC in Mavueni and Kitsoeni ranged from low to medium according to Landon (1991). These values are influenced by both sand and clay. As pointed above Magarini sandstones are dominated by quartz which upon weathering gives rise to soils with high sand content (Wanjogu and Mbuvi, 1995). Sand does not have negative charges to attract cations thus lack the capacity to retain these cations hence susceptible to leaching (CUCE, 2007; Msanye et al., 2003) while the illuvial clay in the Bt horizons retain cations. Ferralsols of Kitsoeni on the other hand are highly weathered soils (WRB, 2014) which due to the high sand content are also unable to retain cations hence easily leached. The low CEC imply low fertility. These soils therefore require addition of organic matter to boost retention of cations and improve fertility (Moore, 1998). Soils of Ngombeni, Vyambani and Ngamani have moderate to relatively high CEC (Landon, 1991). The high CEC is also traced from the parent material. Upper Jurassic shales produce clay minerals as part of the weathering product. These clay minerals have negative charges within their structure which attract and retain cations. The more the clay contents in soil the higher the retention of cations (Hazelton et al., 2007; Brady and Weil, 2002). This is also observed where CEC increases with increase in clay content down the soil profile of Mavueni pedon.

Exchangeable bases followed Mg> Ca> K > Na order in all soil with inconsistent distribution with depth. These cations maybe derived from their parent materials as shown in. Mg^{2+} ions are derived from a variety of minerals as revealed in the petrography analysis. Olivines $(Mg^{2+},Fe^{2+})_2SiO_4$, brucite $Mg(OH)_2$, biotie $K(Mg, Fe)_3(AlSi_3O)$ and spinel $MgAl_3O_4$ minerals produce Mg^{2+} ions upon weathering (Longwell et al., 1969) and this could be the reason for domination of Mg in all soils of the studied area. Ca^{2+} ions in Kitsoeni are derived from calcite ($CaCO_3$) which is the major component of Kambe limestone (Table 7). Ca^{2+} ions in Vyambani and Ngamani on the other hand are derived from weathering of feldspars (Sumner, 2002; Haung, 1997). Na^+ and K^+ ions emanate from weathering of feldspars (FAO, 1972; Mohr et al., 1972) as identified in the Upper Jurassic shales of Vyambani and Ngombeni. Biotite is another source of K^+ ions which was present in both Kambe limestone of Kitsoeni and Upper Jurrasic shales of Vyamabani and Ngamani.

Base saturation reflects on the amount of basic cations (Ca^{2+}, Mg^{2+} and K^+) available on the soil exchange complex (Atofarati et al., 2012). Base saturation is dependent on soil pH such that at pH below 7 the exchange complex is usually occupied by acid cation (H^+ and Al^{3+}) resulting to low base saturation while at pH above 7 the base saturation tend to be high since the exchange complex is usually occupied by basic cations (Sumner, 2002). The pH of all soils in the studied area ranged between 5.3- 81 which may have attributed to the base saturation values of >50%. However some soils were observed to have base saturation of > 100% and this may be due to unavoidable extraction of free Calcium and Magnesium in soil solution that are not attached to the exchange complex (Karuma, 2019).

The soils were not prone to sodicity hazard because the ESP values are < 15% (FAO, 1994) except for the Ap and Bt1 horizons of Mavueni and B and BC horizons of Ngamani pedons. The sodicity hazard ranged from light to moderate and moderate to high respectively. Crops not tolerant to such sodicity are majorly affected hence replacement of sodium with calcium is required to enhance growth and development of crops.

5.4 Relationship between minerals present in the parent materials and soils

Primary minerals as presented in table 7c such as SiO2 and K have been shown that their values in the rock significantly correlate with those in the soil. This shows that the minerals present in the rocks are derived from the underlying parent rock while for the case of Al2O3 and Fe2O3 where the correlation is negative may have been an indication that there is active movement of these minerals from the soil to the underlying parent material. This supports the findings of Boxem et al. (1983) that mineralogical properties of the underlying parent materials influence respective soil types and soil properties. Singh and Chandra (2015) reported that there are similarities in chemical composition of parent materials and soil.

The Kambe Limestone rock from Kitsoeni was dominantly composed of calcite mineral that was clearly observed on the thin sections (Fig 2) and the XRD analysis (Fig 3). Limestone is the parent material in this area that weathered and gave rise to calcite (Singh and Chandra; 2015 Dana et al., 1985). Inclusions were observed on thin slides which were olivine [$(Mg^{2+}, Fe^{2+})_2$ SiO_4, magnesite ($MgCO_3$) and spinel ($MgAl_2O_4$) with trace amounts of brucite [$Mg(OH)_2$], biotite ($K_3AlSi_3O_{10}$) and quartz (SiO4). Other minerals present parent material analyzed by XRD were pyrite (FeS2), aragonite (CaCO3), carlinite (Ti_2S), dolomite [$CaMg(CO_3)_2$], magnetite (Fe_3O_2), nitratine ($NaNO_3$) and periclase (MgO).

This rock is highly weathered as the quartz content is very low (0.5 %). Almost all the Silica has undergone weathering and removed from the rock leaving highly resistant minerals such as oxides and hydroxides of Iron and Aluminium (Sumner, 2002). This is true as the XRF analysis showed SiO2 is completely absent from the rock and the soil had 52%. The result is formation of soil with sandy texture, having high sand (Silica) content. The sand content of this soil ranged between 63- 65% with a sandy clay loam texture (Table 5). The challenge with such soil is aggravated leaching of cations which results to low CEC as revealed by chemical data in table 6. Similar observations have been supported by findings of Wanjogu and Mbuvi (1995).

Olivine and biotite are sources of Magnesium in this soil. Olivine is a ferromagnesium which not only release Mg^{2+} ions but also Fe^{2+} ions, clay minerals and silica (Longwell et al., 1969). The clay minerals help in retaining the Mg^{2+} ions and release them slowly for plant uptake. Olivine, magnetite, pyroxene and biotite are Iron rich minerals which upon weathering release Fe^{2+} ions in solution. This iron released by all these minerals coupled with good drainage is responsible for the red color of this soil.

Petrography analysis revealed the Upper Jurrasic Shale rock Vyambani pedon was dominated by Feldspars. Feldspars are aluminosilicate minerals which undergo chemical weathering to give rise to clay minerals such as kaolinites and illites as secondary minerals and Na^{+}, Ca^{2+} and K^{+} ions in solution. This weathering process is the primary source of cations in the soil. Their quantity is determined by how much the rock releases and the type of feldspar in the rock. Feldspars weathering are important in improving and sustaining soil fertility (Singh and Schuze, 2015). The clay minerals they release are negatively charged which attract and retain the Na^{+}, Ca^{2+} and K^{+} ions released in the soil solution that later are slowly released to plants for uptake. This is also responsible for the medium CEC of the soil. Other important mineral identified as inclusions is olivine that was highly weathered (Fig 4). Olivine under natural state is a mineral which is less stable and highly susceptible to weathering (Brady and weil, 2008; Huang, 1977). As indicated above olivine weather to give rise to iddingsite (a combination of clay minerals, Fe^{2+} and Mg^{2+}) (Sumner, 2002). The iron from this mineral together with the one releasesd from weathering of magnetite and biotite are responsible for the reddish color of this soil. Minerals identified in Ngamani rock were similar to those in Vyambani because the parent material was the same (Upper Jurrasic shales). Most soil properties were similar except for the color.

CHAPTER SIX

6.0 CONCLUSION

The studied soils exhibited a great spatial variation along the toposequence. They are developed on sedimentary rock under the different formations that are the Magarini sands, Upper Jurassic shale and Kambe limestone. Magarini sands are dominated by quartz, Upper Jurassic shale by clay minerals and Kambe limestone by calcite. Minerals identified in these parent materials are brucite, biotite, magnesite, olivine, spinel and quartz in Kambe limestone of Kitsoeni; feldspars, olivine, quartz, biotite and magnetite in Upper Jurrasic shales of Vyambani and; biotite, olivine, quartz, feldspars, magnetite, brucite and spinel in Upper Jurrasic shales of Ngamani. These parent materials have strongly influenced morphological, physical, chemical and mineralogical properties of soils of the studied area which is confirmed by their analyses. The high sand content in soils of Mavueni and Kitsoeni were derived from quartz grains in Magarini sands and Kambe limestone respectively while high clay content in soils of Ngombeni, Vyambani and Ngamani are derived from the Upper Jurassic shales. Composition of sand, clay and silt in the later is related to their distribution in their parent material. Soil colour is also influenced by the parent material such that iron present in Kambe Limestone and Upper Jurassic shales of Vyambani has given soils red colour. The presence of quartz in soils of Mavueni and Kitsoeni have resulted to low CEC due to high susceptibility of leaching of cations. Unlikely clay from the shales have the capacity to retain cations hence high CEC. Presence of feldspars in soils of Vyambani and Ngamani indicate high potential for nutrient reserves unlike soils in Mavueni and Kitsoeni whose parent materials are composed of nutrient poor quartz. All soils had high exchangeable Mg^{2+} ions which is derived from olivines, brucite, biotite and spinel minerals present in the parent materials. High exchangeable Ca^{2+} ions in Kitsoeni were derived from calcite mineral while in Vyambani and Ngamani were derived from feldspars. These soils are classified according to WRB, 2014 on the basis of their morphological, physical and chemical properties as Protoargic Sideralic Chromic Arenosol (endostagnic) in Mavueni, Pontofluvic Fluvisol (Clayic, Oxyaquic, Protovertic, Magnesic) in Ngombeni, Leptic Lixisol (Hypereutric, Magnesic, Clayic) in Vyambani, Ferritic Lixic Ferralsol (loamic) in Kitsoeni and Eutric Sodic Cambisol (clayic, Magnesic, Densic) in Ngamani. The degree of variation in these soil properties indicate the existence of different degree of potential, limitation and management requirement hence consideration for sustainable use sustainable of these soil resources is fundamental.

6.1 RECOMMENDATIONS

- Future land evaluation study is recommended to utilize this soil information generated especially suitability of each soil type for crop production to assist farmers within the study area make informed decision and sustainably use the soil resource.
- Further studies are required to explore the parent materials' potential for nutrient reserves.
- Appropriate measures need to be put in place to curb soil erosion especially on soils that are highly susceptible such as the Cambisols of Ngamani.

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APPENDICES

Appendix 1: Mavueni profile

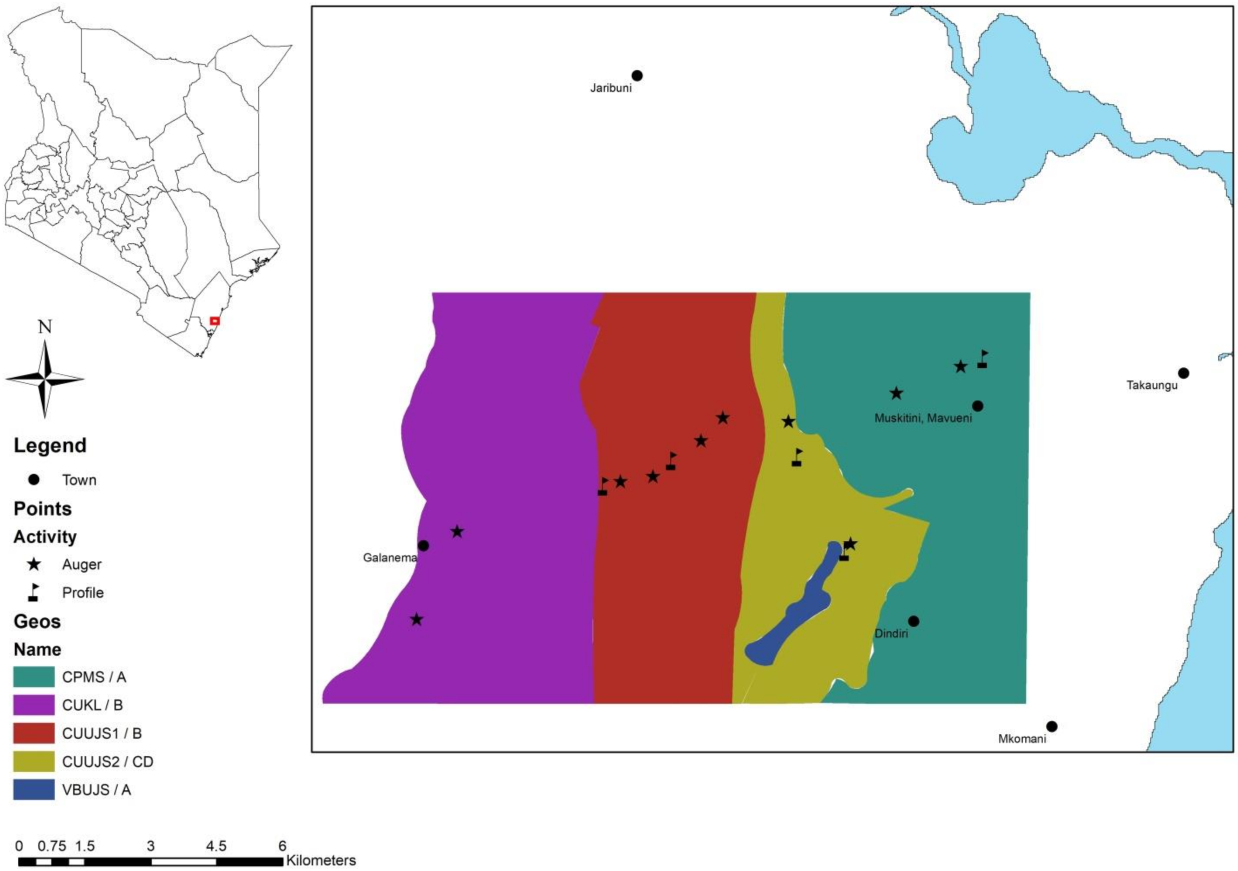
Appendex 2: Ngombeni profile

Appendix 3: Vyambani profile

Appendix 4: Kistoeni profile

Appendix 5: Ngamani Profile

Appendix 6: Soil map of the study area



Legend

CU Coastal Upland

KL Soils developed on Kambe Limestone

CUKL

Well drained, very deep, dark reddish brown, soft to friable, sandy clay loam [Ferritic Lixic Ferralsol (loamic)].

UJS Soils developed on Upper Jurassic Shales

CUUJS1

Moderately well drained to well drained, shallow, dark reddish brown to reddish brown, very hard to very firm, clay [Leptic Lixisol (Hypereutric, Magnesic, Clayic)]

CUUJS2

Poor drained to moderately drained, moderately deep, very dark grayish to olive brown, very hard to very firm, clay, severe gully erosion, sodic phase [Eutric Sodic Cambisol (clayic, Magnesic, Densic)]

CP Coastal Plain

MS Soils developed on Magarini sands

CPMS

Moderately well drained to well drained, very deep, dark brown to brown, slightly hard to friable, sandy clay loam, in places mottled [Protoargic Sideralic Chromic Arenosol (endostagnic)]

VB Valley bottom

UJS Soils developed on Upper Jurassic Shales

VBUJS

Poorly drained, moderately deep, gray to black, extremely hard to extremely firm, clay, surface, fluvic properties, [Pontofluvic Fluvisol (Clayic, Oxyaquic, Protovertic, Magnesic)]