DISTRIBUTION AND CHARACTERISTICS OF CALCRETES AND CALCRETE-SOIL PROFILES ON THE NORTHERN LOWER SLOPES OF ULUGURU MOUNTAINS IN MOROGORO, TANZANIA

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ABSTRACT

This study was conducted on the area extending northwards from the footslopes of the Uluguru mountains towards the Ngerengere river. Kihonda transect was selected for detailed characterization of different calcrete forms and the associated soils and regolith so as to understand the origin of calcretes, their characteristics and their influence on soil properties.

Near Ngerengere river, the calcrete layer is considerably thinner (27.5 cm) than those on the lower slope (76 cm), midslope (135 cm), crest (106 cm) and neighbouring depression (142 cm) implying the influence of Ngerengere river on calcrete formation. Less developed calcretes occur near the river while the most developed calcretes occur at or near the crest.

Nodular, honeycomb and massive calcretes are the major forms of calcretes occurring on the transect. Their proportions along the transect which reflect their lateral extension follows the order: nodular (94.9%), honeycomb (87.2%) and massive (51.3%). A considerable difference in purity exists among different calcrete forms ranging from 47.6% in nodular calcrete, 75.0% in honeycomb and 97.5% in massive form. This difference in purity is explained in terms of their difference in degree of development.

A sharp difference in average $CaCO_3$ content ranging from 7.7% in soil solum to 65.0% in calcrete layer exists. The latter implies a lithological discontinuity at the soil-calcrete interface. The difference is gradual from 65.0 to 37.7% at the calcrete-regolith interface. The source of the $CaCO_3$ in the calcretes is therefore the underlying parent material. The calcretes are mainly constituted of micritic calcite. Sparite occurs on top of massive calcrete, in fissures, voids and around the relic minerals implying a multi-phase precipitation of calcite. Minor minerals are quartz, opaline silica and feldspars.

The studied calcretes were formed during the last glacial period, about 41,000 or more years ago. The gravel and soil layers are considerably younger.

DECLARATION

I, Eliab Sentozi, do hereby declare to the senate of the Sokoine University of Agriculture that this dissertation is my original work and that it has never been submitted for a degree in any other University.

signature.....

Eliab Sentozi

Date.....19/3/1997

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DEDICATION

Dedicated to brother Niyokwizegwa Birusha whose love and material support gave me a good educational base during my early school life.

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LIST OF ABBREVIATIONS

Al_2O_3	= Aluminium oxide
BP	= Before present
Ca^{2+}	= Calcium ion
$CaCO_3$	= Calcium carbonate
CO_3^{2-}	= Carbonate ion
CO_2	= Carbon dioxide
CEC	= Cation exchange capacity
Cl^-	= Chloride ion
cmol(+)/kg	= Centimoles per kilogram
F^-	= Fluoride ion
FAO	=Food and Agricultural Organization of the United Nations
Fe_2O_3	= Iron(III) oxide
g/l	= Grams per litre
HCO_3^-	= Bicarbonate ion
km	= Kilometre
m.a.s.l.	= metres above sea level
me/l	= Milliequivalent per litre
mg/l	= Milligrams per litre
Mg^{2+}	= Magnesium ion
Na^+	= Sodium ion
ppm	= Parts per million

SiO_2	= Silica
SO_4^{2-}	= Sulphate ion
SUA	= Sokoine University of Agriculture
UDSM	= University of Dar es Salaam
USDA	= United States Department of Agriculture
Å	= Angstrom
$\delta^{14}C$	= Composition of carbon-14 isotope in a given material
$\delta^{18}O$	= Composition of oxygen-18 isotope in a given material
µm	= Micrometre

CHAPTER ONE

INTRODUCTION

Calcrete is a general term used to describe a material composed dominantly but not exclusively of calcium carbonate and involving cementation of, accumulation in and/or replacement of greater or lesser quantities of soil, rock or weathered material primarily within voids, channels or pore spaces (Goudie, 1973).

Calcrete occurs as a terrestrial accumulation in which the calcium carbonate occurs in a variety of physical forms, ranging from powdery to highly indurated (Strong *et al.*, 1992). The physical forms of calcretes are important with respect to the understanding of the process of their formation and their influence on the soil with which they are associated.

Calcrete formation is favoured by deficit of moisture which contributes towards its precipitation and induration. Calcretes are hence associated with semi arid or arid environment (Ducloux and Laouina, 1989; Goudie, 1971; Wang *et al.*, 1994). On the contrary, calcretes in the present study on the northern lower slopes of Uluguru mountains occur in the area where the climate is humid.

Calcretes develop from a variety of sources of calcium carbonate. Some calcretes have formed by *in situ* weathering of basement rocks (Klappa, 1983; West *et al.*, 1988b) while others have formed either by acolian deposition (Gile *et al.*, 1966; Hay and Reeder, 1978) or by precipitation of calcium carbonate from the ground water (Raghavan *et al.*, 1991; Thomas, 1996). The large variation of both environmental conditions under which calcretes are encountered and the wide range of geological basement over which calcretes are found make it difficult to schematize their mechanism of formation or to relate a given deposit with another.

In order to be able to interpret the genesis of calcretes, geomorphological and paleoclimatological approaches (Radtke *et al.*, 1988) together with calcrete characterization are required. Age information has also been mentioned to be an important information required in any attempt to understand the genesis of calcretes (Radtke, *et al.*, 1988). Association of the age of calcretes and the corresponding paleoclimate may serve as an indicator of the origin and the processes involved during its formation.

Calcretes may occur exposed on the earth surface or underlying a soil solum. Depending on the depth of occurrence from the soil surface, calcretes may influence the land use type. Also calcretes being rich in calcium carbonate may be suspe

exchange properties. A proper knowledge about the effect of calcretes on soil properties is required in order to determine the proper use of such a land and soils. This need is necessitated by the fact that these soils have the potential for food production. However, several studies that have been conducted elsewhere have not addressed the relationship of calcretes to the behaviour of soils in the areas where they occur.

Information on calcretes in Tanzania is very limited. In fact, the studies on calcretes in Tanzania are so scanty that any new work would serve the purpose of information build up. Among the areas which may require priority in the understanding of calcretes in Tanzania are the origin, characteristics and impact of calcretes to the behaviour of the associated soils.

This study was therefore carried out with the aim of making an inventory of the calcretes occurring on the northern lower slopes of Uluguru mountains taking into account their distribution, mode of formation and the characteristics of soil-calcrete profile.

The specific objectives of the study were:

1. to find out the location of the calcretes and the factors which have contributed to their formation
2. to characterize in detail the studied calcretes in terms of their physical, chemical and mineralogical properties
3. to determine the influence of calcretes on the properties and behaviour of soils associated with them.

CHAPTER TWO

LITERATURE REVIEW

2.1. Definition of calcretes

Calcrete is defined as a terrestrial material composed dominantly but not exclusively of calcium carbonate and involving cementation of, accumulation in and/or replacement of greater or lesser quantities of soil, rock or weathered material primarily within the vadose zone (Goudie, 1972). Formation of calcretes took place mainly during the quaternary and tertiary periods (Warren, 1983) although their existence in earlier geological formations has been widely reported (Reeves, 1976; Goudie, 1983).

The term calcrete signifies either pedogenic deposits of calcium carbonate which are hence formed in soil with addition of only rain water and aeolian dust as well as *in situ* alteration of parent rocks (Klappa, 1983; Machette, 1985) or non pedogenic deposits which are mainly of ground water origin (Machette, 1985). In this respect, there are two types of calcretes namely pedogenic and non-pedogenic calcretes.

Pedogenic calcretes are formed due to processes similar to those involved in soil formation. These processes include removal, translocation, transformation and neoformation of mobile constituents (Klappa, 1983). Such changes produce horizon

differentiation and formation of calcrete profile (Klappa, 1983). Ground water calcretes are formed by precipitation of calcite from ground water (Raghavan *et al.*, 1991; Thomas, 1996). This occur by capillary rise of ground water and the evaporation of soil moisture. This leads to the formation of calcareous nodules in poorly drained soils (Raghavan *et al.*, 1991; Thomas, 1996). Ground water calcretes normally lack horizon differentiation (Raghavan *et al.*, 1991).

2.2 Occurrence and distribution of calcretes

2.2.1 Geographical Distribution

Calcrete commonly occurs in several parts of the world with calcareous rocks and sediments which are associated with net annual water deficit. Calcretes are known to occur in the Kalahari desert, in South Africa and Namibia (Goudie, 1971, 1972, 1973; Watts, 1980); in Yorkshire, England (Strong *et al.*, 1992); in New Mexico (Gile *et al.*, 1966; Monger *et al.*, 1991); in Israel (Dan, 1977; Verrecchia, 1990); in South Western Kansas, U.S.A. (Schultz, 1969); South Western U.S.A (Hay and Wiggins, 1980); Majove desert California (Schlesinger, 1985); Central Texas (West *et al.*, 1988a&b) and many other places.

In East Africa, calcrete are known to occur in the drier areas situated adjacent to the eastern rift valley. Examples of the places where calcretes occur in East Africa include Magadi, Kisumu, Serengeti plain, Northern frontier District and Wajir basin in Kenya (Goudie, 1973); and Olduvai gorge in Tanzania (Hay and Reeder, 1978).

2.2.2 Occurrence of calcretes on the landscape

Calcretes are commonly found in valleys under arid and semi arid conditions especially in basins (Ducloux and Laouina, 1989; Goudie, 1971; Wang *et al.*, 1994). Pre-lake areas may also possess layers of strong calcrete accumulation (Bissel, 1963). Calcretes are also associated with old lake shorelines following the retreat of the lake (Grove, 1969). Other areas with calcrete formations are those around pans; along water courses; and those with aeolian depositions (Goudie, 1973). Calcretes have also been reported to occur in valleys especially in areas merging with drainage lines, and in plains surrounded by hills (Vaniman *et al.*, 1994) and in alluvial plains (Theriault and Desrochers, 1993; Vogt and Delvalle, 1994). Calcretes are frequently associated with landscapes with extensive flat topped tablelands and plateaux (Goudie, 1973).

2.3 Genesis of calcretes

2.3.1. Pedogenic calcretes

Calcrete is formed where there is a sufficiently permeable material to absorb $CaCO_3$ by solution transport and net water deficit to facilitate the subsequent precipitation (Blümel, 1982). According to Thomas (1996), pedogenic calcretes are confined to areas with rainfall between 400 and 600 mm/year. Pedogenic calcretes are thus widespread within the semi arid zones in which local sources of calcium

are not enough to explain their occurrence. Many workers have attributed the occurrence of pedogenic calcretes in areas with non calcareous origin to wind blown dust (Gile *et al.*, 1966.; Hay and Reeder, 1978; Milnes, 1992).

Just like in soil forming processes, calcrete formation cause modification in sediments or weathered rock by removal, translocation, transformation and neoformation of mobile constituents (Klappa, 1983). Such changes generally produce horizon differentiation and formation of calcrete profile (Klappa, 1983). According to Klappa (1983), the process of calcrete profile development and subsequent weathering of pedogenic calcretes involves six stages. They include preparation of the host material, soil formation, accumulation of calcium carbonate, profile development, induration and reworking or dissolution.

The preparation of host material involves mechanical and biophysical disintegration, physico-chemical dissolution and biochemical weathering of an initially consolidated bedrock. The soil formation stage involves transformation of weathered detritus into a soil by changes produced by the action of either organisms or movement of water through a sediment. Accumulation of calcium carbonate involves progressive enrichment of the soil with calcium carbonate. During this process, the pore spaces become lined or filled with calcite. Relic quartz grains together with other minerals inherited from the host material become progressively replaced by calcite. The stage is followed by profile development, induration and subsequent reworking of the

indurated profile.

2.3.2 Non pedogenic (ground water) calcretes

These are formed by precipitation of calcite from ground water (Raghavan *et al.*, 1991; Thomas, 1996), a process which is determined by the loss of carbon dioxide by degassing from the ground water (Thomas, 1996). Loss of CO_2 and evaporation, together, produce supersaturation of the $CaCO_3$, hence precipitation of calcite (Thomas, 1996). The distribution of ground water calcrete is determined by the chemistry of ground water (Goudie, 1972). Ground water calcretes are likely to be formed where the ground water is rich in ions such as Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-} and other ions which are commonly found in calcretes.

2.4 Factors influencing calcrete formation

2.4.1 Rock type

Pedogenic calcretes can be found over carbonate rocks and sediments (Birkeland, 1974; Dan, 1977; Goudie, 1973; Klappa, 1983; Walsh, 1960; West *et al.*, 1988b). Dan (1977) reported the occurrence of pedogenic calcretes over chalks and marls in Israel. Calcretes have been found directly overlying a limestone parent material in a number of places. Typical examples of such places include the Bomba region, Libya, the Kaap plateau in South Africa and the Jurassic limestone of Wajir in Kenya (Goudie, 1973). Studies conducted in Kenya by Walsh (1960) have shown

that calcretes occur over marble in the Taita hills. These calcretes are of pedogenic origin.

Pedogenic calcretes have also been reported to occur over calcium rich rocks. In the Canary islands, Goudie (1973) reported the occurrence of pedogenic calcretes over basalts. Goudie (1973) reported the occurrence of calcretes over basic igneous rocks containing minerals rich in calcium such as apatite, grossularite, augite and hornblende in Tuli, Botswana. Pedogenic calcretes are also known to exist in areas where the parent material *in situ* is not a contributing factor for their formation. These include areas in which calcium carbonate has been carried either in solution or by aeolian means. Occurrence of calcrete formed by movement of $CaCO_3$ in solution has been documented by Birkeland (1974) and West et al. (1988b). According to Birkeland (1974), the build up of $CaCO_3$ in the soil is the function of the rate at which it can be translocated by leaching waters in the soil profile. West et al. (1988b) reported the calcretes formed from lateral movement of solutions from upslope carbonate sources in central Texas, U.S.A.

Formation of calcrete by aeolian deposit of calcium carbonate is well documented. Dicesare et al. (1963) and Gile et al. (1966) reported the occurrence of such calcretes in Giarabub region, Libya and New Mexico, U.S.A. respectively. Blümel (1982) reported the existence of this type of calcretes in eastern Namib and Erongo mountains in Namibia and in South Eastern Spain. In Kenya, the calcretes which

occur near Lake Magadi are associated with aeolian origin (Baker, 1958). In Tanzania, calcretes of this nature have been found in Olduvai gorge and Ndolanya beds, in northern Tanzania (Hay and Reeder, 1978).

2.4.2 Climate

Climate is a major determinant of the boundaries of both pedogenic and non pedogenic calcrete deposits on a macroscale basis. Goudie (1973) summarised from different parts of the world a wide range of rainfall regime under which calcretes develop. Accordingly, in Spain, calcretes are rare where precipitation is more than 400 mm, while in the Sahara and in Lebanon, calcretes occur where annual precipitation is as low as 250 mm and 500 mm respectively.

In South America, Angola and Tanzania, calcrete extends into zones of higher rainfall. In South America, calcretes extend to zones of 1200 mm annual precipitation (Goudie, 1973). In Angola, calcrete occurs in areas with up to 850 mm which forms the humid limit (Goudie, 1973) while in Tanzania, calcretes have been found in areas with up to 750 mm per annum of precipitation (Goudie, 1973). The existence of calcretes in regions with contemporary high rainfall has been linked to the past climates (Thomas, 1996). According to this author, the past climates which were characterized by aridity led to the formation of calcic horizons in some soils. The aridic climate favoured the precipitation of carbonates (Hay and Reeder, 1978). A deficit in moisture content is always necessary for calcrete formation because

where rainfall exceeds evapotranspiration, calcium carbonate leaches out of soil profile to underground waters (Goudie, 1973).

2.4.3 Geomorphology

The geomorphic factor which plays a role in the distribution of calcretes particularly on the micro-scale basis is the slope angle (Watts, 1980). Calcretes are commonly associated with the low-angle surfaces (Watts, 1980) especially in areas where calcretes have been derived from alluvial deposition or underground waters (Goudie, 1973). In areas where calcretes developed from lime-rich bedrock or where large quantities of calcareous loess have been deposited over a landscape, calcrete may develop on high slope angles by pedogenic processes (Goudie, 1973).

2.4.4 Drainage

Transport of calcium and carbonate ions in river water can cause calcification in areas with non calcareous bedrock. Also, local high ground water levels in depressions may account for calcrete distribution in many low lying areas (Goudie, 1973).

2.5 Characteristics of calcretes

The most important properties of calcretes are physical, chemical and mineralogical characteristics.

2.5.1 Physical characteristics

The term physical characteristic signifies the physical form of an individual calcrete. The physical forms of calcretes include calcified soil, powdery, nodules, honeycomb, dense hardpans and extremely dense boulders (Netterberg, 1967).

According to Netterberg (1967), a calcified soil is a very lightly to strongly carbonated soil. It has little or no nodular development, and is sometimes soft and friable with very little structure except the one inherited from the original deposit.

Powder calcrete shows very little trace of soil particles, but is still soft, friable and has no nodular development (Goudie, 1973).

Nodular calcrete may exist in a nodular, glaebular or accretionary form and consists of distinct, hard concretions, some of which may have a diameter of over 7 cm. They frequently show evidence of fracture and recementation.

Honeycomb calcrete is a form of calcrete formed by coalescence of concretions of the nodular calcretes. It consists of a soil filled voids between rounded masses of calcrete.

Hardpan (massive) calcrete is a peak calcrete development stage referred to as mature calcrete. The hardpan is often not very thick but the whole body of the calcrete is massive and tough.

Boulder calcretes are formed as a result of degradation (weathering) of massive calcretes. The degradation of massive calcrete is mainly facilitated by penetration, dissolution and fracturing of the massive calcrete by plant roots (Klappa, 1983). If the dissolution and weathering of massive calcrete goes beyond a certain stage, it breaks down into massive calcrete boulders. A mature pedogenic calcrete profile is normally divisible into several layers with different calcrete forms (Arakel, 1982; Read, 1974). The succession of these calcrete forms from top to bottom generally follows the order laminar calcrete, hardpan (massive) calcrete, honeycomb calcrete, nodular calcrete and powder calcrete (Blümel, 1982; Gile *et al.*, 1966; Hay and Reeder, 1978; Milnes, 1992; West *et al.*, 1988b).

2.5.2 Chemical characteristics

Calcretes consist of calcium carbonates, silica, magnesium carbonates, water-soluble salts particularly phosphates or gypsum and insoluble residues in that order of decreasing abundance (Goudie, 1972). Calcretes are dominated by the presence of calcium carbonates. The world mean value is estimated to be 79.28% which is equivalent to a CaO content of 42.62% (Goudie, 1973). The calcium carbonate in calcretes exists in a form of microcrystalline calcite (Goudie, 1973).

Magnesium carbonate content is relatively low in calcretes. The average MgO content in calcretes is 3.05% and the CaO:MgO ratio is 13.96:1 (Goudie, 1973). However, higher magnesium contents have been reported in Etosha and Ovamboland, South-west Africa (Goudie, 1972), Kemois in South Africa and in Hawaii (Goudie, 1972). Where $MgCO_3$ forms a major part of deposits, such deposits are referred to as dolocretes, magnesilcretes or terrester dolomit (Goudie, 1972).

The low content of $MgCO_3$ in calcretes is attributed to the high solubility of $MgCO_3$ in the presence of carbon dioxide which accounts for its loss through leaching where drainage allows (Goudie, 1972). When drainage is poor, $MgCO_3$ accumulates together with $CaCO_3$ (Goudie, 1973). Another reason which can explain the generally low magnesium carbonate content of calcretes is the removal of magnesium from soil pore water by cation exchange on clay minerals

particularly smectites (Goudie, 1973).

The second most important constituent of calcretes is silica. It averages 12.30% of the total calcrete constituents (Goudie, 1973). Silica content in calcretes varies inversely with the $CaCO_3$ content (Goudie, 1973). According to Watts (1980), there are four different types of silica cements in calcretes: a thin (Usually < 5 μm) diffuse layer of opaline silica; a moderately thick (40-90 μm) zone of semi opaque, brown, length-slow chalcedony which often grows in discrete to coalesced botryoidal aggregates; a sequence of rapid alterations of length-fast and length-slow chalcedony (possibly with a fine opaline coat and a crystalline quartz fill).

Insoluble residue is another component of any calcrete. This is the residue which remains after treating the sample with 10% solution of hydrochloric acid (Goudie, 1973). This residue is composed of three main parts which are: the amorphous silica cementation, the coarser grains, predominantly quartz grains; and the clay minerals (Goudie, 1973). However, the amounts of insoluble components in calcretes are relatively low (Goudie, 1973).

Minor constituents of calcretes are the sesquioxides which include aluminium oxide (2.12%) and ferrous oxide (2.03%). Their ratio to SiO_2 is 1:5.80 (Al_2O_3) and 1:6.06 (Fe_2O_3) (Goudie, 1973).

2.5.3 Mineralogical characteristics

The principle mineral of calcretes is calcite (Goudie, 1973; Hay and Reeder, 1978; Knox, 1977; Watts, 1980). However, there are other minerals, particularly clays which are commonly found in calcretes. The most important ones are palygorskite, sepiolite, 2:1 silicate clays and mixed layer clays (Goudie, 1972; Goudie, 1973; Watts, 1980).

2.5.3.1. Palygorskite

Palygorskite is a fibrous clay with a formula of $Si_8Mg_5O_{20}(OH)_2.4H_2O$ (Watts, 1980). It consists of 2:1 layer structure with five octahedral positions, four of which are filled (Watts, 1980). Palygorskite forms in a variety of environments such as marine environments (Watts, 1980); deposition in lagoons (Weaver and Beck, 1977); lakes and playas (Parry and Reeves, 1968). Its origin has been ascribed to neoformation, alteration of montmorillonite (Yaalon and Wielder, 1976) and to palygorskite rich materials (Watts, 1980). Although little work has been done on the clay mineralogy of calcretes, Watts (1980) reporting on few studies made in the Kalahari, South Africa indicated that palygorskite is present in reasonable quantities. According to this author, palygorskite is the major clay mineral in calcretes while other clay minerals are generally insignificant. Palygorskite has also been found in nodular calcretes in Cairo and Alexandria, Egypt (Goudie, 1973) and in Central Afghanistan (Watts, 1980).

2.5.3.2 Sepiolite

Sepiolite is another mineral found in calcretes. This mineral is commonly associated with palygorskite and it resembles the latter in structure (Parry and Reeves, 1968). According to Watts (1980), sepiolite conforms to the general chemical formula $(Mg_3(Si_4O_{11})OH_2O.4H_2O$. It is stable in Mg-rich environment from which it is formed by neoformation and it is found in lacustrine or playa-lake deposits, marine environments and arid zone soils (Watts, 1980).

2..5.3.3 2:1 silicate clays

Smectites commonly occur in immature calcretes and may be detrital or a weathering product of primary minerals (Goudie, 1972). Illites in calcretes are also detrital and occur in low content (Goudie, 1972). In Kalahari calcretes, illite occurrence ranges from well crystallized and degraded to mixed layer lattice clays (Watts, 1980).

2.5.3.4 Mixed layer clays

These are composed of regular to random interlayered mixtures of a variety of primary clays and are common in weathering profiles (Watts, 1980). In the Kalahari, Watts (1980) reported existence of mixed layer clays particularly illite/montmorillonite in mature profiles. According to this author, these clays could have formed by partial weathering of illite.

2.6 Age of calcretes

The formation of calcretes took place mainly during the quaternary and tertiary periods although their existence in earlier geological formations has been widely reported (Warren, 1983).

The calcretes of New Mexico, U.S.A. were formed between 18,300 and 4,500 years BP (Gile *et al.*, 1966). In Patagonia, Argentina, the formation of calcretes took place between 36,500 and 27,200 years BP (Vogt and Delvalle, 1994). In Namibia and South Eastern Spain, the calcretes have the ages ranging from 30,000 to 15,000 years BP (Blumel, 1982). The calcretes of the Olduvai gorge and Ndolanya beds in northern Tanzania vary in age between 3.5 million and 2000 years BP (Hay and Reeder, 1978). Morogoro calcretes vary in age from 25-26,000 years to 40,000 years BP (Sorensen and Kaaya, 1996, personal communication).

2.7 Stable isotope abundance in calcretes

In quaternary terrains, the isotopic composition is one of the important criteria used to identify the calcretes formed by *in situ* accumulation of carbonates (Read, 1974; Harrison, 1977). The important isotopes which are used for this purpose are Carbon-13 and oxygen-18.

2.7.1 Carbon-13

Talma and Netterberg (1983) worked out and reported the average of 300 world wide measurements of carbon and oxygen stable isotope ratios which revealed that $\delta^{13}C$ values of the carbonates range from -12 to +4. In tropical regions the values have been found to be -5 to +2 (Talma and Netterberg, 1983). On the basis of the global values obtained, the authors concluded that the mechanically accumulated carbonate is able to preserve its isotopic composition.

2.7.2 Oxygen-18

The ^{18}O content of calcrete is directly related to that of the water from which it was formed (Talma and Netterberg, 1983). The carbonate $\delta^{18}O$ content values range from -9 to +3 world wide (Talma and Netterberg, 1983). This range agrees with the values found in rain water in drier parts of the world where most calcrete are found (Talma and Netterberg, 1983). The factors that are possibly responsible for ^{18}O on global values are local rainfall, temperature and extent to which the water underwent free surface evaporation before or during the period of calcrete formation (Talma and Netterberg, 1983).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Location

The study area is located in Morogoro region and in particular, in the Morogoro municipality zone (Figure 1). It extends within the piedmont which stretches from the northern footslopes of the Uluguru mountains to the Ngerengere river floodplain and north of the this river to near the footslopes of Mindu mountains on the western part and to about 10 km from the Ngerengere river bridge on the Morogoro-Dodoma road. The area has a shape of a polygon which covers a total of 4493 hactres. The area extends from Magadu to the footslopes of Mindu hills on the west. In the south, the border is defined by the Uluguru mountain footslopes at, Magadu, SUA farm as well as the Kola hills. The missionary village and Tungi sisal estate mark the eastern boundaries while the Ngerengere river does the same on the north. Some of the points which define the boundaries of this area have the following co-ordinates: ($6^0$46'58"S, $37^0$42'50"E); ($6^0$48'07.4"S, $37^0$42'50"E); ($6^0$48'75"S, $37^0$40'00"E); ($6^0$50'90.1"S, $37^0$38'75"E); ($6^0$50'90.1"S, $37^0$37'50"E); and ($6^0$46'25"S, $37^0$38'31.4"E).

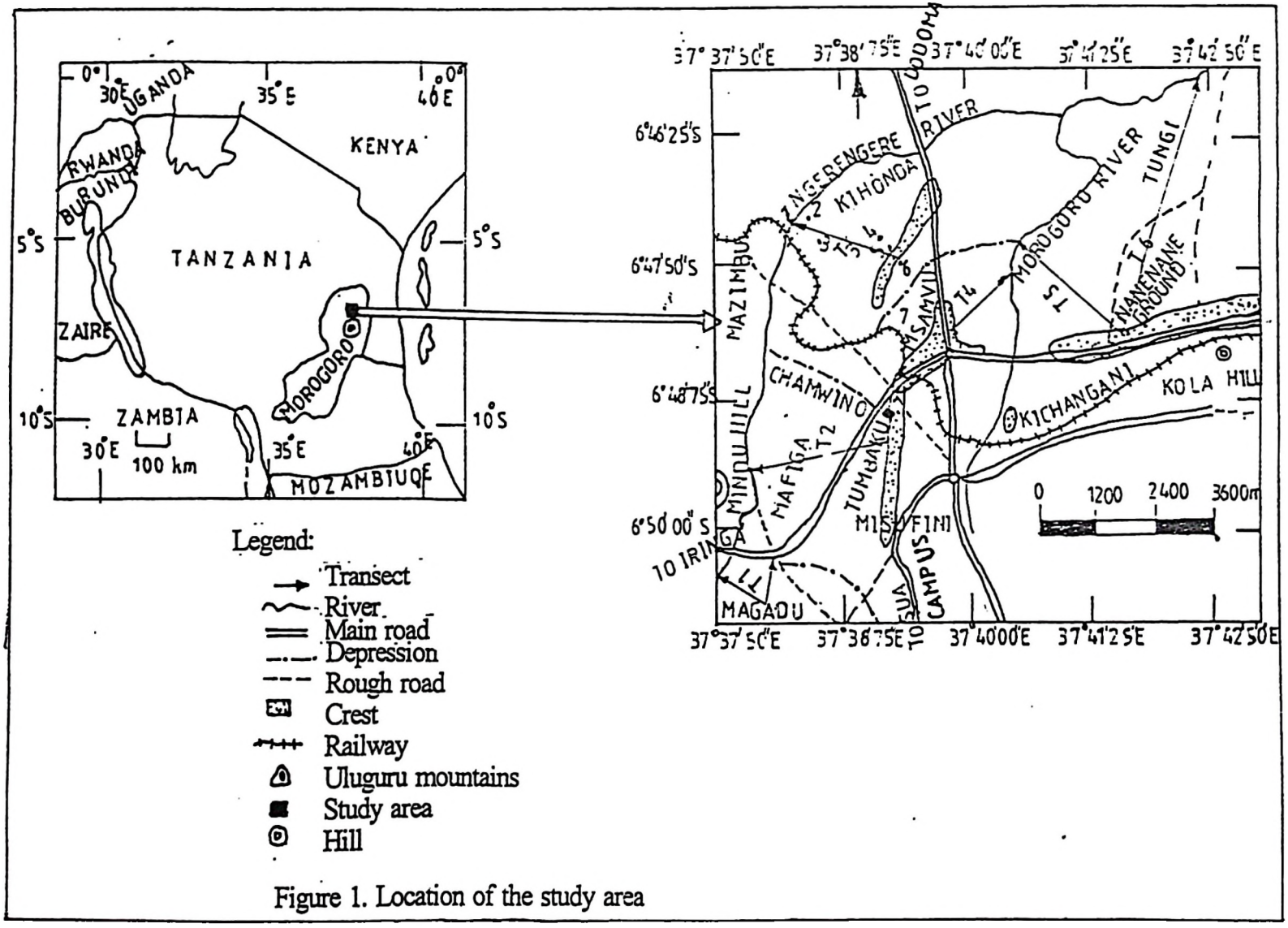


Figure 1. Location of the study area

3.2 Description of the environment

The environment of the studied area is described in terms of climate, vegetation, geomorphology and geology.

3.2.1 Climate

The description of climate is done while taking into account the contemporary climatic data as well as paleoclimatic information.

3.2.1.1 Present climate

The climatic data presented were obtained from Morogoro meterological station and they cover a period of sixty four years (1931-1994). Some data presented by Mpepo (1986) and Rapp *et al.* (1973) were also incorporated. The mean annual precipitation is 891 mm. There are two rain periods, the short period known as vuli which lasts from November to January, and the relatively long one, also known as Masika which lasts from February to May (Figure 2). The mean temperature fluctuates between 18.6°C and 28.8°C, giving a mean annual value of 23.7°C. The warm season starts from mid September to end of April while the relatively cool period lasts from May to mid September (Figure 2).

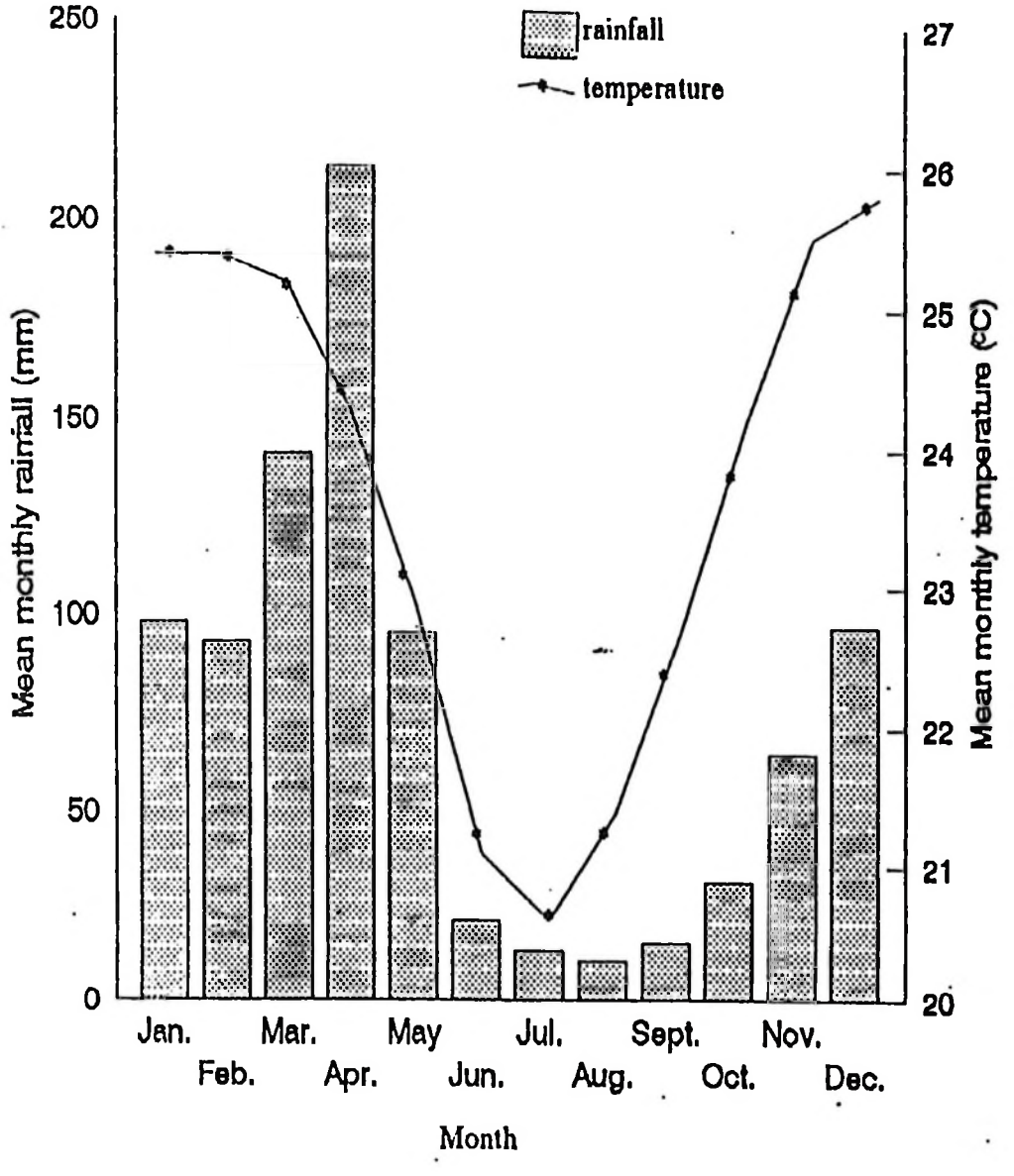


Figure 2. Mean monthly rainfall and temperature

3.2.1.2. Paleoclimate

The paleoclimatic information available is not specific for study area but covers a much broader zone of the humid tropical region to which the former belongs.

The region under consideration is characterized by changes in the periods of major climatic regimes. There was a long dry period which may have lasted from ca. 70,000-40,000 years BP (Thomas and Thorp, 1995). This was followed by a severely dry climate, particularly from 38,000 to 26,000 BP (Thomas, 1996).

Eventually, there was the last glacial period which dated between 25,000 to 15,000 years BP. The latter period was marked by a decrease of the mean temperature and mean annual precipitation. In the catchment of Lake Tanganyika for example, the decrease was 4.2 ± 3.6°C and 180 ± 183 mm/year respectively (Vinces *et al.*, 1993). It was during this period when the lowest temperature could reach up to -5.8 ± 3.4°C (Vinces *et al.*, 1993). This maximum cooling was associated with a severe aridity marked by precipitation decrease of -276 ± 198 mm which occurred between 22,000 and just before 18,000 years BP (Vinces *et al.*, 1993).

The last glacial maximum which took place between 20,000 and 18,000 years BP, was characterized by convectional rainfall which led to reduction of rainfall distribution and intensity by 50% and 33% respectively. According to Thomas and Thorp (1995), the total rainfall was reduced by two thirds.

Between 15,000 and 12,000 years BP, there was an increase in temperature and rainfall of about -2.1 ± 2.5^{0}C and -87 ± 168 mm respectively (Vinces *et al.*, 1993). Thomas and Thorp (1995) reported that the period after 13,000 years BP was a period which was characterized by prolonged rainfall (Thomas and Thorp, 1995). This period was followed by continuous increase in warming and wetness in the area during postglacial period, 12,000 years BP onward (Thomas, 1996). The humid conditions therefore returned after 12,000 BP (Thomas, 1996). A rapid warming with unstable climates and prolonged heavy rains in tropical Africa existed between 12,500 and 11,000 C^{14} years BP (Thomas and Thorp, 1995). The latter was interrupted by younger Dry cold event (11,000-10,000 BP), (Thomas, 1996).

3.2.2 Vegetation and land use

The study area was under sisal cultivations for at least thirty years to the period ending during the late nineteen seventies. Due to the sisal plantation, the natural vegetation was completely cleared. This caused the clearing of virtually all of the natural vegetation. The prevailing vegetation consists mainly of grasses and scattered shrubs. The dominant grass species are *Digitaria spp*, *Brachiaria spp* and *Penisetum spp*. These are prevalent along the Ngerengere river basin. *Solanum spp*, *Tylaccium africanum* and *Trichodesma zeylenicum* are among the most common shrubs in the area.

Following the decline of sisal demand in the world market in the late nineteen seventies, a greater part of the sisal plantations was put under maize production. Maize is still being grown in some areas formerly cultivated with sisal. However, due to the rapid expansion of Morogoro municipality some parts of the study area are being left for urban development.

3.2.3 Geomorphology

The area under the study forms a small part of Mkata surface as defined by Sampson and Wright (1964). The surface is in the form of peneplain extending from west and north of Morogoro for tens of kilometres, finally merging into the flood plain of Mkata and Wami rivers. This surface is referred to as Miocene peneplain by Temperley (1958) and mid Tertiary surface by Quennel *et al.* (1956).

Specifically, the study area is characterized by an undulating topography with a slope that varies between 0-2% at the crest and 0.5-1.% on the Ngerengere river floodplain. In between these two extremes, the slope gradient varies between 5 and 10%. The greatest slopes is generally linear though localized variations do also exist.

Apart from minor seasonal streams, the drainage of the studied area consists of the Ngerengere and Morogoro rivers. Both rivers rise from Uluguru mountains. Ngerengere river flows through the study area in a north easterly direction at about

500 to 460 metres above sea level. The slope gradient of the main water course in the study area does not exceed 1%. Morogoro river flows towards north direction at about 490 to 460 metres above sea level.

3.2.4 Geology

The geology of the area belongs to the Usagaran system of the Mozambican belt (Muhongo, 1994). The system consists of precambrian metamorphic rocks which are composed of hornblende gneiss and granulites, hornblende-pyroxene granulites (Sampson and Wright, 1964). The dominant rocks are micaceous gneisses and amphibolites (Sampson, 1962). Granular feldspathic groundmass are also common rocks in the area. Irregular patches of mafic minerals, either pyroxene or amphiboles with quartz rich veins are also typical of the area (Sampson, 1962). Apatite, biotite and spinel are locally distributed. According to Sampson and Wright (1964), the parent materials are the colluvial and alluvial materials derived from the surrounding Uluguru.

3.2.5 Geochemistry of the drainage waters

3.2.5.1 Surface waters

A detailed analysis of both ground and surface water in this area has just been completed by Kaboni (1996). According to this author, the chemical composition of the surface waters in the study area is as follows:

The pH, electrical conductivity at 25°C (dS/M) and total soluble salt concentration (g/l) in the area ranges from 7.3 to 8.4, 0.2 to 1.6 and 0.1 to 1.0 respectively. The composition of soluble calcium, magnesium, potassium, ranges from 0.4 to 2.5 me/l, 0.3 to 2.1 me/l and 0.01 to 0.20 me/l respectively. The soluble carbonate and bicarbonate vary from trace to 5.2 me/l and 2.1 to 11.3 me/l respectively.

3.2.5.2 Ground waters

The chemical composition of the ground water in the study area has been studied to a detailed extent. According to Mpepo (1986), the ground waters in the SUA farm is as follows: 6 ppm F^-, 432 ppm Cl^-, 388 ppm HCO_3^-, 406 ppm SO_4^{2-}, and 1719 ppm total dissolved solids. In the Kihonda area, the ground water is mainly dominated by Ca^{2+}, Mg^{2+}, Na^+, HCO_3^- and Cl^- (DHV, 1980). The $CaCO_3$ content calculated from ionic composition varies between 324 and 2180 mg/l. The Magnesium, calcium, sodium, bicarbonate and chloride varies between 24.3 and 364 mg/l, 40 and 300 mg/l, 299 and 2737 mg/l, 305 and 1098 mg/l and 200 and 5150 mg/l respectively (DHV, 1980).

According to Kaboni (1996), the pH, electrical conductivity and total soluble salt concentration of the ground water varies between 7.3 and 8.3, 5.5 and 26.4 dS/M at 25°C and 3.5 and 16.9 g/l respectively.

The concentrations of soluble calcium, magnesium and potassium in the ground waters vary from 0.8 to 9.0 mc/l, 1.0 to 5.3 mc/l, 0.02 to 0.05 mc/l respectively (Kaboni, 1996). The concentrations of soluble carbonates and bicarbonates in the ground waters vary from 9.2 to 56.8 mc/l and 7.0 to 32.6 mc/l respectively (Kaboni, 1996).

3.3 The study of the calcretes

This work was comprised of two major types of study; field survey where calcretes existed and laboratory analysis of soils, calcretes and regolith collected from the study area.

3.3.1 Field work

The identification of the location of calcretes was done by free survey work. The purpose of this approach was to locate the zones with calcrete formation within the study area. In order to map the location of the calcrete areas, a base map was prepared at a scale of 1:12,500 from aerial photos taken in 1992 at the same scale.

The second approach was to determine the calcrete-landscape relationship which led to carrying out observations along six selected transects. These transects were named after the names of their locations as follows:

Magadu-Ngerengere river, Tumbaku-Mafiga-Ngerengere river, Msamvu-Kihonda-Ngerengere river, Msamvu-Morogoro river, Nanenane trade fair grounds-Morogoro river and Nanenane trade fair ground-Tungi-Ngerengere river. For convenience, they have been numbered T1, T2, T3, T4, T5 and T6 respectively (Figure 1).

The last approach consisted of carrying out the detailed investigation of the chemical, physical and mineralogical properties of the different types of calcretes found in one of the six transects, characterization of the overlying soils and the underlying regolith. This work was done on pits which were excavated along the Msamvu-Kihonda-Ngerengere river transect. For convenience purposes, the transect will be known as Kihonda transect in the rest of this document.

3.3.1.1 Free survey

The work involved examination of the vertical sections of the soil profile to the weathered material and where possible to the parent rock. Vertical sections were observed on existing trenches, roadcuts and natural exposures such as deep erosion gulies. Fresh pits as well as bore augering were made where it was necessary to do so for the purpose of demarcating boundaries. The selection of the observation

points was determined by changes of the topography. Apart from the physical identification, both calcium carbonate containing rocks and secondary lime materials were tested with dilute hydrochloric acid for the presence of calcium carbonate.

Where calcareous materials existed, the depth of their occurrence and the type of the basement material were both noted. A total of 165 observations were made, each of them being noted on the base map. The findings were eventually compiled as a map of the distribution of calcretes.

3.3.1.2 Multi transect study

This work was done on six transects which were selected on the basis of the results of the free survey work. In this investigation, the physical forms of calcretes and the depth of occurrence of the latter were studied where possible. The accompanying landform, vegetation and the parent material were described based on procedures outlined by FAO (1990). In this work, the drainage was also studied.

3.3.1.3 Detailed transect study

This work was carried out along the Kihonda transect. The choice of the transect was based on the fact that it was the one among the transects studied which showed the largest diversity in terms of calcrete forms. A total of sixteen pits were dug and described in detail. Of these, seven denoted as 1, 2, 3, 4, 5, 6 and 7 were earmarked for sampling. The location of these pits is shown on Figure 3. The positioning of

the individual pits was such that each pit represented a geomorphological unit. For convenience, the corresponding units were named river bank, river terrace, lower slope, midslope, upper slope, crest and depression despite the fact that the whole study area is referred to as "lower slopes" with reference to Uluguru mountains (Sampson and Wright, 1964). The units were also identified as (a), (b), (c), (d), (e) and (f).

The depth of the individual pits was chosen so as to include at least a metre of depth of the regolith. The depth of the individual pits hence varied in accordance with the thickness of the soil solum and that of the calcrete layer.

The soil profiles were described according to the guidelines for soil profile description by FAO (1990). Soil samples were collected from the individual horizons or layers for laboratory analysis.

Measurements concerning the depth of occurrence and the thickness of the calcrete layer were made. The individual physical forms of calcretes as defined by Netterberg (1967) were identified. The order of occurrence of the individual forms along the transect as well as their vertical succession were studied. Assessment of the purity of the calcrete layer was attempted. This was done by estimating the area occupied by calcretes within a square metre area selected at random on the side of the pit. The estimation was done by using a one metre square frame subdivided into

100 units with one square decimeter each. The frame was leaned against the pit side at the layer to be measured. The area occupied by calcretes was then estimated by summing up the approximate areas occupied by calcretes in individual 1 dm^2 units. The values were then presented as percentages of the total area. The procedure was repeated four times for each pit.

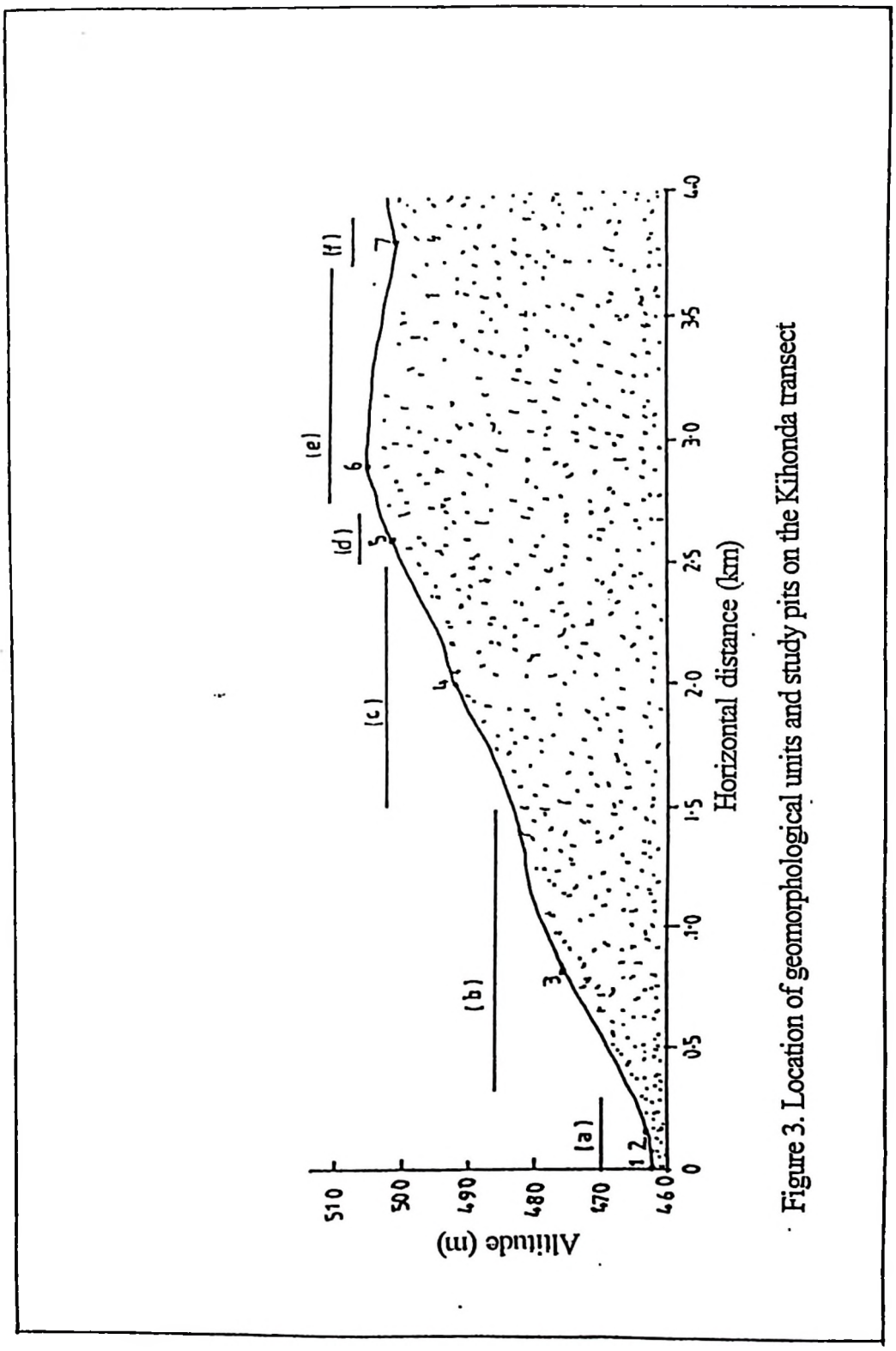


Figure 3. Location of geomorphological units and study pits on the Kihonda transect

Sampling was carried out for both chemical and mineralogical analyses from all the pits which contained calcretes. Supplementary calcrete samples were collected from pits 4 and 6 for micromorphological studies. These pits were chosen because they were the ones which contained the major forms of calcretes.

Detailed work was done on the regolith which underlaid the calcrete layer. It included the measurement of the depth at which it occurred and identification of the rocks from which the regolith was formed. The identification of minerals and rocks were done according to standard identification keys (Esser, 1995, personal communication). Determination of percent composition of different rock types in the regolith followed the method used in the determination of the purity of calcrete layers. Sampling was done from each rock type.

3.3.2 Laboratory analysis

Laboratory analyses were done on the soil, calcrete and regolith samples. Prior to analysis, each of these categories of samples was prepared in a particular manner for analysis. The soil samples were air dried, ground and passed through 2 mm sieve. The calcrete and regolith samples were washed and rinsed in de-ionized water, crushed and then passed through a 100 μm sieve.

The following analyses were carried out on soil samples: particle size analysis, pH, organic carbon, cation exchange capacity, exchangeable bases, total calcium carbonate and silica content.

The investigations conducted on the calcrete samples included the mineralogical analysis, micromorphological analysis, determination of the total calcium carbonate and silica content, radiocarbon dating and stable isotope abundance. The mineralogy of the calcretes was determined by x-ray diffraction. Regolith samples were analyzed for calcium carbonate and silica.

3.3.2.1. Analysis of physical properties

The particle size analysis of soils was performed following Bouyocos hydrometer method after dispersing the soil samples with a 5% sodium hexametaphosphate solution (Juo, 1979).

The physical characterization of calcretes was performed in accordance with the approach employed by Nettterberg (1967). It involved an assessment of sizes and shapes of the calcretes. The calcretes which were nodular, glaebular or accretionary with up to 7 cm diameter were termed as nodular calcretes.

The calcretes whose diameter was over 7 cm and had soil-filled voids between rounded masses of calcrete were referred to as honeycomb calcretes. The hardpan (massive) calcretes were those calcretes whose whole body was massive and tough. Some parts were conglomeratic.

3.3.2.2 Analysis of the chemical properties

pH was measured potentiometrically in water and in 1N KCl at the ratio of 1:2.5 soil-water and soil-1N KCl suspension respectively (Mclean, 1982). Organic carbon was determined by the wet oxidation method of Nelson and Somers (1982).

The cation exchange capacity and exchangeable bases were determined by saturating the soil with neutral 1N ammonium acetate (Thomas, 1982). The displaced bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) were determined by atomic absorption spectrophotometer. The results were expressed as cmol(+)/kg soil.

Determination of total calcium carbonate followed the procedure after Muller (1967). The sample was digested by concentrated hydrochloric acid. The digested sample was mixed with distilled water, filtered and brought up to at least pH 12 with strong sodium hydroxide solution. The resulting solution was titrated with 0.1M EDTA. 1 ml of 0.1M EDTA corresponds to 10.009 mg of $CaCO_3$ (Muller, 1967). The calcium carbonate content was thus calculated from the equation:

$$\% CaCO_3 = \text{ml of 0.1M EDTA used} \times 10.009 \times 1000.$$

The use of two different methods in determination of total $CaCO_3$ and exchangeable Ca^{2+} in the soil was caused by the use of two different laboratories, UDSM geology laboratory and SUA soil science laboratory respectively.

Determination of silica followed the procedures of Hesse (1971) and Jackson (1958). The sample was digested by a mixture of concentrated hydrochloric acid and perchloric acid. After digestion, the silica was dehydrated by evaporation with perchloric acid, filtered off and washed. The crude silica was weighed directly after ignition to a constant weight. The mixture was then heated with a mixture of sulphuric acid and hydrofluoric acids to volatilize the silica. The ignited residue was then weighed. The loss in weight represented pure silica. The results were presented as percentage.

3.3.2.3 Mineralogical analysis

X-ray diffraction was done on samples earmarked for mineralogical analysis while using a Shimadzu, XD-D1 model, x-ray diffractometer equipped with CU-tube.

3.3.2.4 Micromorphological analysis

The analysis was performed on the calcrete materials taken from profiles 4 and 6. The profiles were selected because they contained all the three forms of calcretes identified on the Kihonda transect. Thin sections were made from both massive,

honeycomb and nodular calcrete samples. The viewing in plane polarized light (PPL) and the magnification during examination and photography (50x) were performed. The latter were described following the procedure outlined by Bullock *et al.* (1985).

3.3.2.5 Dating of calcretes

The dating was performed in U.S.A. by the Beta analytic inc., at Miami, Florida. Prior to the dating procedure, the individual samples were washed, crushed and dispersed. Etching with hydrochloric acid was done in order to eliminate any secondary carbonates.

3.3.2.6 Determination of stable carbon and oxygen isotopes

The analyses were carried out at the Isotope Laboratory, University of Bergen, Norway, on an Atomic Mass Spectrometer for light isotopes.

3.3.3 Soil classification.

The studied soils were classified following the principles established by FAO (1989) and USDA (1990).

CHAPTER FOUR

RESULTS AND DISCUSSION

The results which are presented include the location of calcretes in the study area, their physical and chemical properties and the occurrence and the properties of soil sola and regolith overlying and underlying the calcretes respectively.

4.1 Distribution and properties of the studied calcretes

4.1.1 Distribution of calcretes in the study area

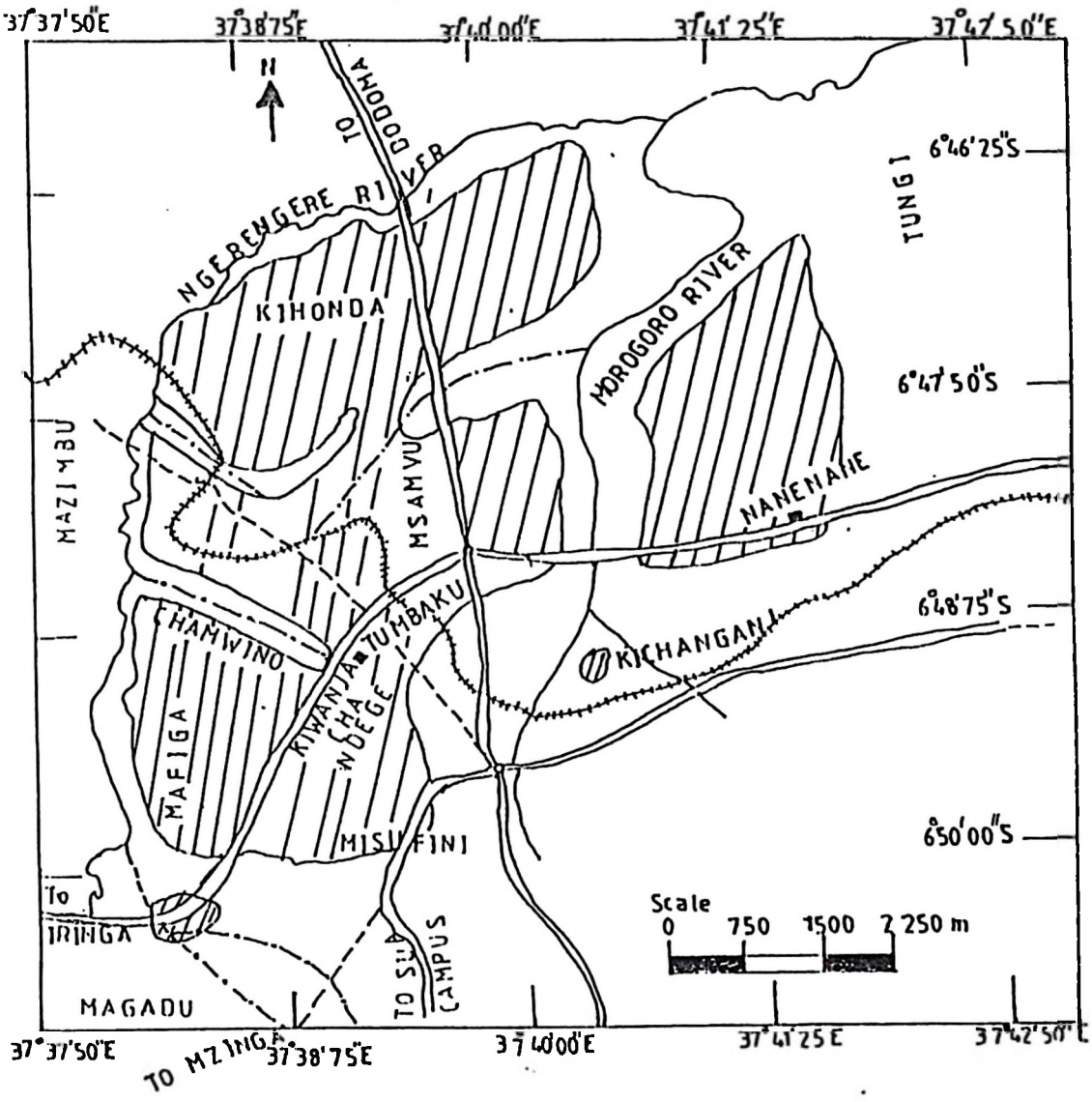
The spatial distribution of calcretes in the study area is shown on Figure 4. Calcretes occurred at large extension at Kihonda, Kiwanja cha Ndege, Msamvu and Tumbaku areas. Other places where calcretes were also widely extended included parts of Kichangani, Nanenane show grounds and Mafiga part of the SUA farm. There were localized calcium carbonate glaebules at Magadu.

All areas which contained calcretes or calcium carbonate glaebules occurred on the southern part of the study area which is situated south of the Ngerengere river. Calcretes were absent on the northern side of the river except for two very localized areas. One of these sites was on the northwest of the study area on the south eastern slopes of Mindu hills. In this area, calcretes occurred as isolated spots within the thick sand layer derived from granitic rocks. The second place where calcretes occurred was on the north eastern part of the study area within the

migmatite rocks about 6 km north of Ngerengere river bridge along the Morogoro-Dodoma road.

It is important to note that calcretes occurred either exposed at the surface or at a shallow depth ranging from 10 to 20 cm from the soil surface on the crest positions. In the other locations of the landscape, calcretes were found overlain by relatively deep soil solum with a thickness which ranged from 50 to 160 cm. The shallow depth calcretes occurred at Msamvu, Nanenane, Kichangani and Tumbaku while the deeply placed ones occurred at Kihonda, Mafiga and Chamwino.

It is also important to note that it was along the Kihonda transect where the greatest diversity of calcrete physical forms was observed. This called for a need to examine the calcretes of this transect in detail.



Legend:

- Calcrete occurrence
- Railway
- Main road
- Depression
- Rough road
- River

Figure 4. Distribution of calcretes in the study area

4.1.2 Distribution of calcretes along the Kihonda transect

Calcretes occurred almost throughout the transect. The thickness of the calcrete layer varied considerably along the transect (Table 1). It ranged from 25 to 142 cm. In general, the thickness of calcretes decreased from the crest towards the Ngerengere river. For instance, the average thickness of the calcretes situated at the crest and the bordering depression was 124 cm. The corresponding average thickness of the river bank and terrace calcretes was 27.5 cm. The calcretes located in between these two geomorphological positions had an average thickness of 105.5 cm.

The depth at which the calcretes occurred varied with the position on the transect. It was at the crest where calcretes occurred at the shallowest depth. In this portion of the landscape, the calcretes were found at 14 cm depth. At the midslope and lower slope positions, calcretes occurred at 60 to 112 cm depth respectively, which corresponded with an average depth of occurrence of 72 cm. On the river bank and the river terrace calcretes were found at a depth of 105 to 124 cm which gave an average of 114.5 cm. The soil solum over the calcrete was the thickest in the depression near the crest.

Table 1. Variation of the depth of occurrence and thickness of calcrete layer along the Kihonda transect

Position on the transect	Depth to the calcrete layer (cm)	Thickness of calcrete layer (cm)
River bank	105	30
River terrace	124	25
Lower slope	112	76
Midslope	60	135
Upper slope	-	-
Crest	14	106
Depression	158	142

4.1.3 Major forms of calcretes and their distribution along the Kihonda transect

The most prevalent forms of calcretes along the Kihonda transect were massive, honeycomb and nodular (Table 2). The nodular form occupied 94.8% of the transect length followed by the honeycomb calcrete which occupied about 87.1%. The massive calcrete was the least widely distributed. It covered 51.2% of the transect length.

Table 2. Distribution of different forms of calcretes on the Kilonda transect

Position on the transect	Calcrete form present	Thickness (cm)	Coverage within the calcrete horizon (%)	Coverage along the transect (%)
River bank	Nodular	30	10-20	
River terrace	Nodular	25	9-12	7.7
Lower slope	Honeycomb	40	75-90	30.8
	Nodular	36	60-70	30.8
Midslope	Massive	55	95-100	30.8
	Honeycomb	20	75-90	25.6
	Nodular	60	60-75	25.6
Crest	Massive	46	95-100	25.6
	Honeycomb	18	75-90	25.6
	Nodular	42	60-70	25.6
Depression	Honeycomb	47	60-80	5.1
	Nodular	95	50-75	5.1

The thickness of the individual forms of calcrete also varied to an appreciable extent (Table 2). The nodular form had a thickness which ranged from 25 to 95 cm with an average of 48 cm while that of the honeycomb varied from 18-47 cm, the average being 31.3 cm. The massive had a thickness which ranged from 47-55 cm, with an average of 51 cm.

The calcrete layers studied were not pure. They contained soil and saprolite materials as inclusions. However, the proportion of calcrete varied with its physical form and the position on the transect (Table 2). In general, the nodular calcrete layer tended to have a lower level of purity than the rest of the forms. It ranged from 9 to 75% with an average value of 47.6%. The purity of the honeycomb layer ranged from 60 to 90% while that of the massive form ranged from 95 to 100%.

There was an orderly sequential arrangement of the various physical forms of calcretes where more than one form occurred in a given vertical section (Table 2). The nodular form was always overlain by the honeycomb form which in turn was overlain by the massive form.

4.1.4 Properties of calcretes

The chemical, physical, mineralogical and micromorphological data are presented in this section.

4.1.4.1 Chemical properties

The total calcium carbonate and silica content of the studied calcretes is shown on Table 3. Calcium carbonate dominated in all forms of calcretes. It ranged from 56.2 to 66.4% in massive calcretes; 59.2 to 71.5% in honeycomb and 54.8 to 80.7% in nodular calcretes. The total calcium carbonate content of the calcretes thus followed the order nodular > honeycomb > massive.

The content of silica ranged from 4.3 to 16.7%. There was no specific order of variation of the silica content with respect to the form of calcrete studied. For instance, both the lowest and highest contents of silica were measured in the nodular calcretes.

Table 3. Total calcium carbonate and silica content of selected calcretes

Position on the transect	Form of calcrete	$CaCO_3$ (%)	SiO_2 (%)
River bank	Nodular	54.8	16.7
Lower slope	Honeycomb	59.2	12.4
	Nodular	74.3	4.4
Midslope	Massive	56.2	4.3
	Honeycomb	59.7	6.4
	Nodular	62.5	10.1
Crest	Massive	66.4	13.2
	Honeycomb	71.5	7.3
	Nodular	80.7	4.7

4.1.4.2 Mineralogical properties of calcretes

The x-ray diffractograms of the studied calcretes are shown on Figure 5. All forms of calcretes had x-ray diffraction peaks at 3.04Å, 2.29Å and 2.10Å which are characteristic of calcite (Dixon and Weed, 1989). Other peaks which were characteristic of all calcretes were obtained at 3.20Å and 2.49Å. There were other peaks which were not characteristic of all calcretes. These were 4.05Å, 3.35Å and 4.26Å. While 3.35Å was associated with both massive and nodular calcretes, 4.05Å and 4.26Å were associated with nodular and massive calcretes respectively. 4.05Å and 3.20Å indicated the presence of feldspars; 4.26Å and 3.35Å indicated the presence of quartz and 2.49Å indicated the presence of opaline silica (opal-CT) (Brindley, 1980) in association with the calcretes.

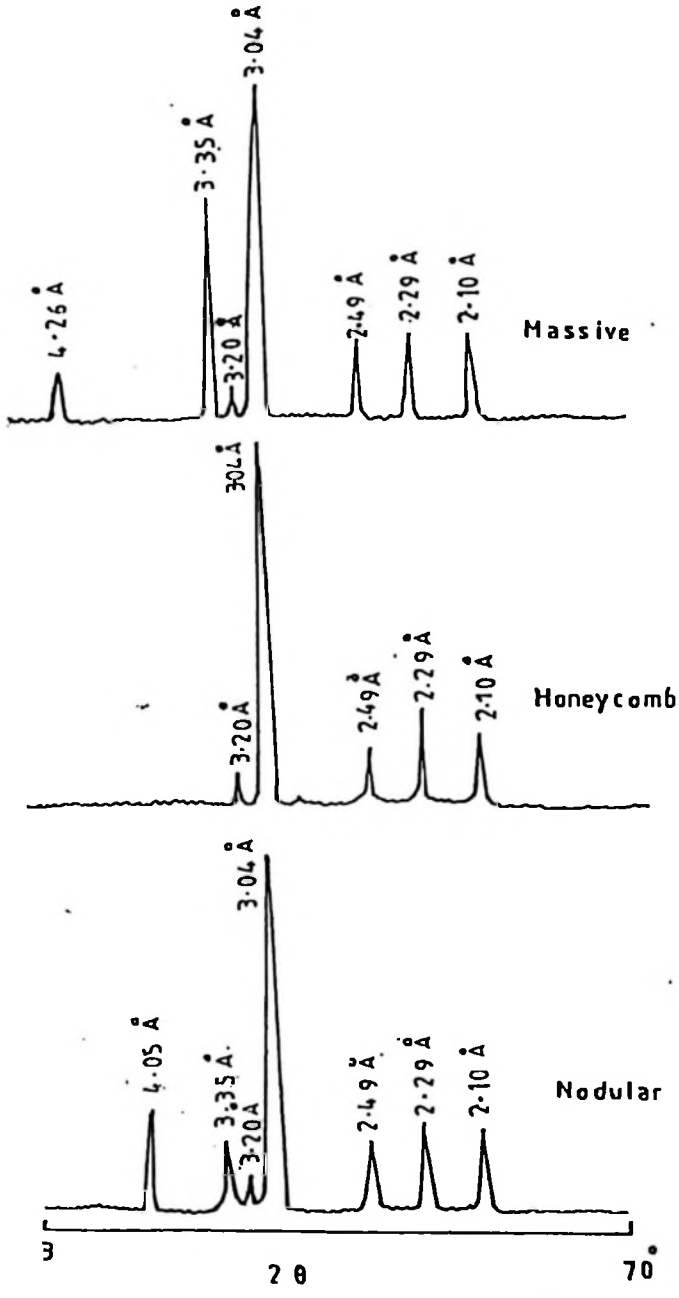


Figure 5. X-ray diffractograms of the major forms of calcretes studied

4.1.5 Micromorphology of major forms of calcretes

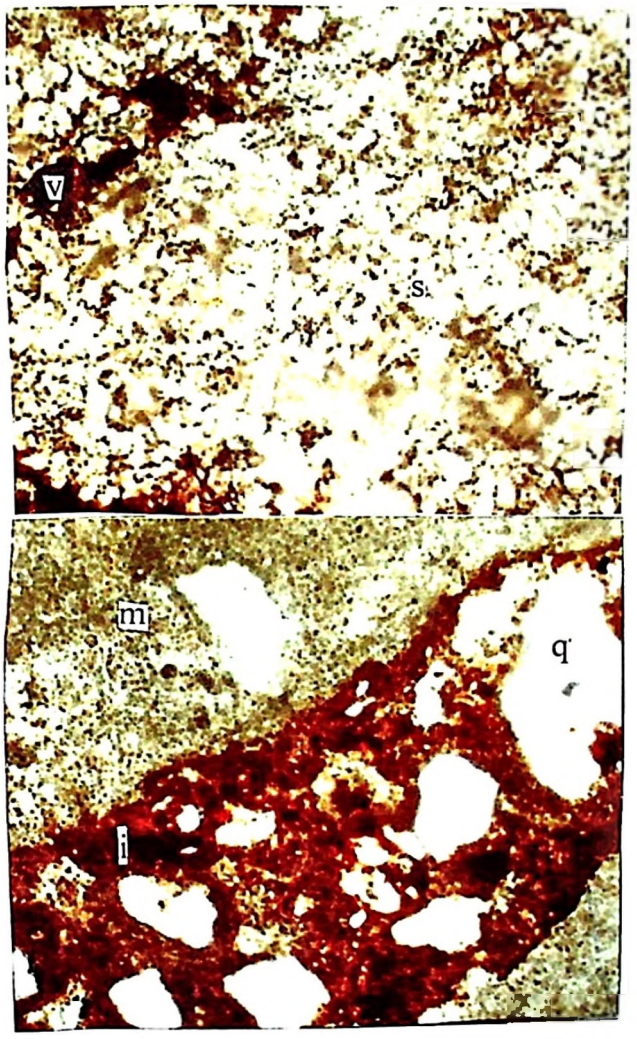
The micromorphological features of the studied calcretes are summarized on Table 4. Specific features are presented on Figures 6, 7, 8 and 9. The massive calcrete showed two major features which were the presence of sparry calcite and micritic calcite groundmass. The upper part of massive calcretes was found to have a groundmass of pure sparry calcite. However, it contained few voids which were filled by clay and/or iron oxides. The sparry calcite graded gradually to the micrite dominated groundmass on the lower part. The features found within the micritic groundmass included a large fissure (filled with clays and/or iron oxides and quartz crystals) (Figure 6), relic minerals (such as plagioclase and biotite), voids and small fissures which were coated with microsparry calcite (Figure 7).

In honeycomb calcretes, the whole groundmass consisted mainly of micritic calcite (Figure 8). It contained biotite as relic mineral. The sparry calcite was only found in voids and fissures. The clays and/or oxides of iron were widely distributed within the groundmass.

In nodular calcretes, the whole groundmass was mainly comprised of micrite in which both quartz and biotite were engulfed as relic minerals (Figure 9). The engulfed minerals were immediately surrounded by sparry calcite. The microsparite and micrites were formed further away from relic minerals and the boundary was diffuse. The voids were also coated by sparry calcite.

Table 4. Major micromorphological characteristics of the forms of calcretes studied

Form of calcrete	Dominant features	Minor features
	(i) groundmass of pure sparry calcite	(i) Few voids
Massive	(ii) Micritic calcite groundmass	(ii)-Fissures filled by quartz, clay and/or iron oxides -relic minerals
Honeycomb	Micritic calcite groundmass	-Engulfed relic minerals, clays and/or iron oxides -sparite in voids and fissures
Nodular	Micrite groundmass	Relic minerals (biotite and corroded quartz) sparite, voids, clays and/or iron oxides

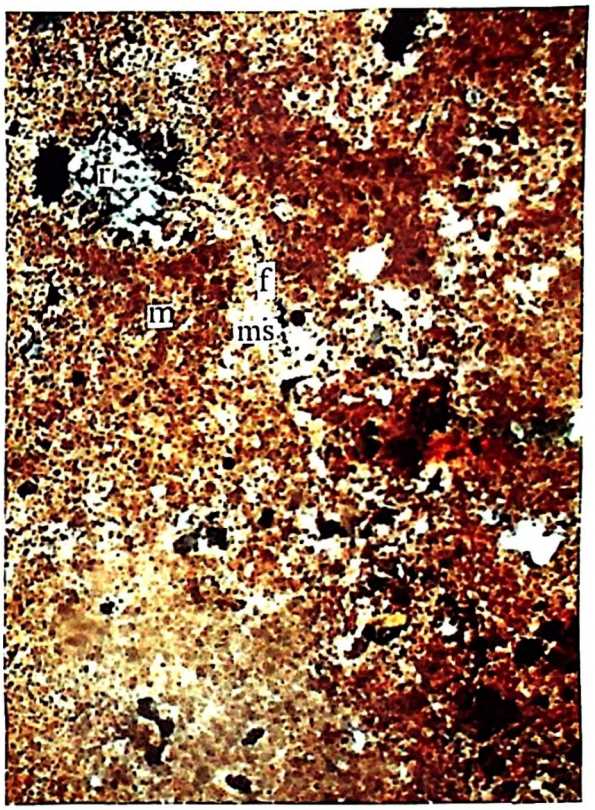


s = sparry calcite v = void

m = micritic calcite i = iron oxide

q = quartz

Figure 6. Micrograph of a massive calcrete (profile no.4) (PPL, 50x)



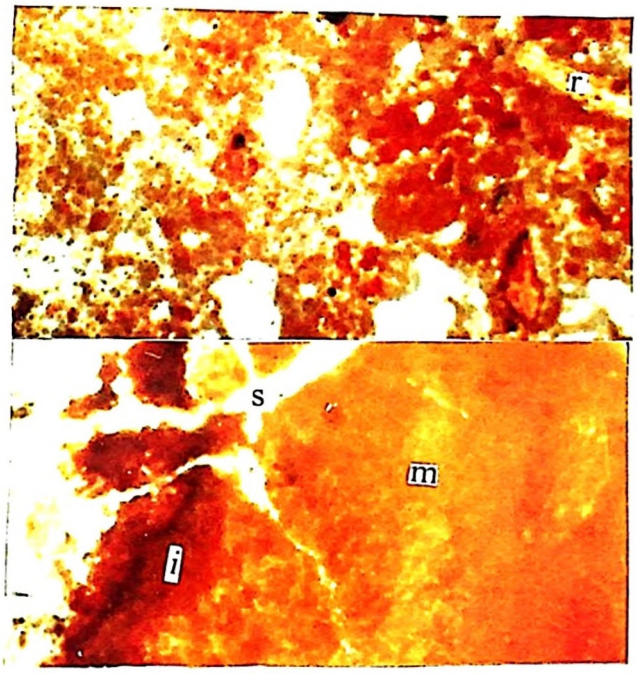
m = micritic calcite

r = relic minerals

ms = microsparry calcite

f = fissure

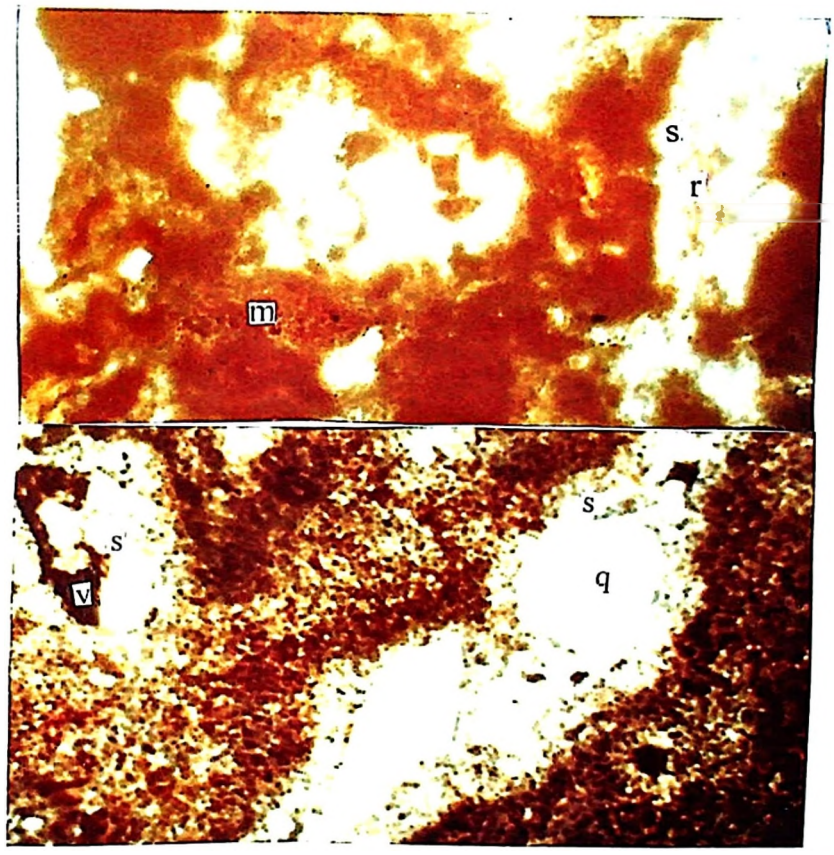
Figure 7. Micrograph of a massive calcrete (profile no.6) (PPL, 50x)



r = relic minerals s = sparry calcite

i = iron oxide m = micritic calcite

Figure 8. Micrograph of a honeycomb calcrete (PPL, 50x)



s = sparry calcite

m = micritic calcite

v = voids

r = relic minerals

q = quartz

Figure 9. Micrograph of a nodular calcrete (PPL, 50x)

4.1.6 Age and stable isotope abundance in the calcretes

The age of the massive calcrete was found to be 41,040 ± 840 radiocarbon years before present (*Beta-92202*). The study on the stable isotope abundances showed that the $\delta^{13}C$ and $\delta^{18}O$ of Kihonda calcretes were -3.37 and -3.55 respectively.

4.2 Characteristics of the regolith

4.2.1 Regolith composition

The rock types of the studied regolith materials are presented on Table 5. The major rock type of all the regolith materials studied was amphibolite which was rich in mica, particularly biotite. Minor components were quartzite associated with feldspars (mainly oligoclase), and marble. While the mica rich amphibolite occurred all over the whole transect, the quartzite and marble were only limited to the lower and upper positions of the transect respectively.

Table 5. Rock types present in the regolith

Position on the transect	Regolith composition		
	quartzite (%)	mica rich amphibolite (%)	marble (%)
River bank	20-30	70-80	-
River terrace	25-40	60-75	-
Lower slope	10-15	85-90	-
Midslope	-	40-60	40-60
Upper slope	-	> 90	< 10
Crest	< 5	> 90	< 5
Depression	-	100	-

4.2.2 Total calcium carbonate and silica content

Total calcium carbonate and silica contents of the regolith materials are presented on Table 6. With the exception of lower slope (profile no.3) and midslope (profile no.4) where some carbonates were present as fissure fillings, in the rest of the profiles, the calcium carbonate present in amphibolite varied from 11.8 to 35.3% with an average of 21.7%. In the samples taken from the lower slope (profile no.3) and the midslope (profile no.4), the total $CaCO_3$ contents were 45.9 and 57.9% respectively.

Total silica content in amphibolite ranged from 22.4 to 48.3%. It was 45.0% and 48.3% in the regolith collected from the crest and upper slope respectively. The amphibolite which occurred in the other positions of the transect had lower total silica contents as follows: 22.4% at the midslope; 23.4% at the lower slope and 31.10% at the river bank.

The marble was very rich in total calcium carbonate but poor in total silica. The content of the two constituents ranged from 60.0 to 62.8% and from 10.1 to 12.7% respectively.

Table 6. Total calcium carbonate and silica content of selected regolith materials

Position on the transect	Type of regolith	$CaCO_3$ (%)	SiO_2 (%)
River bank	Mica rich amphibolite	35.3	31.1
Lower slope	Mica rich amphibolite	45.7	23.4
Midslope	Mica rich amphibolite	57.9	22.4
	Marble	60.0	12.7
Upper slope	Mica rich amphibolite	18.1	48.3
	Marble	62.8	10.1
Crest	Mica rich amphibolite	11.8	45.0

4.3 Characteristics of soil profiles overlying the calcretes

4.3.1 Morphological properties

The soils studied were dark reddish brown to red with a reasonable content of clay and a well developed structure. These soils were generally well drained. They were underlain by the gravel layer rich in quartz gravels and pebbles together with feldspars and some iron glaebules. Manganese glaebules were rarely encountered in the gravel layer. Some of the pebbles had smooth surfaces and a few had a rounded shape which is an indication that the layer consists of materials which were once transported by water.

The gravel layer is very characteristic as it marks the boundary between the soil solum and the underlying calcrete. Both the thickness and the depth of occurrence of the gravel layer are variable (Figure 10). Its thickness varied from over 10 to about 30 cm. Its position from the soil surface varied with the position on the transect.

4.3.2 Physical properties

The content of clay, silt and sand of the soils studied is shown on Table 7. The percent clay was relatively high in all soil profiles studied. It ranged from 32 to 64%. There was a general tendency for the clay content to increase with depth in the soil profiles located at the river terrace, lower slope, midslope and depression. On the river terrace, there was a clay increase of 45.2% between the A horizon and

Bck. On the lower slope, the increase in clay content between Apk horizon and Btk was 27.5%. The increase of 23% and 20% were observed between A and B horizons on the upper slope and depression respectively. The silt content was relatively low and ranged from 5 to 12%. The soils studied tended to contain more silt on the surface horizon than in the subsurface horizon. This trend was examplified in nearly all profiles studied.

4.3.3 Chemical characteristics

4.3.3.1 Soil reaction and organic carbon

The soils studied had a soil reaction with a very narrow range of pH. The latter varied from 6.3 and 7.8 (Table 7). With the exception of the soils situated at the lower slope where the pH decreased with soil depth, there was no specific trend of variation of pH with depth in the rest of the soil profiles studied.

The organic carbon contents of the top soils ranged from 0.8 to 1.8%. As it would have been expected, there was a decrease of organic carbon content with depth in all profiles.

4.3.3.2 CEC and exchangeable bases

The cation exchange capacity of the soils varied from 20.2 to 40.2 cmol(+)/kg soil (Table 7). This was equivalent to a range of 51 to 99 cmol(+)/kg clay. In most profiles, the CEC tended to increase with soil depth, though this tendency was not

noticed in the profiles located at the upper slope and midslope. On the river terrace, the CEC increased by 30.1% from an A horizon to Bck. An increase of 17.8% occurred between the Apk horizon and the Btk horizon in the profile situated at the lower slope. In the soil profile located at the depression, the CEC increased by 42.6% between the A horizon and B horizon. There was a slight decrease in CEC with depth by 1.5% in the soil profile situated at the upper slope.

There was a general tendency for the soils neighbouring Ngerengere river to have higher CEC than those neighbouring the crest. The soils which lie between the river terrace and the lower slope had CEC range of 30.7 to 40.2 cmol(+)/kg soil, while those soils situated between the midslope and the crest had CEC which varied from 20.2 to 33.6 cmol(+)/kg soil. When the CEC was expressed in cmol(+)/kg clay, the corresponding values were 74 to 99 and 51 to 78 cmo(+)/kg respectively. It is important to note that the magnitude of the CEC of the soil profiles with and without calcretes were very similar.

The soils occurring on the river bank and the lower slope had the highest level of base saturation. On the contrary, the soils located at the upper slope had the lowest base saturation. The remaining soils had intermediate values. Calcium was the most abundant exchangeable base in all the soils while exchangeable potassium and sodium were the least abundant. In most cases, the soils with relatively high base saturation had also high exchangeable calcium.

Table 7. Physical and chemical characteristics of the studied soils

position on the transect	Horizon	depth (cm)	clay (%)	silt (%)	sand (%)	pH (H_2O)	Org. C(%)	CEC (Cmol(+)/kg soil	CEC clay	Exchangeable bases Cmol(+)/kg Ca	Mg	K	Na	BS (%)
River bank	Ak	0-75	43	12	45	7.5	1.4	39.9	93	33.2	4.3	1.0	0.3	97
River terrace	Ap	0-22	31	10	59	7.1	1.7	30.7	99	10.7	3.3	1.2	0.1	50
	BA	22-66	37	9	54	7.0	0.7	33.8	91	8.8	4.0	0.9	0.2	41
	Bck	66-110	45	6	49	7.1	0.7	40.2	89	17.1	5.4	0.5	0.2	58
Lower slope	Apk	0-16	32	12	56	7.8	1.6	27.5	86	23.8	1.6	0.6	0.2	95
	BAk	16-44	38	9	53	7.3	1.6	31.5	83	27.2	1.9	0.4	0.2	92
	Btk	44-87	44	12	44	7.3	0.1	32.4	74	27.6	3.2	0.4	0.2	97
Mid-slope	Ap	0-20	35	8	57	6.4	1.0	27.4	78	8.0	2.0	0.4	0.2	39
	AB	20-49	39	5	56	7.5	0.6	27.4	70	7.4	2.4	0.4	0.2	38
Upper slope	Ap	0-10	40	10	50	7.1	0.9	27.7	69	5.3	2.5	0.5	0.2	31
	BA	10-30	47	6	47	6.3	0.7	27.5	59	3.8	2.7	0.3	0.2	25
	B	30-102	49	8	43	7.3	0.4	27.5	57	3.7	2.7	0.3	0.2	25
Crest	Apck	0-14	64	10	26	7.5	1.8	33.6	53	18.0	1.5	0.4	0.2	60
Depre-ssion	Ap	0-24	40	10	50	6.7	0.8	20.2	51	7.9	2.9	0.8	0.2	58
	AB	24-58	44	6	50	6.7	0.7	23.7	54	7.4	3.1	0.5	0.2	47
	B	58-158	48	5	47	7.3	0.5	28.8	60	10.0	3.3	0.4	0.4	49

4.4 Total calcium carbonate content of soil-calcrete-regolith succession

The calcium carbonate content in the soil-calcrete-regolith succession is presented on Table 8.

Calcium carbonate varied from 0.9 to 15.4% in the soil solum, 54.8 to 80.7% in the underlying calcrete layers and 11.8 to 57.9% in the regolith. It is apparent that the transition between the soil solum and the calcrete was characterised by a greater change in $CaCO_3$ than it was between the latter and the regolith. For example on the river bank, the calcium carbonate increased from 8.7 in the soil solum to 54.8 in the calcrete layer but decreased to only 35% in the underlying regolith. The same trend was observed in the rest of the soil profiles with calcrete. In the non-calcrete profile, the $CaCO_3$ content was relatively low in the soil solum and the underlying regolith. However, the change in $CaCO_3$ content between the two was also considerable, 0.9 versus 18.1%.

Table 8. **Vertical distribution of calcium carbonate in the studied soil profiles**

Position on the transect	Horizon/calcrete or regolith layer	$CaCO_3$ (%)
River bank	Ak	8.7
	Nodular	54.8
	Regolith	35.3
Lower slope	Apk	7.0
	Btk	15.4
	Honeycomb	59.2
	Nodular	74.3
	Regolith	45.7
Midslope	A	4.0
	AB	3.3
	Massive	56.2
	Honeycomb	59.7
	Nodular	62.5
	regolith	57.9
Upper slope	A	2.0
	B	0.9
	Regolith	18.1
Crest	Apck	7.9
	Massive	66.4
	Honeycomb	71.5
	Nodular	80.7
	Regolith	11.8

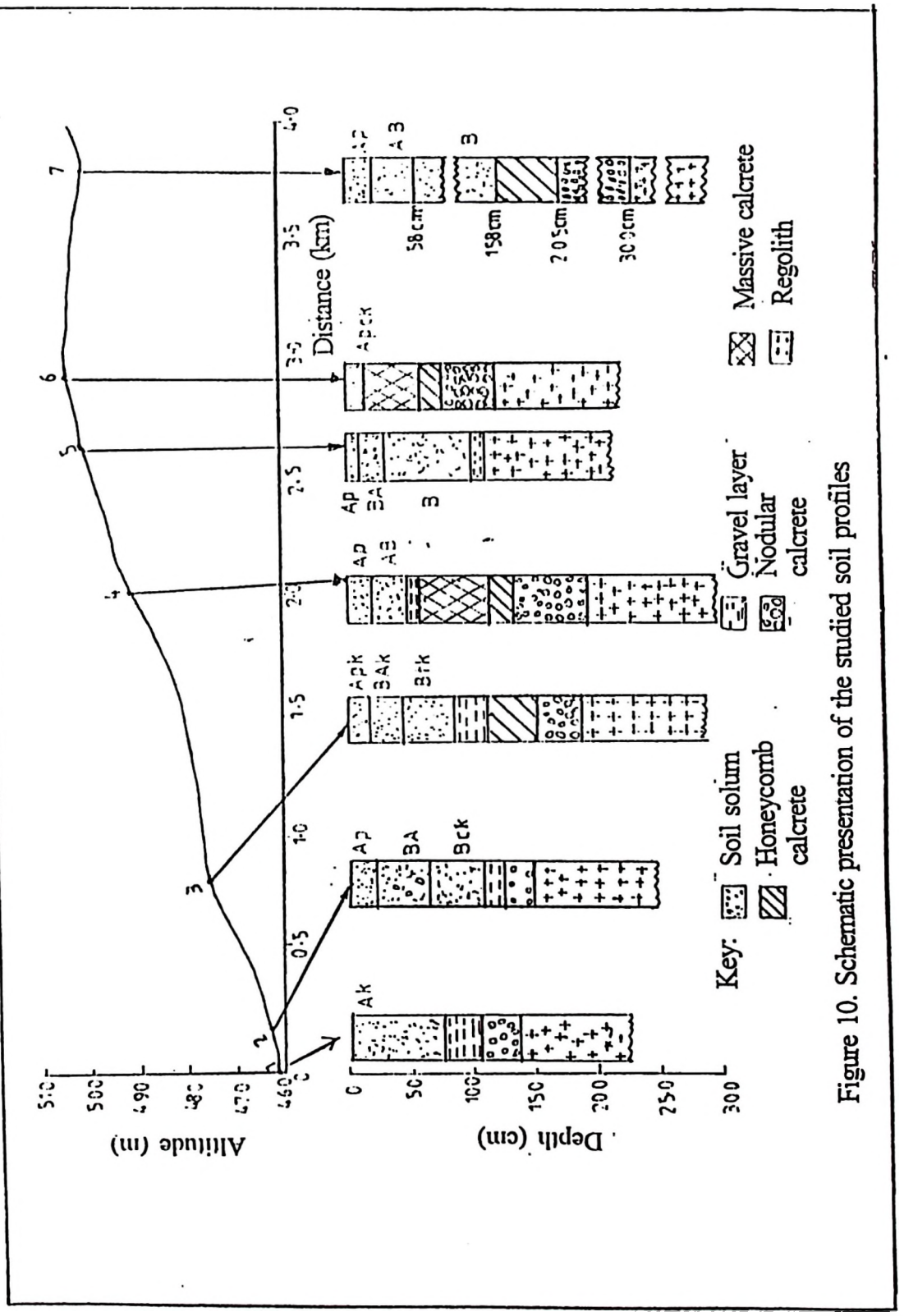


Figure 10. Schematic presentation of the studied soil profiles

4.5 Classification of the studied soils

The data on soil chemical and physical characteristics (Table 7) together with their morphological characteristics (Appendix 1) enabled the classification of the studied soils as shown on Table 9.

Table 9. Classification of the studied soils

Position on the transect	Soil classification system	
	FAO (1989)	USDA (1990)
River bank	Calcaric Fluvisols	Ustifluvents
River terrace	Calcic Luvisols	Typic Eutroprepts
Lower slope	Calcic Luvisols	Typic Eutroprepts
Midslope	Umbric Leptosols	Entic Haplumbrepts
Upper slope	Haplic Alisols	Typic Rhodustalfs
Crest	Eutric Leptosols	Ustarents
Depression	Haplic Alisols	Typic Rhodustalfs

4.6 Discussion

4.6.1 Distribution and origin of calcretes in the study area

4.6.1.1 General distribution

The occurrence of calcretes at a wide extension south of Ngerengere river and their absence on the equivalent landscape positions on the northern part of the Ngerengere river bank is an interesting feature. This sharp boundary in the distribution of calcretes may be associated with the nature of the underlying bedrock. In areas where calcretes are widely extended, they overly an amphibolitic rock which is associated with some marble, calcic plagioclase (oligoclase, 10-30 mol % Ca) and quartzite. The occurrence of these rocks in the studied area has also been reported by Muhongo (1994), Sampson (1962) and Sampson and Wright (1964). With the exception of quartzite which is rich in silica (Barth, 1967), amphibolite and marble are rich in calcium (Loughnan, 1969). On the contrary, the rocks on the neighbouring lower slopes of Mindu and Lugalla hills just on north and western side of Ngerengere river where calcretes do not exist, consist of migmatite gneiss. This observation appears to suggest that the studied calcretes were developed mainly from the basement rocks. On the basis of the standard ratings of calcareousness developed by EUROCONSULT (1989), the rocks underlain by calcretes are slightly calcareous to calcareous. The formation of calcretes from *in situ* alteration of calcareous basement rocks has been widely reported (Goudie, 1973; Dan, 1977; West *et al.*, 1988a&b; Verrecchia, 1990).

The radio carbon dating of massive calcrete at the upper part of calcrete profile gave an age of 41,000 years or more. The lower part of the calcrete must be even older, if the mode of formation followed the normal pattern of pedogenic calcrete formation (Klappa, 1983; West *et al.*, 1988a&b). This age coincides with the widely documented last glacial aridity which took place after 100,000 years BP in the tropical region (to which Morogoro belongs) (Vicens *et al.*, 1993; Thomas and Thorp, 1995 and Thomas, 1996). The latter would have been favourable for precipitation of calcretes.

4.6.1.2 Distribution, thickness and purity of calcretes along the transect

Relating the distribution of calcretes along the studied transect with the present landscape is not a straightforward task as the pre-calcretizational landscape of the area is not clearly known. However, the thinner calcrete layer near the Ngerengere river as opposed to the thicker ones near the crest with intermediate thickness in the middle positions of the transect may be attributed to the effect of Ngerengere river. The wetter conditions near the Ngerengere river might have reduced the rate of $CaCO_3$ precipitation by masking the evaporation rate.

The three physical forms of calcretes found in the study area have also been reported in previous studies elsewhere (Blümel, 1982; Gile *et al.*, 1966, Klappa, 1983; Knox, 1977). Also, vertical succession of these forms is in agreement with the previous findings (Blümel, 1982; Gile *et al.*, 1966, Klappa, 1983; Knox, 1977)

and in accordance with the mechanism of formation of the different physical forms of calcrete proposed by Klappa (1983) and Netterberg (1967). In this proposed mechanism of calcrete formation, nodular form become transformed to honeycomb form which in turn gets transformed to massive.

The observed wide variation in purity of calcrete layers with different forms of calcretes in the lower slope positions, middle of the slope positions and upper slopes around the crest may be attributed to differences in development stages among the forms of calcretes. The lower the development stage, the more the non calcrete materials in the calcrete layer, and hence the lower the purity (Gile *et al.*, 1966; Milnes, 1992). According these authors, the extent of development of the physical forms is as follows: nodular < honeycomb < massive form.

4.6.2 Mechanisms responsible for the formation of the studied calcretes

The presence of micrite as the main groundmass of all forms of calcretes reflects the difficulty of forming large crystals of calcium carbonate within the soil mass which characteristically had restricted porosity. Recently, Monger *et al.* (1991) attributed the presence of micrite groundmass to a process in which soil particles with restricted porosity are pushed ahead of micrite crystallization front, a situation which leads to formation of small crystals.

The presence of fissures frequently observed in the honeycomb and massive calcretes tends to suggest that these calcretes have passed the alternating dry-wet periods. Klappa (1983) attributed the presence of fissures in calcretes to an exposure to the cycles of dry-wet climates.

Formation of sparite in fissures and voids found in massive and honeycomb calcretes might have been caused by plugging of carbonate rich solution in fissures and voids. Knox (1977) and Monger *et al.* (1991) have attributed the development of sparry calcite in voids and fissures to long period (multi-phase) plugging of calcium carbonate solutions associated with slow crystallization rate. The formation of sparite immediately after relic minerals as observed in nodular calcretes can be explained by the nucleation role played by these minerals on the formation of calcite. Wielder and Yaalon (1974) explained the formation of sparite around the relic minerals as a result of the nucleation role played by the relic minerals serving as centres for $CaCO_3$ precipitation.

4.6.3 Soil-calcrete relationship

The systematically sharp variation of calcium carbonate content between the soils and the underlying calcrete layers along the transect can be attributed to lithological discontinuity between the two phases. It is not likely that the high total $CaCO_3$ levels in calcretes were derived from overlying soils as the soils are considerably younger than the calcretes.

The higher levels of $CaCO_3$ and exchangeable calcium obtained in calcrete-soil profiles over those obtained in non calcrete-soil profile might be indicating the influence of calcretes on soil characteristics. However, this study can not give a firm conclusion on this finding due to limited number of non-calcrete soil profiles studied and lack of information on levels and dynamics of calcium in the original colluvium. A separate study is needed to tackle these areas.

Morphologically, the soil and calcrete layers are separated by a gravel layer with abrupt boundaries both at the soil-gravel layer interface and gravel layer-calcrete interface indicating the difference in depositional phases among them. Although the ages of gravel and soil layers are not known, their deposition may be associated with post glacial onset of humid climate in the tropical region after 13,000 years BP (Thomas and Thorp , 1995; Thomas, 1996). The occurrence of some pebbles with smooth surfaces and rounded shapes in these layers is an indication that the materials were once transported by water.

Agronomically, where calcretes occur in a massive form at a shallow depth, they are obviously a limitation to the deep growth of plant roots.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Calcretes cover a considerable area on the northern lower slopes of Uluguru mountains which extends from its lower footslopes towards the Ngerengere river. They are widely extended south of Ngerengere river where mafic amphibolite rock dominates.

The most prevalent forms of calcretes occurring on the studied transect are massive, honeycomb and nodular calcretes. The relative proportion of their lateral extension along the transect follows the order: nodular (94.8%), honeycomb (87.1%) and massive (51.2%). The thickness of calcrete layers at profile numbers 1, 2, 3, 4, 6 and 7 are 30 cm, 25cm, 76 cm, 135 cm, 106 cm and 142 cm respectively.

Total calcium carbonate content ranges from 56.2 to 66.4% in massive calcretes; 59.2 to 71.5% in honeycomb and 54.8 to 80.7% in nodular calcretes. Calcretes are mainly constituted of calcite. Minor mineral components are quartz, opaline silica (opal-CT) and feldspars.

On the basis of radiocarbon dating, the studied calcretes were formed during the Late Pleistocene age (41,000 years or more BP). The last glacial aridity was a determining factor for their precipitation. The overlying gravel and soil layers are considerably younger.

The influence of calcretes on the properties of the overlying soils is still not clearly understood.

5.2 RECOMMENDATIONS

Due to limited or lack of knowledge on distribution and characteristics of calcretes in Morogoro and Tanzania as a whole, I recommend the following to be done:

1) More data on calcrete distribution, both laterally and vertically, in Morogoro and other parts of Tanzania should be collected with the purpose of mapping the calcrete areas in Tanzania.

2) Further characterization of northern Morogoro calcretes other than the Kihonda transect, in other areas of Morogoro and Tanzania should be performed. Since thin-section study seems to be the most effective method of investigation, it should be given an emphasis.

3) Mineralogical investigation of calcretes and soils should be done more thoroughly. The underlying regolith and/or parent rocks should also be investigated.

4) More dating and stable isotope measurements on soils and different forms of calcretes at different locations (both lateral and vertical) should be done. The dating of gravel layer is also recommended to give more insight on the past activities that took place in the area.

5) An effort should be made to understand the landscape that existed in the study area during the time of calcrete formation. The latter will give more insight on the factors that determined the distribution of calcretes along the landscape.

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APPENDICES

APPENDIX 1: SOIL PROFILE DESCRIPTIONS

APPENDIX 1.1. SOIL PROFILE NUMBER 1

General information on the site and soil

Author and date of examination: Sentozi, E. on 20/2/1996. **Location:** on the eastern Ngerengere river bank, 1.2 km E60°N of Mazimbu campus of the Sokoine University of Agriculture, latitude 6°47'03.8"S and longitude 37°38'31.4"E. **Elevation:** 462 m.a.s.l. **Landform:** river flood plain. **Slope of site:** 0.5-1%. **Vegetation and landuse:** the site is dominated by shrubs and grasses. The land is currently under fallow but normally is put under rice and maize. **Season/weather condition:** two rainy sesons, separated by a long dry season. **Parent material:** alluvial. **Drainage:** class 3 moderately well drained. **Moisture conditions during the time of profile description:** wet.

Soils: Very dark brown with no horizon differentiation, clay, slightly calcareous soil overlying a stone-line layer.

Soil classification: Calcaric Fluvisols (FAO, 1989), Ustifluvents (USDA, 1990).

Soil profile description

A	Very dark brown (7.5YR2.5/4) wet; clay; fine to coarse
0-75 cm	subangular blocky structure; slightly sticky, slightly plastic wet; many very fine and fine pores; slightly calcareous; many fine and few very coarse roots; clear smooth boundary towards the gravel layer.

75-105	**Gravel layer:** many fine to coarse, roundish to angular, non weathered to slightly weathered quartz gravels; few fine roundish to angular non weathered feldspar gravels; abrupt smooth boundary towards the calcrete layer.
105-135	calcrete layer

APPENDIX 1.2. SOIL PROFILE NUMBER 2

General information on the site and soil

Author and date of examination: Sentozi, E. on 3/2/1996

Location: on the river terrace 1.5 km E60°N of Mazimbu campus of the Sokoine University of Agriculture, latitude 6°47'01.1"S and longitude 37°38'34"E. **Elevation:** 463 m.a.s.l. **Landform:** river terrace. **Slope of site:** almost flat (1-2%). **Vegetation and landuse:** the site is dominated by shrubs and grasses. The land was formerly under sisal plantation, currently it is under maize. **Season/weather condition:** two rainy sesons separated by a long dry season. **Parent material:** alluvial/colluvial. **Drainage:** class 4 well drained. **Moisture conditions in profile or soil:** the soil profile was moist throughout. **Evidence of erosion**: very slight sheet erosion. **Human influence:** clearing of vegetation for agriculture. **Soils:** deep, non calcareous, very dark gray topsoil to slightly calcareous, dark reddish brown subsoil.

Soil classification: Calcic Luvisols (FAO, 1989), Typic Eutroprepts (USDA, 1990).

Soil profile description

Ap	Very dark gray (5YR2.5/1) moist; sandy loam; weak to
0-22 cm	moderately weak very fine and coarse subangular blocky structure; slightly sticky, slightly plastic wet, very friable moist; many very fine and fine pores; few very fine to medium roots; clear smooth boundary towards BA.

BA Dark reddish brown (5YR3/2 moist); sandy clay;

22-66 cm moderate to strong medium sub angular blocky structure; slightly sticky, slightly plastic wet, friable moist; common very fine and fine pores; very few small spherical quartz fragments; few very fine to medium roots; diffuse smooth boundary towards Bkc.

Bkc: Dark reddish brown (5YR3/3 moist); sandy clay loam;

66-110 cm strong coarse subangular blocky structure; slightly sticky, slightly plastic wet, friable moist; few very fine and fine pores; very few small spherical quartz fragments; few small irregular hard carbonates nodules; very fine roots; abrupt smooth boundary towards the underlying gravel layer.

110-124 **Gravel layer:** many fine to coarse, roundish to angular, non weathered to slightly weathered quartz gravels; few fine roundish to angular non weathered feldspar gravels; abrupt smooth boundary towards the calcrete layer.

124-149 Nodular calcrete layer

APPENDIX 1.3. SOIL PROFILE NUMBER 3

General information on the site and soil

Author and date of examination: Sentozi, E. on 31/1/1996

Location: lower slope, 300 m W36°N of Ahmadiyya medical centre, latitude 6°47'13.4"S, longitude 37°38'45"E. **Elevation:** 476 m.a.s.l. **Landform:** gently undulating, **Slope of site:** 5%. **Vegetation and landuse:** the site is dominated by shrubs and grasses. The land was formerly under sisal plantation, currently it is under maize. **Season/weather condition:** two rainy sesons separated by a long dry season. **Parent material:** colluvial. **Drainage:** class 4 - well drained. **Moisture conditions in profile or soil:** the soil profile was moist throughout. **Evidence of erosion:** slight sheet erosion. **Human influence:** clearing of vegetation for agriculture. **Soils:** Slightly calcareous, deep, dark reddish brown, sandy loam top soil to calcareous, sandy clay subsoil.

Soil classification: Calcic Luvisols (FAO, 1989), Typic Eutroprepts (USDA, 1990).

Soil profile description

Ak	Dark reddish brown (5YR3/3) moist; sandy loam;
0-16 cm	slightly sticky, slightly plastic wet, very friable moist; weak very fine and fine subangular blocky structure; common very fine and fine pores; very few small angular quartz fragments; very fine and coarse roots; slightly calcareous; gradual smooth boundary towards BA.

BAk	Dark reddish brown (5YR3/3) moist; sandy clay loam;
16-44 cm	slightly sticky, slightly plastic wet, friable moist; moderate to moderately weak coarse to fine subangular blocky structure; common very fine and many fine pores; very few small angular quartz fragments; slightly calcareous; very fine to coarse roots; gradual smooth boundary towards Btk.
Btk	Dark reddish brown (2.5YR3/4 moist); sandy clay;
44-87 cm	slightly sticky, slightly plastic wet; friable moist; weak to moderate fine to coarse subangular blocky structure; many, faint, partly intersecting slickensides on ped surfaces; many very fine to fine pores; very few small angular quartz fragments; very fine to fine roots; calcareous; abrupt wavy boundary towards the gravel layer.
87-112 cm	**Gravel layer:** many fine to coarse, roundish to angular quartz gravels; few roundish to angular feldspar gravels; abrupt weavy boundary towards the calcrete layer.
112-188 cm	Calcrete layer

APPENDIX 1.4. SOIL PROFILE NUMBER 4

General information on the site and soil

Author and date of examination: Sentozi, E. on 13/2/1996

Location: midslope, 120 m W20°S of polytex club, latitude 6°47'18.2"S, longitude 37°39'11.3"E. **Elevation**: 492 m.a.s.l. **Landform:** piedmont. **slope of the site:** flat or almost flat (1-2%). **Vegetation and landuse:** the site is dominated by grasses. The land was formerly under sisal plantation, currently it is both under agriculture (cleared for maize planting) and urban development. **Season/weather condition:** two rainy sesons separated by a long dry season. **Parent material:** colluvial. **Drainage:** class 4 - well drained. **Moisture conditions in profile or soil:** the soil profile was moist in the top soil and dry in subsoil. **Evidence of erosion:** very slight sheet erosion. **Human influence:** clearing of vegetation for agriculture.

Soils: shallow, non calcareous, dark reddish brown, sandy loam topsoil to sandy clay loam subsoil, well drained.

Soil classification: Umbric Leptosols (FAO, 1989), Entic Haplumbrepts (USDA, 1990).

Soil profile description

Ap	Dark reddish brown (5YR3/3) moist; sandy loam;
0-20 cm	slightly sticky, slightly plastic wet, very friable moist; weak very fine to medium subangular blocky structure; many very fine to medium

pores; few small angular quartz fragments; very fine and fine roots; non calcareous; clear smooth boundary towards AB.

AB 20-49 cm — Dark reddish brown (5YR2/4 dry, 5YR3/3 moist); sandy clay loam; slightly sticky, lightly plastic wet, very friable moist, slightly hard dry; moderate medium and coarse subangular blocky structure; few medium and common fine pores; frequent small angular quartz fragments; few very fine roots; non calcareous clear wavy boundary towards the underlying gravel layer.

49-60 cm — **Gravel layer:** many fine to coarse, roundish to angular, non weathered quartz gravels; abrupt weavy boundary towards the calcrete layer.

60-195 cm — Calcrete layer.

APPENDIX 1.5. SOIL PROFILE NUMBER 5

General information on the site and soil

Author and date of examination: Sentozi, E. on 14/2/1996

Location: Upper slopes, 200 m W90°N of north western end of air strip, latitude 6°47'27.6"S, 37°39'17.3"E **Elevation:** 501 m.a.s.l. **Landform:** piedmont. **Slope of the site:** gently undulating (3%). **Vegetation and landuse:** the site is dominated by grasses. The land was formerly under sisal plantation, currently it is both under agriculture (cleared for maize planting) and urban development. **Season/weather condition:** two rainy sesons separated by a long dry season. **Parent material:** colluvial. **Drainage:** class 4 - well drained. **Moisture conditions in profile or soil:** the soil profile was dry throughout. **Evidence of erosion**: None. **Human influence:** clearing of vegetation for agriculture.

Soils: deep, well drained, dark reddish brown top soil with red subsoil; sandy clay loam topsoil with clay subsoil. Non calcareous overlying a stone-line with no calcrete layer.

Soil classification: Haplic Alisols (FAO, 1989), Typic Rhodustalfs (USDA, 1990).

Soil profile description

Ap	Dark reddish brown (2.5YR3/4) moist and dry; sandy
0-10 cm	clay loam; slightly sticky, slightly plastic wet, friable moist, hard dry; moderate fine and coarse subangular blocky structure; many fine and very fine pores; few very fine roots; non calcareous; diffuse smooth boundary towards BA.

BA	Dark red (2.5YR3/6) moist and dry; clay loam; lightly
10-30 cm	sticky, slightly plastic wet, friable moist, slightly hard dry; strong medium and coarse subangular blocky structure; common very fine pores; few small angular quartz fragments; few very fine roots; non calcareous; diffuse smooth boundary towards B.
B	Red (2.5YR4/8) dry, dark reddish brown (2.5YR3/4)
30-102 cm	moist; clay; non-sticky, non-plastic wet, very friable moist, soft dry; weak very fine subangular blocky structure; few very fine pores; frequent small angular quartz fragments; very fine roots; non calcareous; clear wavy boundary towards the gravel layer.
102-112 cm	**Gravel layer:** many fine to coarse, roundish to angular, non weathered quartz gravels; few fine to medium, roundish to angular, non weathered to slightly weathered feldspar gravels; abrupt weavy boundary towards the regolith.

APPENDIX 1.6. SOIL PROFILE NUMBER 6

General information on the site and soil

Author and date of examination: Sentozi, E. on 17/2/1996.

Location: on the crest, 30 m W50'S of air strip middle, latitude $6^0$47'44.1"S, longitude $37^0$39'20.3"E. **Elevation:** 505 m.a.s.l. **Landform:** piedmont. **Slope of the site:** flat/almost flat (0.5-1%). **Vegetation and landuse:** the site is dominated by shrubs and grasses. The land is currently under maize and urban development. **Season/weather condition:** two rainy sesons separated by a long dry season. **Parent material:** colluvial. **Drainage:** class 4 - well drained. **Moisture conditions in profile or soil:** the soil profile was dry. **Human influence:** clearing of vegetation for agriculture.

Soils: very shallow, well drained, slightly calcareous dark reddish brown; silty loam soil.

Soil classification: Eutric Leptosols (FAO, 1989), Ustarents (USDA, 1990).

Soil profile description

Apck	Dark reddish brown (5YR3/3) moist and dry, silty loam;
0-14 cm	non-sticky, non-plastic wet, very friable moist, soft dry; weak very fine to medium subangular blocky structure; common very fine pores; frequent small angular quartz fragments; frequent small

irregular hard carbonates nodules; common very fine to medium roots; slightly calcareous; clear smooth boundary towards the massive calcrete layer.

14-120 calcrete layer

APPENDIX 1.7. SOIL PROFILE NUMBER 7

General information on the site and soil

Author and date of examination: Sentozi, E. on 23/2/1996.

Location: In the depression near the crest, between air strip and Msamvu TANESCO institute, latitude 6°48'07.7"S, longitude 37°39'12.6"E. **Elevation:** 501 m.a.s.l. **Landform:** piedmont. **Slope of the site:** gently undulating (3%). **Vegetation and landuse:** the site is dominated by shrubs and grasses. The land is currently under urban development and maize production. **Season/weather condition:** two rainy sesons separated by a long dry season. **Parent material:** colluvial. **Drainage:** class 4 - well drained. **Moisture conditions in profile or soil:** the soil profile was moist throughout. **Human influence:** clearing of vegetation for agriculture and house construction.

Soils: very deep, non calcareous dark reddish brown; sandy clay.

Soil classification: Haplic Alisols (FAO, 1989), Typic Rhodustults (USDA, 1990).

Soil profile description

Ap	Dark reddish brown (5YR3/3) moist; sandy clay;
0-24 cm	slightly sticky, slightly plastic wet, friable moist; weak very fine to medium subangular blocky structure; common fine to medium pores; common fine roots; non calcareous; diffuse smooth boundary towards AB.

AB	Dark reddish brown (5YR3/3) moist; sandy clay;
24-58 cm	slightly sticky and slightly plastic wet, friable moist; moderate fine to coarse subangular blocky structure; many very fine and few fine pores; few very fine roots; non calcareous; diffuse smooth boundary towards B.
B	Dark reddish brown (2.5YR3/4) moist; sandy clay;
58-158 cm	slightly sticky and slightly plastic wet, friable moist; moderate fine to medium subangular blocky structure; few fine and very fine pores; very fine roots; non calcareous; clear wavy boundary towards the calcrete layer.
158-300 cm	Calcrete layer.