NLH
NORGES
LANDBRUKSHØGSKOLE

INSTITUTT FOR JORD- OG VANNFAG

DEPARTMENT OF SOIL AND WATER
SCIENCES

Geology, Landscape Evolution, and Soil Development in the northern part of Morogoro District, Tanzania.

by

Rolf Sørensen and Abel K.Kaaya

Report no. 5 / 1998 (67)

Agricultural University of Norway
Department of Soil and Water Sciences
P.O.Box 5028
N-1432 AAS NORWAY

ISSN 0805 - 7214

INSTITUTT FOR JORD- OG VANNFAG
Norges Landbrukshøgskole
Postboks 5028, 1432 Ås Telefon: (09) 94 75 00 - Agriuniv. Ås
Telefax: (09) 94 82 11 Rapportarkiv: (09) 98 82 04
ISSN 0805 - 7214

Rapportens tittel og forfatter(e):

Geology, Landscape Evolution, and Soil Development in the northern part of Morogoro District, Tanzania.

by

Rolf Sørensen & Abel K. Kaaya

Rapport nr : **5/1998 (67)**

Begrenset distribusjon: **Fri**

Dato: **August, 1998**

Prosjektnummer:

Faggruppe: **Jordfag**

Geografisk område: **Tanzania**

Antall sider (inkl. bilag): **69**

Oppdragsgivers ref.:

ABSTRACT

The area between the Uluguru and Kaguru - Rubeho mountains in the northern part of Morogoro District, Tanzania, has been investigated. Two different groups of bedrock, the granulites and biotite-hornblende gneisses, and the migmatites and muscovite-biotite gneisses have been considered as the most important parent materials for saprolite and soils. Saprollite thickness range from almost zero to > 50 meters, depending on rock properties. Landscape development in the the area, and palaeoecological development of East Africa have been reviewed from recent literature, and adapted for the study area. Climatic cycles of approximately 41 and 100 kyr duration, with cool/dry and warm/ humid phases have influenced vegetation cover, geological processes and soil development in the study area. Late Holocene sediment accumulation rates on the Mkata and Ngerengere River floodplains have been calculated to 0.7 and 2 mm yr^{-1} respectively. Earlier studies on local erosion report rates from 0 to 0.28 mm yr^{-1}, and regional rates of denudation in central Tanzania that range from 30 to 60 mm kyr^{-1}. Saprolite formation and denudation are assumed to have been in near balance during the Quaternary period. Several forms of pedogenic calcrete occur on the moderate to lower slopes, over different bedrocks. Calcite or low Mg-calcite dominate in the calcretes, and stable oxygen isotope analyses indicate their formation in a cooler climate. The carbonate concretions formed 26 - 30 kyr BP, and more mature calcretes have probably formed during the Quaternary 'glacial' episodes. Clayey colluvium on the northern footslopes of the Uluguru Mts. have mainly been formed by landslides and mudflows during the termination of the 'glacials'. The sandy colluvium along Mindu Mts. have formed by slope wash during the last 100 kyr. Two toposeqences are described with respect to parent material formation, slope processes and soil development. The latter has been strongest during interglacials, but indication of weak soil development 30 to 40 kyr ago has been observed. Some further investigations are suggested.

4. Key words: Soil mineralogy; soil profiles; toposequence; Uluguru mountains, Tanzania; weathering.

Prosjektleder:

Rolf Sørensen

Rolf Sørensen

For administrasjonen:

Gunnar Abrahamsen

Gunnar Abrahamsen

ACKNOWLEDGEMENTS

We express our sincere thanks to the following institutions and persons:

NORAD through the Department of Soil Science, Sokoine University of Agriculture (SUA), provided financial support during fieldwork and for some of the ^{14}C- and TL/OSL datings; Dr. J.P. Mrema, the Head, Department of Soil Science, SUA, for providing transport and assistance during field work. Enthusiastic help from Dr. M.Kilasara and Mr. I. K.M. Diwani is highly acknowledged.

DHV-Consulting Engineers, Ammersfoort, The Netherlands, for permission to publish geological information from their report on the water management plan for Morogoro District.

Professor S. Muhongo, Geology Department, University of Dar es Salaam, for discussions about the geology of Uluguru Mts. and their surroundings.

Associate professor Odd Nilsen, Department of Geology, University of Oslo, for numerous discussions on mineralogy and geology in Morogoro District, for identification of the 'heavy mineral' fraction from SUA ravine, and for help with microscopic interpretation of thin-sections of sand from the Mindu and SUA ravine sections.

Senior technician Turid Winje, Department of Geology, University of Oslo, for providing laboratory facilities and carrying out XRF analyses of sand and clay samples.

Dr. David S. Brown, The Natural History Museum, London, for identifying the fossil shells found in the river-bank sediments at one of the tributaries to Mkata River.

Senior technician Lars Kirkesæther, Institute for Energy Technology, Kjeller, Norway, for preparation of thin-sections and for carrying out mineralogical analyses on rock samples from our study area.

Discussions with late Dr. Vagn Mejdahl, The Nordic Laboratory for Luminescence Dating, Roskilde, Denmark, about the TL / OSL-analyses of the Mindu section.

Technician Leif Jacobsen for preparing and running a number of samples on XRD.

The technicians Åslaug Borgan and Berit Hopland for drawing and digitizing most of the figures in this report, and for their patience regarding numerous requests for changes presented at the last moment.

Technician Anne-Grethe Kolnes for help with reproduction of all the papers.

Dr. Kjell Esser and Professor Per Jørgensen for critical reading and comments on the manuscript.

Jacqueline Esser for correcting the language.

Last but not least, to the Department of Soil and Water Sciences for providing laboratory facilities, carrying out some chemical analyses, and for giving some financial support.

6.3.2 The 'SUA' ravine section *30*
6.3.3 Formation and age of the colluvial fans / aprons - A summary *35*
6.4 The red and brown clayey soils (Nxf) 35
6.5 Fluvial deposits and the mbuga and swamp soils 36
6.6 Calcretes (superficial limestone, Nzc) 39
6.6.1 Distribution and occurrence in the field *39*
6.6.2 Calcretes and soil formation *46*
7. Soil Formation and local toposequence models 47
7.1 Soils with mixed mineralogies 47
7.2 The Ngerengere Valley toposequence 48
7.3 The Lubungo - Mkata toposequence 52
8. Concluding remarks 55
9. References 58
APPENDIX: BRIEF DESCRIPTION OF LABORATORY METHODS 65

LIST OF TABLES

Table 2.1 A selection of analyses from the Uluguru granulite complex and neighbouring rocks. *8*

Table 6.1 Mineralogical composition of the fine sand fraction (125 - 63 µm) from the Mindu Colluvial Apron. *30*

Table 6.2 Chemical composition of the fine sand fraction (125 - 63 µm) from the Mindu Colluvial Apron and the SUA ravine section.. .... *30*

Table 6.3 Mineralogical composition of clay and sand fractions from SUA ravine section *33*

Table 6.4 Chemical (mol-% of the soluble fraction) and mineralogical composition of some calcretes from part of the northern Morogoro District. *43*

Table 6.5 Radio-carbon dates and stable isotopes of calcretes and other materials. *44*

Table 7.1 List of weathering index minerals in soils from the northern part of Morogoro District.. .... *49*

1. Introduction

Some studies of geomorphic processes on the slopes of the Uluguru mountains in Morogoro District have been reported by Rapp et al. (1972), Temple and Murray-Rust, (1972), Temple & Rapp (1972), and Lundgren (1978). Their results include estimates of soil erosion, sediment transport, description of different landslides, and the re-establishment of vegetation and soil formation in the erosion scars under the present day climatic conditions. A knowledge of paleoecology, as far back as one or two million years before present (the Quaternary Period) is important for the understanding of landscape evolution and soil development. Although the science of soil development is primarily concerned with present-day landscapes, it attains historical usefulness by extension into the past (Buol et al., 1980). Changes in climate, plant communities, action of geologic agents, cycles of wind and water erosion and deposition during the Pleistocene, processes which are still active, have had a profound influence on the soil parent materials. The end of the Pleistocene (and beginning of the Holocene) is reported to have been characterized by a rapid change of climate with a corresponding change in vegetation. These changes have influenced soil and landscape development. Finally, we will draw attention to the influence of man on the ecosystem, during the last two to three thousand years.

There is limited information relating to geology, landscape development, previous environmental conditions, and soil development in the northern part of Morogoro District. The existing comprehensive information about geology of the area was published by Sampson and Wright (1964). These workers attempted also to describe briefly the geomorphology of the area in relation to geology.

This study was carried out in order to evaluate the existing geological and geomorphological information, and to adapt modern palaeoecological studies from East Africa to the northern Morogoro region. With the collection of new data, we will try to establish a preliminary chronology of events related to landscape and soil development for the last hundred thousand years.

Soil development will be discussed in relation to the 'factors of soil formation' (Jenny 1941, 1980). The landscape development is discussed in a long (ca. 200 mill. years) and short (100 - 10 kyr) time perspective. Special attention will be given to the concept of 'polygenetic soils' (Bryan & Albritton 1943), with relation to cyclicity in climate and its effect on parent material formation.

of the high to very high metamorphic grade of the rocks, they are all more or less banded and foliated, and contain characteristic mineral suites.

The mapping units (on Fig. 2.1) are compiled from different geological maps, and given general names. Relatively large variation in appearance and mineralogy may be expected within each unit. The classification of the surficial deposits (mainly called Neogene deposits on the geological maps) are modified in accordance with modern views on their genesis.

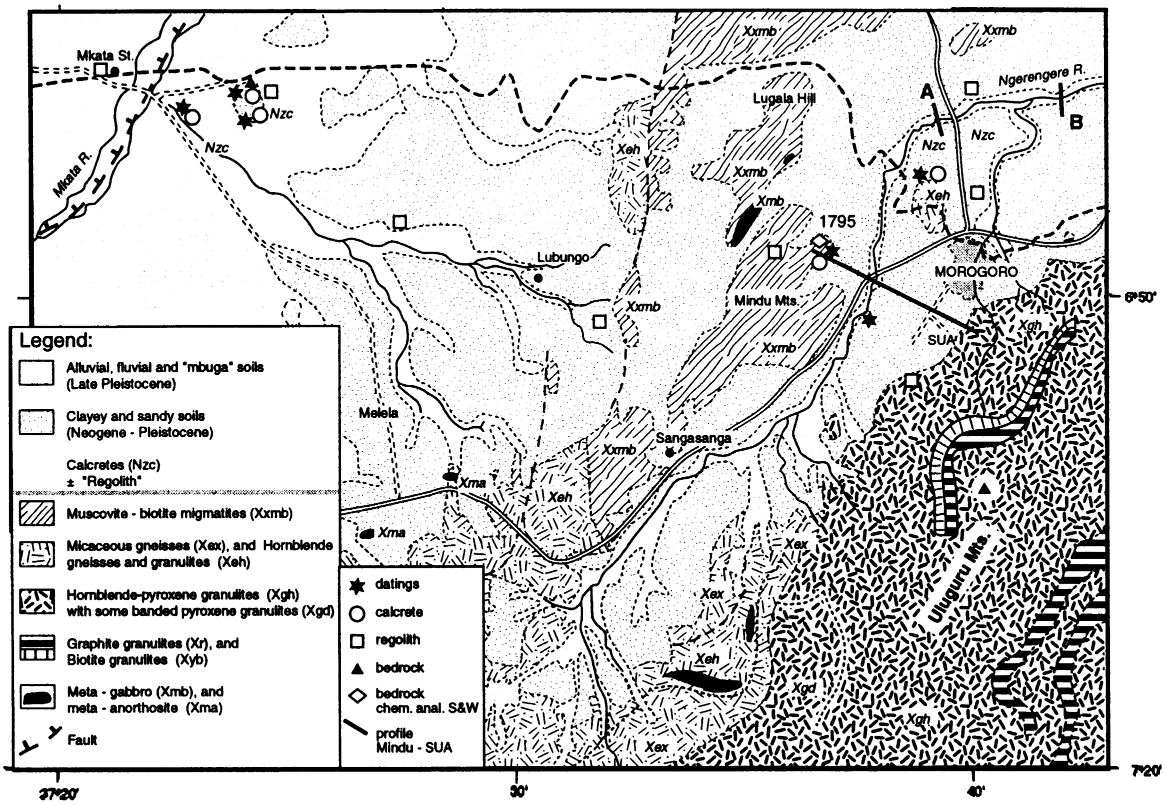

Fig. 2.1 *Geological map covering a part of the northern Morogoro District.*
For location, see Fig. 1.1. Modified from Sampson et al. (1961), Sampson & Wright (1964), and Fozzard (1965).
The profile from SUA to Mindu is shown in Fig. 7.2 .

2.1 Rocks of the Uluguru Massif

This rock complex is divided into five sub-units by Sampson & Wright (1964). Only the two dominating units will be considered here. The others have either limited areal extent or are mineralogical oddities in a soil parent material context.

2.1.1 *The hornblende - pyroxene granulites* (Xgh)

These rocks contain calcium-rich plagioclas, some biotite and garnets, and low but varying amounts of quartz. Potassium feldspar is usually rare. The pyroxenes are usually of the hypersthene $(Mg,Fe)SiO_3$ and the diopside $Ca,Mg\ Si_2O_6$ types. The hypersthene is a 'diagnostic

The biotite-hornblende gneisses are more common on the northern slopes of the Ulugurus than shown on Fig.2.1. Soil profile MAG 5 (Kaaya 1997) is developed on a micaceous (biotite) gneiss.

Our own observations between Morogoro Town and Bondwa Peak indicate that amphibolites are common on the northern slopes of the Uluguru Mts. Rock samples from amphibolites near the top of Bondwa Peak (Fig. 1.1) and near Mkata Ranch (Fig. 2.1) have been collected for Apatite Fission Track analyses, supplementary to those by Noble et al. (1997). These samples have also been analysed under microscope. They contain more than 95 % amphibole minerals (mainly hornblende) and plagioclase (An 36 - 42). Pyroxene and scapolite are common, and accessory minerals are iron ore, apatite and rutile. Quartz and biotite occur sporadically (L. Kirkesæther, personal communication 1998).

Ten analyses of amphibolites in the Kilombero area within the same bedrock complex as the Uluguru Mts. contain 1 to 3 % titanium oxide (O. Nilsen, personal communication 1997). We assume that the amphibolites upslope of the Magadu profiles and the SUA ravine have a similar chemistry.

Generally, the content of biotite is important when it comes to soil formation, because of its rapid transformation to vermiculite and other clay minerals (Kaaya et al. 1998). Near the surface, biotite-rich zones containing hydro-biotite and vermiculite are a mineral resource that may have some potential for improving the cation exchange capacity of leached soils in the region. A larger part of the Mkata - Wami Plain and the Ngerengere Valley are underlain by biotite-hornblende gneisses related to those in the Uluguru Massif.

2.2 The igneous meta-anorthosite complex (Xma)

A large oval intrusive body (12 x 30 km) of mainly plagioclase rocks is found in the western part of the Uluguru Massif. The rock contain normally a granular, pink to white feldspar is normally of a 'labradorite' type (50 % or more calcium in the plagioclase), together with garnets and pyroxenes (diopside is most common). Hornblende, biotite, muscovite and scapolite occur commonly in minor amounts. Iron ore (titaniferous magnetite) occurs locally in high concentrations, or as an accessory mineral together with apatite, ilmenite, rutile, zircon and sphene. Smaller bodies of ultrabasic rocks (eclogites and pyroxenites) are found within the meta-anorthosite complex.

Green and brown muscovite has been mined from pegmatites at the boundary or within these rocks (Sampson & Wright 1964). The chemical composition of one meta-anorthosite is shown in Table 2.1; sample 875. This rock complex is interesting in a saprolite and soil formation context (cf. Section 6.1).

bands and lenses. Accessories include apatite, rutile and iron ore. There are occasional dark-coloured bands and lenses of hornblende-bearing rocks with garnets, epidote and biotite (Sampson & Wright 1964).

Due to a very high metamorphic grade, the rocks have been partly melted and thus produced *migmatites.* The term is defined as: «A composite rock composed of igneous or igneous-appearing and / or metamorphic materials, which are generally distinguishable megascopically» (Bates & Jackson 1980). Due to the process of migmatisation, veins of *pegmatite* are common in these rocks. The pegmatites contain lenses of pure microcline and quartz, with macrocrystals of muscovite and biotite.

The mica gneisses and migmatites produce light coloured sandy soils rich in quarts, often developed as colluvial aprons on the footslopes of the hills. One of these aprons, on the south-eastern slopes of Mindu Mts. (Fig. 6.1 - 6.3), has been investigated in detail by Sørensen, Murray and Kilasara (in prep.).

The chemical composition of three mica gneisses / migmatites are shown in Table 2.1; samples 101G, 975 & 1795.

2.5 The bedrocks in the area as soil parent materials

Several of the mapping units on Fig. 2.1 have a limited areal extent and they are only of local importance as soil parent materials, although they might be interesting for special weathering studies. This applies to the map units. meta-gabbro and meta-anorthosite (Xmb & Xma), and to the units; biotite and graphite granulites (Xyb & Xr).

The following rock-groups are of regional importance in a soil parent material context:

1. The hornblende-pyroxene and pyroxene granulites (*Xgh* & *Xgd*) are mafic (*basic*) rocks which to a large extent are located in a moist environment on the Uluguru Mts, and their weathering would favour gibbsite formation (Sherman et al. 1967). The high An-contents in the plagioclases are also a specific feature of these granulites, as well as high contents of ilmenite, at least locally.
2. The micaceous and hornblende gneisses and granulites (*Xex* & *Xeh*) show considerable mineralogical and textural variation in the field. They occur over a large area with different morphology, and their response to weathering in terms of saprolite thickness and content of secondary minerals is also variable. Generally, the relatively high contents of biotite and other iron-containing minerals will produce red and clayey soils (Kaaya 1998).

The other pronounced land surface of the region is the 'Mkata - Wami Plain', with a level of 400 - 650 m a.s.l. It has been referred to as the 'Mid-Tertiary' or 'the Miocene peneplain'. A view of the Mkata Plain is shown in Fig. 3.1. Isolated residual mountains, such as Mindu, Lugalla, and Nguru ya Ndege, rise sharply out of the plain. One of the youngest land-features is the Ngerengere Valley (Fig. 3.2) which has eroded into the Mkata Plain (Sampson & Wright 1964). It has developed mainly during the Pliocene - Pleistocene (the last 3 mill. years).

The Mkata - Wami Plain is bound to northwest by the 'Tanganyika Scarp', a complex fault-zone of varying age and morphological development (Quennell et al. 1956).

3.2 Dating of Pre-Quaternary erosion episodes and land surfaces

Before Late Jurassic (more than 165 mill. years ago), eastern Tanzania was a stable tectonic land-mass, and the so called 'Gondwana land surface' was fully developed (King 1967). With the break-up of Gondwanaland in Late Jurassic, large rift structures developed along old faults from Permian and older geological periods, and the margins of southern Africa were uplifted.

During Early Cretaceous (ca. 140 mill. years ago), a phase of accelerated erosion (due to strong uplift) is recognized both on the southwestern margin of Africa (Brown et al. 1990) and in Eastern Tanzania (Noble et al. 1997). The episode in Tanzania is confirmed by a marked increase in sedimentation on the coast near Dar es Salaam, and on the Islands of Zanzibar and Pemba (Kent et al. 1971).

During the following approximately 35 mill. year period of crustal stability, the 'African land surface' had time to develop. Again a new phase of strong uplift and accelerated erosion occurred in the Morogoro District between 60 - 80 mill. years ago (Noble et al. 1997), and a similar peak in coastal sedimentation is recorded (Kent et al. 1971). A third phase of uplift and erosion occurred between 30 - 40 mill. years ago, and since then only minor crustal movements have taken place according to the AFT-measurements. Apatite fission track thermochronology (AFT) can date continental uplift and strong erosion episodes up to Late Tertiary (Brown et al. 1990, Noble et al. 1997). However, the sedimentation rates on the Dar es Salaam and Zanzibar coasts indicate a fourth strong erosion episode in the catchments of Wami and Ruvu Rivers some 20 mill. years ago (Kent et al. 1971). The 'Mid-Tertiary' land surface must therefore have developed prior to this event, during a more stable period of ca. 25 mill. years.

During the last 20 mill. years, sedimentation rates on the coast have been low (Kent et al. 1970), indicating moderate erosion and land surface lowering in the Morogoro District. According to Sampson & Wright (1964), the Ngerengere Valley and 'Kingolwira land surface' have developed during this time span.

values which are mainly related to the estimation of the geothermal gradient (Brown et al. 1990), and the data are therefore very approximate (+/- 500 m).

Calculation of average denudation rates for the Morogoro District, based on Fig. 9 in Noble et al. (1997), varies between 30 mm kyr^{-1} for the Uluguru Mts. and 100 mm kyr^{-1} for the Ngerengere Valley. Calculations for the Orange River basin in southern Namibia (Brown et al. 1990) show an exponential decrease in denudation rates from more than 1000 mm kyr^{-1} during the Early Cretaceous, to less than 20 mm kyr^{-1} in Early Tertiary. The present-day total denudation rates in the Orange River basin is 28 mm kyr^{-1} (Summerfield & Hulton 1994). The more rugged topography and climate (both present and past) in the Morogoro District will most likely produce slightly higher denudation rates than in the Orange River basin, which is the nearest comparable catchment discussed by Summerfield & Hulton (1994).

With an approximate average lowering of the land surface of 30 mm kyr^{-1} in the study area during Holocene, the total denudation for the last 10 000 years will be ca 0.3 m. It is therefore likely that imprints from the older land surfaces can be seen in the present regolith / saprolite and soil formation in the region. The age of the saprolite and soils in the area are discussed in sections 5.3 and 7.2.

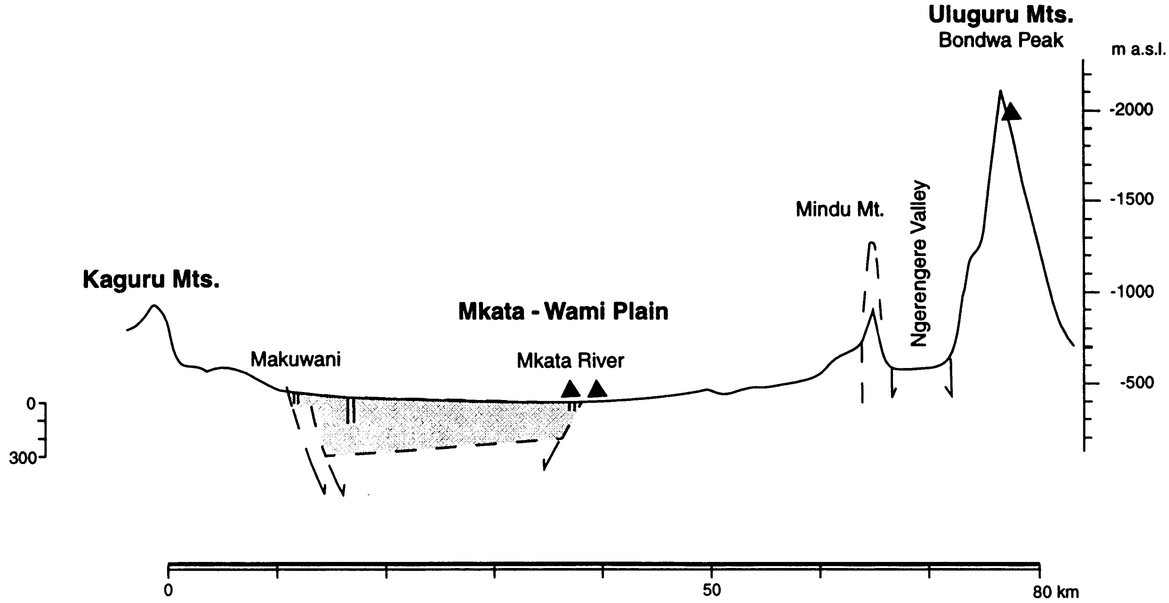

Fig. 3.3 *Tectonic / geomorphological profile from Bondwa Peak to the Kaguru Mountains.*
For location of profile, see Fig. 1.1) Data between Mkata River and Makuwani are from DHV-Consultant Engineers (1980). The triangles show locations of rock samples for new AFT-analyses.

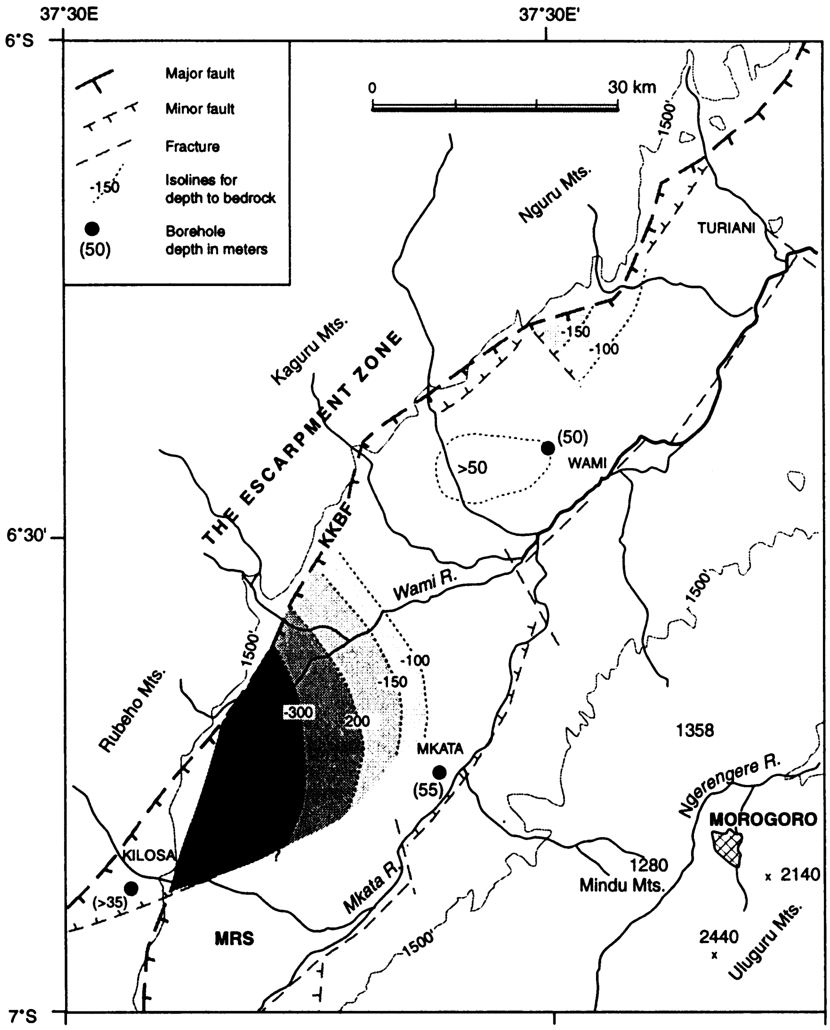

Fig. 3.4 *Tectonic boundaries and distribution of Quaternary sediments on the central part of the Mkata Plain.*
Compiled from investigations by DHV-Consulting Engineers (1980).
Base maps for the figure are; Sheet M-5D & M-5C Series TPC. The 1500 ft contour line is marked on the figure, to show the extent of the plain. Other numbers are in meters.
MRS: The Mkata Rift Segment **KKBF**: The Kilombero - Kilosa Boundary Fault

In more recent times (during the Early Holocene wet period), most of the basin may have been covered by large swamps or even lakes, where fine-grained sediments were deposited during floods. In the last few thousand years, the pattern and the shape of the river channels seem to have changed from a braided river system to more confined channels, and an air-photo study of the Mkata River between Mkata railway station and Magurumane Village, a few km east of the railway station, show that some meanders have been isolated as oxbows. This reflects probably a change in stream regime and that Mkata River at present is cutting a deeper channel in its former flood-plain in this area. A similar pattern is shown by the Morogoro River where it is cutting deep into the alluvial fan near the Boma, and by Mkondoa River where it enters the plain at Kilosa (Fig. 3.4) and has eroded in the inner part of the low-angle alluvial fan. A long term extent controls the climate in both hemispheres, and where cycles of 23, 41, and 100 kyr dominate (Hays et al. 1976, Martinson et al. 1987).

4.2 Environmental changes in East Africa

The first glaciation on Mt. Kenya is dated to ca. 1.8 mill years by Mahaney et al. (1997), i.e. at the very beginning of the Quaternary period, while the oldest glacial deposits found on the slopes of Mt. Kilimanjaro are ca. 0.5 mill. years old (Downie & Wilkinson 1972). The following discussion will be focused on the last 150 kyr only.

The present-day climate in equatorial eastern Africa is considered one of the most complex on the African continent (Nicholson 1996), but the same author concludes that the East African climatic variations are linked to sea surface temperatures in the Indian Ocean (cf. Fig. 4.1 A & B), and occasionally to the SST in the South Atlantic. The long-term rainfall fluctuations are generally linked to the global variations mentioned in section 4.1.

The longest climatic record close to Tanzania is presented in Fig. 4.1, curves B & C, from the Madagascar Strait. The SST variations show a 100 kyr long period with temperatures 1 - 3 °C lower than present, and the TST-curve (C) based on vegetation changes (pollen-analyses) in the Limpopo River catchment show temperatures 1 - 2 °C lower in the same period. Another typical feature of the curves in Fig. 4.1 are the numerous and rapid oscillations of temperature.

The temperatures on land during the last 130 kyr have been lower than today for more than 70 % of the time (curve C, Fig. 4.1), and the precipitation has been considerably less than at present (curve D). This is the general world wide trend, and it will certainly also apply to the climate in the Morogoro District.

More detailed data on palaeo-climate from East Africa are only available for the last 40 - 30 kyr. They are mainly based on vegetation changes (pollen analyses). This method was recommended by Flenly (1985) for the East African mountains, and since then a large number of investigations have been carried out. Two of these studies are presented in Fig. 4.2.

Calculated palaeo-temperatures and precipitation show the same trends as in curves C & D in Fig. 4.1, but in much more detail. Of the last 40 kyr, only 8 000 years have been warmer than at today (up to 2 °C), and during the Last Glacial Maximum (LGM) the temperatures were ca. 5 °C lower than at present. The precipitation has been higher than today for only 6.5 % of the last 40 kyr, but approximately 30 % lower during LGM at the Kashiru site.

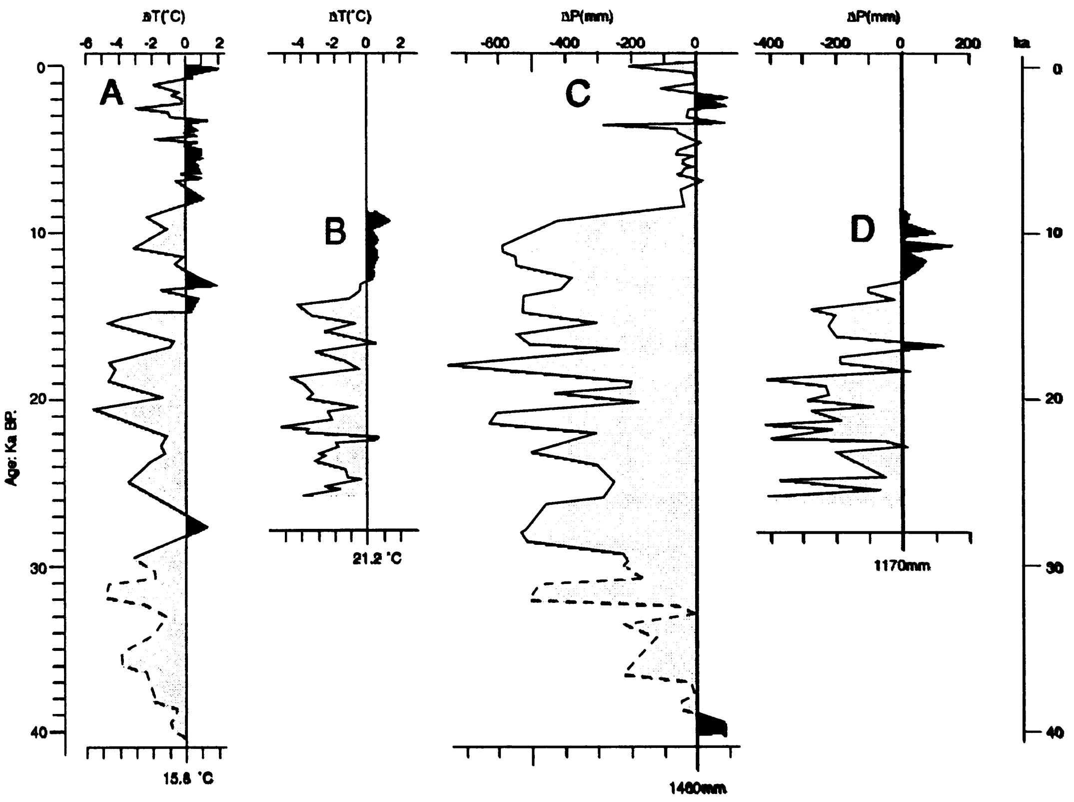

Fig. 4.2 *Palaeo-temperatures and precipitation estimates inferred from pollen analyses in an alpine mire near Kashiru, Burundi, and from southern Lake Tanganyika (core MPU-12).*
Curve **A** & **C**, Bonnefille et al. (1990), Curve **B** & **D**, Vincens et al. (1993).
The temperature curves show gray as colder and black as warmer than present. The precipitation curves show gray as drier and black as moister than present. All the curves have been adjusted to a linear time-scale, based on radio-carbon dates in the two publications.

The deviation from present-day temperatures is given as ΔT, and the precipitation deviation as ΔP, at the top of each curve. Present-day yearly mean of temperatures and precipitation is given at the bottom of each curve.

The rain forests (both montane and low-land) were almost completely destroyed in the equatorial region during LGM (Maley 1996). The lowland forests (below 2000 m) and different woodland types were most likely changed to treeless semi-arid bushlands and semi-dessert grasslands, with some montane species (Jolly et al. 1997).

An effect of the dry and cool climates and reduced vegetation cover, as well as higher wind speeds, was increased aeolian activity (Brook et al. 1996) with considerable transport of dust (loess) over large areas, also in the Morogoro region. The period of most intense sand-dune formation and dust transport occurred during Last Glacial Maximum (Sarnthein 1978).

Other effects of the glacial / interglacial climates are lake level fluctuations. Lake Naivasha has the longest record with five lake-level highstands between about 400 and 20 kyr, and a well

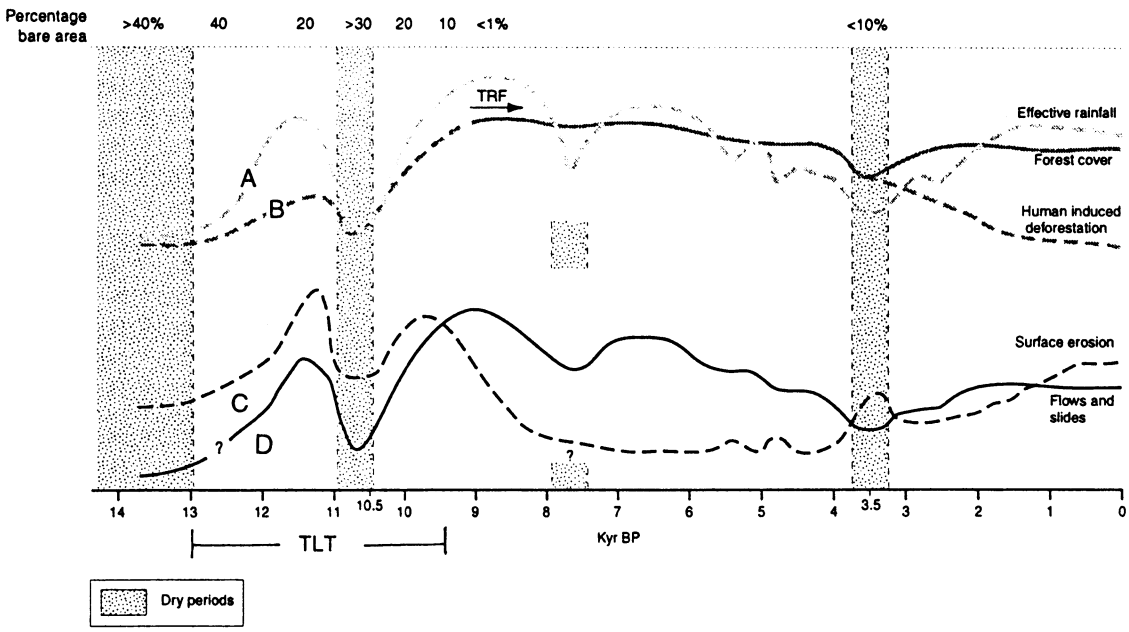

Fig. 4.3 *Interrelations between climate, vegetation and slope processes during the last 14 kyr.*
Slightly modified from Thomas & Thorp (1995).
TRF: The establishment of regional Tropical Rain Forests from local refugias.
TLT: The Last Termination (approximate time-span).

In 1964 Lake Tanganyika had its highest level since the 1870s (Grove 1996), due to increased rainfalls in Tanzania in the early sixties and a strong ENSO (Nicholson 1996). The Morogoro District has most likely experienced the same climatic and hydrologic variations during the Quaternary period, as described in the previous sections.

4.3 Implications for landscape development and soil formation

Except for the last 2 - 3 kyr of human influence, the landscape and soils in the study area have been controlled by climate and its effect on vegetation and geological processes. This has been summarized in Fig. 4.3.

Before 13 - 12 kyr the area had a sparse vegetation cover due to low precipitation (ca.500 mm yr^{-1} = 30 % reduction compared to present-day conditions, see Fig. 4.2). With a sudden increase in rainfall on steep slopes with little vegetation cover around 12 kyr BP, the erosion and land-sliding must have been intense, see curve C & D on Fig. 4.3 (cf. Temple & Rapp 1972). The short dry period between 11 - 10.5 kyr BP has probably been less important in our study area than Fig. 4.3 depicts. The general effect of increased rainfall between 12.5 to 9 kyr BP, before the forest cover was fully established, is very important for understanding soil formation in the area. Large amounts of mixed pre-weathered soil and slightly weathered saprolite were transported downslope. This will be discussed more explicit in Chapter 7.

during Holocene. The higher value may be relevant for the upper humid parts of the Uluguru Mts.

5.2 Distribution and properties of saprolite in the study area

A survey of saprolite distribution, properties and formation in Tanzania has been done by Mutakyahwa & Valeton (1995). In their survey weathering profiles in the Iringa - Njombe area, and Kibuko - Chanzema area in the Uluguru Mts. were studied.

Deeply weathered rocks and the transition from saprolite to solid rock can be observed many places in the Morogoro District. In our study area, saprolites have been observed in some of the soil profiles described by Kaaya (1997) and during general mapping. In addition, a number of deep wells drilled thorough soil and saprolite into the unweathered rocks for ground-water supply, have been recorded from the district (DHW-Consulting Engineers 1980).

In many of the profiles there seems to be a slight enrichment of quartz and sometimes potassium feldspar. Other primary minerals have been more or less transformed or dissolved. Normally the original rock structures can be observed (see Fig. 5.1) and the saprolites are moderately hard (can be augered with some difficulty). 'Core-stones' are not observed, but small stones and gravels are common. The saprolite from Mgeta (Fig. 1.1) is granular loamy sand to sand.

Saprolite thickness is reported to be 8 - 10 m in the Iringa - Njombe area and up to at least 30 m in the Uluguru Mts. (Mutakyahwa & Valeton 1995). Thickness of weathered rock in our study area, mainly in the micaceous hornblende gneisses (units *Xex* & *Xeh* on Fig. 2.1) are reported to be ca. 50 m at Wami, > 55 at Masimbu Raiway St., > 35 m at Kilosa, > 30 m at Mkata Railway St. Near Morogoro (at Kihonda and Tungi) the thickness of weathered rock varies between 0 - 15 m, and up to 70 m within distances of a few hundred meters (all data from DHW-Consulting Engineers (1980). East of Lubungo (Fig. 2.1), 27 m of weathered rock was registered in a new borehole. It is not possible to postulate an 'average' depth of weathering (the position of the weathering front), in the variable bedrocks of Morogoro District (and probably not anywhere else).

Some of the saprolites have been sampled for mineralogical analyses, and they show local variations related to differences in primary mineralogical composition. Sample A on Fig. 5.2 is a clay-separate from the upper part of a saprolite at the top of Mindu Mts. The others are 'bulk' mineralogies. Quartz and feldspars are dominant in the 'bulk' samples, but other primary minerals as amphiboles and mica are present in some of the saprolites. In the clay fraction kaolinite is common or dominant, but vermiculite and smectite are often present (Fig. 5.2 curves E & F).

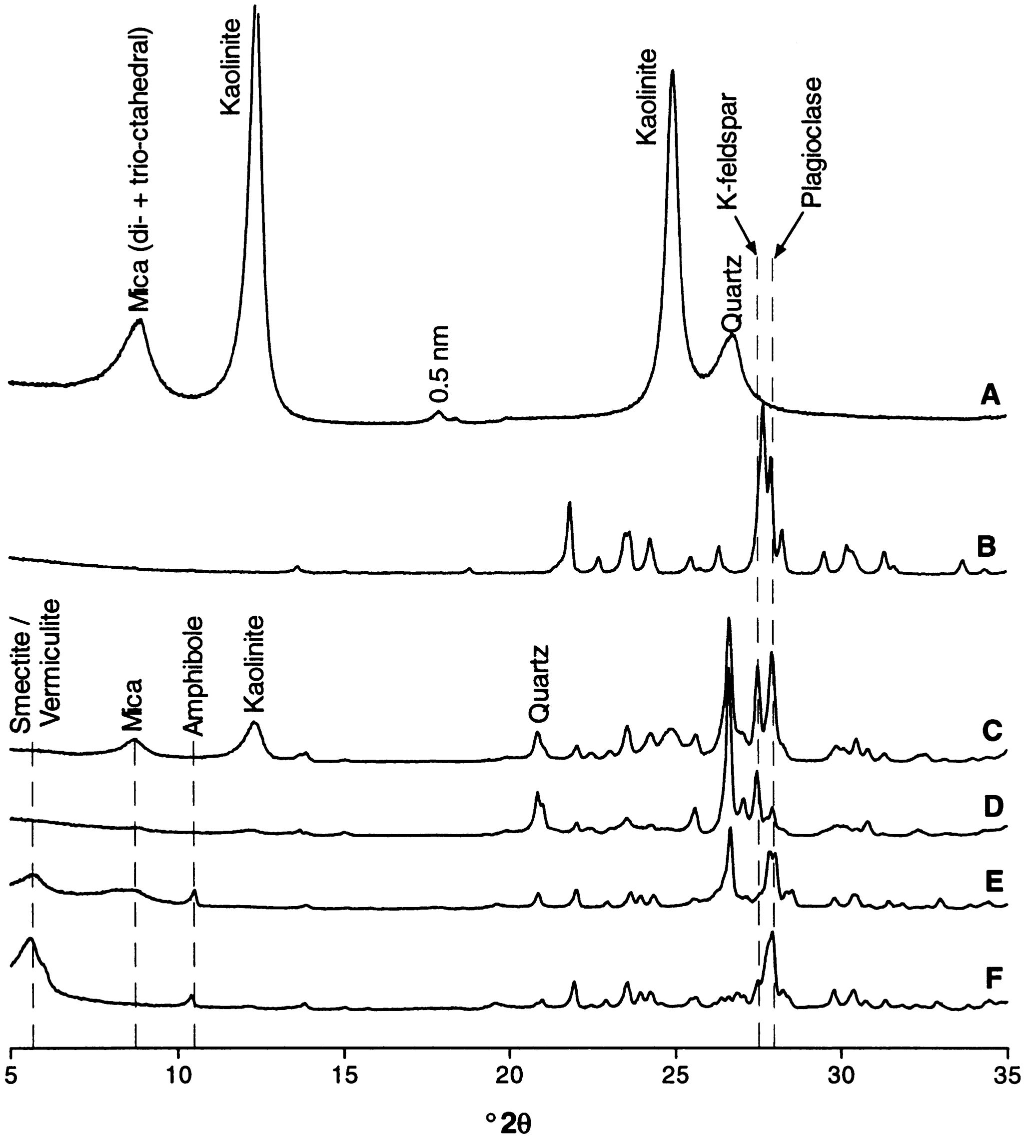

Fig. 5.2 *X-ray diffraction curves of saprolite from the northern part of Morogoro District.*
A = *weathered from mica- migmatite gneiss (40 - 80 cm deep) at the top of Mindu mountains.*
B = *weathered from meta-anorthosite (labradorite) from the Mgeta area.*
C = *weathered from biotite gneiss from the Magadu ridge (Profile MAG 5, Kaaya, 1997).*
D = *weathered from biotite-hornblende gneiss in Lubungo Village, West of Mindu mountains.*
E = *weathered from biotite-hornblende gneiss in a ravine between Lubungo Village and Mkata Ranch.*
F = *weathered from biotite-hornblende gneiss in a gravel pit near Mkata Ranch (Fig. 5.1).*
Curve **A** *is a clay fraction (< 2μm) while* **B - F** *are bulk samples.*

years ago. There was a world wide dry-spell during Late Miocene, and the previous period with moist climates occurred in the Middle and Early Miocene.

It is therefore generally assumed that the youngest of the most intense saprolite production-phases was in the Middle Tertiary, some 40 - 20 mill. years ago, in accordance with the conclusions of Mutakyahwa & Valeton (1995, Tab. 2). This is the assumed age of the youngest of the regional top of Mindu Mts., (Fig. 5.2). Sampson (1956) suggests that these clay soils may be very old, and this view is supported by Mutakyahwa & Valeton (1995, p.28). However, an alternative explanation could be that the permanently high humidity in vegetation and soils on both mountains, can cause intense weathering and saprolite formation over a relatively short time-span. The protection by forest on the high surfaces of Uluguru Mts. has reduced the denudation, but enhanced saprolite formation, and the 'forest-cap clays' and underlying saprolite can have been formed in 1 - 2 mill. years. However, during glacial climates the forest limit was depressed far below the areas with 'forest-cap clays', but high humidity may still have been prevalent.

The saprolite on the forested and grass-covered upper slopes of Mindu Mts. is conspicuously thick and permeable compared to the development in the Miombo - Combretum woodland lower down on the mountain slope. This can be explained by a former dense forest cover over the whole mountain top during Holocene (before human impact), and by strong erosion on the very steep slopes.

6.2 Alluvial fans

«The alluvial sands, silts and muds are probably the most extensive Neogene deposits in the area» (Sampson & Wright 1964). These authors used the term *alluvial* more or less synonymous with *fluvial* sediments. In this paper the two sediment types are given different definitions and age of formation, see below and section 6.5.

There are some geomorphological evidences for alluvial fans (as defined by Lecce 1990) on the northern slopes of the Uluguru mountains, particularly where Morogoro River reaches the plain (in Mororgoro township), and where other large perennial streams or rivers from the mountain enter the plains.

Investigations in the Kihonda and Tungi areas near the Morogoro River (Fig. 2.1) show that 2 - 4 m of sandy loam regularly overlay gravels, sometimes with calcretes (DHW-Consulting Engineers 1980). Gravel layers on top of calcretes (and sometimes directly on saprolite) were also observed by Sentozi (1997). The coarser material in the sub-soil can represent alluvial sediments from the last 'termination' (see Fig. 4.3) deposited on the outer part of the 'Morogoro River Alluvial Fan'. If this assumption is correct, the overlying soils must have been deposited at the end of the last termination, some 9 - 10 kyr before present. Except for these data, there are no good alluvial sections available. The possibility that 'alluvial - fluvial' structures, like layering and textural differences may be destroyed during post-depositional weathering, should also be considered. On the north-western margin of the Mgeta - Wami Plain several large alluvial fans have developed along the footslopes of the 'Tanganyika Scarp' where perennial rivers drain the Rubeho, Kaguru and Nguru Mountains (see Fig. 1.1). One bore-hole from Kimamba show

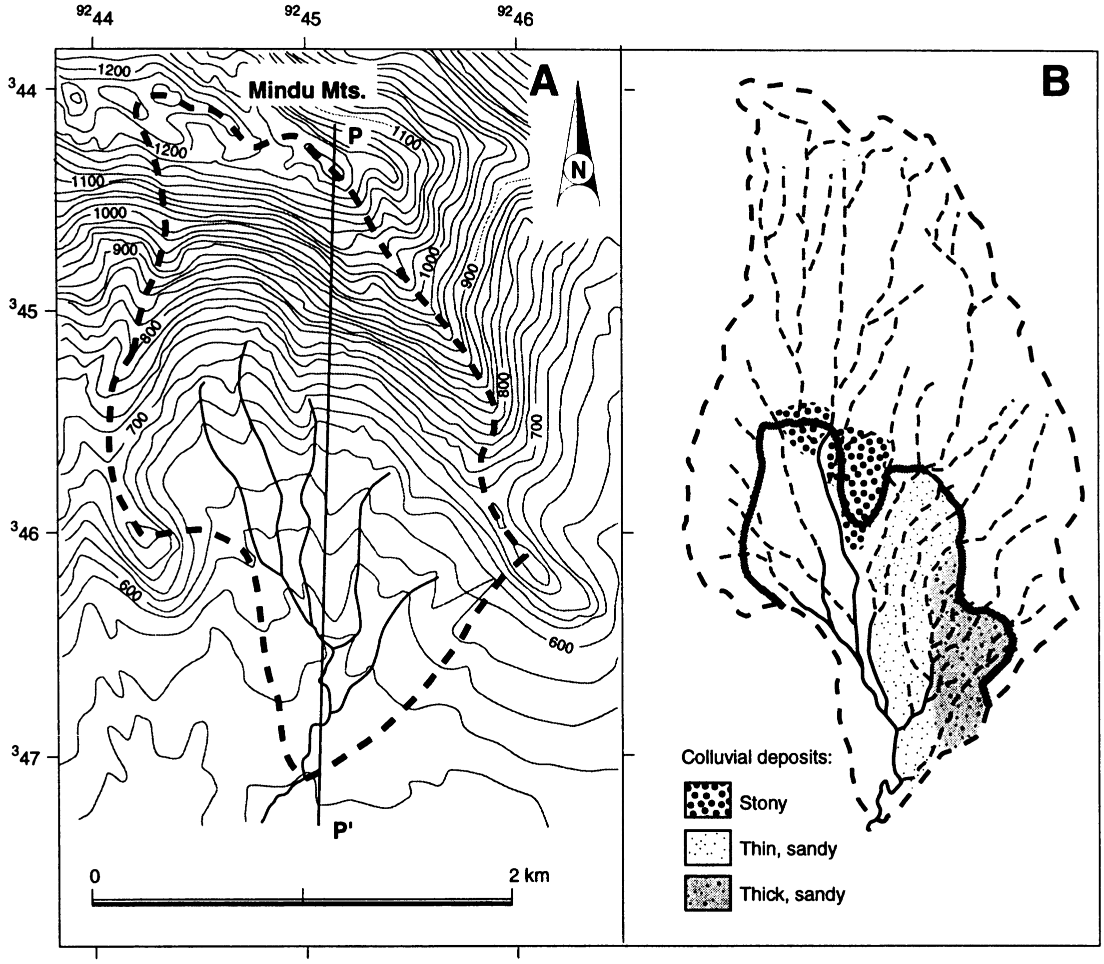

Fig. 6.1 The Mindu mountain catchment

A. *Topographic map of the south-eastern part of the Mindu Mountains, with outline of a small catchment area. Terrain profile P - P'is shown on Fig. 6.2.* The map is redrawn and enlarged from map sheet 183/3, Morogoro.

B. *Airphoto interpretation of drainage channels within the catchment outlined on Fig. 6.1 A, and with the distribution of different types and thicknesses of colluvium.* Air-photo No. 100, series 1695, July 1964. The main stream channels are drawn with full line. All channels are seasonal. The slope change at the foot of the mountain is marked with a broad line. This is also the upper boundary of sandy colluvium.

The areas with thick sandy deposits are eroded and dissected by a few large gullies. Some of these sand deposits are presently being exploited for building materials. Several vertical sections, 2 - 15 m deep, have been investigated and a full discussion will be presented in a separate paper by R. Sørensen, S. Murray and M. Kilasara.

The location and main features of the key section are presented in Figs. 6.2 and 6.3. The following main units can be found: In the upper meter of the loose, medium sand a weakly developed soil is developed. It is classified as Ustoxic Quartzipsamments by Møberg et al. (1982). The light reddish brown sands (5 YR 6/3 moist) has a thickness of 2 - 3 m (Fig. 6.2). In the areas with thinner colluvial sand, only this upper light coloured unit has been observed.

The light coloured upper unit was most likely deposited during the last glacial maximum (LGM), mainly as slope-wash, but a contribution from wind-blown sand can not be excluded. The lower unit (between ca. 5 m to 11 m depth) is generally coarser and with some indistinct gravel layers. These sediments must have been transported by running water (slope wash) from higher grounds within the catchment.

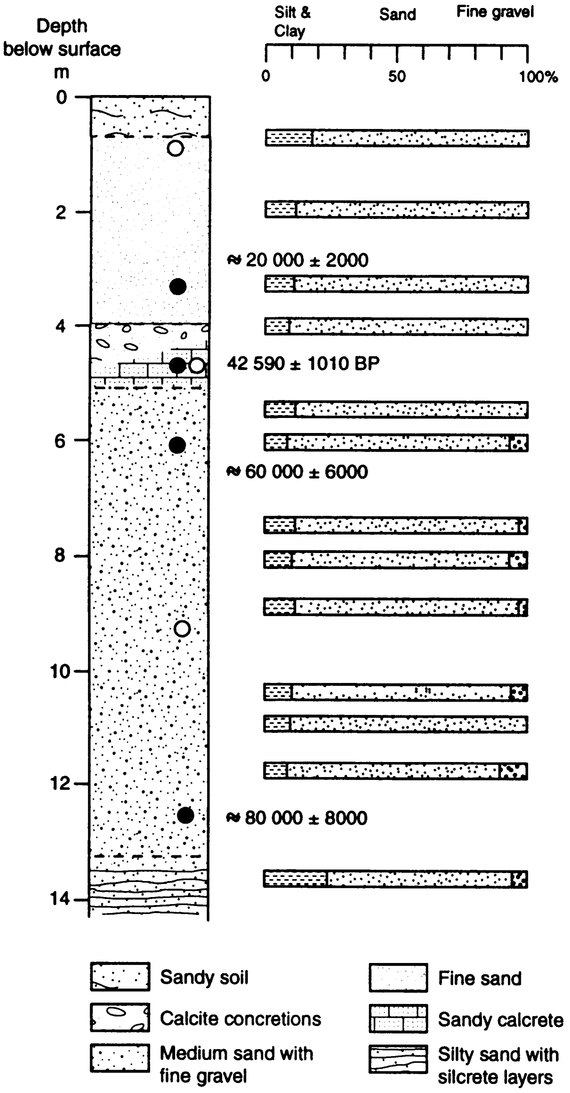

Fig. 6.3 *Lithology, grainsize distribution, and datings from the Mindu apron section.*
Filled circles: TL / OSL- and ^{14}C-dated samples
Open circles: Samples sent for dating

Thermoluminescence (TL/OSL) dating has been done on three samples from this section, and two more are being analysed. Preliminary results are presented in Fig. 6.3. The radio-carbon dated calcrete fits well in between the TL/OSL dated layers, and it seems that the whole colluvial apron has been formed during the last glacial period, between ca. 90 kyr and the last termination (ca. 10 kyr BP). Mineralogical analyses (XRD) of the fine sand, the fine silt and clay fractions, have been done on all the units. Thin-section microscopical analyses of undisturbed samples have been done on three of the units. Both methods show that there is remarkably little weathering in the fine sand fraction, with 'fresh' plagioclase and potassium feldspars, and some mica. The sand

Although the scales of the two air photos are not exactly the same, comparison between them can still be made. There is a change in the ravine development between 1955 and 1964. It seems that the expansion at the head of the ravine has been approximately 2.5 m pr year. During the last ten years the ravine has continued to expand and deepen. Since 1994 extensive conservation measures have been applied, and the accelerated erosion has been minimized.

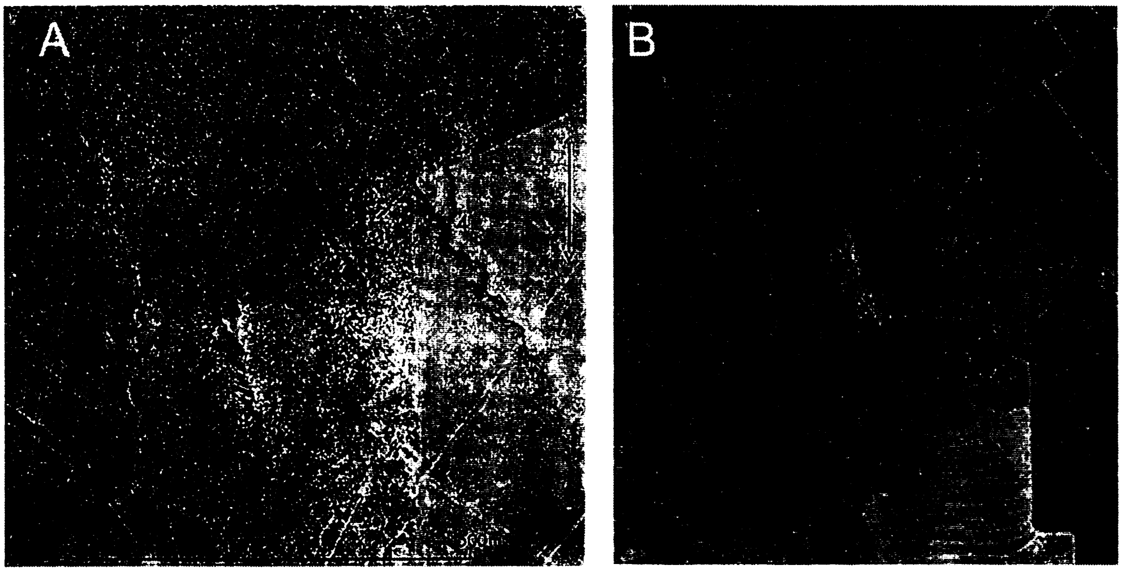

Fig. 6.4 Enlarged sections of air-photos from 1955 and 1964, covering the area where the University Campus is located today. The location and development of the large ravines are shown.
Photo A; from Rapp (1972). Photo B; No. 99, Series 1695, July 1964.

The maximum depth of the ravine is roughly measured to 11 m. The section is divided into four lithological units (Fig. 6.5). Soil samples for chemical, mineralogical and grain-size analysis were taken from each of the units at the following depths: 1 m, 3.5 m, 7 m and 9.5 m. A sample of sorted sand from the bottom of the ravine was taken for heavy mineral analyses.

The upper unit lacks an A horizon due to severe surface erosion, and it consists of a 2 - 3 m thick, clayey B-horizon with the lowest cation exchange capacity in the section, i.e. CEC of 8.6 cmol(+)kg^{-1} (Fig. 6.6). The next unit, between 3 to 6 m depth is called a BC- horizon, with considerably less clay and a high CEC. The two upper units contain mainly kaolinite with only traces of illite in the clay fraction (Fig. 6.7), with low plagioclase and high ilmenite contents in the sand fraction (Table 6.3).

The third unit (from 6.5 - ca. 8 m depth) is composed of weathered soil material and rock fragments ranging from gravels to large boulders with diameter of up to about 1 m. This was designated as a 'C'- horizon, where the soil matrix consists of more than 50 % sand and less than 20 % clay.

Table 6.3 Mineralogical composition of clay and sand fractions from SUA ravine section (XRD analysis).

Sample No.	Depth	CLAY			SAND			
		Kaolinite	Illite	Other 2:1 Minerals	Quartz	K-Feldspars	Plagioclase	Ilmenite
	(m)	(%)			(%)			
1/97	1.0	86	14	0	47	30	12	11
2/97	3.5	81	19	0	47	34	9	10
3/97	7.0	42	29	29	23	25	44	8
4/97	9.5	77	9	14	41	26	24	9

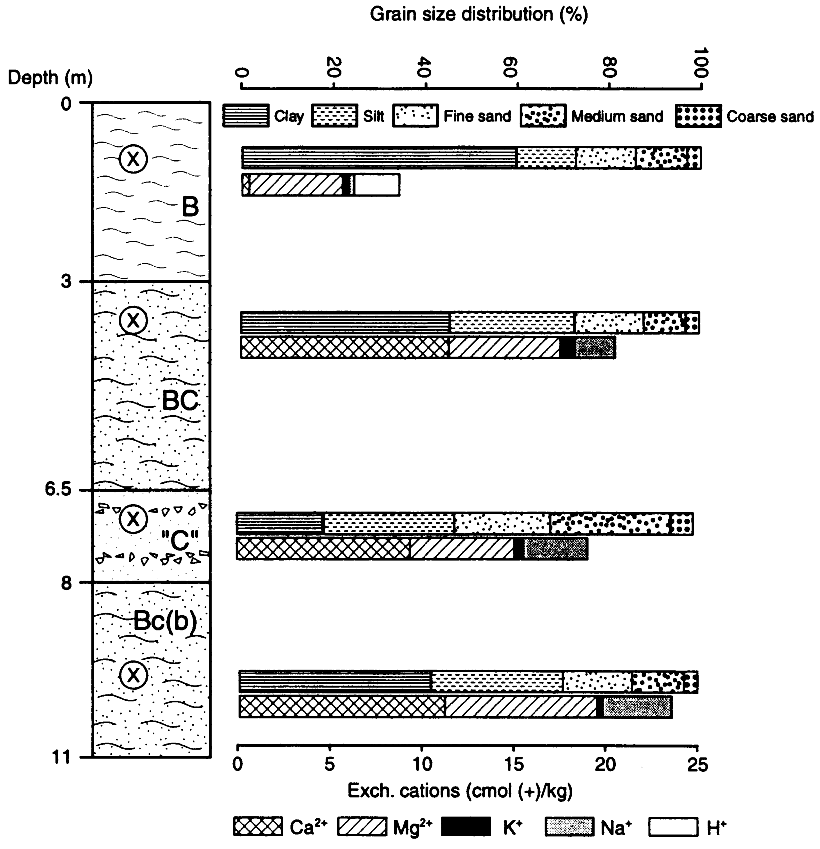

Fig. 6.6 Grain size distribution and cation exchange properties of the SUA ravine section.

Upper bar: texture legend. Lower bar: CEC legend.

The unit 'C' is a typical mud flow, whereas the upper unit (B) must have been deposited from a more 'shallow' land-slides, and/or by long-term sheet erosion of top-soil from the small catchment area, since it contains only highly weathered minerals. Also the BC-layer contains some rock fragments distributed in irregular layers, which represent a small contribution from up-slope saprolite. However, the mineralogy (Fig. 6.7) indicates that the bulk of this unit must have been eroded from highly weathered top-soils.

compared to the ratio in fresh rocks. The remaining plagioclase (relatively enriched in sodium) will be registered by the same reflection in the XRD-analysis. Determination of the An-content in the sand-sized plagioclase grains was not done. Scanning electron microscopy would probably have solved the problem of determining the actual Ca-reserve in these soils.

6.3.3 Formation and age of the colluvial fans / aprons - A summary

In the Mindu section four levels are dated, and the preliminary results indicate that the sediments were deposited through the last cool - dry 'glacial' period. If this occurred in episodes or by slow accretion can not be decided, but the main process is thought to be slope-wash, possibly with some additional deposition of wind-blown dust in the upper unit.

In the SUA ravine section the deposition is assumed to have taken place mainly during the 'Last termination' (see Fig. 4.3). However, the material in this section can not be dated with presently available methods, and the age-estimate is therefore uncertain. At least two of the units in the section (BC & 'C') seem to have been deposited as mud-flows, and the high clay contents would favour such processes. However, sheet erosion from the sediment source areas must also have played a part in the formation of this clayey colluvium.

In both the Mindu and the SUA ravine sections some indications of palaeosol formation can be seen. A period with more humid climate has been reported from several places in tropical Africa between 30 - 40 kyr BP (see Fig. 4.2, curve C), and this could be the period of when the Mindu calcrete and the $B_{c\,(b)}$-horizon in the SUA ravine section was formed. Our own dates can also be interpreted in this direction. This will be discussed further in section 6.6.2.

The formation of ravines in both types of colluvial aprons are assumed to have occurred during Holocene. The data from these two sections will be used in the 'soil formation model' described in section 7.2.

6.4 The red and brown clayey soils (Nxf)

Most of these well - to moderately well drained soils have developed from parent materials rich in biotite, amphibole or other iron-rich minerals. Their age have been given as 'Neogene' by Sampson & Wright (1964) who called them 'Deep red earth', but they were most likely formed during Pleistocene, since many of them are definitely younger than 100 kyr, and some are even younger than 10 kyr BP. Thickness of these soils (over saprolite / weathered bedrock and sometimes over calcrete) vary considerably, from very shallow to several meters.

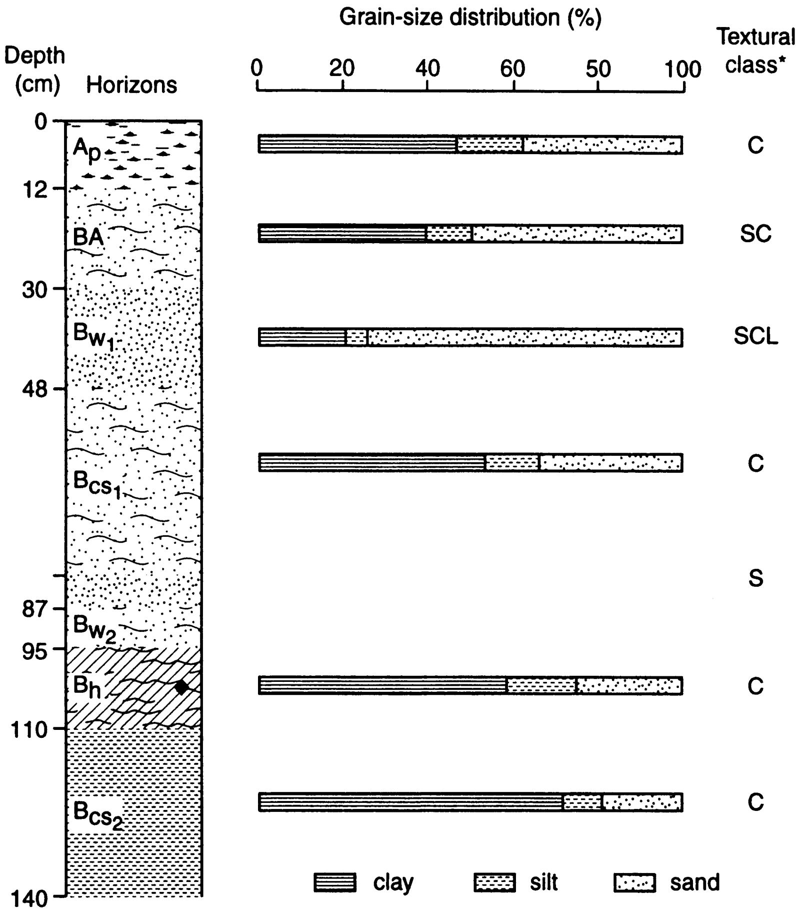

Fig. 6.8 Grain-size distribution and ^{14}C-dating in a soil profile on the Ngerengere River Plain. (MAG 1, Kaaya, 1997). ◆ Position of ^{14}C-dating: T-12486A Age: 1420 - 1615 AD.

The last type has been radiocarbon dated, and give a calibrated age between 2 325 and 2040 BC (ca. 4000 yrs. old). *Pilata ovata* lives in swamps and temporary pools, whereas *Cleopatra ferruginea* lives in a variety of water bodies (D. Brown, personal communication 1995). According to Maley (1997) it was relatively wet in East Africa earlier than 3.8 kyr BP, and our findings support that. However, a single date is difficult to interpret, but it gives an indication of sedimentation rates for this part of the Mkata Plain. Assuming that ca. one meter has been eroded at this location, Fig. 6.9, then the average sedimentation rate will be approximately 0.7 mm yr^{-1}. We find this a reasonable figure for such fine-grained soils defined as 'over-bank' sediments on a flood-plain.

The underlying sandy clay contains calcite concretions that have been dated to ca. 27.6 kyr BP, and in a very similar profile near Mikumi Game Park headquarters (Fig. 1.1), calcite concretions below dark cracking clays have been dated to ca. 26.3 kyr BP. The formation of pedogenic calcrete will be discussed in section 6.6.1, but the two dates presented above indicate that the more sandy and gravelly clay below the vertisols on Mkata plain were deposited sometimes during the 'glacial′ period.

6.6 Calcretes (superficial limestone, *Nzc*)

The terminology used in this paper is mainly after Netterberg (1967) and Goudie (1983). Some of the studied types are of pedogenic origin, but some may have been formed as a combination of pedogenic and ground-water calcretes. Pedogenic calcretes are normally formed in semi-arid climates with rainfalls between 400 and 600 mm yr^{-1}, and their age of formation span the whole Quaternary (Milnes 1992, Thomas 1994). However, mature calcretes have developed in only a few thousand years in northern Tanzania (Hay & Reeder 1978). Botha et al. (1994) report from Kwa-Zulu Natal, South Africa, that «Authigenic, septarian carbonate nodules developed within the profile over a period of about 1000 years». The source of calcium in the secondary calcite may be local carbonates, but many authors report that Ca is brought in with wind-blown dust (Gile et al. 1966, Blümel 1982), or by lateral soil water movements (Ruellan 1971; cited in Milnes 1992).

According to Gile et al. (1966) the first phase of carbonate accumulation can be seen as thin coatings on mineral grains, preferably on the lower side of sand and pebbles due to evaporation of soil moisture. During the second stage some inter-pebble fillings and a few nodules (concretions) are formed. Stage three is characterized by many nodules and some inter-nodular fillings. An advanced development of stage three is called 'honey-comb' calcrete. The inter-nodular fillings form a carbonate skeleton with irregular hollows, often filled with soil. As calcite progressively precipitates the material becomes plugged and massive laminar calcrete forms as the last stage. All these forms are observed in calcrete profiles in the study area, but rarely all stages in the same profile. A generalized 'complete' calcrete profile is presented in Fig. 6.10.

6.6.1 *Distribution and occurrence in the field*

Superficial limestones have been reported as small occurrences on the southeastern footslopes of, and near Kimbambila west of Lugalla Hills; south-west of the Sangasanga ridge[1] (Sampson & Wright 1964), and in a detailed study of calcrete distribution and properties was carried out in the Kihonda area between Morogoro town and Ngerengere River (Sentozi 1997).

Calcretes in the study area occur in the following forms:

1. As concretions in clay soils. This is observed in sections in the steep eroded banks of Mkata River in Mikumi Game Park, in tributaries to Mkata River, near Mkata Ranch (Fig. 6.9), and near Mbesegera stream (in profile LUB 2, Kaaya 1997).

---

[1] Not the Sangasanga on Fig. 2.1. Another location east of Lugalla Hill.

There is no preferred orientation of calcite coatings ('phase 1', Gile et al. 1966) on these grains, and they may have been through a short transport phase, between local erosion and sedimentation.

Stage two in the sequence described by Gile et al. (1966) is the formation of nodules, which were observed several places in our study area.

Three samples have been examined in thin-sections, and they all show concentric growth lines (Fig. 6.11-C). The calcite concretions contains some detrital material (angular grains of quartz, feldspars and amphibole are most common) in a micritic calcite groundmass. A carbonate nodule from the lower horizon in the Mkata stream-bank profile (Fig.6.9) contains some voids lined with sparry calcite, see Fig. 6.11-C. This indicates at least two phases of crystallization. Both samples of calcite concretions contain some magnesium (Table 6.4), but XRD analyses show sharp calcite reflections at 0.303 nm, thus the mineral type must be a low Mg-calcite (Fig. 6.12, curve B).

The concretionary calcretes from Mikumi and Mkata were formed before the last glacial maximum (26.3 - 27.6 kyr BP). $\delta^{18}O$ values considerably lower than recent values, indicate a cooler and/or a more continental climate (Table 6.5). The calcite concretions from the Mkata tributary stream-bank (Fig. 6.9) were formed in a special environment. The small seasonal stream must have some sub-surface drainage since the stream channel disappears several places. The enrichment of calcium and formation of calcite concretions must have been caused by lateral sub-surface flow of water as suggested by Ruellan (1971).

The honey-comb and massive/laminar calcretes are apparently the most common forms in the Morogoro District (Sentozi 1997). With one exception, all these calcretes consist mainly of calcite, mixed with ca. 5 % detrital quartz, feldspars and some amphibole. The lower part of the Mkata Ranch calcrete contain ca. 15 % dolomite (by XRD-analysis, see Fig. 6.12, curve C). The soluble fraction of this calcrete contains 5.3 % Mg. The massive calcrete in soil profile LUB 1 (Kaaya 1997) and the Kihonda calcrete (Sentozi 1997) contain almost pure calcite with ca. 99 mol % calcium in the soluble fraction (Table 6.4).

The LUB 1 calcrete contains some detrital minerals, and amphibole is identified both by XRD and in thin-section analyses. Fig. 6.11-A from profile LUB 1, shows a micritic matrix with sparry calcite linings in a void. Some of the voids might be former root channels. The Kihonda calcrete shows sparry calcite crystallization around grains of quartz and feldspar, in a micritic matrix (Fig. 6 11 D). Such crystallization has been observed in most of the analysed calcretes, and it may represent remnants of the first phase of calcrete formation according to Gile et al. (1966).

The microscopic analyses show that most of these calcretes were formed by more than one phase of crystallization. Their ^{14}C-dates are close to the limit of the dating method (Table 6.5), and they

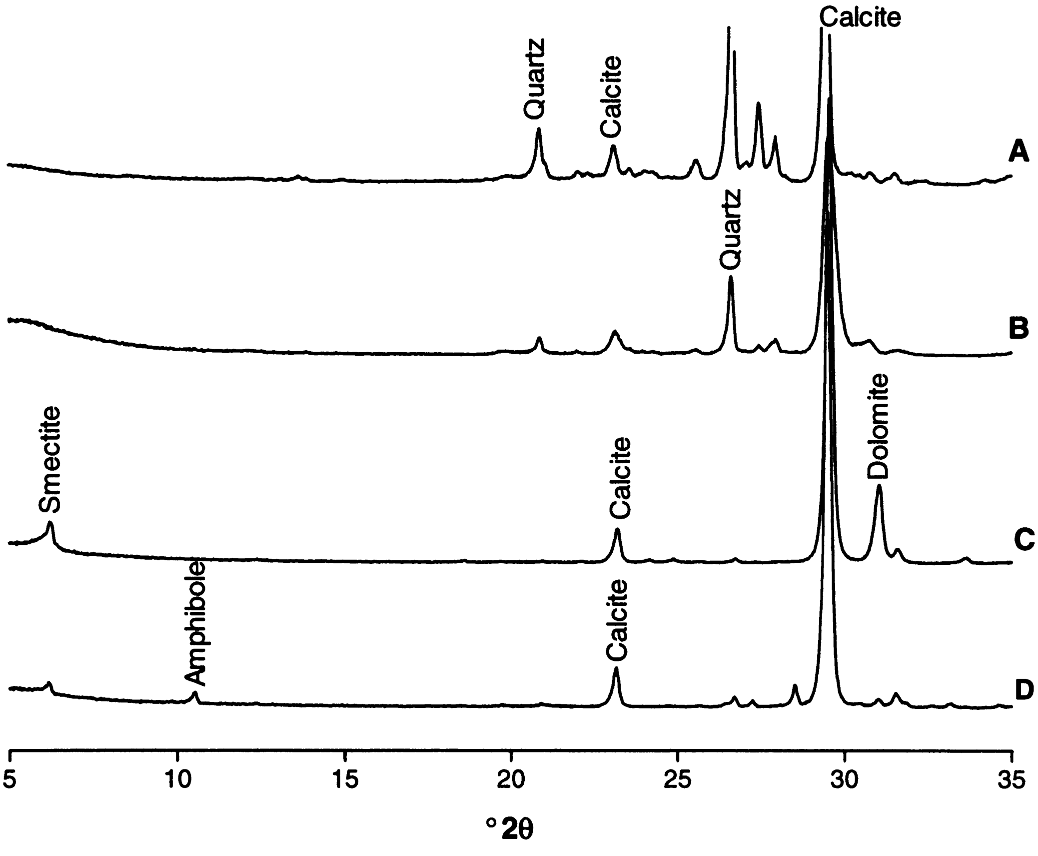

Fig. 6.12 X-ray diffractograms showing mineralogy of some calcretes from the study area.

A: Concretionary calcrete from the Mindu colluvial apron (depth ca. 4.5 m).

B: Concretionary calcrete from stream bank of one of the Mkata River tributaries.

C: Honey-comb calcrete from the Mkata Ranch gravel pit.

D: Massive platy calcrete from the Mkata plain (1 m depth in profile LUB 1, Kaaya 1997)

Table 6.4 Chemical (mol-% of the soluble fraction) and mineralogical composition of some calcretes from part of the northern Morogoro District.

Location name	*Type of material*	*Soluble fraction of the calcretes*			*Mineral composition by X-ray diffraction*	
		Mol-% Ca^{2+}	*Mol-% Mg^{2+}*	*Mol-% K^{+}*	*Calcite § (%)*	*Other minerals (%)*
Mkata R. tributary	Ca-concretion	93.9	6.0	0.1	ca. 95	ca. 5
Mkata Ranch	Calcrete *	94.7	5.3	+	ca. 80	ca. 20
LUB 1	Calcrete **	99.0	0.9	0.1	ca. 95	ca. 5
Mikumi River	Ca-concretion	96.8	3.2	+	ca. 95	ca. 5
Kihonda	Calcrete **	99.4	0.6	+	ca. 98	ca. 2
Mindu section	Calcrete	98.7	0.8	0.5	ca. 35	ca. 65

* Upper part of slightly weathered honey-comb calcrete.

** Platy development

§ Calcite (low magnesian) is identified by major reflection at 0.303 nm have $\delta^{18}O$ values between - 0.2 to - 1.3 ‰, and the $\delta^{13}C$ values vary between 1.5 to 2 ‰ (Ricketts & Johnson 1996). To day the $\delta^{18}O$ values in the precipitation decrease with approximately 3.5 ‰ from the coast at Dar es Salaam to Ndola in northern Zambia (Rozanski et al. 1996). The generally low $\delta^{18}O$ values presented in Table 6.5 indicate that less oceanic moisture reached the Morogoro District during the formation of the calcretes, or the climate was cooler. Both statements support the conclusion that these calcretes were formed during a 'glacial' climate.

The processes of calcrete formation are complex, and several sources of calcium are possible within our study area. Data on the chemical composition of present day precipitation is scarce, but some data has been collected from Lake Malawi in the southern part of Tanzania (Bootsma et al.1996). Contributions to the ionic species in rain-water in this continental part of Africa are mainly from aerosols produced by biomass burning and from soil deflation. Normally Ca would amount to approximately 30 % of the total cations. Some very high Ca values were reported at the beginning of the rains, when there was much dust in the air (Bootsma et al.1996). The situation in the Morogoro area must be fairly similar, but possibly with slightly higher contents of Ca and higher contents of Mg since this area is closer to the coast.

During the 'glacial' climates and even during dry periods of the Holocene, more wind-blown materials were deposited also over our study area (Sarnthein 1978, Talbot 1981). Many authors claim that Ca transported as an aerosol is an important source for Ca needed for calcrete formation (cf. Gile et al. 1966, Blümel 1982, and Milnes 1994). We have no conclusive evidence for deposition of wind-blown dust, but there are several indications. We therefore assume that some wind-blown Ca has been deposited and washed down through the soil to form calcrete.

Some of the bedrocks in the area contain plagioclase with high Ca contents. Calcium released during weathering of plagioclase can therefore contribute to the formation of soil carbonates. Some calcite (occasionally dolomite) do occur in the hornblende-biotite gneisses, and would be an obvious source for secondary calcite precipitation. However, some of the calcretes were formed over rocks which are very poor in calcium, and other sources of Ca must be looked for.

Several places it seems that the calcretes have formed in an environment where lateral movement of calcium with soil water has been the main process which has given high enough concentrations of Ca for precipitation. However, the sources of Ca may have been the local bedrock, downward transported Ca from wind-blown dust, or from precipitation. Short-range recrystallization of calcite has also been observed in most of the calcretes.

7. Soil Formation and local toposequence models

> *«Detailed soil-landscape studies in the last 30 - 50 years combined with reasonably accurate methods of dating events indicate that soil development can be much more rapid than originally thought. If these studies tell us anything, they point out that erosion and deposition, not uncommonly of catastrophic proportions, are part of the normal evolution of the earth´s surface».*
>
> *Hall, Daniels & Foss (1982).*

Soils of two toposequences from the northern part of Morogoro District have been described and discussed by Kaaya (1997, 1998), and by Kaaya et al. (1998). The two soil associations described by Moberg et al. (1982) do also give important information to our concept of 'soil formation models'. The sedimentological and mineralogical data from the Mindu and SUA ravine sections presented in this paper, are also important inputs to the models, as well as some of the dates that can establish the time-frame for the events discussed.

The term 'polygenetic soils' introduced by Bryan & Albritton (1943) is redefined and called 'polycyclic soils' referring to soils that have been exposed to two or more weathering cycles during the Quaternary climatic oscillations. It is also assumed that some of these soils have stable surfaces, only slightly eroded or that they have experienced only slight accumulation of younger materials (Fig. 7.2 B). These last requirements may not be realistic on a geological time-scale, but we present them as theoretical possibilities.

Another term; 'two-phase mineralogy' has also been introduced. In the present geographical setting it implies that different proportions of highly weathered mineral components occur together with slightly weathered primary minerals.

And finally the term 'polygenetic mineralogy' is used, mainly for fluvial sediments, where several types of bed-rock, parent materials, and soils occur in the catchment of the river that has transported the sediments. Erosion in the river bed and stream-banks will produce a complex mixture of mineralogies from more or less weathered soils, and from saprolites in different stages of development.

7.1 Soils with mixed mineralogies

The list of weathering index minerals set up by Jackson et al. (1948) is used with some modifications in this paper to demonstrate the 'two-phase mineralogies' of the Mindu and SUA ravine sections (Fig. 7.1). The index mineral list is adapted to the actual minerals found in the study area, and presented in Table 7.1

Table 7.1 List of weathering index minerals in soils from the northern part of Morogoro District. Modified from Jackson et al. (1948).

Index No.	Minerals:	Comments:
1	(Gypsum, halite)	(May occur sub-surface)
2	**Calcite**, *dolomite*, apatite	Secondary in calcretes and some soils
3	**Ca-plagioclase**, *amphiboles*, pyroxene, (olivine)	Derived from granulitic rocks
4	*Biotite,* (chlorite)	As trioctahedral illite
5	**Alkali feldspars, Na-plagioclase**	Derived from migmatite gneisses
6	**Quartz**	Content reduced with reduced grain-size
7	*Muscovite - hydro-muscovite*	As dioctahedral illite
8	Vermiculite	Mainly trioctahedral, 'short-lived' phas
9	**Smectite**, hydroxy interlayer vermiculite	In vertisols and fluvial sediments
10	**Kaolinite,** (allophane)	Mainly in clay and silt fractions - all soils
11	*Gibbsite*	Mainly in 'Uluguru soils'
12	*Hematite, magnetite*, goethite	Occur in most soils
13	*Titanium oxides*, zircon, (corundum)	Mainly derived from granulitic rocks

Bold: Present in considerable amounts.
Roman: Occur as traces only.
Italic: Fairly common or in small amounts.
(allophane): Not observed - most likely not present.

There is still few data about the former 'glacial' period in East Africa, but in the northern hemisphere there are considerable information on the development of climate over the past 300 kyr or more. The deglaciation phase (termination) of the previous and the last glaciation is characterized by very rapid changes in temperature and precipitation. Also during the two 'glacial' periods (dry - cool phases in the tropics) climatic changes have been similar, with some extreme dry and cold periods and shorter intervals where temperatures and precipitation have been close to present day conditions. New data on the older parts of the Quaternary are accumulating also for the tropics, and when the results from the deep boreholes in the East African rift valleys begin to appear, detailed data about palaeoclimates through the Quaternary period are expected.

Fig. 7.2A shows the three investigated sections which altogether contain sedimentological evidence for the last 100 000 years. All three sections are described in this paper, and additional mineralogical information from the 'floodplain section' is given by Kaaya et al. (1998).

On Fig. 7.2B and C the landscape development during the last and previous climatic cycles (including two 'terminations', see Fig.4.3) is modelled for the Ngerengere Valley and the foot-slopes of Uluguru and Mindu mountains. Moreover, it is assumed that slope processes were insignificant and that little weathering took place during the cool - dry phases.

The SUA ravine section represents the clayey colluvium on the northern footslopes of the Uluguru Mts. in our model. Here we suggest that most of the activity occurred during the 'termination' period, i.e. between 13 - 9.5 kyr BP (Fig. 4.3) for the last termination, and during a similar climatic change at the previous termination (Fig. 7.2 B & C). With unvegetated slopes and increased precipitation at the beginning of the termination, slope processes were at a maximum for surface erosion as well as flows and slides. Fig. 7.2 B shows the accumulation of soil material on the foot-slopes of Uluguru Mts., and with corresponding gully/ravine erosion higher up on the slopes during the previous termination. A mixture of highly weathered soils, some saprolite, and even some fresh rock material from the mountain slopes was depositeed as colluvial/alluvial materials on the mountain foot-slopes.

During the following 'interglacial', gully and sheet erosion transported some soil further down-slope to the valley-bottom, i.e. the Ngerengere flood-plain. However, there were no agricultural activities in the region during the previous warm - moist period as the early man who possibly lived in the area 110 - 130 kyr ago was a hunter - gatherer. Both the mountain slopes and the valley were probably covered with dense forest for most of the interglacial time, and erosional processes were most likely less intense than during the Holocene. On the model, Fig. 7.2 B, a part of the middle slope has neither received any accumulation from the outer part of the colluvial fan (apron), nor has it been affected by surface erosion. The old soil from previous climatic cycles is still preserved, and it did develop further during the 'interglacial' period. Soil development must also have taken place on the river plain, when river flow was reduced before the onset of the last 'glacial' period. However, no old soil profile has been observed in the sediments on the Ngerengere River plain, and if it is preserved it will probably be found more than 10 m below the present surface (cf. section 6.5).

Fig. 7.2 C should illustrate the situation just after the last termination. The processes and the sequence of events (see Fig. 4.3) are assumed to have been more or less identical to the previous termination presented on Fig. 7.2 B. New units of colluvium and fluvial sediments have accumulated on the foot-slopes of the mountain and on the river plain. These processes have produced 'mixed soils' with 'two-phase mineralogies' on the footslopes of the Uluguru Mts., and 'polygenetic mineralogies' on the river plain. The relatively 'fresh' mineral material mixed into the foot-slope soils, would account for the overall impression of less weathered soils, and the occurrence of Alfisols, in the US. Soil Taxonomy (ST) or Lixisols in the FAO-Unesco classification (FAO) (Kaaya 1997). Although the soil mineralogy on the river plain is polygenetic with components from old soils, the classification of these soils will normally be Aquents or Fluvents (ST) and Gleysols or Fluvisols (FAO), or other related 'young' soils.

Some of the ravines/gullies have been enlarged and deepened, and some might have been filled in with 'fresh' colluvium, as described by Botha et al. (1994).

The toposequence is underlain by two contrasting types of bedrock. The muscovite-biotite gneisses and the migmatites have a granitic composition and produce light coloured sandy and shallow soils over the dissected hill in the southeastern part of the toposequence. The biotite-hornblende gneisses and granulites dominate in the rest of the toposequence, and they produce red clayey and deeper soils.. Two massive amphibolite bands are observed (marked on Fig. 7.3), but thinner bands and lenses must be present because amphibole minerals are found both in the soils and as residual material in the calcretes.

The landform is part of the 'Mkata surface' which is slightly tilted as a result of Late Tertiary - Quaternary tectonic movements. The landform is modified considerably near the Sangasanga - Kipera ridge where streams have cut small v-shaped valleys more than 20 m into the bedrock. On the middle and lower slopes the streams have cut into the land-surface and formed open valleys between the gently sloping interfluves with relative relief of 5 - 10 m. Also on the plain there are some wide interfluves between depressions, with a relative relief of less than 5 m. Even on the individual interfluves there are small depressions and slight highs (relative relief < 2 m), providing areas where either erosion or accumulation can take place. This is indicated on Fig. 7.3.

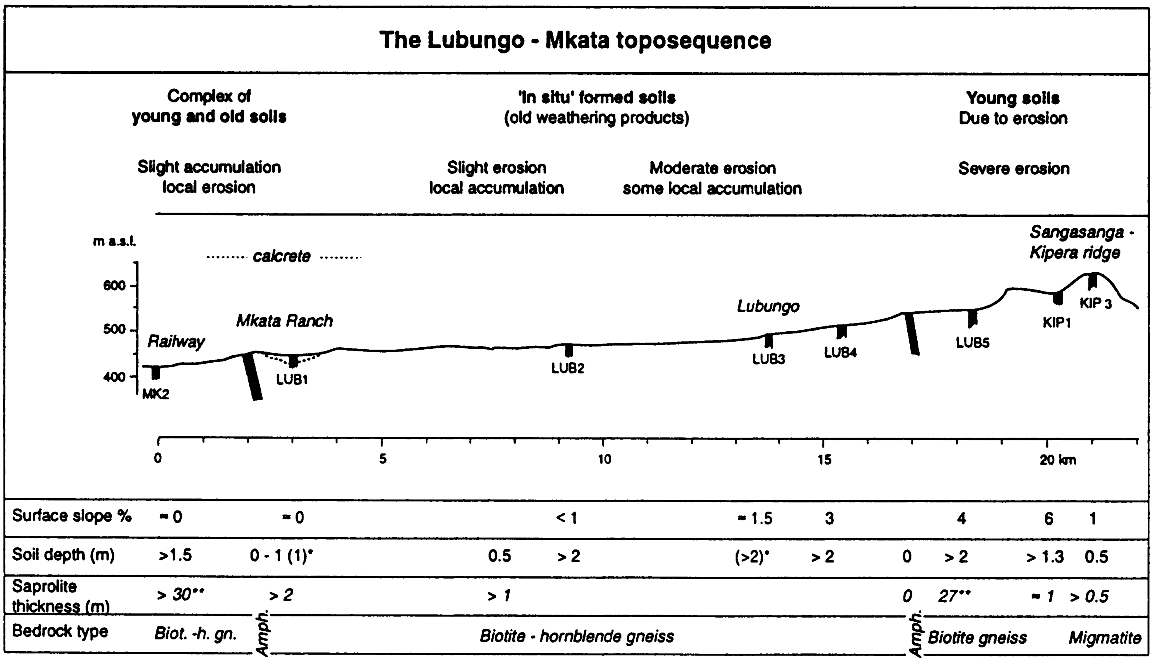

Fig. 7.3 The Lubungo-Mkata toposequence. A transect from Mkata Ranch to the Sangasanga-Kipera ridge. Soil data from Kaaya (1997) and Kaaya (1998).

The saprolites are of varying thickness due to differences in the bedrock. They are exposed several places along the transect, and a 2 m deep section is exposed in a gravelpit near Mkata Ranch (Fig. 7.3 & Fig. 5.1). The calcretes overlying the saprolite have been dated to Late Quaternary (see Table 6.5). The saprolites must be older, probably considerably older.

to a much larger area of moderately sloping land which also is of considerable agricultural importance.

8. Concluding remarks

1. Two groups of bedrock can be recognized as the most important ‘parent materials’ for the soils in the study area.

    - *The granulites and biotite-hornblende gneisses* produce generally clayey and red soils. On gentle slopes *in situ* (autochthonous) weathering will be dominant and the characteristics of the parent material will often show a direct relationship to the overlying soils. However, «The upper soil layer(s) are seldom truly autochthonous, but exhibit many signs of lateral transfer of material both physically and in solution» (Thomas 1994). The findings of Kaaya et al. (1998) and Kaaya (1998) support this citation.

      In sloping terrain the physical properties of the saprolite and soils, such as hydraulic conductivity, erodibility, texture, and clay activity are important features controlling susceptibility for mass movements (slides and flows). The granulitic rocks seem to produce both saprolite and soils which are susceptible to landslides and mudflows. Previous investigations (Temple & Rapp 1972) show that the slopes of the Uluguru mountains become easily unstable. Slides are also common today on cleared land with steep slopes. The sequence of sediments in the SUA ravine also indicates that mass movements are important in the formation of colluvial aprons on the foot-slopes of northern Uluguru Mts.

    - *The migmatites and muscovite-biotite gneisses* weather to light coloured soils with a sandy texture. However, on the top of the Mindu Mts. the *in situ* formed soil have fairly high contents of clay and silt (a type of ‘forest-cap clays’). There are few signs of landslides on the slopes of Mindu Mts. The section in the colluvial apron on the south-eastern foot-slope of the mountain, clearly shows that the down-slope movement of soil seems to have been dominated by slope wash. The sandy soils are only slightly weathered, and the mineralogy is similar to the underlying bedrock.

    - Two other rock-complexes in the region are interesting for studies of saprolite and soil formation, and the relations between soils and parent rocks. The almost mono-mineralic *meta-anorthosite* in the Mgeta area is ideal for the study of plagioclase weathering in a humid tropical environment (cf. Clayton 1986). The large area with *the crystalline limestone group* south of Mkuyuni on the southeastern side of Uluguru Mts. have soils developed on pure dolomitic limestone, and it could be interesting to see what effect the parent rock had on these soils.

densities and from cultivated land within the study area are needed if calculations of sustainable land use shall be reliable. Chemical denudation has not been considered here, but rates between 1 - 4 mm kyr^{-1} for Africa are reported by Summerfield & Hulton (1994).

- Late Holocene sedimentation rates have been obtained for one site along the Ngerengere River, and for another in a tributary stream of Mkata River. The values are 2 and 0.7 mm yr^{-1} respectively. More data on sediment accumulation rates in the lower parts of the landscape could improve the understanding of vertisol development.

5. *The calcretes* seem to be quite common in the study area (Sentozi 1997), and they may locally have an impact on landscape and soil development; as a 'hardpan' in the sub-soil, and as a protection against saprolite erosion where the soil has been removed.

   - The obtained dates can be divided in three age-groups; One phase of soil carbonate crystallisation occurred between 26.3 and 29.2 kyr, one ca. 42 kyr, and one > 47 kyr BP (Table 6.5). The last one has been U/Th-dated to between 156.5 and 193.7 kyr before present. At least one of the dates around 42 kyr are most likely outside the range of ^{14}C-dating.
   - More work is needed for a better understanding of calcrete formation and their age. The use of soil micromorphology, stable isotope analyses, chemical, XRD-mineral analyses, and dating by several different methods are recommended.

6. *Soil formation rates:* Modern 'slide scars' in the Mgeta area have been investigated for recolonisation of vegetation and establishment of an A-horizon. An increase in organic matter from 0.16 to 0.44 %, compared to 1.8 % in the surrounding topsoils has been reported over a period of seven years (Lundgren 1978). Hall et al. (1982) refer to studies in North Dakota, USA, where a 15 cm thick A-horizon had formed in 50 years, and work from Iowa, USA, where an A-horizon had developed in 100 years in silt sediments. The time needed for the establishment of other properties reflecting soil development is presented by Hall et al. (1982); Sub-soil colour develops in ca. 50 years; A Cambic horizon can form in 200 - 500 years; Moderate structure develops in ca. 2 kyr, and an argillic horizon may form in 2 - 5 kyr (all data from central USA). Similar time intervals are reported by Birkeland (1974). The appearance of reddish or brownish soil colours took only 2 - 3 years in the Mgeta area (Temple & Rapp 1972).

   In our study area soil formation was probably most intense during the first half of Holocene, but too little data on rates of soil formation exist. Some times during the last 'glacial' (30 - 40 kyr BP) there are some indications of a weak soil development. Otherwise one must go ca. 130 kyr back in time to find environmental conditions similar to Holocene (the last 10 kyr) and conditions for strong soil development.

Büdel, J. 1957. Die 'doppelten Einebungsflächen' in den feuhten Tropen. *Zeitschrift für Geomorphologie N.F.*, 1, 201 -288.

Buol, S.W. 1994. Saprolite - Regolith Taxonomy. An Approximation. *In:* Cremeens, D.L., Brown, R.B., & Huddleston, J.H. (eds). Whole Regolith Pedology, 119 - 132. SSSA Special Publication No. 34. Madison. 136 pp.

Buol, S.W., Hole, F.D. & McCracken, R.J. 1980. Soil genesis and Classification. 2nd Edition. The Iowa State University Press, Ames. 406 pp.

Callen, R.A., Wasson, R.J. & Gillespie, R. 1983. Reliability of radiocarbon dating of pedogenic carbonate in the Australian arid zone. *Sedimentology* 35, 1 - 14.

Clayton, J.L. 1986. An estimate of plagioclase weathering rate in the Idaho Batholith based upon geochemical transport rates. *In:* Coleman, S.M. & Diether, P.D. (eds). Rates of chemical weathering of rocks and minerals, 453 - 466. Academic Press, Orlando. 603 pp.

Cremeens, D.L., Brown, R.B., & Huddleston, J.H. (eds.) 1994. Whole Regolith Pedology. SSSA Special Publication No. 34. Madison. 136 pp.

DHV-Consulting Engineers. 1980. Morogoro Domestic Water Supply Plan. Vol. IV: Hydrogeology - Annexes and Data. Ministry of Water, Energy and Minerals, Tanzania & Amersfoort, The Nederlands.

Douglas, I. & Spencer, T. (eds) 1985. Environmental change and tropical geomorphology. Allen & Unwin, London.

Downie, C. & Wilkinson, P. 1972. The geology of Kilimanjaro. Department of geology, University of Sheffield. 253 pp.

Dypvik, H., Nilsen, O. & Kaaya, C. 1997. Geological guide to Rift Valleys of Tanzania. University of Oslo - Univeristy of Dar es Salaam. 81 pp.

Flenly, J.R. 1985. Relevance of Quaternary palynology to geomorphology in the tropics and subtropics. *In:* Douglas, I. & Spencer, T. (eds). Environmental Change and Tropical Geomorphology, 153 - 164. Allen & Unwin, London. 378 pp.

Fozzard, P.M.H. 1965. KIMAMBA, Quarter degree sheet 182. Geological survey of Tanganyika, Survey Office, Dar es Salaam, Tanzania.

Gee, G.W. & Bauder, J.W. 1986. Particle-size analysis. *In*: A. Klute (ed). Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd Edition. Agronomy Series No. 9 (Part 1), ASA, SSSA, Madison, Wisc., p. 383 - 411.

Gile, L.H., Peterson, F.F. & Grossman, R.B. 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science* 101, 347 - 360.

Goudie, A.S. 1983. Calcrete. *In:* Goudie, A.S. & Pye, K. (eds) Chemical sediments and geomorphology: precipitates and residua in the near-surface environment, 93 - 131. Academic Press, London.

Grove, A.T. 1996. African river discharges and lake levels in the twentieth century. *In:* Johnson, T.C. & Odada, E.O. (eds) The Limnology, Climatology and Paleoclimatology of the East African lakes, 95 - 100. Gordon & Breach Publ. Rotterdam, 663 pp.

Guillet,B., Faivre, P., Mariotti, A. & Khobzi, J. 1988. The ^{14}C dates and $^{13}C/^{12}C$ ratios of soil organic matter as a means of studying the past vegetation in intertropical regions:

Klappa, C.F. 1983. A process-response model for the formation of pedogenic calcretes. *In:* Wilson, R.C.L. (ed) Residual deposits: Surface related weathering processes and materials. Geological Society; Special Publication 11, 211 - 220. Blackwell Scientific Publication, London 258 pp.

Ku Teh-Lung, Bull, W.B., Freeman, S.T. & Knauss, K.G. 1979. Th^{230} - U^{234} dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, southeastern California. *Geological Society America Bulletin* 90, 1063 - 1073.

Lecce, S.A. 1990. The Alluvial Fan Problem. *In:* Rachocki, A.H. & Church, M. (eds.) Alluvial Fans - A field approach, 3 - 24. John Wiley & Sons, Chichester. 391 pp.

Lundgren, L. 1978. Studies of soil and vegetation development on fresh landslide scars in the Mgeta Valley, western Uluguru Mountains, Tanzania. *Geografiska Annaler* 60A, 91 - 127.

Mahaney, W.C., Barendregt, R.W. and Vortisch, W. 1997. Relative ages of loess and till in two Quaternary palaeosols in Gorges Valley, Mount Kenya, East Africa. *Journal of Quaternary Science* 12, 61 - 72.

Maley, J. 1997. Middle to Late Holocene changes in tropical Africa and other continents: Paleomonsoon and sea surface temperature variations. *In:* Nuzhet Dalfes, H., Kukla, G. & Weiss, H. (eds). Third Millennium BC Climate Change and Old World Collapse. NATO ASI Series, I 49, 611 - 640. Springer Verlag, Berlin.

Marchant, R, & Taylor, D. 1997. Late Pleistocene and Holocene history at Mubwindi Swamp, Southwest Uganda. *Quaternary Research* 47, 316 - 328.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.C. & Shackleton, N.J. 1987. Age dating and orbital theory of the ice ages: Development of a high-resolution 0 to 300 000-year chronostratigraphy. *Quaternary Research* 27, 1 - 29.

Mejdahl. V. 1990. Thermoluminescence Dating. *Norwegian Archaeological Review* 23, 21 - 29.

Milnes, A.R. 1994. Calcrete. *In:* Martini, I.P. & Chesworth, W. (eds) Weathering, Soils & Paleosols, 309 - 347. Elsevier, Amsterdam. 618 pp.

Møberg, J. P. 1974. The mineralogy of the clay, silt and sand fraction of soils from various parts of Tanzania, and its relation to the soil forming factors and processes. Report from Department of Chemistry, The Royal Veterinary and Agricultural University, Copenhagen.

Moberg, J.P., Msanya, B.M. & Kilasara, M. 1982. Pedological and edaphological properties of the soils of two soil associations in the Morogoro area, Tanzania. Tropical Agriculture (Trinidad) 59, 139 - 148.

Muhongo, S. 1994. Neoproterozoic collision tectonics in the Mozambique Belt of East Africa: evidence from the Uluguru mountains, Tanzania. Journal of African Earth Sciences 19: 153 - 168.

Mutakyahwa, M.K.D, & Valeton, I. 1995. Late Cretaceous - Lower Tertiary weathering event and its laterite-bauxite formation in Tanzania. Mitteilung Geol.-Palæont. Institute, University of Hamburg 78, 1 - 65.

Netterberg, F. 1967. Some road making properties of South African calcretes. Proceedings 4th Regional Conference Soil Mechanics and Foundation Engineering, Cape Town, SA., pp. 77 - 81. Balkema, Cape Town.

Sarnthein, M. 1978. Sand deserts during glacial maximum and climatic minimum. *Nature* 272, 43 - 46.

Schwaighofer, B. & Müller, H.W. 1986. Verwitterung und Tonmineralgenese im Kristallin der Uluguru-Berge, Tanzania. Mitteilungen Ges. Geol. Bergbaustud. Österreich 33: 207 - 220.

Sentozi, E. 1997. Distribution and characteristics of calcretes and calcrete - soil profiles on the northern lower slopes of Uluguru Mountains, Morogoro District. MSc-thesis, Sokoine Agricultural University (unpublished). 131 pp.

Sherman, G.D., Cady, J.G., Ikawa, H. & Blumsberg, N.E. 1967. Genesis of the bauxitic Hailu soils. Hawaii Agricultural Experiment Station, Technical Bulletin 56. *Striae* 16, 17 - 20.

Summerfield, M.A. & Hulton, J. 1994. Natural controls of fluvial denudation rates in major world drainage basins. *Journal of geophysical research* 99, 13 871 - 13 883.

Talbot, M.R. & Livingstone, D.A. 1989. Hydrogen index and carbon isotopes of lacustrine organic matter as lake level indicators. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 70, 121 - 137.

Talbot, M.R., 1981. Holocene changes in tropical wind intensity and rainfall: Evidence from southeast Ghana. *Quaternary Research* 16, 201 - 220.

Talbot, M.R., 1982. Holocene chronostratigraphy of tropical Africa. *In:* Mangerud, J., Birks, H.J.B. & Jager, K.-D. (eds) Chronostratigraphic subdivision of the Holocene.

Talma, A.S. & Netterberg, F. 1983. Stable isotope abundances in calcretes. *In:* Wilson, R.C.L. (ed) Residual deposits: Surface related weathering processes and materials. Geological Society; Special Publication 11, 221 - 133. Blackwell Scientific Publication, London. 258 pp.

Temple, P.H. & Murray-Rust, D.H. 1972. Sheet wash measurements on erosion plots at Mfumbwe, Eastern Uluguru mountains, Tanzania. *Geografiska Annaler,* 54A, 195 - 202.

Temple, P.H. & Rapp, A. 1972. Landslides in the Mgeta area, western Uluguru mountains; geomorphological effects of a sudden heavy rainfall. *Geografiska Annaler,* 54A, 157 - 193.

Thomas, G.W. 1982. Exchangeable Cations. *In*: A.L. Page (Editor), Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties, 2nd Edition. Agronomy Series No. 9 (Part 2), ASA, SSSA, Madison, Wisc., p. 159 - 165.

Thomas, M.F. & Thorp, M.B. 1996. The response of geomorphic systems to climatic and hydrological change during the Late Glacial and early Holocene in the humid and sub-humid tropics. *In:* Branson, J., Brown, A.G. & Gregory, K.J. (Eds) Global Continental Changes: the context of palaeohydrology. Geological Society Special Publication 115, 139 - 153.

Thomas, M.F. 1994. Geomorphology in the tropics. A study of weathering and denudation in low latitudes. John Wiley & Sons, Chichester. 460 pp.

Trauth, M.H. & Strecker, M.R. 1996. Late Pleistocene lake-level fluctuations in the Naivasha Basin, Kenya. *In:* Johnson, T.C. & Odada, E.O. (eds) The Limnology, Climatology and Paleoclimatology of the East African lakes, 549 - 557. Gordon & Breach Publ. Rotterdam. 572 pp.

APPENDIX: BRIEF DESCRIPTION OF LABORATORY METHODS

- Grain size distribution of the fine earth (< 2 mm) was determined by the pipette method (Gee and Bauder, 1986), and by wet-sieving the sand fractions.
- Cation exchange properties were determined as described by Thomas (1982). Exchangeable bases were extracted with NH_4OAc (pH 7), and then Ca^{2+} and Mg^{2+} determined with atomic absorption and K^+ and Na^+ with flame photometer.
- The total chemical analysis of some sand and clay fractions were carried out by x-ray fluorescence (XRF) analysis after crushing, igniting at 1000 °C, and fusing the samples with Li-tetraborate following the techniques described by Bennett and Oliver (1992).
- Mineralogy of soil, saprolites and calcrete samples was determined by x-ray diffraction analysis (Brindley and Brown, 1980). Quantification of minerals in some of these samples was based on the x-ray analysis data and their total chemical analysis. In addition, selective dissolution of calcretes and calcite concretions with 1.25 *N* HCl was carried out, and then Ca and Mg determined with atomic absorption, and K by flame photometer.
- Radiocarbon dating of the calcretes (soil carbonate) has been done at Beta Analytic Inc., Florida, USA, with conventional methods (Bradley 1985). Dating of soil organic matter and the fossil snails have been done at the Radiological Dating Laboratory, Trondheim, Norway, also with conventional methods. Special problems related to the dating of soil organic matter has been discussed by Wang et al. (1996).
- One Uranium/Thorium dating of a calcrete has been carried out at The Uranium-series Dating Laboratory, at University of Bergen, Norway, under the supervision of S.-E. Lauritzen. Principles of the method are described by Bradley (1985), and problems related to dating of soil carbonates are discussed by Ku et al. (1979.).
- Stable isotopes of oxygen and carbon have been measured at The Geological Mass-spectrometric Laboratory, at University of Bergen, Norway, under the supervision Dr. E. Jansen. The method is described in Bradley (1985).
- Thermoluminescence and Optical Dating of sand from the Mindu section have been done at the Nordic Laboratory for Luminescence Dating, Roskilde, Denmark, under the supervision of late Dr. V. Mejdahl. Methods for Thermoluminescence (TL) and Optical Stimulated Luminescence (OSL) are described by Aitken (1985, 1992), and by Mejdahl (1990).