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Morphology, genesis and classification of the soils in the Lubungo-Mkata toposequence, Morogoro, Tanzania

by

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Abstract

A study was carried out in soils of a toposequence in the Lubungo-Mkata area, Morogoro in order to interpret the genesis of some of their morphological features based on their catenary relationships. Soils were characterized and related to their landscape position and parent materials. Soil profiles were then classified into the US Soil Taxonomy and FAO-Unesco. System.

Eight soil profiles were described and sampled in the field and analysed in the laboratory. The profiles included well drained soils formed from quartz rich two-mica gneisses and migmatites southwest of Mindu mountains; well drained *in situ* weathered soils from hornblende biotite gneiss on middle slope; and imperfectly drained 'mbuga' soils formed from old and recent fluvial materials on the Wami-Mkata plains.

Abrupt changes observed in morphological, physico-chemical and mineralogical properties in the studied soil profiles clearly demonstrate the influence of parent material. Soils developed from the quartz rich two-mica gneisses and migmatites in the upper parts of the landscape are moderately weathered, shallow to moderately deep, light coloured sandy soils with mixed clay mineralogy. The soils are classified as Oxic Ustropets (Chromic Cambisols). The soils from the hornblende biotite gneiss on the middle slope are highly weathered, deep red soils with high kaolinitic clay contents. The profiles are classified as Rhodic Kandiustalfs (Haplic Lixisols) and Kandic Paleustalfs (Haplic Lixisols). Soils on the lower landscape position are mainly black soils, with high clay contents dominated by smectite, and most of them are characterized by accumulation of carbonates in their subsoils. The profiles are classified as Fluventic Ustropepts (Calcic Fluvisols), Petrocalcic Calciusterts (Calcic Vertisols) and Chromic Haplusterts (Eutric Vertisols).

Most of the soil properties appear to be controlled by the nature of the parent materials and their position in the landscape. These properties include degree of soil profile development, clay content, soil mineralogy, soil colour, soil depth, cation exchange characteristics and accumulations of carbonates or Fe-oxides in some profiles. Most of these properties and their interpretations in relation to pedogenic processes have been discussed, and are also reflected in the classification of the studied profiles.

4. Key words: diagnostic horizons; soil classification; soil mineralogy; pedogenic processes.

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Preface

This report is part of my Ph.D. thesis titled '**Characterization, genesis and classification of some soils of northern part of Morogoro District, Tanzania**' to be submitted to the Department of Soil and Water Sciences, Agricultural University of Norway. My Ph.D. study progarmme is including this work is funded by the SUA-NORAD Project TAN-091 in the Department of Soil Science, Sokoine University of Agriculture.

I wish to extend my heartfelt appreciation to Assoc. Prof. Rolf Sørensen and Prof. Per Jørgensen for their constructive criticism of this report. Their useful comments and suggestions helped to improve the original draft considerably.

I also express my gratitude to my colleague Kassim O. Ali for proofreading this report.

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1. Introduction

Topography is one of the important factors affecting soil development (Jenny, 1941; 1980). Several studies have been done on the influence of this factor on pedogenesis by evaluating the variation in soil development with slope position, the type of variation referred to as soil catena (Milne, 1935a; 1935b) or toposequence (Jenny, 1980; Birkeland, 1984). Similar studies have been done on soil associations of the northwestern slopes of Uluguru mountains and eastern slopes of the Mindu mountains by Møberg, (1981) and Moberg *et al.* (1982). In Morogoro, much less information is available about the soils of the flat Wami-Mkata plains and their relationship with the adjacent soils on the gently sloping to strongly sloping topography. Recent investigations by Kaaya (1997) indicates that the soils associations in the current study area differ from those reported by Møberg, (1981) and Moberg *et al.* (1982) in the area between Mindu and Uluguru mountains. Also, the present day climatic conditions in the Wami-Mkata plains are generally drier than those of the northwestern Uluguru mountains. This report presents morphology, genesis and classification of some soil profiles on the Lubungo-Mkata toposequence west of the Mindu mountains.

During soil survey, it was assumed that there is a pattern of order in the spatial distribution of soil characteristics which are determined by the factors of soil formation including parent material, climate, organisms, relief and time as proposed by Jenny (1980). These factors including human activities determine the nature and intensity of pedogenic processes in soils, and consequently the properties of soils found in the area.

Earlier pedological investigations in the northwestern slopes of the Uluguru mountains and the plains in the northern part of Morogoro District show that the most common soils in the area include Inceptisols, Ultisols and Alfisols in the upper slopes; Ultisols and Oxisols in the gently sloping plains; Inceptisols and Entisols on the river plains, and Vertisols in depressions (Møberg, 1981; De Pauw, 1984; Møberg *et al.*, 1982; Kaaya, 1997). Survey of the soils in the Lubungo-Mkata area by Kaaya (1997) indicated that from the western slopes of the Mindu mountains down to Mkata River plains, the most common soils in the area include the US Soil Taxonomy orders Inceptisols, Alfisols, Inceptisols and Vertisols which were correlated to Cambisols, Lixisols, Fluvisols and Vertisols respectively, in the FAO-Unesco system of soil classification.

Detailed soil classification provides better understanding and prediction of their behaviour under certain management practices, the information required to enable land users and planners in deciding the best (or sustainable) land use and suitable management practices. This information may also be useful in other areas of the northern part of Morogoro District with similar soils and environmental conditions. General soil characterization and profile classification carried out by Kaaya (1997) was considered to be insufficient to enable an individual (land users or land use planners) to accurately and readily discern properties important for proper interpretations of their soil use and management. However, these results have formed the basis for further studies on soil genesis and detailed soil classification based on the properties of their representative soil profiles; and this has been the main objective of this study. In carrying out the investigation, the mineralogy and catenary relationships of the 'mbuga' soils of the Wami-Mkata plains will be studied.

2. Nature of the study area

2.1 Location

The toposequence selected for this study extends from the Sangasanga-Kipera ridge southwest of Mindu mountains westwards to Mkata River near Mkata Railway Station in the northern part of Morogoro District, Tanzania. It is approximately located between longitude 37° 20' E and 37° 33' E, and latitudes 6° 43' S and 6° 54' S.

2.2 Geology and geomorphology

Descriptions of the geology and geomorphology of the Lubungo-Mkata toposequence have been reviewed and described with some recent findings by Sørensen and Kaaya (1998). The salient geomorphological and geological features of the Lubungo-Mkata toposequence are summarized in Fig. 2.1 (from Sørensen and Kaaya (1998). The studied soil profiles are underlain by two contrasting types of bed-rocks, the two-mica gneisses and migmatites with granitic composition which produce sandy and relatively shallow soils SW of Mindu mountains (profile KIP 3 and KIP 1), and biotite-hornblende gneisses which dominate the rest of the area. Due to differences in the nature of the underlying rocks, the thickness of the saprolite along the toposequence is very variable ranging from < 1 m on the Sangasanga-Kipera ridge to > 30 m west of Mkata Railway Station (Sørensen and Kaaya, 1998).

2.3 Climate, Vegetation and Land use

Palaeo-climates and their effects on vegetation, geological and geomorphological processes in the area have been reviewed by Sørensen and Kaaya (1998). The present day climate in the Morogoro District is of sub humid type with well defined wet and dry seasons. However, there is a marked local variation of climatic factors which is associated with variation in the relief features of the study area. This has been described briefly by Sampson and Wright, 1964, Pocs, 1976, De Pauw, 1984 and Msanya et al., 1994 and reviewed by Kaaya (1997). Following the Soil Taxonomy classification system, the soil moisture regime is ustic while the soil temperature regime is iso-hyperthermic.

Description of the present day vegetation and land use types were presented during soil mapping and characterization (Kaaya, 1997).

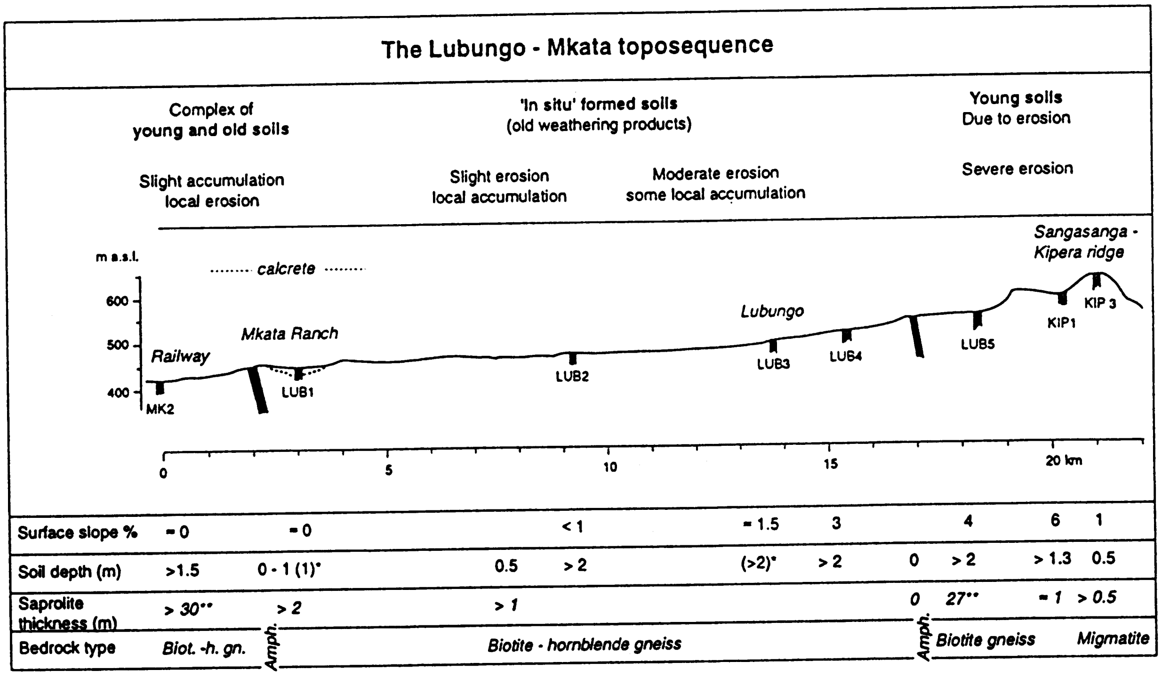

Fig. 2.1 The Lubungo-Mkata toposequence (a transect from the Sangasanga-Kipera ridge to Mkata Ranch). Adopted from Sørensen and Kaaya (1998).

3. Materials and methods

3.1 Field and Laboratory methods

Figure 2.1 shows locations of the studied soil profiles relative to their positions on the slope along the toposequence. All soil profiles were examined and sampled in freshly dug pits as part of the soil mapping and characterization reported by Kaaya (1997). Profile descriptions were made according to the 'Guidelines for soil profile description' (FAO, 1990). Soil samples were also taken from each horizon for physical, chemical and mineralogical analysis. The samples were air-dried, ground to pass through a 2-mm sieve before analyses. Methods used for physical and chemical analyses have been described in the soil mapping and characterization report (Kaaya, 1997).

Mineralogical analysis of clay, silt and sand fractions were mainly by x-ray diffraction, and the methods used for analysis and quantification of minerals in each fraction are similar to those used by Kaaya et al., (1998).

4. Morphology, genesis and classification

4.1 Morphological, mineralogical and chemical properties

Detailed description of the profiles selected for this study have been presented in the soil mapping and characterization report (Kaaya, 1997). Based on the similarities in the properties of the studied soil profiles, the soils have been categorized into three groups including: soils of the upper part of the toposequence, soils of the middle part of the toposequence and soils of the nearly flat plain. Some physical and other salient morphological properties associated with genesis of the studied profiles have been summarized in Table 4.1. Also some selected chemical properties are presented in Table 4.2. Mineralogical composition of clay, silt and sand fractions are shown in Tables 4.3, 4.4 and 4.5, respectively.

4.1.1 *The upper part of the toposequence*

Morphological properties

The upper parts of the toposequence, around the Mindu mountains and Sangasanga-Kipera ridge have relatively shallow, well drained, moderately developed soils with sandy loam to sandy clay loam texture. Profiles KIP 1 and KIP 3 (Fig. 2.1) represent these soils. They have A-Bw-C profiles typical of Cambisols (or Inceptisols). The profiles show moderate weathering with no observable clay illuviation. They contain some slightly weathered and unweathered feldspar gravels throughout their depths. Profile KIP 3 near the top of Sangasanga-Kipera ridge has a thin A horizon mainly due to erosion. Soil erosion in the area is accelerated by human activities especially deforestation, animal grazing and frequent bush fires associated with charcoal burning. These activities account also for the generally low organic matter contents of the soils of this area. Profile KIP 1 has developed from colluvial material from the same parent rocks accumulated in a local depression on the slope.

The hue of the colour of the surface soils is 10YR for profiles KIP 1 and KIP 3. The colour of the B horizon of profile KIP 3 is red to reddish brown (with hue of 2.5YR, and chroma ≥ 4), whereas the B horizon of Profile KIP 1 is yellowish red to yellowish brown with hue in the range of 5YR to 10YR, and chroma ≥ 6. This may indicate presence of some hydrated ferric oxides in the clay fraction (Young, 1976). The lower part of the B horizon of profile KIP 1 is faintly mottled (reddish) indicating that there has been oxidation-reduction reactions associated with imperfect drainage conditions possibly caused by fluctuating perched water table.

Chemical and mineralogical properties

The bulk soil samples from profiles KIP 1 and KIP 3 have fairly low CEC ranging from 8.6 to 14.0 cmol(+)/kg dry soil. This is mainly due to their low clay contents (Table 4.1). Their clay CEC values are moderate to high and range from 18.5 to 51.1 cmol(+)/kg clay. The soil reaction is medium acid to neutral with pH values ranging from 5.9 to 6.6 and base saturation > 50% throughout.

The clay mineralogy (Table 4.3) shows that the clay fraction in profile KIP 1 is composed of various minerals including kaolinite, illite (dioctahedral and trioctahedral), smectite, mixed illite-smectite, and traces of quartz and feldspars. Clay mineralogy of profile KIP 3 is mainly illite (dioctahedral and trioctahedral) and kaolinite, with traces of mixed illite-smectite and quartz. Both profiles KIP 1 and KIP 3 are classified under the mixed mineralogy class (Soil Survey Staff, 1996). Most of the clay minerals in these profiles have been formed as a result of *in situ* weathering. Location of profile KIP 1 in a local depression on the slope and presence of mottles in the subsoil indicate existence of local imperfect drainage conditions which provide favourable conditions for formation and preservation of smectite and mixed layered illite-smectite. The silt and sand fractions are mainly composed of feldspars and quartz with small amounts of mica and kaolinite in the silt fraction. Presence of considerable amounts of weatherable minerals in all fractions of these profiles is an indication that the soils are relatively young.

Table 4.1 Some macro morphological and physical characteristics[§] *of the studied profiles*

Hori-zon	Depth (cm)	Munsell soil colour		Particle-size analysis			Text-ure	Structure	Consistence			Other features	Horizon boundary
		moist	dry	clay (%)	silt (%)	sand (%)			dry	moist	wet		
Profile KIP 3: Shallow, well drained, overlying mica gneiss and migmatites, in situ *weathering at 640 m asl*													
Ah	0 - 8	10YR 3/2	10YR 5/4	18.2	13.2	68.6	SL	MO,FM,GR	SHA	FR	NST,NPL		C,S
Bw	8 - 18	2.5YR 3/4	2.5YR 4/6	33.6	8.2	58.2	SCL	MO,ME,AB	HA	FI	ST,PL		C,S
BC	18 - 55/65	2.5YR 3/4	2.5YR 4/4	34.2	15.7	50.1	SCL	MO,FM,AB	HA	FR	ST,PL		C,W
C	55/65 - 92+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	slightly weathered gravels and stone	--
Profile KIP 1: Moderately deep, moderately well drained, developed from slope-wash sand on a local depression overlying mica gneiss and migmatites at 610 m asl,													
Ah	0 - 19	10YR 3/2	10YR 4/2	16.2	4.2	79.6	SL	MO,FI,GR	HA	FR	NST,NPL		C,S
Bw1	19 - 42	5YR 4/6	5YR 5/8	28.3	4.2	67.5	SCL	MO,FI,SB	VHA	FR	ST,PL		G,S
Bw2	42 - 71	5YR 4/6	5YR 5/6	26.3	6.2	67.5	SCL	MO,FM,AB	VHA	FR	ST,PL		C,W
Bw3	71 - 80/98	10YR 5/8	10YR 5/8	33.3	3.2	63.5	SCL	MO,ME,AB	VHA	FI	ST,PL	reddish mottles, few Fe-Mn nodules	C,W
Bcs	80/98 - 134+	2.5YR 7/6	2.5YR 5/8	n.d.	n.d.	n.d.	n.d.	MA	VHA	FR	SST,SPL	reddish mottles, many Fe-Mn nodules	--
Profile LUB 5: Very deep, well drained, in situ *weathering from underlying biotite-hornblende gneiss at 580 m asl*													
Ah	0 -20	5YR 2.5/2	5YR 3/3	47.8	10.8	41.4	C	MS,FI,GR	HA	FR	ST,PL		C,S
BA	20 - 38	2.5YR 2.5/4	2.5YR 3/6	69.1	4.2	26.7	C	MS,FI,SB	HA	FR	ST,PL		C,S
Bt1	38 - 134/138	10R 3/6	10R 4/8	76.4	4.8	18.8	C	MO,FI,SB	SHA	FR	SST,SPL	clay cutans, very few Fe-Mn nodules	G,W
Bt2	134/138-200+	10R 3/6	10R 4/8	73.4	7.0	19.6	C	MO,FI,SB	SHA	VFR	SST,SPL	clay cutans, very few Fe-Mn nodules	--
Profile LUB 4: Very deep, well drained, in situ *weathering from underlying biotite-hornblende gneiss at 535 m asl*													
Ah	0 - 19	5YR 3/3	5YR 3/3	45.6	12.8	41.6	C	MO,FI,SB	HA	FR	ST,PL		C,S
Bt1	19 - 33	2.5YR 2.5/4	2.5YR 3/6	68.4	8.1	23.5	C	MO,FI,SB	SHA	FR	ST,PL		G,W
Bt2	33 - 90	10R 3/6	10R 4/8	57.9	11.6	30.5	C	MO,ME,SB	HA	FR	SST,SPL	clay cutans, very few Fe-Mn nodules	G,W
Bt3	90 - 200+	10R 3/6	10R 4/8	57.9	18.7	23.4	C	MO,ME,SB	HA	FI	SST,SPL	clay cutans, very few Fe-Mn nodules	--

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[§] Abbreviations used for texture, structure, consistence and horizon boundaries are from the 'Guidelines for Soil Profile Description' (FAO, 1990)

Table 4.1 continued[§]

Hori-zon	Depth (cm)	Munsell soil colour		Particle-size analysis			Text-ure	Structure	Consistence			Other features	Horizon boundary
		moist	dry	clay (%)	silt (%)	sand (%)			dry	moist	wet		
Profile LUB 3: Very deep, well drained, in situ *weathering from underlying biotite-hornblende gneiss at 495 m asl*													
Ap	0 - 25	5YR 3/3	5YR 3.5/4	30.7	12.9	56.4	SCL	WM,FM,GR	HA	FR	SST,SPL		C,S
Bt1	25 - 39	2.5YR 3/6	2.5YR 4/6	55.6	5.3	39.1	C	ST,FM,SB	HA	VFR	ST,PL	faint clay cutans	C,S
Bt2	39 - 101	2.5YR 3/6	2.5YR 4/8	60.6	7.5	31.9	C	WE,FM,SB	SHA	VFR	ST,PL	distinct clay cutans, Fe-Mn concretions	G,W
Btcs	101 - 150	2.5YR 3/6	2.5YR 4/8	56.2	11.8	32.0	C	MO,FM,SB	SHA	FR	VS,VP	distinct clay cutans, Fe-Mn concretions	A,S
Bv	150 - 200+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	ferricretes (discotinuous cementation)	--
Profile LUB 2: Deep, imperfectly drained, developed from fluvial deposits underlying biotite-hornblende gneiss at 470 m asl													
Ah	0 - 28/30	10YR 2/1	10YR 3/2	35.8	11.6	52.6	SC	ST,FM,AB	VHA	FI	ST,PL		G,W
Bw	28/30 - 40/48	10YR 3/2	10YR 4/3	41.1	16.0	42.9	C	ST,ME,AB	VHA	FI	VST,VPL	slightly calcareous	C,W
Bck	40/48 - 83	10YR 4/4	10YR 5/4	42.2	14.1	43.7	C	MO,ME,SB	HA	FI	VST,VPL	calcareous, Ca concretions, reddish mottles	C,S
BCck	83 - 130	2.5Y 5/4	2.5Y 6/4	38.2	11.9	49.9	SC	MO,FM,SB	HA	FI	VST,VPL	calcareous, Ca & Mn concretions, mottled	G,S
Cck	130 - 200+	2.5Y 5/4	2.5Y 6/4	36.8	11.6	51.6	SC	MA	HA	FI	ST,PL	slightly calcareous, Ca & Mn concretions	--
Profile LUB 1: Moderately deep, imperfectly drained, developed from old alluvial deposits and in situ *weathering of underlying amphibole-containing biotite-hornblende gneisses at 445 m asl*													
Ah	0 - 25	5Y 2.5/1	5Y 3/1	50.2	12.2	37.6	C	ST,FI,AB	VHA	FI	VST,VPL		C,W
Bck1	25 - 65	5Y 2.5/1	5Y 2.5/1	55.3	9.9	34.8	C	ST,CO,PR	VHA	FI	VST,VPL	slickensides, carbonate concretions	G,W
Bck2	65 - 90	5Y 2.5/1	5Y 2.5/1	55.2	12.2	32.6	C	ST,CO,PR	VHA	FI	VST,VPL	slickensides, calcareous (Ca concretions)	C,S
Ckm	90 - 110+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	cemented (petrocalcic horizon)	--
Profile MK 2: Deep, imperfectly drained, developed from old alluvial deposits and in situ *weathering of underlying amphibole-containing biotite-hornblende gneisses at 400 m asl*													
Ah	0 - 12	2.5Y 4/1	2.5Y 4/1	44.4	12.5	43.1	C	MS,FM,SB	VHA	FI	VST,VPL		G,S
Bw1	12 - 102	2.5Y 4/1	2.5Y 4/1	48.2	11.5	40.3	C	ST,MC,PR	EHA	VFI	VST,VPL	slickensides	G,S
Bw2	102 - 159+	2.5Y 5/4	2.5Y 6/4	50.8	13.0	36.2	C	MO,ME,SB	VHA	VFI	VST,VPL	slickensides, Fe-Mn concretions	--

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[§] Abbreviations used for texture, structure, consistence and horizon boundaries are from the 'Guidelines for Soil Profile Description' (FAO, 1990)

Table 4.2 Some selected chemical properties of the studied soil profiles in the Lubungo-Mkata toposequence

Hor-zon	Depth (cm)	pH (H_2O)	Organic Carbon	Sum of bases	Exch. Al^{3+}	ECEC		CEC (NH_4OAc)		Base saturation
						soil	clay	soil	clay	
			(%)			(cmol(+)kg^{-1})				(%)
Profile KIP 3										
Ah	0 - 8	6.5	1.00	6.20	0.60	6.80	18.42	7.86	24.24	78.9
Bw	8 - 18	5.9	0.83	6.27	0.40	6.67	11.33	10.80	23.63	58.1
BC	18 - 55/65	6.2	0.26	5.32	0.50	5.82	14.40	7.22	18.49	73.7
Profile KIP 1										
Ah	0 - 19	6.4	1.16	7.60	1.88	9.48	33.83	10.68	41.24	71.2
Bw1	19 - 42	6.2	0.22	8.11	1.88	9.99	32.62	12.86	42.76	63.1
Bw2	42 - 71	6.2	0.05	9.03	1.96	10.99	41.13	13.62	51.13	66.3
Bw3	71 - 80/98	6.6	0.17	10.16	1.58	11.74	33.50	14.00	40.28	72.6
Bcs	80/98-134+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Profile LUB 5										
Ah	0 -20	5.9	1.60	9.21	1.20	10.41	10.24	13.20	16.07	69.8
BA	20 - 38	5.8	0.92	6.82	2.10	8.92	8.32	11.20	11.62	60.9
Bt1	38 - 134/138	5.4	0.31	5.73	3.00	8.73	10.03	9.80	11.43	58.5
Bt2	134/138-200+	5.6	0.23	5.37	3.20	8.57	10.60	8.62	10.66	62.3
Profile LUB 4										
Ah	0 - 19	6.2	1.54	10.25	0.70	10.95	12.37	13.60	18.18	75.4
Bt1	19 - 33	6.1	1.01	7.89	2.20	10.09	9.66	15.20	17.13	51.9
Bt2	33 - 90	5.6	0.47	7.33	0.20	7.53	10.21	12.80	19.31	57.3
Bt3	90 - 200+	6.4	0.25	9.05	0.00	9.05	14.14	14.40	23.38	62.8
Profile LUB 3										
Ap	0 - 25	7.6	1.37	13.84	0.30	14.14	30.67	15.60	35.43	88.7
Bt1	25 - 39	6.4	0.75	11.50	0.20	11.70	16.39	15.20	22.69	75.7
Bt2	39 - 101	6.3	0.50	12.39	0.40	12.79	18.26	16.02	23.59	77.3
Btcs	101 - 150	6.5	0.54	8.81	0.60	9.41	13.43	13.60	20.89	64.8
Bv	150 - 200+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Profile LUB 2										
Ah	0 - 28/30	7.4	1.15	17.82	0.00	17.82	38.70	19.20	42.56	92.8
Bw	28/30 - 40/48	8.1	0.31	20.62	0.00	20.62	47.57	20.80	48.01	99.1
Bck	40/48 - 83	8.4	0.14	27.00	0.00	27.00	62.84	27.20	63.31	99.3
BCck	83 - 130	8.2	0.18	26.80	0.00	26.80	68.53	28.00	71.67	95.7
Ckm	130 - 200+	8.5	0.10	25.81	0.00	25.81	69.20	26.40	70.80	97.8
Profile LUB 1										
Ah	0 - 25	7.6	1.47	42.98	0.00	42.98	75.52	47.60	84.72	90.3
Bck1	25 - 65	8.4	1.05	47.39	0.00	47.39	79.15	52.40	88.21	90.4
Bck2	65 - 90	8.5	1.11	56.98	0.00	56.98	96.29	57.60	97.41	98.9
Cck	90 - 110+	n.d..	n.d..	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Profile MK 2										
Ah	0 - 12	7.5	1.89	27.32	0.06	27.38	46.99	28.02	48.43	97.5
Bw1	12 - 102	8.0	1.38	31.89	0.00	31.89	56.29	31.96	56.44	99.8
Bw2	102 - 159+	8.3	0.45	34.32	0.00	34.32	64.50	34.92	65.69	98.3

Table 4.3 Mineralogical composition of the clay fractions of selected soil profiles along the Lubungo-Mkata toposequence

Profile	Horizon	Profile depth (cm)	Smectite	Illite/ Smectite.	Illite	Kaolinite	HIV	K-Feldspars	Plagioclase	Quartz
							(%)			
KIP 3	Ah	0 - 8	0.0	4.9	54.4	37.8	0.0	0.0	0.0	3.0
	Bw1	8 - 18	0.0	5.4	41.8	51.2	0.0	0.0	0.0	1.7
	BC	18 - 55/92	0.0	0.0	35.9	62.6	0.0	0.0	0.0	1.6
KIP 1	Ah	0 - 19	9.8	10.7	25.7	36.9	0.0	8.0	5.5	3.3
	Bw1	19 - 42	11.0	16.5	16.5	43.5	0.0	6.9	4.6	0.9
	Bw2	42 - 71	11.3	13.8	17.1	43.4	0.0	6.9	5.0	2.6
LUB 5	Ah	0 - 20	2.0	0.0	9.5	88.6	0.0	0.0	0.0	0.0
	Bt1	38 - 134/138	1.5	0.0	9.7	88.8	0.0	0.0	0.0	0.0
	Bt2	134/138 - 200	0.0	0.0	6.0	94.0	0.0	0.0	0.0	0.0
LUB 3	Ap	0 - 20	2.7	0.0	29.8	67.5	0.0	0.0	0.0	0.0
	Bt2	39 - 101	0.0	0.0	21.1	75.0	0.0	4.0	0.0	0.0
	Btcs	101 - 150	2.3	0.0	16.2	78.1	0.0	3.4	0.0	0.0
LUB1	Ack	0 - 25	74.4	0.0	0.0	5.5	9.2	1.5	1.7	7.7
	Bck1	25 - 65	83.4	0.0	0.0	3.8	6.8	0.9	0.9	4.3
	Bck2	65 - 90	82.6	0.0	0.0	3.9	7.1	0.9	1.0	4.4
MK 2	Ah	0 - 12	41.9	0.0	17.9	20.4	0.0	8.4	8.7	2.8
	Bw1	12 - 102	44.2	0.0	12.1	18.5	0.0	10.7	11.2	3.2
	Bw2	102 - 159	24.6	0.0	12.9	21.9	0.0	13.0	15.4	12.3

Table 4.4 Mineralogical composition of the silt fractions of selected soil profiles along the Lubungo-Mkata toposequence

Profile	Horizon	Profile depth (cm)	Quartz	K-Feldspars	Plagioclase	Mica	Kaolinite	Illite/ Smectite	Amphibole	Smectite	Ilmenite
							(%)				
KIP 3	Ah	0 - 8	32.0	12.2	42.7	9.8	3.2	0.0	0.0	0.0	0.0
	Bw1	8 - 18	31.1	13.7	39.0	11.2	4.9	0.0	0.0	0.0	0.0
	BC	18 - 55/92	52.4	16.6	20.2	7.6	3.2	0.0	0.0	0.0	0.0
KIP 1	Ah	0 - 19	38.6	20.8	35.4	2.8	1.4	0.5	0.0	0.4	0.0
	Bw1	19 - 42	36.3	19.8	36.2	0.8	1.3	5.0	0.0	0.7	0.0
	Bw2	42 - 71	40.6	20.2	33.7	0.6	0.9	3.7	0.0	0.4	0.0
LUB 5	Ah	0 - 20	67.0	10.4	13.5	3.3	3.9	0.0	0.0	0.0	1.6
	Bt1	38 - 134/138	84.3	4.4	4.1	0.4	1.1	0.0	0.0	0.0	4.9
	Bt2	134/138 - 200	76.4	3.2	6.9	3.3	7.2	0.0	0.0	0.0	2.4
LUB 3	Ap	0 - 20	59.0	19.8	14.3	2.1	2.7	0.0	0.0	0.0	1.8
	Bt2	39 - 101	68.6	20.2	6.4	2.3	0.9	0.0	0.0	0.0	1.3
	Btcs	101 - 150	65.4	21.7	6.5	3.9	1.1	0.0	0.0	0.0	1.3
LUB1	Ack	0 - 25	72.8	1.1	22.0	0.0	0.1	0.0	2.9	1.2	0.0
	Bck1	25 - 65	76.6	0.8	18.3	0.0	0.4	0.0	1.6	2.2	0.0
	Bck2	65 - 90	64.2	0.9	32.1	0.0	0.0	0.0	1.9	1.0	0.0
MK 2	Ah	0 - 12	45.6	15.6	36.9	0.8	0.4	0.0	0.2	0.6	0.0
	Bw1	12 - 102	48.5	15.6	35.4	0.0	0.0	0.0	0.5	0.0	0.0
	Bw2	102 - 159	57.5	10.9	29.1	0.1	0.2	0.0	1.5	0.6	0.0

Table 4.5 Mineralogical composition of the sand fractions of selected soil profiles along the Lubungo-Mkata toposequence

Profile	Horizon	Depth	Quartz	K-Feldspars	Plagioclase	Amphibole	Ilmenite
		(cm)	(%)				
KIP 3	Ah	0 - 8	35.6	9.6	54.8	0.0	0.0
	Bw1	8 - 18	44.5	9.8	45.7	0.0	0.0
	BC	18 - 55/92	66.1	16.3	17.6	0.0	0.0
KIP 1	Ah	0 - 19	43.5	10.8	45.7	0.0	0.0
	Bw1	19 - 42	46.2	12.1	41.8	0.0	0.0
	Bw2	42 - 71	44.8	12.4	42.8	0.0	0.0
LUB 5	Ah	0 - 20	72.5	4.8	16.4	1.0	5.2
	Bt1	38 - 134/138	82.7	4.6	8.5	0.0	4.2
	Bt2	134/138 - 200	83.5	4.8	7.4	0.0	4.3
LUB 3	Ap	0 - 20	70.8	8.2	17.8	0.9	2.2
	Bt2	39 - 101	76.8	9.6	11.4	0.0	2.2
	Btcs	101 - 150	75.6	9.5	12.7	0.0	2.2
LUB1	Ack	0 - 25	63.7	4.9	27.2	4.2	0.0
	Bck1	25 - 65	58.8	4.6	32.7	4.0	0.0
	Bck2	65 - 90	61.1	3.6	31.7	3.5	0.0
MK 2	Ah	0 - 12	86.4	4.7	8.8	0.0	0.0
	Bw1	12 - 102	72.7	7.3	19.2	0.8	0.0
	Bw2	102 - 159	61.7	7.6	28.2	2.5	0.0

4.1.2 *The middle part of the toposequence*

Morphological properties

The middle part of the toposequence has deep, well drained strongly weathered red clay soils, which have mainly formed *in situ*. The subsurface horizons show low silt:clay ratios reflecting advanced weathering. Although Sampson and Wright (1964) referred to these soils as deep red earth of Neogene origin, most of them were developed during the Quaternary (Sørensen and Kaaya, 1998). Profiles LUB 5, LUB 4 and LUB 3 represent these soils (Fig. 2.1). Due to local variations in micro-topography, the area experiences slight accumulation and slight to moderate erosion (Fig. 2.1). Most of the materials have developed from the underlying biotite-hornblende gneiss rocks (Sørensen and Kaaya, 1998). The profiles lie on a slope between 1.5 % and 4 % and according to FAO (1990), surface erosion in the area varies from slight to moderate. The horizon sequence is A-Bt-C in the three profiles. The average thickness of the A horizon for the three profiles is 20 cm with a colour hue of 5YR. All the subsurface horizons have colour hue redder than 5YR and chroma > 5 which according to Schwertmann (1993) reflects hematite-containing soils. The red colour of these soils is mainly due to staining of the soil particles by Fe-oxides. Since weathering of biotite gneiss and hornblende often results in staining of soil particles by Fe-oxides (Allen and Hajek, 1989), then the red colour of these soils must be associated with weathering in the underlying hornblende biotite gneiss. Presence of clay cutans, blocky structure and higher clay content in the B horizon than the overlying horizon indicate that the soils are still actively evolving by weathering of primary minerals and translocation of clay (Young, 1976). The wet consistence of these soils range from slightly sticky and slightly plastic to sticky and plastic in the A and B horizons, reflecting the presence of some expanding-lattice clay minerals. Profile LUB 3 which is located lower in the landscape (Fig. 2.1) has ferricretes occurring below 150 cm depth from the surface.

Chemical and mineralogical properties

Profiles LUB 5, LUB 4 and LUB 3 have low CEC with values between 8.5 and 14.1 cmol(+)/kg dry soil, and < 16 cmol(+)/kg clay indicating their low nutrient reserves. However, their base saturation is > 50%, and their soil reaction range from medium acid to mildly alkaline with pH values within 5.4 to 7.4 (Table 4.2). The relatively higher CEC values of the surface soils compared to the subsurface horizons could be associated with relatively higher organic matter contents resulting from biocycling processes (Rust, 1983). However, base-rich aeolian deposition could also account for some of this.

The clay mineralogy of profiles LUB 3 and LUB 5 is dominated by kaolinite (Table 4.3). Profile LUB 4 is assumed to have similar mineralogy. The three profiles belong to the kaolinitic soil mineralogy class (Soil Survey Staff, 1996). Profile LUB 3 contains some K-feldspars and more dioctahedral illite than profile LUB 5. They both contain very small amounts of smectite, with relatively higher contents in the surface than the subsurface horizons. A possible explanation for this could be that the smectite has been deposited on the surface as wind -blown dust from the Wami-Mkata plains. Silt and sand fractions of these profiles are dominated by quartz, with relatively small amounts of K-feldspars and plagioclase and some ilmenite (Tables 4.4 and 4.5). Dominance of kaolinite in the clay fraction, the low silt:clay ratio, dominance of quartz, relatively low contents of feldspars, and presence ilmenite in the silt and sand fractions are all indicators of advanced weathering in these profiles. The absence of amphiboles in the silt and sand fractions is another indication of advanced weathering since these minerals have been observed in some fresh rocks in this part of the toposequence (Sørensen and Kaaya, 1998) as shown in Fig. 2.1. Presence of the highly resistant ilmenite ($FeTiO_3$) could be a result of relative accumulation during weathering of the parent rock. The higher contents of some weatherable minerals (feldspars) in the surface horizon compared to the immediately underlying horizons in these profiles could be due to deposition and slight accumulation of less weathered materials brought by surface erosion from the upper parts of the toposequence. The deposition must have occurred on the already *in situ* weathered profiles.

4.1.3 *The lower part of the toposequence*

Morphological properties

The soils in the lower part of the toposequence are complex with very young soils formed during the Late Holocene and relatively 'older' *in situ* weathered soils, but most likely formed in Late Pleistocene (Sørensen and Kaaya, 1998). The underlying rock is hornblende-biotite gneiss, and the soils are represented by profiles LUB 2, LUB 1 and MK 2 (Fig. 2.1) which differ mainly in their morphological and mineralogical characteristics. The profiles are imperfectly drained, and the consistence of the subsurface horizons is very sticky and very plastic (when wet), and very hard (when dry) indicating the presence of significant amounts of expanding-lattice clay minerals as confirmed later by analysis of the clay mineralogy. The particle-size distribution is generally uniform and clayey throughout the profiles.

Profile LUB 2 is located on almost flat topography with a general slope of < 1%. The surrounding area experiences slight erosion and local accumulation due to some local variations in relief (relative relief of < 2 m). The profile has developed from fluvial sediments deposited by one of the seasonal tributaries of Mbesegera River which drains into Mkata River . The subsurface horizons are characterized by Ca-concretions contained in moderately to strongly calcareous soil matrix.

Profiles LUB 1 and MK 2 are also located on almost flat topography with slope ≈ 0%. However, due to some local variation in relief, the area experiences slight erosion and slight local accumulations. The profiles show minimum horizon differentiation due to pedoturbation, they have high clay contents, and during the dry seasons they develop deep wide cracks which close during wet seasons. They are characterized by dark colour throughout the profile indicating that organic matter is intimately associated with the expanding lattice clays. The micro-relief is dominantly gilgai, which is a result of the physical behaviour of most vertisols. The subsurface horizons are characterized by partly intersecting slickensides. Profile LUB 1 has a petrocalcic horizon below 90 cm from the soil surface and has platy Ca-concretions throughout the B horizon.

Chemical and mineralogical properties

The profiles have a high cation exchange capacity (CEC) and a high base saturation of > 90%. The soil reaction ranges from mildly alkaline in the surface to moderately alkaline in the subsurface horizons. The CEC in profiles LUB 1 and MK 2 is very high in the range of 28 - 58 cmol(+)/kg dry soil, and 48 - 97 cmol(+)/kg clay (Table 4.1).

The clay mineralogy of profiles LUB 1 and MK 2 (Table 4.2) is dominated by smectite. The two profiles are therefore classified under the smectitic mineralogy class (Soil Survey Staff, 1996). The high amounts of smectite in these soils accounts for their high CEC and their other physico-chemical characteristics. Profile MK 2 contains also considerable amounts of kaolinite and illite (mainly dioctahedral) and some K-feldspars, plagioclases and quartz, whereas profile LUB 1 contains some hydroxy-interlayered vermiculite (HIV), kaolinite and quartz and only traces of K-feldspars and plagioclases.

In situ weathering, addition of fluvial materials and sheet erosion from the middle and upper parts of the toposequence make the interpretation of the soil forming processes complex. However, the source of high contents of smectite could be one or more of the following:

a) *formation from solution*: it is likely the main source of smectite in these soils. Genesis and preservation of smectite in a soil environment requires restricted drainage conditions and accumulation in the solum of its elemental constituents including basic cations such as Ca and Mg (Borchardt, 1989). Imperfect drainage conditions of these profiles, and possible accumulation of basic cations leached from the middle parts of the toposequence provide a suitable environment for precipitation of smectite from solution.

b) *transformation from mica*: transformation smectite is known to be formed from micaceous minerals. Environmental requirements for this process have been documented by Borchardt (1989) and Fanning et al. (1989). The low K^+ and Al^{3+} and high Ca^{2+} and Mg^{2+} contents, high soil pH of > 7.0, imperfect drainage, presence of illite and wetting and drying conditions in profile MK 2 provide a suitable environment for transformation of clay-size mica (illite) to smectite. Normally, the process is by depotassication as follows:

$$\text{Illite (or micas)} \xrightarrow{-K\ +\ \textit{hydrated exchangeable cations}} \underset{\textit{(unstable intermediate)}}{\text{Vermiculite}} \rightarrow \text{Smectite}$$

c) *inherited smectite*: some of the smectite could be inherited from the fluvial materials deposited in this part of the landscape. Since most soils of the extensive Wami-Mkata plains are smectitic, deposition of smectite containing wind-blown dust could be an additional source.

The silt and sand fractions of profiles LUB 1 and MK 2 are mainly composed of quartz, plagioclase and K-feldspars (Tables 4.4 and 4.5). They also contain some amphiboles. The contents of amphiboles in these fractions must be associated with its presence in the underlying rocks (Sørensen and Kaaya, 1998).

4.2 Soil genesis

Pedogenesis has been described by Graham *et al.* (1994) as a result of processes within the regolith that are driven by external environmental factors. These soil-forming processes produce a set of properties which differentiate the soil material into genetic horizons. According to Soil Survey Staff (1996), genetic horizons are not the equivalent of the diagnostic horizons of the U.S. Soil Taxonomy. Designations of genetic horizons express a qualitative judgment about the vector of changes that are believed to have taken place, while diagnostic horizons are quantitatively defined features used to differentiate between taxa in the U.S. system of Soil Taxonomy. Horizon symbols indicate the direction of presumed pedogenesis while diagnostic horizons indicate the magnitude of that expression. In this study, soil genesis is discussed in relation to soil forming processes which resulted in the formation of genetic horizons in the studied profiles.

The surface horizons in all the studied profiles have developed as a result of organic matter being intimately mixed with mineral fractions. This accounts for their relatively dark colour compared to that of the subsurface horizons. Man, through activities such as grazing, bush fires and deforestation have to a large extent modified the physical and chemical properties of the surface horizon of these soils. Processes leading to development of the subsurface horizons vary from one profile to another in the toposequence depending on the nature of parent material and position of the profile in the terrain.

Profiles KIP 3 and KIP 1

Profiles KIP 1 and KIP 3 have an Ah-Bw-C horizon sequence and they represent moderately developed soils showing slight or moderate weathering of the parent material. Soil erosion on the surface accounts for the thin surface horizon in profile KIP 3 and other soils on the ridge. Weathering or transformation of primary minerals from the parent materials in profiles KIP 1 and KIP 3 is not yet at an advanced stage, as indicated by the presence of appreciable amounts of weatherable minerals in all fractions (Tables 4.3, 4.4 and 4.5). Hydrolysis of easily weathered primary minerals has resulted in formation of some clays and liberation of some sesquioxides as shown by the reddish soil colour. These processes have resulted in formation of the Bw horizon. Presence of reddish mottles and Fe-Mn concretions in the lower part of profile KIP 1 suggests that oxidation, reduction and segregation of iron and manganese have also been important processes. Location of this profile in a local depression on the slope created restricted drainage conditions which favoured oxidation-reduction reactions. In the process, soluble Fe and Mn were translocated by leaching, and then precipitated into mottles and concretions as a result of fluctuating water table (perched) in the lower part of this profile.

Profiles LUB 5, LUB 4 and LUB 3

These profiles are considered together because they have almost similar morphological, physical and mineralogical properties. Although the C horizon was below the profile depths, they all have the A-Bt-C horizon sequence. These profiles might have started their development under a wetter climate than the present, but with alternating wet to dry seasons. The occurrence of ferricretes in the lower part of profile LUB 3 (which is located in the lower part of the landscape) could be an indication of wetness in the past. The profiles have developed mostly from the underlying hornblende-biotite gneiss rocks. The strong leaching conditions resulted in strong weathering which is clearly indicated by dominance of kaolinite in the clay fraction, and by low contents of easily weatherable minerals in the silt and sand fractions of these profiles (Tables 4.3, 4.4 and 4.5). The dark red colour of these profiles is a result of 'rubifaction', a process which involves release of Fe from primary minerals and dispersion of Fe-oxide particles in increasing amounts, and their progressive dehydration (or oxidation) giving the soil mass red colours (Arnold, 1983).

The profiles have developed a thick Bt horizon, a mineral horizon with accumulation of silicate clays some of which has formed in the horizon by weathering processes, as a result of illuviation. The presence of clay cutans in the B horizon and low contents of clay in the overlying eluvial horizons are evidences of movement of clay in suspension and their subsequent deposition in this horizon. The strong clay mineralogical similarity which exists between the eluvial and illuvial horizons (Table 4.3, profiles LUB 3 and LUB 5) also supports clay migrating dominantly as clay rather than products of weathering that were later synthesized to form clay-sized particles. Presence of some amounts of 2:1 layer lattice clays and their decrease with increasing profile depth could be due to aeolian deposition in more recent times (between 4500 and 3800 yrs. before present) when the climate had changed towards drier and windier conditions in tropical Africa (Talbot, 1981). The most probable source could be wind-blown smectite deposits from the Wami-Mkata plains.

Below the Bt horizon in profile LUB 3, lies ferricrete layer. Formation of this layer must have resulted from absolute accumulation of sesquioxides through enrichment from outside the horizon. These would be brought by vertical and lateral movements following strong weathering in the overlying horizons, and in the upper parts of landscape respectively. The accumulation was followed by segregation of iron mottles, due to alternating reduction-oxidation conditions caused by seasonal fluctuations of water table at this level during the time of their formation. In times of water saturation, the iron was in ferrous form and due to its high mobility it was easily redistributed. When the water table was lowered, the iron precipitated as ferric oxide which would not , or only partially re-dissolve in the next wet season. As the land became drier and deforestation occurred following the change in climate, hardening (or dehydration) of the precipitated ferric oxides occurred, forming ironstone (ferricretes). The water table could also have been lowered due to down cutting of the nearby Mbesegera River tributary.

Profile LUB 2

Profile LUB 2 has mainly developed from pre-weathered fluvial materials from the upper parts of slope. These materials were transported and deposited by one of the Mkata River tributaries during periods of high humidity in the early Holocene or earlier. It is also possible that some aeolian deposits of base-rich weathered materials were added during the drier and windier conditions in tropical Africa between 4500 and 3800 yrs before present (Talbot, 1981). It is likely that development of this profile started when the climatic conditions were dry, and favourable for accumulation of carbonates. The horizon sequence of the profile is Ah-Bw-Bck-Cck indicating some carbonate accumulation in the form of concretions in the lower part of the B horizon. However, the Ca-content was estimated to be insufficient to meet requirements for diagnostic calcic horizon (FAO, 1988; Soil Survey Staff, 1996). The main pedogenic processes involved in development of this profile is removal of carbonates from the upper horizons (decalcification) and their accumulation in the lower B horizon (calcification). The lower contents of carbonates in the surface and lowermost horizons compared to the middle horizons indicates that the accumulation was mainly pedogenic, although contributions from groundwater can not be ruled out. The amounts of carbonates were estimated from the abundance of Ca-carbonate concretions and the strength of effervescence produced by the soil matrix when tested with diluted HCl.

Profiles LUB 1 and MK 2

These profiles represent the vertisols of this area. They have developed in local depressions and almost flat landforms. Their parent material could be a mixture of the saprolite weathered from the underlying hornblende-biotite gneiss and fluvial materials of different ages. Various dated materials indicate that the age of soil material range from < 3800 years on the bank of Mkata River tributary to > 47 kyr near profile LUB 1 (Sørensen and Kaaya, 1998). Smectite dominate the clay mineralogy in the two profiles, although profile MK 2 (near Mkata River) contains relatively less amounts of smectite and higher contents of kaolinite, illite, K-feldspars and plagioclase which must have been inherited from the fluvial materials. The Ca, Mg and Si-rich environment in the area is favourable for their transformation to smectite. The neo-formation of smectite from parent materials containing transported hydrous mica (illite) and kaolinite were also reported by Moberg et al. (1982) on the soils of the Ngerengere River valley, between Mindu and the Uluguru mountains. Hydroxy-interlayered vermiculite (HIV) was present only in profile LUB 1.

Sørensen and Kaaya (1998) reported active fluvial deposition in the river valleys and slight local erosion and deposition of soil materials due to variation in micro-relief on the Mkata plains. The plains are characterized by the occurrence of slightly elevated wide interfluves separated by slight depressions giving rise to a relative relief of up to 2 m. The gravel pit near Mkata Ranch is located on one of these interfluves in the flat Mkata plains.

Fluvial deposition on the river plains during the Holocene have resulted in the formation of very young (< 3.8 kyr) vertisols near river valleys. Relatively much older vertisols occur elsewhere in the Wami-Mkata plains. The clay mineralogy of profiles MK 2 (near Mkata River) and LUB 1 (about 9 km away from Mkata River) supports this observation (Table 4.3). Profile LUB 1 contains comparably less weatherable primary minerals and more smectite which is more stable under the current environmental setting of the area and their position on the slope. It seems that most of the primary minerals in the relatively older vertisols (LUB 1) have been weathered to smectite.

Several soil forming processes have been active in formation of these profiles, but haploidization by pedoturbation seems to have been dominant. Wetting and drying cycles cause shrinking and swelling of expanding clays resulting into deep wide cracks which facilitate churning (self mulching). These processes have resulted in formation of vertic structure in the subsoils and gilgai surface micro-topography. Also, shrink and swell characteristics in these profiles has caused some coarse fragments including calcretes in profile LUB 1 to be pushed to the surface. The mechanisms of these processes are well documented in most of the literature about genesis of vertisols.

Formation, distribution and properties of calcretes in this area have been described in detail by Sørensen and Kaaya (1998). This is closely associated with the formation of a petrocalcic horizon below 90 cm depth in profile LUB 1. Radiocarbon dating shows that this horizon is older than 47 kyr (sample B- 81839 by Sørensen and Kaaya, 1998), which is in agreement with the idea that petrocalcic horizons occur mainly in soils older than Holocene. The radiocarbon date of the petrocalcic horizon in profile LUB 1 and the clay and silt mineralogy of profiles LUB 1 and MK 2 reflect a more advanced (older) soil development in profile LUB 1 compared to profile MK 2.

The main pedogenic processes involved in the development of petrocalcic horizon in profile LUB 1 (including Ca-carbonate accumulations in profile LUB 2) is decalcification in upper horizons and subsequent calcification in the subsoil. Pedogenic accumulations of $CaCO_3$ normally occur in semi arid climates with annual rainfall between 400 - 600 mm. The process involves dissolution and leaching of $CaCO_3$ from the overlying horizons during humid seasons, and their subsequent accumulation and hardening in the dry seasons. The sources of high contents of Ca in these soils could be enrichment of Ca by lateral soil water movements, Ca-rich aeolian deposits during the dry and windy periods in tropical Africa (Talbot, 1981) and surface erosion of the Ca-rich aeolian deposits from the upper slope positions.

4.3 Soil classification

Classification of the studied profiles in the US Soil Taxonomy (Soil Survey Staff, 1996) and in the FAO-Unesco system (FAO, 1988) and the applied diagnostic criteria are presented in Tables 4.6 and 4.7, respectively. Following the definitions by the Soil Survey Staff (1996), the soil temperature and moisture regimes throughout the toposequence are *iso-hyperthermic* and *ustic*, respectively. The profiles were classified to family level in the US Soil Taxonomy and to soil unit level in the FAO-Unesco system. Since most of the diagnostic horizons and characteristics used by these classification systems are related to pedogenic processes, the results of soil classification reflect to a large extent the genesis and degree of weathering of the studied profiles.

Sandy soils in moderately to severely eroded upper parts of the slope and ridge tops (profiles KIP 1 and KIP 3) have only developed a cambic (cambic B) horizon in addition to an ochric epipedon (ochric A) indicating weak to moderate profile development. Profiles KIP 1 and KIP 3 are therefore classified as Typic Ustropepts and Oxic Ustropepts, respectively, both under the family *fine, mixed, iso-hyperthermic* (Soil Survey Staff, 1996); and both profiles as Chromic Cambisols in the FAO-Unesco system.

The middle part of the toposequence contains relatively more weathered soils compared to the upper or lower positions in the toposequence. Its soils have developed an argillic (argic B) horizon below an ochric epipedon (ochric A) or a kandic horizon with low nutrient reserves but high base saturation. Due to the presence of an argillic horizon with CEC between 16 and 24 cmol(+)/kg clay, profiles LUB 3 and LUB 4 were classified as Kandic Paleustalf, under the family *fine, kaolinitic, iso-hyperthermic*. Profile LUB 5 which have a kandic horizon with CEC $\leq$ 16 cmol(+)/kg clay and ECEC $\leq$ 12 cmol(+)/kg clay was classified as Rhodic Kandiustalf under the family *very fine, kaolinitic, iso-hyperthermic* in the Soil Taxonomy. Due to their high base status and low CEC, the three profiles in the middle slope were classified as Haplic Lixisols in the FAO-Unesco system.

Profile LUB 2, which has most likely developed from fluvial materials, is in a transition zone between well drained red soils on the middle slope and the imperfectly drained black (or mbuga) soils of the lower terrain in the toposequence. Presence of fluvic properties and developments of both an ochric epipedon (ochric A horizon) and a cambic (cambic B) horizon were used to classify the profile to subgroup level, and at the family as Fluventic Ustropept, *fine, mixed, iso-*

hyperthermic in the US Soil Taxonomy. The same properties plus the calcareous nature of the profile were used in classifying the profile as Calcaric Fluvisol in the FAO-Unesco system. Classification of this profile in the FAO-Unesco system reflects the genesis of this profile better than the US Soil Taxonomy system because both the fluvic properties and the calcareous nature of the profile are reflected in the soil unit, whereas in the US Soil Taxonomy only the fluvic properties are reflected.

High clay contents, presence of intersecting slickensides and cracks that open and close periodically with seasons were used to classify profiles LUB 1 and MK 2 into suborder Ustert in the US Soil Taxonomy. Profile LUB 1 was classified into the Petrocalcic Calciustert subgroup due to presence of a petrocalcic horizon, while profile MK 2 was classified into the Chromic Haplustert subgroup due to high pH (in water), and absence of a salic, calcic or petrocalcic horizon, and its colour value moist of ≥ 4 throughout the profile. The two profiles are placed in the family: *fine, smectitic, iso-hyperthermic* . In the FAO-Unesco system, the same profile characteristics together with base saturation of ≥ 50% were used to classify profile MK 2 into soil unit Eutric Vertisol; while profile LUB 1 was classified as Calcic Vertisol due to presence of a petrocalcic horizon below 90 cm from the surface.

Table 4.6 Diagnostic characteristics and classification of the studied soil profiles into the USDA Soil Taxonomy system (Soil Survey Staff, 1996)

Profile No.	Diagnostic horizons	Diagnostic criteria used to classify the profiles from order to family level (Soil Survey Staff, 1996)[¶]	Soil classification
KIP 3	i) Ochric epipedon, ii) Cambic horizon	a) presence of cambic horizon and an ochric epipedon; b) iso-temperature regime warmer than iso-mesic (iso-hyperthermic); c) ustic soil moisture regime and a base saturation of ≥ 50 % throughout the profile, d) CEC of ≤ 24 cmol(+) kg^{-1} clay throughout the profile e) loamy particle-size class; mixed mineralogy class, iso-hyperthermic soil temperature regime, shallow	Oxic Ustropepts, fine, mixed, iso-hyperthermic
KIP 1	i) Ochric epipedon, ii) Cambic horizon	a) presence of cambic horizon and an ochric epipedon; b) iso-temperature regime warmer than iso-mesic (iso-hyperthermic); c) ustic soil moisture regime and a base saturation of ≥ 50 % throughout the profile, d) meets none of the requirements for the other sub groups e) fine particle-size class; mixed mineralogy class, iso-hyperthermic soil temperature regime	Typic Ustropepts, fine, mixed, iso-hyperthermic
LUB 5	i) Ochric epipedon, ii) Kandic horizon	a) presence of argillic horizon and a base saturation > 35 %; b) ustic moisture regime; c) CEC of ≤ 16 cmol(+) kg^{-1} clay and an ECEC of ≤ 12 cmol(+) kg^{-1} clay throughout the argillic horizon; no densic, lithic, paralithic or petroferric contact or clay decrease with increasing depth of ≥ 20 % (relative) from the maximum clay content within 150 cm of the mineral soil surface. d) kandic horizon with a hue of 2.5YR or redder, a value moist of ≤ 3 and a value dry ≤ one unit higher than the value moist e) very fine particle-size class; kaolinitic mineralogy class, iso-hyperthermic soil temperature regime.	Rhodic Kandiustalfs, very fine, kaolinitic, iso-hyperthermic
LUB 4	i) Ochric epipedon, ii) Argillic horizon	a) presence of argillic horizon and a base saturation > 35 %; b) ustic moisture regime; c) no densic, lithic, or paralithic contact within 150 cm of the mineral soil surface and an argillic horizon which within 150 cm of the mineral soil surface has no clay decrease with increasing depth of ≥ 20 % (relative) from the maximum clay content, and its lowest sub-horizon has a hue redder than 7.5YR and a chroma of > 5; d) CEC of < 24 cmol(+) kg^{-1} clay throughout the argillic horizon. e) fine particle-size class, kaolinitic mineralogy class, iso-hyperthermic soil temperature regime.	Kandic Paleustalfs, fine, kaolinitic, iso-hyperthermic
LUB 3	As LUB 4 above	As for LUB 4 above (a to e)	As LUB 4 above

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[¶] a) Order level; b) Sub order level; c) Great group level; d) Sub group level, e) Family level

Table 4.6 continued

Profile No.	Diagnostic horizons	Diagnostic criteria used to classify the profiles from order to family level (Soil Survey Staff, 1996)¶	Soil classification
LUB 2	i) Ochric epipedon, ii) Cambic horizon	a) presence of cambic horizon and an ochric epipedon; b) iso-temperature regime warmer than iso-mesic (iso-hyperthermic); c) ustic moisture regime and a base saturation of ≥ 50 % throughout the profile; d) irregular decrease in organic carbon content from a depth of 25 cm from the mineral soil surface to a depth of 125 cm and almost flat plain. e) fine particle-size class; mixed mineralogy class, iso-hyperthermic soil temperature regime	Fluventic Ustropepts, fine, mixed, iso-hyperthermic
LUB 1	i) Ochric epipedon, ii) Cambic horizon, iii)Petrocalcic horizon	a) intersecting slickensides; a clay content of > 30 % in the fine earth fraction throughout the profile; cracks that open and close periodically; b) cracks are > 5 mm throughout the profile for > 90 cumulative days per year (ustic soil moisture regime); c) $\text{pH}_{\text{(water)}} > 5.0$, presence of petrocalcic horizon with its upper boundary within 100 cm of the mineral soil surface (below 90 cm) and absence of salic and gypsic horizons; d) petrocalcic horizon with its upper boundary within 100 cm of the mineral soil surface (below 90 cm); e) fine particle-size class; smectitic mineralogy class, iso-hyperthermic soil temperature regime.	Petrocalcic Calciusterts, fine, smectitic, iso-hyperthermic
MK 2	i) Ochric epipedon, ii) Cambic horizon	a) Similar to a) in KIP 1 above b) Similar to b) in KIP 1 above c) $\text{pH}_{\text{(water)}} > 5.0$, lacks salic, gypsic, calcic or petrocalcic horizons; d) a colour value, moist ≥ 4 throughout the profile, e) fine particle-size class; smectitic mineralogy class, iso-hyperthermic soil temperature regime.	Chromic Haplusterts, fine, smectitic, iso-hyperthermic

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¶ a) Order level; b) Sub order level; c) Great group level; d) Sub group level, e) Family level

Table 4.7 Diagnostic characteristics and classification of the studied soil profiles according to the revised legend of the FAO-Unesco (1988)

Profile No.	Diagnostic horizons	Diagnostic properties and other profile characteristics used for classification to major soil groups and soil units	Soil classification
KIP 3	Ochric A, Cambic B	no other diagnostic horizons; base saturation of > 50% throughout the profile; lacks salic properties; lacks characteristics diagnostic for vertisols; lacks gleyic properties within 50 cm of the surface; non calcareous throughout the profile; hue redder than 7.5YR in the cambic B horizon; lacks vertic and gleyic properties 100 cm of the surface.	Chromic Cambisols (CMx)
KIP 1	Ochric A, Cambic B	Similar to KIP 3 above	Chromic Cambisols (CMx)
LUB 5	Ochric A, Argic B	abrupt textural change from the surface horizon to the B_{t1} horizon; argic horizon with CEC of < 24 cmol(+) kg^{-1} clay and a base saturation of ≥ 50 % throughout the B horizon; lacks albic E horizon, ferric properties and plinthite within 125 cm of the surface; lacks gleyic and stagnic properties within 100 cm of the surface.	Haplic Lixisols (LXh)
LUB 4	Ochric A, Argic B	Similar to LUB 5 above.	Haplic Lixisols (LXh)
LUB 3	Ochric A, Argic B	Similar to LUB 5 above.	Haplic Lixisols (LXh)
LUB 2	Ochric A, Cambic B	no other diagnostic horizons; fluvic properties; absence salic properties and characteristics diagnostic for vertisols; absence of gleyic properties within 50 cm of the surface; calcareous below 28 cm to depth > 200 cm (calcaric); lack of vertic properties.	Calcaric Fluvisol (FLc)
LUB 1	Ochric A, Cambic B, Petrocalcic horizon	> 30 % clay content in the fine earth of all horizons to a depth > 90 cm; cracks of ≥ 1 cm width from the surface to a depth of > 50 cm during the dry seasons; intersecting slickensides below 12 cm to 90 cm depth; petrocalcic horizon below 90 cm of the soil depth.	Calcic Vertisol (VRk)
MK 2	Ochric A, Cambic B	> 30 % clay content in the fine earth of all horizons to a depth > 150 cm; cracks of ≥ 1 cm width from the surface to a depth of > 50 cm during the dry seasons; intersecting slickensides below 12 cm to > 159 cm depth; absence of gypsic, calcic horizons or soft powdery lime within 125 cm of the surface; base saturation of > 50% throughout the profile.	Eutric Vertisols (VRe)

5. Summary and conclusions

The soil profiles investigated represent a typical toposequence in the Lubungo-Mkata area. The results of the study indicate that parent material and landscape position greatly influence pedogenic processes and consequently the morphological, physico-chemical and mineralogical properties of the soils in the toposequence. Møberg (1981) and Moberg et al. (1982) reported almost similar variations in soils of the northwestern slopes of the Uluguru mountains in Morogoro.

Lateral variations in the initial parent materials exists along the toposequence, and this has been demonstrated clearly by abrupt changes in the morphological, physico-chemical and mineralogical characteristics of the studied soil profiles. Abrupt changes are observed especially from the soils of the upper parts of the toposequence to those in the middle parts, and also from the soils of the middle parts of the toposequence to those of the lower terrain positions. Soils in the upper parts of the slope around Mindu and Sangasanga-Kipera ridge (profiles KIP 1 and KIP 3) have developed in a saprolite from quartz-rich two-mica gneisses and migmatites (Sørensen and Kaaya, 1998) resulting in the formation of moderately weathered, light coloured and shallow to moderately deep, dominantly sandy soils. Their clay mineralogy is dominated by almost equal amounts of illite and kaolinite, while their silt and sand fractions are dominated by quartz, K-feldspars and plagioclase (mostly oligoclase). The soils in well drained middle parts of the slope (profiles LUB 5, LUB 4 and LUB 3) have developed mainly from *in situ* weathered micaceous and hornblende gneisses which have relatively high contents of easily weatherable minerals such as biotite and other iron-rich minerals (Sørensen and Kaaya, 1998), resulting in the formation of deep, highly weathered red soils with high contents of kaolinitic clay. Their silt and sand mineralogy is dominantly quartz with small amounts of feldspars and some ilmenite indicating a more advanced stage of weathering. The highly resistant ilmenite was found only in highly weathered red soils in the middle parts of the toposequence. Its presence agrees with the suggestion by Kaaya et al (1998) that ilmenite may be a marker mineral for soils developed from this particular geological unit.

The black soils in the lower part of the slope (profiles LUB 2, LUB 1 and MK 2) have mainly developed from fluvial materials of variable ages. Although some of their parent materials have weathered from the underlying rocks, there exist a close catenary relationship between the soils in the middle part of the slope and those on the lower parts of the slope. Surface erosion plays a role in transportation of some weathered materials including hydrous mica (illite) and kaolinite from the middle slope and their subsequent deposition in the lower terrain positions where they undergo transformation to smectite. Also, weathering of iron-rich hornblende-biotite gneisses in the well drained environment on middle slope positions release basic cations into the soil solution, which are then subjected to leaching. Consequently, these ions are laterally translocated and they accumulate in the lower terrain positions which are imperfectly drained. The accumulation of basic cations especially Ca and Mg in this high pH and Si-rich environment provides favourable conditions for smectite formation, and consequently formation of vertisols (profiles LUB 1 and MK 2). As bases are leached from the more weathered soils in the middle parts of the slope, it is expected that Fe^{3+} compounds would remain in the soil and aluminium would mostly be retained in kaolinite, and some in Al-oxides. These processes account for the red colour and kaolinitic mineralogy of profiles LUB 3, 4 and 5.

Based on the Soil Taxonomy (Soil Survey Staff, 1996) and the FAO Unesco system (FAO,1988) in brackets, the soils of the Lubungo-Mkata toposequence are classified as Oxic Ustropepts (Chromic Cambisols) and Typic Ustropets (Chromic Cambisols) in the upper parts of the toposequence; Rhodic Kandiustalfs (Haplic Lixisols) and Kandic Paleustalfs (Haplic Lixisols) in the middle parts of the toposequence; and Fluventic Ustropepts (Calcic Fluvisols), Petrocalcic Calciusterts (Calcic Vertisols) and Chromic Haplusterts (Eutric Vertisols) in the lower parts of the toposequence. Adequacy of a soil classification depends on the purpose for which it is intended. Although there are minor exceptions, the two classification systems used in this study seem to provide fairly adequate groupings of the studied soil types for land suitability evaluation especially at higher categories. For example the sandy soils in the upper parts of the toposequence where erosion is severe, are classified or grouped as Inceptisols (US Soil Taxonomy), or as Chromic Cambisols (FAO-Unesco). Depending on the land use type, most of the required soil qualities can be inferred from their classification. In the more weathered soils of the middle slope, the US Soil Taxonomy provides more relevant information to soil suitability evaluation because it differentiates the soils in two taxonomic groups based on their natural fertility status (i.e. Paleustalfs and Kandiustalfs), while the FAO-Uneso puts all of them in the same group (i.e. Haplic Lixisols). The FAO-Unesco soil unit Haplic Lixisol may possibly be modified at sub unit level so as to differentiate Haplic Lixisols with CEC ≤ 16 cmol(+)/kg clay from those with CEC > 16 cmol(+)/kg clay. This will also allow for better correlation between the two classification systems. The calcareous nature of profile LUB 2 is not reflected in the US Soil Taxonomy classification, but in the FAO-Unesco system. Since this property is one of the important soil qualities in evaluation of soil suitability for various annual crops, it would be more useful if it could be inferred from the taxonomic unit. The vertisols seems to be adequately classified in both systems to provide most of the information required for land evaluation for the existing land use types.

From the definitions of diagnostic horizons (Soil Survey Staff, 1996), an argillic horizon with CEC of ≤ 16 cmol(+)/kg clay may sometimes meet the requirements for a kandic horizon. This problem was encountered in classification of profile LUB 5 in the US Soil Taxonomy. However, in the classification of this profile, the diagnostic horizon was considered to be a kandic horizon. To clear this confusion it is suggested to include in the definition of the argillic horizon, a phrase that will exclude horizons which have a set of properties that define a kandic horizon.

The results of this study form the basis for further interpretations in terms of land suitability evaluation of the soils of the Lubungo-Mkata area for the existing and other alternative sustainable land use types. This is planned as a next step of this study and the results will be presented as a separate report. In the process, the results of this study will be one of the important inputs for land suitability evaluation which will also involve developing soil management technologies for sustained land use systems in the Lubungo-Mkata area. Since most of the cultivated soils in the northern part of Morogoro District are either similar to those in the middle parts of the slope (Alfisols / Lixisols) or to those on the lower parts of the slope (vertisols or soils with vertic properties) the soil management technologies for the Lubungo-Mkata area can easily be transferred to other parts of the district with similar soils and similar environmental conditions.

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