Soil formation by termites
a study in the Kisii area, Kenya

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Proefschrift

ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
op gezag van de rector magnificus,
dr. C. C. Oosterlee
in het openbaar te verdedigen
op woensdag 24 oktober 1984
des namiddags te vier uur in de aula
van de Landbouwhogeschool te Wageningen.

Copies may be purchased from the Department of Soil Science and Geology, Agricultural University, P.O. Box 37, 6700 AA WAGENINGEN, The Netherlands. The price of Dfl. 16,- includes postage.

STELLINGEN

1. Biologische processen in de bodem zijn van wezenlijk belang voor het voortbestaan en de ontwikkeling van kapitaal-arme landbouwbedrijven in de tropen.

Dit proefschrift.

2. Het verdient aanbeveling meer onderzoek te doen aan de manipulatie van de bodemfauna.

Dit proefschrift.

3. De biologische activiteit draagt, sterk bij tot een vermindering van de erodeerbaarheid van gronden.
Bij de bepaling van de K-faktor wordt hiermee over het algemeen geen rekening gehouden.

Zie bijv. Greenland, D.J. en R. Lal (eds.) 1977. Soil conservation and management in the humid tropics. John Wiley and Sons.

4. Geomorfologen gaan er meestal van uit, dat "stone lines" in tropische bodems het gevolg zijn van erosie en sedimentatie. Deze hypothese kan leiden tot verkeerde conclusies over landschapsvorming en over paleoklimaten.

Zie bijv. Ab Saber, A.N., 1982 in: Biological diversification in the Tropics, p. 41-59 en Ruhe, R.V., 1959. Soil Sci. 87: 223-231.

5. Bij het opstellen van legenda's voor bodemkaarten, waarbij moedermateriaal als indelingscriterium wordt gebruikt, houdt men vaak onvoldoende rekening met bijmenging van aeolische sedimenten.

"Reconnaissance Soil Survey Reports" van de Kenya Soil Survey.

6. Genese en eigenschappen van gronden met weinig actief aluminium maar toch veel röntgenamorf materiaal zijn onvoldoende onderzocht.

Wielemaker, W.G. en T. Wakatsuki, 1984. Geoderma 32: 21-44.

7. Veel eigenschappen van kleideeltjes worden meer bepaald door de aard van het oppervlak dan door hun chemische samenstelling en struktuur.

8. Het veelvuldig voorkomen van Planosolen op vulkanische as zoals o.a. beschreven voor Chili en Colombia, hangt samen met de grote mobiliteit van de klei.

Chili: Servicio Agricola y Ganadero, 1968. Estudio agrologico del area del embalse digua, 72 p.
Colombia: Faivre, P., 1977. Science du Sol 2: 95-108.

9. In zijn bespreking van de goede resultaten van "multiple cropping systems" veronachtzaamt Sanchez ten onrechte de invloed van de bodemfauna en de bodemflora.

Sanchez, P.A., 1976. Properties and management of soils in the tropics. John Wiley and Sons.

10. Gevleugelde termieten (alaten) zouden een belangrijker deel kunnen uitmaken van de voeding van de bevolking in de tropen dan thans het geval is.

11. Tot de zorg voor ons milieu behoort ook de handhaving van de winkel op de hoek.

Proefschrift van W.G. Wielemaker
Soil formation by termites, a study
in the Kisii area, Kenya
Wageningen, 24 oktober 1984

Abstract

Wielemaker, W.G., 1984. Soil formation by termites, a study in the Kisii area, Kenya. Doctoral thesis, Department of Soil Science and Geology, Agricultural University, Wageningen (XII) + 132 p., 16 tables, 39 figs, 119 refs, 4 appendices, Dutch summary.

Mineralogical and chemical characteristics of samples from a number of soils were used to demonstrate that soil materials from volcanic ash and local rock are thoroughly mixed.

The mineralogy, micromorphology and grain-size distribution were studied to estimate the role of termites in mixing soil materials and in forming physical properties. Effects of other processes on mixing and on formation or decay of physical properties were also estimated.

The role of termites in forming horizons free of gravel underlain by stone lines, and in slope processes, was estimated from an analysis of grain-size distribution and mineralogy of soils in a catena. Measurements of slope transport were also made.

The significance of termites for soil conservation and for a sustained use of the land, is discussed.

Key words: termites, mixing, soil formation, agro-ecosystems, mineralogy, volcanic ash.

Aan mijn ouders

Aan Ad, Martin, Erik en Sander

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Thanks to the continuous support and helpful suggestions of professor Dr. L. van der Plas, I was able tò develop the appropriate mineralogical methods so essential for the theme of my work.

The Wanjare catena would not have been so thoroughly sampled and described if Dr. S. Slager has not been there to assist me and the students during fieldwork in Kenya and micromorphological work in Wageningen.

I thank the Kenyan authorities, particularly Mr. W.W. Wapakala, for the confidence entrusted in our University, when it applied for permission to start a field training programme in Kenya. That allowed me to know so many fine people in this part of Africa and to establish contacts with many institutes and research organisations.

I highly appreciate, among others, the long-lasting and friendly coöperation with the Kenya Soil Survey (Dr. N.N. Nyandat and Mr. F.N. Muchena), the University of Nairobi, Faculty of Agriculture (professor Dr. P. Ahn and professor Dr. S.O. Keya) and with the National Agricultural Research Station at Kisii (Mr. W. Nzabi). I also convey my thanks to the Department of Geology and Mines, which offered its facilities to investigate certain chemical and mineralogical characteristics of volcanic ash.

I am grateful to the following persons, who were with me in Kisii:
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C U R R I C U L U M   V I T A E

De auteur werd geboren in 1942 te Silvolde. In 1960 behaalde hij het diploma gymnasium- b aan het gemeentelijk Lyceum te Doetinchem, waarna hij aansluitend zijn studie aan de Landbouwhogeschool te Wageningen, begon. In 1968 studeerde hij af in de regionale bodemkunde (tropische specialisatie) met als keuzevakken de algemene bodemkunde en bemestingsleer en de cultuurtechniek.

Van 1968 tot 1971 was de auteur als assistentdeskundige bij de FAO werkzaam in bodemkarteringsprojekten t.b.v. irrigatie, in Chili. In 1971 werd hij aangesteld als medewerker tropische bodemkunde bij de vakgroep Bodemkunde en Geologie van de Landbouwhogeschool. In die funktie was hij o.a. werkzaam in Turkije (1971) en Kenia (1973-1979), waar hij leiding gaf aan bodemkundig onderzoek en onderwijs in projekten van deze vakgroep. In Kenia verrichtte hij tevens zijn promotieonderzoek, dat hij verder in Wageningen afrondde.

Contents page

1 Introduction

This report describes the effects of termite activity on soils in a humid tropical area in southwestern Kenya. Some attention was given to mole rats and ants, but their occurrence was less ubiquitous than that of termites. Only few earthworms were observed in the area of study, so their effect on soil was not studied. Microfauna and their effect on cycling of organic matter were not evaluated.

Despite Darwin's (1881) early work on the effects of earthworms on soils and landscapes, soil fauna received only scanty attention of soil scientists. The pages in journals and handbooks dedicated to soil fauna and its effect on soil are but few if compared with those dedicated to physical, chemical and mineralogical properties of soil (Hole, 1981).

This does not mean that the importance of soil fauna for the formation of soils was altogether ignored. In temperate regions, it was the Russian school of soil science, led by Dokuchaev (in Rode, 1962), who already in the past century emphasized the role of fauna in soil genesis. Dokuchaev stressed the concept of soil as a biogeocoenose or ecosystem of which fauna forms an integral part and not just its inhabitants. In this concept soil is a dynamic system in which soil formation changes if the biotic factor is affected. Such views spread through Europe and came especially to the fore in work of German (Kubiena, 1948; Laatsch, 1957), Dutch (Hoeksema and Edelman, 1960; Slager, 1966) and other European soil scientists (Russell, 1910; Lunt and Jacobson, 1944 and Ghilarov, 1956).

For tropical regions their view is underlined with work on termites of Drummond (1887), Dimo (1910, cited by Volubuev, 1964), Kalshoven (1936, 1941), Pendleton (1942), Grassé (1950), Hesse (1953, 1955), de Heinzelin (1955), Nye (1955), Boyer (1955, 1956) and many others to follow. Studies of other soil animals such as ants (Alvarado et al. 1981), worms (Scrickande and Pathak, 1951; Wasawo and Visser, 1959; Scheltema, 1964; Madge, 1969; de Meester, 1971, Lee, 1983 and Lavelle, 1983) and moles (Abaturov, 1972) are less numerous than those on termites, which indicates that termites are generally more important in tropical regions than the other mentioned soil animals. The importance of termites is further illustrated by the work of Zimmerman et al. (1982) who calculated that areas occupied by termites account for roughly two third of the earth's land area.

Moreover, termites and particularly the fungus growing *Macrotermitidae* are among the fastest and most efficient decomposers of dead organic material in nature (Wood and Sands, 1978). A large proportion of energy and nutrients locked up in organic matter, will thus be restored and used in the soil ecosystem. What is known about their effects on soil materials and their spatial arrangement has been reviewed by Lee an Wood (1971a) and will be discussed later in this report.

If termites so thoroughly affect tropical soils it is surprising that many earth scientists (Ruhe, 1956 and Bigarella, 1964 among others) did not recognize their importance. Even Mohr, van Baren and van Schuylenborgh (1972) in their "comprehensive" study on the genesis of tropical soils did not discuss the action of soil fauna, thus reducing soil to a lifeless entity. As regards termites, soil scientists commonly think of them as pests for crops, not being aware of their other role in ecosystems, nor realizing that only certain species are harmful for crops. Recently the termite's contribution to the world's annual production of carbon dioxide and methane was compared with that of other sources. Such studies, if not speaking of the role of termites in ecosystems, easily create a one-sided and therefore rather false imagery of their function in ecosystems, as is clear from a quotation of the study by Zimmerman et al. (1982) in Scientific American (1983) where termites were blamed for causing air pollution.

The author's interest in the effects of termite activity on soils was initially excited through the observation of the great number of termites in virtually every spade-full of soil and through the observation of the following properties which seemed related to their presence:

1. The deep reddish clay soils in the area of study were so porous and stable that no surface run-off and virtually no erosion were observed even on intensively cultivated slopes of up to 20 percent.
2. Soil materials above the stone line were homogeneous with virtually no gravel and with very gradual horizon boundaries, while in view of the well developed structure and the presence of argillans (Wielemaker and Boxem, 1982)

a clear horizon differentiation was to be expected.

3. Layers of volcanic ash, observed in very poorly drained soils, were not seen in adjacent well drained soils.

Could termites be responsible for the turbation of soil materials, the disappearance of layering and the creation of porous soils? If so, what could they have contributed to weathering, slope transport and landform?

The presence of volcanic ash with a chemistry and mineralogy so different from that of the older country rocks in Kisii (Wielemaker and Wakatsuki, 1984) would certainly leave its fingerprints if mixed with soil from country rock; so it seemed an excellent situation to illustrate the possible effects of termites on pedogenesis, in the area of study.

Would properties be equally affected by termites on all types of soil in the area of study or would there be differences according to the soil's suitability as a habitat for termites, or due to variation in land-use and vegetation and/or kind of soil materials? The answer to such questions seems important in view of the present labour intensive type of agriculture practiced on the well drained soils. The impact of agricultural management practices, such as introduction of new crops, cropping practice, fertilizers, pesticides and machinery, on termite populations is not known. If termites are beneficial for the productivity of soils what would then happen to this productivity if termites were harmed so that their numbers declined?

Before the questions raised above are discussed, the reader finds in Chapter 2, a description of the present environment and its historical development. Changes in climate and vegetation will get particular attention, because they may have affected faunal activity in soils. Most important meso and macrofauna[1] representatives in the area under study are described here as well. Then, in Chapter 3, a short description follows of the soils studied and why they were chosen.

The actual results of studies are divided in two parts. The first part deals with mineralogical and chemical methods used in estimating degree of admixture of various soil materials (Chapter 4). This is background information for Chapters 5, 6 and 7, where the role played by termites in formation of soils, is treated. Chapter 5 describes factors affecting their distribution and activity in soils and also some effects of their activity on

1. Mesofauna comprises animals that are 0.2-10 mm long, macrofauna comprises animals that are longer than 1 cm (Wallwork, 1970).

chemical properties of soil. Then, in Chapter 6, follows an appraisal of pedogenetic processes responsible for mixing and of the role played by termites. Chapter 7 describes what effect termites have on formation of texture profiles and stone lines and what this means for soil and landscape formation.

Data of studies discussed in Chapters 5, 6 and 7 are synthesized in Chapter 8, where it is attempted to construct a model explaining the role of termites in natural and agro-ecosystems and the factors that control their functioning and effectivity in those systems. What termites possibly mean for a sustained use of the land and how they interact with various land-use practices is discussed as well and some ideas are advanced on how agriculture can profit from soil biological processes in general and from termites in particular.

2 The physical and biological environment

2.1 SITUATION, ALTITUDE AND POPULATION

The region of study is situated just south of the equator in the south-western part of Kenya and comprises an area, which extends from the Great Rift Valley in the east to near Lake Victoria in the west (Fig. 1). The area where most of the research was concentrated (Fig. 1) has an altitude of 1300 to 2130 m a.s.l. (Fig. 3).

The rolling to hilly landscape with generally deep soils is intensively cultivated by the Kisii who are Bantus (Ochieng, 1974). Luos, who are Nilotes (Ogot, 1967), live in the lower, drier and western part, which has a rolling topography. The latter part, where more soils are shallow and poorly drained than in the higher part, is not so intensively cultivated (Wielemaker and Boxem, 1982).

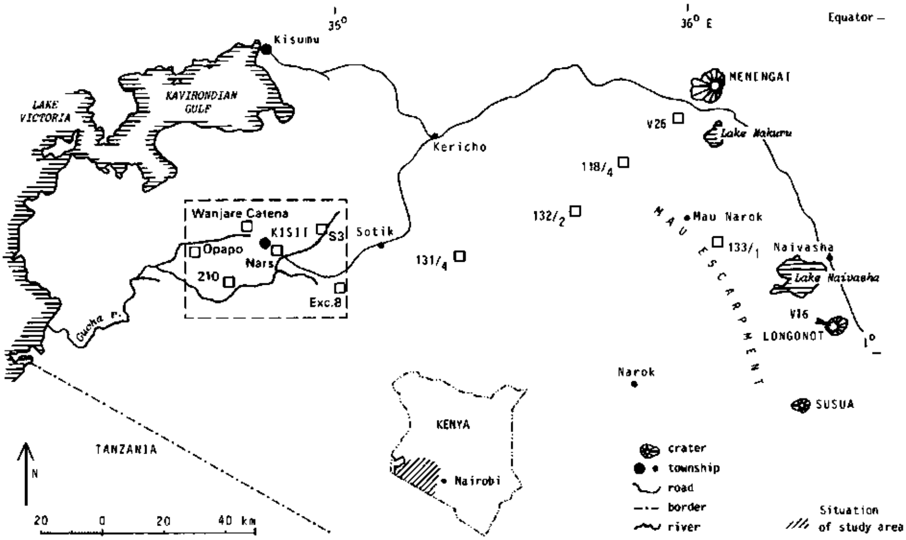


Fig. 1. Map indicating location of the main area of study (⊏⊐), and of profiles and sites studied (□).

2.2 GEOLOGY

The area is entirely composed of Precambrian intrusives and volcanic rocks, and sediments. These rocks are all more or less tectonically influenced and some show traces of a low temperature, low pressure metamorphism as for instance the rhyolites.

The geological studies of the area (Huddleston, 1951) mention the occurrence of diorites, granites, felsites, basalts, andesites, rhyolites, conglomerates and quartzites (Figs. 2 and 3).

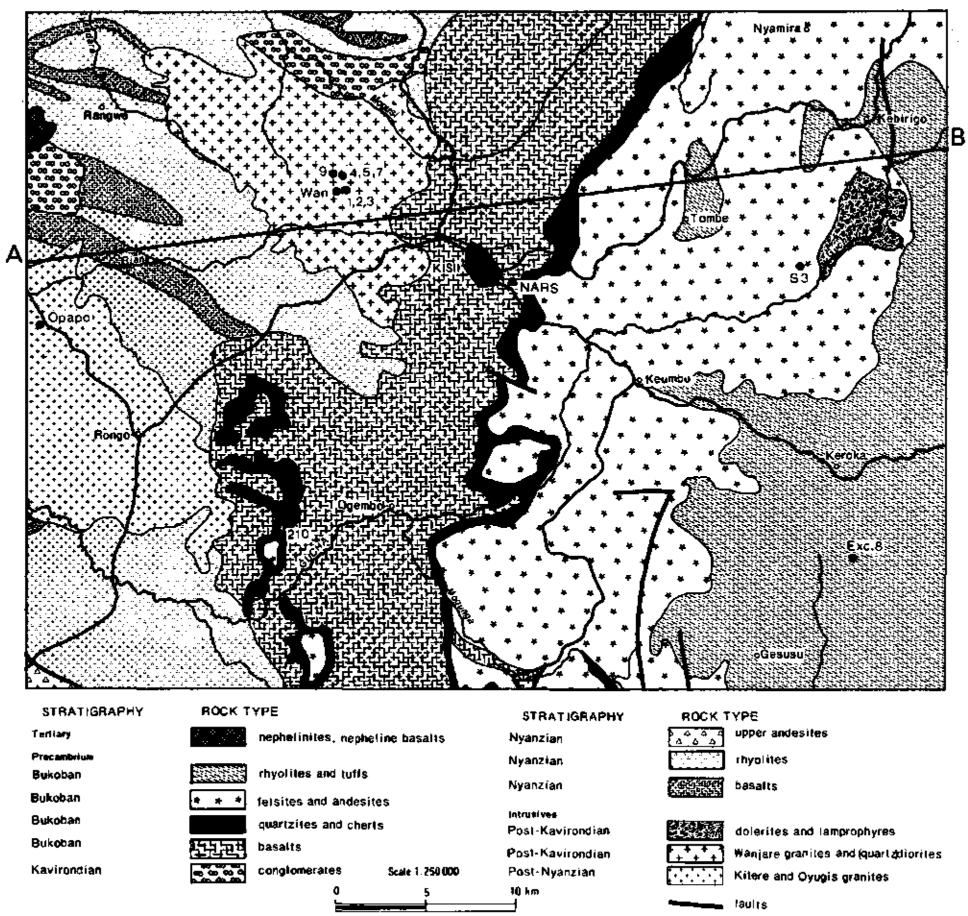
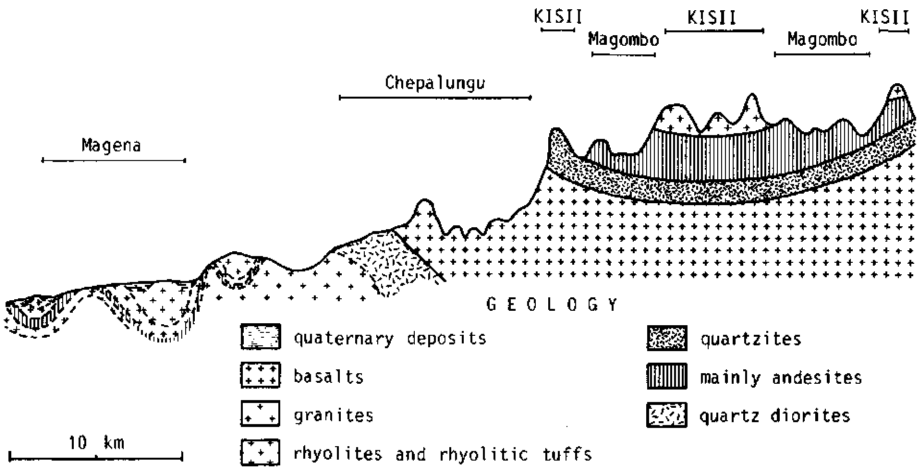


Fig. 2. Simplified geological map of the main area of study (Fig. 1) adapted from Huddleston (1951) with location of profiles and sites (•), and cross-section AB (Fig. 3).



erosion surface	surface remnants	parent material	depth of AB-hor.(m)	classification soil taxonomy
KISII	gently undulating ridge crests	a. East Kisii: > 5m volcanic ash	2-3	Paleudoll and Argiudoll
		b. West Kisii: volcanic ash and local rock	2-6	Haplohumox and Paleudoll
MAGOMBO	broad, gently undulating ridge crests	mainly volcanic ash	> 8	Paleudoll and Palehumult
CHEPALUNGU	broad, gently undulating ridge crests	volcanic ash and local rock	1.5-3	Paleudoll and Paleudult
MAGENA	plains (dissected)	Volcanic ash, local rock and coarse alluvium	1.0	Tropaqualf (abruptic)

Fig. 3. Cross-section AB (for location see Fig. 2) through main area of study with some characteristics of erosion surfaces, parent materials and soils.

Since the Tertiary and probably up to the middle of the last century (Wielemaker and Wakatsuki, 1984) volcanic ash from the Rift Valley was deposited in the area of study. It covered the region almost completely from the Rift Valley up to the eastern part of Kisii district. Farther west, ash layers were only observed in flat-bottomed valleys (Wielemaker and van Dijk, 1981), although studies on adjacent well drained soils showed that nearly all soils contained minerals from volcanic ash (Wielemaker and Boxem, 1982). The volcanic ashes were pantelleritic trachytes derived from the Rift Valley volcanoes (Wielemaker and Wakatsuki, 1984). Those trachytes have a high molar ratio of Fe to Al (2.3-2.65), a high mass fraction of alkali-ions and no free silica (for chemical composition see Table 1).

Table 1. Mass fractions (g/kg) of elements (calculated as oxides) in volcanic ash samples from the Longonot (V16) and the Menengai (V26).

Sample	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	H_2O^+
V16	619	145	33	41	3	2	14	64	56	7	2	7
V26	597	145	45	44	4	6	17	51	51	11	1	23

2.3 GEOMORPHOLOGY

The data discussed hereafter are based on a study by Wielemaker and van Dijk (1981).

(a) The Kisii Highlands proper (Fig. 2) at an altitude of 1500 to 2130 m consist of a rolling and hilly topography. The area forms a block of high land due to the resistant quartzites and rhyolitic tuffs, which form ridges running mainly NE-SW (Figs. 2 and 3). The rather flat summits of these ridges form the remnants of the Kisii or highest erosion surface, which was correlated with the Cretaceous peneplain (Shackleton, 1951). Summit levels of the lower ridges (Fig. 3) form remnants of the Magombo surface which was dated as early Tertiary. The surface is now associated with flat-bottomed valleys.

(b) The area surrounding unit (a) at an altitude of 1300 to 1500 m has predominantly a gently undulating to rolling topography. Two surfaces are of interest, called Chepalungu and Magena. The first probably formed during the later Tertiary and the latter during the Mid-Pleistocene. The first consists of ridges with rather wide crests within a rolling topography; the second is a dissected plain.

2.4 SOILS

The following data are based on publications by Wielemaker and Boxem (1982) and Wielemaker and van Dijk (1981). Soils are well drained and very permeable on surfaces older than Magena. Soils on the Magena surface and in bottomlands are poorly drained and very slowly permeable.

The depth of non-gravelly soil materials is 2 m or more on the Chepalungu and older erosion surfaces (Fig. 3). The soil mantle is deepest over the Magombo surface, where it reaches depths of 10 m and more. Because this surface is the second oldest it indicates that surfaces experienced a different degree of erosion since their development. If a stone or gravel layer is present then it is usually found at the transition from non-gravelly soil materials to saprolite. Clays in the well drained soils are kaolinitic, apart from the upper horizon of soils on the Magombo surface and soils more east on the Kisii surface, which contain also some 2:1 type clay minerals. The last mentioned soil materials have less than 60 percent clay, while all other soils have more than 60 percent clay. All well drained soils have a reddish to reddish brown B horizon.

In the eastern part of Kisii district all soils have a mollic epipedon, which is very dark and 40-80 cm deep. They also have an argillic horizon, which is especially deep in soils on the Magombo surface, so that soils there are classed as *Paleudolls* (Soil Survey Staff, 1975), unless base saturation in the B horizon is less than 35%, which places them in the *Paleudults*. Volcanic ash is the main parent material.

In contrast with soils in the east, soils in the west of the area of study on the Kisii and Chepalungu surfaces, show a clear relation with the country rock. Intermediate to basic parent materials (felsite and basalt) carry *Paleudolls* and *Palehumults* similar to those of the Magombo surface. Over quartzite, granite and diorite more weathered soil materials occur, particularly in the highest and most level positions. These soils have a dark colored topsoil with a low base saturation and an oxic or weakly developed argillic horizon; they are classed as *Haplohumox* and *Paleudults*. The soils over diorite in sloping positions have a higher base saturation and a more developed argillic horizon; they are classed as *Paleudolls*.

Soils of Plains and Bottomlands carry heavy textured deuse soils with silty bleached toplayers (*abruptic Tropaqualfs*). The Bottomlands are filled with 4 m deep deposits of quaternary volcanic ash and alluvium. Soils of the

Plains overlie, at 80-100 cm depth, a weathered rock. In the dense clay, rounded gravel and stones occur, usually at the transition to the weathered rock.

2.5 CLIMATE AND VEGETATION

2.5.1 *Present climate*

Rainfall is highest in the Highlands proper, which enjoy a humid high altitude tropical climate. The area west of it at lower elevation has a lower rainfall (Fig. 4). Figures of monthly rainfall and evaporation (Fig. 5) of

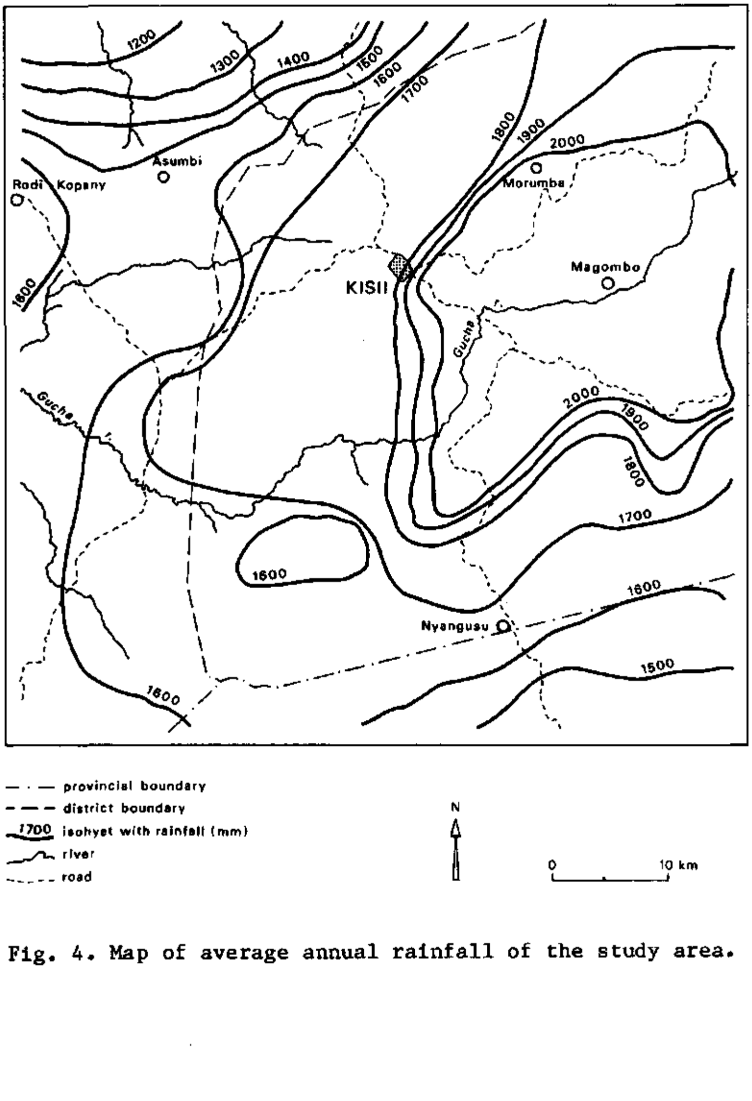


Fig. 4. Map of average annual rainfall of the study area.

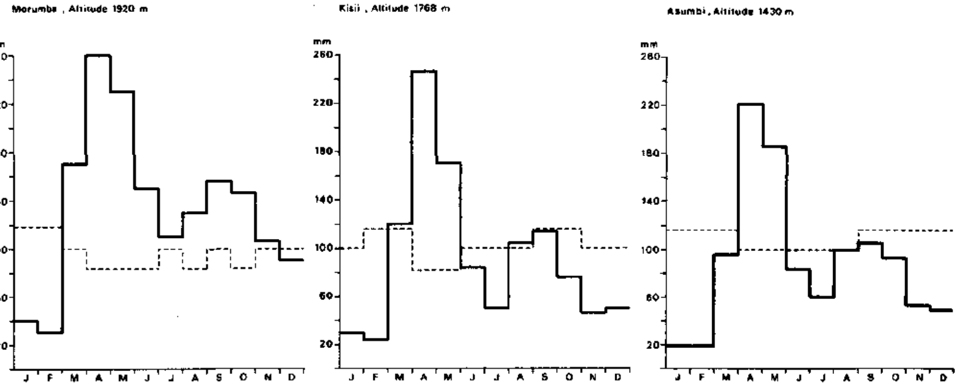


Fig. 5. Average monthly rainfall (solid line), reached or exceeded in three out of four years and the average monthly potential evapotranspiration (ET = 2/3 Eo, broken line), for the stations Morumba, Kisii and Asumbi (for location see Fig. 4).

stations situated in both areas (Fig. 4) show a dry season from December till March and a less pronounced dry season in June and July, particularly in the lower lying area. The main rainy season is from March till June. Annual rainfall fluctuates considerably from about 1000 to 1800 mm in the lower part near Asumbi and from about 1500 to 2500 mm in the higher part near Morumba. The range in temperatures for the Kisii area is as follows (Braun, 1980):

altitude	1300 m	1600 m	2130 m
mean max. temperature	27.8°C	26.0°C	22.8°C
mean min. temperature	15.6°C	13.5°C	9.8°C
mean temperature	21.8°C	19.8°C	16.4°C
absolute max. temperature	35.3°C	33.7°C	30.8°C
absolute min. temperature	7.8°C	5.8°C	2.3°C

2.5.2 *Past climate and vegetation*

During the Quaternary, climate changed considerably in East Africa. From around 15000 - 12000 B.P. the climate was so dry that Lake Victoria was without an outlet, while lake waters were alkaline (Kendall, 1969). Later than 12000 B.P. Lake Victoria overflew into the Nile again with an interruption around 10000 B.P. A wetter period occurred from 9000 - 6500 B.P. (Kendall, 1969). During that period both Lake Naivasha and Lake Rudolf (Butzer et al.

1972) had an outlet. The smaller number of forest pollen after 6000 to 3000 B.P. compared with the period before, could be due to either an increased deforestation for agriculture or to a change in climate.

More generally the period from 60000 to 12500 B.P. is considered dry with more humid periods particularly around 40000-21000 B.P. and a really dry period from 21000-12000 B.P. (Butzer et al. 1972; Livingstone, 1975; UNESCO, UNEP, FAO, 1978; Street and Grove, 1976).

Studies on the Ruwenzori mountains learned that during the more arid periods glaciers extended far below their present level. At around 14750 B.P. they were found as low as 3000 m, which is 2400 m below their present level (Livingstone, 1962). According to Osmaston, cited by Livingstone (1975) temperatures were then 4-6°C lower on East African mountains. This estimate is based on the lowering of the fern line, which extended to 630 m below its present level. This lowering was not only due to a drop in temperature as Osmaston assumed, but also to a greater aridity, so that this estimate of the drop in temperature is probably conservative. The drop in temperature might then be as much as the 6-7°C estimated by van der Hammen (1974) for the Andean mountains. The occurrence of sand dunes from the Sahara well into the Congo basin (de Ploey, 1964; Grove, 1969 and Sarntheim, 1978) further illustrates to what extent tropical Africa was affected by aridity in the not too distant past.

The drastic changes in climate even rather recently did not leave the vegetation untouched. Even during the last 20000 to 12000 years desert and savanna belts north and south of the equator encroached upon the lowland tropical rainforest, which dwindled to only a fraction of its original size (Livingstone, 1975). Likewise the montane rainforest reduced in size due to a descent of the tree line and due to a climate that was drier than before. Because the climatic patterns during the Quaternary were linked with the occurrence of glacials and interglacials (van der Hammen, 1974) at higher altitudes, vegetation belts in East Africa will have shifted repeatedly with an expansion of rainforest towards lower altitudes when the climate became warm and moist and an expansion of savanna towards higher altitude, when the climate became dry and cool.

A pollen analysis was carried out by v.d. Berg van Saparoea[1] in

1. R.M. van de Berg van Saparoea. Department of Soil Science and Geology, Wageningen, the Netherlands.

cooperation with Hamilton[2], who helped to determine pollen types on a profile situated in a poorly drained flat-bottomed valley near Profile S3 (Fig. 1). The profile had a depth of 350 cm down to solid rock and consisted of peat from 0-110 cm depth, of peaty clay from 110-340 cm and of loamy sand with peat from 340-350 cm. C^{14} ages were approximately 5800 B.P. at 340 cm depth, 4510 B.P. at 230 cm depth, 2850 B.P. at 140 cm depth and 1615 B.P. at 100 cm depth (Wielemaker and van Dijk, 1981).

Tentative results indicated an open woodland vegetation since at least 4000 B.P. This conclusion is based on the high percentage (50) of pollen from Gramineae in the pollenspectra above a depth of 220 cm and on the occurrence of scattered trees in the present day landscape. Below a depth of 220 cm pollen from a Macaranga type, a tree which probably grew under poorly drained conditions, outnumbered pollen of Gramineae (pollen of sedges and spores of ferns were excluded from the sum of pollen, because they probably originated from the direct surroundings of the site). Unidentified pollen were 20-30% of the pollensum.

The percentage of pollen from Gramineae was about 25 near the surface of the profile. The small number of pollen of this type in the surface horizon, compared with deeper layers could be due to an increase in the intensity of grazing during the past millennium.

Pollen from crops could not be identified apart from maize of which pollen grains were observed in the upper 3 cm of the profile.

2.6 LAND-USE

Although agriculture was probably introduced in western Kenya as early as 250-300 A.D., linked with the arrival of dimple based pottery (Soper, 1969 cited by Morrison and Hamilton, 1974), it was only recently that it was greatly intensified. Several mzees (old men) living in Kisii district recounted the situation that during their youth hills were widely covered with forest. Nowadays, natural forest virtually disappeared from the better drained areas, except on some rocky hilltops and along some very steep sided valleys (Wielemaker and Boxem, 1982). The intensification of agriculture only dated from the last three or four decades when the population doubled in number

2. A.C. Hamilton. The New University of Ulster, Coleraine Co. Londonderry, Northern Ireland. BT 52 1SA.

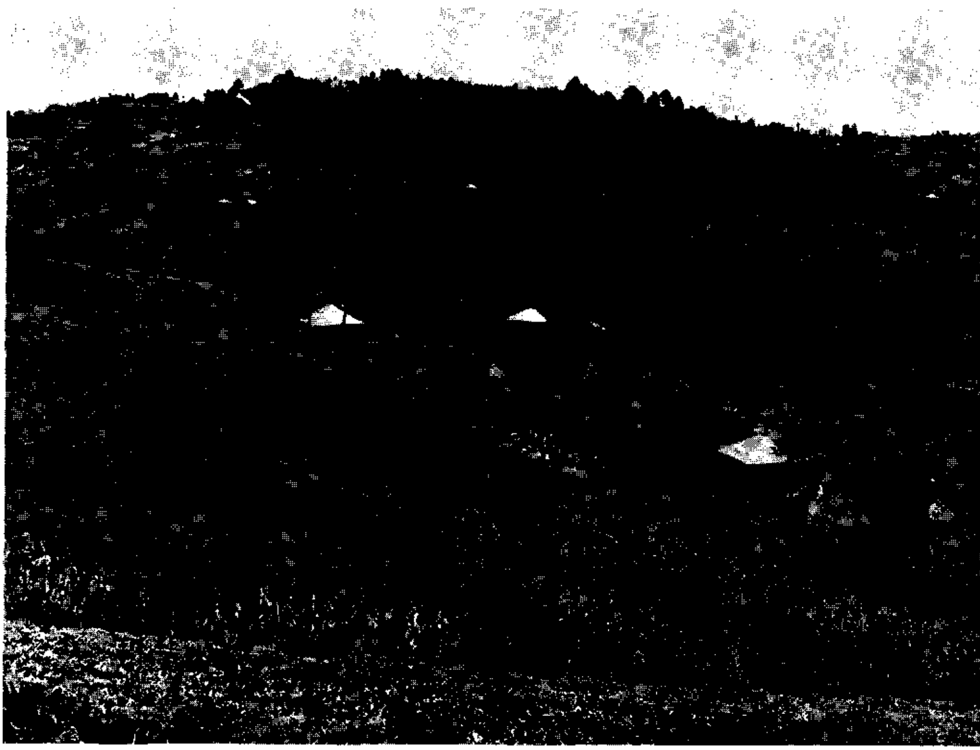


Fig. 6. Intensively cultivated land in Kisii district at an elevation of almost 2000 m.

(Ministry of Agriculture, 1975).

Crops grown can be subdivided into perennial crops such as coffee, tea, bananas and sugar-cane, which give a rather permanent cover to the soil, and annual crops such as maize, beans, potatoes, pyrethrum and tobacco, which cover the soil temporarily (Fig. 6). According as the area per farm declined, soils were more permanently cultivated. To raise production per ha, fertilizers and pesticides were commonly applied, but use of heavy machinery was mainly restricted to the cultivation of sugar-cane (Wielemaker and Boxem, 1982).

The grazing of cattle was traditionally important, but the number of cattle were declining, because people needed more land for foodcrops. The flat-bottomed valleys and the Plains with imperfectly drained soils unsuitable for agriculture, were used entirely for grazing.

2.7 SOIL MESO AND MACROFAUNA IN THE AREA OF STUDY

Termites were the most numerous and widespread representatives of soil meso and macrofauna (Chapter 1). How they live and what determines their activity will be treated in Chapter 5.

Below follows some information regarding the distribution and activity of some other soil macrofauna groups. They rarely affected soil materials so thoroughly as termites did, so that they'll receive little attention in the subsequent chapters.

The African mole rat *Tachyoryctes* sp. (Romer, 1966) feeds on living plants of which it eats mainly the roots. Its size and form are similar to the mole, *Talpa europaea* (Grzimek, 1970). It also makes tunnels which were mainly observed in the upper 30 cm of the soil profile and less frequently down to a depth of 120 cm. Excess soil is thrown as heaps on the surface with an air dry weight per heap of 0.5 to 4 kg. Heaps were observed everywhere except on very shallow and rocky soils and in poorly drained soils. On well drained deep soils mole rat activity varied from one field to the next but also with season. They were especially frequent in land used for grazing, where they have a great impact on slope transport (see Section 7.2).

Ants, particularly *Myrmicaria eumenoides* (Werff, van der, 1978), or in the Kisii language *Chimonyo Chimbariri*, built 15-40 cm high heaps with a basal diameter of 60-100 cm. They feed on dead plant remains, dead insects and also on living termites. They tolerated a wide range in drainage conditions; only on very poorly drained soils, in which also topsoil was usually waterlogged, no Chimonyo ants were observed. Many nests occurred on the imperfectly to poorly drained abruptic Tropaqualfs of valley bottoms in East Kisii, which were under natural pasture. Their activity in these soils was correlated with the fluctuation in groundwater level. A rising watertable considerably increased their activity near the surface, probably due to lack of nest space. Also the temperature affected their digging activity from no activity at a surface temperature of 6.5°C to a maximum activity at 25°C and a minimum again at 35-40°C (Werff, van der, 1978).

Many other ant species were observed, but their digging aetivity was less conspicuous compared to the ones discussed.

Aardvark *Orycteropus afer* (Dorst and Dandelot, 1970) feed mainly on termites. Searching for termites, they excavate mounds and subterranean nests. Because fungus chambers are commonly found down to a depth of 1 m, their holes may be as deep as that. The holes of aardvark were observed especially in uncultivated areas; no records are available regarding their effect on microrelief.

Dung beetles *Scarabaeoidea* (Brussaard, 1983) make balls of dung which in the area of study were observed at depths down to 120 cm; their occurrence was linked with cattle grazing. The holes were 1 cm wide. The soil excavated from the hole was deposited on the soil surface. The overall effect of the dung beetle on soil transport and microrelief was apparently small compared with that of ants and mole rats.

3 Soils studied

3.1 GENERAL

Figure 1 shows locations of sample and observation sites. Sites were chosen for different reasons; some were selected for only one purpose, others served several purposes (Table 2). Profile descriptions and detailed analytical information are given in Appendix 1. Hereafter follow brief descriptions of the studied profiles and sites, according to the purpose for which they were selected. The clay mineralogical data given in this chapter are from Wielemaker and Boxem, (1982).

3.2 SAMPLE SITES FOR THE DETECTION OF SOIL MATERIALS FROM VOLCANIC ASH

Profiles Exc. 8, S3, 210 and Wan 9 of group I in Table 2 occupy nearly flat positions on ridge crests within the main area of study (Fig. 1) and in a sequence at increasing distance from the Rift Valley from where volcanic ash originated. Members of this sequence, situated nearer to the Rift Valley, are described in Wielemaker and Wakatsuki (1984). Profiles east of Exc. 8 inclusive of Exc. 8 are developed from volcanic ash only (Wielemaker and Boxem, 1982; Wielemaker and Wakatsuki, 1984), but profiles more to the west are from volcanic ash and local country rock (Table 2). All profiles are well drained.

Members of the Wanjare catena, used for detection of soil materials from volcanic ash in mixed profiles (indicated with 1 and 2 in Table 2) are described in Section 3.3.

Stage of soil development of profiles on ridge crests is related with distance to the Rift Valley as this determined the amount of recent additions of volcanic ash (Wielemaker and Wakatsuki, 1984). So Profiles Exc. 8 and S3 have a mollic epipedon and an argillic horizon, indicative of a relatively young stage of soil development, while Profiles 210 and Wan 9 have an oxic horizon and an umbric epipedon, which are indicative of an advanced stage of

Table 2. Some data of the studied profiles. Group 1 was selected for detection of soil materials derived from volcanic ash and an estimate of the amount in soil; Group 2, for an estimate of effects of termites on soil material and soil transport and Group 3 for an estimate of the rate of creep. n.a. = not applicable.

	Profiles studied							
	V26	133/1	118/4	132/2	131/4	Exc.8	S3	210
Group	1	1	1	1	1	1	1	1,2
Altitude(m)	2200	3000	3000	2700	2090	2145	1880	1833
Land-use	grazing	arable land/ pasture	bambu forest	wood-land	pasture	pyrethrum	pasture	pasture
Erosion-surface	n.a.	?	?	?	?	Kisii	Magombo	Kisii
Slope %	3	1-2	1	0.5	0.5	2.0	5	3
Depth of AB-horizon (cm)	40	>150	>200	>200	>160	140	750+	180
Depth of (cm) saprolite	>400	>300	>300	>300	>300	>300	1000+	10
Underlying rock	volcanic ash	volcanic ash	volcanic ash	volcanic ash	volcanic ash	volcanic ash	andesite	quartzite
Color B-hor.	$10YR^4/_4$	-	$5YR^3/_4$	$5YR^3/_4$	$5YR^4/_6$	$2.5YR^3/_4$	$5YR^3/_4$	$2.5YR^3/_6$
Clay % B.	16.6		54.9	43.9	55.9	33	68	75.6
CEC of B-hor.in mmol/kg soil at pH 7.0	-	-	201	205	165	89	136	22
Base saturation in B-horizon	-	-	15	56	29	100	30	9
Drainage	somewhat excessive	good	good	good	good	good	good	good
Epipedon	ochric	mollic	umbric	mollic	mollic	mollic	mollic	umbric
Subsurface horizon	-	-	cambic	cambic	argillic	argillic	argillic	oxic

Wan 1	Wan 2	Wan 3	Wan 9	Wan 4	Wan 5	Wan 7	Opapo	NARS
1,2	1,2	1,2	1,2	1,2	1,2	2	2	3
1647	1634	1567	1571	1528	1523	1516	1345	1695
shrub-land grazing	shrub-land grazing	bananas maize	pasture	maize	maize	pasture	pasture	pasture
?	?	?	Chepa-lungu	n.a.	n.a.	n.a.	Magena	n.a.
2	12	8	0	10	10	5	1	12
20-35	135	345	310	320	275	90	85	300
5	30	400+	?	40	35	-	200+	?
granite	granite	diorite	diorite	diorite	diorite	diorite	granite	basalt
-	2.5YR $^{3}/_{6}$	2.5YR $^{4}/_{5}$	2.5YR $^{4}/_{6}$	2.5YR $^{4}/_{4}$	7.5YR $^{5}/_{2}$	10YR $^{3}/1$	10YR $^{2}/_{2}$	2.5YR $^{3}/_{6}$
-	20.1	63	61	66	36	55	73	n.d.
-	61	120	63	101	106	260	240/290	n.d
-	18	66	26+	63	76	79	56	n.d.
somewhat excessive	good	good	good	good	somewhat imperf.	poor	poor	good
umbric	umbric	mollic	umbric	mollic	umbric	ochric	umbric	mollic
-	argillic	argillic	oxic	argillic	argillic	argillic	argillic	argillic

soil development. Profile S3 on the Magombo surface is very deep, compared with Profiles Exc. 8 and 210 on the older Kisii erosion surface; this anomaly was ascribed to a different degree of erosion experienced by both surfaces (Wielemaker and van Dijk, 1981), but it is also likely that the poor weatherability of the quartzite rock played a role in the case of Profile 210.

3.3 PROFILES FOR THE EFFECTS OF TERMITE ACTIVITY ON TRANSPORT AND SPATIAL ARRANGEMENT OF SOIL MATERIALS

Profiles selected, differed in depth, drainage, clay mineralogy, fertility and slope percentage. So the effects of termites on soil materials and transport of soil materials could be studied in relation to these variables.

Most research was concentrated on profiles of the Wanjare catena (Fig. 7). Catena is a term coined by Milne (1935). He defines this as "a grouping of soils which, while they fall wide apart in a natural system of classification on account of fundamental genetic and morphological differences, are yet linked in their occurrence by conditions of topography and are repeated in the same relationship to each other wherever the same conditions are met with".

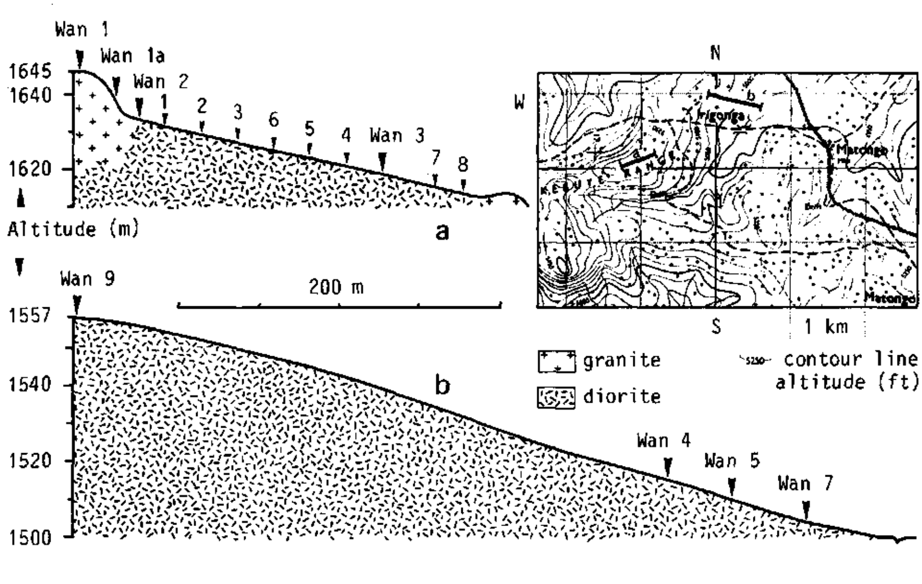


Fig. 7. Cross-section of upper (a) and lower (b) Wanjare catena with situation of profiles (▼) and deep augerings (▾).
For situation of map see Fig. 1.

Upper profiles of that catena are shallow (Wan 1) to moderately deep (Wan 2), which points at considerable slope transport, and because the rock underlying these profiles is granite, downslope soil transport will certainly leave its fingerprints in the mineralogy and particle size distribution of soils downslope, which overlie diorite. To study the effects of slope transport versus in situ formation of profiles more thoroughly, deep augerings were made (Fig. 7); they were only sampled for determination of particle size distribution, sand mineralogy and profile depth.

To study the relation between termite activity and the fertility level of soils, Profile 210 (group I, Table 2) was included, because it has the lowest fertility of all soils studied in the area, as indicated by its low CEC and base saturation. It also has very few weatherable minerals and a kaolinitic clay mineralogy just as Profiles Wan 9 and Wan 3. Wan 3 has, however, a much higher base saturation and a finer and stronger structured A-horizon than Wan 9 and 210, while otherwise the only observable differences are an argillic horizon, a deep saprolite layer and a 12% slope in the case of Wan 3, versus no argillic horizon, a shallow saprolite layer and no slope in the case of Profiles Wan 9 and 210.

Profiles Wan 4 and Wan 5 at the lower part of the catena (Fig. 7) are less weathered than Profiles 210, Wan 3 and Wan 9 as reflected by the high percentage of weatherable minerals in the fine sand fraction (App.1), the presence of some 2:1 clays and the high CEC and base saturation. The lower profiles also have strongly developed argillic horizons and some signs of impeded drainage, but no abrupt textural change. An abrupt textural change is present in the poorly drained Profile Wan 7 which is representative of a strip of land in a small, flat-bottomed valley at the bottom of the catena. Profiles with a similar morphology and drainage as Wan 7 occupy extensive flat remnants of the Magena erosion surface (Fig. 3).

Several profiles from a cross-section through a termite mound on the Magena surface near Opapo (Fig. 1) were sampled and described to study the effects of termites on these soils with very slowly permeable and compact subsoils, consisting mainly of 2:1 clays over a weathered granite rock at 80-100 cm depth (abruptic Tropaqualfs according to Soil Taxonomy, Soil Survey Staff, 1975 and Planosols according to FAO/UNESCO, 1974, Appendix 1).

3.4 PROFILE FOR MEASUREMENT OF CREEP

The profile at the National Agricultural Research Station (Fig. 1 and Table 2) is representative of many deep well drained reddish clayey soils. Also the long (400 m) and straight slopes of about 12% are representative of many slopes in the area of study. Classification and slope morphology are similar to Wan 3, but land-use and type of country rock differ.

The profile was used to measure the rate of creep.

4 Chemical and mineralogical indications for mixing

4.1 INTRODUCTION

This chapter treats chemical and mineralogical characteristics of soil materials studied, so far as they reflect the effect of mixing. It provides background information for the succeeding chapters, where the impact of termite activity on soil properties and processes will be discussed.

Mixing of the soil materials in the region under study was evident from the presence of glass fragments of volcanic ash in soil materials derived from underlying rocks (Wielemaker and Boxem, 1982); because termites were abundantly present, they were held responsible for the process of mixing. Whether the termites were solely responsible for this process has still to be proved. Strong slope transport due to changes in climate, could have contributed to the mixing of soil materials and may even be entirely responsible.

If soil material from various parent materials is mixed, the chemistry and mineralogy of the mixed material may still reflect this. However, some of the characteristics may fade through the weathering of certain minerals or through leaching of certain elements. Such properties are particularly useful to show the presence of recently added soil or parent material, but they can not be used to estimate the proportion of added soil material. To estimate this, minerals resistant to weathering and elements little susceptible to leaching could be useful. The degree of mixing and the accumulation of soil from various parent materials over a long period of time could then be estimated, under the assumption that these minerals and elements are typical of one of the constituent parent materials.

In addition, the ratios of minerals and of chemical elements typical of a certain type of parent material in composite soil samples could also be used to analyse the distribution and amount of various parent materials in such mixed soils.

This approach seemed very promising for an estimate of the degree of mixing because the peralkaline volcanic ash from the Rift Valley has a composition, which is very different from that of the local rocks in the area under study (Section 2.2 and Wielemaker and Wakatsuki, 1984). In addition to mixing by termites, the effect of slope transport could be estimated in profiles of the Wanjare catena (Fig. 7). The upper part of this catena is over granite and the lower part over diorite. If lateral transport was important then the soils of the lower part will reflect this in their mineral composition.

4.2 THE ANALYSIS OF MIXING

Before describing the methods used for the analysis of various aspects of mixing, this paragraph gives first an inventory of minerals typical of each of the constituent soil materials in mixed profiles. Methods for the analysis of soils and rocks are given in Appendix 2.

4.2.1 *Minerals as indicators of mixing*

Minerals typical of volcanic ash. The chemical composition of the peralkaline ash from the Rift Valley is given in Table 1 and the mineral composition of very fine sand with a density of >2.89 of soils formed in this type of volcanic ash is given in Wielemaker and Wakatsuki (1984). The composition of the magnetic very fine sand fractions with a density of >2.89 is given in Table 3 and the composition of the non-magnetic fraction with a density of >2.89 is given in Appendix 1.

Volcanic glass, sanidine, apatite, aegirine augite, barkevikite and a certain magnetite species (M-II) are typical for this type of volcanic ash and because they do not occur in the local rocks of the area under study they could serve as possible indicators of mixing.

The mass fraction of volcanic glass in very fine sand of fresh volcanic ash is about 80 percent. Glass has mainly a density of <2.5, but a small fraction has a density between 2.5 and 2.89. The last fraction weathers very easily as follows from its absence in samples of more weathered volcanic ash in soils farther from the Rift Valley (Wielemaker and Wakatsuki, 1984).

Of the transparent crystalline minerals, sanidine is most important. It

Table 3. Mass fractions of heavy minerals (density > 2.89) in very fine sand (50–105 µm) and mass fractions of strongly magnetic (s.m), weakly magnetic (w.m) and non-magnetic (n.m) heavy minerals in the fraction with a density of > 2.89 in profiles at increasing distance from the Rift Valley (Fig.1). Magnetite-1, Ml; magnetite-II, MII; ilmenite, Ilm; haematite, Hm; rutile, Ru; amphibole, A and pyroxene, P. Mass fractions were estimated from X-ray fluorescence analysis: +++++, > 0.9; ++++, 0.6–0.9; +++, 0.3–0.6; ++, 0.15–0.3; +, 0.05–0.15; tr, < 0.05 and – , not detected.
*Profiles from local rock and volcanic ash.

Profiles on volcanic ash	Depth (cm)	Distance from Rift Valley (km)	Mass fractions of heavy minerals: in very fine sand (50–105µm)	as magnetic separation: s.m	w.m	n.m	Composition according to X-ray fluorescence: strongly magnetic: Ml	MII	Ilm	Hm	Ru	weakly magnetic: Ilm	Ru	MII	A	P
V26	0–23	15	0.014	0.188	0.376	0.437	–	+++++	–	–	tr	+	tr	+++++	–	–
133/1	40–50	46	0.021	0.259	0.724	0.017	++	++++	+	+	tr	–	tr	–	+++++	++
118/4	40–50	85	0.021	0.205	0.727	0.068	++	++++	+	+	tr	+	tr	+	+++	+++
132/2	40–50	92	0.025	0.305	0.678	0.017	++	++++	+	+	tr	+	tr	+	++++	–
131/4	40–50	123	0.016	0.110	0.816	0.074	++	++++	+	+	tr	+++	tr	–	++++	–
Exc.8	22–66	160	0.015	0.135	0.667	0.198	++	++++	+	+	tr	+++	tr	–	++	–
S 3*	50–79	170	0.013	0.131	0.743	0.126	+++	+++	–	–	tr	+++++	tr	–	+	–
												zircon				
Wan 3*	40–55	210	0.133	0.029	0.736	0.234	+	+	++++	+	+	+++++	+	–	–	–
			in 50–420 µm							A						
diorite			0.437	0.023	0.110	0.867	+++	–	+++	+		++	–	–	+	–
granite			0.038	0.342	0.547	0.112	+++	–	++	++		–	–	–	+++++	–

is more resistant to weathering than volcanic glass, which caused an increase in its mass fraction with distance from the source (Wielemaker and Wakatsuki, 1984).

Aegirine augite, a green to bluish-green transparent weatherable mineral, is not so common in mixed profiles as volcanic glass and sanidine.

Barkevikite, which is a very dark brown almost opaque hornblende, is observed in mixed profiles, but sometimes confused with opaque minerals.

Apatite is only common in the samples of fresh to little weathered volcanic ash (V26 in Fig. 1). Smithson (1941) and Pettijohn (1941) cited by Brewer (1976) consider apatite a stable mineral. The absence of apatite in the soils from volcanic ash indicates, however, that it weathered very easily.

Magnetite-II with d-values of 2.56, 1.50 and 2.99 (powder diffraction file of JCPDS card No. 10-319) proved typical of volcanic ash. It is the commonest magnetite species in X-ray diffraction patterns from this type of volcanic ash (Table 3). The less common species in the ash (magnetite-I) with d-values of 2.53, 1.49 and 2.97 is also the species occurring in the strongly magnetic fraction from local rocks in the area of study (Table 3). Magnetite-II has *d*-values similar to those of jacobsite. The Mn-content of magnetite-II is, however, too low for jacobsite and does not differ significantly from that of magnetite-I. The only difference is a higher content of Ti in the case of magnetite-II. Substitution of Ti for Fe in the crystal lattice of magnetite-II can have caused d-values intermediate between ulvospinel and magnetite-I and similar to those found for jacobsite.

Minerals not typical of volcanic ash. The following minerals were, in some situations, typical for one of the constituent soil materials.

Opal phytolith with a density of <2.5 is a secondary amorphous mineral consisting of silica. Its form is usually tubular and it has the structure of plant cells (Fig. 8). The distribution of opal phytolith is associated with the distribution of volcanic glass in well drained profiles. Formation and decay of opal phytolith are probably related to the concentration of silica present in the soil solution, which may explain its association with glass, because glass is probably the most important source of silica and so determines its concentration in the soil solution.

Epidote was rarely observed in profiles from volcanic ash because it is a metamorphic mineral. It is, however, common in profile S3, which at first was thought to be derived from volcanic ash only. Because the underlying parent

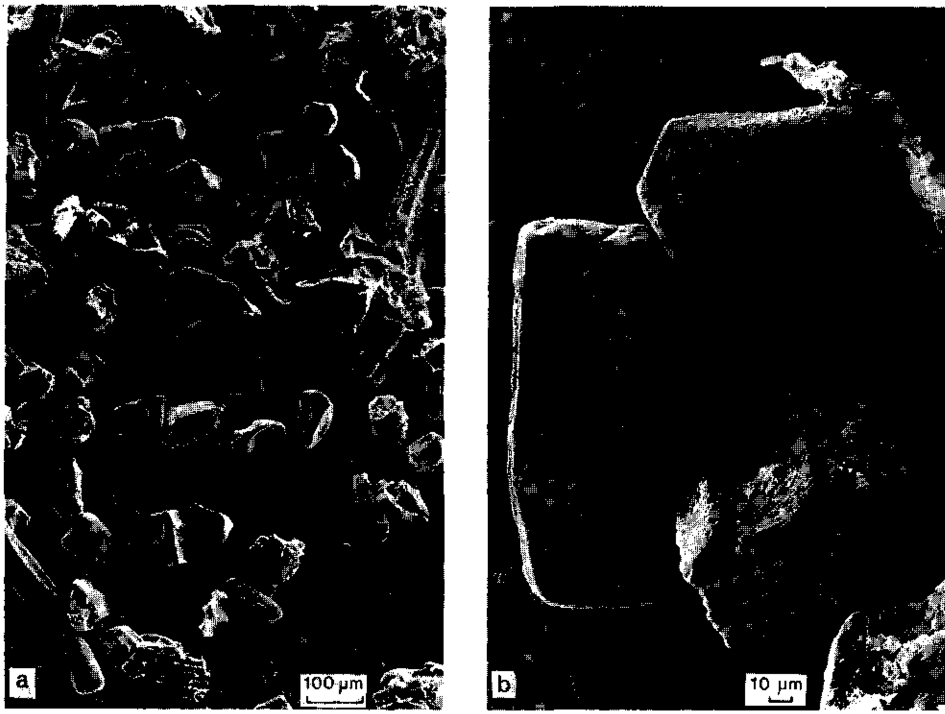


Fig. 8. Electron micrograph (A) showing some forms of opal phytolith. The most common type (B) seems to be derived from grass (personal communication of J. Hayma).

material of profile S3 contains a relatively high mass fraction of epidote, its presence in the solum proves that Profile S3 is a mixed profile.

All country rocks in the area of study and also volcanic ash contain zircons with a well developed typical crystal morphology. Fission track dating showed that zircons from volcanic ash with an age of 700 to 900 thousand years (App. 4) still have their original form. In profiles of the Wanjare catena developed from granite and diorite, zircon morphology ranges from well formed idiomorphic crystals to zircons with corroded edges and rounded zircons. In the latter profiles it was nearly impossible to distinguish zircons from volcanic ash, from zircons derived from the country rock; moreover zircons in ash are rare in comparison with zircons from the granitic or dioritic rock.

The situation in Profile S3 is different, with soil mainly derived from volcanic ash. This profile is underlain by a parent material which besides many epidote minerals contains few zircons, which were all rounded. The rounded zircons contained an uncountable number of fissions, which indicates that they are very much older than the well formed crystals from volcanic ash. The presence of epidote and also the presence of rounded zircons throughout the profile indicates that Profile S3 (Fig. 1), which seemed to be derived from volcanic ash only, is in fact a mixed profile.

4.2.2 *An estimate of soil materials from volcanic ash in mixed profiles*

Amount of volcanic glass and of magnetite-II in mixed profiles are used as indicators for the distribution of relatively young and relatively old soil materials from volcanic ash in mixed profiles. They are among the most common minerals in this type of volcanic ash and have the advantage of being easy to determine.

Volcanic glass weathers easily, so that its presence represents relatively young soil material from volcanic ash. Magnetite, although much more resistant to weathering than glass, particularly in the oxidizing environment of the well drained profiles under study, is, however, not considered by all authors to be a very stable mineral. Pettijohn (1941) considers it less stable than zircon, ilmenite and apatite and Weyl, 1952 (cited by Brewer, 1976) places it in the stability group of zircon, rutile, tourmaline and sphene.

If magnetite-II is very resistant to weathering its mass fraction in mixed profiles could serve as an estimate of the soil materials derived from ash. To judge its stability, mass fractions of magnetite-II in Table 4 were compared with mass fractions of ilmenite and zircon. It appears that fractions of ilmenite and zircon increase in samples farther from the Rift Valley, while the fraction of magnetite-II remains constant or decreases slightly. In fact, the mass ratio of magnetite-II to ilmenite decreases from 10 or more in samples near the Rift Valley to 0.3-0.6 in samples far from the Rift Valley such as in samples from Profile Exc. 8. It seems, however, unlikely that the difference in density or the difference in form of the two minerals could have caused the drastic decrease in the fraction of magnetite-II compared with ilmenite and zircon, with the exception of the possible effect of winnowing described later. Because the ratio of magnetite-II to ilmenite is rather similar in old and young deposits of little weathered volcanic ash, the decrease in the content of magnetite-II compared with ilmenite and zircon seems due to its lower resistance to weathering.

Table 4. Mass fractions in very fine sand (50-105 μm) x 10^{-3} of magnetite-II = MII, ilmenite = Ilm, zircon = Z and weatherable minerals (amphibole, pyroxene) = W, estimated from X-ray fluorescence analysis (Table 3) and from the number of transparent minerals in the non-magnetic fraction (Appendix 1) of profiles on volcanic ash (Volc.P.) and in mixed profiles (Mixed P.). For sample depth and distance from the Rift Valley, see Table 3.

Volc.P.	MII	Ilm	Z	W	MII/Ilm	Ilm/Z
V26	7.1 -7.9	0.3- 0.8	0.00	6.1	9 -23	-
133/1	1.6 -3.2	0.3- 0.8	0.04	13.7-15.2	2 - 5	7 - 19
118/4	1.6 -3.5	1.0- 2.9	.	9.2-15.3	0.6 - 1.6	.
132/2	3.3 -7.5	1.2- 3.7	0.09	10.2-15.3	0.9 - 2.8	12 - 37
131/4	1.0 -1.6	4.0- 10.4	0.28	7.8-11.8	0.1 - 0.3	14 - 36
Exc.8	1.2 -1.8	3.1- 6.3	0.21	3.1- 6.1	0.2 - 0.4	15 - 30
Mixed P.						
S 3	0.5 -1.0	8.7- 9.7	0.08	0.5- 1.0	0.05 -0.06	112 -125
Wan 3	0.19-0.58	90.4-102.5	36-46	0	0.002	1.9- 2.9

A reliable estimate of the amount of volcanic ash in mixed profiles according to its magnetite-II content was further hampered by two other effects:

(i) Winnowing. The mass fraction of magnetite-II to soil materials derived from volcanic ash should first be estimated in soils from pure volcanic ash. Such profiles are, however, at a minimum distance of 40 km (Profile Exc. 8 in Fig. 1) from the mixed profiles of the Wanjare catena (Fig. 7). This distance would certainly affect the ratio because, when distance to the source of ash increases, the fraction of heavy minerals in soils will decrease (winnowing effect). It follows then that the ratio in Profile Exc. 8 is not representative of soil materials from volcanic ash in mixed profiles of the Wanjare catena.

(ii) Stage of weathering of soil materials. This would affect the ratio of magnetite-II to total soil materials from volcanic ash in mixed profiles. To avoid this effect, the ratio of magnetite-II to total Al in soil materials from volcanic ash was used, because in the soils studied Al seemed not susceptible to leaching and therefore independent of stage of weathering.

These effects prevented an exact estimate of the fraction of Al derived from volcanic ash in mixed profiles. Therefore only an estimate of the relative distribution of that fraction in mixed profiles was possible.

Distribution of volcanic glass in mixed profiles. In deep profiles of the Wanjare catena (for situation see Fig. 7), glass is especially observed in the upper 100 cm, where its mass fraction decreases from the surface down to about 100 cm. Below that depth the amount of glass is low, compared with the upper part, but remains nearly constant down to the gravel line at depths of 300 to 350 cm (Profiles Wan 3 and Wan 9 in Table 5) or the bottom of the pit (Profiles Wan 4 and Wan 5 in Table 5). Below the gravel line some glass fragments are still detected in Profile Wan 3 in the part with soil structure down to the bottom of the pit at a depth of 7 m (Table 5).

Distribution of magnetite-II and Al from volcanic ash in mixed profiles. Fig. 9 shows the trend in mass fractions of Al from volcanic ash in Profile Wan 3 according to its magnetite-II content, assuming a mass fraction of Al from ash in topsoil of 0.63 (this value is based on the ratio of magnetite-II in very fine sand to total Al, in samples of fine earth from Profile S3. The calculation procedure is explained in App. 2). Mass fractions in the upper 160 cm are slightly higher than in the lower part of this profile. Below 330 cm depth, no magnetite-II was detected.

Table 5. Number of volcanic glass fragments per 100 grains (Appendix 1) in the very fine sand fraction (50-105 µm) recalculated as mass fractions of fine earth in profiles of the Wanjare catena (x 10^{-3}).

Profile Wan1		Profile Wan 3		Profile Wan 9		Profile Wan 4		Profile Wan 5	
Depth (cm)	glass	Depth (cm)	glass	Depth (cm)	glass	Depth (cm)	glass	Depth (cm)	glass
0- 35	0.42	10- 25	0.8	0- 18	0.35	20- 36	0.025	8- 23	0.27
		40- 55	0.026	18- 38	0.33	50- 65	0.022	38- 53	0.07
		70- 85	0.059	38- 80	0.21	95-110	0.013	70- 85	0.04
Profile Wan 2		85-100	0.23	80-130	0.025	170-185	traces	110-125	0.016
Depth	glass	145-160	0	130-210	0.035	211-226	traces	166-182	0.013
(cm)		190-205	tr.	210-286	0.008	260-275	traces	198-214	0.017
0- 16	0.13	240-255	0	287-300	0.05	320-335	-	280-295	0.019
5- 30	0.04	255-270	0.074						
55-165	traces	315	traces						
		↓							
		750							

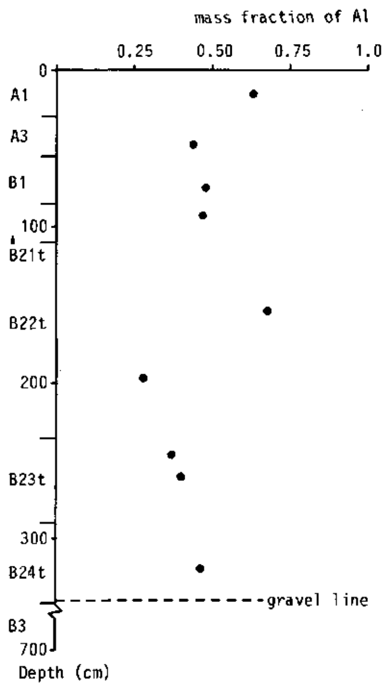


Fig. 9. Al from volcanic ash (•) as mass fraction of total Al in samples of profile Wan 3. Amount of Al from volcanic ash is estimated from the content of magnetite-II in the very sand fraction, as explained in Appendix 2.

4.2.3 *An estimate of mixing according to the ratio of ilmenite to zircon*

The mass ratio of ilmenite and zircon in samples of very fine sand of soils from volcanic ash ranges from 12-40, which is much higher than in samples from soils overlying the Wanjare diorite which has ratios lower than 3 (Table 4). Because ratios of ilmenite to zircon are so characteristic for each parent material, trends of ratios in mixed profiles may give information on the degree of mixing of soil materials from volcanic ash and the rock underlying the profiles of the Wanjare catena.

Because ilmenite and zircon have a similar density of about 4.7 and also a similar surface area, the ratio will not change with distance to the Rift Valley due to winnowing. Furthermore, weathering seems to have little effect on the ratio as a result of the similarity in ratio values in older and younger soils from volcanic ash. The ratio could not be determined for soils nearest to the Rift Valley because no zircons were detected in the heavy fraction. Its value must be lower than that of Profile 133/1 because the ilmenite content of both samples is similar, while the zircon content of the sample from Profile V26 is apparently smaller than that of Profile 133/1.

Fig. 10 shows the trend in ratios of ilmenite and zircon in very fine sand of Profile Wan 3. A ratio respresentative for soil materials from diorite was taken to be 2.1. This ratio was found in the part with weathered rock just below the solum, where stage of weathering may differ least from soil materials above it (To compare ratios from different parts of the profile, stage of weathering should differ as little as possible, because it may affect distribution of minerals over different size classes (Brewer, 1976)).

Addition of volcanic ash with high ratios of ilmenite to zircon would raise the ratio. This is indeed observed, but in contrast with the distribution of glass and magnetite-II, ratios of ilmenite to zircon would indicate that more volcanic ash was added to the part below 150 cm depth, than to the part above it. This anomaly might be due to slope transport because soil materials in profiles upslope had low ratios of 0.3 or less, so that addition of those materials to the upper part of Profile Wan 3 could have caused the decrease in ratios. More evidence for this hypothesis will be given

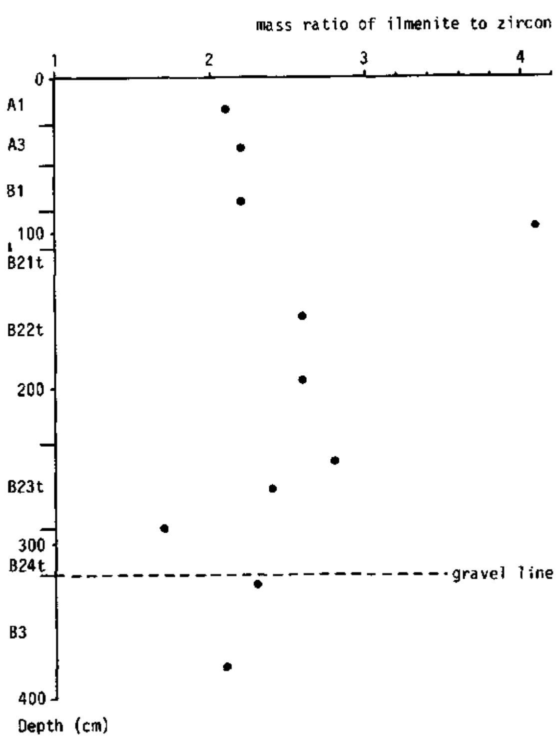


Fig. 10. Mass ratios of ilmenite to zircon in the 50-100 μm fraction of samples from Profile Wan 3, estimated from X-ray fluorescence data (App. 1) and from countings of zircons in the non-magnetic fraction (App. 1).

in Sections 5.4 and 6.3, where it will be shown that slope transport affected the mineralogy of the upper part of Profile Wan 3, particularly its upper 30 cms.

4.2.4 *Zinc and potassium oxide as indicators for presence of relatively young volcanic ash*

The mass fraction of zinc was $(0.2\text{-}0.3).10^{-3}$ and that of potassium oxide was 0.5-0.6 in the little weathered samples of volcanic ash from the Rift Valley. Those mass fractions are very high for most soil materials. Zinc and potassium are susceptible to leaching, so that mass fractions of zinc and potassium oxide are a good indication for the amount and distribution of relatively little weathered soil materials from volcanic ash.

Fig. 11 shows how Zn-content of topsoil decreases from east to west in the Kisii area. The figure also shows that Zn-content of topsoil is always higher than that of subsoil, except in the most westerly soils, where the lowest Zn concentrations occur. Concentration of Zn is apparently linked with mass fractions of young soil materials from volcanic ash in soils, resulting from the decrease in concentration with distance from source and with depth.

The trend in the content of potassium oxide in soils from east to west Kenya is similar to the trend in Zn-contents. A comparison of the deep soil Profile S3 from East Kisii with the deep Profiles Wan 3 and Wan 9 from West Kisii (Fig. 1) shows that Profile S3 has a mass fraction of 0.017 K_2O in topsoil decreasing gradually to 0.008 at 7 m depth (App. 1). In contrast, Wan 3 and Wan 9 have mass fractions in the upper 3 m, ranging from 0.005 to 0.009. Because S3 is a deep soil, the high content of potassium oxide in the topsoil of Profile S3 can be ascribed to the presence of volcanic ash.

4.2.5 *An estimate of mixing according to the molar ratio of Al to Fe*

To estimate mass fractions of soil materials from volcanic ash in mixed profiles, the molar ratio of Al to Fe (III) seemed promising. Both elements are nearly immobile under well drained conditions, so that the ratio will hardly be affected by leaching. There were, moreover, no indications that Fe and Al cheluviated with organic matter.

The ratio in well drained profiles from volcanic ash ranges from 2.3-2.5

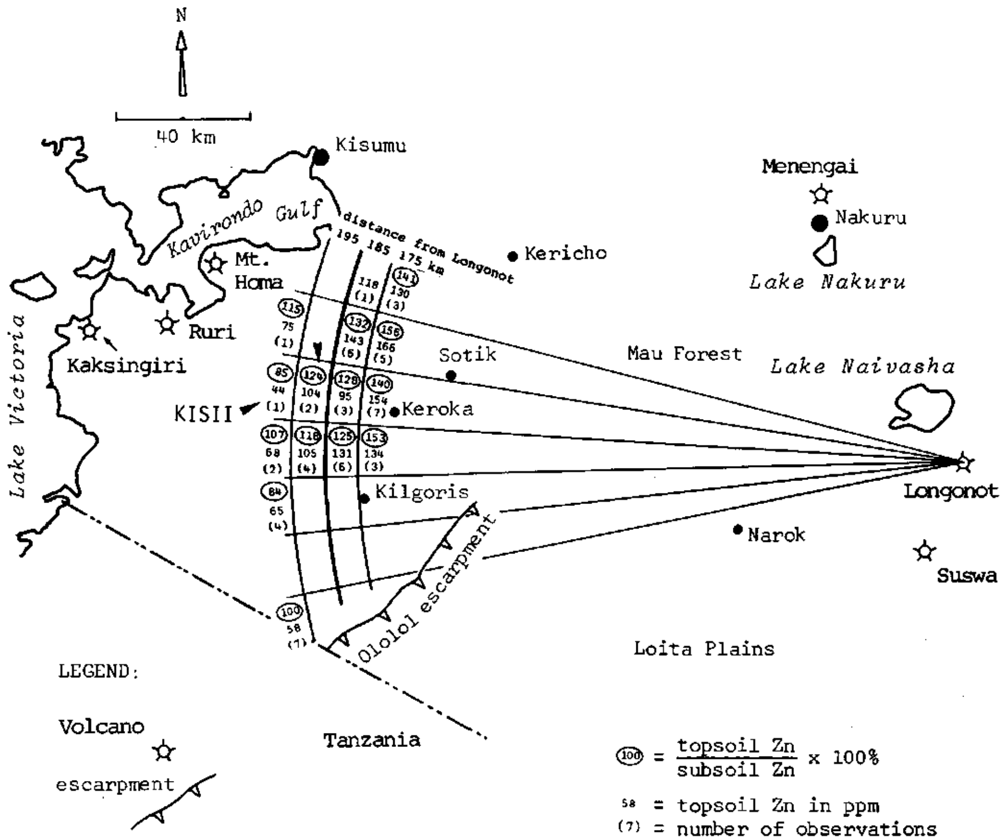


Fig. 11. Relation between zinc content in soils and distance to the Longonot volcano.

(Wielemaker and Wakatsuki, 1984 and Table 6, Profile Exc. 8), which is low in comparison with a ratio of 3.46 in diorite and 4.3 in granite measured in rocks, underlying profiles of the Wanjare catena.

Despite the fact that Profile S3 proved to be a mixed profile, its soil materials in the well drained part seemed mainly derived from volcanic ash; this followed from the ratios of Al to Fe, which were within the range of soil materials derived from volcanic ash.

If it were possible to know the ratio of Al to Fe in soil materials from diorite or granite present in the mixed profiles, then the mass fractions of soil derived from volcanic ash and local rock could be reliably estimated. This is however not possible, because ratios in the zone with saprolite and rock are affected by alternating reduction and oxidation of iron (see e.g.

Table 6. Molar ratios of Al to Fe (III) in fine earth of profiles Exc. 8 and S 3 (for situation see Fig. 1).

Depth (cm)	Exc. 8 Ratio	Depth (cm)	S 3 Ratio
0- 22	2.33	0- 50	2.29
22- 66	2.35	79-270	2.56
90-105	2.41	340-345	2.32
150-165	2.23	740-750	2.02
170-200	2.12		
200-250	2.03	C-hor.	2.86

Profile Exc. 8 at a depth of >150 cm in Table 6). Such conditions lowered the ratio in the upper part of the reduced zone and raised it in the lower part, where reduced conditions were more permanent; this had occurred in the weathered rock sample of Profile Wan 2 with a ratio of 9.9, compared with 4.3 in the hard rock. Lateral transport of iron could cause a decrease of the iron content particularly in freely drained profiles on ridge crests so that an increase, rather than a decrease, of the ratio is to be expected.

Due to reasons mentioned above a reliable estimate of the molar ratio of Al to Fe for soil materials derived from local rocks is not possible. The trend in ratios in the well drained part of the profile may, however, still reflect how soil materials from volcanic ash and local rocks are mixed, assuming that soil materials derived from the local rocks in the well drained part of the profile have a uniform ratio due to homogenization.

Fig. 12 shows a decreasing fraction of Al derived from ash with increasing depth of soil down to about 300-350 cm, where the zone of alternating reduction and oxidation starts. The trend in ratios of Profiles Wan 3 and Wan 9 is very similar, although Profile Wan 9 is situated on a level ridge top and Profile Wan 3 on a slope. So it seems that slope transport did not cause a situation leading to serious overestimation of the fraction of Al derived from ash in Profile Wan 3, which could have occurred if an important fraction of soil materials from upslope with high ratios of Al to Fe (see Profile Wan 2 in App. 1) had been added. Effects of slope transport will be further discussed in Section 7.2.

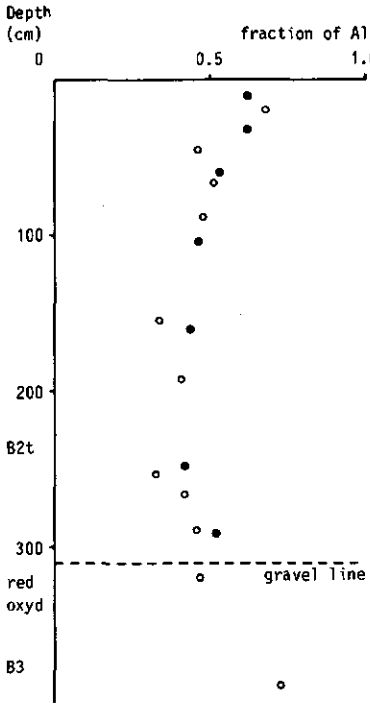


Fig. 12. Fractions of Al from volcanic ash in fine earth of profile Wan 3 (o) and Wan 9 (•), calculated with molar ratios of Al to Fe (III) of 2.3 for volcanic ash and of 3.5 for diorite. Mass percentages of oxides of Al and Fe in fine earth of profiles Wan 3 and Wan 9 are given in Appendix 1.

4.3 DISCUSSION AND CONCLUSIONS (TABLE 7)

Concentration of zinc and potassium oxide was useful to detect addition or admixture of relatively recent volcanic ash, especially in deep weathered soils. Chemical elements were, however, not specific for a particular parent material, so that detection of a small mass fraction of allochthonous material was not possible. For this purpose, volcanic glass fragments proved very useful. Their numbers decrease from the surface down to about 1 m and then remain nearly constant down to the gravel line. Below this line, glass fragments are present in the part with soil structure down to the bottom of the profiles investigated (7 m in Profile Wan 3 and 10 m in Profile S3).

According to the small fraction of glass at a depth of more than 1 m, only a small but consistent fraction of relatively young soil materials from volcanic ash is present. Methods indicating the total fraction of soil materials derived from volcanic ash in mixed profiles, showed that those fractions did not differ much with depth above the gravel line. X-ray fluorescence analysis could not detect very small fractions of magnetite-II,

Table 7. Summary of methods used in estimating presence of soil materials from various sources in soils and their applicability. xx, reliable results; x (x), reliable if ratios differ significantly and if enough minerals are present; x, reliable only if content is high enough, no reliable quantitative estimate possible; Ω, only in some profiles applicable; -, not applicable.

Method	Presence of soil materials from volcanic ash			Semi-quantitative estimate	Difficulties
	young	old	country rock		
Zinc	x	-	-	-	leaching
potassium	x	-	-	-	leaching
volcanic glass	xx	-	-	-	weathering
aegirine augite	xx	x	-	-	not common, demanding method
zircon	-	-	Ω	-	demanding
epidote	-	-	Ω	-	weathering
magnetite-II/I	x	xx	x	x	winnowing and weathering
ilmenite/zircon	-	x	x (x)	x	size frequency
Al/Fe	x	xx	x	x	leaching or accumulation due to reduction and oxidation of Fe in deep subsoil

that may have occurred in the part below the gravel line or in relatively young profiles such as Wan 4 and Wan 5. Neither did this method work in samples from profiles derived from granite, having a large fraction of normal magnetite (Profile Wan 2).

The ratio of ilmenite to zircon shows that the upper 1.5 m of Profile Wan 3 was derived from three parent materials: diorite, granite and volcanic ash. Soil material from granite was apparently added to this part of the profile by slope transport.

Detection of epidote and rounded zircons in Profile S3, which, according to its ratio of Al to Fe seemed mainly derived from volcanic ash, shows that minerals from the underlying rock at a depth of >10 m had been mixed throughout the profile.

That minerals from recent and old volcanic ash were present throughout the profiles shows that the process of mixing was active over a long period of time and is still active. The results illustrate what impact vertical and sometimes lateral transport processes have on chemical and mineralogical properties of the profiles studied. Why soil materials became so intimately mixed will be explained in the succeeding chapters, dealing with the effect of termites on soil properties.

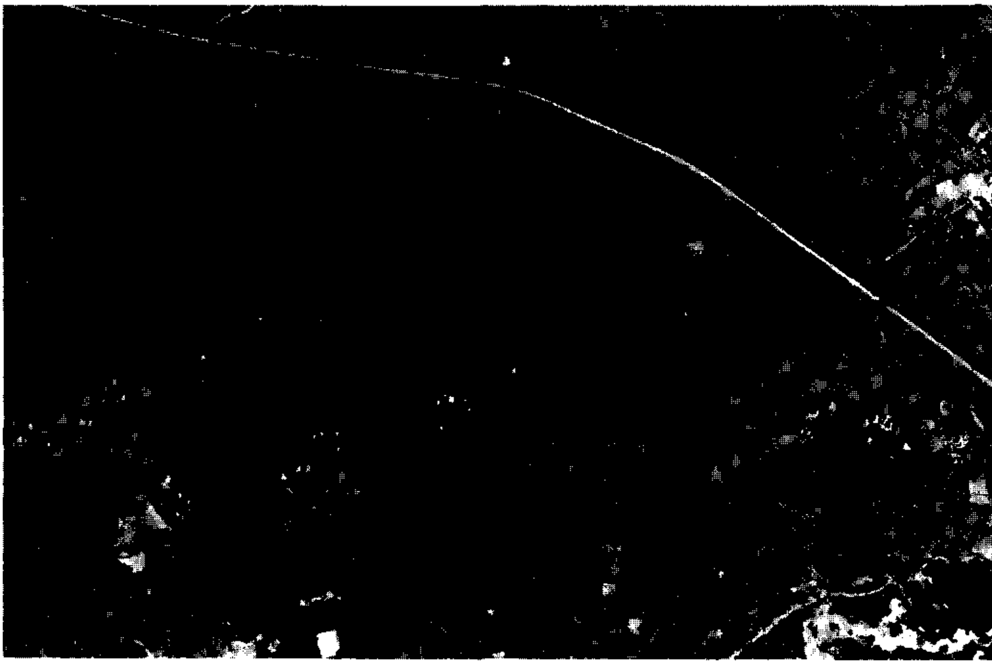


Fig. 13. Aerial photograph of the Magena surface at Opapo; dark spots are mounds covered with shrubs and trees; grass grows between the mounds. In foreground Luo homesteads.

5 Requirements of termites and some chemical effects of termite activity on soils studied

5.1 INTRODUCTION

The following chapters will demonstrate the effects of termite activity on soil properties. Why termites do certain things in soils and how this relates to their requirements and to primary land conditions, is discussed in section 5.2 of this chapter.

Differences in requirements of termites are partly related to the type of nest they make. Three nest types are known: mounds, subterranean nests and nests in trees. Nests in trees were not observed in the area under study. Mounds were especially observed on shallow soils and on imperfectly to poorly drained soils. The most common mound types were:

(i) Bare mounds of about 50 cm high and 100 cm wide at the base, made by *Cubitermes* spp.. Their mounds were not observed in tilled fields. Mound density was 250 ha^{-1} on the shallow soils near Wan 1 and 50-70 on the poorly drained soils near Opapo (for location see Fig. 1).

(ii) Mounds of about 1-3 m high and 3-12 m diameter at the base were made by *Pseudacanthotermes* spp. and *Macrotermes* spp. (identified by C. Kooyman, personal communication). The largest mounds were observed on the poorly drained soils of the Magena surface, where shrubs and trees grew on the mounds and they numbered about 5-8 ha^{-1} (Fig. 13).

(iii) Small mounds of *Pseudacanthotermes* (identified by C. Kooyman) with a height of 30-60 cm were observed in well drained soils west of Kisii Town at an altitude of less than 1600 m. They were conspicuous along roads and footpaths. On the shallow soils near Wan 1 they numbered about 50. ha^{-1}.

Subterranean nests, made by *Odontotermes* spp. and *Microtermes* spp. were common. Their nest centre was difficult to locate in the well drained deep soils particularly if these soils were porous with a low bulk density (110 kg. m^{-3}) as was the case with the majority of soils in the area of study. Fungus chambers seemed distributed randomly through the soil. Most chambers with a

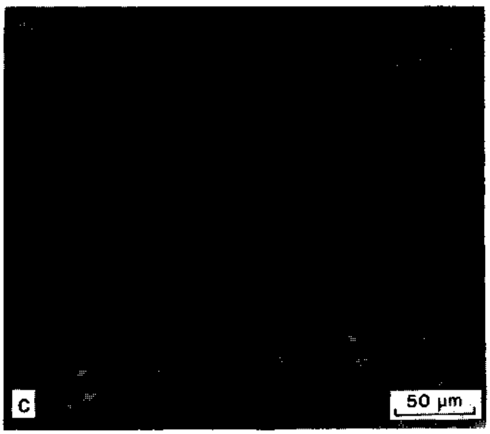


Fig. 14. A. Young nest of Odontotermes in poorly drained soil on the Magena surface near Opapo.
B. Fungus combs and empty chambers of nest shown in A.
C. Thin section of fungus comb, built of faecal pellets consisting of macerated organic material.

diameter of 10–25 cm occurred at a depth of 50–100 cm, but some small fungus combs (2–5 cm Ø) were observed at depths of over 200 cm.

In the imperfectly drained soils of Valley Bottoms in the eastern part of the area of study, only nests of *Odontotermes* (Fig. 14) occurred. Nest sites were distinct due to a vegetation of shrubs and trees, absent on soils between mounds, which carried a vegetation of grass.

Most work in the area of study was done to describe and estimate the effect of termites on transport and spatial arrangement of soil materials. Less emphasis was placed on the effects of termite activity on chemical properties, because these are extensively treated in the literature. A summary of these effects and some results from the area of study follow in Section 5.3 of this chapter.

5.2 THE REQUIREMENTS OF TERMITES

The presence of termites, their numbers and what they do in soils is related to their requirements and to the degree the environment meets these requirements or can be changed to meet them.

Termites are very demanding as regards the climate in their nests and galleries, although they occur in widely differing climatic regions from the humid rainforest to the semi-desert and from the equator to the mediterranean area, where night frost may occur. They occur in well drained soils but also in poorly drained and compact clay soils and in shallow soils. It demonstrates their fantastic ability to modify primary land conditions to suit their needs.

Their needs and abilities to adapt primary land conditions, will be discussed below. Chapters 6 and 7 will show what this constant modification means for soil properties and how difficult it is to modify soil properties.

The requirements of termites concern the following items: sufficient food, a sufficient high temperature, a sufficiently high humidity, sufficient soil depth for nesting, presence of suitable building materials, a low risk of flooding or waterlogging and a low risk of disturbance.

5.2.1 *Food*

Fungus growing termites in the area of study make foraging galleries to the place where they collect the organic detritus (including wood). Inside the soil, walls of main channels are plastered with salivated pellets of earth. Tunnels above ground are entirely constructed of those pellets and radiate to the places where they collect food (Fig. 15). The construction of foraging channels and chambers for fungus combs are important activities through which soil is modified. Combs are built from faecal pellets of macerated organic material on which termites cultivate certain species of fungi (Fig. 14). The fungi effectively decompose organic material including lignin and cellulose so that it becomes digestible for termites. The white spherules of fungal hyphae are a particularly high quality food resource for them (Section 5.3), providing the queen and her off-spring with food rich in nitrogen.

No figures are available about the number of subterranean termites in soils of Kisii and their consumption of organic debris. For comparison data cited by Wood and Sands (1978) are shown in Table 8. As Lee and Wood (1971) rightly observe the total respiration by termites per unit of surface is of

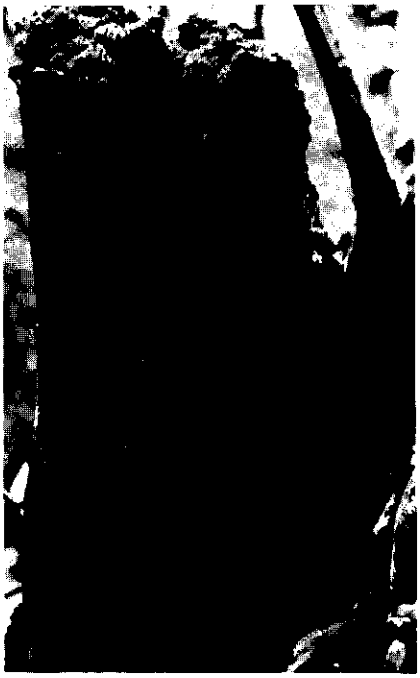


Fig. 15. The termite species in Kisii, which forage above ground, cover the food they eat, with a layer of soil consisting of salivated pellets of earth.

the same order of magnitude as that of large herbivores grazing on the savanna of East Africa.

Most authors agree that termites, particularly the fungus growers, are by far the most efficient cellulose and lignin decomposers in nature (Matsumoto, 1976; Lee and Wood, 1971a; Wood, 1978; Wood and Sands, 1978 and Collins, 1982).

5.2.2 *Temperature*

Termites tolerate only a narrow range in temperature, particularly in their nest. Daily fluctuations in temparature within their nest are controlled through metabolic activity and ventilation. More seasonal fluctuations in temperature are controlled through variation of the depth at which they construct their nest chambers. According to Sands (1965) termites migrate to deeper layers when surface temperatures become too high and they move to upper layers when surface temperatures decrease. Because termites are very susceptible to desiccation, vertical migration could moreover be due to a humidity effect (Bouillon, 1970 and Ferrar, 1982).

Table 8. Biomass, consumption, production and respiration of termites in three savannah ecosystems in West Africa and rainforest in Malaysia (after Matsumoto, 1976) from Wood and Sands, 1978.

Ecosystem	Live weight (g per m^2)	Annual consumption[β] g per m^2	Annual consumption[β] kJ per m^2	Annual production[ψ] (kJ per m^2)	Annual respiration (kJ per m^2)
Sahel savannah					
Soil-feeders	0	0	0	0	0
Macrotermitinae	0.72	15.8	298	24	31
Others	0.24	2.6	49	4	10
Total	0.96	18.4	347	28	41
S. Guinea savannah					
Soil-feeders	0.66	-	136	11	28
Macrotermitinae	6.39	139.9	2635	209	272
Others	3.54	38.7	729	58	143
Total	10.59	178.6	3500	278	443
Derived savannah					
Soil-feeders	0.16	-	33	3	6
Macrotermitinae	0.64	14.0	264	21	25
Others	0.93	10.2	192	15	39
Total	1.73	24.2	489	39	70
Rainforest					
Soil-feeders[α]	1.62	-	-	-	-
Macrotermitinae[α]	1.62	35.5	669	53	72
Others[α]	1.83	20.0	377	30	72
Total	3.55	55.5	1046	83	144

α Soil-feeders not studied but many species present; one species of Macrotermitinae and three species of non-Macrotermitinae studied but many other species present (total species = 56; Abe & Matsumoto, personal communication).

β Consumption: calculated on basis of calorific value of plant tissue = 18.8 kJ per g; consumption by Macrotermitinae = 60 mg per g per day and by non-Macrotermitinae (i.e. 'others') = 30 mg per g per day; for 'soil-feeders' consumption based on same calorific requirements as other non-Macrotermitinae = 206 kJ per g per year.

ψ Production: based on live weight/dry weight = 4.0 and production: biomass ratio for Macrotermitinae = 6:1 and for soil-feeders and other non-Macrotermitinae = 3:1.

Termites,occur throughout the area of study, so that they are able to control the temperatures in their nests at ambient average annual temperatures of 15°C at 2100 m and of 22°C at 1500 m. They are capable of doing this even at much lower ambient temperatures, because they were observed at an elevation of 2400 m in grassland at Nyahururu in Kenya, where absolute lowest and highest air temperatures reach values of 0.6°C and 21.2°C respectively (calculated according to Braun, 1980).

5.2.3 *Moisture*

Termites need moisture for (1) maintenance of a high humidity level in their fungus gardens, (2) the production of saliva and (3) to prevent desiccation. Part of their water need is met by their metabolism but during periods of drought this is insufficient and then termites are reported to descend to the groundwater table even at depths of 20 m or more (Watson, 1974; Lee and Wood, 1971; Cloud et al. 1980). In Wan 3 termite burrows were found down to the bottom of the pit at 7 m in the zone of fluctuating groundwater.

5.2.4 *Soil depth for nesting and building materials*

Subterranean termites need a certain depth of non-indurated soil for construction of their nests, so that they were not observed in the shallow soils near Wan 1. Most termites also need some clay for the construction of nests and channels and where they are not able to find enough clay, a site will become unsuitable for them. The occurrence of termite heaps on sandy soils in Aruama State of Rio de Janeiro in Brasil illustrates this: where the clayey subsoil was at a depth of less than 125 cm, heaps were present, but not where clay was deeper than 125 cm (J. Bennema, personal communication).

5.2.5 *Risk of flooding or waterlogging*

Termites are reported not to be susceptible to low concentrations of oxygen in soil air (Lee and Wood, 1971a). Only high carbon dioxide concentrations of 30-40% had effect on lower termites (all termites except the Family of the Termitidae); at these concentrations the termites became motionless, even in the presence of 20% oxygen. Coaton (1958) reports that *Hodotermes mossambicus* was able to survive in terrains flooded for periods of

3 months; they apparently lived from the oxygen and food reserves in their waterproof nests.

Walls of mounds observed in seasonally waterlogged areas in the area of study were impervious to water, because no water entered laterally even though adjacent soils were completely waterlogged. No mounds were observed, however, in almost permanently waterlogged areas in valley bottoms in East Kisii.

5.2.6 *Risk of disturbance*

Disturbance of nests and galleries may be caused by animals as well as man. Antbears when searching for termites thoroughly disturb the nest. Other predators, such as ants caused no damage to termite structures.

Man disturbs nests when ploughing his fields, particularly nests of the mound building species. Therefore mounds of humus feeders were not observed in cultivated fields.

Because effects of cultivation on termites is a subject of further study, it will not be discussed here.

5.3 EFFECTS ON CHEMICAL PROPERTIES

5.3.1 *A literature review*

Fungus growing termites feed mainly on wood and leaf litter which have very low nitrogen contents (0.05%, page 173, La Fage and Nutting, 1978). By contrast the termite's body has a high N content. Matsumoto (1976) studied the flow and accumulation of nitrogen during food preparation. He found the N content of comb material to be only slightly higher than that of its source materials, but the white spherules of fungal hyphae showed high N contents (7.3% of dry weight). Matsumoto's data indicate, that the nitrogenous substances are concentrated step by step during the production of food by termites. The white spherules finally provide the appropriate nitrogenous food for termites to build their bodies, which have a N content of 9-12% (dry weight) and a C/N ratio of approximately 4 to 6. Matsumoto did not investigate the role of nitrogen fixing bacteria, but Boyer (1955, 1956a) and Pathak and Lehri (1959), cited by Lee and Wood (1971a) found nitrogen fixing bacteria in combs of Macrotermitinae. No data are available to estimate the effect of nitrogen fixing bacteria in accumulating nitrogen during food production.

Studies regarding chemical effects of termites on soil materials are usually based on a comparison of chemical characteristics of termite mounds with those of adjacent soils (Hesse, 1953, 1955; Boyer, 1956b; Lee and Wood, 1971b; Cornaby and Krebs, 1975; Pomeroy, 1976a; Watson, 1976; Miedema and van Vuure, 1977; De Wit, 1978 and Arshad, 1981, 1982).

The high level of bases in mounds, particularly of Ca, Mg, K and sometimes Na compared with the adjacent soil, is explained as follows:

- Large amounts of cellulose and lignin containing materials are accumulated in termite nests and decomposed. During this process carbon is efficiently transformed to CO_2 leaving residual material rich in ash. In the process organic matter becomes saturated with bases and looses its acid character.
- Leaching is reduced due to the impermeable walls of the mounds (Umbrella effect).
- If necessary, nest chambers are moistened with water or with moist soil material derived from the humid subsoil. Furthermore, channels made by termites improve permeability for air, so that humid air from the subsoil may pass more rapidly towards the dry topsoil. Both effects accelerate accumulation of salts and minerals in mounds, particularly in dry regions.
- In poorly drained soils, capillary rise from the saturated zone may be important.

Environmental conditions may thus have an important effect on the amount of bases accumulated in termite mounds (Watson, 1976).

Studies regarding the chemical effects of subterranean termites with their diffuse and inconspicuous nest systems are relatively scarce. Robinson (1958) compared the characteristics of soil transported by termites to cover mulch, with the characteristics of topsoil and subsoil. Although the color of the transported soil was more like that of subsoil, its organic matter content and its CEC were nearly as high as that of topsoil. He found a systematic higher pH and saturation with Ca^{++} and Mg^{++}, especially with respect to subsoil, but also with respect to topsoil. The possible effect of saliva in this respect is emphasized by Harris (cited by Robinson, 1958).

That addition of saliva to soil increases the exchangeable Ca content is also mentioned by Miedema and van Vuure (1977); it may at the same time raise the organic matter content as suggested by Pomeroy (1976b) and Wood (1976).

5.3.2 *Results from the area of study*

Chemical effects of the activity of termites on poorly drained soils of the Magena surface were studied near Opapo (Fig. 1), where a transect was dug through a termite mound.

The difference in chemical properties of soils from a mound of Pseudacanthotermes and the adjacent soil was conspicuous (Fig. 16 and Table 9).

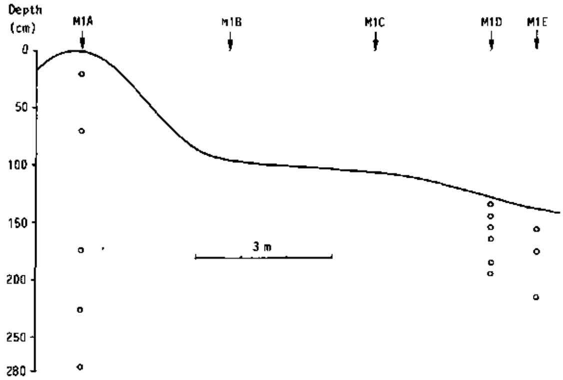


Fig. 16. Cross-section through a termite mound with locations of profiles and depths of sampling.

Table 9. Analytical data of profiles (Pro.) of a cross-section through a termite mound. For situation of profiles and samples see Fig. 16. CEC = cation exchange capacity by NH_4OAc at pH7 in mol/kg dry soil and B.S. = base saturation.

Pro.	Depth (cm)	Org. C. (g/kg)	pH		Exchangeable bases (mol/kg soil)				CEC-	B.S.	SiO_2/Al_2O_3 in clay
			H_2O	KCl	½Ca	½Mg	K	Na		%	(mole %)
M1A	20	17	.	.	170	51	4	2	280	81	4.2
	170–180	14	6.7	5.7	248	46	4	6	301	100+	4.4
	220–230	11	7.6	6.1	250	35	4	6	317	93	4.8
	270–280	1	n.d.	n.d.	265	39	3	11	303	100+	4.2
	fungus material	51	6.5	5.4	305	54	5	8	358	100+	4.8
M1D	0–10	15	5.8	4.0	72	18	2	2	148	64	4.4
	10–20	10	5.8	3.8	61	9	1	6	122	63	4.8
	20–30	6	5.9	3.6	66	7	2	7	129	64	4.0
	30–40	8	5.5	3.5	78	8	2	12	173	58	3.8
	50–60	9	5.6	3.5	101	11	2	18	229	58	3.4
	60–70	8	5.6	3.5	95	10	2	17	205	60	3.5
M1E	10–20	9	5.8	3.7	39	2	1	4	91	51	4.5
	30–40	7	5.9	3.8	32	1	1	5	79	49	3.9
	60–90	12	6.0	3.7	133	3	3	36	378	46	2.9

The base saturation ranged from approximately 1 in the centre of the mound to 0.5 in the adjacent soil. The pH (KCl) decreased accordingly from 5.7 to 6.1 in the mound to 3.5 to 3.8 in the adjacent soil. The organic matter content in the mound differed little from that of the adjacent soil. The results are in line with similar studies discussed earlier.

When considering SiO_2/Al_2O_3 molar ratios (Table 9), values were higher in the mound (4.2-4.8) than in the adjacent soil (2.9-4.5). These higher ratios could point at a different mineralogy of clay in the mound and the adjacent soil. Bachelier (1978) quotes several authors who found higher ratios in mounds. Some of them found montmorillonite in mounds, whereas adjacent soils contained kaolinite and gibbsite only. Conditions of a high pH, in the presence of much Ca, Mg and Si in the soil solution as commonly occur in mounds, would favour formation of 2:1 type clay minerals.

Concentration of silica in the soil solution of soils in the area under study was probably rather high. This follows from the presence of poorly crystalline clay constituents with a high molar ratio of SiO_2 to Al_2O_3. These high ratios may be the result of the weathering of the highly siliceous peralkaline volcanic ash (Wielemaker and Wakatsuki, 1984 and Wielemaker, 1984) from which part of the finer soil materials were derived.

6 Micromorphological studies of spatial arrangement of soil materials by termites

6.1 INTRODUCTION

Chapter 4 showed that soil materials from various parent materials were intimately mixed. Mixing is the result of transport and rearrangement of soil ·als. Which pedogenetic processes are responsible for mixing and how they follows from an interpretation of micromorphological features, described s chapter.

When not considering the possible role of erosion and sedimentation, which will be treated in the next chapter, rearrangement and transport of soil material are the result of two sets of interacting pedogenetic processes. To the first set of processes belong:

(i) Transport of soil materials by soil fauna.

(ii) Transport due to physical processes such as shrinking and swelling, when soil materials become alternately dry and wet.

During the first set of processes, pores and cracks are being formed allowing the second set of processes to take place. To the second set of processes belong:

(i) Infilling of pores and cracks due to dispersion and translocation of clay.

(ii) Collapse of pores and cracks due to instability of structure.

(iii) Compression of pores and cracks due to an overburden.

(iv) Compaction of pores and cracks due to farm machinery or trampling by cattle and game.

(v) Structural decay due to practices such as ploughing.

(vi) Surface sealing due to insufficient coverage by vegetation or crops.

Weight of overburden, rheological characteristics of soil materials, moisture content and changes in moisture content are important rate determining characteristics for processes i, ii and iii and partly iv and vi. Management practices are especially important for processes iv, v and vi. The second set of processes leads to complete compaction of soil materials if collapsed structures and pores are not replaced or restored.

Restoration of structure and pores due to physical processes is especially important in soils with a large fraction of 2:1 clays, but the majority of soils in the tropics has clays with a lower ratio of Si to Al. Particularly in the latter soils, speed of transport of soil materials is thus regulated by:

(i) the activity of soil fauna and

(ii) the rate at which voids and structure elements decay.

These two processes are interacting. It is in fact a homeostatic control mechanism, which will function as long as the ability or potential of soil animals for restoration is not exceeded.

6.2 METHODS

The definitions used in the micro-morphological analysis are those according to Brewer (1976). Area fraction of argillans and papules was determined in the solid phase by point counting; the area fraction of other features was determined by a ranking of thin sections for each feature. pF: mass fraction of moisture in saturated soil and soil after equilibration with a sandbox at pF 0.4, 1.0, 1.5 and 2.0, a kaolin box (for pF 2.3 and 2.7) and pressure equipment for pF 3.0, 3.7 and 4.2 (Stakman et al., 1969).

6.3 RESULTS

6.3.1 *Termite-made pellets*

Two types of pellets, made by termites, were observed in thin sections; the smallest with a diameter of 40-80 μm were nicely round with a smooth surface (Fig. 17). The bigger ones with a diameter of 200-800 μm had an irregular but smooth surface.

Both types occurred as backfill material in channels and chambers down to and between the weathered rock or as matrix material in the upper horizons of some profiles such as Wan 1, 2 and 3. The depth at which they were observed and also the arched pattern of some of the backfillings suggested that the

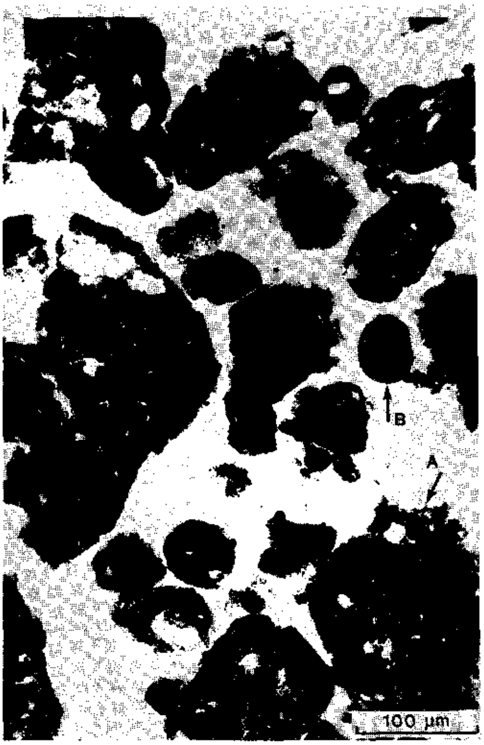


Fig. 17. Oral (A) and faecal (B) pellets in backfill material, observed in a thin section, taken from a depth of 300-315 cm in profile Wan 3.

Fig. 18. Arched pattern in channel, backfilled by termites.

pellets were made by termites (Fig. 18).

The bigger pellets were apparently formed by the mandibles of the termites, but the smaller pellets had a form and size similar to the pellets from which fungus combs are built and which were faecal in origin (Fig. 14C).

In the well drained deep soils, the area fraction of termite-made pellets decreased strongly from the surface down to a depth of 100-200 cm; it then remained nearly constant or decreased slightly down to the gravel line. Below the gravel line the area fraction decreased with depth; the decrease coincided with an increase in the area fraction of weathered rock (Table 10).

Most termite-made pellets were observed in thin sections of Wan 1, 2 and 3, followed by Wan 9 and 210. Least pellets were observed in Wan 4, Wan 5 and 2 M/4, in decreasing order.

Table 10. Area fraction of the solid phase composed of oral and faecal pellets in the studied profiles, estimated by ranking of thin sections (+++,>0.5; ++, 0.5-0.2; +, 0.2-0.05; (+), <0.05-0.0 and -, not detectable). [x] Part with soil structure; [xx] part with rock structure.

Wan 1		Wan 3		Wan 9		Wan 4	
Depth (cm)	ranking	Depth (cm)	ranking	Depth (cm)	ranking	Depth (cm)	ranking
5- 13	+++	0- 40	+++	40- 60	++	0-214	+
		40-115	++		+	260-275	(+)
		115-315	+	305-325	(+)	320-335	-
		315-700	(+)	330-350[x]	+		
				330-350[xx]	-		
Wan 2		**210**		**M1E**		**Wan 5**	
Depth (cm)	ranking	Depth (cm)	ranking	Depth (cm)	ranking	Depth (cm)	ranking
0- 30	+++	5- 20	++	0- 50	+	0-125	+
55-100	++	40-150	+	50-110	-	166-295	-
120-165	+						

6.3.2 *Voids and porosity*

The total area occupied by voids (pores) was biggest in the upper part of the soils down to a depth of 100-200 cm, particularly in Wan 1, Wan 3, Wan 4 and Wan 5 (Fig. 19). This trend was also observed in Fig. 20, assuming a relation between the area occupied by larger voids and water held between pF 0 and pF 3. The amount decreased down to about 100 cm and remained relatively constant below that depth. Type of voids and their relative distribution differed among soils and with depth as shown in Fig. 19.

Voids between pellets and grains. Where termite-made pellets dominated the matrix, the area occupied by pores was almost continuous between pellets (compound packing voids in Fig. 19 and 21A). Deeper in the profile termite-made pellets seemed to have merged together, so that voids were less continuous (interconnected vughs) or merely consisted of isolated openings (vughs) (Fig. 21A). The numerous transitions which existed between loosely

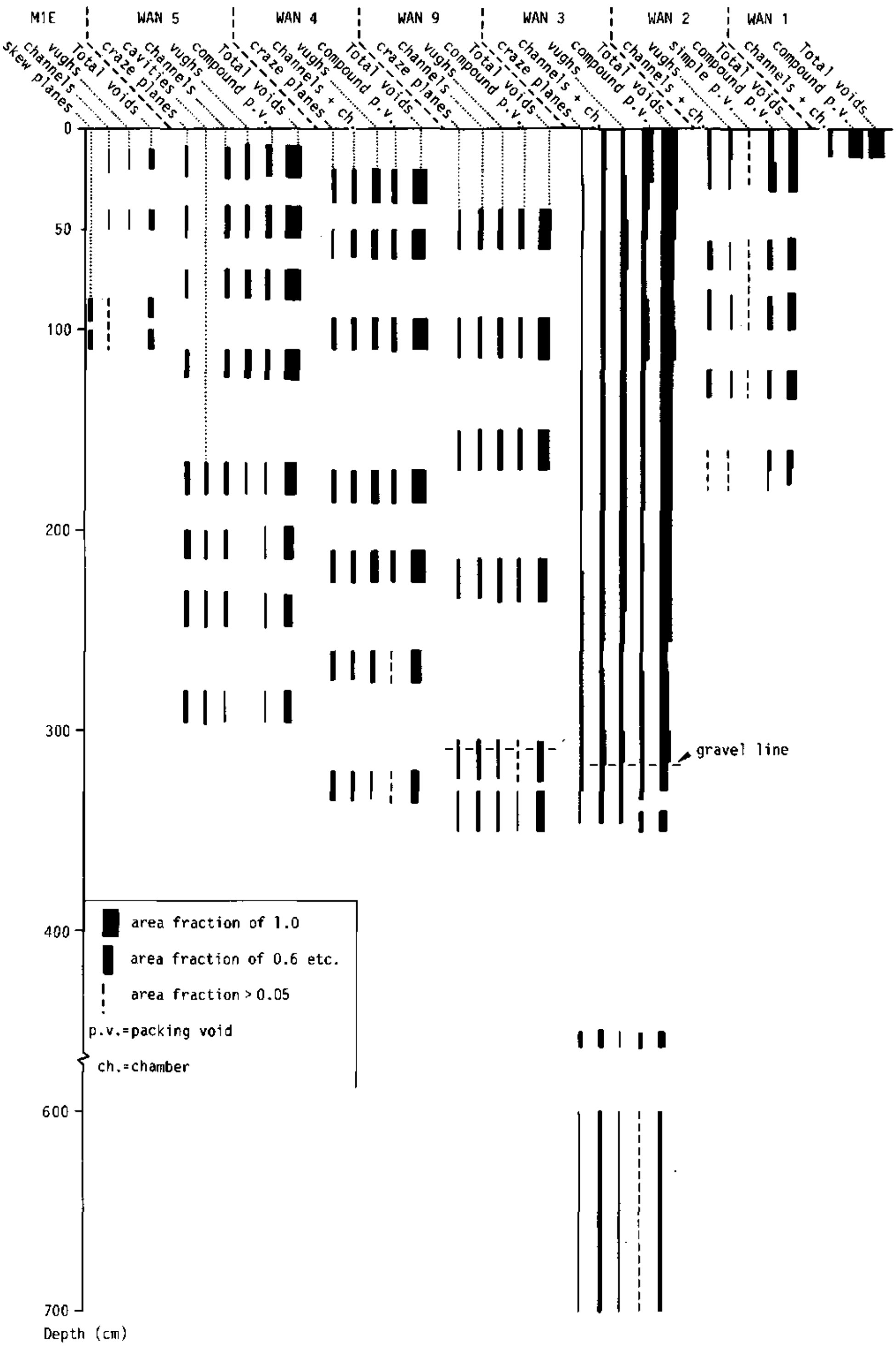


Fig. 19. Ranking of the area fraction of voids in thin sections. p.v. = packing void; ch = chamber.

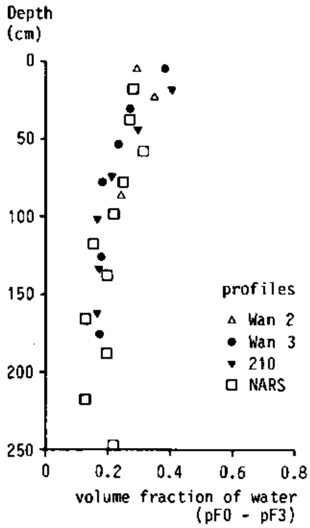


Fig. 20. Volume fraction of water held between pF0 and pF3 at different depths in well drained soils.

packed termite-made pellets and a matrix in which individual pellets were no longer recognizable suggested, however, a faunal origin, even for the isolated openings (vughs), though much degraded compared with their original form.

Similar vughs were not degraded, where they occurred in densely packed walls of chambers and channels made by termites (Fig. 21B). The vughs between large-sized quartz grains in thin sections of profile Wan 2 (simple packings voids in Fig. 19) were not faunal in origin.

Channels, chambers and cavities. Channels had a diameter of 0.8–5 mm of which the larger sized were usually lined with pellets. The form of the channels and also their distribution throughout the profile indicated their termite-made origin. The area fraction of channels varied little with depth and soil type except for the imperfectly to poorly drained subsoils of Wan 5 and MIE and the horizon below the gravel line in the well drained profiles (Fig. 19).

The macro-morphology of fungus chambers was described in chapter 5. In thin sections of well drained soils only backfilled chambers were observed, easily recognizable from their densely and regularly constructed walls (Fig. 21B) and from the backfill material composed of loosely packed termite-made pellets (see for instance Fig. 17).

Irregular shaped backfilled cavities were also observed amid weathered rock in the weathered rock zone, which were probably developed as a result of the termite's search for water and/or wet clay (Bachelier, 1978; Lee and Wood,

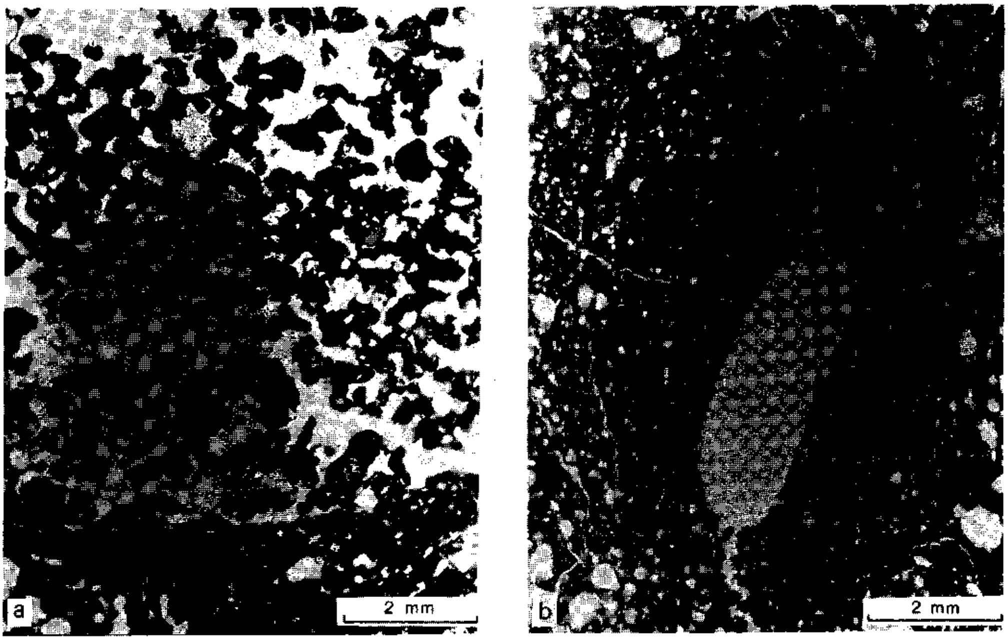


Fig. 21. A. Transitions between a matrix with compound packing voids (1), and a matrix with interconnected vughs (2) and simple packing voids (3) suggest that pellets loosely packed by termites gradually merge together as the matrix grows older.
B. Simple packing voids if occurring in a regular pattern in walls of chambers and channels, are made by termites.

1971a). The imperfectly drained subsoil of Wan 5 showed 3-10 mm wide cavities, partly infilled with very fine sand, silt and clay (Fig. 22). Though few of these cavities were backfilled by termites, their persistence at that depth could hardly be imagined without the action of termites. In the subsoil (100-110 cm) of Profile M1D, all channels were backfilled by termites.

Cracks. Cracks (craze and skew planes) caused by shrinking and swelling were common in thin sections of the subsoil of Wan 4, Wan 5 and most important in the subsoil of M1E.

6.3.3 *Redistribution and reorientation of skeleton grains and plasma*

Illuviated soil materials and their redistribution. Illuviation of clay with or without silt and sand is a decay process, which leads to texture

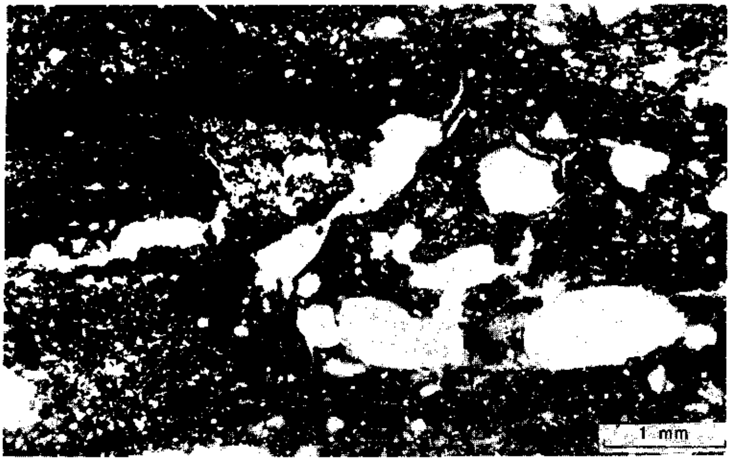


Fig. 22. Composite cutans consist of parallel layers of illuviated fine sand, silt and oriented clay (thin section from profile MID at a depth of about 60 cm).

differentiation and compaction of the illuviated horizon, unless counteracted by redistribution, due to physical and/or biological processes (see Section 6.1).

Illuviated clay occurs as argillans (oriented clay) or ferri-argillans if stained by iron (Brewer, 1976). Argillans were observed in parts of the profiles studied except in Wan 1. In the subsoils of Wan 4, Wan 5 and M1D, ferri-argillans were commonly associated with parallel bands of illuviated silt and fine sand (Fig. 22). These composite illuviation features are called composite cutans. The term matri-ferriargillan as defined by Van Schuylenborgh et al. (1970) does not apply here because the term refers to illuviation of a mixture of clay, silt (sand) and organic matter. Thickness of the argillans, depth of occurrence and also their association with different fabrics were recorded in order to estimate past or present strength of illuviation processes.

On the other hand papules (pieces of oriented clay) were signs of redistribution. They were often observed within termite-made pellets, but also in a matrix in which individual pellets were less clear. In the subsoils of Wan 5, M1D, M1E, big (500 μm) and small (20 μm) irregularly shaped papules were observed. Size and shape excluded a faunal origin of the bigger papules.

Illuviation phenomena were weak or absent in the upper 2-3 m of Profiles 210 (Table 11) and Wan 9, common and distinct in Profiles Wan 2 and Wan 3

Table 11. Area fractions of oriented clay (ferri-argillans and papules) determined on the solid phase, and the displaced fraction (displ.) of oriented clay (papules) for three profiles of the Wanjare catena and for profile 210. Papules with asterisk were not of faunal origin.

Wan 2			Wan 3			Wan 5			210		
depth (cm)	total	displ.	depth (cm)	total	displ.	depth (cm)	total	displ.	depth (cm)	total	displ.
0- 30	-	-	0- 15	<0.003	.	8- 23	<0.001	0.50	5- 20	-	-
55- 70	0.017	0.30	40- 55	0.017	0.24	38- 53	0.003	0.48	40- 55	-	-
83- 98	0.023	0.23	85-100	0.023	0.26	70- 85	0.016	0.33	70- 85	-	-
120-135	0.014	0.21	130-145	0.016	0.44	110-125	0.047	0.38	100-115	0.002	tr
			160-285	<0.003	n.d	166-182	0.081	0.06*	135-150	0.009	tr
			285-300	0.014	0.29	232-247	0.036	0.60*			
			315-330	0.022	0.45	280-295	0.090	0.11*			
			345-350	0.062	0.13		0.056	0.20*			
			600-700	0.055	0.05						

(Table 11) particularly above a depth of 160 cm and frequent and strongly developed in Profiles Wan 5 (Table 11), Wan 4 and M1D (Fig. 22). Along cracks and in cavities in the subsoil of the last three profiles, big (100-1000 μm) composite cutans were observed (Fig. 22). This and the presence of big papules (Table 11) pointed at instability of the soil fabric.

In contrast with Profile M1D, which was situated on the slope of a termite mound, the adjacent Profile M1E showed only few composite cutans. The subsoil of this profile was, however, very compact; no cavities and only few cracks were observed, probably due to the absence of termite activity. Moreover, the eluvial horizon had lost most of its clay, so that the process of eluviation had come to an end. Under such circumstances illuviation can hardly take place, while existing features may disappear due to shrinking and swelling (Appendix 3).

Reorientation due to shrinking and swelling. According to the plasmic-fabric (Appendix 3) shrinking and swelling phenomena are weak or absent in the well drained profiles, moderate in the somewhat imperfectly drained subsoils of profiles Wan 4 and Wan 5 and strong in the subsoil of the poorly drained profile M1E.

Redistribution due to the soil fauna. The zone of weathered rock in Wan 2 (depth 1.60 m), Wan 3 (4->7 m) and Wan 9 (>3 m) was illustrative of what transport by soil fauna can achieve. Soil at those depths consisted of two contrasting fabrics. One fabric seemed old as it was associated with thick well developed ferri-argillans within a rather dense fabric. The other fabric consisted of loosely packed pellets, which had not merged so that the fabric seemed young. The absence of papules in the young fabric indicated that the pellets dit not originate from the surrounding matrix. The proportion of plant opal and glass minerals observed in these pellets (Fig. 23) and also their form and color were similar to that observed in pellets of the upper 70 cm of the profile, in contrast with the "old" fabric where such minerals were not observed. The pellets were found as backfill material in cavities and also as linings of larger sized channels (Ø 1 cm).

Contrasting colors in A and B horizons indicated transport of soil material from the A to the B horizon and from the B to the A horizon. The dark colored material in the upper part of the B horizon was usually found in backfilled chambers and channels and in the deeper part only in large channels and small chambers. The pattern of the backfillings was usually arched (Fig. 18) which left little doubt about the faunal origin of those backfillings. Similar arched patterns at 15 m depth in soils of Zambia were attributed to termites (Cloud et al. 1980). Visible relicts of transport by soil fauna were most clearly expressed in Profiles Wan 3, Wan 2 and Wan 9 (Table 12), but pellets observed in Profile 210 did not contrast with the surrounding matrix.

Fig. 23. The presence of opal phytoliths (bar-shaped minerals) and glass fragments (not observable), and the morphology of the pellets with dark finely divided humus, observed in a backfilled cavity at a depth of 350 cm in Profile Wan 3, indicate that pellets originated from the upper horizon of the profile.

Table 12. Ranking of biological (Biol.) and degradational (Degr.) properties in the studied profiles, based on Tables 10 and 11 and descriptions in 6.3.3. Ranking of biological properties was based on an estimate of the area fraction of V (voids): compound packing voids, channels, chambers and cavities from -, not detectable to ++++, very big; S (structure): termite-made pellets from -, not detectable to +++, big; P (papules), made by the soil fauna from -, not detectable to ++, fairly big and R (relicts): soil originating from other horizons and transported by termites from -, not detectable to +++, big. Ranking of degradational properties was based on an estimate of the area fraction of V (voids): skew and craze planes and masepic fabric, from -, not detectable to 000, big; A (argillans): from -, not detectable to 000, big and P (papules): not of biological origin from -, not detectable to 000, big. Reduction phenomena, if present, are indicated with: g1, slight reduction; g2, moderate reduction; g3, moderately strong reduction; g 4, strong reduction and g5, very strong reduction. tr, traces; n.d. not determined. Depth in cm.

	Profiles							
	Wan 9	210	Wan 3	Wan 2	Wan 4	Wan 5	M_1E	M_1D
Depth	0-50	0-50	0-50	0-50	0-50	0-50	0-50	0-50 g3
Biol. V	+ (+)	n.d	++++	++	+	++	(+)	n.d
S	+ (+)	+ (+)	+++	+++	+	+	+	n.d
P	tr	tr	+	+	++	+(+)	(+)	n.d.
R	+	(+)	+++	++	+	+	-	n.d.
Degr. V	-	-	-	-	-	-	-	-
A	-	-	0	0	00	0(0)	-	000
P	-	-	-	-	-	-	-	-
Depth	50-100/115	50-100	50-110	50-100	50-120	50-130 g1	50-100 g5	50-100 g3
Biol. V	+(+)	n.d	++(+)	+(+)	+	++	-	n.d
S	+	+	++	++	+	+	-	n.d
P	tr	tr	+	+	++	+(+)	-	n.d
R			++	+	-	-	-	n.d
Degr. V	-	-	-	-	(0)	(0)	000	n.d
A	-	-	0	0	00	0(0)	0	000
P	-	-	-	-	-	-	(0)	-
Depth	100/115-315	100-150	110-315/345	100-170	120-250 g1	160-300 g3		
Biol. V	+(+)	n.d	+(+)	+(+)	+	(+)		
S	(+)	+	+	+	+	-		
P	tr	tr	(+)	(+)	+	-		
R			+	+	-	-		
Degr. V	-	-	-	-	(0)	0		
A	-	-	(0)(to 160cm)	0	00	000		
P	-	-	-	-	0	000		
Depth	>315-350+		345-700+		250-335 g2			
Biol. V	+		+		+			
S	+		+		-			
P	tr		tr		(+)			
R	+		+		-			
Degr. V	-		-		(0)			
A	00		00		00			
P	tr		tr		0			

Redistribution due to mechanical transport. Presence of composite cutans in the subsoils of Wan 4, Wan 5 and M1D suggested backfilling of large cavities by sedimentation from water. This and the presence of big papules were suggestive of a process of internal erosion and collapse of structure, which would continue to operate as long as termites kept excavating new holes and cavities (Section 6.1).

This process may also help to explain certain features of gley, which appeared in thin sections as distinct and well developed dark ferric nodules, but also as dense dark reddish brown matrix domains. Sometimes the domains resembled the weathered rock (bottom part of Profile Wan 5 and Wan 9), but they also resembled an oxidized reddish brown matrix or a more reduced grayish brown matrix (Profile Wan 5, 70-85 cm). Their rounded forms and distinct boundaries could well be the result of abrasion in view of the continuous displacement of soil materials. Disintegrating nodules and domains were also observed, which suggested their incorporation in the surrounding matrix.

Presence of organic matter. The organic matter in the plasma of fabrics discussed in Appendix 3 was dark colored and intimately mixed with the mineral fraction. It was not acidic so that the organic matter conforms to the definition of mull (Kubiena, 1955). Pieces of dark humus, if present, were especially observable in loosely packed pellets (Fig. 23) but humus was usually present like a dye giving the peds an opaque dark color.

6.4 DISCUSSION AND CONCLUSIONS

6.4.1 *Features made by the soil fauna and features indicative of their degradation*

Table 12 shows that the area fraction of features indicative of degradation in the upper metre of the soil profile increases from Wan 9 to M1E and M1D.

Impeded drained profiles. In Profiles Wan 4, Wan 5 and M1E these properties are correlated with drainage conditions because their area fraction and intensity increase from Profile Wan 4 to Profile M1E and M1D. But properties indicative of degradation such as argillans seem to disappear due to shrinking and swelling if there is no fauna to restore the pore system so that clay can illuviate (Section 6.1).

When decay processes are so strong that clay, silt and fine sand actively illuviate, termite activity must also be strong to prevent formation of a compact horizon and an abrupt textural change such as developed in Profile M1E. This means that Profile Wan 5, which has properties indicative of strong degradation, would have been a degraded soil, were it not for the very high biological acitivity, which apparently prevented texture differentiation and compaction of the subsoil with its unstable structure. Furthermore, the presence of composite cutans around cavities in the reduced and therefore most unstable part of the matrix, reflect processes operating at present.

In the somewhat better drained Profile Wan 4, degradational processes were apparently less strong than in Wan 5, but stronger than in the well drained Profiles Wan 9, 210, Wan 3 and Wan 2 (Table 12), as follows from the area fraction of argillans in these soils. The presence of many papules of biological origin and the absence of a sharp texture change indicate a high biological activity even though there were not so many biological voids and structure elements as in Profile Wan 3.

Well drained profiles. Properties indicative of degradation were least developed in Profile Wan 9 and Profile 210, which follows from the virtual absence of argillans in the upper part of the soil. Argillans were only observed in and below the gravel line, in the "old" dense fabric, which strongly contrasted with the apparently more recent fabric made up of loosely packed pellets. Because the younger fabric did not show any argillans, illuviation of clay seemed not to be an active process.

When properties indicative of degradation and of faunal activity in Profiles Wan 9 and 210 are so weak, it follows that present activity of the soil fauna is much smaller than in Profiles Wan 3 and Wan 2, which had more properties indicative of degradation and of faunal activity. Despite the few signs of degradation in Profiles Wan 9 and 210, they were most susceptible to sealing, structure decay and erosion (Wielemaker and Boxem, 1982) of all profiles presented in Table 12 (except for M1E and M1D). This apparently contradicts with the absence of properties indicative of degradation (Table 12), but can be explained by assuming that old termite-made pellets are less stable than fresh ones.

The stability of fresh pellets could be due to the presence of microbial slime probably composed of muco-polysaccharides (Hayes, 1983) and also to the high saturation with Ca ions. Products of microbial slime are easily decomposed (Van Dijk, 1961) and Ca ions may gradually leach, so that stability declines as pellets grow older.

This process of "ageing" would also result in morphological changes such as disintegration or merging together of individual pellets (Bal, 1973), unless the soil were consumed again before this occurred. Ageing of the soil fabric and a consequent loss of stability could then only occur in soils or soil layers with a low biological activity such as Wan 9 and 210 and this could explain why these profiles are so susceptible to sealing and surface erosion.

Besides structure stability, termites also controlled other physical soil characteristics such as porosity and permeability (Table 12). All pores in the well drained profiles down to the groundwater table were either made by the soil fauna or derived from pores made by the soil fauna. Only the most poorly drained soils had mainly pores of physical origin (Fig. 19, skew and craze planes). Porosity and consequently permeability in all soils studied were, therefore, determined by the activity of soil fauna and ranged from a very rapid permeability and a high porosity in the well drained soils to a slow permeability and a very low porosity in the most poorly drained soils (M1E).

Formation and disappearance of features of gley seemed also controlled by termite activity. The numerous transitions between weathering rock, concretions, oxidized soil matrix and reduced soil matrix observed in imperfectly drained soil horizons, suggested that pieces of soil fabric were continuously translocated and this propably caused their transformation, disappearance and new formation.

6.4.2 *Pedoturbation and mineral distribution*

The mineralogical properties as described in Chapter 4, showed particularly that parent material from volcanic ash and local country rock were intimately mixed. How the turbation process works and what effect it has on mineral distribution in soils follows from an appraisal of the results of Chapter 4 and this chapter.

Distribution of volcanic glass and plant opal. In well drained deep soils volcanic glass, an easily weatherable mineral, was especially observed in the upper 40 cm of the profiles studied; it then decreased irregularly to a low but measurable mass fraction at a depth of 100-120 cm; below that depth it remained practically constant down to the gravel line (Table 5). Below the gravel line it decreased with depth due to an increase in the area fraction of soil with rock structure (Section 4.2, Profile Wan 3). Three kinds of mechanisms could have played a role in the formation of this distribution:

(i) Active upward and downward transport of minerals related to the construction of foraging channels on the soil surface and to the construction and backfilling of chambers and channels.
(ii) Downward transport of minerals by gravity.
(iii) A difference in the degree of weathering of glass minerals from upper and lower horizons due to a difference in age.

The observation of termite-made pellets containing glass and plant opal minerals in cavities in the zone of weathered rock and along main channels in the zone above it (Section 6.3) suggests an active transport of soil particles from the A horizon even down to the zone of fluctuating groundwater. Mechanism (ii) seems irrelevant because no signs of mass transport by water were observed apart from some illuviated clay in Profile Wan 2 and the upper part of Profile Wan 3. Also mechanism (iii) seems unlikely because pellets and glass grains in topsoil and subsoil are similar.

Although signs of mass transport by water were not observed, the deposition of soil on the surface and the regular passage of animals through a soil with a loosely packed matrix may increase the chance, that glass minerals sink in the profile. This process, if operative, will only be important above 100 cm depth where big pores were most common. Mechanism (ii) would, below this depth result in a decreasing number of glass grains with increasing depth, which is denied by the constant mass fraction of grains observed there.

Presence of composite cutans in the imperfectly to poorly drained subsoils of Wan 4, Wan 5 and M1E with unstable structures are a sign of gravity transport by water. Plant opal minerals were commonly observed in the composite cutans and their distribution is probably related to this downward transport. In contrast with the well drained soils, mechanism (ii) seems an important process especially in horizons with poor drainage conditions.

Distribution of epidote. The mass fraction of ash-derived soil material in Profile S3 was quite uniform even to a depth of more than 7 m (Section 4.2.5), but the mass fraction of epidote minerals, decreased from the surface down to a depth of about 10 m where epidote strongly increased (Appendix 1).

It shows that soil material from a depth of at least 10 m is transported to the upper soil horizon (slope transport can be discarded as a source of epidote minerals, because Profile S3 is situated on the flat part of a ridge). That termites add soil from a depth of at least 7 m to the upper soil horizon was already observed when studying glass distribution. The epidote distribution tells us that it is preferentially added to the top 50-100 cm of the soil profile, so that this horizon gets enriched with fresh epidote minerals. Because also the deeper horizons consist of mixed soil materials it seems that the lower percentage of epidote in those horizons is due to weathering. The continued addition of ash to the surface horizon and its mixing with soil containing little or no ash, will result in very deep mixed soils, as is indeed reflected by the mineralogy of the soils (Chapter 4).

Distribution of magnetite-II. Magnetite-II, a rather stable mineral, was only detected in relatively old and deep soils (Chapter 4). In contrast with glass, it was rather evenly distributed down to the gravel line at about 3 m (Fig. 9).

Its distribution in soils is the result of mixing over a very long period of time, so that even a low transport activity of termites below a depth of 1 m (but above the stone line if present), resulted in a thorough mixing and accumulation of stable minerals from volcanic ash.

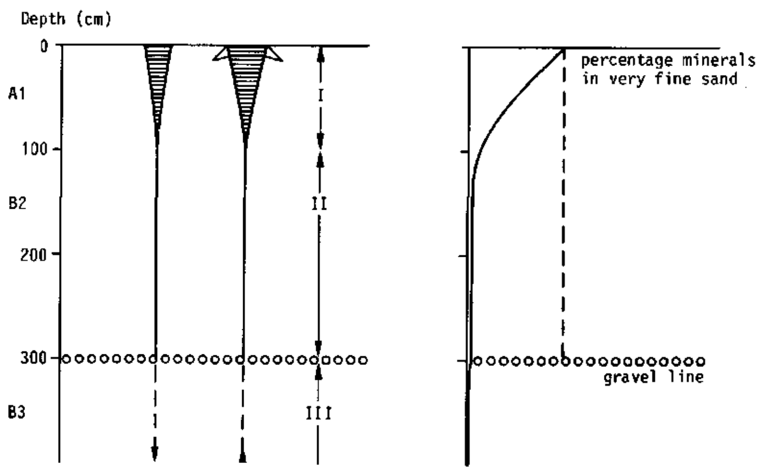


Fig. 24. A. Width of the arrows indicates schematically, downward and upward transport activity as a function of depth in deep well drained soils. I, zone of nesting and foraging; II, zone of refuge and passage to groundwater; III, zone of moisture supply in time of drought below the gravel line (oooo).
B. Schematic distribution of rather recent (glass, solid line) and old (magnetite II, broken line) minerals from volcanic ash in well drained profiles.

Transport activity and mineral distribution. Results of studies concerning transport activity of termites and its effect on mineral distribution in the deep well drained soils are summarized in the model presented in Fig. 24. Fig. 24A shows that termites are most active in the upper metre of the profile which is the zone of nesting and foraging. Activity in the zone below 1 m is much lower, but decreases only slightly with depth down to the stone or gravel line. Below that line activity did not decrease in the parts with soil structure; the overall activity did decrease, however, due to an increase in the volume of saprolite.

The glass distribution represents the result of transport activity over a relatively short period of time, while the magnetite-II distribution results from a much longer period of mixing (Fig. 24B).

The results show that termites with subterranean nests were active in the deep subsoil, which contradicts Bachelier's (1978) statement that termites with subterranean nests would derive soil materials from surface layers only.

7 Formation of texture profiles in relation to vertical and lateral transport

7.1 TERMITES AND TEXTURE PROFILES

7.1.1 *Introduction*

Most soils in the Kisii area have a relatively gravel and stone free upper horizon over a layer rich in gravel and stones. This layer usually overlies weathered rock (Fig. 25) or ironstone, but it occurs also on top of a B2t horizon. Such texture profiles are common in many soils of the tropics, but there is considerable debate regarding their formation (Section 7.3).

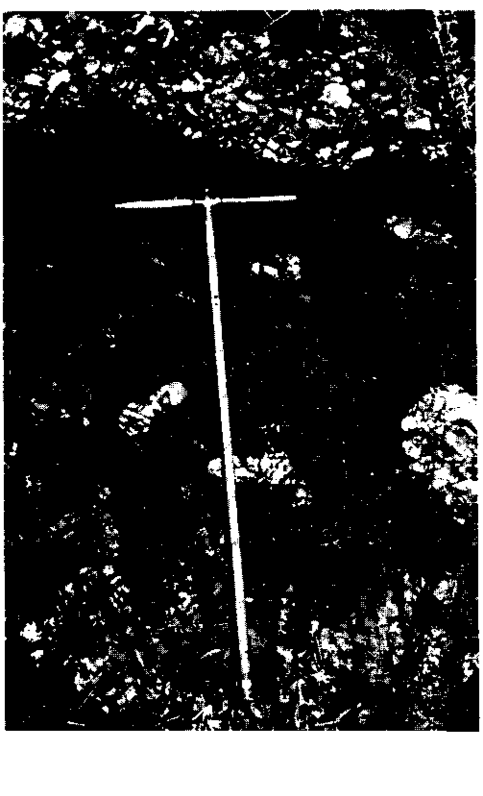


Fig. 25. The layer consisting of quartz gravel separates an upper horizon free of gravel from a BC horizon in which geodes are still in situ. Geodes above the gravel-layer were the source of the gravel, that accumulated in the gravel layer.

Studies described here, are all done in a rather humid environment. The important role termites play in forming texture profiles with stone lines will first be demonstrated on the well drained soils of the Wanjare catena. It is also demonstrated on the poorly drained soils of the flat Magena surface.

7.1.2 *Methods*

Cumulative curves of mass percentages of the logarithm of different size fractions of sand and gravel (50-4000 µm) are shown in Fig. 29 (page 70). Size fractions were: 50-100 µm, 100-250 µm, 500-1000 µm, 1000-2000 µm and 2000-4000 µm.

The quartile measures and median values were determined on graphs according to Krumbein and Pettijohn (1938). Q1 is the grain-size diameter with 25 percent of the grain-sizes smaller than Q1 and Q3 is the grain-size diameter with 75 percent of the grain-size smaller than Q3. The median is the grain-size diameter separating equal weights (50%) of larger and smaller grain-sizes.

Log S_o is used as a measure for the degree of sorting, it is equivalent to (log Q3-log Q1)/2.

7.1.3 *Results and discussion*

7.1.3.1 Texture profiles in well drained soils of the Wanjare catena

Selective transport by termites. Fig. 26 shows the size of pellets transported by termites and used for the construction of their nest opening. It indicates that they make pellets of a size, related to the opening between their mandibles.

When comparing grain-size distribution of termite-made channels with that of the adjacent soil with rock structure in the zone of weathered rock of Profile Wan 3, it shows that channel walls and their infillings have more grains larger than 2 mm than the adjacent soil (Table 13). As explained in Section 6.3 termites transport materials from the weathering rock upwards, so that they caused the increase in grains larger than 2 mm.

Fig. 27 illustrates the same effect on a profile scale. Fine grained material is removed from the deeper part of the profile and transported

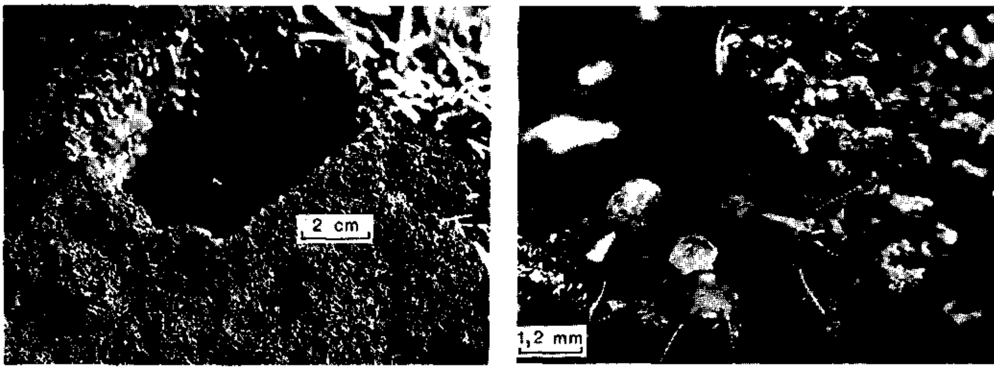


Fig. 26. A. Ventilation shaft of a nest of Odontotermes showing the size of pellets made by the worker termites.
B. Pellets are fixed with a glue of saliva.

Table 13. Grainsize distribution of sand and gravel (0.05 - 4mm) from weathered rock, and from soil material in channels at a depth of 6.5 m in profile Wan 3.

	Fractions (mm) and mass percentages					
	2-4	1-2	0.42-1	0.21-0.42	0.105-0.210	0.05-0.105
Soil	25.4	38.4	21.0	7.0	5.1	3.1
Rock	10.2	43.8	26.3	10.3	6.8	2.6

upwards, where it forms a horizon composed of fine grained material. In the lower part of the profile where the fine grained material is removed, the proportion of coarse grained material increased. Termite activity decreases, however, with depth so that the grain-size distribution of soil materials deeper down gradually equals that of the original saprolite.

Sorting by termites. Fig. 28a and 28b show that grain-size distribution of a termite mound depends on that of the corresponding substratum. In the mound near Wan 1 only the mass fraction of grains larger than 1 mm decreased compared with the grain-size distribution of the substratum, but in the mound near Wan 4, which is over a finer textured substratum, also the mass fraction of grains larger than 0.5 mm decreased. The mound of Wan 4 had the best sorted sand (log So = 0.236, from log So = (log Q3 - log Q1)/2, Q3 and Q1 from Fig. 29), while sand in the mound of Profile Wan 1 was least sorted (log So =

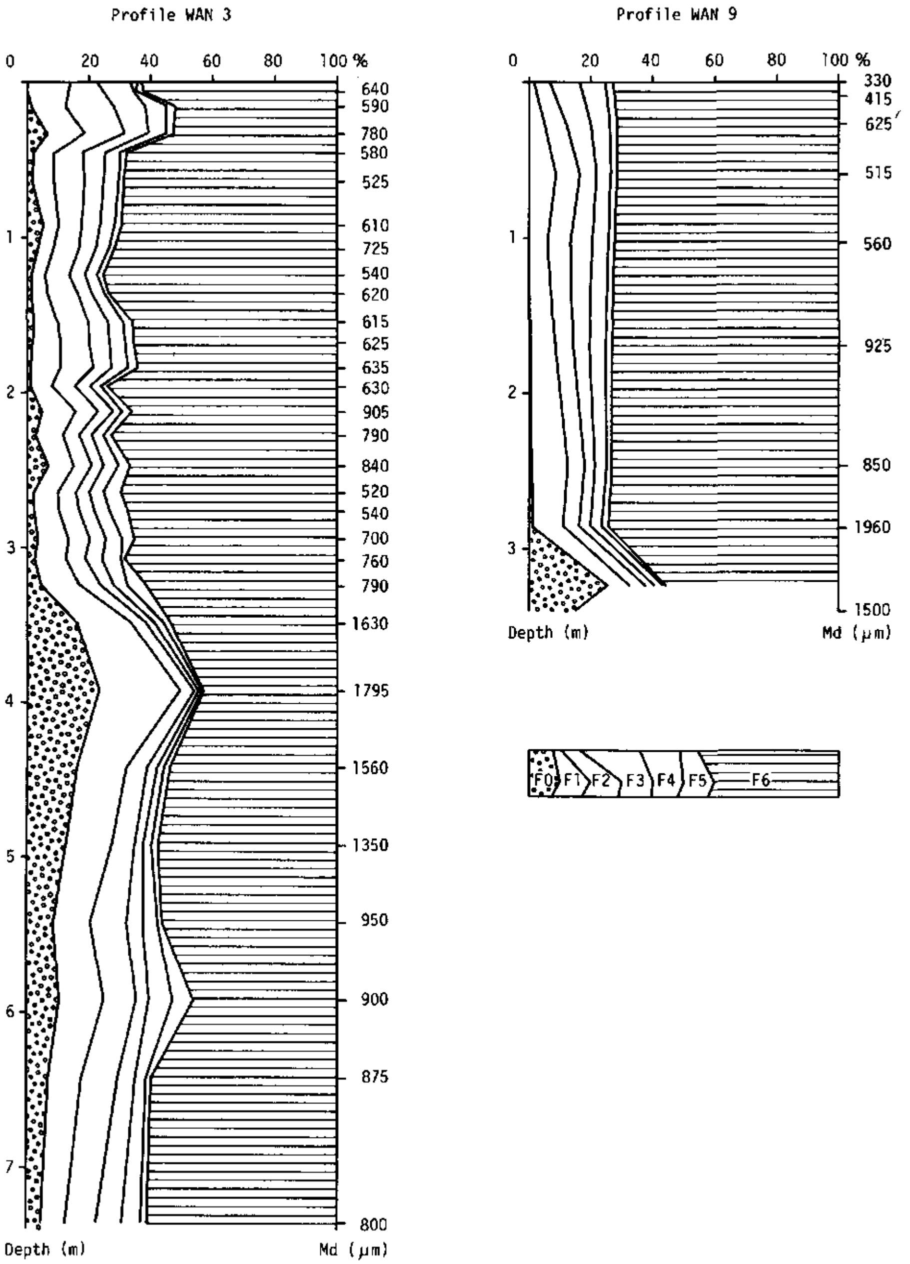


Fig. 27. Grain-size distribution and median diameter (Md) values in profile Wan 3 over diorite and profile Wan 9 over quartz diorite. Size fractions are: gravel, 2000–4000 μm; F1, 1000–2000 μm; F2, 500–1000 μm; F3, 250–500 μm; F4, 100–250 μm; F5, 50–100 μm and F6 < 50 μm. The Md value is of sand and gravel only.

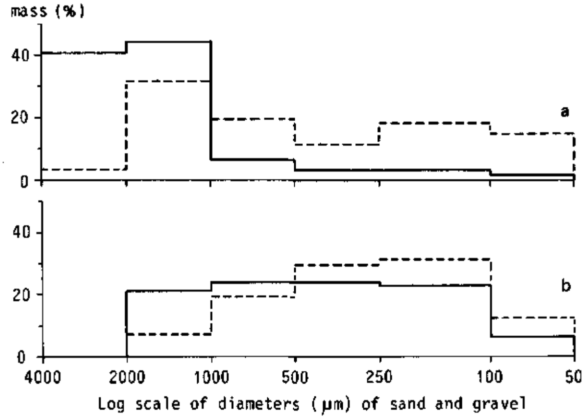


Fig. 28. Relation between mass percentages of different size fractions in sand and gravel (50-4000 μm) of a termite mound (---) and its corresponding substratum (—) for profile Wan 1 A, 14-40 cm (a) and profile Wan 4, 95-110 cm (b).

0.449). From a comparison of median diameter values of sand in mounds and of sand in the adjacent soils, it follows that termites prefer finer sand (<1000 μm) than coarser sand (>1000 μm) so that continued termite activity will

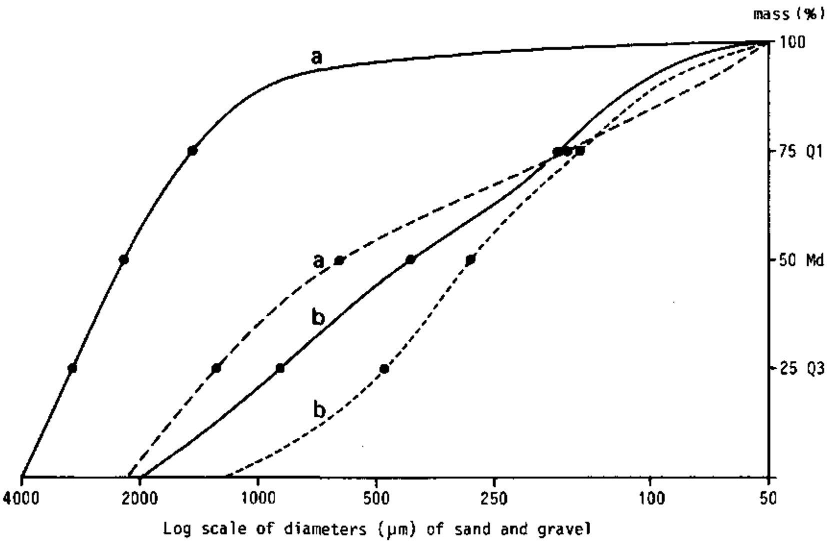


Fig. 29. Cumulative curves of mass percentages of sand and gravel (50-4000 μm) of profile M1A, depth 14-40 cm (—a—) and its corresponding mound (-a-); of profile Wan 4, depth 95-110 cm (—b—) and its corresponding mound (··b··). Quartile (Q1 and Q3) and median diameter (Md) values are indicated with dots on the respective curves.

shift median diameters of sand in topsoil to lower values until the distribution is to the "termites' taste" (Fig. 30).

Such a grain-size distribution in sand of topsoils will only develop, when the fine grained material brought up by termites is not removed by surface erosion. It can then accumulate and become increasingly fine as termite activity continues. If instead, fine grained material of the mound is removed by surface erosion, then a coarse textured substratum will result, composed of grains which termites can not transport, as is probably the case in profiles Wan 1 and Wan 2. Sand in such profiles is well sorted (log So = 0.15) because termites selectively removed the finer fractions.

Although termites with subterranean nests make no mounds, their effect on soil texture will be essentially the same as that of mound building species, namely a net transport of fine textured material to upper horizons. This material will become increasingly fine-textured unless coarse sand is added to it from deeper layers or from upslope.

What slope transport means for composition of soils will be demonstrated in Section 7.2 on soils of the upper Wanjare catena.

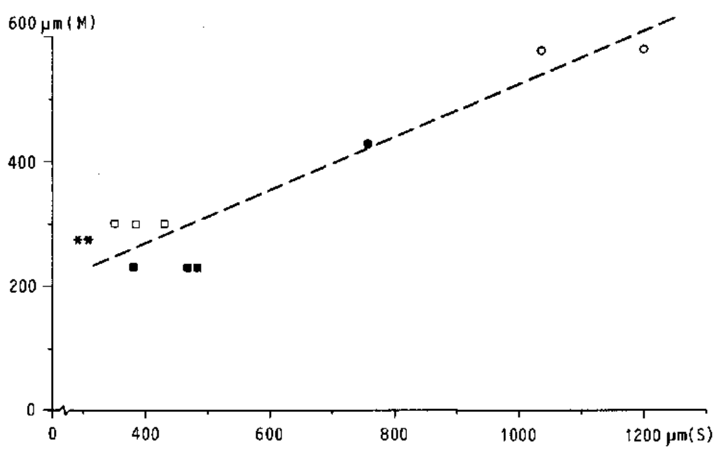


Fig. 30. Relation between the median diameter value of sand and gravel in a mound (M) and its corresponding substratum (S). Wan 1 (   ) with mound of Cubitermes; Wan 1A (o) with mound of Pseudacanthotermes; Wan 4 (   ) and Wan 5 (   ) with mounds of Pseudacanthotermes and Odontotermes and trial field of D. van der Eijk (*) with a nest of Odontotermes.

7.1.3.2 Texture profiles in poorly drained soils of the Magena surface

Soils on the flat surface remnants are strongly differentiated (Planosols according to FAO-Unesco, 1974 and abruptic Tropaqualfs according to Soil Taxonomy, Soil Survey Staff 1975). The profiles between mounds consist of a rather sandy A and A2 horizon overlying a dense clayey B horizon. In the B horizon a stone line occurs, consisting of rounded alluvial gravel and stones, not derived from the underlying rock.

The very good correlation of the mineral composition of sand with the underlying rock indicates, however, that the light textured material of the A and A2 horizon is mostly derived from the country rock. How could this sand, which is derived from the local rock, occur on top of an allochthonous B horizon and if pedoturbation was responsible for this situation, how could soils then be so strongly differentiated. The processes responsible for formation of this texture sequence were studied in a cross section through a termite mound and in adjacent soils.

Pedoturbation by termites. When comparing grain-size distribution of the soil in the centre of the mound with that of the adjacent profile (Fig. 31), it follows that termites thoroughly mixed material from A, B and C horizon,

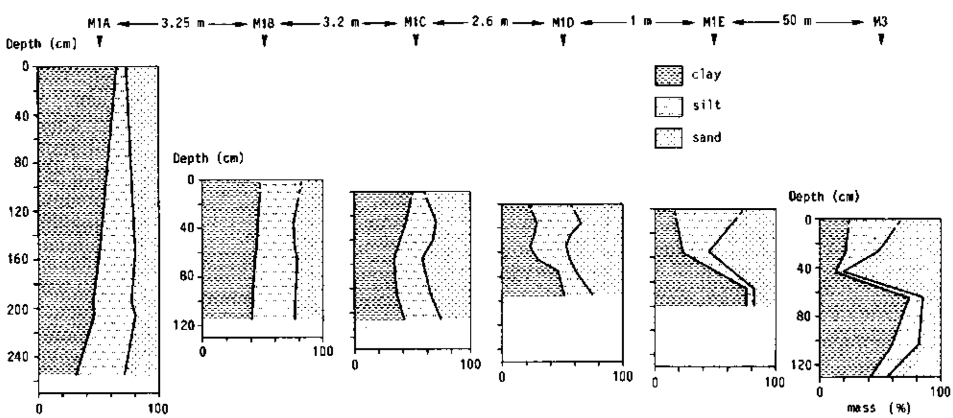


Fig. 31. Mass fractions of sand, silt and clay in profiles of a cross-section through a termite mound of the Magena surface. M1A represents the centre of the mound and M1E the adjacent soil (M1B, M1C and M1D are intermediate in position between M1A and M1E). M3 is situated in the plain between mounds.

except material coarser than 2 mm, which formed a layer at the transition to the weathered rock. Horizon differentiation increases from the centre of the mound outwards (Fig. 31 Profile M1E). This phenomenon can be ascribed to the great structural instability and to the mobility of the clay in these soils, as follows from the following observations:

(i) In pits dug in these Planosols, thick clay flows were observed on the walls of the pit after only one shower, while grey sandy to silty material remained, where clay was leached.

(ii) In termite-made cavities in a thin section of soil M1D well developed composite cutans were observed (Fig. 22). Even in a chamber with live fungus combs, illuviated clay occurred.

The formation of the texture sequence in these Planosols can thus be explained as follows:

- Pedoturbation by termites enriches soils with sand, clay and some silt derived from the weathered granite.
- Horizon differentiation is caused by illuviation of clay, so that the A and A2 horizons become enriched relatively with silt and sand and the B horizon with clay.

The soils grade, therefore, from a homogeneous soil in the centre of the mound, where bioturbation most strongly counteracts illuviation, to a soil where bioturbation is not strong enough to counteract illuviation.

Pedoturbation due to vertic properties. The following three phenomena in Planosols were, however, not explained by bioturbation or clay illuviation:

- The stone line in soils between the termite mounds undulated with a position between the top of the weathered rock and the top of the B horizon, whereas termites would leave it at a position just above the weathered rock.
- Material too coarse for termites to transport was sometimes found on top of the B horizon.
- The horizons overlying the B horizon fluctuated in depth.

Field studies showed that slickensides were well developed in one direction. They were parallel with the upper part of the B horizon, where they connected a relatively low with a relatively high position. The stone line in the B2t followed the same direction as the slickensides and was sharply interrupted, where it reached the surface of the B horizon (Fig. 32).

The slickensides and the position of the stone line could be the result of differential pressure which developed after illuviation of clay in cracks

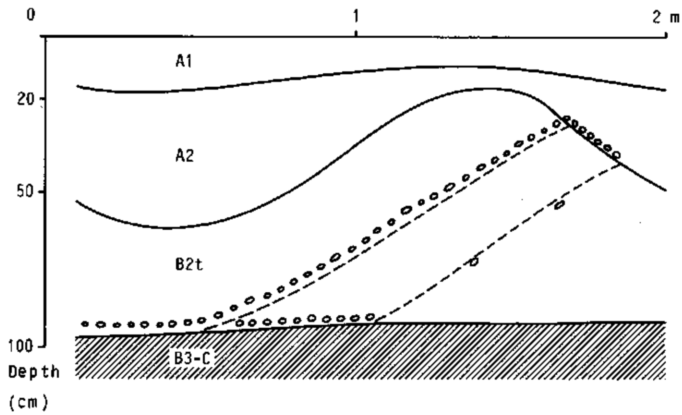


Fig. 32. Schematic cross-section through a pedon of a Planosol showing the effect of differential pressure and clay illuviation on the situation of slickensides (broken line), horizon boundaries (solid line) and the stone line (000).

and successive wetting and expansion of the clay. Due to this pressure, clay with stones could have been pushed upwards. They did not reach the surface, because clay was probably washed down vertically in cracks or laterally to the depressions in the B horizon (Fig. 32). So the upward movement of soil with stones and the successive leaching of clay, reasonably explains the presence of coarse textured material, including stones, directly on top of the B horizon.

Bioturbation and vertic turbation contributed to present soil characteristics. Erosion of abandoned mounds and the start of new mounds at different locations will have occurred repeatedly. This also follows from the observation of some young mounds during the field survey. So the whole surface will have been affected by bioturbation since its formation some 500 000 years ago (Wielemaker and van Dijk, 1981).

7.1.4 *Conclusions*

Results showed that termites in the profiles studied, have the following effects on grain-size distribution in well drained and poorly drained soils:
(i) Removal of fine grained material from deeper soil horizons and weathered rock, causing a concentration of grains, which termites are not able to transport. This process results in formation of a gravel or stone layer.

(ii) Termites have a preference for a certain grain-size, so that their continued activity shifts the median values of sand to that preferred value and, in so doing, sand becomes increasingly sorted. The thickness of the well sorted and gravel-free layer increases as termites keep on adding material from below the gravel layer.

In contrast with transport by termites, vertic movement can bring material coarser than 2 mm to upper soil horizons, so that it may disturb the work of termites in forming horizons without gravel. This explains why coarse material (>2 mm ∅) in large termite mounds on the Magena surface was only found at the transition to the weathered rock and in soils between mounds, also in the B2t horizon and on top of it.

7.2 LATERAL TRANSPORT PROCESSES

7.2.1 *Introduction*

In the preceding part of this chapter it was explained how termites form texture profiles. Soil movement along the slope was mentioned, but its effects on formation of the texture profiles and the role of soil animals in the lateral displacement of soil material was not explained.

The situation on the Wanjare catena, where the upper part consists of granite and the lower part of diorite, is ideal to estimate the effect of lateral displacement of soil material on mineral composition of soils downslope. At what rate lateral movement took place can, however, not be deduced from the mineral composition of soils. Therefore, some measurements were done on both parts of the catena where different types of lateral transport occur. On the shallow rocky upper part exposed soil materials are moved by surface run-off. Termite heaps seem an important source of soil material exposed to erosion. There is also a small area fraction of bare soil around stones exposed to erosion.

On the straight lateral slope of the Wanjare catena, where soils are well drained, permeable and deep, the following types of transport were recognized:
(i) Downslope displacement of soil, when soil animals excavate soil and deposit it more downslope than upslope from the opening. At present, cultivation may also cause downslope displacement of soil material.
(ii) Splash of exposed soil materials. Under a permanent vegetation, this

process only moved soil materials exposed by soil animals or falling trees, but since cultivation of soils strongly intensified during this century, the process became much more important.

(iii) Creep (the result of small disturbances in the soil under the influence of shear stress acting upon a slope) (Carson and Kirkby, 1972). In the previous chapter it was shown that most disturbances in the well drained deep soils are caused by the soil fauna, so that their activity will mainly determine the rate of creep.

(iv) Run-off of water over very short distances, in the range of a few mms or cms.

(v) Slumps and landslides were not seen in the Wanjare catena, but were sometimes observed where slopes were undercut by springs at the side of valley-bottoms.

Particular items (i) and (iii) were and still are important processes of transport on the deep well drained soils, so that an estimate of these was made. Unfortunately no figures are available regarding the amount of soil raised to the surface by ants and subterranean termites. To have an idea about the possible impact of this surface soil transport, mole rat activity was estimated (see Section 2.7). Literature data show that moles can raise enormous quantities of soil to the surface. This amounted to 20 $t.ha^{-1}.a^{-1}$ in the Luxembourg Ardennes (Imeson, 1976) and to 55 $t.ha^{-1}.a^{-1}$ in Ivory Coast (Abaturov, 1972).

7.2 *Methods*

Mineral composition of very fine sand in soils of the Wanjare catena. Detailed methods of analysis are given in Appendix 2.

Soil erosion from mounds. This requires an estimate of the total weight of soil accumulated in mounds. Two types of mounds were observed: the mound of Cubitermes with a semi-circular form and the mound of Pseudacanthotermes with the form of a cone (Fig. 33). The mass of soil of a Cubitermes mound was calculated as follows: $2/3\pi\ r^3$ x (s.m.). With r = 0.28 m and s.m. = 900 $kg.m^{-3}$, the mass of soil per mound amounts to 41.4 kg. The mass of soil of a Pseudacanthotermes mound was calculated as follows: $1/3\ h\pi\ r^2$ x s.m. As h is taken the average height of two cones. With r = 1.5 m, average h = 0.9 and

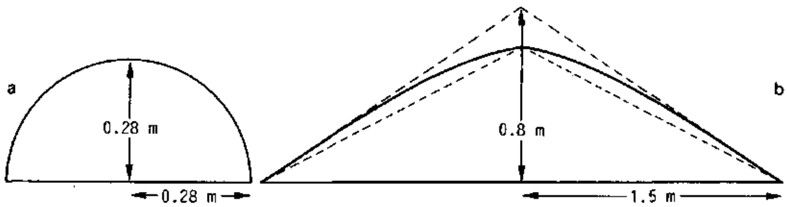


Fig. 33. Cross-section through heaps of Cubitermes (a) and Pseudacanthotermes (for explanation see text).

s.m. = 1000 kg. m^{-3}, mass of soil per mound amounts to 1/3 x 0.9 m x π x (1.5 $m)^2$ x 1000 kg. m^{-3} = 2120 kg. Actual erosion from a Cubitermes mound was estimated with steel needles inserted at several places into a mound. Length of the needle above the surface of the mound was measured after insertion and again after one year. The difference in length of the needle above the surface of the mound was used as an estimate for the annual erosion from it.

Surface erosion measurements. The contact of soil with rock outcrops or boulders was painted at several places in order to estimate soil removal around rocks during a one year measuring period. After one year the cleared part of the rock below the paint was measured. Additional recorded data were: slope at the site of observation, degree of soil coverage, area fraction of stones and boulders.

Downslope displacements of soil by mole rats. Mole rat activity was measured on grazing land near Magombo during a 5 day period in the month of May. The mass of soil deposited on the soil surface, was air-dried and weighed. The fractions of the total mass deposited downslope was estimated with the following formula: $\frac{2 \text{ x slope}^\circ}{180^\circ}$, assuming that the mole heap has the volume of half a globe. The average downslope displacement of soil from mole heaps was calculated as follows (Fig. 34): ODE = ½ surface of OCA. GH is rectangular to OF and cuts DE in half, OH is the average downslope displacement of the fraction of soil (OCA) on slope that moves downslope due to mole activity. It does not include erosion by splash.

Creep. Steel needles were inserted into a vertical wall of the soil pit at NARS (Chapter 3). They were placed in a vertical row at regular distances from the top of the pit down to the stone line at about 3 m. Position of the top of

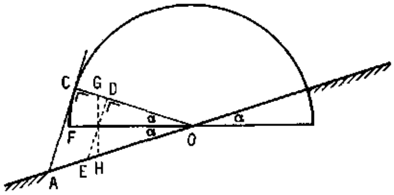


Fig. 34. Downslope displacement of soil due to mole rats.

the needles was recorded with respect to a plummet; positions were recorded again after two years. The difference between both measurements was a measure for soil creep. The bottom needle was used as a reference (no displacement).

7.2.3 *Results*

7.2.3.1 Slope transport and median diameters of sand in the upper Wanjare catena

Fig. 35 shows how the depth of soil with median diameters of less than 100 µm, increases from 0 at deep augering DA2 to more than 3 m at Profile Wan 3. Simultaneously the median diameters in the upper soil horizons decrease from nearly 100 µm at Da2 to less than 400 µm at DA7. The well sorted and coarse textured gravel layer is found at increasing depth below the surface downslope of profile Wan 2. Its deepest occurrence is at Wan 3 just above DA2. DA2 is apparently over harder rock.

As discussed in Section 7.1 fine material brought up by termites is removed by erosion from Profiles Wan 1 and Wan 2 and moved downslope. During its transport downslope sand becomes increasingly fine (Fig. 35). It indicates, that termites had sufficient time to sort soil materials during their transport downslope, so that lateral movement was probably slow.

It is also possible that long ago lateral transport was much more important and that termites gradually sorted soil materials after their deposition on top of the gravel layer. Which processes were at work, will be discussed below.

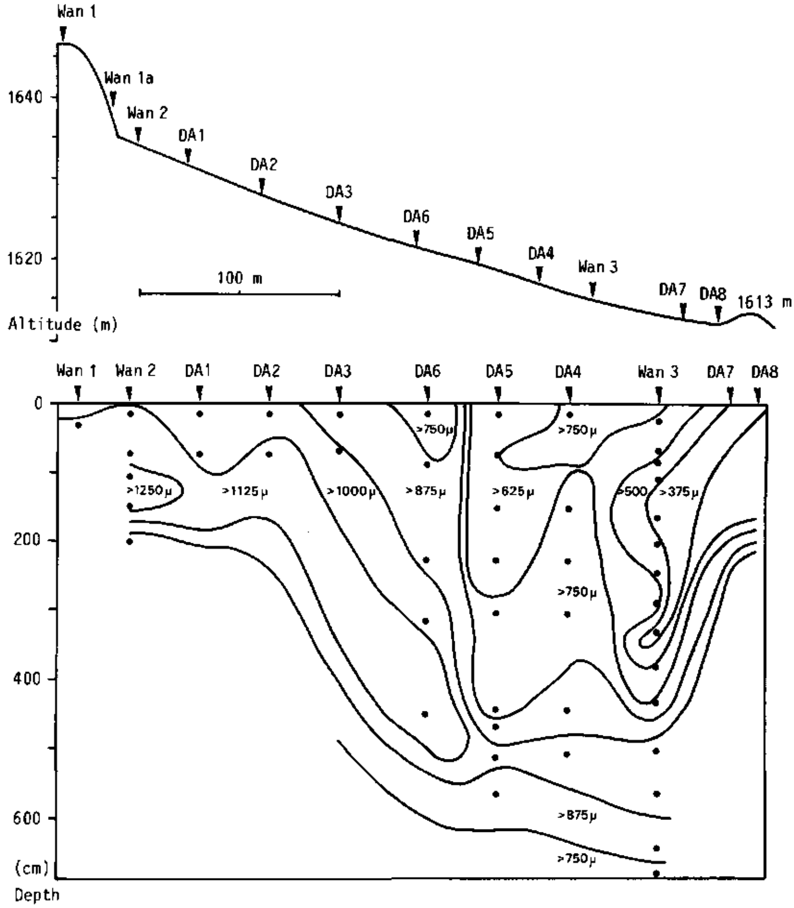


Fig. 35. Map of iso-median diameter values of sand fractions (50-2000 µm) of the upper Wanjare catena (For situation of profiles, see Fig. 7). Sampling depths are indicated with dots.

7.2.3.2 Slope transport and mineral composition of sand

Because the rock upslope is granite and downslope diorite, the mineral composition of soil materials downslope may indicate the importance of vertical and lateral transport processes. The mineral composition of soil materials (Table 14 and Fig. 36) gives us the following information about lateral transport of soil materials from granite:

(i) Only samples from the upper metre of profiles downslope contained a detectable number of minerals derived from granite. It means that slope

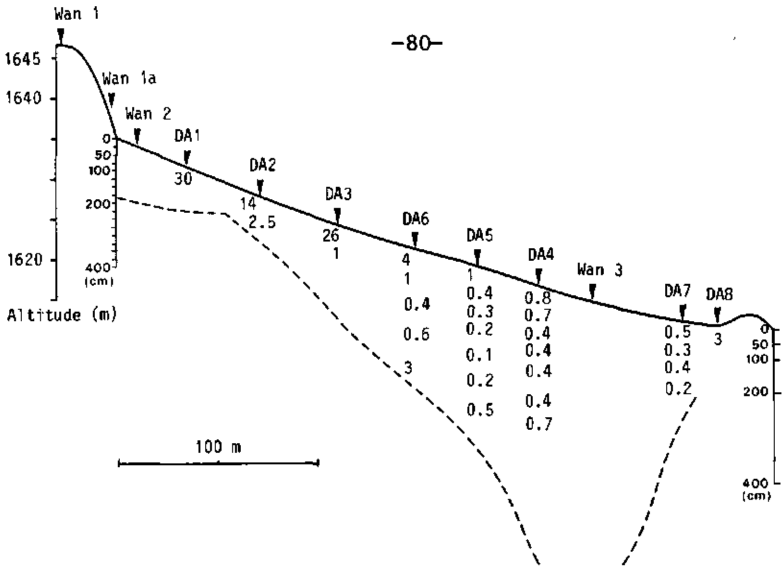


Fig. 36. Mass percentage of strongly magnetic minerals (mainly magnetite) in sand (50–420 µm) with a density > 2.89 in samples from the upper Wanjare catena. DA= deep augering. Scale of altitude is 0.25 x depth scale and 4 x horizontal scale.

Table 14. Semi quantitative estimates of mass fractions of heavy minerals in sand (50–420 µm) of profiles and deep augerings from the upper Wanjare catena (Fig.). Mass fractions: +++++ >0.9; ++++, 0.6 - 0.9; +++, 0.3 - 0.6; ++, 0.15 - 0.3; +, 0.05 - 0.15; tr, <0.05 and -, not detectable.

Profile	Depth (cm)	Ilmenite	Zircon	Rutile	Anatase	Magnetite	Haematite	Amphibole
Wan 1	0- 35	++	+	+	+	++	++	++
Wan 2	0- 16	++	+	+	+	++	++	+
DA 1	0- 15	+++	+	+	+	+	+++	-
	60- 65	++++	+	+	+	+	++	-
DA 2	0- 15	++++	+	+	+	tr	++	-
	60- 65	+++++	+	+	tr	-	tr	-
DA 3	0- 15	+++	+	+	+	++	+++	-
	60- 65	+++++	+	tr	tr	tr	+	-
DA 6	0- 15	+++++	++	tr	tr	tr	+	-
	165-170	++++	++	tr	tr	-	-	-
	245-250	++++	++	tr	tr	-	-	-
	340-355	+++++	++	tr	tr	-	tr	-
DA 5	0- 15	+++++	++	tr	tr	-	-	-
	120-125	++++	++	tr	tr	-	-	-
	245-250	++++	++	tr	tr	-	-	-
	440-445	+++++	++	tr	tr	-	-	-
DA 4	0- 15	+++++	+	tr	tr	-	-	-
	120-125	+++++	+	tr	tr	-	-	-
	245-250	+++++	+	tr	tr	-	-	-
	390-395	+++++	++	tr	tr	-	-	-
Wan 3	10- 25	+++++	tr	tr	-	-	-	-
	315-330	+++++	tr	tr	-	-	-	-
	saprolite	+++++	tr	-	-	-	-	-
DA 7	0- 15	+++++	+	tr	tr	-	-	-
	160-175	+++++	+	tr	-	-	-	-

transport occurs and occurred especially in the upper metre of the profile.
(ii) The number of stable minerals from granite such as rutile and anatase decreased less in profiles downslope than the less stable minerals magnetite and haematite (cf. Chapter 4). Weatherable minerals such as hornblende were not present in profiles further downslope, but the ratio of ilmenite to zircon in Profile Wan 3 showed that soil material from granite was present in the upper metre of Profile Wan 3 (cf. Chapter 4). The selective weathering of heavy minerals (Table 14) during transport downslope shows that lateral transport was slow.
(iii) The decreasing number of stable minerals from granite in the upper metre of profiles downslope indicates that soil materials from granite are gradually mixed with other materials during transport downslope. Results of studies discussed in Chapter 6 showed that termites transport soil material from the upper meter to the deep subsoil and vice-versa. This mechanism may explain the gradual decrease of soil materials from granite due to mixing during their transport downslope.

7.2.3.3 Downslope displacement of soil materials from the rocky upper part of the catena

Mass of soil accumulated in mounds. On a surface of 400 m^2, 10 mounds of Cubitermes and 2 mounds of Pseudacanthotermes were counted. Mass of soil per mound is 41.4 and 2120 kg respectively (see Section 7.2.2), so that the mass of soil accumulated in mounds equals 10344 kg. ha^{-1} for Cubitermes and 106.000 kg. ha^{-1} for Pseudacanthotermes, totalling 116.3 t. ha^{-1}.

Annual erosion from mounds. According to measurements with needles, 1.5 cm of soil material was eroded from the lateral side of a Cubitermes mound in one year. This would mean that a mass fraction of 0.15 was eroded from the whole mound. This seemed an overestimation, because part of the mound had a less steep slope; 0.1 seemed therefore a more reasonable estimate for the mass fraction of soil removed from the mound during one year.

Lee and Wood (1971b) among others, estimated that dead mounds eroded in 5 to 10 years. They observed that dead mounds usually number more than 1 out of 5. A ratio of 1 dead mound in 9 live mounds in the area of study seemed therefore a safe estimate. Assuming that eroded material from live mounds is reused by termites and that the annual eroded mass fraction from dead mounds is 0.1 times their maximum weight, then the dwonslope erosion will amount to 0.01 x 116 300 kg. $ha^{-1}.a^{-1}$ = 1163 kg. $ha^{-1}.a^{-1}$. In an equilibrium situation this would probably be the minimum amount of soil that leaves the upper slope each year. With a catchment of 0.545 ha per 100 m contourline, 11.63 kg x 0.545 = 6.34 kg of soil per metre contourline per annum would be added to the lower slope.

Nye (1955) estimated the amount of soil eroded from his gently sloping upper catena was one third of the total amount of soil brought to the surface by termites. His estimate for the eroded amount was 5000 t. ha^{-1} in 12000 years or 417 kg. $ha^{-1}.a^{-1}$.

Removal of soil material due to run-off from rock outcrops and boulders. Real depth of the soil layer removed by run-off ranged from 0.2-1 cm around rocks on a slope of 10-20% to 0.5-3 cm on the steeper slopes. Erosion was negligible if the soil bordering the rock was well covered with grass. The measurements were representative for a small fringe of about 10 cm wide around the rocks with a surface area estimated at about 500 $m^2.ha^{-1}$. On a hectare basis about 0.5-1 $mm.a^{-1}$ could have been displaced by run-off from rocks. This soil mass equals 5000-10000 kg. $ha^{-1}.^{-1}$ (s.m. = 1000 kg. m^{-3}). If all this soil material left the upper slope it would mean a downslope addition of 27.3 to 54.5 kg. a^{-1} per metre of contourline.

Which fraction actually reaches the footslope, was not estimated. Imeson (1976) calculated that on a wooded slope of 17° in the Luxembourg Ardennes 70-80% of 20000 kg of soil raised to the surface by moles, moved downslope. The rate at which this material left the slope was estimated at 0.18 kg per metre of riverbank per annum or a mass fraction of 0.001. If such a mass fraction applied to the soil displaced by run-off, 0.027-0.054 kg. a^{-1} per metre of contourline would leave the upper slope. Because of higher and more intensive rainfall in the Kisii area the figure can at least be doubled.

7.2.3.4 Lateral transport of soil materials in deep well drained soils

Downslope displacement of soil by mole rats. Estimates of displacement by mole rat activity amounted to 7 kg air dry soil per 100 m^2 per 5 days or 50 t. $ha^{-1}.a^{-1}$, assuming that the 5 day period was representative for the year (see Section 2.7). On a slope of 12%, $\frac{14°}{180°}$ x 50 t. $ha^{-1}.a^{-1}$ = 3900 kg. $ha^{-1}.a^{-1}$

would move downslope over a distance of 7 cm. It means that a soil layer with an average thickness of 0.04 mm moves 7 cm downslope annually.

Creep. In Fig. 37 three zones can be distinguished:
(1) From 0-70/80 cm: zone with great variation in observed displacement, coinciding with the zone of major biological activity. The yearly creep with respect to the reference level at 300 cm depth was 1-4 mm for the upper 30 cm and 1-1.5 mm from 30-70/80 cm depth.
(2) 70/80-200 cm depth. The yearly creep with respect to the reference level at 300 cm depth was 0.5-1 mm.
(3) 200-300 cm depth. The yearly creep decreased from 0.5-1 mm at 200 cm depth to 0 at 300 cm depth.

The displacement in zone 3 was bigger than in zone 2. This could be due to a lower shear strength in zone 3 than in zone 2 and also to more shrinking and swelling as a result of alternating dry and wet conditions in this zone (see mottling data in the NARS profile, App. 1). Micromorphological analysis

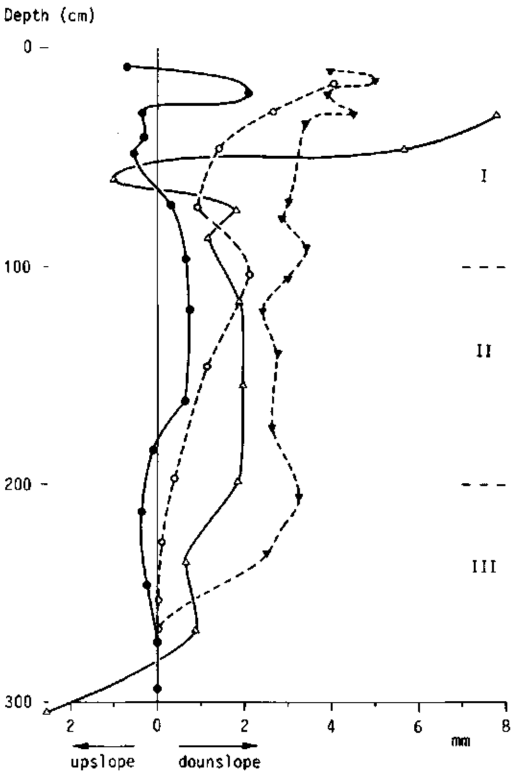


Fig. 37. Downslope displacement of needles in the well drained profile at NARS during a two year period.

of thin sections from well drained soil horizons (Chapter 6) showed that soil fauna seemed responsible for most disturbances in these horizons.

The displacement due only to the soil fauna could then amount to a maximum of 3 m per 1000 years in the upper 30 cm, to 0.5m/1000 years from 30-70/80 cm, to 0-0.5 m/1000 years from 70/80-200 cm and 0 m/1000 years below 200 cm depth.

7.2.4 *Discussion and conclusions*

Results of studies may be represented by the following model (Fig. 38).

1°. Burrowing activity of termites in shallow soils on steep slopes of the Wanjare catena is the most important source of erodible soil materials.

2°. Soil materials eroded from the granitic upper part of the catena, are fed to the upper horizons of deeper soils at its food, where processes of creep dominate.

3°. Granitic soil materials with a grain-size favorable for transport by termites remain concentrated in the upper meter of the deep profiles due to a high transport activity of soil fauna, compared with a low activity below 1 metre. In contrast, material too coarse for transport by termites gradually sinks below the layer of main activity, so that that material moves downslope very slowly.

4°. Decrease of the percentage of soil material from granite during transport downslope is due to a gradual admixture with soil from diorite derived from deeper layers and due to a slow but gradual transport of soil material from the upper metre to the part of the profile below 1 m. This effect cumulates downslope in the mixing of soil materials from granite throughout the profile. Soil materials from granite are then, however, so diluted that their minerals are no longer detectable.

In fact, the difference in vertical distribution of materials from granite in profiles upslope and downslope reflects the time of mixing. A similar difference due to time of mixing was observed between the distribution of glass fragments and magnetite-II minerals. Glass fragments representing relatively recent additions of volcanic ash were concentrated mainly in the upper metre of the profile, while the magnetite-II minerals representing much

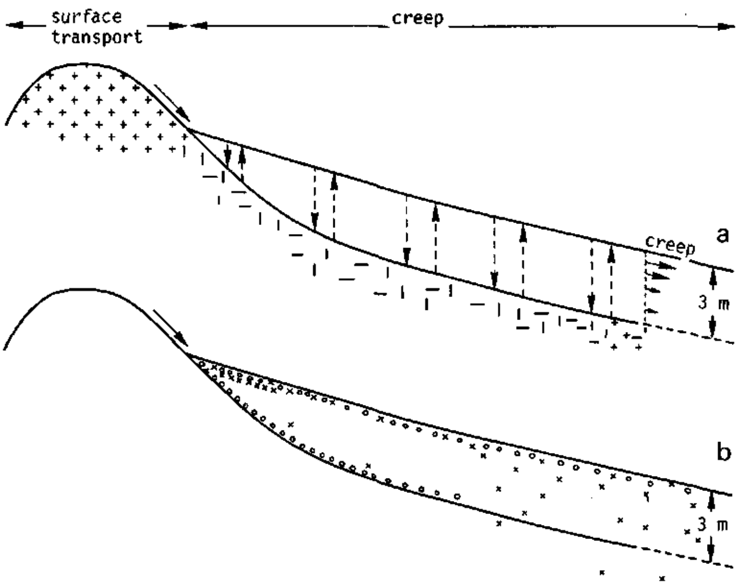


Fig. 38. Arrows indicate schematically transport activity in deep well drained soils on a slope (a) and its cumulative effect on the distribution of stable (x) and less stable (o) minerals in very fine sand from upslope in the soils downslope (b).

older additions of volcanic ash, were rather evenly distributed throughout the profile.

5°. Lateral movement of soil material is so slow that even rather stable minerals selectively weathered. This excludes an important contribution of surface transport because it would take only 3500 years for soil materials moving with a speed of 7 cm annually to reach Profile Wan 3; with that speed minerals would not have been weathered. Due to mixing soil particles will, however, not remain in the surface layer. They will in fact move continuously from one layer to the next. How fast a particle moves downslope will depend on the fraction of time it resides in the various layers. Because the fast moving surface layer is only 0.04 mm thick, soil particles will mainly reside in the soil layer below it, where processes of creep dominate.

If estimates of transport due to creep apply to the Wanjare catena, it would take 80000 years for soil material in the upper 30 cm to reach Profile

Wan 3 and 500 000 years for soil materials at a depth of 30-90 cm to reach it. Soil material below that depth moves at an even slower speed. Because rather stable minerals disappeared during transport downslope, the estimated speeds seem rather high, which is probably because the slope of the Wanjare catena is more gentle than the slope where creep was measured.

The absence of a detectable number of minerals from granite in soil materials deeper than 1 metre gives no indication that lateral transport was different in the past.

6°. Continued reworking of soil materials by termites shifts coarse median diameters of sand to lower values until they are "to their taste" (Section 7.1 Fig. 30). Lateral movement in the deep soils is controlled by termites, so that this effect of termites on grain-size distribution is also noteworthy in a downslope direction (Fig. 35).

7.3 THE FORMATION OF TEXTURE PROFILES WITH STONE LINES

7.3.1 *Prevailing theories*

Even today a number of authors claim that all texture profiles with stone lines are the result of geogenetic processes. In their view the stone line is an erosion rest on which a sediment without gravel and stones is deposited. These authors seem unaware or can not imagine that pedogenetic processes can form such profiles. So they ignore the view of many soil scientists and biologists, who long ago showed that soil animals, especially termites, can form texture profiles with stone lines (Grassé, 1950; Nye, 1955; de Heinzelin, 1955; Boyer, 1956a; Watson, 1960; de Ploey, 1964; Levêque, 1969 and Moeyersons, 1978). The present study, in an area with a humid to subhumid climate, confirms the latter point of view. That also other processes can result in formation of similar profiles with a stone line, is not ignored by the author even for areas with a similar climate.

Some authors who believe that texture profiles with a stone line result from geogenetic processes only, state that they are formed in a semi-arid environment (see for instance Ab'Saber, 1982 and Bigarella et al. 1965).

The bio-pedogenetic theory showed us that a dry climate is not necessary for formation of such texture profiles. This has important implications for landscape development in the past. In the discussion below the geogenetic theory of formation of the texture profiles will be tested to see if the results from the area of study could also be explained by this theory.

The following conditions in the Wanjare catena, are not in line with this theory:

- The absence of a lithologic discontinuity. This feature is one of the arguments Ruhe (1959) and Fölster (1969) used to prove their theory of formation of the texture sequence, but soil material directly above and below the stone line in the Wanjare catena, was not different.
- The presence of a 3 metre deep soil cover on flat surface remnants of a dissected Tertiary erosion surface. How could soil material removed by erosion from the flat surface have been replaced since the dissection of that surface during and after the Tertiary? Without replenishment of soil materials through upward transport from below the stone line, gradual erosion of soil materials would have left the stone line at the surface, while it is now covered with three meter of well sorted fine earth. Furthermore, soil materials would not have been mixed if no upward transport from below the stone line had taken place.

7.3.2 *Other theories*

When a desert pavement, a pediment or a coarse textured river alluvium gets covered by finer wind or water deposits, it may appear like a stone line sequence, particularly after sediments are weathered.

The stone line on the Pleistocene Magena surface (Wielemaker and van Dijk, 1981) may have formed mainly as described above. The studies showed, however, that the fine earth above the stone line originated not only from a deposit on the stone line (volcanic ash) but also from the weathered rock below the stone line.

Sharpe (1938) and Ireland et al. (1939) explain stone lines from the incorporation of coarse fragments in the subsurface by soil creep. The fragments would be detached from dikes or other resistant layers. Their theory does not explain adequately how the coarse material detached from dikes, becomes concentrated in a stone line, nor does it explain how stone lines are formed in soils on top of a ridge.

Termites, which are responsible for vertical transport, fill the gap in this theory.

Laporte (1962) postulates, that stones may sink in the profile due to physical processes. These processes may work in clays with a high plasticity when saturated with water, but not in well drained red soils, which are seldom saturated with water and have a low plasticity (Collinet, 1969; Moeyersons, 1978). In poorly drained soils in the area of study stones did not sink, but were instead pushed upwards due to vertic properties (Section 7.1.3).

None of the theories discussed above gives an adequate explanation for the formation of texture profiles with stone lines in the area of study. Neither the formation of the deep layer of well sorted fine earth above the stone line, nor the stone line itself can be properly explained without the action of termites. It implies that they played an essential role in processes of landscape and soil formation in the area of study. Because termites occur also extensively in South America, they will have also formed stone lines with fine material on top of them. So, their formation will not have been restricted to the dry climatic periods as postulated by Ab'Saber (1982) and Bigarella et al. (1965). Deeply weathered soils with stone lines in Brazil are thus not necessarily the result of repeated erosion and sedimentation; their formation can be due to pedogenetic processes only. Such a view is also adhered to by Bennema (1965), who considers differences in depth and stage of weathering of Brazilian soils mainly the result of differences in time of soil development modified by conditions of topography, parent material and drainage.

8 Termites and land-use

8.1 INTRODUCTION

In the preceding chapters it was shown how soil fauna, particularly the termites, affected well drained soil profiles in the area of study so thoroughly that virtually their whole geometry was controlled by them, even in soil materials at depths of 10 m and more.

It was shown that mineral composition and grain-size distribution were controlled by termites and that they contributed to the formation of a soil mantle of at least 3 m thick on these surfaces, which were Tertiary or older, and that they transformed an important part of saprolite materials below a depth of 3 m.

Deposition and transformation of soil materials by termites occurred in all soil environments studied, but on steep slopes erosion was so strong, that no effective accumulation of soil materials could take place and, under poorly drained conditions, soil materials outside the nest area rapidly lost their architecture made by termites. So it seems that for an effective stabilisation of the termite habitat resulting in accumulation of soil materials with a homogeneous and porous architecture, processes of destabilisation (Chapter 6) such as erosion and structure decay, should not be too strong.

Such interaction between termites and their environment will be demonstrated in a flow chart (Fig. 39) in the next section. The chart is representative of the study area, which is a high altitude humid tropical region, enriched with volcanic ash. Termite species there do not damage the crops and their activity seems positively related with soil conditions for plant growth. In other areas of the tropics termites are not always considered so benifical for agriculture. Some species pose problems for mechanized agriculture such as mound building termites and others as for instance the Hodotermitinae or harvester termites, are considered a pest because they eat the standing crop (Coaton, 1958). As regards soil conditions, low humus content and low water holding capacity of Oxisols in certain tropical regions are ascribed by some people to the predominance of termites.

When discussing significance of termites for maintenance of production levels in agriculture such possible harmful effects will also be considered. The chapter concludes with some recommendations for future research.

8.2 TERMITES AND NATURAL ECOSYSTEMS

8.2.1 *Inflow and outflow of energy and matter*

What effect termites have on flows of energy and matter in natural ecosystems is demonstrated in Fig. 39. The outer circle represents the flow so far as it is controlled by termites. The system is not closed, however; there is an energy and material exchange with a larger ecosystem of which it forms a part: in natural ecosystems, rain, sunshine, carbondioxide, atmospheric dust and colluvial or alluvial deposits form an incoming flow of energy and matter. Rain and sunshine also affect the rate of decay of structure, the rate of erosion of soil materials and the leaching rate of nutrients. How fast this occurs depends on land characteristics, such as climate, type of soil materials, their drainage and geomorphic position, but not in the least on the effect termite activity has on modification of such land characteristics (Fig. 39).

Chapters 6 and 7 showed that the high intake rates in well drained soils in the area of study are due to termite activity and that also the rate of creep is controlled by their activity. Even in the shallow soils, rate of soil transport was regulated by them. Lepage (1981) calculated that foraging holes made by termites during one year in a dry savanna in Kenya occupy an area of 2-4 $m^2 .km^{-2}$, which illustrates their impact on intake rate and surface-runoff in a much drier area than the one studied. So, termites largely control inflow and outflow of water and soil material, with impact on a much wider part of the environment than where they are active. Without their activity rates of erosion will strongly increase causing changes in hydrology which may result in downstream flodding and the silting up of reservoirs.

8.2.2 *Suitability of the habitat for termites*

Soils in the Kisii area have usually a high iron content. The iron, if

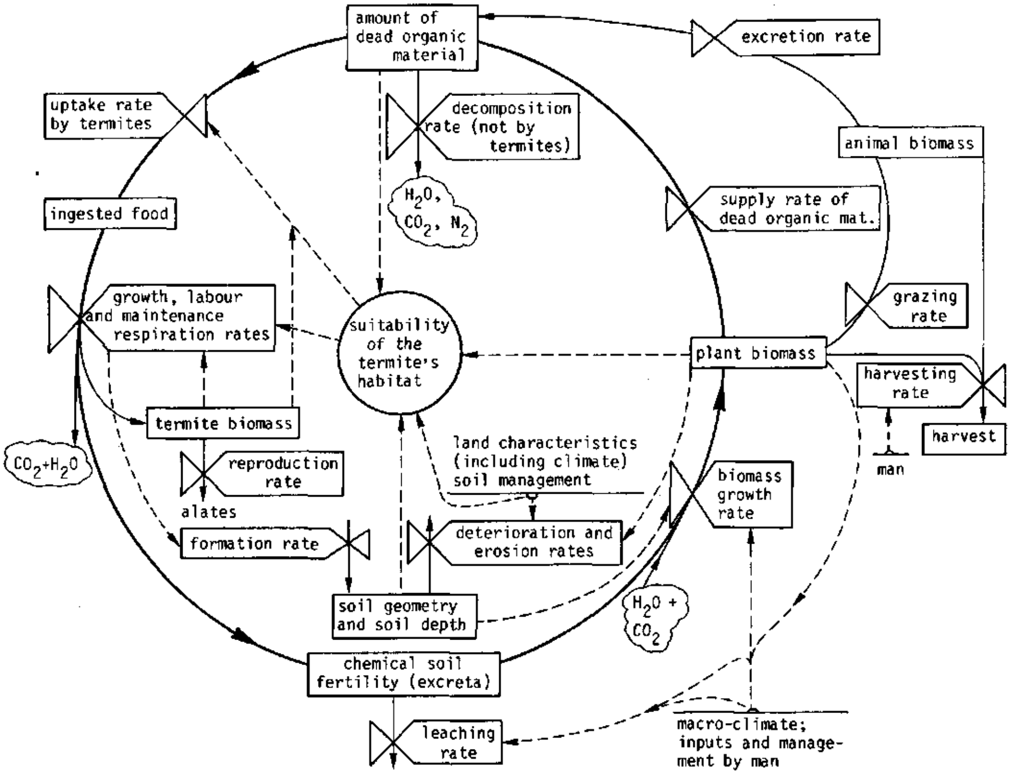


Fig. 39. Schematic presentation of the role of termites in agro-ecosystems in the area of study according to Forester's notations (Forester, 1961).

oxydized, can give soils a high structural stability and that is a condition from which termites profit because it improves the quality of their building materials. So land characteristics, including climate determine to a large degree how suitable a site is for termites, because it decides to what extent they can adapt conditions to their needs. How well conditions are adapted by the termites, determines the suitability of their habitat. It plays a central role in regulating food uptake for growth, for labour and for maintenance of life functions (see Section 5.2).

The work termites do in soils and the excreta they produce, may further stabilize soil materials so that habitat conditions are improved. If in addition, their activity raises the suitability of soils for growth of plants, biomass production will increase. This again has a positive influence on habitat suitability, because it improves the climate for termites and increases supply of dead organic material, either directly as litter from plants or indirectly as faeces from grazing animals.

More biomass will also decrease rates of loss to soil materials, soil structure and nutrients, because it supplies a better soil cover and usually exploits water and nutrients better. This has via soil conditions a positive influence on habitat suitability because it reduces the amount of work termites need to do, to maintain proper nest and channel systems.

So termite activity in soils has two effects on the suitability of their habitat.

- It improves their habitat conditions, so that less work is needed for maintenance and repair and more energy remains for reproduction and growth.
- It increases the amount of dead organic material, from which both termites and other litter feeders profit.

The effect of termite activity on soil conditions and growth of plant biomass seems more complicated than suggested in the flow chart. Termites probably create appropriate physical conditions for other soil dwelling organisms and so stimulate their functions in soils. When litter is in ample supply as was most likely the case in the Kisii area, a very diversified soil flora and fauna will exist not only of termites, but also of other soil organisms. On the other hand when litter is in short supply, for instance in regions with a dry climate, in poor soils or in overgrazed land, certain termite species may still get enough food, while most other litter feeders starve. Buxton (1981) who studied the relation between species diversity among termites and habitat productivity found that, also among termites, diversity declines if rainfall and habitat productivity decrease.

So a decreasing food availability means a decline in functions of the soil flora and fauna, particularly when termites are the dominant litter feeders. It is possible that people refer particularly to such situations when they consider termites harmful for soil conditions. It suggests that for maintenance of proper soil conditions for plant growth a diversified soil flora and fauna is necessary.

The interaction of termites with other litter feeders is still poorly understood so that for the sake of simplicity only a direct relation between amount of dead organic material, termite activity and soil suitability has been considered in the flow chart.

Table 15. Effects of termite activity on soil formation, on soil properties and on suitability of soils for plant production, in the area of study.

Effects on soil formation	Effects on soil properties	Effects on plant production.
Formation of pores (Ø > 1 mm), lining and back-filling of channels and chambers with salivated pellets of earth.	Increase in permeability for water and air and in structural stability. Decrease in bulk density.	A. Beneficial effects: - Increase in rootability and potential for moisture uptake by plants. - Increase in oxygen availability. - Decrease in risk of water stagnation, acid formation and shortage of oxygen.
Mixing of soil materials	Formation of homogeneous soil horizons without gravel and with diffuse transitions	
Transformation of saprolite into soil materials	Increase in soil depth	- Decrease in risk of erosion.
Rapid decomposition of dead organic material including wood. Concentration of bases in organic matter. Formation of humus, rich in bases.	If supply of litter is <u>small</u> termites may cause depletion of soil organic matter so that structural stability declines and poresystems become less heterogeneous (see text).	- More available nutrients through 1. decomposition of of material rich in lignin and cellulose. 2. upward transport of less weathered soil materials. 3. creation of appropiate physical conditions for soil flora and fauna. B. Adverse effects: If litter is in short supply, termites may cause a rapid decline in functions of soil flora and fauna (see text).

What effect termite activity has on soil characteristics was demonstrated in the preceding chapters and is summarized in Table 15, mentioning also what it means for plant production. Not all soils in the area of study were so effectively modified. Table 16 shows which land conditions limited suitability of the habitat for termites and what this means for their effect on soil characteristics: The geometry of the Paleudolls with little or no limitation for termites was strongly controlled by termite activity. The geometry of Haplohumox did not reflect such a high actual termite activity as the Paleudolls did (Chapter 6). It could be that moisture is sometimes limiting, due to the rather hard and impermeable rocks, underlying these soils. Also their position on flat topped ridges may limit moisture availability. Food and nutrient availability in these infertile soils could be limiting causing insufficient functioning of the soil fauna, as explained in Section 8.2.2.

The lithic Humitropepts have limitations for subterranean termites, because soils are too shallow for nesting, while moisture may be sometimes limiting. No accumulation of soil materials can take place due to erosion on those steep slopes (Chapter 7.2).

The poorly drained abruptic Tropaqualfs pose limitations for termites

Table 16. Factors limiting habitat suitability for termites in the area of study and a ranking of soils according to their suitability as a habitat for termites.

Soil type	Limiting factors	Ranking of habitat suitability
Well drained, deep, stable Paleudolls (Wan 3, NARS)	No limitations. Availability of moisture and of suitable temperature fluctuate with climate.	1
Moderately well drained, deep, rather stable Paleudolls. (Wan 4, Wan 5)	Slight limitation due to rather low stability of building materials. Climate as above	2
Well drained, deep, stable Haplohumox. (Wan 9, 210)	Slight limitation due to low nutrient availability and moisture (during the dry season). Climate as above.	2
Somewhat excessively drained, shallow over hard rock on steep slopes. Lithic Humitropept (Wan 1)	Severe limitation of soil depth for termites with subterranean nests due to high risk of erosion. Moisture may be limiting during dry season. Climate as above.	3
Poorly drained, deep unstable abruptic Tropaqualfs. (Opapo, Wan 7).	Severe limitation due to high risk of flooding and very low stability of building materials.	3

because soil materials are unstable so that structures made by termites rapidly decay. Waterlogging and flooding is another limiting factor.

8.3 TERMITES AND AGRO-ECOSYSTEMS

How do agricultural activities affect the flow chart presented in Fig. 39 and what does it mean for the maintenance of adequate soil conditions for plant growth? To explain this, their separate effects on supply of dead organic material, on plant biomass and on soil characteristics will be discussed first. Then a discussion follows of their impact on the termites' habitat and the role of termites in soil. What this implies for land-use is dicussed in the last part of this section.

8.3.1 *Effects on supply of dead organic material*

The biomass growth rate. Rate of biomass production depends largely on the type of produce and how the farmer manages it. So crops like sugar-cane have a much higher biomass growth rate than a crop like pyrethrum. A farmer also raises the growth rate when he fertilizes his land and when he controls diseases and pests. Depending on the amount he harvests, he may so increase amount of dead organic material for soil organisms compared with natural systems.

Proportion of the plant biomass, which is harvested. How large this proportion is, depends on the type of crop and the variety of crop grown. Through breeding, varieties with a high harvestable fraction are selected, so that crops optimally convert available energy and resources in harvestable biomass. Growth of such crops leaves little food for soil organisms. The harvestable fraction depends very much on the type of produce. So fruit trees never achieve as high a fraction as for instance grain crops, nor do grazing systems. In fact, grazing stimulates increase in biomass and if grass is fertilized, more dead organic material becomes available than on ungrazed and unfertilized grassland.

In summary, crops producing a small amount of biomass and crops with a high harvestable fraction, decrease amount of litter, compared with natural systems. So they adversely affect the suitability of the termites' habitat, either directly or indirectly (Section 8.2.2).

8.3.2 *Effects on plant biomass cover*

As shown in Fig. 39 plant biomass also has direct effects on the suitability of the termites' habitat if it affects soil climate. Natural systems tend to give soils a permanent vegetative cover. Under agriculture the soil is sometimes bare, particularly when annual crops are grown in regions with a pronounced dry season.

8.3.3 *Effects on soil characteristics*

Rates of deterioration of geometry and of erosion. Apart from land characteristics (Section 8.2), rates depend among others on the type of crop and on how it protects the soil against rain impact. Use of heavy machinery and frequent tillage are practices which may further increase the risk of erosion and the risk of deterioration of geometry (Chapter 6). If horizon differentiation and compaction are not sufficiently counteracted by formation of root channels, by activity of macrofauna, by swelling and shrinking or by deep ploughing, soils may degrade physically and become susceptible to erosion.

Rate of leaching. Leaching depends mainly on the amount of water passing below the root zone and on the amount of nutrients it carries. Rainfall distribution, uptake of nutrients and water by plants in relation to nutrient and water supply, water uptake and storage by the soil are important rate determining factors in this respect.

Beside indirect effects, agricultural activities also have direct effects on the suitability of the habitat for termites: tillage, particularly with a plough, may disturb nest and channel structures and it is likey that certain species will disappear (Section 5.2) if they experience too much stress. The use of pesticides may also be a stress for them.

As explained in Section 8.2, none of the effects stands alone: a more rapid deterioration of soil physical conditions decreases the suitability of soil for growth of plants and that, in turn, decreases the amount of litter available for soil organisms, so that species diversity becomes less with a consequent decline in their benificial effect on soil conditions for plant growth (Section 8.2.2).

8.3.4 *Farming and termite activity*

Within the context of the socio-economic environment, farmers have the following options to maintain or stimulate beneficial effects of termite activity (or soil fauna in general):

- choose crops or cropping systems, which minimize rates of loss to structure, soil material and nutrients.
- choose crops or cropping systems, which are least susceptible to termite attack (Mielke, 1978 mentions in his paper, that indigenous African crops were hardly susceptible to termite attack, while introduced crops or varieties were quite susceptible).
- suppress harmful termite species and promote beneficial ones.
- choose crops with a low proportion of harvestable biomass (for instance a grazing system).
- increase food available for the soil fauna (a) through application of

- increase food available for the soil fauna (a) through application of fertilizer, mulch, manure or a combination of the three, (b) pest and disease control in crops, without damaging termites.
- apply cropping and tillage systems, which minimize the stress for termites.
- alleviate stress for termites by changing land conditions as e.g. soil conservation and drainage measures. (The numerous transitions which exist between the poorly drained unstable soils and the well drained stable soils in the area of study, show that a slight improvement in drainage improves habitat conditions for termites, because the stability of the soil fabric increases due to the oxidation of iron. Pores do not collapse so easily so that the permeability increases favoring processes of weathering and leaching. Consequent changes in clay mineralogy further stabilize soil materials. In fact, it is not only the work of termites that helps to stabilize their environment. They unlock the potential for stability that these iron rich clays have under well drained conditions).

8.4 SIGNIFICANCE OF TERMITES IN HIGH AND LOW INPUT AGRICULTURE

Is it possible to maintain production levels in agriculture without the beneficial effects of faunal activity as mentioned in Table 15? When answering that question low and high input agriculture can best be separated, because low input agriculture has fewer means to improve land conditions than high input agriculture. So the direct effects of termites on nutrient availability in high input agriculture are of no importance, in contrast to low input agriculture, where this may be important. More difficult and costly is the compensation of loss to pore space and structure. Ploughing may improve structure and porosity in the topsoil but in some situations it can hardly prevent horizon differentiation, compaction and eventual water stagnation in the subsoil. Ensuing erosion and shortage of water and oxygen for plants may to a certain extent be controlled by conservation measures and soil management practices. If at all possible, it will still raise costs of production, particularly in situations where soil materials are susceptible to erosion. Further to this, intrinsic characteristics of soil materials cause great differences in stability of soil materials. So the well drained iron-rich kaolinitic soils in the area of study are physically stable, but in certain areas of the tropics kaolinitic soils have a low iron content, which are very susceptible to physical degradation, when heavy machinery is used (Bennema, 1982). Also the imperfectly to poorly drained soils in the area of study are very susceptible to horizon differentiation, loss of structure and compaction.

In summary, sustained high input agriculture may see its profits greatly reduced if it has to do without effect of activities of fauna on physical properties as mentioned in Table 15, particularly if soils have unstable structures and are susceptible to structure decay and erosion.

How is the situation with respect to low input agriculture, probably the most common type of agriculture in the tropics? Under this type of agriculture the farmer usually lacks the means to invest in costly management and conservation practices. When, formerly, he was confronted with a decline in fertility of his land, he could shift to a different piece of land. In this practice of shifting cultivation he used the ability of natural ecosystems to restore, at least partly, the fertility of his land.

Due to the increase in population pressure and the reduction in farm size, shifting cultivation is hardly practical to restore production capacity of land. He should now try to manage his soil resources and the imcoming energy in such a way that he keeps the production capacity of his land as high as possible and still gets enough from his land.

To achieve this, he should derive the maximum benefit from faunal activity or from soil biological processes in general. Which strategy a farmer can follow to stimulate faunal activity in soils was explained in Section 8.3. As explained in the introduction, the utility of termite or other fauna species for agriculture differs widely. To derive the highest benefit from the activity of soil fauna, their damaging effects should be curtailed and their beneficial effects promoted. The introduction of earthworms in polders of the Netherlands (Hoogerkamp et al. 1983) shows that active manipulation can be quite successful.

The introduction of social insects such as termites and ants as soil ameliorators seems not to be described so far. The efficiency of, particularly, the fungus growing termites in utilizing low quality food resources, pleads for a more efficient use of those insects for maintenance of production capacity in agro-ecosystems. Because they also convert the same low quality food resources in food with a high quality for human consumption, in the form of flying termites or alates (Mielke, 1978), they may be important as secondary producers and so raise the value of the plant biomass production, which can not be harvested.

8.5 RESEARCH NEEDS

This chapter did not give a clearcut answer to the question, which part of the annual biomass production should be directed to maintenance and repair functions of the ecosystem. Neither did it give an answer to which farming practices should be adopted. There are many variables involved which have been rarely investigated in agriculture and are still poorly understood by ecologists (Swift, 1984).

It emphasizes the need for systematic knowledge regarding the ecological requirements and the role of various soil fauna, particularly in the tropics. In addition, information is required, regarding the effects of farming practices on the interaction between soils and soil fauna and regarding beneficial or harmful effects on crop production. Comparative studies between agricultural and natural ecosystems could fill this gap in our present knowledge.

The need for such studies is also emphasized in a proposal for a collaborative programme of research on soil, biological processes and tropical soil fertility (Swift, 1984).

Samenvatting

Titel: BODEMVORMING DOOR TERMIETEN, een studie in het Kisii gebied, Kenia.

De studie laat zien hoe belangrijk de aktiviteit van termieten is voor bodem- en landschapsvorming in de tropen; een onderwerp, dat in bodemkundige literatuur te weinig aandacht heeft gekregen. Wat de resultaten van deze studie kunnen betekenen voor het landbouwkundig gebruik, wordt in een apart hoofdstuk behandeld.

Twee omstandigheden in het studiegebied richtten de aandacht op het belang van de termieten: enerzijds het feit, dat in alle bodems vulkanische as aangetroffen werd, die behalve in het oosten intensief gemengd is met bodemmateriaal afkomstig van de lokale rots en anderzijds het feit, dat in alle bodems grote aantallen termieten aangetroffen werden. De vraag was nu of termieten verantwoordelijk waren voor deze menging en zo ja, hoe dit in zijn werk gegaan was en wat hun aktiviteit verder voor consequenties kon hebben gehad voor bodem- en landschapsontwikkeling.

Het studiegebied, gelegen op een hoogte van 1450-2000 m vlak ten zuiden van de evenaar, heeft een humied tropisch hoogland klimaat met een jaarlijkse neerslag van ± 1500-2000 mm, verdeeld over twee drogere en twee nattere seizoenen. Nog slechts 10.000 jaar geleden is het klimaat belangrijk droger geweest dan nu.

Het landschap is heuvelachtig en bedekt met diepe doorlatende rode tot roodbruine bodems, die nu alle intensief voor landbouw in gebruik zijn. Alleen in vlakke dalen en op slecht gedraineerde schiervlakten komen gronden voor met een zeer compacte klei -B (Planosols) en met een natuurlijke vegetatie van gras en plaatselijk struikgewas.

Het hele gebied heeft mogelijk al sedert het Tertiair de invloed van vulkanische as ondergaan. Deze as is afkomstig van de Rift Vallei, 200 km ten oosten van Kisii. De bijzondere chemische en mineralogische samenstelling van deze peralkalische as, blijkt een belangrijk hulpmiddel bij de analyse van de menging van bodemmaterialen. Het verdelingspatroon van vulkanisch glas is vooral representatief voor menging met meer recente vulkanische as. Glasfragmenten worden in diepe goed gedraineerde gemengde profielen tot dieptes van meer dan 7 m aangetroffen, maar het meeste glas bevindt zich in de bovenste

meter van deze profielen. Magnetiet-II, dat òòk representatief is voor ouder bodemmateriaal gevormd uit vulkanische as, komt regelmatig verspreid door het hele profiel voor, echter niet in aantoonbare hoeveelheden beneden de "stone-line".

Het percentage bodemmateriaal afkomstig van vulkanische as in mengbodems is geschat door vergelijking van de gehaltes aan magnetiet-II in de bodems ontwikkeld op as met die in mengbodems. Op dezelfde manier is gebruik gemaakt van de verhouding van ilmeniet tot zirkoon en van de verhouding van Al tot Fe, er van uitgaande dat de samenstellende bodemmaterialen elk een karakteristieke verhouding hebben. Naast glas blijkt ook de distributie van zink en kalium in profielen, een maat voor recente bijmenging met as.

In de hoofdstukken 5, 6 en 7 wordt verder ingegaan op de rol van termieten bij menging en transport van bodemmateriaal. In het gebied komen vooral schimmelverbouwende termieten voor. Sommige soorten maken bovengrondse nestheuvels, andere nestelen uitsluitend ondergronds. Ook humus etende termieten met kleine nestheuvels werden aangetroffen. Termieten passen het milieu zo mogelijk aan hun behoeften aan. Wat deze behoeften zijn en hoe hun aktiviteit in de bodem samenhangt met deze behoeften wordt in hoofdstuk 5 uitgelegd. De chemische gegevens laten zien, dat termieten ook moeilijk afbreekbaar organisch materiaal zoals hout, grondig omzetten, zodat een rest overblijft die rijk is aan basen.

Het effekt van termietenaktiviteit op de fysische eigenschappen wordt in hoofdstuk 6 gedemonstreerd. Met behulp van mikromorfologische analyses van slijpplaten wordt een schatting van de interaktie van twee processen gemaakt. Enerzijds is dit de vorming van struktuur en poriën, waarop termieten grote invloed hebben en anderzijds het verval van de door hen gevormde "architektuur", waarop eigenschappen van het bodemmateriaal, maar ook landgebruik en ontwateringstoestand, grote invloed hebben. De interaktie van deze beide processen is van groot belang voor menging en transport van bodemmateriaal. Tevens blijkt, dat termieten bodemmateriaal uit de bovengrond door het hele profiel verplaatsen tot dieptes van meer dan 7 m om holtes op te vullen en kanalen te bepleisteren. Omgekeerd vindt ook transport naar boven plaats, dat sterker is dan het benedenwaarts gericht transport.

Hoofdstuk 7 laat zien, dat de graafaktiviteit van termieten in goed gedraineerde gronden verantwoordelijk is voor vorming van diepe homogene en fijn getextureerde gronden met op zekere diepte meestal boven de saproliet, een laag bestaande uit grof materiaal, de zg. "stone-line". In Planosols op slecht gedraineerde vlakken treedt naast bioturbatie ook pedoturbatie op, als gevolg van zwel en krimp; dit veroorzaakt menging van zowel grof als fijn materiaal. Het bodemmateriaal in deze gronden is echter zo instabiel, dat de homogenisatie teniet wordt gedaan als gevolg van illuvatie van klei, silt en fijn zand, zodat Planosols blijven bestaan.

Mineralogische en ook textuur gegevens van de Wanjare katena tonen aan, dat "creep" de belangrijkste vorm van lateraal transport was in de diepe goed gedraineerde gronden. Termieten aktiviteit blijkt verantwoordelijk voor de mate van "creep". Op ondiepe bodems vond wel materiaal transport langs het oppervlak plaats, vooral geleverd door termieten.

In hoofdstuk 8 wordt het effekt van termietenaktiviteit op energie en stofkringlopen gedemonstreerd in een model. Een adequaat funktionerende makrofauna (termieten) blijkt voor een handhaving van fysische bodemeigenschappen van groot belang. Instandhouding van deze aktiviteit is niet alleen belangrijk voor de landbouw, maar ook voor de bodembescherming en de waterhuishouding van grotere gebieden. Landbouw, in het bijzonder "low input farming", zou zoveel mogelijk de (gunstige) bodembiologische processen moeten stimuleren en manipuleren. Tenslotte konkludeert de auteur, dat veel meer vergelijkende studies nodig zijn tussen landbouw en natuurlijke ecostystemen om het effekt van landgebruik op de interaktie tussen bodem en bodemfauna te leren kennen.

Appendix 1. Profile descriptions and analytical data.

Soils were classified according to Soil Taxonomy (Soil Survey Staff, 1975) and according to FAO/Unesco (1974). New catagories proposed by Kenya Soil Survey (see Wielemaker and Boxem, 1982) to be included in the FAO/Unesco (1975) legend of the soil Map of the World and awaiting international approval, are indicated with an asterisk in Appendix 1.

<u>Profile Exc. 8</u>

Classification:	Soil Taxonomy: Aquic Argiudoll, F A O /Unesco: Luvic Phaeozem
Location:	South-East Kisii, semi-detailed survey, Kisii district, sheet 130/4; 34°57'23" E., 0°48'42" S.; Elevation 2145 m. Described by I. Guiking; december 1975
Physiography:	gently undulating top of ridge near scarp
Surrounding landform:	steeply dissected
Meso relief:	undulating plateau
Slope:	2 %
Parent material:	rhyolite (Bukoban)
Land-use:	maize and pyrethrum
Soil fauna:	termites, ants and few worms
Drainage:	well drained
Root development:	fine and very fine roots, mainly in upper 60 cm (maize)
A1 0 - 22 cm	dark reddish brown (5 YR 3/2, moist) silty clay; moderate to strong, fine subangular blocky; many very fine and fine biopores; soft, very friable, slightly sticky and slightly plastic; gradual and smooth transition to:
A3 22 - 66 cm	dark reddish brown to dusky red (2,5 - 5 YR 3/2, moist); few, distinct, fine reddish yellow (5 YR 6/8) mottles; silty clay; weak, very fine subangular blocky; many very fine and fine biopores; very friable, slightly sticky and slightly plastic; gradual and smooth transition to:
B21t 66 - 125 cm	dark reddish brown (2,5 YR 3/4 - 5 YR 3/3, moist) clay; weak, very fine subangular blocky; moderately thick, continuous clay cutans; many very fine and fine biopores; friable, sticky and plastic; clear and wavy transition to:
B22t 125 - > 175 cm	dark reddish brown (2,5 YR 3/4 - 5 YR 3/3, moist) clay; moderate, fine angular blocky; clay-manganese cutans, thick, continuous, black; few very fine and fine biopores; firm, sticky and plastic.

Profile 53

Soil classification: dystro*-mollic* Nitosol; ST: orthoxic Palehumult
Ecological zone: II a
Observation: 130/2-3s, Kisii District, E 714.9, N 9926.3, 1880 m, 22-3-1975
Geological formation: bukoban system
Local petrography: andesite
Physiography: saddle between hill-tops
Surrounding landform: hilly
Relief - meso: uniform slope of 500 m
Vegetation: 80% grasses, few bushes
Land use: grazing
Erosion: nil
Surface stoniness: nil
Soil fauna: termites and ants
Slope gradient: 5%
Drainage class: well drained

A11	0-50 cm	dark reddish brown (5YR 3/2, moist) clay; moderate fine subangular blocky; very friable, slightly sticky and slightly plastic; many fine and very fine, common medium and few coarse pores; clear and smooth transition to:
A12	50-79 cm	dark reddish brown (2.5YR 3/3, moist) clay; moderate fine subangular blocky; friable, slightly sticky, slightly plastic; many fine and very fine, common medium pores; gradual and smooth transition to:
B21	79-270 cm	dark reddish brown (5YR 3.5/4 moist) clay; moderate fine angular- subangular blocky; friable, slightly sticky and slightly plastic; moderate thick broken clay-cutans; many fine and very fine pores, few medium pores; from 205-210 cm very many, small soft manganese concretions; clear and smooth transition to:
B22t	270-700 cm	yellowish red (5YR 4/6, moist) clay; moderate medium angular blocky; firm, slightly sticky and slightly plastic; common fine and very fine pores thick broken clay cutans; black continuous coatings from iron and manganese; gradual and smooth transition to:
B23t	700-750+ cm	yellowish red (5YR 4/6, moist) very fine clay; moderate medium-coarse prismatic; firm, slightly sticky and slightly plastic; patchy thick clay cutans, continuous thick cutans of iron and manganese; common fine and very fine pores.

Profile 210

Soil classification: humic Ferralsol; ST: typic Haplohumox
Ecological zone: II a
Observation: 130/3-210, Kisii District, E 6886.3, N 9912.6, 1833 m, 26-2-1974
Geological formation: Middle Kisii series, bukoban system
Local petrography: quartzites and siltstone
Physiography: concave slope near summit of plateau-remnant
Surrounding landform: undulating to rolling
Relief - meso: concave single slope
Vegetation: 80% grasses, 20% shrubs
Land use: extensive grazing
Erosion: nil
Surface stoniness: no stones
Soil fauna: termites
Slope gradient: 3%
Drainage class: well drained

A11	0-12 cm	dark reddish brown (5YR 3/4, dry) clay; moderate very fine and fine subangular blocky; common, very fine continuous random, inped, tubular biopores;very hard, non-sticky and slightly plastic; common fine roots; few coarse, black sand grains; clear and smooth transition to:
A12	12-31 cm	dark reddish brown (2.5YR 3/4, moist) clay; moderate very fine and fine subangular blocky; common very fine, fine and medium, random biopores; friable, non-sticky and slightly plastic; few coarse, black sand grains; abundant very fine and fine roots; clear and smooth transition to:
B1	31-48 cm	dark reddish brown (2.5YR 3/5, moist) clay; moderate, very fine to fine subangular to angular blocky; few very fine and medium, random, biopores; friable, non- to slightly sticky, slightly plastic; common very fine roots; gradual and smooth transition to:
B21	48-95 cm	dark reddish brown (2.5YR 3/6, moist) clay; moderate fine angular blocky; few very fine and fine biopores; friable to firm, slightly sticky and slightly plastic; thin patchy cutans; few very fine roots gradual and smooth transition to:
B22	89-155 cm	dark reddish brown (2.5YR 3/6, moist) clay; moderate fine subangular to angular blocky; common very fine and fine, random, tubular biopores; friable to firm, slightly sticky and slightly plastic; thin patchy cutans; at 130-140 cm depth few large, angular and slightly weathered quartzite gravels; clear and wavy transition to:

Profile Wan 1

Soil classification: Ranker; ST: lithic Humitropept
Ecological zone: IIb
Observation: 130/1-WAN 1, Kisii District, E.689.9, N 9930.1, 1647 m, 19-12-1975
Geological formation: Precambrium/post kavirondian system
Local petrography: Wanjare granite
Physiography: hill top
Surrounding landform: rolling to hilly
Relief - meso: eroded top with termite mounds (30 cm)
Vegetation: dense bushland; 30% shrubs, 20% herbs, 30% grasses
Land use: extensive grazing
Erosion: slight sheet and gully erosion
Surface stoniness/rockiness: extremely rocky, few stones
Soil fauna: termites and ants
Slope gradient: 2%
Drainage class: somewhat excessively drained

A11	0-5/14 cm	dark brown (7.5YR 3/2, dry), dark reddish brown (5YR 3/2 moist) slightly gravelly sandy clay loam; strong very fine granular; due to termite activity abundant pores in all size classes up to 10 mm; soft, friable, slightly sticky and slightly plastic; clear and broken transition to:
A12	5/14-20/35 cm	dark brown (7.5YR 3/2 dry), dark reddish brown (5YR 3/2, moist) slightly gravelly sandy clay loam; strong very fine granular; many fine and fine biopores; soft, friable slightly sticky and slightly plastic; abrupt and broken transition to:
R	20/35+ cm	rock (granite)

Profile Wan 2

Classification:	Soil Taxonomy: orthoxic Tropohumult FAO /Unesco: humic Acrisol
Location:	sheet 130/1 (Gem), near Irigonga school on the slope of the Kebuye range 34°41´53´´E., 0°37´58´´S., elevation 5360 ft./1634 m., described by S. Slager and H. van Reuler (19-12-1975).
Physiography:	upper part of a footslope, just beneath the steeper hillslope to the top
Surrounding landform:	rolling to hilly
Meso relief:	flat, scattered granite boulders
Micro relief:	termite mounds up to 30 cm
Slope:	12%
Parent material:	Wanjare granite (Pre-Cambrian/Post Kavirondian)
Vegetation/land-use:	dense bush land with trees; 15% trees, 60% shrubs, 15% herbs, 40% grasses (5% bare ground), extensively grazed.
Surface stoniness:	very stony (up to 1 m. diameter)
Drainage class:	somewhat excessively drained
Soil fauna:	termites, ants, some beetles and worms

A1 0 - 22 cm	dark brown to brown (7.5 YR 4/2, dry), dark brown (7.5 YR 3/2, moist), gravelly (angular) loamy sand; strongly developed granular structure (diameter 3 mm.) abundant very fine biopores; soft, very friable, slightly sticky and slightly plastic, gradual and smooth transition to:
B2t 22 - 40 cm	yellowish red (5 YR 5/6, dry), yellowish red to red (5 YR 4/6 - 2.5 YR 4/6, moist), gravelly (angular) loamy sand; no macro structure, abundant very fine biopores (many aggrotubules filled with A1 material); soft, very friable, non sticky and non plastic; abrupt and broken transition to:
R 40 - 45/71 cm	rotten rock with hard nucleus of unweathered granite, abrupt and broken transition to:
II B21t 45/71 - 85 cm	yellowish red (5 YR 4/6, dry), dark red (2.5 YR 3/6, moist), very gravelly (angular) sandy loam; few completely rotten rock pieces up to 15 cm diameter; no macro structures, many very fine biopores; hard, friable, non sticky and non plastic; gradual and smooth transition to:
II B22t 85 - 135 cm	yellowish red (5 YR 4/6, dry), yellowish red to dark red (5 YR 3/6 - 2.5 YR 3/6, moist), very gravelly (angular) sandy loam with few completely rotten rock pieces up to 15 cm diameter, no macro structure, many very fine biopores; hard, friable; non sticky and non plastic; gradual and smooth transition to:
II C1 135 - 155 cm	yellowish red (5 YR 5/6, dry), red to yellowish red (2.5 YR 4/6 - 5 YR 4/6, moist), very gravelly (angular) sandy loam with few completely rotten rock pieces up to 15 cm diameter; no macro structure, common very fine biopores; abrupt and smooth transition to:
II C2 155 - 165 cm	hardened material with iron/manganese concretions, 20% distinct brown mottles (10 mm diameter), 60% distinct red mottles (10 mm diameter), 20% prominent black mottles (15 mm diameter), platy structure, few aggrotubules filled with A1 material, hardly breakable, abrupt and smooth transition to:
II R + 165 cm	weathered granite, rapidly changing into fresh granite rock.

Remark: In the topsoil 0 - 45/71 cm some artefacts were found especially in the upper part of the II B21t horizon.

Profile Wan 3

Soil classification: mollic[x] Nitosol; ST: typic Paleudoll
Ecological zone: II b
Observation: 130/1-WAN3, Kisii District, E 689.5, N 9930.1, 1567 m, 30-12-1975
Geological formation: Post kavirondian intrusive in Nyanzian system
Local petrography: quartz diorite
Physiography: upper part of a footslope
Surrounding landform: undulating - rolling
Relief - meso: terraces, developed from thrash-lines
Vegetation: no natural vegetation
Land use: cultivated area (maize)
Erosion: few rills
Surface stoniness: nil
Soil fauna: termite activity
Slope gradient: 8%
Drainage class: well drained

A1	0-30 cm	reddish brown (5YR 4/2, dry) dark reddish gray (5YR 3/2, moist) clay; moderate medium compound subangular blocky, many very fine, fine and few medium biopores; hard, very friable, slightly sticky and slightly plastic; clear and smooth transition to:
A3	30-55 cm	reddish brown (2.5YR 4/3-5YR 4/3, when dry), dark reddish brown (5YR 3/2, moist) clay to sandy clay; moderate very fine and fine angular blocky many very fine, fine and common medium biopores; slightly hard, very friable, slightly sticky and slightly plastic; gradual clear and smooth transition to:
B1t	55-85 cm	reddish brown (5YR 4/4, dry) reddish brown (5YR 4/3, moist) clay; moderate fine subangular blocky; weak to common clay and organic matter cutans; many fine, common medium and a few coarse biopores; hard, friable, slightly sticky and slightly plastic; gradual and wavy transition to:
B21t	85-110 cm	reddish brown (2.5YR 4/4-5YR 4/4, dry), weak red to reddish brown (2.5YR 4/3, moist) clay; moderate fine and medium subangular blocky; moderate common clay/organic matter cutans; many very fine and fine, common medium, few coarse and very coarse biopores; hard, friable, slightly sticky and slightly plastic; gradual and wavy transition to:
B22t	110-235 cm	reddish brown to red (2.5YR 4/5, dry), reddish brown (2.5YR 4/4, moist) clay; moderate fine and medium subangular blocky; moderate common to abundant clay/organic matter cutans; many very fine, common medium and few coarse biopores; very hard, friable, slightly sticky and slightly plastic, gradual and wavy transition to:

B23t	235-290 cm	red (2.5YR 4/6, dry), reddish brown to red (2.5YR 4/5, moist) clay; moderate medium subangular blocky; moderate common clay/organic matter cutans; many very fine, common fine and few medium, coarse and very coarse biopores; hard, very friable, slightly sticky and slightly plastic; clear and wavy transition to:
B24t	290-245 cm	red (2.5YR 3/6, dry), reddish brown (2.5YR 4/4, moist) clay; weak medium and fine subangular blocky; moderate common clay/organic matter cutans; 15% 3-4 mm diameter iron-manganese concretions; many very fine, common fine and few common coarse- very coarse biopores; hard, friable; slightly sticky and slightly plastic; abrupt and wavy transition to:
B31	345-485 cm	yellowish red to red (5YR 5/6-2.5YR 5/6, dry), dark red (2.5YR 3/6, moist), common prominent 3-6 mm diameter manganese mottles; very gravelly clay, no macro structure; common fine and medium biopores, very hard, firm non-sticky and non-plastic; clear and wavy transition to:
B32	485-550 cm	yellowish red to red (5YR 5/6-2.5YR 5/6, dry), dark red (2.5YR 3/6, moist); abundant 5-10 mm diameter manganese mottles; very gravelly clay; no macro structure; common fine and medium biopores; very hard, very firm, non-sticky and non-plastic; gradual and wavy transition to:
C	550-750 cm	multicoloured, varying from red (2.5YR 5/8, dry) to dark red (2.5YR 3/6 moist), red (10YR 5/8, dry) to dark red (2.5YR 3/6 moist), red (10YR 5/8, dry) to red (10YR 5/6 moist), with many white and yellow rotten rock spots; abundant 5-10 mm diameter manganese mottles; very gravelly clay; no macro-structure; common fine and medium biopores (see remark), very hard, very firm non-sticky and non-plastic.
Remark:		many agrotubules diameter 5 mm filled with clay reddish brown (2.5YR 4/4) when moist, they occur from about 5.50 m to the bottom of the pit (7.50 m).

Profile Wan 9

Soil classification: humic Ferralsol ST: typic Haplohumox
Ecological zone: II b
Observation: 130/1-WAN 9, Kisii District, E 687.4, N 9931.0, 1571 m, 2-3-1976
Geological formation: Post Kavirondian intrusive in Nyanzian system
Local petrography: quartz-diorite
Physiography: flat-topped ridges
Surrounding landform: undulating to rolling
Relief - meso: nil
Vegetation: 60% grass, 40% herbs
Land use: grazing
Erosion: nil
Surface stoniness: nil
Soil fauna: termite activity to 2.17 m
Slope gradient: 0%
Drainage class: well drained

A11	0-16 cm	dark reddish brown (5YR 3/3) when moist, clay; weak fine angular to subangular blocky; friable, slightly sticky and slightly plastic; few very fine pores; clear and smooth transition to:
A12	16-38 cm	dark reddish brown (2.5YR 3/4) when moist, clay; moderate fine subangular blocky; friable, slightly sticky and slightly plastic; few medium and fine, many very fine pores; common termite chambers 5-20 cm in diameter; gradual and smooth transition to:
B1	38-80 cm	dark red (2.5YR 3/5, moist clay; moderate fine subangular blocky; friable, slightly sticky and slightly plastic; few medium and fine, many very fine pores; common termite chambers 5-20mm in diameter; gradual and smooth transition to:
B21t	80-130 cm	red (2.5YR 4/5) when moist, clay; moderate very fine angular to subangular blocky; friable, slightly sticky and slightly plastic; moderately thick, common clay cutans; many fine and very fine, few medium pores; small termite holes of 2 cm diameter; gradual and smooth transition to:
B22t	130-210 cm	red (2.3YR 4/6) when moist, clay with some quartz gravel; moderate fine and very fine angular blocky; slightly sticky and slightly plastic; moderately thick common clay cutans; many fine and very fine pores small termite holes of less than 2 cm diameter; one piece of rotten rock with diameter of 5 cm; gradual and smooth transition to:

B23	210-280 cm	like B22, but with 5% rounded soft manganese concretions of 5 cm diameter, clear and smooth transition to:
B24	280-310 cm	like B22, but with 10% soft rounded manganese concretions of 5-10 cm diameter, abrupt and wavy transition to:
B3	310-330 cm	dark red (2.5YR 3/6) when moist, clay with 5% small quartz gravel; moderate very fine angular blocky; firm, slightly sticky and slightly plastic; moderate thick, common, clay and manganese cutans; few fine pores; 75% rounded and angular manganese concretions of 3-8 cm diameter; clear broken and wavy transition to:
	330+ cm	mixtures of rotten rock, quartz diorite stones and gravelly soil.

Remark: at 310-330 cm allochthonic stone fragments were found.

Profile Wan 4

Classification:	Soil Taxonomy: typic Paleudoll acc. to FAO (1974)/ mollic* Nitosol
Coordinates:	34°42'55" E and 0°37'43" S; Altitude: 1528 m described by R.F. Breimer on 15-1-1976
Petrography:	diorite (intrusion in Wanjare granite formation)
Physiography:	general: rounded hills with long straight slopes land unit: lower part of linear slope
Macro relief:	undulating to rolling
Slope:	700 m, convex-linear-slightly concave, 10% gradient
Land-use:	arable land-used for maize
Rock outcrops:	none
General ground water level:	deeper than 2 m
Drainage class:	somewhat imperfectly to well drained
Soil fauna:	very high activity of termites, ants and moles, in the upper metre, from 1-2 m depth a high activity and below 2 m a moderate activity.
Ap 0 - 10 cm	dark reddish brown/grey (5 YR 3 - 4/2, moist), reddish brown (5 YR 5/3, dry), clay; moderate very fine subangular blocky and crumby structure, common fine and very fine pores; hard, very friable, slightly sticky and slightly plastic; clear smooth transition to:

Al 10 - 43 cm	dark reddish brown (5-2.5 YR 3/3, moist), reddish brown (5-2.5 YR 4/3, dry), clay; moderate fine subangular blocky, many very fine and fine, few medium and very coarse pores; hard, friable, slightly sticky and slightly plastic; gradual and smooth transition to:
Bl 43 - 80 cm	dark reddish brown (2.5 YR 3-4/4, moist), reddish brown (2.5 YR 5/4, dry), with dark reddish brown (2.5 YR 3/4) ped surfaces, having at places fine faint dark mottles; clay; moderate fine subangular blocky, many moderate clay cutans, many fine and very fine, few medium and very coarse pores; hard, friable, slightly sticky and slightly plastic; diffuse and smooth transition to:
B21t 80 - 210 cm	reddish brown (2.5 YR 4/4, moist) and (2.5 YR 5/4, dry), with dark reddish brown (2.5 YR 3/4) ped surfaces having fine faint dark mottling; clay; strong fine subangular blocky to angular blocky, many continuous thick clay (+ manganese) cutans; many very fine and fine, few medium and coarse pores; very hard, firm to friable, slightly sticky and plastic; clear and slightly wavy transition to:
B22t 210 - 235 cm	reddish brown (5-2.5 YR 4/4, moist), and (5 - 2.5 YR 5/4, dry), with many fine and medium prominent black mottles; clay; strong fine subangular to angular blocky, many moderate clay (+ manganese) cutans, many very fine and fine, few medium and coarse pores; very hard, firm, slightly sticky and plastic; common 2-20 mm big black manganese (+ iron ?) concretions; gradual wavy transition to B3:
B3 235 - 320 cm	reddish brown (5 YR 4/4, moist) and (5 YR 5/4, dry), with many medium prominent black mottles; slightlu gravelly clay; moderate fine to medium subangular to angular blocky, common moderate clay (+ manganese) cutans; common very fine, few fine and medium pores; very hard, firm, slightly sticky and plastic; common 1-5 mm big black manganese/iron concretions, gradual and wavy transition to:
BC 320 - 360 cm	reddish brown (5 YR 7/4) mixed with black and reddish yellow rotten rock colours; very gravelly clay; weak fine angular blocky structure; few very fine pores; very hard, firm, sticky and plastic, many 1-5 mm big rounded black manganese/iron concretions, clear and wavy transition to the hard rock.
R - horizon:	diorite rock at 350 - 370 cm depth with a thin decomposed rock cover.

Profile Wan 5

Classification:	Soil Taxonomy: typic Argiudoll. FAO /Unesco: Luvic Phaeozem (Hl).
coordinates:	34°42'56" E and 0°37'43" S; altitude: 1523 m described by R.F. Breimer on 5-1-1976.
Petrography:	diorite (intrusion in Wanjare granite formation)
Physiography:	general: rounded hills with long straight slopes land unit: lower part of linear slope.
Macro relief:	undulating (5-8 %) to rolling (8-16 %)
Slope:	700 m, convex-linear-slightly concave, 10 % slope
Land-use:	maize
Rock outcrops:	none
General ground water level:	from 60-120 cm to very deep
Drainage class:	moderately well drained
Soil fauna:	0-100 cm: high activity of ants and termites 100-150 cm: moderate activity over 150 cm: no visible activity
A1 0 - 30 cm	dark brown (7.5 YR 3/2, moist), brown (7.5 YR 5/2, dry), sandy clay loam; moderate fine to medium subangular blocky and moderate very fine crumby; many very fine and fine, few medium and coarse pores; slightly hard, very friable, slightly sticky and slightly plastic; gradual and smooth transition to:
B1 30 - 55 cm	dark reddish grey (5 YR 4/2, moist), clay loam; moderate medium to fine subangular blocky; many very fine, common fine and few medium and coarse pores; hard, friable, slightly sticky and slightly plastic; clear and wavy transition to:
B21t 55 - 95 cm	reddish brown (5 YR 4/3 - 4, moist), clay loam; with many coarse prominent black mottles; moderate medium to fine subangular blocky, common cutans; many very fine, common fine, few medium and coarse pores; very hard, friable to firm, slightly sticky and slightly plastic; many manganese/iron concretions of 1-5 mm diameter; gradual and wavy transition to:
B22t 95 - 150 cm	mixed brown colours (7.5 YR 5/2 + 5/4, moist), clay loam with many coarse prominent black mottles; moderate medium to fine subangular blocky, common clay and manganese cutans, common very fine, few fine, medium and coarse pores; very hard, friable to firm, sticky and slightly plastic; many 1-5 mm big manganese concretions; clear and wavy transition to:

At the transition a 5 cm thick layer occurs, consisting of small gravels and black concretions.

B23tg 150 - 215 cm	mixed grey and brown (7.5 YR 5/1 + 5/3, moist), slightly gravelly clay with common medium to coarse prominent black mottles and many fine prominent strong brown (7.5 YR 5/6) mottles; moderate to strong fine to medium angular blocky, many strong clay and manganese pressure cutans; few very fine and fine pores; very hard, firm, sticky and plastic; many 0.5-2 cm big manganese/iron concretions; clear and wavy transition to:
B3g 215 - 310 cm	dominant colour is pinkish grey (7.5 YR 6/2), mixed with brown (7.5 YR 5/2, moist); slightly gravelly clay with many medium to coarse prominent strong brown (7.5 YR 5/6) and black mottles; weak fine to medium angular blocky; many strong manganese and pressure cutans, few very fine and fine pores; very hard, firm, sticky and plastic; abrupt and wavy transition to the rock boulders.

The depth of the rock varied between 2.75 and more than 3.20 m, due to boulder weathering of the diorite rock.

Termite mound sequence at Opapo

Profiles, M1A, D and E are associated soils. M1A is located in the active part of the termite mound, M1D is located on the slope of the mound and M1E is located in the Plain, where no influence of the mound is noticeable. Profile M1E is similar to M3 of which description and analytical data are given as description no. 36 in App. 1 of Wielemaker and Boxem, 1982.

Date of observation:	19-7-1978; described by M. Nachenius and W.G. Wielemaker
Location:	Opapo, South Nyanza district, Nyanza Province in Kenya (Sheet 130/1, grid lines 9923/671); 1340 m.
Physiography:	Plain; slope: 0 - 1 %
Parent material:	Granite overlain by alluvium and volcanic ash.
Macro relief:	Gently undulating; meso-relief-flat;
micro relief:	termite mounds of 1 - 2 metre high and with a diametre of 3 - 10 metre at distances of 30 - 50 metre.
Vegetation and land use:	On the mound shrubs; between the mounds grass, which is extensively grazed.
Drainage:	On the mound, well drained, but between the mounds, poorly drained.
Surface stoniness:	nil; erosion: nil
Classification:	M1E is an abruptic Tropaqualf (ST) and a eutric Planosol (FAO/Unesco)
Processes:	In profile M1A termites have thoroughly mixed the different horizons as occurring in profile M1E. M1D is a transition to M1E.

Profile MlA

+ 190 - + 30 cm	Dark brown (7.5 YR 3/2) dry, many medium faint brown (7.5 YR 4/4) mottles, clay; strong very fine angular blocky; slightly sticky, slightly plastic, very hard dry; gradual, smooth transition to:
+ 30 - 110 cm	Very dark grey (10 YR 3/1) dry, common medium distinct dark greyish brown (10 YR 4/2) mottles; clay; strong medium to coarse angular blocky; hard dry, slightly sticky, non plastic; clear wavy transition to:
110 - 165 cm	Mixed colours, dark greyish brown (10 YR 4/2) clay and white (10 YR 8/1) dry; gravelly heavy clay; massive with many rounded stones (5 to 20 cm), many gravel, clear wavy transition to:
C 165 + cm	Mixed colours greyish brown (10 YR 5/2) and pale olive (5 YR 6/4) moist, gravelly clay; massive; many angular quartz gravel.

Profile MlD

A1 0 - 28 cm	Light grey to light brownish grey (10 YR 6/1.5) dry, very dark greyish brown (10 YR 3/2) moist; clay loam; weak very fine angular blocky; friable; slightly sticky, slightly plastic; few gravel; clear wavy transition to:
A2 22 - 45 cm	Light grey (7.5 YR 7/0) dry, common medium distinct yellowish brown (10 YR 5/4) mottles; clay loam; weak coarse prismatic to porous massive; friable; non sticky, non plastic; few gravel; gradual smooth transition to: Remark: common continuous thick clay cutans line pores and holes especially in the lower part of the A_2 horizon.
B2t45 - 85 cm	Very dark greyish brown (10 YR 3/2) moist, dark greyish brown (10 YR 4/2) clay, common fine faint yellowish red (5 YR 4/6) mottles; clay; moderate medium angular blocky; slightly sticky, slightly plastic dry; few gravel; abrupt and wavy transition to: Remark: A_2 material is present along cracks;
85 - 105 cm	90 % gravel and stones, embedded in clay
105+ cm	As in B_{2t} above

Profile MIE

A1 0 - 12 cm	Very dark greyish brown to dark greyish brown (10 YR 3.5/2) moist, dark grey (10 YR 4/1) dry, common faint dark yellowish brown mottles; loam; weak to moderate very fine subangular blocky; very friable; slightly sticky and slightly plastic; few very fine and fine pores; few fine and very many very fine roots; clear and smooth transition to:
A21 12 - 42 cm	Dark greyish brown (10 YR 4/2) moist, grey (10 YR 5/1) dry; common fine faint dark yellowish brown mottles; sandy clay loam; weak very fine subangular blocky; very friable, slightly sticky, slightly plastic; few very fine and fine pores; common very fine and very few fine roots; clear and wavy transition to:
A22 42 - 50 cm	Like A_{21} above, but gravelly coarse sandy loam; abrupt and broken transition to:
B2t1 50 - 60 cm	Very dark brown (10 YR 2/2) moist, many medium prominent red (2.5 YR 5/8) mottles; clay; strong fine angular blocky; firm; sticky and slightly plastic; thick continuous clay cutans; few very fine pores; common fine roots; clear and wavy transition to:
B2t2 60 - 105 cm	Very dark brown (10 YR 2/2) moist, many distinct fine reddish yellow mottles; gravelly and stony clay; strong fine angular blocky; few weak not intersecting slickensides; sticky and slightly plastic; thick continuous clay cutans; no pores; common fine roots; stones are mainly quartzitic with a few jaspis and weathered granites; clear and wavy transition to:
B3 105+ cm	Dark grey (10 YR 4/1) moist; common fine distinct yellowish brown and white mottles; clay with weathered rock particles; weak coarse angular blocky; firm moist, sticky and slightly plastic, wet; no pores.

Profile NARS.

Soil classification:	mollic[x] Nitosol; ST: typic Paleudoll
Ecological zone:	IIb
Observation:	130 NARS, Kisii District, E698.2, N9925.50, 1885 m, 18-10-1976.
Geological formation:	bukoban system (Precambrium)
Local petrography:	basalt
Physiography:	middle part of straight lateral slope
Surrounding landform:	rolling upland

Relief-meso:	nil; micro: ant and termite heaps
Land-use:	grazing
Erosion:	nil
Surface stoniness:	nil
Soil fauna:	termites; dung beetles; ants and mole rats
Slope gradient:	12 %
Drainage class:	well drained

A1 0 - 40 cm	dark reddish brown (5 YR 3/4 dry and moist) slightly gravelly clay; moderate fine subangular blocky; hard, firm, non sticky and non plastic; clear and smooth transition to:
B1 40 - 70 cm	dark reddish brown (5 YR 3/3, moist) gravelly clay; strong fine to medium subangular blocky; hard, firm, slightly sticky and slightly plastic; clear and smooth transition to:
B21t 70 - 80 cm	dark reddish brown (5 YR 3/4, moist) clay; fine broken dark clay cutans; weak medium subangular blocky; hard, firm, slightly sticky and slightly plastic; gradual and smooth transition to:
B22t 80 - 150 cm	dark red (5 YR 3/6, moist) clay; strong medium angular blocky; broken fine dark clay cutans; hard, firm, non sticky and slightly plastic; diffuse and smooth transition to:
B23t 150 - 200 cm	dark red (2.5 YR 3/6, moist) clay with black spots; strong subangular blocky; few fine clay cutans; friable , slightly sticky and slightly plastic; diffuse and smooth transition to:
B24t 200 - 300 cm	dark red (2.5 YR 3/6, moist) clay with common, medium and distinct black mottles; few moderate clay and Fe/Mn cutans; strong very fine, fine and medium subangular blocky; friable, slightly sticky and slightly plastic; abrupt and smooth transition to:
B3 300 - 330 cm	Gravelly, bouldery and stony clay with common black and yellow spots; few moderate clay and Fe/Mn cutans; moderate, very fine angular blocky; friable, slightly sticky, slightly plastic.

Profile	Depth (cm)	Particle size distribution% sand fractions (mm) 2-0.25	0.25-0.1	0.1-0.05	sand	silt	clay	Density separations (%) in sand (0.05-0.1mm) d<2.5	2.5-2.9	>2.9
V26	0- 23	n.d.	n.d.	17	70	15	15	92.6	6	1.4
133/1	10- 20	8.7	7.0	3.1	18.8	46.8	34.4	22.5	77.2	0.3
	40- 50	8.6	7.5	3.1	19.2	44.4	36.4	37.3	60.5	2.1
	80- 90	9.2	7.0	2.6	18.8	43.3	37.9	46.1	51.7	2.3
118/4	10- 20	8.6	2.6	2.2	13.2	24.3	62.2	52.5	45.4	2.1
	40- 50	2.4	3.6	2.4	8.4	63.9	27.6	58.0	39.8	2.1
	80- 90	1.5	2.8	1.5	5.8	39.3	54.9	40.9	56.4	2.6
132/2	10- 20	7.9	5.2	2.8	15.9	43.9	40.2	20.7	75.9	3.4
	40- 50	2.6	3.5	2.7	8.8	49.5	41.7	25.0	72.5	2.5
	80- 90	2.7	4.7	3.5	10.9	45.2	43.9	26.1	70.8	3.0
131/4	10- 20	3.0	2.7	0.8	6.5	77.4	15.9	21.0	77.3	1.7
	40- 50	2.5	2.9	0.8	6.2	57.2	36.6	28.9	69.5	1.6
	150-200	10.4	5.3	4.0	19.7	37.3	42.9	28.6	70.1	1.3

Profile	Depth (cm)	Particle size distribution (mass %) sand fractions in mm 1-2	0.5-1.0	0.25-0.5	0.1-025	0.05-0.1	sand	silt	clay	Density separations (%) in sand (0.05 - 0.1 mm) d<2.5	2.5-2.9	>2.9
Exc. 8	0- 22	3.1	6.8	7.4	8.0	7.8	33.1	45.7	21.2			
	22- 66	4.0	5.0	5.5	6.2	6.2	26.9	41.6	31.4	13.8	84.7	1.5
	90- 105	4.6	5.2	6.0	6.5	6.0	28.3	38.9	32.7			
	150- 165	6.0	7.4	6.6	6.3	5.6	32.0	46.1	21.9	.	.	2.1
	200- 250											
S 3	0- 50	0.9		1.6	2.3	1.9	6.7	31.2	62.1	6.9	89.4	1.1
	50- 79	0.6		1.7	2.3	2.3	6.9	28.4	64.7	7.7	91.0	1.3
	79- 270	0.4		1.8	2.0	1.6	5.8	26.1	68.1	21.8	77.1	1.1
	340- 345	0.5		1.8	2.6	2.1	7.0	21.0	72.0	15.6	83.2	1.2
	600- 610	1.0		2.1	2.7	1.8	7.6	19.3	73.1	15.4	83.9	1.6
	740- 750	0.7	1.8	3.1	4.2	2.5	13.0	17.3	69.7	12.8	85.7	1.4
S 1	950-1000	.		.	.	.	20.7	50	29.3	41.8	57.6	0.6
210	10- 20	2.2		1.9	2.8	2.3	9.2	20.9	69.9	9.6	90	0.4
	30- 40	1.4		1.8	2.6	2.2	8	19.8	72.2	10.6	89.0	0.4
	50- 70	1.2		1.5	2.3	2.2	7.2	17.2	75.6	13.9	85.6	0.5

Profile	Depth (cm)	Org.C (g/kg)	pH H_2O	KCl	Exchangeable bases (mmol/kg) ½Ca	½Mg	K	Na	CEC(NH_4Ac) at pH 7.0 (mmol/kg)	Base saturation (%)	Bulk density (g/kg)
Exc. 8	0- 22	.	6.2	5.5	200	30	24	.	250	100	.
	22- 66	.	6.1	5.2	126	21	6	.	168	91+	.
	90-105	.	6.0	5.0	53	16	8	.	86	90+	.
	150-165	.	6.0	5.3	37	26	15	.	89	88+	.
	200-250	.	5.9	4.9	37	25	23	.	95	89+	.
S 3	0- 50	24	5.2	4.8	86	30	4	.	203	59+	1090
	50- 79	17	5.5	4.8	67	35	5	.	187	57+	.
	79-270	4	5.4	4.2	11	20	7	.	136	30+	1100
	340-345	.	4.5	4.0	16	6	7	.	140	25+	1190
	600-610	.	4.7	4.1	39	11	8	.	150	39+	1220
	740-750	.	5.0	4.1	47	17	8	.	144	50+	1220
210	10- 20	27	5.0	4.0	2	1	1	-	118	3.4	940
	30- 40	17	5.0	4.1	tr	tr	tr	-	100	1.0	n.d.
	50- 70	9	5.1	4.2	tr	tr	tr	-	87	1.1	1130
	90-110	4	5.3	4.3	1	tr	tr	-	88	2.3	1180
	130-150	3	5.0	4.3	tr	tr	tr	-	81	1.2	1150

Analytical data of profiles on volcanic ash outside the main area of study. Chemical, some mineralogical and morphological data are given in Wielemaker and Wakatsuki, 1984; profile V26 = 1; 133/1 = 2; 118/4 = 3; 132/2 = 4 and 131:4 = 5; . = not determined.

Profile	Depth (cm)	Magnetic separates (%) in sand (0.05-0.1mm, d>2.9) s.m.	w.m.	n.m.	zircons per 100 grains in n.m. fraction
V26	0- 23	18.8	37.6	43.7	-
133/1	10- 20	25.0	69.0	6.0	.
	40- 50	25.9	72.4	1.7	13
	80- 90	21.4	76.9	1.7	.
118/4	10- 20	21.9	73.4	4.7	.
	40- 50	20.5	72.7	6.8	.
	80- 90	28.3	62.2	9.6	.
132/2	10- 20	34.5	63.3	2.1	.
	40- 50	30.5	67.8	1.7	34
	80- 90	47.1	51.1	1.8	.
131/4	10- 20	11.0	84.1	4.9	.
	40- 50	11.0	81.6	7.4	57
	150-200	11.0	84.0	5.0	.

Analytical data of profiles within the main area of study.

Profile	magnetic separates % in sand (0.05-0.1mm,d>2.9) s.m	w.m	n.m	minerals per 100 transparent grains in the non-magnetic fraction: zircon	Aegirine-augite	Amphibole	Pyroxene
Exc. 8							
	13.5	66.7	19.8	23	-	-	-
	5.8	39.9	54.3	.	.	.	.
S 3	4.0	81.0	15.0	.	.	.	.
	13.1	74.3	12.6	20	8	26	1
	10.6	73.6	15.6	13	40	20	1
	1.1	86.0	12.9	26	11	26	0
	17.8	68.0	14.1	38	7	22	0
	5.7	84.6	9.8	70	tr	5	0
S 1	3.0	45.9	51.1	0.0		epidote 100	
210	14.8	63.0	22.2				
	12.5	62.5	25.0				
	4.5	50	45.4				

Profile	s.m	Composition according to X-ray fluorescence: strongly magnetic M1	M2	I	H	R	Z	weakly magnetic I	R	A	M2	M1	H
S 3	4.0	+++	+++	-	-	tr	-	+++++	tr	+	-	tr	tr
	13.1	+++	+++	-	-	tr		+++++	tr	+	tr	tr	tr
	10.6	+++	+++	-	-	tr	-	+++++	tr	+	+	tr	-
	1.1					+	-	+++++	tr	+	-	tr	tr
	17.8	+++	+++	-	-	tr	-	+++++	tr	+	-	-	+
	5.7	+++	+++	-	-	tr	-	+++++	tr	+	-	-	+
S 1	3.0	+++++	-	-	-	tr	-	+++++	tr	+	-	+	-

Profile	Depth (cm)	Moisture % volumic mass at pF 2.0	3.0	4.2	Mass % of major elements in fine earth (calculated as oxides) SiO_2	Al_2O_3	Fe_2O_3	K_2O
Exc. 8	0- 22	.	.	.	58.4	12.1	8.0	2.6
	22- 66	.	.	.	60.7	13.4	8.9	2.8
	90-105	.	.	.	61.7	14.8	9.5	3.1
	150-165	.	.	.	61.7	14.8	10.4	2.7
	200-250	.	.	.	57.7	15.0	12.7	2.7
S 3	0- 50	48.5	28.9	22.5	47.5	20.2	13.8	1.7
	50- 79	.	.		.	.	.	.
	79-270	45.6	32.4	25.5	46.5	24.0	14.7	1.4
	340-345	46.2	38.8	31.1	44.3	23.9	16.1	1.1
	600-610	52.9	34.1	29.9	.	.	.	.
	740-750	58.8	46.8	28.8	45.4	22.2	17.2	0.8
210	10- 20	.	.	.	47.8	20.8	11.8	0.7
	30- 40	43.7	23.7	21.2	46.9	21.8	14.6	0.7
	50- 70	45.9	27.3	25.0	47.7	23.0	14.0	0.7
	90-110	47.0	37.3	26.7.	47.5	23.7	14.3	0.8
	130-150	41.9	37.7	27.5	47.5	23.4	14.6	0.8

Profiles of the upper Wanjare catena

Profile	Depth (cm)	Particle size distribution (mass %) gravel >2.0	sandfractions (mm) 1-2	0.5-1.0	0.25-0.5	0.1-0.25	0.05-0.1	sand	silt	clay	Density separations(%) in sand (0.05-0.106mm) d<2.5	2.5-2.89	>2.89	Magnetic separates(%) in sand(005-0.106mm, d>2.89) s.m	w.m	n.m
Wan 1	0- 35	20.2	19.6	10.5	7.3	7.7	4.6	49.5	19.2	31.3	4.1	92.2	3.7	19.9	50.4	29.7
Wan 1A	0- 14	47.2	28.9	6.1	6.3	9.1	3.1	54.4	12.8	32.8	.	.	.	30.3	58.8	10.9
Wan 2	0- 16	32.2	54.8	10.9	5.7	5.5	1.9	78.9	6.7	14.4	6.6	90.9	2.5	.	.	.
	15- 30	41.5	68.4	10.3	3.0	2.6	1.2	85.5	4.1	10.4	8.6	88.1	3.2	37.8	34.4	30.9
	55- 70	54.5	53.6	11.4	2.0	0.4	0.9	24.2	4.9	26.8	36.3	60.8	2.9	.	.	.
	83- 98	42.7	67.6	6.9	0.5	0.6	0.4	76.1	3.8	20.1	23.9	73.8	2.3	15.4	42.0	42.5
	120-135	61.8	68.2	5.5	0.6	1.0	1.2	32.3	4.9	18.7	24.5	73.0	2.5	24.8	41.5	33.7
	160-165	40.1	21.2	10.3	3.8	3.3	7.7	42.6	35.2	22.2	31.3	65.0	3.7	0.6	12.3	87.1
Wan 3	10- 25	1.7	11.3	15.8	10.9	6.7	2.9	46.6	1.0	52.4	14.0	76.9	9.1	2.4	73.0	24.6
	40- 55	1.5	6.7	10.2	7.5	5.2	1.5	31.0	7.3	61.7	6.3	80.4	13.3	2.9	73.6	23.4
	70- 85	3.2	5.3	8.9	7.4	5.8	2.5	27.4	10.7	61.9	15.7	72.2	12.1	2.2	74.4	23.4
	85-100	5.3	5.2	8.2	6.3	4.9	2.6	27.1	9.8	63.1	28.3	60.3	11.4	2.1	89.3	8.6
	145-160	2.2	7.5	10.2	6.5	5.2	3.1	32.6	6.2	61.2	26.6	60.6	12.7	2.6	73.8	23.5
	190-205	0.8	6.9	7.6	4.8	3.5	1.8	24.6	8.6	66.8	17.6	69.3	13.0	1.8	74.0	24.2
	240-255	7.1	8.9	6.1	4.6	4.8	3.9	28.4	9.0	62.6	24.4	67.2	8.3	1.7	76.0	22.4
	255-270	2.1	7.7	6.0	4.6	4.7	5.9	29.0	7.9	63.1	8.9	81.8	9.3	1.1	73.4	25.5
	285-300	3.5	10.0	7.2	5.6	5.4	3.6	31.9	3.9	64.2	3.3	86.4	10.3	0.0	66.3	33.7
	315-330	5.0	12.6	6.8	4.9	4.7	6.4	35.4	7.0	57.6	9.8	80.8	9.3	1.2	72.0	26.9
	385-400	29.9	34.4	5.7	2.0	1.5	0.8	44.4	5.4	50.2	12.2	78.8	9.0	0.9	70.4	28.7
	435-450	19.0	20.1	7.1	3.7	2.9	2.0	35.7	10.3	54.0	13.9	74.1	12.0	0.7	69.8	29.5
	485-500	14.7	16.5	7.5	4.2	34	2.4	34	28.6	37.4	n.d.	n.d.	8.8	0.8	74.4	24.8
	535-550	9.6	12.8	12.7	6.4	5.0	1.3	38.3	21.3	40.4	21.6	66.7	9.4	0.7	66.0	33.3
	635-650a	11.8	17.8	9.7	3.3	2.4	1.5	34.6	<-65.4->		25.6	65.2	9.2	0.4	62.1	37.5
	termite soil saprolite b	6.3	27.0	16.2	6.3	4.2	1.6	55.4	<-44.6->		n.d.	n.d.	6.1	n.d.	n.d.	n.d.
	735-750	5.1	7.8	11.1	8.3	6.5	2.8	36.6	27.1	36.3	18.3	71.8	9.0	0.9	65.1	34.0

Profile	Depth (cm)	Org.C (g/kg)	pH H_2O	KCl	Exchangeable bases (mmol/kg) ½Ca	½Mg	K	Na	CEC(NH_4Ac) at pH 7.0 mmol/kg	Base saturation (%)	Bulk density (g/kg)
Wan 1	0- 35	24.1	4.0	3.6	9	4	5	n.d.	189	9+	970
Wan 1A	0- 14	n.d.	5.5	4.2	2	1	2	n.d.	123	4.1	.
Wan 2	0- 16	27	4.6	3.9	22	6	4	n.d.	104	30.8	1490
	15- 30	24	4.5	3.7	9	2	3	n.d.	92	15.2	1440
	55- 70	n.d.	4.6	3.9	5	1	2	n.d.	57	14.0	n.d.
	83- 98	4	5.0	3.8	6	3	2	n.d.	61	18.0	1510
	120-135	3	4.9	3.8	5	3	4	n.d.	74	16.2	.
	160-165	6	5.0	4.1	10	10	2	n.d.	52	42.3	.
Wan 3	0- 25	22.0	6.0	5.2	136	28	10	n.d.	175	99.4	1170
	25- 55	18.0	5.2	4.3	63	15	4	n.d.	133	61.6	1210
	55- 85	14.0	5.2	4.5	60	14	4	n.d.	144	62.9	1240
	85-100	18.0	5.3	4.5	62	14	3	n.d.	120	65.8	1170
	145-160	8.0	5.2	4.7	36	17	5	n.d.	87	66.7	.
	190-205	5.0	5.5	5.1	40	19	8	n.d.	91	73.6	1240
	240-255	3.0	5.1	4.4	20	6	13	n.d.	85	45.9	.
	255-270	2.0	5.2	4.5	50	14	18	n.d.	80	100+	.
	285-330	2.0	4.8	4.0	20	7	13	n.d.	82	49.1	.
	485-550	tr.	4.8	3.8	19	7	4	n.d.	47	70.0	.
	730-740	tr.	4.8	3.8	22	6	3	n.d.	59	52.5	.

Depth (cm)	Composition according to X-ray fluorescence: Strongly magnetic M1	M2	Ilm	Hm	Ru	Z	weakly magn. Hm	Dm	Z	A	Minerals per 100 transparent grains in very fine sand: d<2.5 glass	plant opal	d>2.89, non-magnetic zircon	Amphibole+pyroxene	
0- 35	+++	-	++	+++	tr	-	++	++	++	+++	22.1	4.1	78	15	
0- 14	++++	-	+++	+	-	tr	-	-	-	+++++	.	.	50	n.d.	
0- 16	.	.	.	.	.	.	.	.	.	.	10.4	2.6	n.d.	n.d.	
15- 30	++	-	++	+++	tr	+	++	+++	+++	+	8.6	2.0	68	17	
55- 70	.	.	.	.	.	.	.	.	.	.	0	1.1	n.d.	n.d.	
83- 98	++	-	++	+++	+	tr	++	+++	++	tr	0	0	96	1	
120-135	++	-	++	+++	+	+	++	+++	++	tr	0	0	96	1	
160-165	++	-	++	+++	+	-	++	+++	++	-	tr	0	96	1	
10- 25	++	+	++++	++	+	tr	-	+++++		+	-	19.6	11.0	100	-
40- 55	+	+	++++	+	+	tr	-	+++++		+	-	2.7	0.5	99	-
70- 85	+	+	++++	+	+	tr	-	+++++		+	-	1.5	0.7	100	tr
85-100	+	+	++++	+	+	tr	-	+++++		+	-	3.1	-	100	tr
145-160	+	+	++++	tr	+	tr	-	+++++		tr	-	0	2.0	100	-
190-205	+	+	++++	tr	+	tr	-	+++++		tr	-	tr	0.5	100	-
240-255	+	+	++++	tr	+	-	-	+++++		tr	-	0	tr	100	tr
255-270	++	+	++++	++	+	-	-	+++++		tr	-	1.4	1.0	100	-
285-300	.	.	.	.	.	.	.	.	.	.	tr	1.8	100	-	
315-330	++	+	+++	++	+	-	-	+++++		tr	-	0	0	100	tr
385-400	++	-	+++	++	tr	-	-	+++++		tr	-	tr	0	98	-
435-450	+	-	+	-	-	-	-	+++++		tr	-	0.8	tr	100	-
485-500	++	-	++	+++	-	-	-	++++	tr	-	.	.	99	0.6	
535-550	++	-	++	+++	-	-	-	+++++		tr	-	tr	tr	96	tr
635-650a	.	.	.	.	.	.	.	.	.	.	1.0	tr	96	2	
termite soil															
saprolite b	++	-	++	+++	-	-		+++++		tr	-	0	0	87	-
735-750	++	-	++	+++	-	-	-	+++++		tr	-	tr	tr	96	-

Profile	Depth (cm)	Moisture %, volumic mass at pF 2.0	3.0	4.2	Mass% of chemical elements in fine earth (calculated asoxides) SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5
Wan 1	0- 35	35.2	17.7	11.0	67	12.5	4.5	0.0	0.2	0.2	1.3	2.2	0.5	0.1
Wan 1A	0- 14	.	.	.	79	10	3.9	0.0	0.1	0.1	1.0	1.6	0.2	0.1
Wan 2	0- 16	23.7	12.9	8.8	79.1	9.3	3.1	0.1	0.1	0.1	0.6	1.6	0.4	0.1
	15- 30	21.4	10.4	8.0	80.4	9.4	3.2	tr	0.1	0.1	0.7	1.4	0.3	0.1
	55- 70	n.d.	n.d.	n.d.	81.0	10.4	3.6	0.0	0.1	tr	0.6	0.5	0.3	0.1
	83- 98	22.1	15.0	9.4	73.6	14.3	5.1	tr	0.1	tr	0.2	0.6	0.4	0.1
	120-135	.	.	.	78.4	11.2	4.6	tr	0.1	tr	0.1	0.7	0.4	0.1
	160-165	.	.	.	52.2	14.6	21.2	1.1	0.1	1.1	tr	0.9	0.5	0.1
Wan 3	0- 25	34.3	25.1	18.0	60.8	14.9	8.6	0.3	0.2	0.3	tr	0.9	1.1	0.2
	25- 55	37.2	29.1	22.0	56.3	19.8	10.5	0.3	0.1	0.3	tr	0.7	1.2	0.2
	55- 85	35.5	31.5	27.6	52.9	20.7	11.2	0.3	0.1	0.3	tr	0.7	1.3	0.2
	85-100	42.6	35.7	25.2	56.9	20.0	10.7	0.3	0.1	0.3	tr	0.7	1.2	0.2
	145-160	.	.	.	53.5	22.7	11.5	0.1	0.1	0.1	tr	0.6	1.3	0.1
	190-205	40.4	33.0	26.4	53.1	22.6	11.8	0.2	0.2	0.2	tr	0.7	1.3	0.1
	240-255	.	.	.	54.7	22.4	11.3	0.2	0.1	0.2	tr	0.7	1.3	0.1
	255-270	.	.	.	52.6	22.8	11.8	0.2	0.1	0.2	tr	0.7	0.9	0.1
	285-330	.	.	.	55.1	21.7	11.5	0.2	0.1	0.2	tr	0.6	0.9	0.1
	485-550	.	.	.	59.9	17.5	11.2	0.1	0.1	0.1	tr	0.9	0.7	0.1
	730-740	.	.	.	63.5	17.4	10.3	0.1	0.1	0.1	tr	1.0	0.7	0.1

Deep augerings of the upper Wanjare catena and composition of granite and diorite.

Deep augering	Depth (cm)	Particle size distribution (mass %)								magnetic separates (fraction 0.05-0.42mm)			mass% of sand with d>2.9 in fraction 0.05-0.42mm
		sand fractions (mm)								d > 2.9			
		1-2.0	0.5-1.0	0.25-0.5	0.1-0.25	0.05-0.1	sand	silt	clay	s.m	w.m	n.m	
1	0- 15	45.9	11.6	7.2	7.3	2.6	74.6	9.7	15.6	30.5	37.6	31.9	.
2	0- 15	38.2	10.9	5.3	4.5	1.7	60.6	14.2	25.1	14.3	54.5	31.2	.
	60- 65	25.5	5.3	2.8	3.0	1.5	38.1	17.2	44.7	2.5	60.8	36.7	.
3	0- 15	20.3	11.7	5.2	4.5	3.2	44.9	15.3	39.9	26.5	43.0	30.5	.
	60- 65	22.4	8.1	5.7	5.1	2.5	43.8	6.9	49.3	1.2	51.8	47.0	.
6	0- 15	26.1	10.1	5.5	5.7	2.3	49.7	13.0	37.4	4.0	73.0	23.0	.
	60- 65	18.7	9.2	4.6	3.7	1.4	37.6	36.0	26.4	0.9	75.4	23.7	3.2
	165-170	14.2	7.1	4.4	4.2	1.4	31.3	7.5	61.1	0.4	74.2	25.4	.
	245-250	23.6	6.0	3.0	3.2	1.9	37.7	9.1	53.2	0.6	70.2	29.2	.
	350-355	33.3	8.2	3.4	3.0	2.0	49.9	8.3	41.9	3.0	74.6	22.4	.
5	0- 15	12.3	8.2	7.1	7.0	3.0	37.6	14.0	48.5	0.1	79.8	19.2	.
	60- 65	10.8	7.6	5.1	4.4	2.0	29.9	9.6	60.6	0.4	82.8	16.8	3.6
	120-125	7.5	7.6	5.0	4.3	1.6	26.0	19.4	54.6	0.3	77.5	22.2	.
	160-170	7.5	7.7	5.4	4.6	1.3	26.5	7.7	65.8	0.2	73.1	26.7	3.9
	245-270	11.7	5.6	3.8	4.8	1.5	27.4	9.0	63.6	0.1	75.6	24.3	.
	345-350	12.1	6.1	3.9	3.9	2.3	28.3	34.5	37.2	0.2	78.1	21.7	4.7
	390-395	15.4	5.8	3.2	2.8	1.4	28.6	10.4	60.9	0.6	63.7	35.8	3.3
	440-445	16.4	8.5	4.2	3.4	2.2	34.7	10.0	55.4	0.5	89.6	9.9	.
4	0- 15	16.4	11.7	7.1	5.5	2.5	43.2	12.4	44.4	0.8	74.7	24.5	1.7
	60- 65	9.8	10.1	5.9	3.3	0.6	29.7	6.5	63.9	0.7	64.7	34.6	3.4
	120-125	13.7	7.1	4.8	3.7	0.3	29.6	37.1	33.1	0.4	87.2	12.4	3.9
	165-170	10.3	6.2	3.8	4.0	2.1	26.4	8.5	65.2	0.4	71.5	28.2	3.9
	245-250	11.2	5.8	3.6	3.4	2.1	26.1	9.1	64.8	0.4	69.6	30.0	3.9
	350-355	14.1	7.1	4.0	3.0	1.7	29.9	11.6	58.4	0.4	80.2	19.4	4.1
	390-395	23.6	9.2	3.6	2.8	1.9	41.1	7.6	51.4	0.7	66.7	32.7	0.7
7	0- 15	5.3	8.7	7.4	5.9	2.4	29.7	11.0	59.4	0.5	84.0	15.5	1.7
	60- 65	5.0	7.3	4.8	3.8	1.6	22.5	14.7	62.7	0.3	78.9	20.8	3.8
	120-125	5.7	7.2	5.2	4.5	1.6	24.2	8.3	67.4	0.4	75.3	24.4	3.8
	160-170	15.1	8.3	4.2	3.2	1.4	32.2	9.1	58.7	0.2	79.3	20.5	1.6
8	0- 15	10.3	8.8	7.3	7.1	3.1	36.6	16.5	47.0	3.0	75.7	21.3	2.6
granite rock										30.3	58.8	10.9	3.8
diorite rock										2.3	11.0	86.7	43.7

Profile	Depth (cm)	Org.C (g/kg)	pH H_2O	pH KCl	Exchangeable bases (mmol/kg) ½Ca	½Mg	K	Na	CEC(NH_4Ac) at pH 7.0 mmol/kg	Base saturation (%)	Bulk density (g/kg)	Moisture %, volumic mass at pF 2.0	3.0	4.2	Mass % of major elements in fine earth (calculated as oxides) SiO_2	Al_2O_3	Fe_2O_3	K_2O
Wan 9	0– 18	25	5.1	4.1	27	12	3	.	130	32+	1190	41.4	35.4	21.0	55.4	18.5	10.5	0.5
	18– 38	18	5.0	4.2	24	9	2	.	116	30+	.	.	.	.	55.7	19.1	10.7	0.5
	38– 80	18	4.9	4.2	18	5	2	.	96	26+	1150	42.9	33.2	.	52.7	21.2	11.6	0.5
	80–130	7	5.1	4.6	22	5	2	.	63	46+	1170	46.3	31.1	.	53.1	21.9	11.6	0.5
	130–210	5	5.0	4.3	8	2	2	.	61	19+	.	.	.	.	53.0	22.2	11.7	0.4
	210–286	.	5.1	4.2	6	2	2	.	59	17+	.	.	.	.	51.2	23.7	12.4	0.5
Wan 4	20– 36	9	.	5.1	60	19	5	.	125	67+	.	.	.	.	60.4	16.9	10.3	1.0
	50– 65	4	.	4.6	42	19	2	.	99	64+	.	.	.	.	59.1	18.0	10.8	1.0
	95–110	4	.	4.2	38	17	3	.	122	48+	.	.	.	.	55.2	20.4	11.5	0.8
	170–185	3	.	4.2	44	17	3	.	101	63+	.	.	.	.	56.1	20.0	11.4	0.8
	211–226	2	.	4.4	36	14	2	.	97	54+	.	.	.	.	55.7	18.1	12.7	0.8
	260–275	2	.	4.3	47	17	2	.	100	66+	.	.	.	.	60.2	17.0	9.3	0.8
	320–335	1	.	4.6	35	13	2	.	80	63+	.	.	.	.	53.8	17.1	16.5	1.0
Wan 5	8– 23	14	.	4.3	38	11	2	.	103	50+	.	.	.	.	72.3	10.0	7.7	1.0
	38– 53	8	.	4.2	40	13	2	.	121	45+	.	.	.	.	68.5	11.7	8.8	1.0
	70– 85	4	.	4.2	45	20	1	.	103	64+	.	.	.	.	68.7	11.4	8.8	1.0
	110–125	3	.	4.6	54	26	1	.	106	76+	.	.	.	.	67.6	11.8	9.2	1.0
	166–182	2	.	4.4	94	39	2	.	163	83+	.	.	.	.	65.4	13.4	11.8	0.8
	198–214	2	.	4.4	98	41	3	.	171	83+	.	.	.	.	62.4	13.6	12.3	0.9
	232–247	1	.	4.9	47	22	2	.	116	61+	.	.	.	.	51.2	12.0	25.3	0.5
	280–295	1	.	4.7	71	30	3	.	135	77+	.	.	.	.	48.0	14.8	21.9	0.5

Profiles of the lower Wanjare catena

Profile	Depth (cm)	Particle size distribution (mass %): gravel >2.0	sandfractions (mm) 1-2	0.5-1.0	0.25-0.5	0.1-0.25	0.05-0.1	fine earth: sand	silt	clay	Density separations(%) in sand (0.05-0.106mm): d<2.5	2.5-2.9	>2.9	magnetic separates(%) in sand(d>2.9): s.m	w.m	n.m	Minerals per 100 transparent grains in very fine sand, d < 2.5: glass	plant opal	d > 2.9, non-magnetic: zircon	amphibole + pyroxene
Wan 9	0- 18	0.1	2.9	5.5	9.2	7.7	2.3	27.6	21	51.4	9.7	83.4	6.8	1.5	82.8	15.7	15.8	4.5	84	13
	18- 38	0	5.2	6.9	7.9	6.4	2.2	28.5	12.6	58.9	4.1	89.1	6.8	2.8	88.6	8.6	36.3	14.7	.	.
	38- 80	0.02	9.0	7.2	5.6	4.6	1.8	28.3	11.7	60.0	8.8	84.0	7.1	1.0	51.6	47.4	13.4	4.3	86	5
	80-130	0.1	5.9	7.9	5.4	5.2	1.7	27.1	11.6	61.3	9.7	82.5	7.8	1.6	63.3	35.1	1.5	4.5	95.3	2
	130-210	0.1	8.2	5.8	5.0	5.2	2.1	26.3	9.0	64.7	5.4	88.3	6.3	1.0	78.1	20.9	3.1	4.1	96.0	0.6
	210-286	0.1	12.5	5.5	3.7	3.8	1.1	26.6	10.2	63.2	6.8	85.8	7.3	1.3	69.9	28.8	1.1	1.1	97.0	3
	287-300	25.1	10.9	5.3	3.7	3.9	1.8	26.6	10.7	62.7	11.0	80.4	8.6	1.0	84.1	14.9	2.3	1.2	99	1
Wan 4	20- 36	-	3.3	8.1	9.5	8.0	2.3	31.2	17.6	51.3	5.0	86.7	8.3	3.8	80.2	16.0	2.2	5.5	50.6	49.2
	50- 65	-	2.6	5.7	7.1	7.0	2.1	24.5	18.8	56.7	7.0	84.2	8.8	1.3	82.9	15.8	1.5	27.5	33.0	62.0
	95-110	-	5.8	6.6	6.6	6.3	2.0	27.3	7.0	65.8	12.8	81.0	6.2	5.5	71.4	23.1	0.5	3.5	62.5	29.9
	170-185	-	5.3	6.0	6.0	5.7	1.9	24.9	19.5	55.8	6.0	85.1	8.9	3.9	78.9	17.2	tr	8.0	74.2	21.7
	211-226	-	4.6	7.0	8.1	5.4	2.4	27.5	16.9	55.5	5.9	86.2	7.9	1.1	85.3	13.7	tr	4.1	84.7	3.6
	260-275	-	6.8	7.4	6.7	6.4	2.7	30.0	18.3	51.5	5.3	86.7	8.0	1.7	84.9	13.4	tr	12.2	90.6	9.4
	320-335	-	4.3	4.4	4.3	4.0	1.9	18.9	43.3	37.6	14.2	75.1	10.7	0.2	37.6	62.2	-	tr	31.4	68.3
Wan 5	8- 23	-	9.8	15.6	15.0	11.6	2.7	54.7	18.9	26.4	3.7	84.1	12.2	0.7	78.9	20.3	27	36	33	65.9
	38- 53	-	10.0	13.1	10.8	3.5	3.7	41.1	24.5	34.4	3.2	88.9	7.8	0.8	79.0	20.2	6	59	27.3	72.8
	70- 85	-	4.6	10.9	12.9	10.7	4.1	43.2	24.0	32.9	4.7	86.9	8.4	0.6	80.5	18.9	2	63	46.9	50.1
	110-125	-	7.2	13.7	11.3	8.6	3.3	44.1	19.9	35.9	4.7	87.7	7.6	0.5	80.8	18.8	1	64	44.6	55.1
	166-182	-	12.7	12.5	7.6	6.4	2.8	42.0	17.4	40.6	4.7	87.1	8.2	0.1	60.4	39.4	1	21	54.5	38.4
	198-214	-	12.8	9.5	7.1	6.8	3.3	39.5	24.3	36.3	5.2	88.0	6.8	0.5	70.4	29.1	1	31	44.1	56.0
	232-247	-	7.3	8.9	6.7	5.7	3.5	32.1	13.4	54.6	.	.	.	.	.	.	.	.	.	.
	280-295	-	7.3	4.9	4.7	4.3	10.8	32.0	14.8	53.6	1.8	58.8	39.4	0.5	3.1	96.5	1	23	tr	99

Appendix 2 Methods

Morphological and chemical methods

Morphology of the profiles was described according to the standards and terminology of FAO (1967). Laboratory analysis are listed below:

(1) Particle size: organic matter was destroyed with hydrogen peroxide (volume fraction 0.3); carbonates and iron coatings were removed with HCl (conc. 2 mol/l). The sample was diluted and siphoned three times, wet sieved with a 0.05mm sieve to separate sand. The rest was collected in a sedimentation cylinder and dispersed with sodium pyrophosphate (conc. 0.120 mol/l). After shaking, silt (<0.05mm) and clay (<0.002mm) were pipetted off. After drying the sand was sieved into fractions 2.0-1.0, 1.0-0.50, 0.05-0.25, 0.25-0.10 and 0.10-0.05mm.

(2) pH-H_2O and KCl: soil was intermittently shaken for 2 d with distilled water and potassium chloride (conc. 1 mol/l) in a volume ratio of 1:2.5. The pH of the supernatant was measured with a combined glass calomel electrode.

(3) Mass fraction of carbon: Walkley and Black method (Black, 1965, p. 1372-1376) with 1.43 as correction factor.

(4) Content of exchangeable cations: leach soil with ammonium acetate (conc. 1 mol/l) of pH 7.0. Estimate Na, K and Ca by emission spectrometry and with addition of lanthanum chloride for calcium. Estimate Mg by atomic absorption spectrometry.

(5) Cation-exchange capacity: After leaching out exchangeable cations (see method 4), wash the soil with aqueous ethanol (vol. fraction 0.95) and percolate with acidified NaCl. Steam-distil off the ammonia and titrate against HCl (conc. 10 mmol/l) (Houba et al. 1979).

(6) Total chemical composition: X-ray fluorescence spectrometry (Si, Al, Fe, Mg, Ca, Mn, K, Na, P, Ba); after destruction of the sample with HF and H_2SO_4, Na was determined spectrometrically (Begheijn, 1980).

(7) Zinc: air-dried fine earth was grined in a mortar. The powdered sample material was shaken with HCl (conc. 6 mol/l); zinc was determined with a spectrophotometer (Department of mines and geology, Nairobi, Kenya).

Mineralogical methods

A weighted sample of sand (after treatment with H_2O_2 and DCB: see method 1 above) preferrably in the 50-100 à 105μm size fraction was separated in heavy and light mineral fractions with bromoform (d>2.89). For further separation of the light fraction, a mixture of bromoform and decaline (d = 2.5) was used.

Heavy minerals were further separated with a hand magnet in a strongly magnetic (s.m.), a weakly magnetic (w.m.) and non-magnetic fraction (n.m.). The strongly magnetic minerals were separated moving a handmagnet repeatedly under a thick piece of paper, covered with heavy mineral grains. Remaining minerals were then repeatedly touched with the same handmagnet. Grains adhering to it were removed from it with a brush and collected. This was the weakly magnetic fraction. The remaining minerals were called non-magnetic. All fractions were weighed.

Composition of strongly and weakly magnetic fractions were estimated by X-ray fluorescence analysis of powdered samples. Grain mounts were made in Canada resin of the fractions with d<2.5, with 2.5<d<2.89 and of the non-magnetic fraction with d<2.89. At least 100 transparent grains were counted in each grain mount according to the line counting technique.

Methods to estimate the fraction of Al from volcanic ash in mixed profiles.

Estimates according to the magnetite-II content. Principle of the method: the mass ratio of magnetite-II to Al in a sample of soil from volcanic ash is used to estimate the fraction of Al in a soil from volcanic ash and local rock (mixed soil). For that purpose also the mass ratio of magnetite-II in the fine earth of a sample of mixed soil to its total Al content should be known.

Calculation procedure: mass fraction of Al203 derived from volcanic ash in a sample of fine earth from a mixed soil is the result of the following calculation: $\frac{A2}{A1} \times \frac{B}{C}$ in which A = mass fraction of magnetite-II in the 50-100μm sand fraction as mass fraction of fine earth. It is calculated as follows: (mass fraction of 50-100μm fraction) x (mass fraction of strongly magnetic fraction) x (mass fraction of strongly magnetic fraction) x (mass fraction of magnetite-II in strongly magnetic fraction):

A1 is mass fraction of magnetite-II in sample of fine earth from volcanic ash

A2, same as A1 but in a sample of fine earth from a mixed soil

B is mass fraction of Al_2O_3 in a sample of fine earth from volcanic ash

C is as B, but in a sample of fine earth from a mixed soil.

This calculation procedure was used to estimate $\frac{A1}{B}$ values of samples from profile S3. The average values of 5 samples ranged from (31-62) x 10^{-6}. With those values and with the C and A2 values of samples of profile Wan 3, average fractions of Al from volcanic ash in samples of profile Wan 3 could be approximated.

Estimates according to the molar ratio of Al to Fe

Calculation procedure: A + x (B-A) = C

A = molar ratio of Al to Fe in volcanic ash
B = molar ratio of Al to Fe in the country rock
C = molar ratio of Al to Fe in sample of mixed soil
x = fraction of Al derived from country rock
1-x = fraction of Al derived from volcanic ash

Appendix 3 Plasmic fabric in the profiles studied

The dominant plasmic fabric in the well drained profiles Wan 2, 3 and 9 was insepic, apart from the topsoil, which was more undulic. In profiles Wan 4 and 5 the insepic fabric changed at depth in a masepic fabric, especially in the greyish part of the matrix. The masepic fabric, which is indicative of swelling and shrinking, was stronger expressed in the subsoil of Wan 5 than in the subsoil of Wan 4, while the subsoil of MlE was very strongly masepic.

Appendix 4 Fission track data (Source "Stichting voor Isotopen Geologisch Onderzoek" at Amsterdam).

Profile	Sample depth (cm)	Mineral	ρ_s x10^6 t/cm^2	ρ_i x10^6 t/cm^2	ϕ x10^6 t/cm^2	T x10^6 yr	± 2σ x10^6 yr	# grains	r,$\bar{s}$	U ppm
S3	50- 79	zircon	0.19 (58)	16.1 (2462)	0.99 (2061)	0.7	0.2	10	0.83	470
S3	600-610	"	0.16 (47)	12.3 (1751)	"	0.8	0.2	12	0.38	359
S3	740-750	"	0.17 (62)	13.1 (2313)	"	0.8	0.2	9	0.38	382
131/4	10- 20	"	0.09 (30)	12.7 (1928)	"	0.5	0.2	11	0.23	344
131/4	80- 90	"	0.14 (52)	12.0 (2176)	"	0.7	0.2	10	0.7	351
-	standard	"	0.43	0.97	"	26.7	1.2	6	0.99	283

Note: λ_d = 1.55 E-10 yr^{-1}; λ_f = 7.03 E-17 yr^{-1}; $^{235}U/^{238}U$ = 0.00725; σ = 580.2 E-24 cm^2
the numbers in the brackets refer to the tracks counted
the uranium content is a biased estimate of the actual sample value
for the standard zircon an age of 28.4 ± 2.3 Ma is recommended

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