Land Resource Study

19 Land Resources of the Northern and Luapula Provinces, Zambia- a reconnaissance assessment. Volume 4 The biophysical environment

Land Resources Division, Ministry of Overseas Development

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Land Resources of the Northern and Luapula Provinces, Zambia - a reconnaissance assessment

Volume 4

The biophysical environment

24538

MINISTRY OF OVERSEAS DEVELOPMENT

With the Compliments of the

Land Resources Division

Tolworth Tower

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England

Land Resources Division

Land Resources of the Northern and Luapula Provinces, Zambia - a reconnaissance assessment

Volume 4

The biophysical environment

J E Mansfield, J G Bennet, R B King, D M Lang and R M Lawton

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Tolworth Tower, Surbiton, Surrey, England KT6 7DY
1976

THE LAND RESOURCES DIVISION

The Land Resources Division of the Ministry of Overseas Development assists developing countries in mapping, investigating and assessing land resources, and makes recommendations on the use of these resources for the development of agriculture, livestock husbandry and forestry; it also gives advice on related subjects to overseas governments and organisations, makes scientific personnel available for appointment abroad and provides lectures and training courses in the basic techniques of resource appraisal.

The Division works in close co-operation with government departments, research institutes, universities and international organisations concerned with land resources assessment and development planning.

List of volumes

Title:	Land resources of the Northern and Luapala Provinces, Zambia - a reconnaissance assessment; J E Mansfield, J G Bennett, R B King, D M Lang and R M Lawton
Volume 1	Introduction, conclusions and recommendations
Volume 2	Current land use
Volume 3	Land capability and development potential
Volume 4	The biophysical environment
Volume 5	Social and economic factors
Volume 6	The land systems

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TEXT MAPS

SEPARATE MAP (inside rear cover)

Abstracts and keywords

ABSTRACT

Volume 4 examines those aspects of the biophysical environment of the Northern and Luapula Provinces of Zambia which are considered important for future agricultural development: climate, geology, soil and vegetation. Ten text maps and one separate map accompany this volume, and representative soil profile descriptions are appended.

An abstract of the whole report is given in Volume 1.

RÉSUMÉ

Le Volume 4 examine les aspects de l'environnement biophysique des Northern et Luapula Provinces de Zambie qui sont considérés comme importants pour l'exploitation agricole future: climat, géologie, sol et végétation.

Dix cartes dans le texte et une carte séparée accompagnent ce volume, et des descriptions représentatives des profils géologiques sont annexées.

Un résumé du rapport dans son ensemble est présenté en Volume 1.

DESCRIPTORS FOR CO-ORDINATE INDEXING

Climate/agrometeorology/geology/economic geology/ geomorphology/ engineering/ land units/soil survey/soil morphology/ soil classification/ soil physical properties/ vegetation survey/ plant ecology/ ecological formation/Zambia.

Parts 1-6

Part 1

Preface

This, the fourth volume of the "Land resources of the Northern and Luapula Provinces" is a slightly modified version of "The biophysical aspects" contained in Volume 1 of the Draft Land Resource Study presented to and approved by the Zambia Government in 1973. It describes the climate, geology, soils and vegetation of the area upon which the land system descriptions (Volume 6) and land capability (Volume 3) are based.

Part 2

Climate

This section is primarily concerned with the possible limiting effects of climate on both the range of the crops which can be grown and their optimum performance and with any significant climatic differences in the project area.

The main climatic differences appear to occur between the Central Plateau and the Western Rift land provinces. Unfortunately full climatological data are only available for stations in the former area, but this is by far the largest land province.

ANNUAL AND SEASONAL VARIATION

The annual weather cycle in north-east Zambia can be defined in terms of rainfall regime, to which seasonal variation of the other climatic elements is closely related (Text Maps 4-1 and 4-2). This will be appreciated from the climatic diagrams for Mbala in the north of the project area, and Mpika in the south (Figures 4-1 and 4-2).

The dry season (May-October)

The dry season starts in May in the north and mid-April in the south of the project area. Rain is sporadic and the mean monthly temperature is 16-21°C (61-69°F). Mean monthly temperatures rise to 24°C (75°F) in September or October, with absolute maxima reaching 35°C (95°F). These months have been called the hot season by Howe (1953) in contrast to the midwinter season of June and July with its low temperatures. Relative humidity is at its lowest in the hot season, while wind speed increases slightly as the wind backs.

The wet season (November-April)

The wet season usually starts in November over most of north-east Zambia and lasts 145-190 days in the project area. Prolonged rain spells are uncommon, although storms become more frequent as the wet season develops. The wettest months are usually December or January with 25 cm (10 in) of rain. In southern Zambia the wet season often ends abruptly in mid-March, but in the north-east storm activity steadily decreases through mid- or late April.

During the wet season, mean monthly temperatures are about 21°C (70°F) with mean maxima about 10°C (18°F) higher. Mean relative humidity is about 80% for most of the year, but decreases towards April. In April the wind speed increases to over 4.1 m/s (8 kn), accompanied by a veer in direction under the influence of high atmospheric pressure building up over southern Africa.

Howe (1953) called April a post-rainy season when cloud cover decreases and the wet ground begins to dry out. The mean May rainfall in north-east Zambia is nowhere over 2.5 cm (1 in), and this month is usually included in the dry season. These seasonal variations are discussed in more detail below.

RAINFALL

Mean monthly rainfall data for a selection of stations, shown in Table 1 and Figure 4-3, clearly show the contrast between wet (November-April) and dry seasons (May-October) but the period of transition between the two seasons varies considerably. In the southern part of the area (Mansa, Twingulu and Mpika), there is a one-peak distribution of rainfall, which becomes bimodal in the north (Kafulwe, Mporokoso and Mbala). The difference is due to the influence of the inter-tropical convergence zone (ITCZ), and has the effect of lengthening the wet season by 40-50 days in the north-west of the central plateau compared with the south-east. Chaplin (1954) used his arbitrary definition of the wet season commencement (a period of 4 days, on at least 3 of which more than 0.25 mm (0.01 in) of rain was recorded, and a total rainfall during the period greater than 10 mm (0.4 in) to determine the average dates for the change of season for the whole of Zambia (Figures 4-4 and 4-5).

Rainfall probability

Average annual rainfall values are of little use without some measure of the reliability of the rain each year. Initially a time series analysis of the rainfall data was considered to see if there was a systematic element in the temporal rainfall pattern, but a preliminary examination of the data applying crude run tests showed that there was no significant trend or periodicity greater than 12 months and therefore annual rainfall totals can safely be assumed to be independent events.

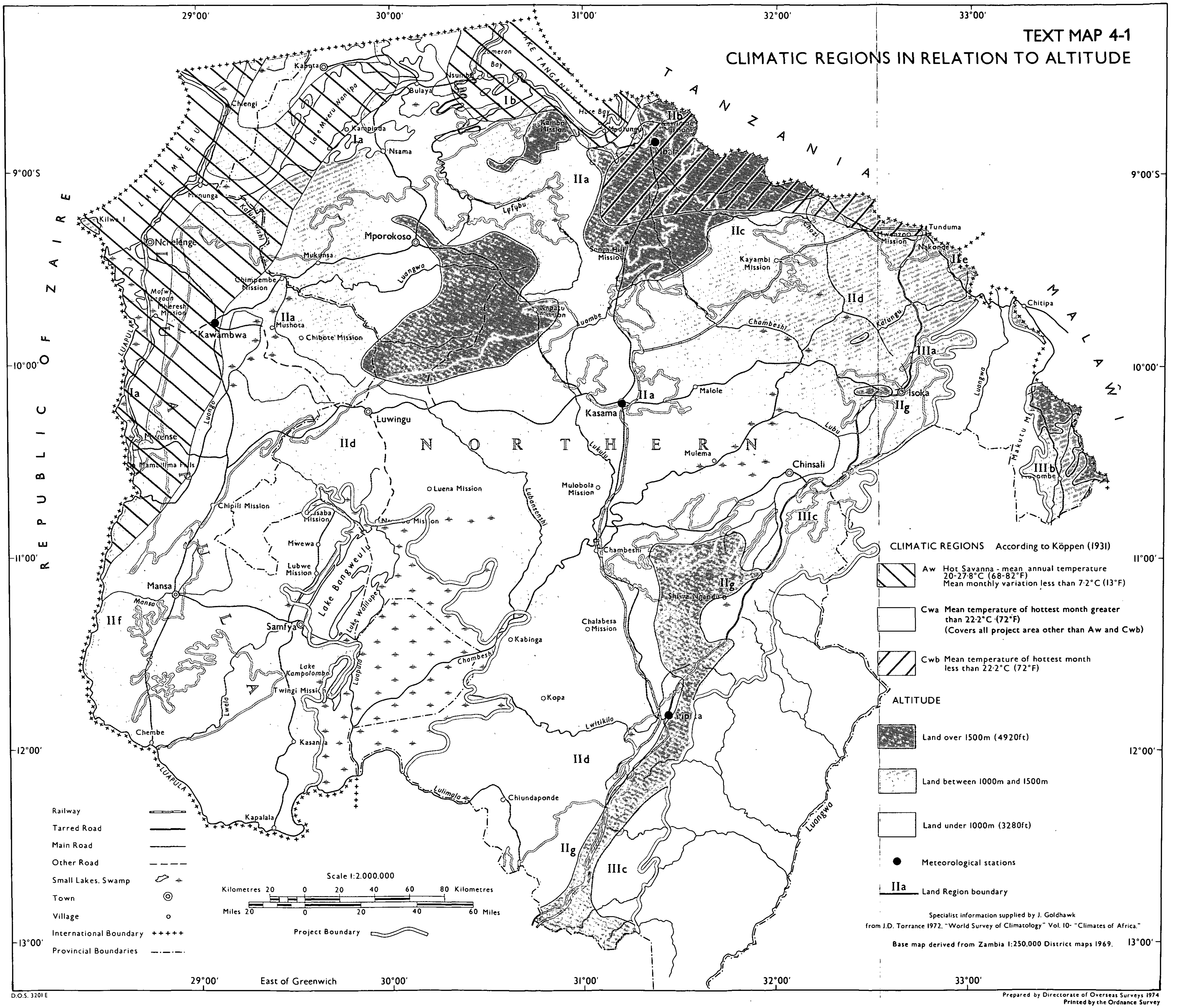
Of the 174 known rainfall stations in the Northern and Luapula Provinces of Zambia, 62 had long enough records (more than 10 years unbroken) suitable for statistical analysis of rainfall reliability (see data in Supplementary Report No. 5). Stations are unevenly distributed over the two provinces, which results in the isohyets being indeterminate, and some uncertainty over the representativeness of results. However, a general picture can be obtained.

A simple form of statistical analysis to predict rainfall reliability was used. The method first applied by Glover and Robinson (1952) in East Africa assumes that recorded monthly and annual rainfall totals at any station are approximately normally distributed in time. For use in deciding crop suitability an accuracy of ± 3 in for estimates of probable annual rainfall, and ± ½ in for monthly estimates is considered acceptable. From examination of the data this approximation is considered to be valid for the Zambian stations, within certain limits which are discussed below.

Periods of record ranged from 62 years (Abercorn) started in January 1904, to 1 year (Nkolemfumu). The records for the majority of stations, run to June 1967. Stations with less than 10 years of complete records were eliminated as providing insufficient data for analysis, but the remaining station records were checked for errors and inconsistencies and re-examined in order to eliminate unreliable figures and years containing fragmentary records. In a few cases it was considered preferable to estimate a missing figure in order to obtain a usable record. Some stations near to others with longer records were discarded in favour of the latter.

With regard to the treatment of the data for analysis on an annual or monthly basis, the minimum period of record of 10 years or longer was not required to be continuous, nor were the records required to cover a common period of time. Given the basic assumption of normal distribution, no significant improvement in the estimation of the true probabilities will result from the introduction of these conditions, as the breaks in record are essentially randomly distributed and in this instance the elimination of a large proportion of the data by the adaption of more rigorous criteria would have resulted in a considerable reduction in the usefulness of the results. The analytical data for each station include the following:

1. The minimum annual rainfall which may be expected to occur with probabilities of 75, 80 and 90%
2. The probability, expressed as a percentage, of receiving less than 500, 750, 1 000 and 1 250 mm (20, 30, 40 and 50 in) in any year


TEXT MAP 4-1
CLIMATIC REGIONS IN RELATION TO ALTITUDE
TANZANIA
MALAWI
REPUBLIC OF ZAIRE
NORTHERN
LUAPULA
LAKE TANGANYIKA
LAKE MWERU
Lake Bangweulu
Mporokoso
Kasama
Luwingu
Chinsali
Isoka
Mansa
Samfya
Kawambwa
Mpika
Tunduma
Chitipa
Nakonde
Kaputa
Chiengi
Nchelenge
Kapalala
Chembe
Chiundaponde
Kopa
Kabinga
Mulobola Mission
Luena Mission
Chalabesa Mission
Chambeshi
Malole
Mulema
Kayambi Mission
Kasanka
Mwewa
Lubwe Mission
Chipili Mission
Chibote Mission
Mushota
Mukupa
Nsama
Kampinda
Bulaya
Mbala
Shiwa Ngandu
Mwenzo Mission
Isoka
Luangwa
Chambeshi
Luapula
Kalungu
Lukulu
Lubansenshi
Lwitikila
Lulimala
Ia
Ib
IIa
IIb
IIc
IId
IIe
IIf
IIg
IIIa
IIIb
IIIc
29°00′
30°00′
31°00′
32°00′
33°00′
9°00′S
10°00′
11°00′
12°00′
13°00′
East of Greenwich
CLIMATIC REGIONS According to Köppen (1931)
Aw Hot Savanna - mean annual temperature 20-27·8°C (68-82°F) Mean monthly variation less than 7·2°C (13°F)
Cwa Mean temperature of hottest month greater than 22·2°C (72°F) (Covers all project area other than Aw and Cwb)
Cwb Mean temperature of hottest month less than 22·2°C (72°F)
ALTITUDE
Land over 1500m (4920ft)
Land between 1000m and 1500m
Land under 1000m (3280ft)
Meteorological stations
IIa Land Region boundary
Railway
Tarred Road
Main Road
Other Road
Small Lakes. Swamp
Town
Village
International Boundary
Provincial Boundaries
Scale 1:2.000.000
Kilometres 20 0 20 40 60 80 Kilometres
Miles 20 0 20 40 60 Miles
Project Boundary
Specialist information supplied by J. Goldhawk
from J.D. Torrance 1972. "World Survey of Climatology" Vol. 10- "Climates of Africa."
Base map derived from Zambia 1:250.000 District maps 1969.
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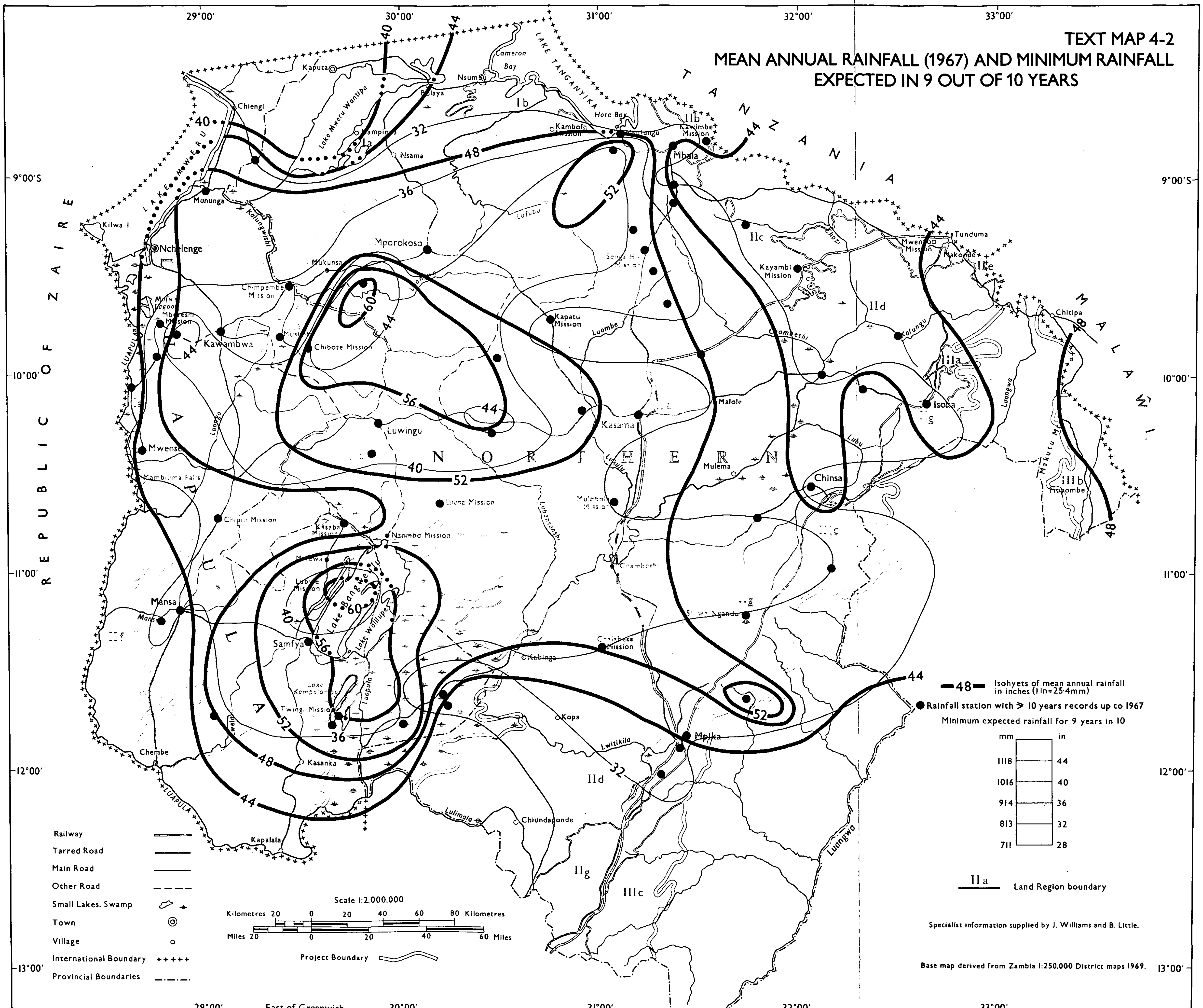

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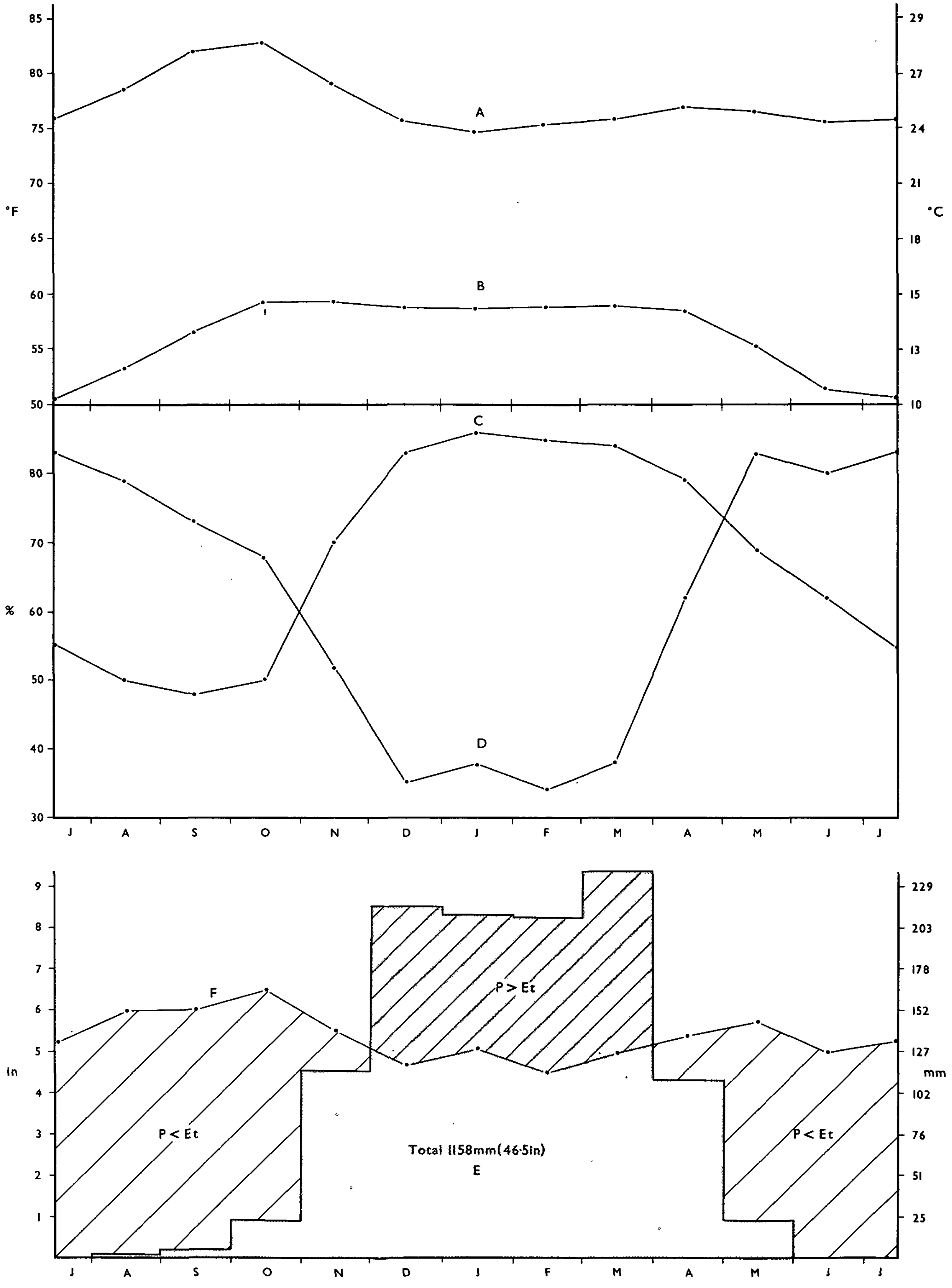

A Mean monthly maximum temperature 1936-60

B Mean monthly minimum temperature 1936-60

C 12 hour mean monthly relative humidity 1951-60

D Monthly percentage of maximum possible sunshine hours 1956-60

E Mean monthly rainfall 1926-56

F (Et) Potential evapotranspiration (modified Penman estimate)

P Precipitation

FIGURE 4-1 Mbala climatic diagram.

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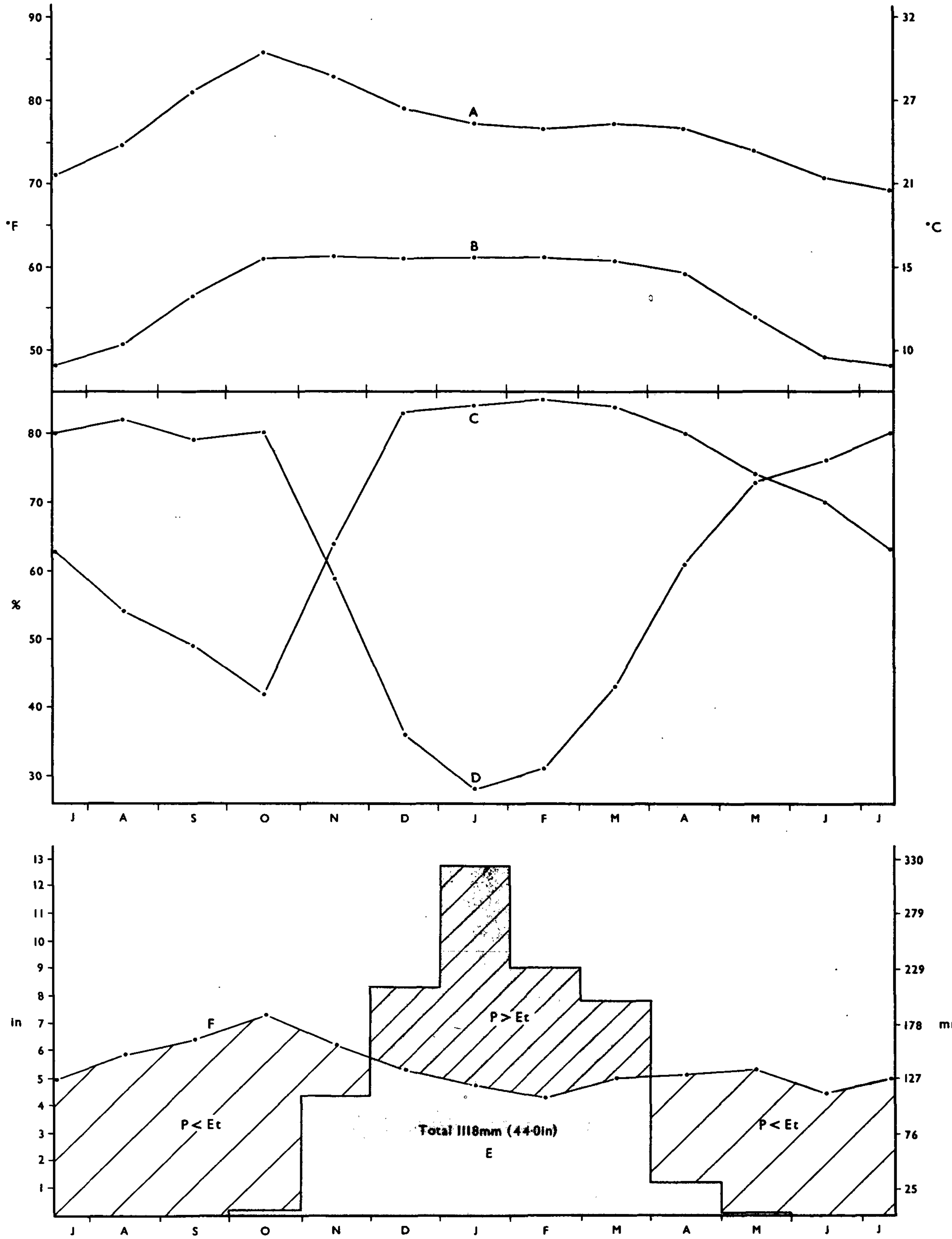

A Mean monthly maximum temperatures 1941-56

B Mean monthly minimum temperatures 1941-56

C 12 hour mean monthly relative humidity 1951-56

D Monthly percentage of maximum possible sunshine hours 1946-56

E Mean monthly rainfall 1936-56

F (Et) Potential evapotranspiration (modified Penman estimate)

P Precipitation

FIGURE 4-2 Mpika climatic diagram.

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TABLE 1 **Monthly rainfall distribution for nine selected stations in northern Zambia**

Station		Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Total
Mbala (1)	mm	0	1	5	20	110	220	210	210	230	110	20	1	1 125
	in	0	>1	>1	1	4	9	8	8	9	4	1	>1	44
Mporokoso (82)	mm	0	1	8	55	160	230	220	200	250	120	20	1	1 275
	in	0	>1	>1	2	6	9	9	8	10	4	1	>1	50
Kafulwe (75)	mm	0	3	7	30	120	260	220	210	250	130	12	0	1 250
	in	0	>1	>1	1	4	10	9	8	10	5	1	0	49
Isoka (13)	mm	0	0	1	11	80	210	230	230	230	65	12	0	1 075
	in	0	0	>1	1	3	8	9	9	9	3	1	0	42
Kasama (20)	mm	0	0	1	16	140	250	270	250	260	65	9	0	1 275
	in	0	0	>1	1	6	10	11	10	10	3	>1	0	50
Kawambwa (93)	mm	0	1	11	65	170	250	210	190	240	140	16	1	1 300
	in	0	>1	1	2	6	10	8	8	10	6	1	>1	50
Mpika (164)	mm	0	1	0	7	110	230	300	240	190	25	3	0	1 100
	in	0	>1	0	>1	4	9	12	10	8	1	>1	0	43
Twingulu (157)	mm	0	0	1	12	150	270	320	300	290	50	4	0	1 400
	in	0	0	>1	1	6	10	13	12	11	2	>1	0	55
Mansa (137)	mm	0	0	1	25	140	240	240	220	220	60	6	0	1 150
	in	0	0	>1	1	6	10	10	9	9	2	>1	0	45

As an indication of the accuracy of the estimates, the tables in Supplementary Report No. 5 also show the estimated mean annual rainfall, the standard deviation of this estimate, and the coefficient of variation for each station, and an estimate of the percentage error of the sample mean at a probability level of 95%, using Student's 't' test. The stations are ranked in ascending order of value of the mean annual rainfall.

The figures for Mpulungu Port (included for comparison) are a typical study of the area; their wide scatter probably reflects a rainfall regime peculiar to its location on the shore of Lake Tanganyika surrounded by steep-sided hills. In the absence of more data, the results are not considered representative of the Mpulungu area. Elsewhere, some indication of rainfall reliability can be gained even from 10-year records, provided the figures are treated with caution. For stations with a low mean annual rainfall value of say 1 120 mm (45 in), 25 years or more of records are required to bring the estimated probable error to within ± 75 mm (3 in).

Supplementary Report No. 5 compares the estimated minimum expected annual rainfall at an 80% probability, and the actual proportion of drier years in the record and shows that 29 out of 62 selected stations (47%) had more than one dry year in five. If the estimated figures are adjusted by an error of 75 mm (3 in), the number of stations with more than one dry year in five falls to one (1.6%). Since many of the records were over short periods, and thus the frequency distributions of annual rainfall may have significantly differed from the normal, a cube-root transformation was conducted on some of the data which improved the accuracy of estimates slightly, but made no really significant difference. The most conservative level (9 years out of 10) has been used for mapping minimum expected rainfall isohyets for comparison with the mean annual rainfall pattern (see Text Map 4-2). Even at this level the expected rainfall for most stations is 760-1 020 mm (30-40 in) on the central plateau.

With a few exceptions, the temporal variation in annual rainfall is roughly uniform across the province, the percentage coefficient of variation being 15-20%.

Monthly rainfall

The results of this analysis tabulated in *Supplementary Report* No. 5 show the following:

1. The minimum monthly rainfall which may be expected to occur with a probability of 80% for the months of November to April inclusive. The rainfall for the remaining months of the year is not sufficiently high for reliable estimates to be made. The criterion used here, after Glover and Robinson (1953), is that the standard deviation of the sample mean multiplied by 3/2 should not exceed the value of the mean.

2. The probability, expressed as a percentage, of receiving at least 50 mm (2 in) of rainfall in each month from November to April inclusive.

As expected, the variation in monthly rainfall is much larger than the variation in annual rainfall. Coefficients of variation in annual rainfall are mainly 15-20%, while coefficients of variation for wet-season monthly rainfall in northern Zambia compared to the whole country quoted from the Department of Meteorology (1971) are as follows:

	Northern Zambia	All of Zambia
November	40-80%	35-80%
December	30-40%	30-60%
January	25-35%	25-55%
February	25-35%	25-65%
March	30-40%	30-80%
April	50-80%	50-110%

There is a general tendency for low variation in the north-west and high variation in the south-east. The months of highest rainfall, December to March, have the lowest variability compared to the whole country and even at 90% probability, only six stations (three of these lay in the Western Rift area) had an expected monthly total of less than 130 mm (5 in) for the months December to February.

In November, when maize planting should be carried out, the coefficient of variation for stations in a line running north-west from Mpika are as follows: Mpika 75%, Chalubesa 64%, Luwena Mission 54%, Luwingu 42% and Kawambwa 35% but in the Western Rift area (Makupa Katandula) it rises sharply to 69%. In a line which runs north of Mpika the percentages are as follows: Mpika 73%, Chinsali 60%, Isoka 79%, Chunga Farm 68%. These areas are the ones with the lower rainfall, which would be expected.

Safe planting dates

Text Map 4-3 shows estimated safe planting dates for four years out of five based on an accumulated rainfall of 25 mm (1 in), apart from isolated showers (Lineham, 1960). There is a difference of the order of 25 days across the central plateau. The lines are not extended into the Western Rift area to the north-west where the rainfall is comparable to the east and just as variable because this would move safe planting dates to later than 10 November. Limited local research has indicated that maize yields best when planted early (as has been found elsewhere in Zambia). Although not established locally, this also applies elsewhere for groundnuts and cotton. For certain crops therefore this spatial variation will have obvious importance. November 15 or earlier (held to be an optimum maize planting date elsewhere) is considered to be a safe planting date in only a small area.

A method used by P Brown (unpublished data) in Malawi for assessing the earliest planting date for maize can be applied to the project area. Based on conditions of soil and climate at Lilongwe, the following estimates were used.

1. At the start of the rains only dates on which storms of 13 mm rain fell were considered as possible planting dates. Such storms were considered adequate both to germinate the seed and support seedling growth, without further rain, for as many days as the number of 2.5 mm of rain in that storm (eg 25 mm fall could support seedling growth for 10 days) up to a *maximum of 15 days* (equivalent to 38 mm (1.5 in) of rain). This estimate would vary according to local soil and weather conditions, being less in hotter, drier areas with soils of poor receptivity and possibly more where cool overcast conditions and soils of very high receptivity occurred.

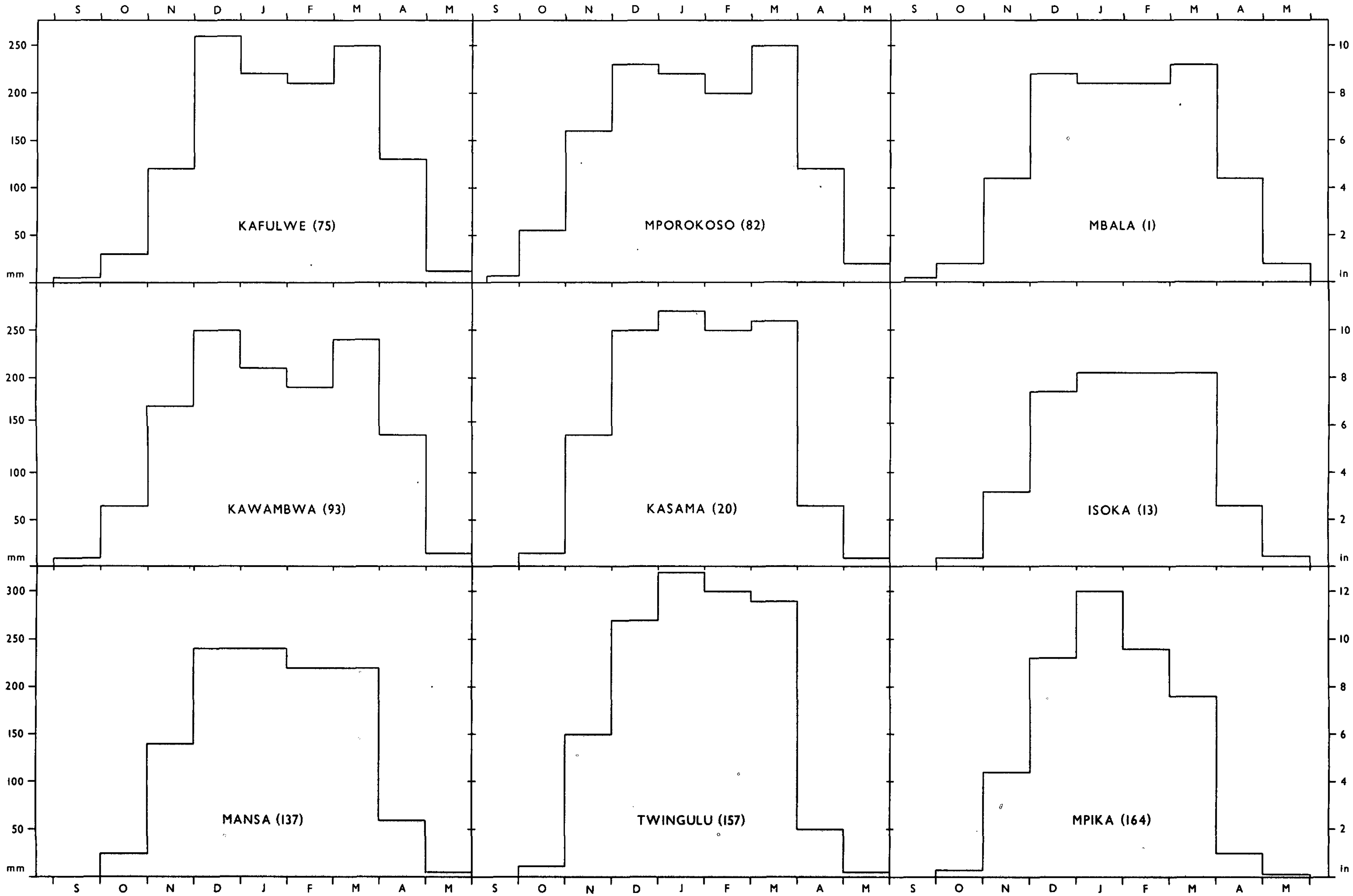

FIGURE 4-3 Monthly rainfall distribution for 9 selected stations in Northern and Luapula Provinces, Zambia. (Station numbers in brackets).

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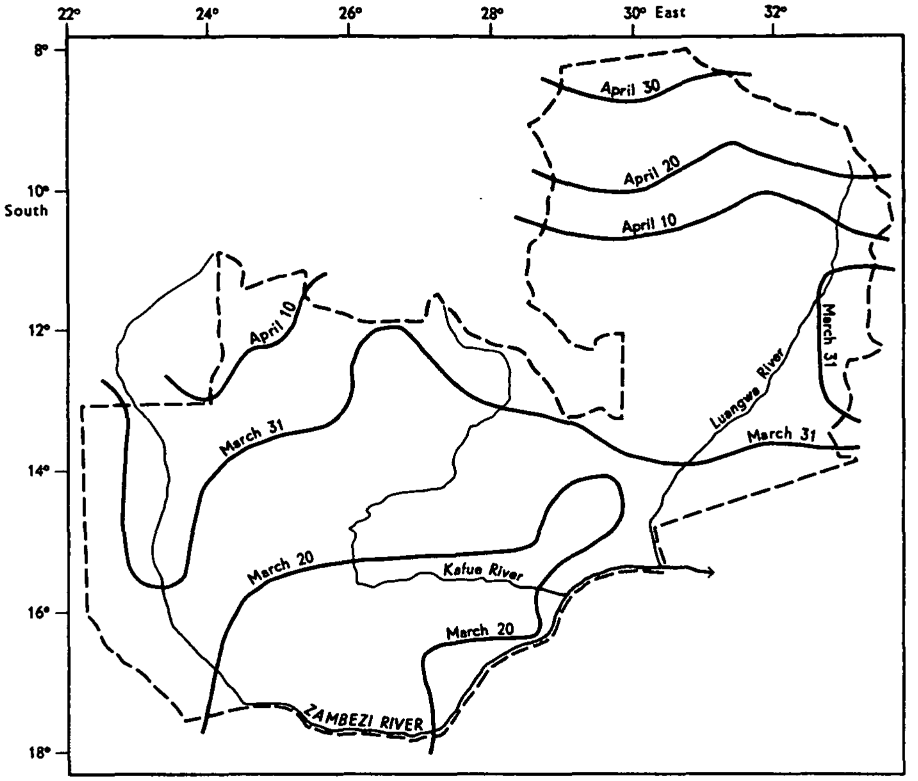

FIGURE 4-4 Mean opening dates for the dry season in Zambia, after Chaplin, 1954.

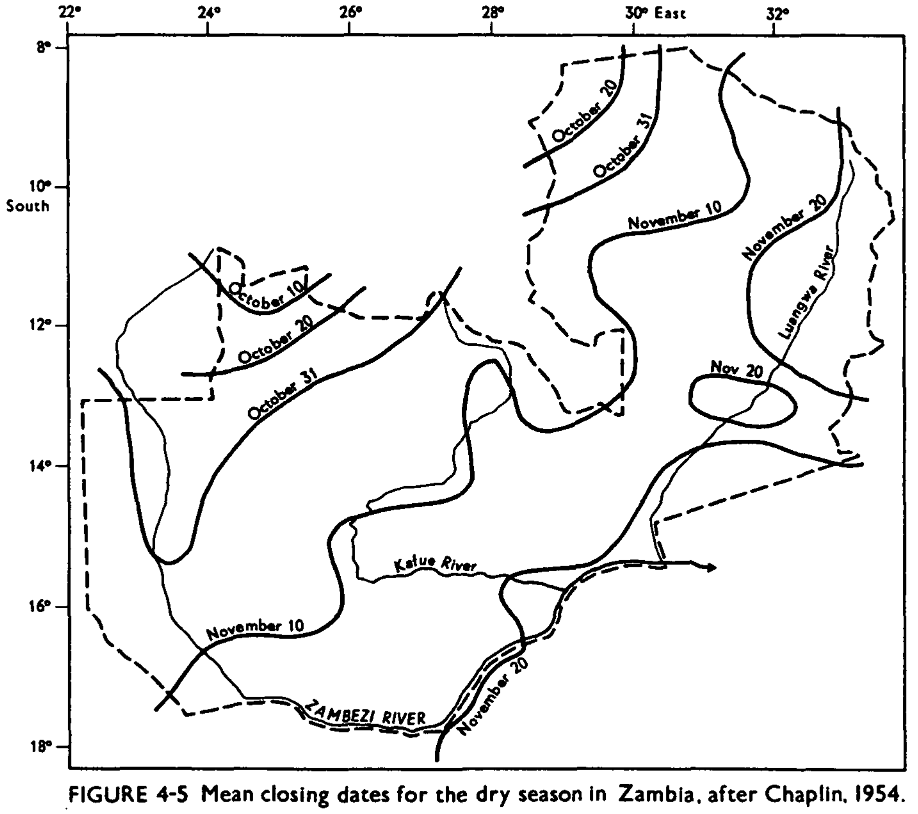

FIGURE 4-5 Mean closing dates for the dry season in Zambia, after Chaplin, 1954.

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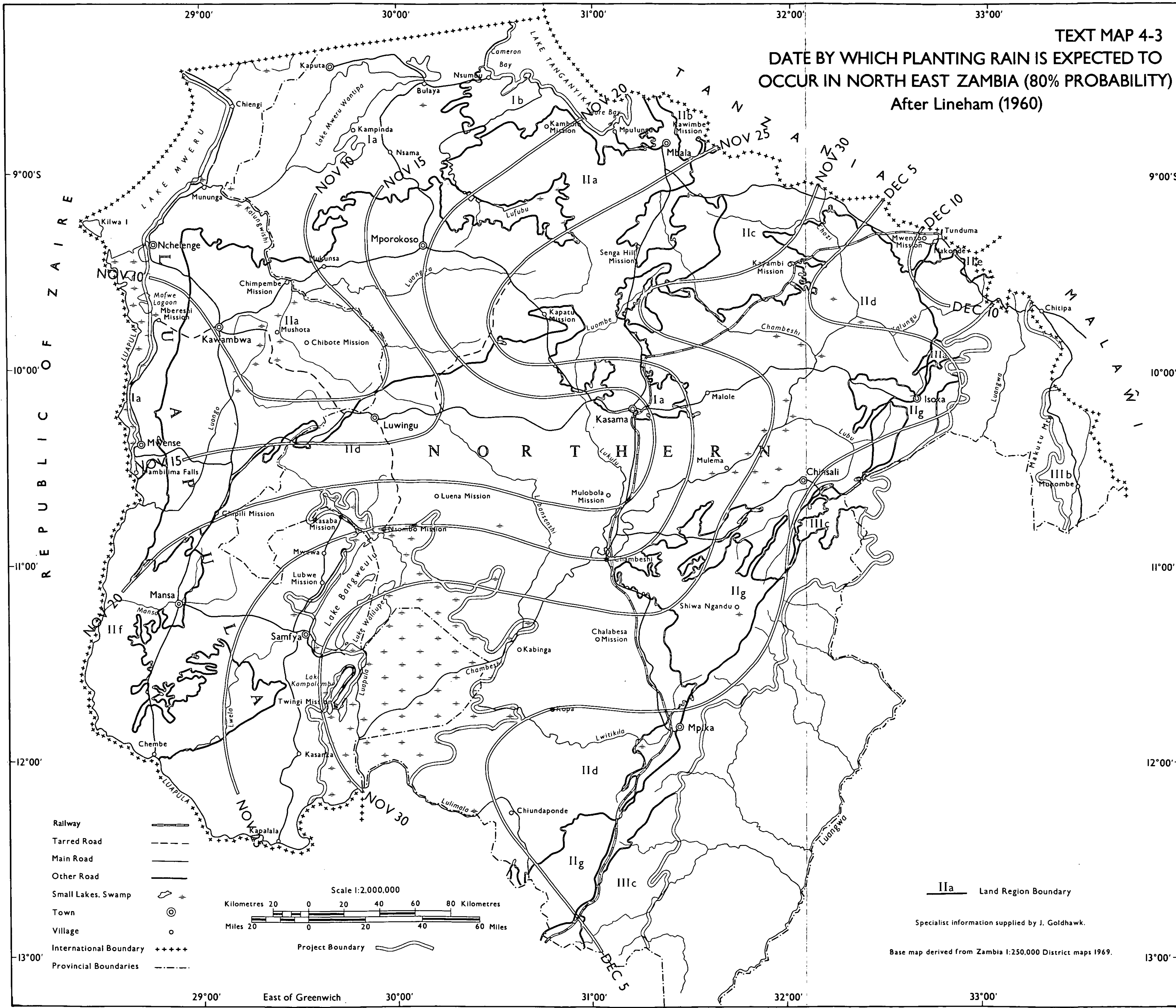

TEXT MAP 4-3
DATE BY WHICH PLANTING RAIN IS EXPECTED TO OCCUR IN NORTH EAST ZAMBIA (80% PROBABILITY)
After Lineham (1960)
NOV 10
NOV 15
NOV 20
NOV 25
NOV 30
DEC 5
DEC 10
REPUBLIC OF ZAIRE
TANZANIA
MALAWI
NORTHERN
LUAPULA
LAKE MWERU
LAKE TANGANYIKA
Kaputa
Chiengi
Bulaya
Nsumbu
Cameron Bay
Kampinda
Nsama
Mbala
Mpulungu
Kawimbe Mission
Kambole Mission
Mununga
Kilwa I
Nchelenge
Mporokoso
Mukunsa
Chimpembe Mission
Mbereshi Mission
Mofwe Lagoon
Kawambwa
Mushota
Chibote Mission
Senga Hill Mission
Kayambi Mission
Kapatu Mission
Tunduma
Mwenzo Mission
Nakonde
Chitipa
Isoka
Malole
Kasama
Luwingu
Mwense
Mambilima Falls
Mulema
Chinsali
Mulobola Mission
Luena Mission
Chipili Mission
Kasaba Mission
Nsombo Mission
Mwewa
Lubwe Mission
Chambeshi
Mansa
Shiwa Ngandu
Samfya
Chalabesa Mission
Kabinga
Lake Bangweulu
Lake Walilupe
Lake Kampolombo
Twingi Mission
Kopa
Mpika
Chembe
Kasanza
Chiundaponde
Kapalala
Muyombe
Ia
Ib
IIa
IIb
IIc
IId
IIe
IIf
IIg
IIIa
IIIb
IIIc
Railway
Tarred Road
Main Road
Other Road
Small Lakes, Swamp
Town
Village
International Boundary
Provincial Boundaries
Scale 1:2,000,000
Kilometres 20 0 20 40 60 80 Kilometres
Miles 20 0 20 40 60 Miles
Project Boundary
IIa Land Region Boundary
Specialist information supplied by J. Goldhawk.
Base map derived from Zambia 1:250,000 District maps 1969.
29°00'
30°00'
31°00'
32°00'
33°00'
9°00'S
10°00'
11°00'
12°00'
13°00'
East of Greenwich
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2. Unless further rain fell within the period covered by a suitable storm (5-15 days), such a storm date was discarded and the possible planting date taken from that of the next suitable storm. If further rain did fall within the period, its day equivalent was assessed as above and added as a cumulative total, with the same maximum limit (15 days) applying. So long as the distribution of rainfall following a suitable storm could support seedling growth until the rains were firmly established, that storm date was taken as a safe planting date for that year.

This method is equivalent to saying that the effective soil water loss was at the rate of 2.5 mm per day of the total rain which fell, within the limits already prescribed. For the project area this figure was increased to 5 mm as being more relevant to the soils. An analysis of selected stations with daily records covering 30 years was carried out and from this both the mean safe planting date and the date by which 80% of the first safe planting dates occurred were assessed. Table 2 shows the results for three stations covering the range of planting dates found using both levels of soil water loss. This shows the dependence of the planting date on the soil water loss figure, but even taking the Lilongwe figures, safe planting dates are early December rather than mid-November for all stations.

TABLE 2 **Dependence of estimated satisfactory planting rain data on estimated rate of soil water loss (crop transpiration loss is considered minimal at this stage of growth), showing the dates after which accumulative rainfall exceeds soil water loss**

Station	Daily soil moisture loss estimated at 2.5 mm (0.1 in)		Daily soil moisture loss estimated at 5 mm (0.2 in)			
	Mean date of commencement of satisfactory rains	Date by which satisfactory rains start 4 years in 5	Number of years estimated loss makes no difference to estimated start of rains (max 30)	Shift in mean date of start of rains	Mean date of commencement of satisfactory rains	Date by which satisfactory rains start 4 years in 5
Isoka	23-24 Nov	2-3 Dec	13	13 days later	6-7 Dec	18-19 Dec
Mbala	17-18 Nov	3-4 Dec	14	10½ days later	28 Nov	16-17 Dec
Malole	12-13 Nov	25-26 Nov	16	9 days later	21-22 Nov	9-10 Dec

Soil-water balance

The data available for the area do not justify a sophisticated approach to this calculation. However, with the highly seasonal distribution of rainfall and the long dry season, some indication of the degree to which the soils of the area are likely to dry out is desirable.

An analysis has therefore been carried out using arbitrarily defined parameters which give an approximate water balance for defined limits of rainfall and available soil moisture and tabulated in a form similar to that used by Woodhead (1970) when calculating his available water index for stations in Kenya (See Tables 3-6).

The tables cover two periods: the main growing season for annual crops (November to May); and the whole year for perennial crops.

Three parameters were used: mean monthly rainfall, evaporation, and available water holding capacity of the soil.

Mean monthly rainfall

This is assumed to be effective rainfall entering the soil. No correction has been made for intercepted rainfall, surface evaporation of light showers or infiltration rate differences related to rainfall intensity and soil surface characteristics.

TABLE 3 **Soil water balance over the growing season for annual crops at two levels of soil AWC to a depth of 91 cm (36 in) for Mpika**

	Nov.		Dec.		Jan.		Feb.		Mar.		Apr.		May	
	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in
R	109	4.3	226	8.9	295	11.6	231	9.1	193	7.6	25	1.0	2	0.1
ET (0.9 x EO)	173	6.8	145	5.7	132	5.2	119	4.7	140	5.5	142	5.6	147	5.8
R – ET	–64	–2.5	+81	+3.2	+165	+6.4	+112	+4.4	+53	+2.1	–117	–4.6	–145	–5.7
Low AWC														
SW change	–64	–2.5	+45.5	+1.8	0	0	0	0	0	0	–117	–4.6	–145	–5.7
SW storage	0	0	45.5	1.8	45.5	1.8	45.5	1.8	45.5	1.8	0	0	0	0
SW surplus	0	0	35.5	1.4	165	6.5	112	4.4	53	2.1	0	0	0	0
SW deficit	64	2.5	0	0	0	0	0	0	0	0	71.5	2.8	145	5.7
High AWC														
SW change	–64	–2.5	81.3	+3.2	64.3	+2.5	0	0	0	0	–117	–4.6	–145	–5.7
SW storage	0	0	81.3	3.2	145.6	5.7	145.6	5.7	145.6	5.7	28.6	1.1	0	0
SW surplus	0	0	0	0	98.4	3.9	112	4.4	53	2.1	0	0	0	0
SW deficit	64	2.5	0	0	0	0	0	0	0	0	0	0	116.4	4.6

R = Monthly mean rainfall ET = Evapotranspiration AWC = Available water capacity SW = Soil water

TABLE 4 **Soil water balance over the growing season for annual crops at two levels of soil AWC to a depth of 91 cm (36 in) for Kawambwa**

	Nov.		Dec.		Jan.		Feb.		Mar.		Apr.		May	
	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in
R	175	6.9	249	9.8	213	8.4	190	7.5	239	9.4	142	5.6	15	0.6
ET (0.9 EO)	147	5.8	130	5.1	147	5.8	130	5.1	142	5.6	153	6.0	162	6.4
R – ET	+28	+1.1	+119	+4.7	+66	+2.6	+60	+2.4	+97	+3.8	–11	–0.4	–147	–5.8
Low AWC														
SW change	+28	+1.1	+17.5	+0.7	0	0	0	0	0	0	–11	–0.4	–147	–5.8
SW storage	28	1.1	45.5	1.8	45.5	1.8	45.5	1.8	45.5	1.8	34.5	1.4	0	0
SW surplus	0	0	101.5	4.0	60	2.4	97	3.8	0	0	0	0	0	0
SW deficit	0	0	0	0	0	0	0	0	0	0	0	0	112.5	4.4
High AWC														
SW change	+28	+1.1	+117.6	+4.6	0	0	0	0	0	0	–11	–0.4	–147	–5.8
SW storage	28	1.1	145.6	5.7	145.6	5.7	145.6	5.7	145.6	5.7	134.6	5.3	0	0
SW surplus	0	0	1.4	0.1	66	2.6	60	2.4	97	3.8	0	0	0	0
SW deficit	0	0	0	0	0	0	0	0	0	0	0	0	12.4	0.5

Evaporation

EO (estimated open water evaporation) is usually related to ET (actual evapotranspiration). For the purposes of these estimates, seasonal ET/EO ratios have been derived for both annual and perennial crops from the monthly figures given by Laurence and Wills (1970). These figures are suitable only for illustrative purposes, since no work has been done within the area to determine actual water use and to relate it to stage of crop development or actual availability of soil water.

TABLE 5 **Soil water balance for perennial crops to a depth of 183 cm (72 in) for Mpika**

	Nov.		Dec.		Jan.		Feb.		Mar.		April		May		June		July		Aug.		Sept.		Oct.	
	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in
R	109	4.3	226	8.9	295	11.6	231	9.1	193	7.6	25	1.0	2	0.1	0	0	0	0	0	0	0	0	8	0.3
ET (0.6 EO)	114	4.5	98	3.9	87	3.4	79	3.1	93	3.7	95	3.7	99	3.9	82	3.2	90	3.5	107	4.2	116	4.6	130	5.1
50% ET	57	2.2	49	1.9	–	–	–	–	–	–	48	1.9	50	2.0	41	1.6	45	1.8	54	2.1	58	2.3	66	2.6
R – ET	–5	–0.2	+127	+5.0	+208	+8.2	+152	+6.0	+100	+3.9	–70	2.7	–97	3.8	–82	3.2	–90	–3.5	–107	–4.2	–116	–4.6	–122	4.8
R – 50% ET	+52	+ 2.1	+177	+7.0	–	–	–	–	–	–	–23	–0.9	–48	–1.9	–41	–1.6	–45	–1.8	–54	–2.1	–58	–2.3	–58	2.3
Low AWC																								
SW change	+52*	+2.1*	+38*	+1.5*	0	0	0	0	0	0	–23*	–0.9*	–48*	–1.9*	–41*	–1.6*	–45*	–1.8*	–54*	–2.1*	–58*	–2.3*	–58*	–2.3*
SW storage	52*	2.1*	92*	3.6*	92	3.6	92	3.6	92	3.6	69*	2.7*	21*	0.8*	0	0	0	0	0	0	0	0	0	0
SW surplus	0	0	89*	3.5*	208	8.2	152	6.0	100	3.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SW deficit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20*	0.8*	45*	1.8*	54*	2.1*	58*	2.3*	58*	2.3*
High AWC																								
SW change	+52*	2.1*	+177*	7.0*	+64*	2.5*	0	0	0	0	–70	2.7	–48*	1.9*	–41*	1.6*	–45*	–1.8*	–54*	2.1*	–58*	–2.3*	–58*	–2.3*
SW storage	52*	2.1	229*	9.0*	293*	11.5*	293	11.5	293	11.5	223	8.8	175*	6.9*	134*	5.3*	89*	3.5*	35*	1.4*	0	0	0	0
SW surplus	0	0	0	0	144*	5.7*	152	6.0	100	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SW deficit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23*	0.9*	58	2.3

*Figures based on 50% ET or affected by such figures.

TABLE 6 ***Soil water balance for perennial crops to a depth of 183 cm (72 in) for Kawambwa***

	Nov.		Dec.		Jan.		Feb.		Mar.		April		May		June		July		Aug.		Sept.		Oct.	
	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in
R	175	6.9	249	9.8	213	8.4	190	7.5	239	9.4	142	5.6	15	0.6	0	0	0	0	0	0	10	0.4	66	2.6
ET (0.6 EO)	98	3.9	87	3.4	98	3.9	87	3.4	95	3.7	102	4.0	108	4.2	95	3.7	102	4.0	114	4.5	107	4.2	118	4.6
50% ET	49	1.9	–	–	–	–	–	–	–	–	–	–	54	2.1	48	1.9	51	2.0	58	2.3	53	2.1	58	2.3
R – ET	+77	+3.0	+162	+6.4	+115	+4.4	+103	+4.1	+144	+5.7	+40	1.6	–93	3.6	–95	–3.7	–102	–4.0	–114	–4.6	–97	3.8	–52	–2.0
R – 50% ET	+126	5.0	–	–	–	–	–	–	–	–	–	–	–39	1.5	–48	–1.9	–51	–2.0	–58	–2.3	–43	–1.7	+8	+0.3
Low AWC																								
SW change	+77	+3.0	+8*	+0.3	0	0	0	0	0	0	0	0	–39*	–1.5*	–48*	–1.9*	–51*	–2.0*	–58*	–2.3*	–43*	–1.7*	+8*	+0.3*
SW storage	84*	3.3*	92	3.6	92	3.6	92	3.6	92	3.6	92	3.6	53*	2.1*	5*	0.2*	0	0	0	0	0	0	8*	0.3*
SW surplus	0	0	154*	6.1	115	4.5	144	5.7	40	1.6	0	0	0	0	0	0	0	0	0	0	0	0		
SW deficit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46*	1.8	58*	–2.3	43*	1.7*		
High AWC																								
SW change	+126*	+5.0*	+154*	+6.0*	+5*	+0.2*	0	0	0	0	0	0	–93	–3.6	–48*	–1.9*	–51*	–2.0*	–57*	–2.3*	–43*	–1.7*	+8*	0.3*
SW storage	134*	5.3*	288*	11.3	293	11.5	293	11.5	293	11.5	293	11.5	200	7.9	152*	6.0*	101*	7.9*	44*	1.7*	1	0	8*	0.3*
SW surplus	0	0	8*	0.3*	110*	4.3*	103	4.1	144	5.7	40	1.6	0	0	0	0	0	0	0	0	0	0		0
SW deficit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

For the annual crop season a ratio of 0.9 has been selected and represents the seasonal value for cereal crops such as maize and sorghum. (In calculating indices for the a.w.c. of soils for our land evaluation, an ET/EO ratio for maize of ≮ 1.1 based on conditions in Rhodesia is assumed. This was used because (a) it was a more severe criterion and (b) it appeared to be geographically more justifiable.) For perennial crops the value selected is 0.6 which represents the annual value for citrus which is the least demanding of many perennial crops and therefore will give the most favourable water balance over the year.

An allowance is made for the fact that the actual ET rate will be reduced once available soil water falls below a certain level. In any month when the available water of the soil falls below 50% for a specified depth (using the original ET value) the ET value is reduced by 50% including those months when available water is zero.

Available water-holding capacity of the soil

The maximum amount of available water which the soil could hold was calculated by choosing two depths from which crops would draw water: (i) down to 91 cm (36 in) for annual crops; and (ii) down to 183 cm (72 in) for perennial crops. Again it is appreciated that the rooting zones for some annual and perennial crops will exceed these limits in order to survive, but they are set at these levels bearing in mind that cessation of growth rather than survival is important when considering crop production. Superimposed on these soil depths are a high and low level of soil a.w.c. based on Maclean's work (1970) on Zambian soils, within which the soils found in the area should fall.

The two levels of available water capacity are taken as 0.5 cm/dm and 1.6 cm/dm. These combinations limit the maximum soil storage capacities as follows.

Depth	a.w.c.	
	low	high
91 cm	45.5 mm	145.6 mm
183 cm	92 mm	293 mm

Rainfall minus the estimated potential evapotranspiration gives an estimate of the quantity of water available for storage in the soil, assuming that none is lost in runoff etc. In Tables 3 to 6, 'surplus soil water' is the quantity by which this figure exceeds the maximum a.w.c. When evapotranspiration exceeds rainfall and there is no available water in the soil this quantity becomes a soil water deficit.

What the tables show are the months when the soil can be expected to reach field capacity and those months when the moisture level falls below permanent wilting point for the depths specified. From these tables the following will be seen.

i. For the period November to May at low a.w.c. levels both areas have soils at field capacity for the 4 months December to March. However for Mpika a.w.c. is zero for November and April. For Kawambwa these two months are 61% and 76% of field capacity and therefore water stress is less likely to occur and the growing season is therefore longer. With its high a.w.c. level the soil at Mpika does not reach field capacity till January and in April it is only at 20% field capacity compared with Kawambwa at 92%.

ii. For the whole year the effect of soil a.w.c. is more marked where these have a low a.w.c. Mpika has 5 months and Kawambwa 3 where the soil is below permanent wilting point although a further 2 months have such low levels of soil moisture as to be virtually at this point. However for the soils with high a.w.c. levels permanent wilting point is only reached for 2 months in Mpika and virtually 2 months for Kawambwa (September/October). For crops with a higher May ET/EP ratio than citrus, ie coffee (0.9) the period of zero a.w.c. would be longer.

iii. Although these data show how it is possible for certain perennial crops to survive the dry season, they also support the view that for optimum growth supplementary irrigation will be essential between May and October in Mpika except on soils with a high a.w.c. for which the period might be a month less, whereas at Kawambwa a month's less irrigation would be necessary.

TEMPERATURE

There are 11 stations in the Northern and Luapula Provinces with good temperature records, seven of which provide 24-hourly means. Six stations observe three times a day (0600, 0800, 1400 h) and the others once at 0800 h. All stations record mean and absolute maximum and minimum. Several stations have records over 20 years long, and most over 10 years.

Seasonal temperature variations

Figure 4-6 shows the mean monthly temperatures for five stations widely spaced over the central plateau area. In Zambia generally, there is no abrupt seasonal temperature change and little variation from year to year (Walker, 1970). In north-east Zambia the mean annual variation is about 6°C (11°F) ranging from the June-July minimum of about 17°C (63°F) to the October maximum of about 23°C (74°F). Temperatures fall slowly from October to midwinter but remain steady through most of the wet season at about 21°C (70°F). After June, temperatures rise steadily as the hot season advances.

Temperature regimes are similar throughout the central plateau area, the only contrast being in actual value which is mainly a function of altitude (compare Mbala and Kawambwa). It can also be seen from Figure 4-6 that maxima and minima converge with the wet season and diverge with the dry season due to summer cloudiness inhibiting extreme day and night temperatures.

However, diurnal variations in both seasons are greater than the annual temperature range.

Diurnal temperature variations

Minimum temperatures occur around dawn, with the maximum temperatures occurring soon after midday. The mean daily range for January and most of the wet season is 7°C (13°F) (Table 7). In July the mean daily range is less than 14°C (25°F) or about twice the summer range, but varies from 11°C (20°F) at Samfya to 18°C (33°F) at Mansa and Mpika. Thus the mean annual diurnal variation is about 9°C (17°F), with a higher range at Mansa and Mpika.

Frost temperatures

There is no ground-level temperature information, but Figure 4-6 shows that absolute minimum temperatures rarely approach freezing point except at Mpika in August where a screen value of -1°C (30°F) has been recorded.

INSOLATION (SUNSHINE HOURS)

Direct radiation measurements are not available for Zambia, but at Bulawayo, Rhodesia, about 8° south of the project area, mean monthly maxima range from 70 cal/cm^2/h in June to 102 cal/cm^2/h in January. High absolute values occur when skies clear during the wet season. Sunshine measurements are made in Zambia and can be used to deduce seasonal radiation variation using the Angstrom formula (Torrance, 1972). At Mbala an

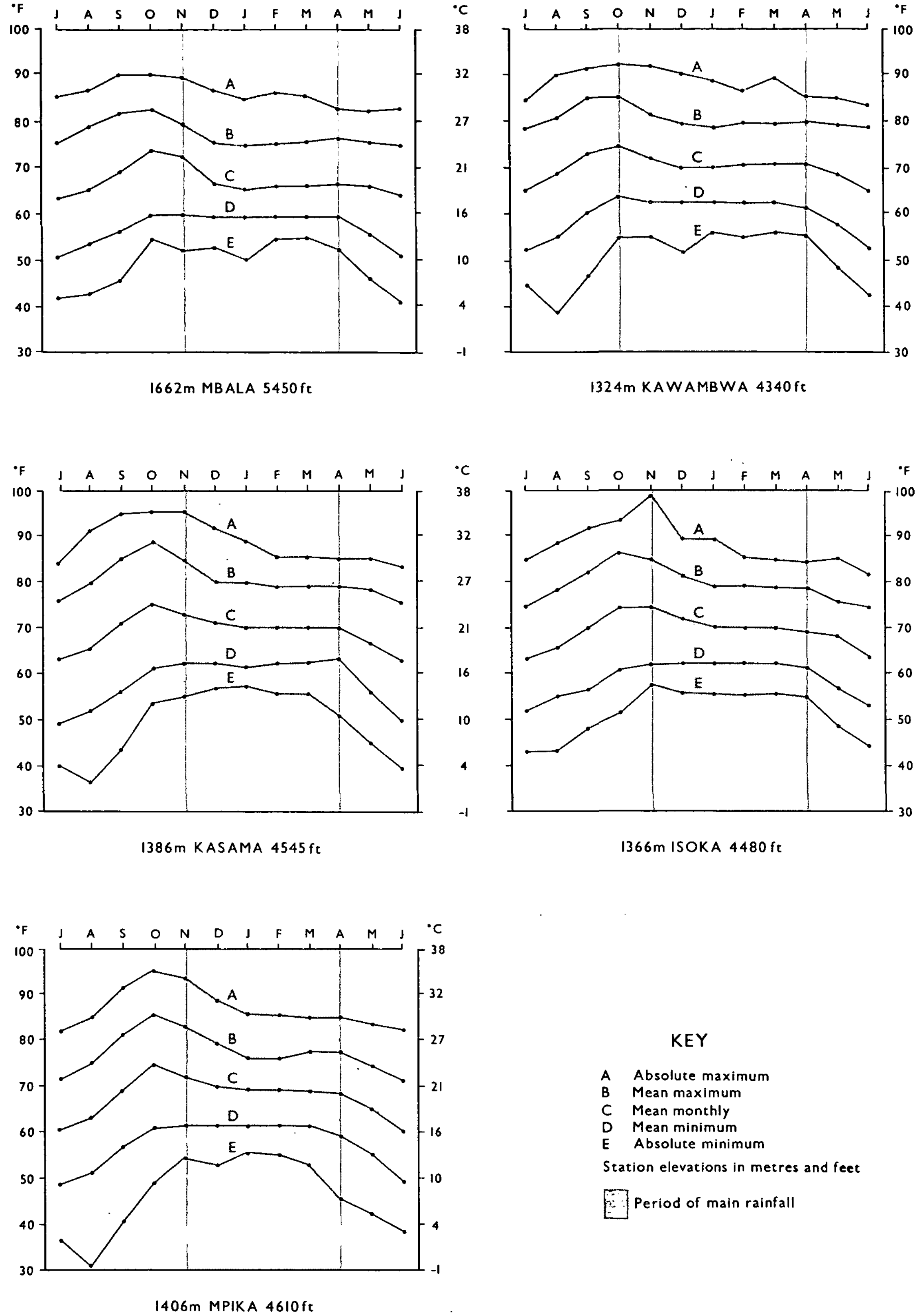

FIGURE 4-6 Mean monthly temperatures for stations in the Northern and Luapula Provinces, Zambia.

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TABLE 7 Mean diurnal temperature range for stations in Northern and Luapula Provinces

Station	Month	0600 h		0800 h		1400 h		Range	
		°C	°F	°C	°F	°C	°F	°C	°F
Mansa 1 200 m (3 940 ft)	January	17.8	64.1	19.7	67.5	25.2	77.4	7.4	13.3
	July	6.0	42.8	12.3	54.1	24.7	76.4	18.7	33.6
	October	14.5	58.1	22.0	71.6	31.6	88.8	17.1	30.7
Kasama 1 380 m (4 545 ft)	January	16.7	62.0	18.8	65.9	24.3	75.7	7.6	13.7
	July	9.9	49.9	14.4	57.9	23.7	74.7	13.8	24.8
	October	16.7	62.0	22.3	72.2	30.3	86.6	13.6	24.6
Mpika 1 500 m (4 160 ft)	January	16.7	44.7	17.9	64.2	24.2	75.5	6.5	13.4
	July	7.1	62.9	8.7	47.7	25.2	77.4	18.1	32.7
	October	17.2	62.0	22.2	72.0	28.8	83.9	11.6	21.0
Kawambwa 1 320 m (4 340 ft)	January	17.3	63.2	19.6	67.3	23.9	75.1	6.6	11.9
	July	11.7	53.0	15.1	59.2	25.0	77.0	13.3	24.0
	October	17.9	64.3	21.9	71.5	28.7	83.7	10.8	19.4
Samfya 1 150 m (3 770 ft)	January	18.6	65.5	21.1	70.0	25.9	78.7	7.3	13.2
	July	11.6	52.9	15.2	59.3	22.4	72.3	10.8	19.4
	October	19.2	66.6	22.9	73.3	29.6	85.3	10.4	18.7
Mbala 1 662 m (5 450 ft)	January	15.5	59.9	17.9	64.2	21.2	70.2	5.7	10.3
	July	10.6	51.0	14.6	58.2	23.1	73.6	12.5	22.6
	October	15.9	60.6	20.6	69.1	26.4	79.6	10.5	19.0

See Text Map 4-4 for locations

TABLE 8 Average daily hours of bright sunshine

Station	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Mean
Mbala	9.7	9.4	8.8	8.4	6.5	4.3	4.8	4.2	4.6	7.4	9.7	9.3	7.3
Kawambwa	10.0	9.7	8.5	7.5	5.6	4.1	4.4	4.5	4.9	7.5	9.4	9.8	7.1
Kasama	10.2	9.9	9.5	8.5	7.2	5.3	4.0	4.2	5.4	7.9	9.0	9.6	7.5
Mpika	9.2	9.6	9.5	9.8	7.3	4.5	3.5	3.8	5.2	7.3	8.5	8.7	7.2

estimated mean daily radiation received in September and October is 600 cal/cm^2 with a minimum of below 450 cal/cm^2 in January. Thus the lowest mean maximum temperatures occur in mid rains, when deep cloud layers reflect much of the short-wave radiation back into space.

Two hundred miles south, at Mpika, yearly radiation shows a double maximum and minimum. Instead of a steady increase in daily radiation as the dry season advances into the hottest months, as observed further north, the effect of latitude on daylight hours reduces the daily values in June and July to below 500 cal/cm^2. The most rapid decline of daily radiation occurs at the onset of the wet season at a rate of 100 cal/cm^2 each month.

Figure 4-7 shows the mean variation in sunshine for four well-spaced stations in the Northern and Luapula Provinces. The curves show the effect of cloud in reducing the proportion of maximum possible sunlight for differing day lengths over the year. It illustrates the marked similarity in insolation pattern for the four stations. At Mpika, high insolation is maintained until October because the cloudy north-west air has not by then reached the south-east sector of the project area. However, when the wet season sets in, insolation falls rapidly at Mpika to the level of the other stations, and in fact is cloudier than they are for 6 months of the year. The general insolation range in the project area is 10 h/day (85%) in July to 4 h/day in January. Table 8 shows the actual mean daily sunshine hours. At 10^{o}S the maximum possible duration of bright sunshine is 11.5 h in June and 12.7 h in December. This annual variation of 1.2 h is small compared with the actual variation of 6.2 h experienced at Kasama (10^{o} 13'S).

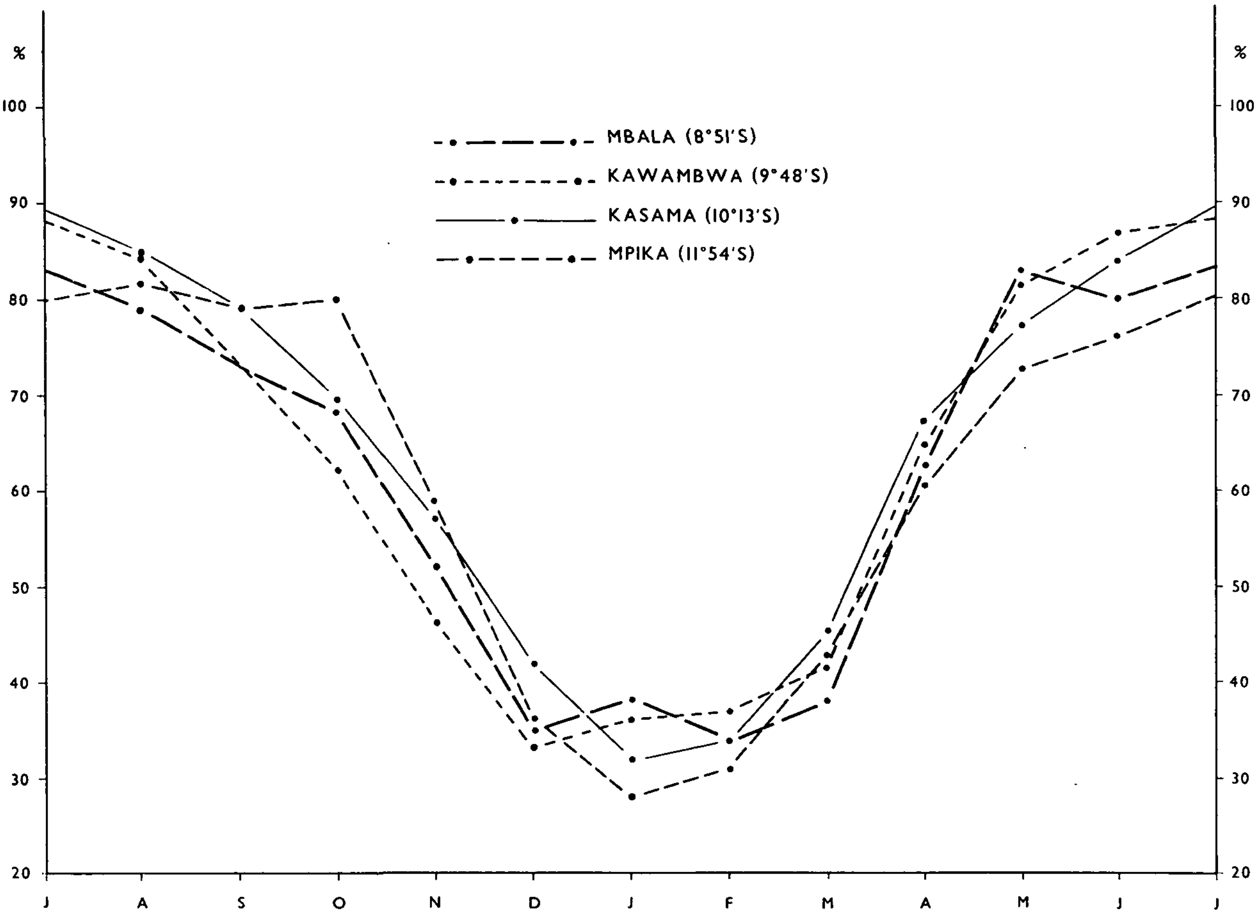

FIGURE 4-7 Monthly percentage of maximum possible sunshine hours 1946-56 for stations in the Northern and Luapula Provinces, Zambia.

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Because the longer days coincide with the cloudy wet season, the effect of the annual day length cycle is merely to produce a damping factor in the annual insolation variations created by alternating wet and dry seasons.

A frequency curve of daily sunshine durations in the dry season has a J-distribution with about 40% of occurrences at maximum possible on the north-east Zambian plateau (Torrance, 1972). Sunshine totals below 4 h/day account for less than 10% of the occasions. In January the distribution is quite different, with nearly all stations showing little variation of frequency.

SURFACE WINDS

In July, northern Zambia experiences a south-easterly airstream blowing from the north side of the Indian Ocean subtropical high. As this pressure belt moves south in the hot season, winds tend to back to north-east before the onset of wet-season Zaire air from the north-west. Winds are not as consistent from this quarter in winter, due mainly to the variability of convective winds in summer storms. Towards the end of the wet season a southerly component strengthens as pressure builds in the south and the ITCZ moves north again. Table 9 shows mean monthly wind speed to be predominantly 2.1-4.2 m/s (4-8 kn), with little seasonal or areal variation. The consistent dry-season trade winds give slightly higher mean values, but maximum winds occur during wet-season storms. Table 10 shows maximum wind speeds for Kasama, where the highest gust occurs in February and the lowest in May. The dry season is significantly less gusty than the wet.

TABLE 9 **Modal interval of mean monthly wind speed with percentage occurrence within modal group (1955-60) in brackets below**

Station	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June
Mbala	3 (34)	2 (35)	2 (42)	2 (51)	2 (50)	2 (46)	2 (45)	2 (48)	2 (47)	2 (36)	2 (38)	2 (34)
Kawambwa	2 (40)	2 (40)	2 (45)	2 (45)	0 (35)	1 (38)	1 (36)	1 (33)	2 (36)	2 (36)	2 (41)	2 (42)
Kasama	2 (48)	2 (50)	2 (42)	2 (51)	2 (46)	2 (40)	2 (42)	1 (37)	2 (36)	2 (53)	2 (56)	2 (47)
Mpika	2 (45)	2 (46)	2 (39)	2 (41)	2 (40)	2 (41)	2 (45)	2 (44)	2 (45)	2 (52)	2 (48)	2 (45)

0 = calm, 1 = 0.5-1.5 m/s (1-3 kn), 2 = 2.1-4.2 m/s (4-8 kn), 3 = 4.6-5.5 m/s (14-18 kn).

TABLE 10 **Maximum monthly gusts at Kasama, 1939-61**

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June
m/s	18	19	19	19	26	32	25	35	26	25	17	21
kn	35	37	37	37	51	62	49	67	50	48	32	41

Summer storms can create a 26 m/s (50 kn) squall from calm in a few minutes, or maintain a 16 m/s (30 kn) wind for 30 minutes. However, hourly values exceeding 10 m/s (20 kn) are unusual even in the wet season. Diurnal wind speed regimes have a recognisably similar pattern over the area. Generally, the minimum speeds occur at dawn after which they increase to a maximum at about 1 000-1 200 hours. Afternoon winds are light to moderate according to convective activity and the mixing level of surface-heated air. A lull usually occurs around sunset followed by light nocturnal winds. Stations near to lakes, such as Mbala and Samfya, experience diurnal fluctuations in wind speed and direction from the 'sea breeze' effect.

RELATIVE HUMIDITY

Diurnal humidity variations tend to have a cycle opposite to that of wind speed. The maximum occurs about 0600 h and the minimum around midday or early afternoon. The difference is greater in the dry season, being over 40% in most places in north-east Zambia. In the wet season, daily range is about 20-30%. Annual variation closely follows the rainfalll regime (Figures 4-1 and 4-2). Table 11 shows the mean monthly and annual relative humidities for stations in Northern and Luapula Provinces, the most significant trend being the increase from October to December at the wet-season onset. Maximum daily humidity is about 90-95% in summer, and minimum about 30% in winter.

TABLE 11 Mean daily relative humidity (%)

Station	Year	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June
Mbala	1969	55	50	48	50	69	84	86	85	85	80	69	62
Mansa	1967	58	52	48	48	65	80	82	83	81	76	69	64
Kasama	1964	55	48	43	41	60	78	81	82	80	76	66	60
Kawambwa	1966	52	46	43	52	73	82	83	82	82	77	65	59
Mpika	1968	63	55	48	44	60	80	83	85	83	79	72	70
Samfya	1971	67	62	56	56	64	79	82	86	81	75	72	72

SPATIAL VARIATIONS

Rainfall

The rainfall distribution is shown on Text Map 4-4. From this it will be seen that the least mean annual rainfall (1 00 mm: 40 in) occurs in the east and west of the region, and the most (1 500 mm: 60 in) in the centre. There are higher areas of rainfall near Lake Bangweulu and at Kalabwe. That near Lake Bangweulu is probably due to local evaporation/precipitation cycles from the lake and surrounding swamp, while the one near Kalabwe is on the northern slope of the higher ground in the centre of the region (see Text Map 4-1 and 4-2), and is probably orographic due to the rising moist airstream from Zaire. Local spatial rainfall variation is likely to be considerable because much of the rainfall is convectional. Three areas with close isohyets are:

1. South of Lake Mweru: a difference of 325 mm (13 in) in average annual rainfall over 40 km (25 mi)

2. South of Lake Tanganyika: a difference of 350 mm (14 in) in average annual rainfall over 45 km (28 mi)

3. North of Lake Bangweulu: a difference of 250 mm (10 in) in average annual rainfall over 35 km (22 mi)

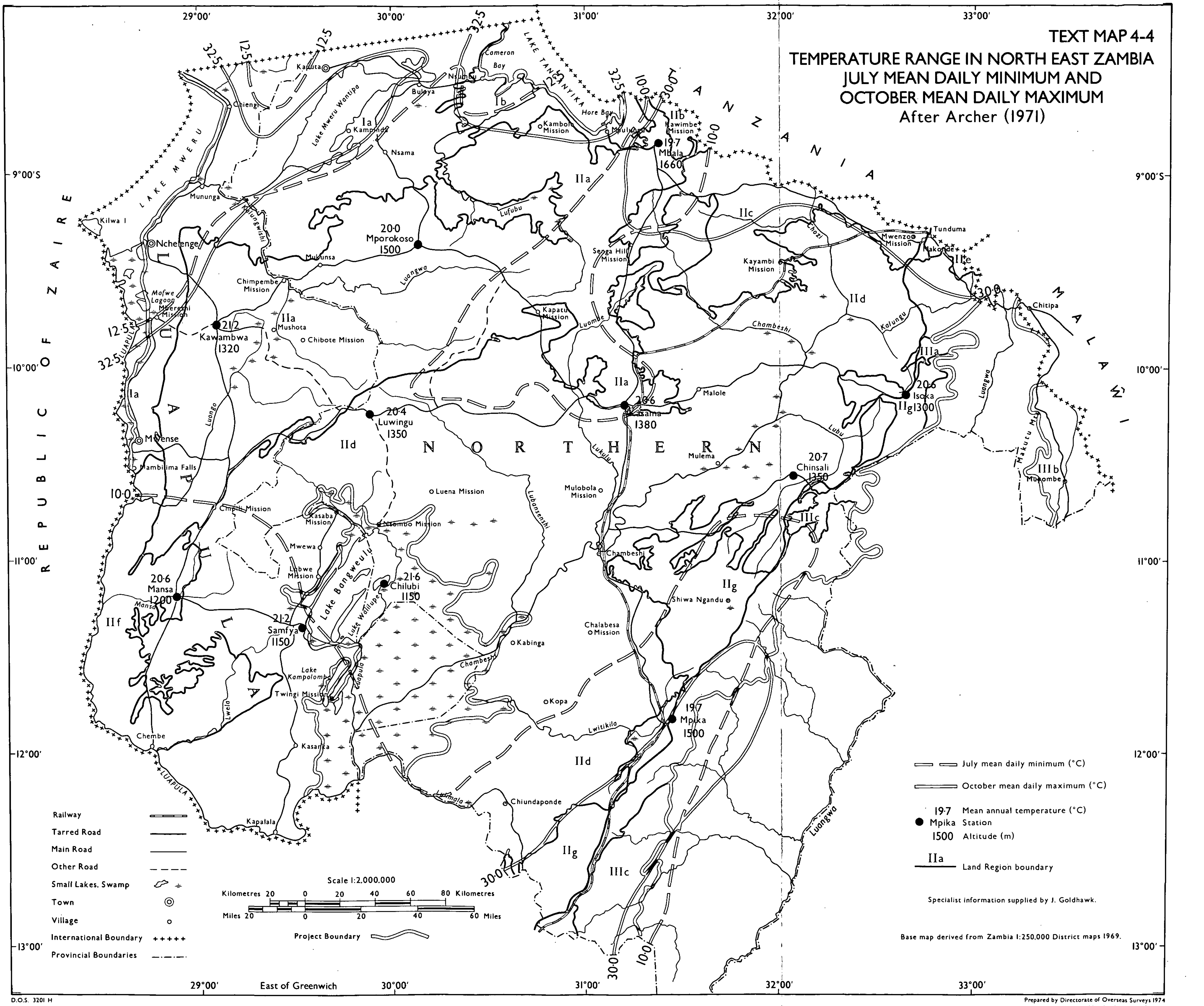
Elsewhere the gradients are not so steep though it is always possible that local anomalies do exist and are, as yet, unrecorded.

Temperature

Text Map 4-4 shows the isotherms of mean July minimum and October maximum temperatures over the project area (Archer, 1971). The difference in the mean annual temperatures of the 11 stations shown is not more than 2°C (3.5°F). Mbala and Mpika have the lowest temperatures, 19.7°C (67.4°F), while Chilubi on Lake Bangweulu has the highest, 21.6°C (70.9°F). However, although no stations are available in the area around the lakes in the north-west corner of the project area, it can be seen from the map that the annual mean for this area is at least 22.5°C (72.5°F).

The Luapula Stocktaking Report gives mean annual maximum temperatures around Lake Mweru as 26.7°C (80°F) and for 8 months of the year 29.4°C (85°F). Over most of the north-east Zambia the annual mean is 20-21°C (68-70°F).

TEXT MAP 4-4
TEMPERATURE RANGE IN NORTH EAST ZAMBIA JULY MEAN DAILY MINIMUM AND OCTOBER MEAN DAILY MAXIMUM
After Archer (1971)



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During the hot season, absolute maximum temperatures reach 37°C (98.5°F) on the central plateau at Isoka and Luwingu, but only 32°C (89.5°F) at Mbala and Mpika. Over the rest of the project area the highest readings are about 35°C (95°F), and usually occur in October. Higher values may occur around the lakes. Republic of Zambia Atlas: Sheet No. 17 shows the mean maximum in October for the Luapula Valley area as lying between 32.5° and 35°C (90.5-95°F).

Text Map 4-4 shows the uniformity in temperature range over the project area. The range between the July mean minimum and October mean maximum is about 20°C (36°F), while the mean annual maximum-minimum range is generally 11°C (20°F).

Comparison between Text Maps 4-1 and 4-4 shows the warmer region round the lakes to be coincident with elevation below 1 000 m (3 280 ft). The ridge extending south from Zaire west of Lake Mweru is picked out by the isotherms as an area of lower temperatures. Cooler areas around Mbala and Mpika correlate with land over 1 500 m (4 920 ft), the latter being the Muchinga Mountains. The area over 1 500 m (4 920 ft) north-east of Luwingu is shown by an extension of the July isotherm from the Mbala area. There is a clear temperature difference of at least 2.5°C (4.5°F) between areas above 1 500 m (4 920 ft) and below 1 000 m (3 280 ft). The standard atmosphere difference in temperature between these heights is 3.2°C (5.8°F) (COESA, 1962).

Insolation

The number of months averaging less than 5 hours' sunshine per day in the project area ranges from five around the north-west lakes to two south of Mpika in the Luangwa Valley. This general trend for cloudiness to increase northward reflects the longer wet season there, but the isohel map of the area displays certain anomalies (Republic of Zambia Atlas: Sheet No. 19). Surface insolation produces less convective activity over water bodies than neighbouring land areas, a fact demonstrated in north-east Zambia by the decreased cloudiness at Lakes Mweru and Tanganyika, and particularly over the Bangweulu lake and swamp area. The dominant east-west isohel trend, created by the twice annual reversal of solar radiation gradient, is interrupted near the Malawi border where altitude rises over 1 800 m (5 500 ft), producing an increase in orographic cloud. Here, the mean total is less than 2 500 h, but most of the project area has over 2 650 h/year sunshine.

Table 8 shows that even in the wet season 4 h of sunshine a day, on average, can be expected. Significant periods of little or no sunshine are infrequent. A 5-day or more overcast occurs on average once a year at Mpika, but once every 2 years at Kasama, on lower ground. At Mbala overcast spells have about the same frequency as Kasama, and Kawambwa, of the four stations with data, probably the fewest periods. Most places in north-east Zambia are likely to have at least one 3-day overcast spell a year.

Relative humidity

Mean annual relative humidity shows little spatial variation. Over most of north-east Zambia it is 65-70%, with slightly less humidity in the Luangwa Valley and over 70% around the Lakes Mweru, Tanganyika and Bangweulu.

CLIMATIC CLASSIFICATION

In applying Köppen's (1931) classification to the area, Torrance (1972) found that most of it experiences a humid mesothermal climate (Cwa), the remainder being humid mesothermal (Cwb) or tropical humid (Aw). These climatic differences are due to differences of altitude, latitude and lake proximity. Text Map 4-1 illustrates these relationships which are discussed below; reference should also be made to Text Maps 4-2 and 4-4 (for rainfall and mean temperature).

For a humid mesothermal climate, winters must be dry and the mean rainfall of the wettest month must be at least ten times that of the driest month.

Humid mesothermal (climate Cw)

This is a warm climate with a dry winter and the mean rainfall of the wettest month is ten times that of the driest month. The temperature of the coldest month must lie between 17.8°C and -2.8°C (64° and 27°F).

For Cwa climates the mean temperature of the warmest month must exceed 22.2°C (72°F), and for Cwb climates the mean temperature must be less than 22.2°C (72°F) and at least 4 months must experience temperatures above 10°C (50°F). The only area which falls into this category is a strip along the Zambia – Tanzania border between Mbala and Nakonde which lies at altitudes above 1 500 m (4 920 ft). Mbala is the only station where the temperature falls below this level.

Tropical humid savanna (Climate Aw)

This is a periodically dry savanna climate, where the mean temperature of the coldest month must be greater than 17.8°C (64°F) and the driest period must occur in winter. Annual mean temperatures must lie between 20.0°C and 27.8°C (68-82°F) and monthly variations less than 7.2°C (13°F), over the year. As no temperature data was available for the lower altitude areas this boundary can not be regarded as real, but is inferred. Kawambwa was the only station where monthly variations were less than 7.2°C (13°F) and it thus comes within the zone.

The fact that mangoes grow well at these low altitudes and a local variety of oil palm is only found in the Lower Luapula Valley supports the assumption that the area around the lakes to the north and below altitudes of 1 000 m (3 280 ft) fall in this division.

This classification fails to recognise the pattern of rainfall which has already been discussed but if Holdridge's classification (1967) is applied, based on zones classified by their mean annual precipitation and biotemperature (annual mean of temperatures between zero and 30°C (86°F)), the project area falls into the subtropical moist forest zone except where the mean annual rainfall is less than 110 cm (43 in) when these areas become subtropical dry forest (see Text Map 4-2).

Part 3

Geology

Much of the project area is Precambrian in age. The geological succession is indicated on Text Map 4-5 which also shows three main lithological units: quartzites and sandstones of the Kibaran System mainly occurring in the north-west but also dominating the Mpika-Isoka Ridge Land Region; granite in a central zone north-east to south-west but also surrounding the Luangwa Valley in the extreme east; and the shales, siltstones, mudstones and sandstones of the Kundelungu System, which is found both along the Luapula Valley where it is known as the Luapula Beds and in the south-east of the Chambesi-Bangweulu Plain Land Region where it is called the Luitikila Beds.

Drysdall *et al* (1972) have subdivided the Basement Complex into Kibaran and pre-Kibaran elements. Whereas the pre-Kibaran element contains the normal sequence of rocks usually associated with the Basement Complex (i.e. schists and gneisses), the Kibaran is far less metamorphosed and age determinations have indicated 'a gap of up to 1 000 million years between them' (Reeve 1963). Zambia was subjected to at least two periods of granitic intrusion (Reeve, 1963); the granite found in the project area, however, seems to belong to the older intrusion. Apart from some very small and scattered basic outcrops, igneous rocks can also be found surrounding the Kibaran System in the north-west of the project area, as an intermittent volcanic or hypabyssal suite. Attention should also be drawn to the two large areas of quaternary alluvium (Land Systems IId2 and IId14), both of which are now seasonally inundated, and were probably previously covered by a lake. The geological map of the project area (Text Map 4-5) is based on a revision of the 1:1 000 000 Geological Map of Zambia published by the Geological Survey of Zambia (formerly Northern Rhodesia) in 1960. Some of the boundaries on the latter map were drawn on the basis of airphoto interpretation, shown by subsequent investigation to be incorrect (Geological Survey of Zambia, 1968). In Text Map 4-5 these boundaries have therefore been omitted which has had the effect of simplification. Since most rock outcrops are shown on Concession map sheets produced by the Luangwa Concessions (N.R.) Limited, the local geology, on the advice of the Geological Survey of Zambia, was assessed from these sheets rather than the Geological Survey map, and as a result, some additional boundaries were added to Text Map 4-5. Further local changes to the Geological Survey map have been due to recent mapping in the Mansa (Thieme, 1970) and Mpika (Marten 1968a) districts, and occasionally by direct field observation. Some small areas (and minor faults) have also been eliminated in the course of scale reduction. The most significant alteration, however, has been the allocation of the Plateau Series to the Kibaran System (Drysdall *et al.*, 1972). Much of the uncertainty about the geology of the area is due to the paucity of outcrop. This is particularly true of the Chambesi-Bangweulu Plain Land Region. Thus the contact shown on Text Map 4-5 between the Kundelungu System and the granite is conjectural.

Major faults have been taken partly from the Geological Survey map and partly from McKinnon (1940) and their alignments altered slightly to fit their topographic expression (e.g. fault scarps) revealed by airphoto mosaics. The areas of Irumide folding largely coincide with the location of the Kibaran System on the old Geological Survey map.

STRATIGRAPHY AND PETROGRAPHY

Pre-Kibaran System

The Pre-Kibaran System is found in LS IIe1, and as scattered patches in Land Regions IIc, IIg and IIIc. Since it is composed of neither very resistant nor easily erodable rocks, it does not have a distinctive topographic expression. It chiefly consists of granitic gneiss and mica schist but pegmatite, migmatite, amphibolite, talcose schist and a variety of other metasediments and metavolcanics can be found. Since it has been granitised in many places, the contact with the grantite is very diffuse.

Kibaran System

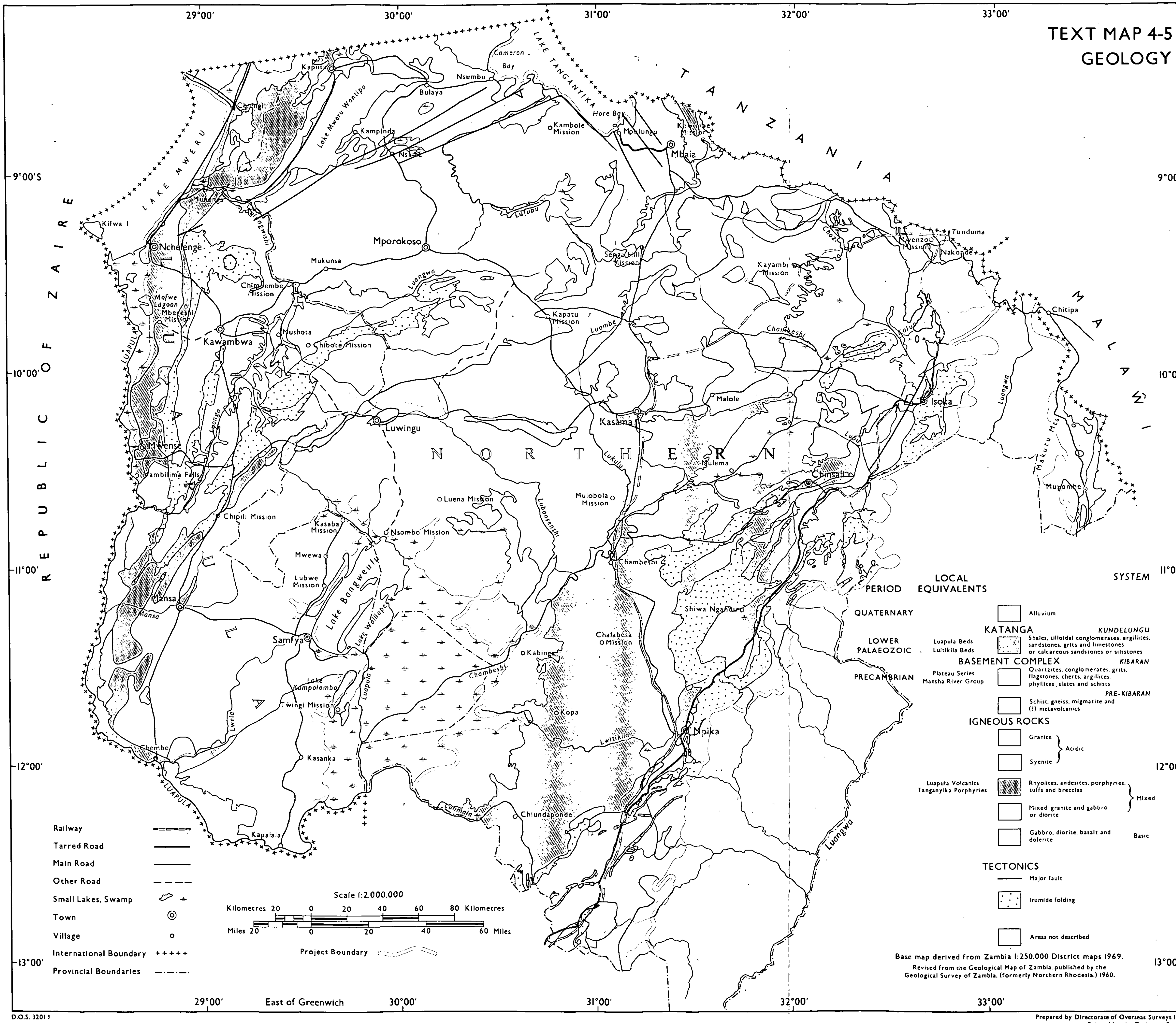
As can be seen from Text Map 4-5 the Kibaran System, which generally appears to lie unconformably on igneous rocks, occupies a large area in the north-west where it is called the Plateau Series, most of the Mpika-Isoka Ridge Land Region, and an area in the extreme south-west. This last mentioned area is seemingly anomalous and, in fact, was demarcated on the original Geological Survey map as belonging to the Kundelungu System (although at that time the Plateau Series was also considered part of the Kundelungu System). It was classed with the Kibaran System since it possesses a strong lithological similarity with the rest of that system, although shale and limestone were found in the Lwela Valley; hence the projection on Text Map 4-5 of the Luapula Beds up the Lwela Valley.

The dominant rock types comprising the Kibaran System are quartzite (Plate 1), micaceous flagstone and sandstone (Plate 2). Most outcrops consist of quartzite because of it resistance to weathering. The colour of the quartzite is greying-white, brown, red, pink or purple (when fresh), most of the colouration being due to the presence of haematite. It is characterised by cross-bedding, and ripple marks can occasionally be seen. There appears to be a basal conglomerate and grit horizon, seen for example along the south-eastern boundary of LS IIa9 and at various exposures in the Mpika-Isoka Ridge Land region. The boulders forming the conglomerate vary from 5 to 150 mm (0.2-6.0 in) in diameter, and are mostly composed of quartzite or quartz. The matrix is quartzitic. Several similar conglomerate horizons are also found higher up the system. Examination of scarp faces and stream beds discloses considerable thicknesses of micaceous flagstone and sandstone, which can be ferruginous, feldspathic or shaly (McKinnon, 1940). Shales are also present, but because of their low resistance to weathering, are very rarely seen. Their true extent is consequently very difficult to ascertain. They would appear to be restricted to definite horizons within the series. Where the system has been intensely folded as in LS IIa12, and along the Mpika-Isoka Ridge, the metamorphic equivalents of the shale horizons are found as slate, phyllite or mica schist, which could also be derived from some of the fine-grained micaceous flagstone. Marten (1968a) has sub-divided the Kibaran System north of Mpika into three pelitic and two quartzitic formations. He estimates the thickness of the pelitic horizons (slates and phyllites) to be between 1 500 and 2 500 m (5 000 - 8 000 ft). The system also contains some thin bedded chert horizons, especially in LS IIa2 and IIa15. Very thin horizons (about 20 cm (8 in)) of siltstone and mudstone have also been discovered (in LS Ia10 and Ia13).

Kundelungu System

As mentioned earlier, this system can be found along the Luapula Valley, where it is called the Luapula Beds, and in the south-eastern part of the Chambesi-Bangweulu Plain Land Region, where it is called the Luitikila Beds. The discovery of siltstone beneath the norther part of LS IId2 may mean the Luitikila Beds extend beneath the alluvium of that entire land system. The Luapula Beds, which rest unconformably on igneous rocks, consist of shale, mudstone, siltstone and sandstone. Thieme (1970), from whom the description of the Luapula Beds is taken, has divided the succession as follows.

1. Upper shales
2. Limestones
3. Sandstone, conglomerate and tilloid
4. Argillite
5. Lower shales
6. Basal conglomerate



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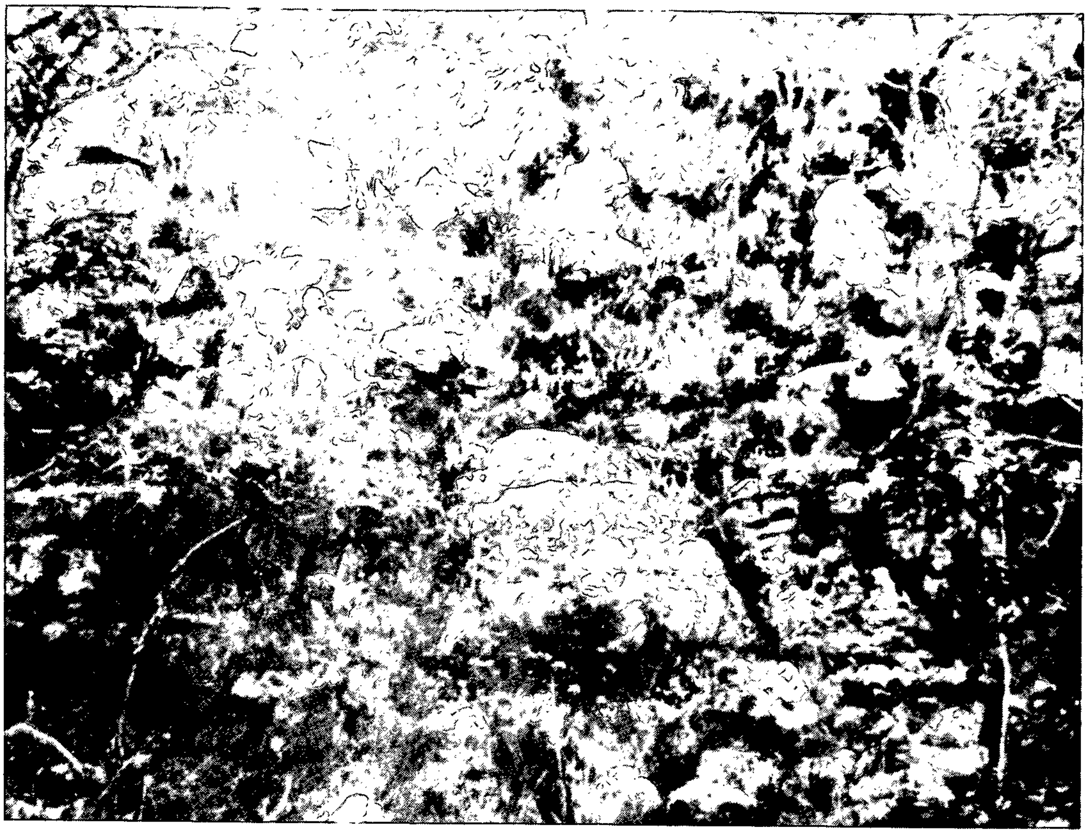


PLATE 1 Typical outcrop of quartzite

PLATE 2 Weathered sandstone bank of the Lufubu River (L.S. IIa1)

PLATE 3 Rounded granitic boulder outcrop

PLATE 4 Sandstone impregnated with quartz veins to give a brecciated appearance

With the exception of the basal conglomerate, however, the horizons are all intercalated with the dominant rock types of other horizons. The thickness of the basal conglomerate varies from 1 - 30 m (3-100 ft). The boulders, which average 30 cm (1 ft) in diameter, are composed of a variety of rock types and lie in a fine-grained matrix. The shales vary from a striped variety consisting of dark and buff-coloured layers to unlaminated blue shales. The mudstones and siltstones, in addition to occurring as inter-calations within the other horizon, comprise the argillite horizon where it attains a thickness of 10-100 m (30-300 ft). They are green to grey in colour, weathering to deep red. The arenaceous succession above the argillite consists of sandstones, grits and pebble beds and contains a widespread tilloidal horizon. The rocks apparently occupy several basins of variable depth . The tilloid, whose thickness varies from 7.5 m to 15 m (25-50 ft), consists of pebbles (10-75 mm (0.5-3.0 in) in diameter) of mainly volcanic and quartzitic rocks and to a lesser extent granite in a clayey matrix. The limestone occupies several disconnected basins and has an explored depth of about 10 m (30 ft). 'The rocks are magnesian limestones with approximately 17 per cent Mg O.' In a more recent publication, Thieme (1971) has recognised an upper conglomerate horizon, whose boulders are mostly composed of quartzite.

The Luitikila Beds, which appear to lie unconformably on the Kibaran System, consist mainly of mudstone, siltstone and sandstone. Most of the description which follows is taken from Marten (1968a). As with the Luapula Beds, there is a basal conglomerate, whose thickness is approximately 45 m (150 ft). The average size of the boulders is also about 30 cm (1 ft) but they are composed exclusively of quartzite. Marten describes the mudstone as being creamy-white in colour, having a marly appearance and being soft and deeply weathered. He also describes a green mudstone which in thin section 'is seen to consist of a felted mass of tiny sericite and, possibly, kaolinite flakes'. The siltstone tends to be micaceous. The sandstone, which is purple, pinkish-buff and around Chalabesa Mission, grey and mainly feldspathic, is well indurated, very tough and compact. Marten describes the sandstones in the area around the headwaters of the Mansha River as containing mudstone flakes, chips and clay galls. Calcareous sandstone and siltstone are also present locally; a particularly wide belt of the latter runs along the south-eastern side of and about 1-3 km (1-2 mi) distant from the Luitikila River, extending from the Kasama-Mpika road to about the point where the river turns to enter the Chibwa Swamp. In some of the sandstones, 'calcite forms most of the cementing material but mostly occurs in well-scattered patches 1 mm or less across'.

Alluvium

Alluvium is mainly found in LS IId2, but is also found in LS Ia1, Ia4, Ia7 and Ia8 and in parts of LS IIIb1. With the exception of most of LS Ia1 and parts of LS IIIb1, alluvium is still being deposited; and with the exception of LS Ia8 which is a series of river terraces, they are probably all former lake sites. A description of their soils will be found under 'Soils' below and in Volume 6.

Intrusive rocks

Granite occupies a central north-east to south-west zone, but is also found scattered throughout the project area with the exception of the Mbala-Kawambwa Land Region. It is deeply but irregularly weathered, so that outcrops and inselbergs are found alongside areas deeply weathered. Outcrops occur as low-curved rises (whalebacks) or rounded boulders (Plate 3). Inselbergs either resemble piles of rounded boulders or the more pronounced bornhardts.

The granites have a variable texture, and are pink to grey 'biotite-microcline-granites in which progressively increasing proportions of plagioclase produce adamellitic and tonalitic phases' (Reeve, 1963). A small but important (see later) syenite intrusion occurs north of Kawambwa in the Lusenga Plain. Basic intrusives, usually fine-grained and of gabbroic to dioritic texture, occur as small and scattered patches throughout the project area. They usually occur as low whalebacks and rarely attain a diameter greater than 50 m (150 ft). Where they do cover greater areas, they are often more resistant than the surrounding rock, and form prominent inselbergs (eg Lilonda Hills in LS IId3 and Mayenzi in LS IIIc5). Some of the largest basic intrusions, which do not however form prominent features, can be found in LS IIc1.

Extrusive and hypabyssal rocks

Mention has already been made of the porphyritic zone surrounding the Kibaran System in the north-west. It has been mapped and described in the area around Mansa by Thieme (1970), who states that it has been extensively intruded by granite and is overlaid unconformably by the Kibaran System. It consists of 'extensively altered ..... tuffs, volcanic breccias, rhyolites and andesites. Except for subordinate andesite horizons, the volcanics are all of rhyolite-rhyodacite composition, occasionally tending to dacite'. The andesites range in composition from andesite to dacite. Both the rhyolites and andesites are porphyritic. The phenocrysts of the former are 2 - 3 mm (0.08-0.12 in) in size, but the latter may exceed 1 cm (0.4 in). West of Kabunda, narrow discontinuous zones of sericite schists and mylonites occur.

The volcanics to the north of Mansa, found along the western part of the Mweru Depression land region, appear similar to those described by Thieme. Ashley (1936) mapped the porphyries east of Mbala as rhyolite porphyry and granite-porphyry, although andesitic and even basaltic porphyries were found in this area during the fieldwork for this report. Other small volcanic outcrops are shown on the Concession sheets scattered throughout the project area. North of Mpika, there is a basaltic mesa (land facet 3 of LS IIg9) and further basaltic outcrops found to the south-west of this mesa, which give rise to smectoid (or more active) clays, are shown on Text Map 4-5.

Vein quartz

Ridges of vein quartz (See Plates 8 and 9), aligned north-south or east-south-east to west-north-west are occasionally found throughout the project area, attaining their greatest development east-north-east of Mporokoso, where they are aligned north-south. They are generally composed of crystalline quartzite and sandstone impregnated with quartz veins (Plate 4) and/or pure quartz (see plate accompanying LS IIa15 Volume 6), usually at the centre of the ridge.

STRUCTURE

The project area largely comprises the Bangweulu craton, one of the primeval resistant blocks which make up the African continent. Because of its resistance, it is mostly the periphery which is affected by major folding or faulting. The south-eastern edge of the project area, including Land Regions IIg, IIIa and IIIc, were affected by the Irumide orogenesis which Vail *et al.*(1967) have dated at 900 to 1 600 million years. This orogenic cycle, forming an east-north-east to north-east structural trend, strongly metamorphosed and intensely deformed both the rocks of the pre-Kibaran and the folded rocks of the Kibaran System (Text Map 4-5). The folded rocks of the Kibaran System attain their maximal width north of Mpika where 'the quartzite formations are repeated six or seven times from north-west to south-east by major folds' (Marten, 1968a). The folding decreases in width north-east and south-west from this area and roughly coincides with LS IIg1. Similar folding, but narrower and producing a V-shaped zone (Text Map 4-5), occupies LS IIa12 and associated with it, the volcanic and granitic rocks of the Mansa area refoliated in a north-north-east to north-east direction (Thieme, 1970). There are no other areas of major folding, although very local micro-folding was occasionally observed in road cuttings far from the major fold zones, both in the rocks of the Luapula Beds as well as in the Kibaran System.

The most extensive faulting is found in the north in Land Regions Ia and Ib. The faults are associated with the East African rift valley system; and north of Mbala, they form the sides of Lake Tanganyika and run parallel to it. Since most of the present fault scarps are 150-250 m (500-800 ft) high, the throw of the faults must be at least as much as this, and considering the depth of Lake Tanganyika, the one forming the south-western shore of that lake must be much more. Further west in the Mweru Depression, the faulting displays a curious splay pattern which may be due to the resistance of the Bangweulu craton. The throw of these faults are on average probably not as great as those paralleling Lake Tanganyika, although the maximal height of throw is probably of the order of 250 m (820 ft). In the far west, 'north-south rift-type faulting along the Luapula valley is considered to have formed a major scarp against which the Luapula Beds were deposited' (Thieme, 1970). The only other known major fault in the area occupies the boundary between LS IId8 and IId12 south-west of Isoka. The granite, Kibaran and Kundelungu rocks all display massive jointing which is reflected in the frequent angulate (sometimes rectangular) drainage pattern.

CORRELATION

The granite in the project area, which would seem to belong to the Older Granite intrusive phase because it appears to be overlain by the Plateau Series, has intruded into the Luapula Volcanics (Thieme, 1970) and therefore postdates them as well as the other associated volcanics. The Luapula Volcanics can be correlated with the 'rhyolites des Marungu' in the Katanga Province of Zaire which postdate the pre-Kibaran System (Cahen, 1954). They are considered early Kibaran by both Abraham (1959) and Reeve (1963), and are overlain by the Kibaran System which has been correlated with the Muva-Ankole of Tanzania and the Karagwe-Ankole of Uganda (eg Coombe, 1948). The Geological Syrvey map shows only the areas affected by Irumide folding (and a few other small areas) in the project area as belonging to the Muva System. The Plateau Series, covering most of Land Regions Ia, Ib and IIa, was correlated with the Katanga Supergroup largely on the basis of a supposed 'disconformity if not an unconformity' between the Plateau Series and the folded rocks. Reeve (1963) continues 'careful examination of aerial photographs gives considerable support to the idea of an unconformity *within* the sequence of what has hitherto been regarded as (undivided) "Plateau Series"'. During the fieldwork for this report, no evidence was seen of such an unconformity. In fact, the lithological similarity between the folded and unfolded rocks was striking. The apparent unconformity seen on the aerial photographs is due to a planation surface truncating the folded strata. It would appear then, and is the view of those members of the Geological Survey who have produced recent maps in the project area (ie Marten, 1968b; Thieme, 1971), that both the folded and unfolded rocks are of the same age, and that the latter is the foreland of the former. The syenite dome, intrusive into the Plateau Series north of Kawambwa has been dated at 1390 ± 70 million years, thus giving a minimal age to the Plateau Series. Both Thieme and Marten consider the Luitikila and Luapula Beds to be equivalent on lithological as well as structural evidence. 'The correlation of the Luapula Beds with the Kundelungu of Katanga is mainly based on similarity of rock-types and structure' (Thieme, 1970). Recent palynological evidence (Vavrdova and Utting, in press) has dated the Lower Shales of the Luapula Beds as being younger than the Precambrian, but older than the Upper Ordovician.

ECONOMIC CONSIDERATIONS

Basicity From an agricultural point of view, the basicity of the rock type is one of the most important lithological considerations because the soils derived from basic rocks tend to be heavier and have a higher cation exchange capacity. Unfortunately, the rocks of the project area are mostly acidic, and the basic areas rarely attain diameters greater than about 50 m (150 ft). Using arbitrary basicity values for different rock types, however, a sketch map (Text Map 4-6)was compiled of the areas which contain slightly more base-rich rocks. The arbitrary values, designated were as follows: '2' for gabbo, basalt, dolerite and talc schist, '1' for mica schist and andesite and '0.5' for quartz schist. Granite and sedimentary rocks were given zero value. Percentage areas occupied by basic rocks were then calculated for each provisional land system (Volume 6) using the Concession sheets. The map shows that most of the project area is very acidic.

Copper Scattered deposits, demarcated on the Concession sheets, occur along the western boundary with Zaire. None of them are economic. It is understood that there is a possibility of copper being found in the Luapula Beds.

Gold A little gold ((0.15-0.3 g/t) (0.1-0.2 dw/ton) has been found in quartz veins near the Musonda Falls (Thieme, 1971).

Manganese Manganese is probably the only mineral of any possible economic significance in the project area. The deposits in the Mansa area, where they mostly occur, have been described in detail by Thieme (1970). The ore bodies occur as vertical veins whose width varies from a few centimetres (or in) to more than 4 m (12 ft). They may be a kilometre or two long ('several thousands of feet'). Their depth extends below 12 m (40 ft) but usually less than 50 m (150 ft). Thieme writes: 'All the previously worked mining locations have been virtually exhausted of high-grade ore, but some potential areas have only been partially investigated, and several new discoveries were made during the course of mapping'.

Iron The widespread occurrence of old iron smelters, especially in the western part of the project area, indicates the extensive occurrence of iron. The iron was found associated with manganese in the Mansa area and with vein quartz. Elsewhere, it was probably obtained from plinthite.

Limestone Limestone is found in the Luapula Beds and can possibly be used as a source for lime (O'Brien, 1954; Thieme, 1970).

Lead and Zinc Lead and zinc are found associated with the above limestone but their variability precludes any economic potential (Thieme, 1970).

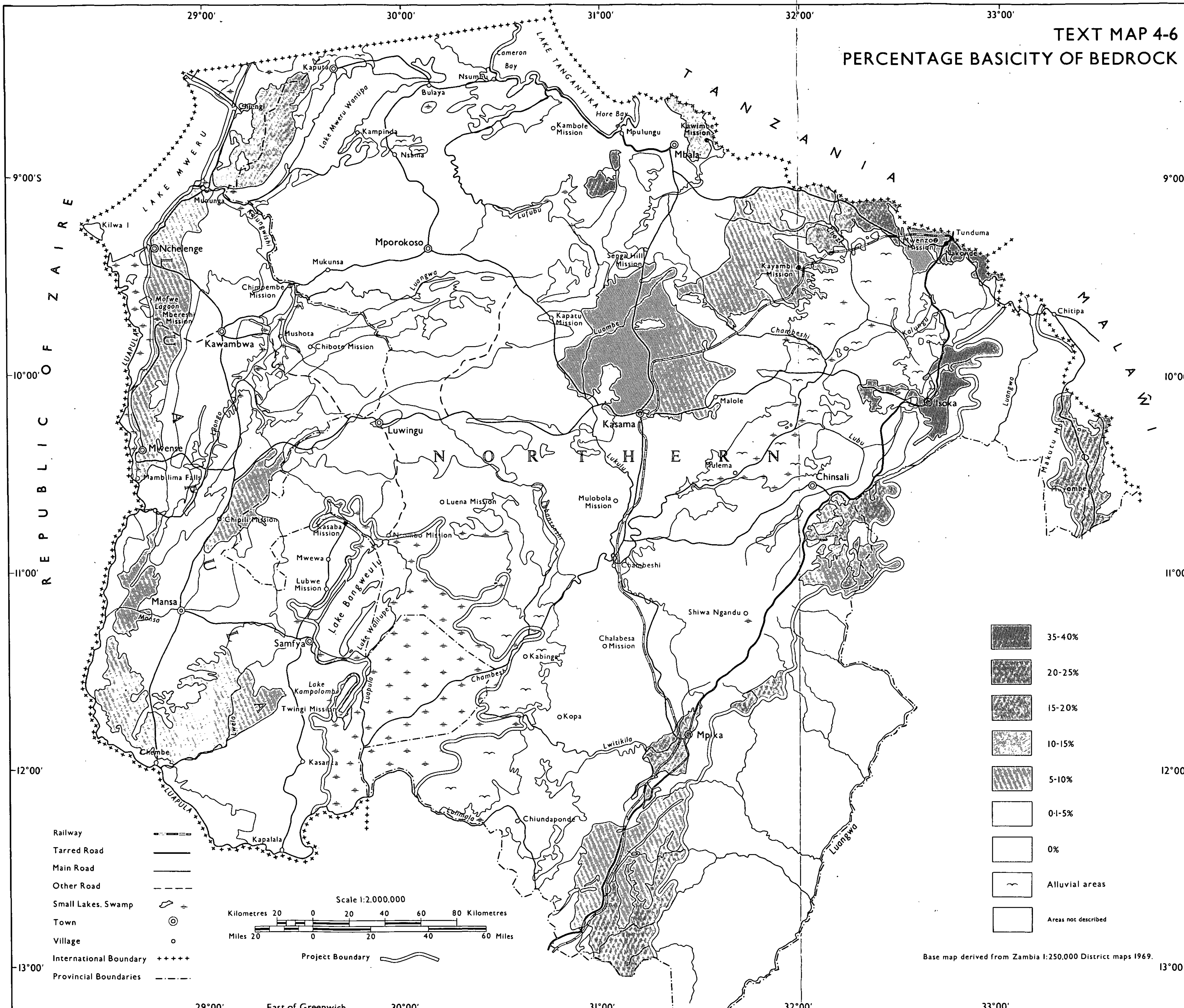
Slate 'The shales of the Luapula Beds are sufficiently fissile for the production of low-to-medium grade commercial slate' (Thieme, 1970). Joubert and Little (1948), however, consider that its grade allows it to be suitable only for a local market.

Salt Salt is extracted from mudflats in the north-western corner of the project area. The muddy water is filtered and the resultant filtrate boiled. This process is carried out at several places, particularly around Chiengi, where at the best deposit, a production of 12.5 litres (2.75 gallons) a day is claimed, and at Kaputa where a production of 3.5-6.0 litres (0.75-1.3 gallons) a day is also claimed. At Chiengi, a bag about 70 cm (27 in) long and 24 cm (10 in) in diameter was sold for K3 in 1970 and at Kaputa, a bag of the same length but only 15 cm (6 in) in diameter for K2.50. The salt is usually found near hot springs.

GEOLOGY AND LAND UNITS

Since a land region has been defined as a unit which 'has the small range of surface form and properties expressive of a lithological unit or a close lithological association having everywhere undergone comparable geomorphic evolution' (Brink *et al.*,1966), geology was used as one of the fundamental criteria for defining the land regions in the project area. The south-eastern and western boundaries of the Mbala-Kawambwa Plateau Land Region are geological. The Mpika-Isoka Ridge Land Region is largely defined to represent the Kibaran System, but in order to avoid too intricate a boundary, it does not exclusively follow the outcrop of that system. As mentioned earlier in this section, the boundary between the Luitikila Beds and the granite is not well known and since there is little difference in topography and soils north and south of the Chambeshi River, there did not seem to be any point in dividing up the Chambeshi-Bangweulu Plain Land Region. Elsewhere topographic boundaries either dominated or coincided with geological ones, or the geological units were considered too small to merit a land region status.

Geology was also used as one of the parameters for differentiating provisional land systems (see Volume 6) where the geological boundaries could be located with some confidence. The most distinctive geological boundary is that separating the Kibaran System from granite along the south-eastern boundary of the Mbala-Kawambwa Plateau. This boundary mostly coincides with an escarpment separating areas with different topographic features. Where the geological boundaries were indistinct (eg LS IIa17), topographic features alone were used as criteria. The geological boundary forming the western limit of the Mbala-Kawambwa Plateau also coincides with a distinct topographic change. Although some of the provisional land system boundaries based solely on geological criteria have been retained, others have been



TEXT MAP 4-6
PERCENTAGE BASICITY OF BEDROCK
REPUBLIC OF ZAIRE
TANZANIA
MALAWI
NORTHERN
LUAPULA
LAKE MWERU
LAKE TANGANYIKA
Lake Mweru Wantipa
Lake Bangweulu
Lake Kampolombo
Lake Waliupe
Kaputa
Chiengi
Kampinda
Nsama
Bulaya
Nsumbu
Cameron Bay
Hore Bay
Kambole Mission
Mpulungu
Mbala
Kawimbe Mission
Kilwa I
Mununga
Nchelenge
Mporokoso
Mukunsa
Chimpembe Mission
Mofwe Lagoon
Mbereshi Mission
Kawambwa
Mushota
Chibote Mission
Luwingu
Mwense
Mambilima Falls
Chipili Mission
Mansa
Samfya
Kasaba Mission
Mwewa
Lubwe Mission
Nsombo Mission
Luena Mission
Twingi Mission
Kasanza
Kapalala
Chembe
Kabinga
Kopa
Chiundaponde
Senga Hill Mission
Kapatu Mission
Kasama
Malole
Mulobola Mission
Chambeshi
Chalabesa Mission
Shiwa Ngandu
Mpika
Mulema
Chinsali
Isoka
Kayambi Mission
Mwenzo Mission
Nakonde
Tunduma
Chitipa
Chilombe
Lufubu
Luangwa
Luombe
Chambeshi
Kalungu
Lubu
Lukulu
Lwitikila
Lukulu
Mansa
Lwela
Luapula
Lufila
Luongo
Kalungwishi
Makutu Mts
9°00'S
10°00'
11°00'
12°00'
13°00'
29°00'
30°00'
31°00'
32°00'
33°00'
East of Greenwich
35-40%
20-25%
15-20%
10-15%
5-10%
0·1-5%
0%
Alluvial areas
Areas not described
Railway
Tarred Road
Main Road
Other Road
Small Lakes, Swamp
Town
Village
International Boundary
Provincial Boundaries
Scale 1:2,000,000
Kilometres 20 0 20 40 60 80 Kilometres
Miles 20 0 20 40 60 Miles
Project Boundary
Base map derived from Zambia 1:250,000 District maps 1969.
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revised to take account of the derived soil pattern. This was done because greater agricultural importance is attached to the soil pattern, and in a deeply weathered environment similar soils may overlie different rocks; for example, soils overlying acidic sedimentary and igneous rocks in the project area are in fact similar.

TOPOGRAPHY

Most of the project area lies between 1 200 and 1 700 m (4 000 - 5 500 ft) and forms part of the Central African plateau which extends from the Great Escarpment of South Africa to the highlands of Ethiopia. Most of the area therefore consists of old planation surfaces. The highest mountain in Zambia, 2 067 m (6 782 ft), occurs at Sunzu on the south-eastern edge of the plateau, south of Mbala; but parts of the project area are as low as 770 m (2 530 ft). A map, showing altitudes at a scale of 1:2 000 000 (Text Map 4-7), was compiled from the few contoured 1:50 000 maps available of the extreme north and extreme south-west, the sporadic spot heights on the old Federal 1:250 000 maps and from altimeter readings taken during the project. The map shows the highest parts of the project area occurring as a belt stretching from the southern end of Lake Tanganyika to Luwingu, along the boundary with Tanzania and along the Mpika-Isoka Ridge. The plateau around Mbala is well known as one of the highest parts of Zambia, but it is not usually appreciated that the plateau north of Luwingu reaches much the same altitide. This deception is most probably due to the obvious escarpment south of Mbala compared with the gradual climb from Kasama to Mporokoso. Furthermore, although the mountains around Shiwa Ngandu can be seen rising to a considerable altitude, the extreme southern tip of the project area also rises to a similar attitude but again only by means of a gentle climb.

As with most of the Central African plateau, slopes are usually very gentle (Text Map 4-8), a very large part of the project area having slopes of 1^{o}. Slope observations were taken at every auger point in each provisional land system. The frequency distribution of slopes measured was used to produce the modal slope map. In every case, the modal slope class covers more than 50% of all observations. In practice, however, except for occasional youthful incisions, confined mostly to narrow valleys, most of the landscape consists of very gentle convex wide interfluves separated by seasonally waterlogged grassland known as 'dambos' (Plate 5; see also Block Diagram 1 in Volume 6)which flank most of the rivers.

Local relative relief, the vertical difference in height between the valley bottom and the nearest adjacent interfluve crest, was calculated for each traverse, and averaged for each provisional land system. In the more dissected land systems, however, parallax bar measurements on aerial photographs were used because ground traverses in these land systems were restricted to gentler slopes. The resultant Text Map 4-9 shows most of the area to have a relative relief of between 20 m and 40 m (65-130 ft). Areas with lower relief however, are predominant in and around alluvial land systems and lakes, although the alluvial area east of Lake Bangweulu (LS IId14) has a relative relief greater than 20 m (65 ft), apparently due to recent youthful incision. Some low values of relative relief coincide with areas of high moderate to high (see Volume 6) stream frequencies (see Figure 4-10), the mature dissection having lowered the divides between the valleys. The only areas with substantial relief are the flanks of the East African rift valley system in the north of the project area between and including Lakes Mweru and Tanganyika, where the altitude is only about 900 m (3 000 ft), and also along the eastern border, where it is represented by the Luangwa Valley, the dissected zones separating the three planation surfaces found in the project area, and areas affected by Irumide folding (Text Map 4-5).

Land provinces and regions

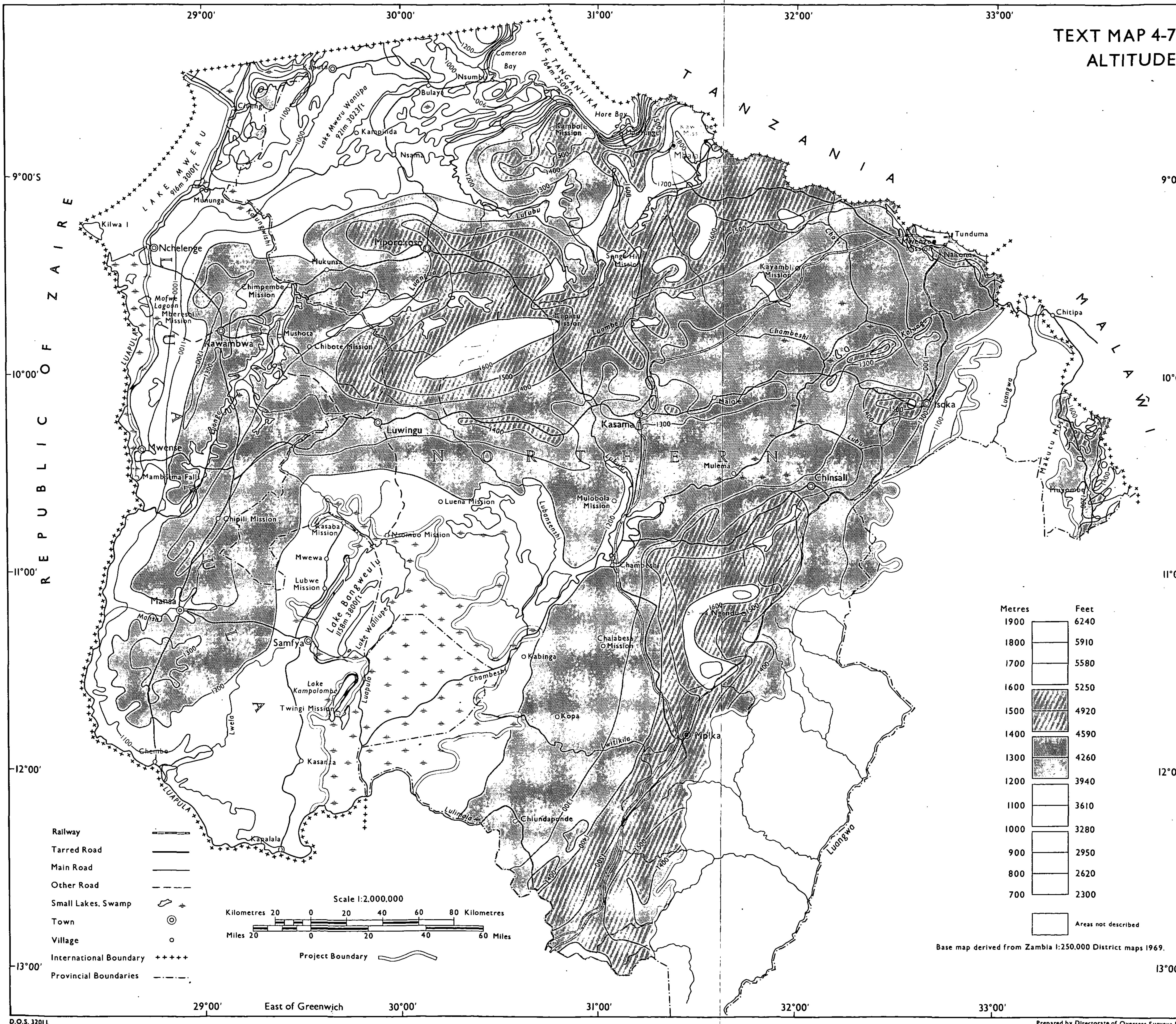
The project area can be divided into three land provinces together comprising four main land regions and seven lesser ones (Text Map 4-10, Table 2 and Figure 4-10).Most of the project area is occupied by the 'Central Plateau' land province, flanked in the north by the 'Western Rift' and in the east by the 'Luangwa Valley' land provinces,. Except for the 'Mweru Depression' and 'Tanganyika Basin', which were designated by

TABLE 12 Land regions

Reference code and name	Area described		Dominant lithology	Altitude range		Slope in degrees	Mean relative relief		Mean stream frequency *		Dissection index † in 10^{-3} units
	km^2	mi^2		m	ft		m	ft	km^{-2}	mi^{-2}	
I Western Rift											
Ia Mweru Depression	13 230	5 109	Quartzite and sandstone	918 - 1 420	3 010 - 4 660	<1	40	140	0.162	0.420	20
Ib Tanganyika Basin	1 720	664	Quartzite and sandstone	773 - 1 630	2 540 - 5 350	>2	250	820	0.643	1.67	200
II Central Plateau											
IIa Mbala-Kawambwa Plateau	32 820	12 680	Quartzite and sandstone	1 150 - 1 870	3 770 - 6 140	<2	50	160	0.241	0.624	20
IIb Kawimbe Inselberg Plain	500	190	Granite	1 500 - 1 740	4 920 - 5 710	2-6	110	370	0.353	0.914	70
IIc Mambwe-Mwengo Dissected Plain	6 070	2 340	Granite	1 300 - 1 660	4 270 - 5 450	1-2	30	100	0.505	1.31	20
IId Chambeshi-Bangweulu Plain	68 040	26 270	Granite, shale, quartzite and sandstone	1 050 - 1 610	3 440 - 5 270	<1	20	80	0.147	0.381	10
IIe Tunduma Hills	280	110	Metamorphics	1 410 - 1 700	4 630 - 5 580	>6	120	410	1.25	3.24	140
IIf Middle Luapula Valley	5 810	2 240	Granite, porphyry and shale	990 - 1 330	3 250 - 4 360	1-6	40	120	0.439	1.14	20
IIg Mpika-Isoka Ridge	12 010	4 640	Quartzite and sandstone	1 070 - 1 870	3 510 - 6 138	>1	100	340	0.414	1.07	70
III Luangwa Valley											
IIIa Upper Luangwa Valley	520	200	Metamorphics and granite	960 - 1 320	3 150 - 4 330	2-6	20	60	0.580	1.50	10
IIIb Plains and Hills West of Nyika	1 140	440	Metamorphics and granite	1 180 - 1 620	3 870 - 5 320	Variable	30	100	1.12	2.90	30
IIIc Luangwa Valley Shoulder	2 970	1 150	Granite and metamorphics	1 190 - 1 730	3 900 - 5 680	2-6	40	130	0.924	2.39	40

* Measured at a scale of 1:125 000.

† Product of mean relative relief and square root of stream frequency.


TEXT MAP 4-7
ALTITUDE
TANZANIA
MALAWI
REPUBLIC OF ZAIRE
NORTHERN
LUAPULA
LAKE MWERU 916m 3010ft
LAKE TANGANYIKA 744m 2500ft
Lake Mweru Wantipa 921m 3023ft
Lake Bangweulu 1158m 3800ft
Lake Wafilupe
Lake Kampolombo
Cameron Bay
Hore Bay
Nsumbu
Bulaya
Kampinda
Nsama
Kambole Mission
Mpulungu
Mbala
Chiengi
Mununga
Kilwa I
Nchelenge
Mofwe Lagoon
Mbereshi Mission
Kawambwa
Mushota
Chibote Mission
Chimpembe Mission
Mukunsa
Mporokoso
Sange Hill Mission
Kapatu Mission
Kayambi Mission
Tunduma
Nakonde
Chitipa
Isoka
Nakutu Mts
Muyombe
Kasama
Luwingu
Mwense
Mambilima Falls
Chipili Mission
Mulema
Chinsali
Mulobola Mission
Luena Mission
Kasaba Mission
Nsombo Mission
Mwewa
Lubwe Mission
Mansa
Samfya
Twingi Mission
Kasanka
Chembe
Kapalala
Kabinga
Chalabesa Mission
Kopa
Mpika
Chiundaponde
Chambeshi
Luangwa
Lubansenshi
Lukulu
Luombe
Kalungwishi
Luapula
Lwela
Lulimala
Mufubu
Metres
Feet
1900 6240
1800 5910
1700 5580
1600 5250
1500 4920
1400 4590
1300 4260
1200 3940
1100 3610
1000 3280
900 2950
800 2620
700 2300
Areas not described
Railway
Tarred Road
Main Road
Other Road
Small Lakes, Swamp
Town
Village
International Boundary
Provincial Boundaries
Project Boundary
Scale 1:2,000,000
Kilometres 20 0 20 40 60 80 Kilometres
Miles 20 0 20 40 60 Miles
Base map derived from Zambia 1:250,000 District maps 1969.
29°00'
30°00'
31°00'
32°00'
33°00'
9°00'S
10°00'
11°00'
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13°00'
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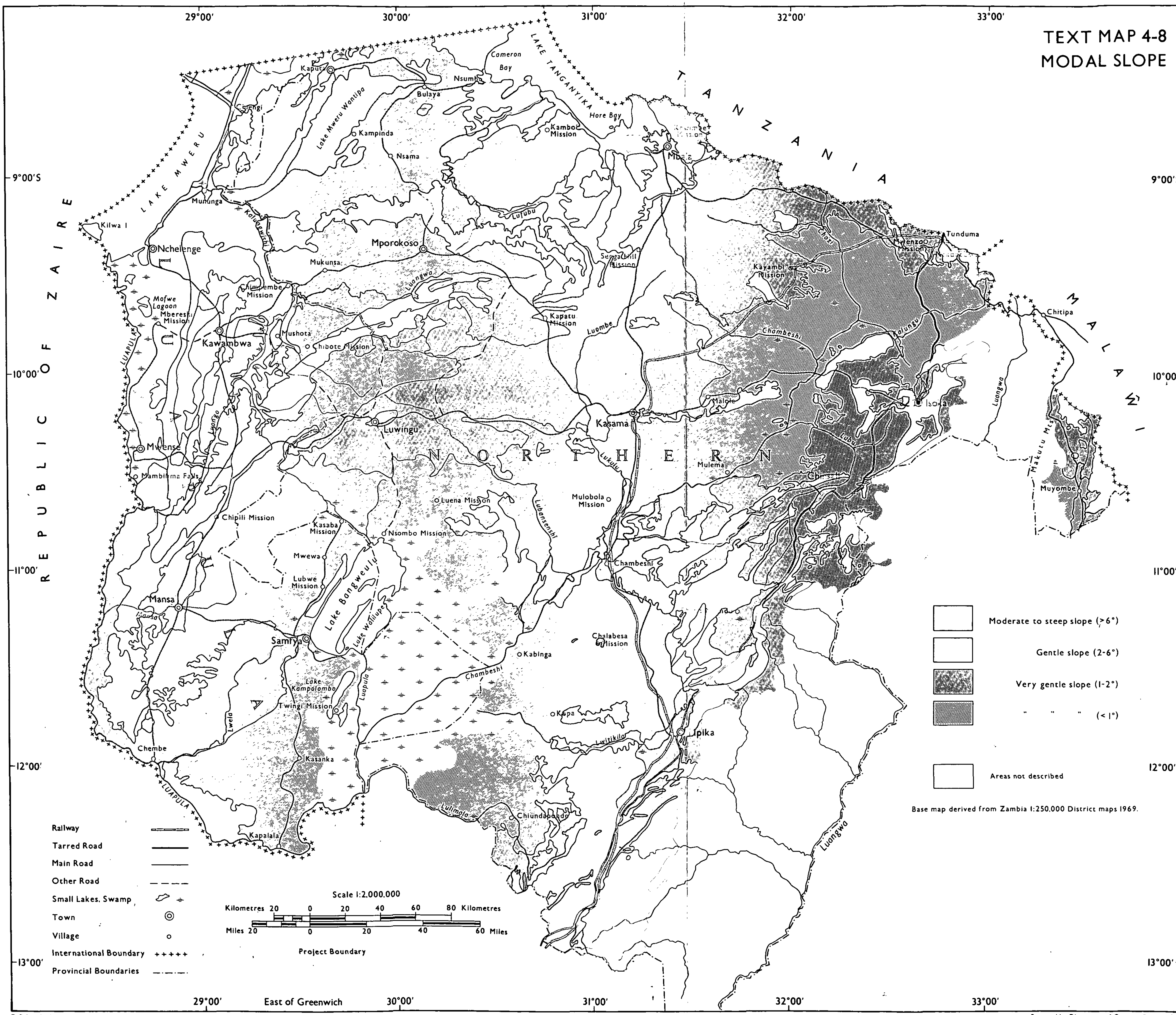

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Dixey (1945), and the 'Plains and Hills West of Nyika' designated by Young and Brown (1962), all the other land regions have been named during the course of the present project.

Mweru Depression

The Mweru Depression occupies the low-lying downfaulted area between Lakes Tanganyika and Mweru (but excluding the deep dissection down to the former lake (ie LS Ib1) and up the Luapula Valley as far as the Mambilima Falls. The slopes of this land region are mostly very gentle (at least within the area described) with three notable exceptions: the dissected terrace along the south-east shore of Lake Mweru (LS Ia2), the dissected cuesta along the north-western shore of Lake Mweru Wantipa (LS Ia5), and the fault scarps in LS Ia9. Geomorphologically, the area is partly made up of downfaulted planation surfaces (around Lake Mweru Wantipa), lake terraces (LS Ia1, Ia2, Ia4, Ia7 and part of LS Ia12) and a Quaternary piedmont produced in front of the receding Muchinga Escarpment (LS Ia10, La11, Ia12 and Ia13).

Mbala-Kawambwa Plateau

South of the Mweru Depression, the high-level Mbala-Kawambwa Plateau extends from just north of Mansa to Mbala and is almost entirely surrounded by an escarpment. It consists mostly of rocks of the Kibaran System (see under 'Geology'), which, with its extensive horizons of quartzite, is largely responsible for the existence of this plateau. Recent very youthful incision has produced greater relative relief (40-60 m, 130-200 ft, Text Map 4-9) than that found over much of the rest of the project area, but the low stream frequency has ensured that most of the slopes are very gentle, except where the surrounding escarpment has been included within the land region and where it has been traversed by the Irumide folded zone (LS IIa12).

Chambeshi-Bangweulu Plain

The Chambeshi-Bangweulu Plain is the most extensive land region. It encompasses the area surrounding and including Lake Bangweulu and the Chambeshi Floodplain, and is characterised by very gentle slopes and slight relief with continuous dambos along the rivers, although the stream frequency is slightly greater and the dambos not so extensive in the granitic zone to the north-west of Lake Bangweulu and the Chambeshi River. Despite its very flat appearance, most of the land region is still undergoing very slight erosion, and the downtilting towards the east of Lake Bangweulu seems to be initiating a new erosive phase. LS IId2 and IId14, however, representing the Chambeshi Floodplain and the eastern fringe of the Bangweulu swamps, are mostly undergoing deposition.

Mpika-Isoka Ridge

The Mpika-Isoka Ridge land region is a high belt of terrain following the Congo Zambesi watershed along the eastern border of the project area. It roughly coincides with the eastern branch of the Irumide folded zone and is characterised by gentle to moderate slopes with a local relative relief frequently between 200 m and 400 m (650 - 1 300 ft). The present phase or erosion is exhuming the folding and the landscape is consequently distinguished by long ridges (see Plate 5) and plunging anticlines and synclines. The land region attains its maximum width north of Mpika where 'quartzite formations are repeated six or seven times' (Marten, 1968a).

Other land regions

Seven other smaller land regions, which are significantly different from those already described, have also been recognised:

1. The Middle Luapula Valley Land Region, comprising a dissected zone in the area surrounding the middle reaches of the Luapula River
2. The Tanganyika Basin Land Region occupying the very dissected area around Lake Tanganyika

3. The Kawimbe Inselberg Plain Land Region, an inselberg plain north-east of Mbala (LS IIb1) which seems to extend northwards into Tanzania
4. The Mambwe-Mwenzo Dissected Plain Land Region along the north-eastern border of the project area, representing a zone below the Mbala-Kawambwa Plateau, which still consists of mature dissection and has not yet been eroded down to the flat Chambeshi-Bangweulu Plain
5. The Tunduma Hills Land Region occupying the high dissected terrain in the extreme north-east corner of the project area, which also extends into Tanzania

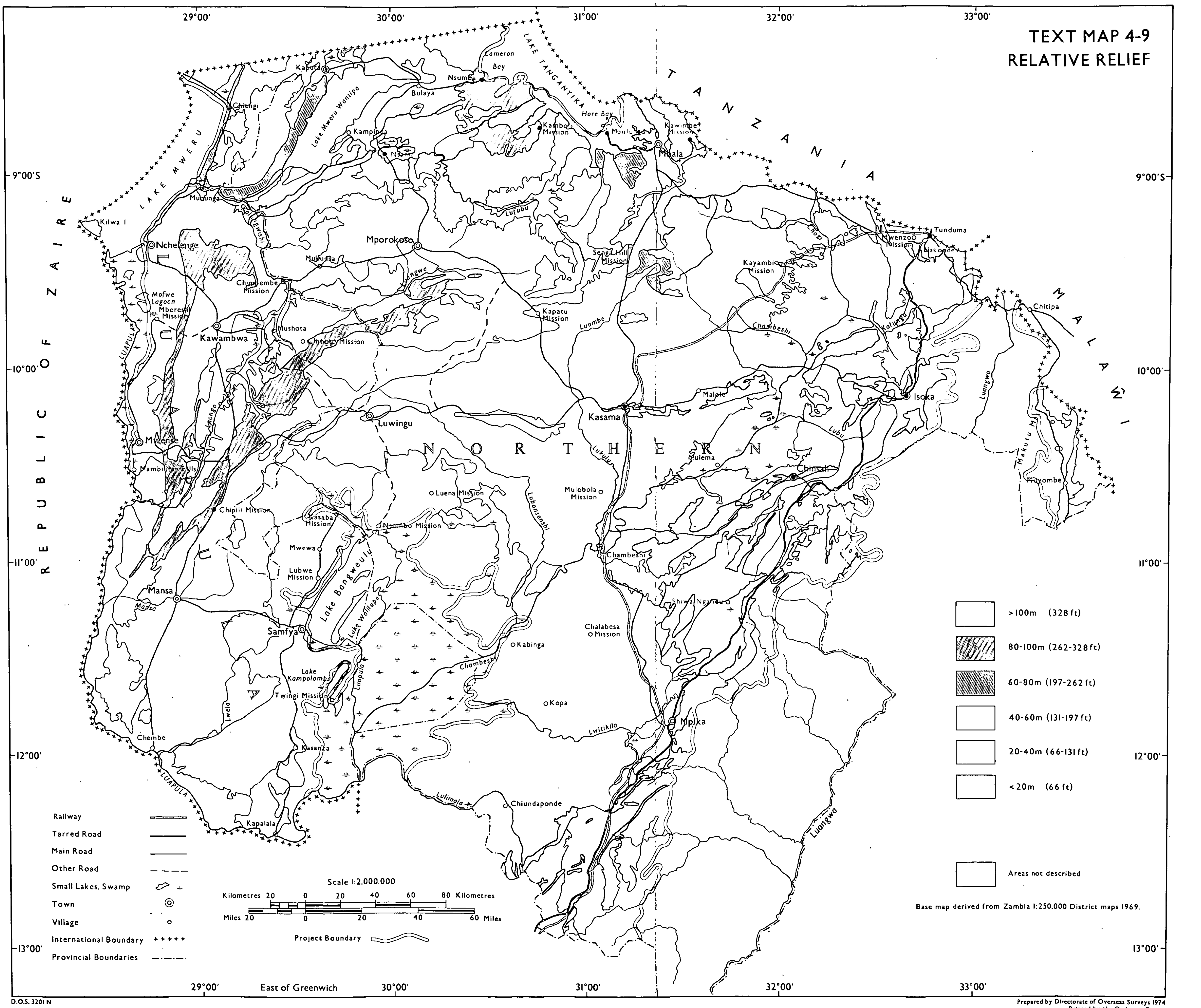
   In the extreme east, east of the Mpika-Isoka Ridge Land Region, the project area intrudes in a number of places into land regions belonging to the Luangwa Valley land province (but excluding those areas where the average slopes exceed 6^{o}). They are:

6. The Upper Luangwa Valley Land Region in the north
7. The Luangwa Valley Shoulder Land Region which is a broad zone east of the Mpika-Isoka Ridge, but above the escarpment along the western boundary of the Luangwa rift
8. An isolated area in the extreme east which has already been designated by Young and Brown (1962) as the 'Plains and Hills West of Nyika'

Drainage

Most of the drainage of the project area (see Text Map 4-10) lies within the Congo catchment area. In fact, the source of the Chambeshi in the escarpment south of Mbala is the source of the Congo. From this escarpment the Chambeshi and its tributaries flow eastwards to enter the Chambeshi Floodplain (LS IId2), which has a large catchment area extending as far as the Great North Road. Just north of the ferry on the Kasama-Isoka road (see Plates 12 and 13), the Chambeshi changes direction to flow south-westwards, and is subsequently joined by other major tributaries such as the Lukulu and Lubansenshi before entering the Bangweulu swamps to the south-east of the lake itself. The present position of the Chambeshi effluence and the drowned valleys on the north-western side of Lake Bangweulu suggest that the lake has been tilted from a position further to the south-east to its present position. The lake and its related swamps are drained by the southward flowing Luapula River which changes direction to flow northwards along the Zaire border to enter Lake Mweru. The sudden change of direction of the Luapula seems to indicate capture of a former river which probably flowed south-westwards from about Kapalala across the Zaire pedicle to join the Kafue (Dixey, 1941, p.33). Lake Mweru is drained at its northern end by the Luvua River which forms part of the headwaters of the Congo. Between Lakes Mweru and Tanganyika lies Lake Mweru Wantipa, whose extent has varied considerably in historical time; for example, Livingstone mapped the area now occupied by the Lake as three interlaced rivers (Waller 1874). Evidence of the lake's former greater extent is provided by the profile of its emergent shore (see diagram accompanying land facet 3 of LS Ia7 in Volume 6) and the terraces flanking its overflow channel (ie Mofwe River in LS Ia8). Most of the area between Mporokoso and Mbala lies within the catchment area of the Lufubu River which after a sinuous course enters Lake Tanganyika south-east of Kasaba Bay. Extensive capture, aided by faulting, has enlarged the catchment area of Lake Tanganyika, and since most of the rivers draining into the lake are eroding headward vigorously, it is due to expand further. However, since the lake is drained by the Lukuga River which enters the Congo, it also belongs to the Congo system. The only part of the project area belonging to the Zambesi catchment area is south-west of the Great North Road where the rivers are tributary to the Luangwa River which joins the Zambesi at Feira.

Stream frequency is low, or to put it another way, the interfluves are mostly very wide. The most common drainage pattern throughout the project area is angulate (see Volume 6), indicating strong structural control by the bedrock. The next most common drainage patterns are dendritic or subdendritic, followed by rectangular



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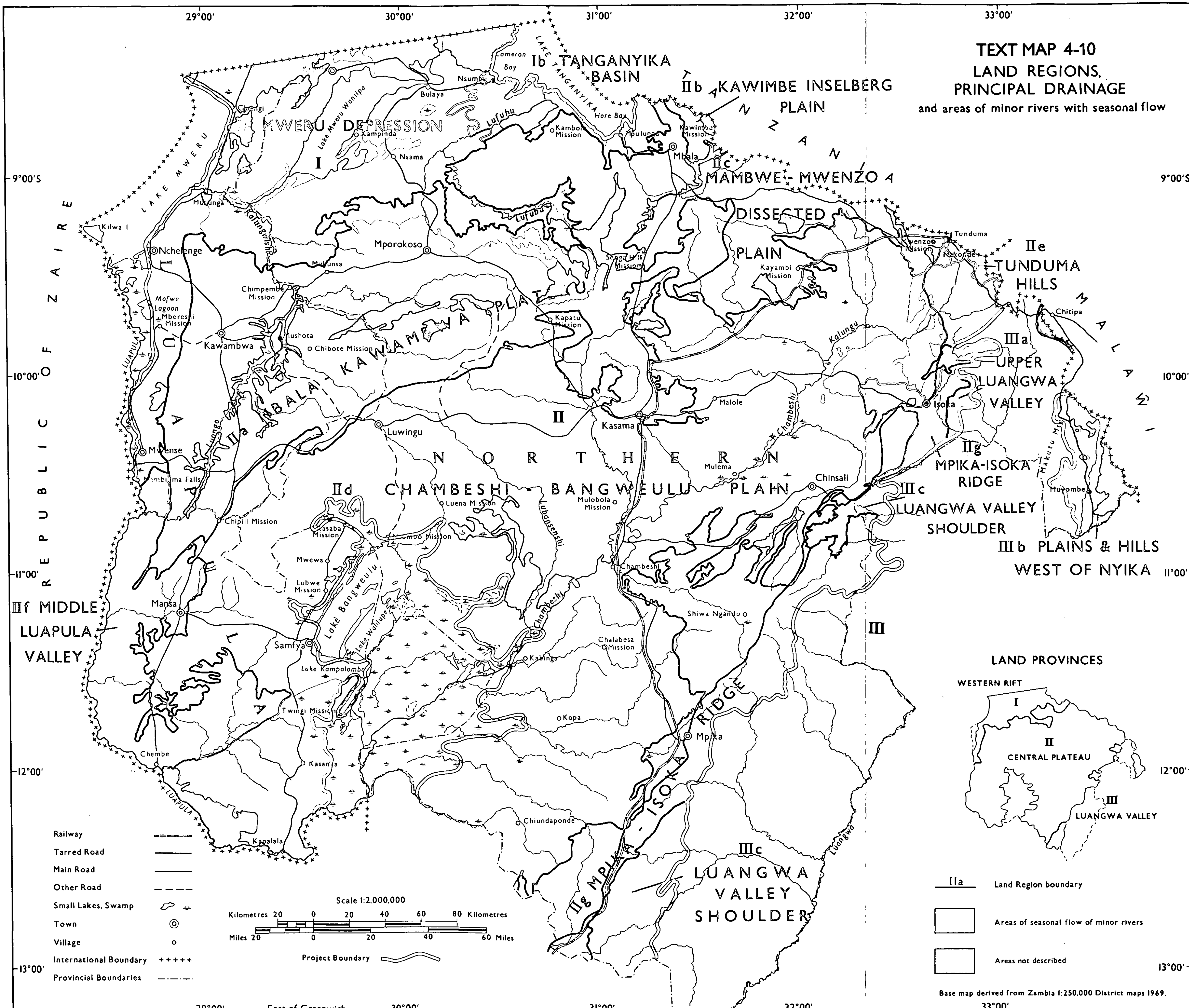

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and subparallel. A study of the effect of geological structure on drainage pattern shows, that of the four major Land Regions Ia, IId, and IIg, the Mbala-Kawambwa Plateau is the most affected by underlying structure, and the Chambeshi-Bangweulu Plain the least, although there is a marked difference between the areas east and west of Lake Bangweulu; in almost the entire western side, structural control is moderate to strong. Of the other Land Regions, IIb, IIe, IIIa, IIIb and IIIc tend to be weakly controlled, mostly areas of high stream frequency; while the Middle Luapula Valley is strongly controlled.

Most of the rivers in the project area are perennial, but in certain peripheral parts such as the low-lying area between Lakes Mweru and Tanganyika and the Isoka district (Text Map 4-10), minor rivers only flow seasonally. The seasonally waterlogged grassland, usually flanking rivers, known as dambos have already been mentioned (see Plate 5). Their widths vary considerably, reaching a maximum of 8 km (5 mi) extending across several rivers, for instance, just west of Kawambwa. (Width is meant here as the distance from the upslope edge of one side of the dambo across the river (or rivers) to the upslope edge on the other side). The widest dambos are mostly found on the Mbala-Kawambwa Plateau, and belong to the type called here 'hanging dambos', so named because instead of occurring in their normal position at the bottom of the valley, they are either perched on one side of the valley or extend over the interfluve into the next valley. They are also sometimes perched on the edges of escarpments. The dambo edges of this latter type often reveal quartzite outcrops (dipping inslope), which are apparently impervious since the dambos overlying them are usually more saturated than any other type. The most extensive dambos downstream are mostly found in the Chambeshi-Bangweulu Plain presumably because there is a relatively higher watertable in this land region; west of Lake Bangweulu they are not so extensive, however. In the well dissected parts of the project area, dambos are infrequent and narrow in width.

Some profiles were levelled across dambo interfluve boundaries with a dumpy level to establish whether there was any change of slope at the boundary. The survey indicated that generally there is no major change in profile across the boundary, and the general convex interfluve cross-section was continued into the dambo below, with no point of inflexion. A convexo-concave cross-section was revealed in some profiles, but the point of inflexion was always some distance from the interfluve-dambo boundary. Many profiles, however, revealed a slight depression just below the boundary (A in Figure 4-8) and a similar depression (B in Figure 4-8) in a semidambo profile coincided with the upper boundary of a well saturated zone. The depressions therefore seem to be related to the emergence of the watertable.

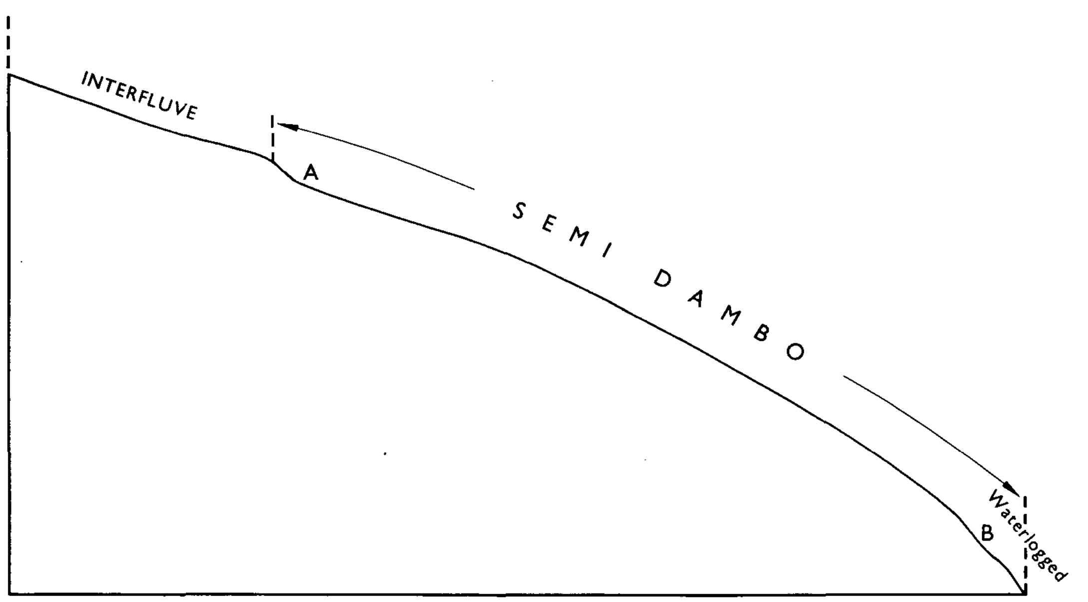

FIGURE 4-8 Profile of a semi dambo 30km (19 mi) east of Mporokoso.
Horizontal scale: 28·8 m to 1 cm (240 ft to 1 in)
Vertical scale: 1·92 m to 1 cm (16 ft to 1 in)

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Planation surfaces

Recognition of planation surfaces is, by necessity, a very subjective process. The planation surfaces described here are based on those described by L C King (1962), who maintains that the two most widespread planation surfaces are of the Early and Late Cainozoic ages respectively. Airphoto and field observation supports the conclusion that there are two widespread planation surfaces in the project area, which can be seen in the area north and south of Kasama (Plate 6). To the south of Kasama the Late Cainozoic surface is almost entirely represented by the Chambeshi-Bangweulu Land Region. Other areas which also seem to belong to this surface are the relatively low-lying part of the Mbala-Kawambwa Plateau in the west (part of LS IIa13) and possibly a downfaulted segment in the extreme north (LS Ia6). The area north of Kasama (LS IIa17) would appear to be part of the Early Cainozoic surface. However, travelling further north, there appears to be a still older surface discernible on Senga Hill and the plateau south of Mbala. The area around Mbala has been recognised as an older surface for some time (Dixey, 1945), but since the area between Luwingu and Mporokoso is at a similar altitude (Text Map 4-7), and the surface on this latter plateau can be traced, via the Chisha Hills and Senga Hill to the plateau around Mbala, it would be not unreasonable to conclude that all these levels belong to the same older surface considered by L C King (1972) to be of Gondwana (late Mesozoic) age. Other remnants of the Gondwana planation surface can be found in the undissected parts of LS IIa19, around Tunduma (the upper parts of LS IIc5 and IIe1), and along the Mpika-Isoka Ridge (LS IIg2 and the remnant plateaux of LS IId7 and IIg1, eg Plate 7). The hills north-east of Mbala (LS IIa11 and IIb1) may be remnants of a still older pre-Gondwana planation surface. The undissected areas between the Gondwana and Late Cainozoic surfaces presumably belong to the Early Cainozoic planation surface, eg the area north of Kasama (LS IIa17), the plateau around Kawambwa (part of LS IIa13), the plateau south of Mansa (part of LS IId10ii) and possibly the tilted plain south-west of Kambole Mission (LS IIa1), although this latter surface might be part of the Gondwana surface. Most of the rest of the Early Cainozoic planation surface is undergoing youthful dissection, eg LS IId5, most of the Mambwe-Mwenzo Dissected Plain, areas south of Shiwa Ngandu (LS IIg8) and Mpika, and the Plains and Hills west of Nyika. Other undissected areas which would appear to belong to the Early Cainozoic planation surfaces are the plain south of Tunduma (LS IId3 and IId9), LS IId12, the area south of Chinsali (part of LS IId8) and possibly some downfaulted areas in the far north (LS Ia3 and Ia9).

Quaternary erosion is active along the Muchinga Escarpment north of Mporokoso and along the Middle and Lower Luapula Valley, resulting in a Quaternary planation surface in the Lower Luapula Valley, (LS Ia12), part of which is probably a lacustrine terrace, and in the pediplain north of the Muchinga Escarpment (LS Ia10 and Ia11). Quaternary erosion is also very active in the Tanganyika Basin. It should be appreciated however that the area immediately below and in front of a retreating escarpment has a recent age, although it may be an extension of an old planation surface. Examples of this can be seen in LS IIIa2, IIg3, IIg7, and at the boundary of LS IId8 and IIg1. Widespread tilting, presumably associated with the East African rift valley system, can be found throughout the project area. Examples (giving the direction of downtilt in brackets) are as follows:

> Lake Bangweulu (NW), LS Ia3 (SE), LS IIa1 (WSW), Mushota (SSW), LS IIg9 (ESE) and the southern part of LS IId8(WNW-W).

Correlation of geomorphic and soil variables

A correlation analysis of various geomorphic and soil variables was attempted. It is hoped that correlations, particularly if they lead to a better understanding of the processes involved, will aid prediction, particularly in airphoto interpretation. However, correlations should not be interpreted too literally in terms of cause and effect. In such a complicated and interacting system, many correlations may not be causal but due to chance, and in addition a large number only appear to correlate because they are both de dependent on a third variable.

PLATE 5 Dambo in L.S. IIg13. Ridge of L.S. IIg1 in the background

PLATE 6 Escarpment separating the Early from the Late Cainozoic planation surfaces west of Kasama. The former comprises the skyline, the latter the foreground. Photograph taken on the Kasama-Luwingu road south of Chilubula Mission

PLATE 7 Gondwana partial planation surface north of Mpika

TABLE 13 Correlation matrix

	Geology				Topography						Vegetation	Climate		Soils												
	% sedimentary rocks	Bedrock relative permeability	% metamorphic rocks	% bedrock basicity	Stream frequency	Relative relief	Dissection index[1]	Altitude	Very gentle slopes		Dambo width	Mean annual precipitation	Precipitation seasonality	Clayey soils		Intermediate soils		Sandy soils		Shallow soils			Subsoil hues		Textural change with depth	
									%<2°	%<1°				% freely drained	% total	% freely drained	% total	% freely drained	% total	% ox.[2] <50 cm depth	% ox.[2] or con.[3] 50-125 cm depth	% ox.[4] + 50 cm depth	% red	% yellow	% uniform	% duplex[5]
% sedimentary rocks	1.000																									
Bedrock relative permeability	0.793	1.000																								
% metamorphic rocks	-0.281	-0.189	1.000																							
% bedrock basicity	-0.320	-0.271	0.654	1.000																						
Stream frequency	-0.242	-0.157	0.378	0.404	1.000																					
Relative relief	0.189	0.211	-0.013	0.028	0.194	1.000																				
Dissection index[1]	0.087	0.100	0.075	0.121	0.420	0.923	1.000																			
Altitude	-0.004	-0.010	0.040	0.154	0.137	0.139	0.104	1.000																		
% <2° slopes	0.098	0.101	-0.278	-0.271	-0.491	-0.361	-0.411	-0.295	1.000																	
% <1° slopes	0.103	0.117	0.192	-0.167	-0.413	-0.379	-0.392	-0.400	0.789	1.000																
Dambo width	0.220	0.220	-0.175	-0.210	-0.374	-0.095	-0.189	0.043	0.266	0.208	1.000															
Mean annual precipitation	0.169	0.189	-0.364	-0.340	-0.265	-0.030	-0.033	-0.020	0.210	0.179	0.104	1.000														
Precipitation seasonality	-0.223	0.475	0.278	0.193	0.157	0.035	0.104	0.419	-0.257	-0.262	-0.123	0.051	1.000													
% freely drained clayey soils	0.100	-0.119	-0.177	0.044	0.056	-0.141	-0.080	0.120	-0.109	-0.040	-0.091	0.138	0.168	1.000												
% total clayey soils	-0.025	-0.121	-0.218	0.012	0.092	-0.138	-0.059	0.088	-0.077	0.003	-0.109	0.100	0.205	0.935	1.000											
% freely drained intermediate soils	-0.004	0.038	-0.076	-0.105	-0.328	-0.071	-0.184	0.244	0.351	0.153	0.265	0.309	-0.029	-0.332	-0.424	1.000										
% total intermediate soils	-0.089	-0.046	0.044	-0.016	-0.341	-0.162	-0.250	0.257	0.384	0.177	0.231	0.274	0.088	-0.395	-0.443	0.877	1.000									
% freely drained sandy soils	0.185	0.213	0.030	-0.086	-0.035	0.524	0.455	-0.029	-0.102	-0.089	0.145	-0.160	-0.133	-0.228	-0.250	-0.128	-0.286	1.000								
% total sandy soils	0.199	0.209	0.059	-0.076	-0.055	0.477	0.410	-0.044	-0.081	-0.045	0.145	-0.131	-0.108	-0.237	-0.049	-0.130	-0.281	0.981	1.000							
% ox[2]<50 cm depth	-0.073	-0.086	-0.104	0.067	0.146	-0.102	-0.044	-0.352	-0.038	0.034	-0.234	-0.286	-0.180	0.018	0.075	-0.509	-0.514	-0.145	-0.156	1.000						
% ox[2] or con.[3] 50-125 cm depth	-0.141	-0.118	0.034	0.210	0.080	-0.122	-0.044	-0.147	-0.010	0.112	-0.178	-0.292	-0.032	0.149	-0.241	-0.430	-0.230	-0.194	-0.182	0.477	1.000					
% ox[4]<50 cm depth	-0.012	0.015	0.144	0.126	0.408	0.001	0.093	-0.356	-0.358	-0.170	-0.331	-0.411	-0.205	-0.069	-0.026	-0.731	-0.724	-0.065	-0.053	0.660	0.380	1.000				
% red subsoil hues	0.213	0.193	0.136	0.270	0.013	0.352	0.288	0.348	-0.208	-0.200	-0.091	0.051	0.140	0.142	0.071	0.220	0.112	0.129	0.113	-0.271	-0.268	-0.269	1.000			
% yellow subsoil hues	-0.166	-0.117	-0.251	-0.364	-0.297	-0.204	-0.252	-0.046	0.404	0.262	0.346	0.263	-0.111	-0.011	-0.076	0.533	0.416	0.040	0.038	-0.290	-0.181	-0.517	-0.530	1.000		
% uniform soils	0.102	0.226	0.042	0.079	-0.004	0.115	0.030	0.304	-0.125	0.179	0.074	0.103	-0.043	-0.235	0.242	0.326	0.287	-0.008	-0.016	-0.153	-0.223	-0.190	-0.205	-0.007	1.000	
% duplex[5] soils	-0.156	-0.259	-0.084	-0.092	-0.117	-0.164	-0.121	0.168	0.124	0.079	0.071	-0.102	0.069	0.151	0.241	-0.188	-0.179	-0.073	-0.049	0.318	0.287	0.064	-0.217	0.072	0.340	1.000

1 Product of relative relief and square root of stream frequency
2 Oxidic duricrust
3 Concretionary horizon
4 Oxidic duricrust or other rock
5 Soils with increase of >10% clay over <20 cm vertical profile

The correlation analysis has been attempted both visually by comparing areal distributions of different variables on maps, and quantitatively using a correlation matrix (Table 13) (derived from a data matrix with provisional land systems as the individuals) and its correlation structure (Figure 4-9) (King 1975a). The soils variables are taken from the soil capability classification in Volume 3.

The 't' statistic was applied to the correlation coefficients and although not all the variable distributions exhibit bivariate normality, the 99.9% probability level was vas found to be a useful level for constructing the correlation structure diagram (Figure 4-9). Even at this level, however, the diagram was still found to be too complicated for easy construction and interpretation. Some variables were therefore amalgamated into 'black boxes' in order to achieve further simplification. Separation of the freely drained subdivisions of the soil textural classes shown in Table 13 does not add to the correlation structure and the subdivisions have therefore been amalgamated in Figure 4-9. Similarly, the subdivisions of the shallow soils and very gentle slopes were reunited. Table 13 shows a very high correlation between bedrock permeability and sedimentary rocks because coarse textured rocks, which are abundant throughout the widespread Kibaran System, are highly rated in Leopold *et al's* (1964) bedrock relative permeability table, from which the values are calculated. Furthermore, there are few basic igneous rocks, so that the metamorphic rocks correlate highly with bedrock basicity (see under 'Geology'). The four geological variables have therefore been amalgamated into two because the latter contribute as much to the correlation structure as the former. The dissection index appears irrelevant to the analysis and has been omitted. Uniform soils correlate negatively with duplex soils at the 99.9% level (as might be expected) but neither of these two variables correlate with any other at this level and they have therefore also been omitted from Figure 4-9.

Figure 4-9 indicates that of the geomorphic and soil variables considered the most closely related are relative relief to sandy soils, and the subsystem involving intermediate and shallow soils and very gentle slopes and stream frequency. In other words soils on the very gentle slopes which occupy most of the project area tend to have an intermediate texture, while areas of higher stream frequency and steeper slopes give rise to shallower soils, as might be expected.

Stream frequency tends to be higher on the metamorphics of the pre-Kibaran, but this is largely because these rocks are situated along the edge of the Luangwa Valley. There is no obvious characteristic topography overlying the Kundelungu System, except for its very subdued nature, and this, together with the great weathering depth, makes delineation of the contact with the granite difficult (see under 'Geology').

Another model, which allows the inclusion of non-numerical variables, was constructed using the information theory statistic (Estabrook, 1967; King, 1975b). In Figure 4-9a 'D' and 'S' are distance and similarity measures respectively: the strength of interdependence or correlation is indicated by the number of lines shown connecting the boxes. The main difference between this model and that produced by the previous correlation one is the central position of the geological variable, which could be incorporated more easily into the information theory analysis. Furthermore, investigation of the conditional probability submatrices used in the information theory analysis shows: 'The Kibaran System is characterised by local relief of the order of 40-60 m, moderate to strong drainage control, a stream frequency of 0.1-0.35 per km, and a greater proportion of red soils and very wide dambos than those overlying granite. It also has a greater proportion of narrow dambos, due to the association of major zones of dissection with the Kibaran System. These dissected areas also cause the Kibaran System to have a greater proportion of shallow and sandy soils. The granite is characterised by local relief of the order of 20-40 m, little structural control of drainage, and although the average stream frequency is 0.1-0.35 per km, it has a greater proportion of higher stream frequencies than the Kibaran System. Duplex soils are also more common over granite' (King, 1975b).

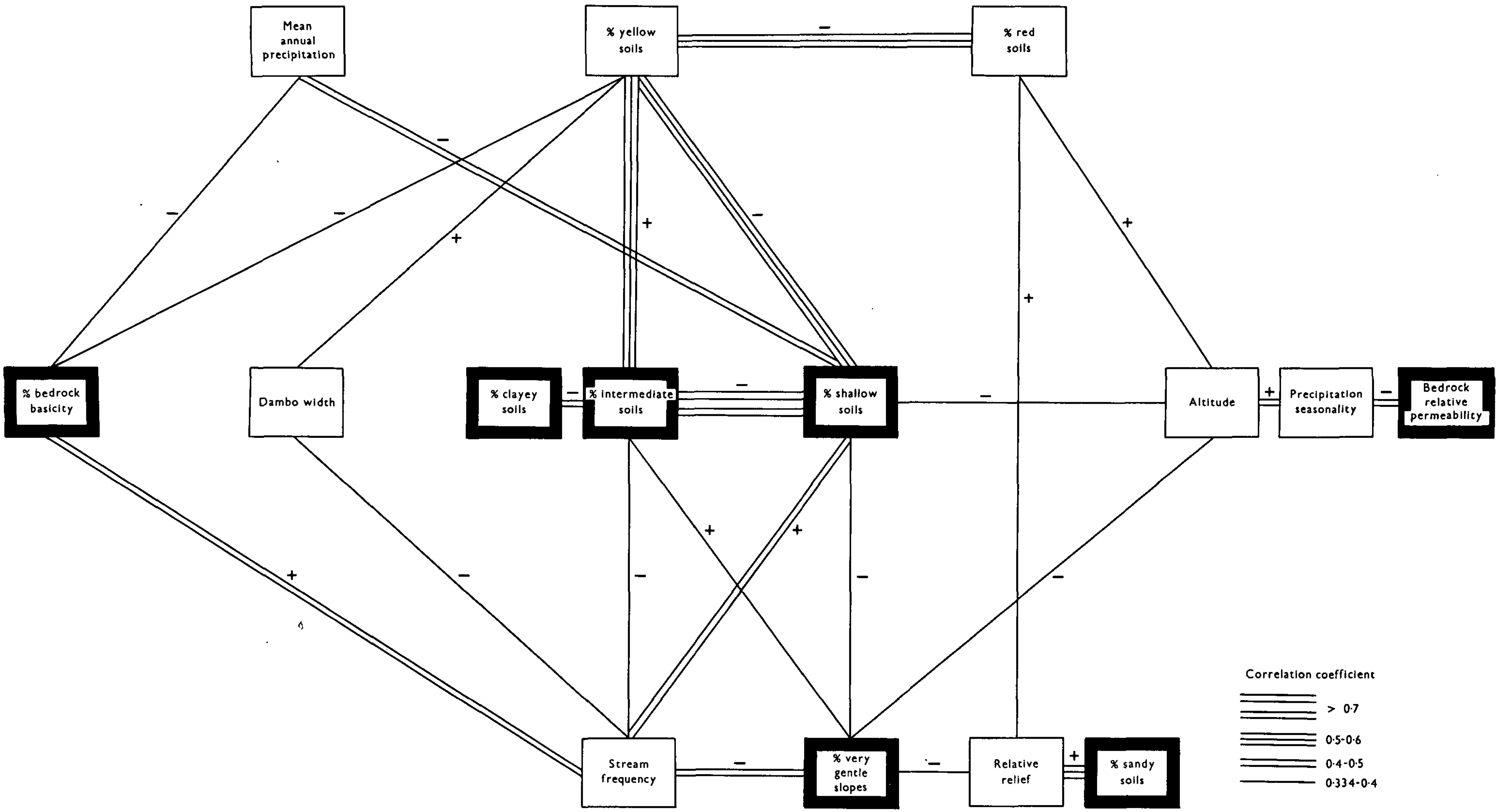

FIGURE 4-9 Correlation structure.

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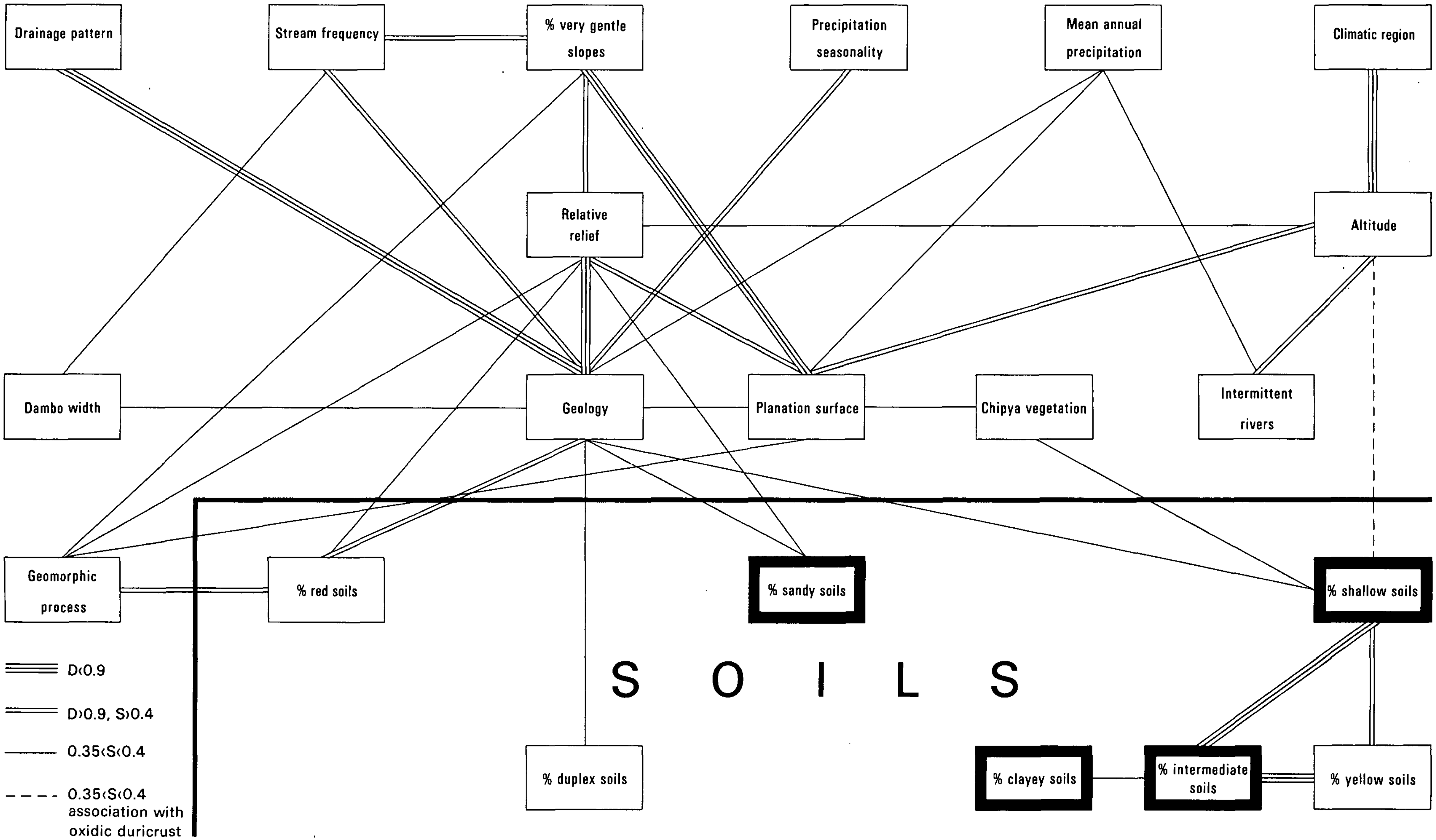

FIGURE 4-9a Information theory interdependence analysis structure

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Dissection index and relief-stream frequency diagram

The three most fundamental variables for describing landscape geometry are relief, stream frequency (or drainage density) and slope. Theoretically, they are interrelated as follows:

$$\tan \theta = KR \sqrt{F}$$

where θ is the angle of slope, R is the relative relief, F is the stream frequency and K is a constant. The product $R\sqrt{F}$ is called here the 'dissection index' and is analogous to ruggedness which is the product of drainage density and relative relief. The least rugged areas will have low values of the index and are likely to be the areas of most use from an agricultural point of view. Dissection index values for each land system are given in Volume 2 and for each land region in Table 13. As indicated by the above equation, they roughly correlate with angle of slope. Alternatively the relative relief and stream frequency data for each land system or land region can be plotted on a scatter diagram, the axes of which represent the two values. This is called a relief-stream frequency or R-F diagram (R B King, 1972) (Figures 4-10 and 4-11). The figures in brackets along the stream frequency axes are the equivalent values for drainage density at a scale of 1:50 000. Where a land system occurs in more than one land region only one name is given in Figure 4-10. Approximate angle of slope isopleths are also shown. Land units in the top right-hand corner have high dissection indices as opposed to those in the bottom left which have low ones. Land units in the top left have high relief values but low stream frequency values, and are characteristic of areas of youthful incision; while those in the bottom right have high stream frequencies but low relief values representing areas of dissection so advanced as to have lowered the interfluves. This could be due to removal of vegetation, susceptibility of the soil to erosion, rainfall or lowering of base level and associated headward dissection of the valleys. This latter process is particularly active in the Luangwa Valley Land Province (Land Province III). The line AB in Figure 4-10 represents the lower limit corresponding to land systems 60-80% of the slopes of which are less than 1°. It would appear therefore that if slopes become more gentle than this, deposition will take place.

Geomorphic processes

In order to understand a landscape, it is important to appreciate the geomorphic processes which have produced it. The process which it is thought produced the planation surfaces, and is now responsible for the erosion of or the retreat of the escarpments, (ie the major features of the landscape), is called 'pediplanation'. It is described by L C King (1953) as parallel retreat of hillslopes with concomitant pediment (or concave footslope) enlargement. However very few of the land systems which fall between the major escarpments appear to show much evidence of pediplanation, a notable exception being LS IIb1; most land systems contain multi-convex profiles indicative of 'peneplanation' or downwearing.

The landscape of the project area is mainly dependent on two factors: tectonic stability and the subhumid subtropical climate with seasonal rains. These two factors influence the degree and speed of river incision, and the rate of weathering and erosion of the interfluves. The project area lies in an extremely stable part of the world, so that wide plains have had time to develop between the infrequent periods of tectonic uplift. At the same time, since the interfluves occur on old planation surfaces, and the climate provides ideal conditions for chemical decomposition, ie high temperature and soils at field capacity during the rainy season, deep weathering is prevalent. At present, the interfluves are mostly well protected from soil erosion by vegetation, as evidenced by the rivers, which are clear even during the rainy season. Removal of this vegetal cover, whether by burning (see under 'Vegetation') or some other means, could, if sufficient care is not taken, lead to serious erosion on inclined surfaces, eg lower interfluve slopes, as shown by the deep gullies found along footpaths and roads after heavy rain. (The presence of rivers with only seasonal flow in LS IIc5 may be due to increased runoff caused by vegetation clearance). However, some natural erosion on the interfluves still takes place in the form of sheetwash, solution and creep aided by termites.

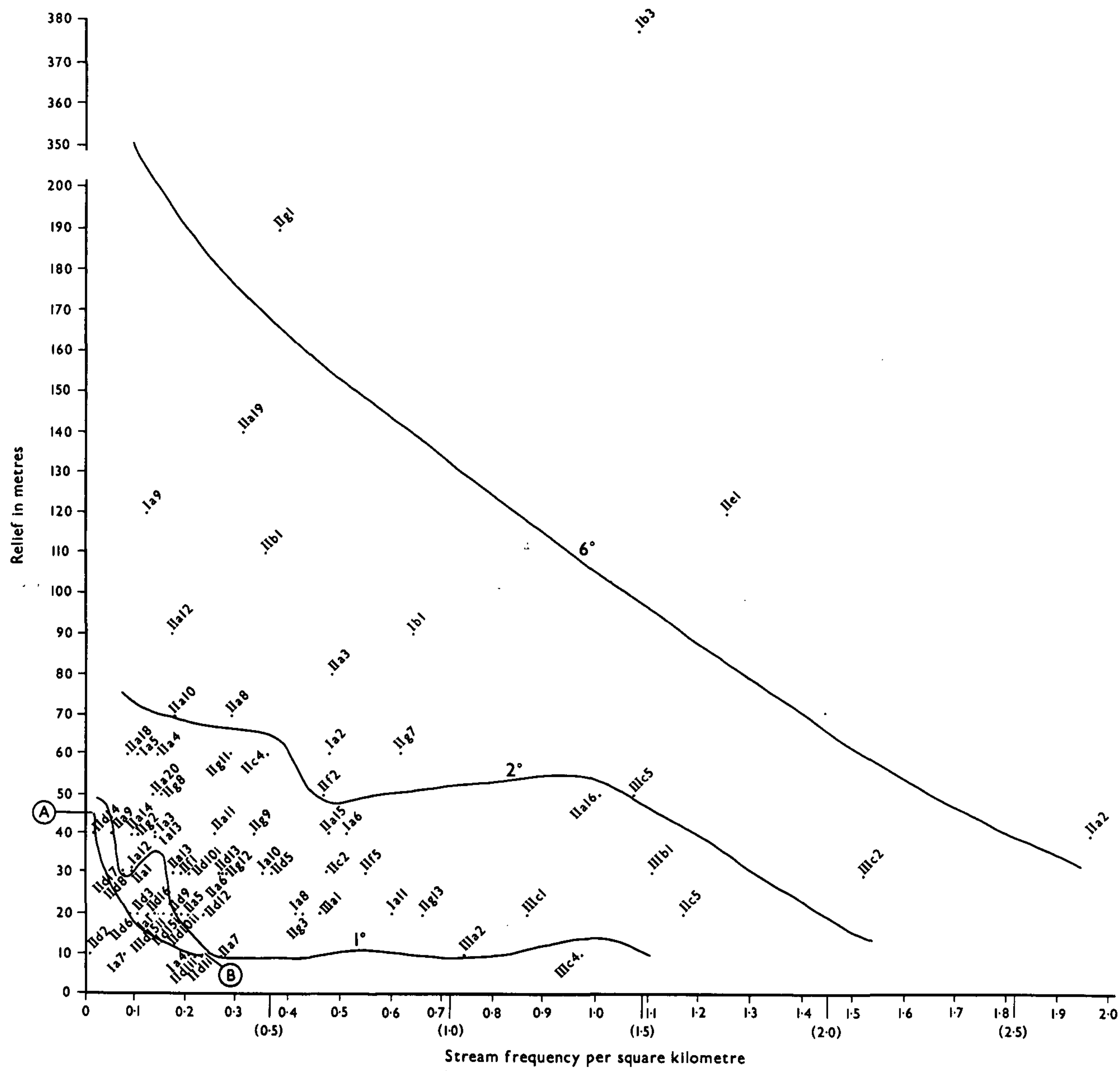

FIGURE 4-10 Land system R-F diagram.

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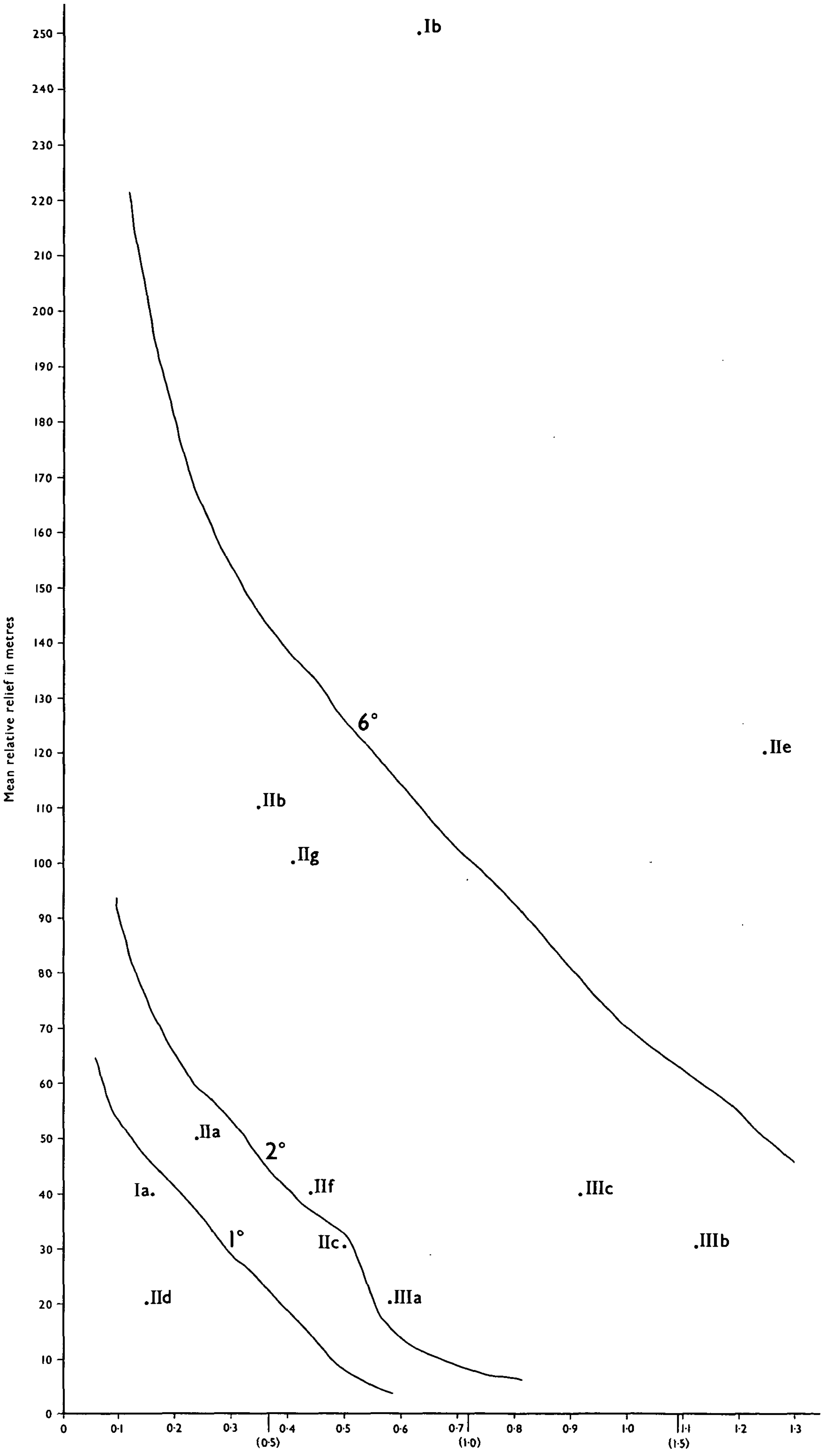

FIGURE 4-11 Land region R-F diagram.

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Thus over most of the project area geomorphic processes are operating very slowly, but this stable situation could be easily reversed by denudation which would lead to soil erosion. Most of the landscape is, in fact, senile and undergoing peneplanation, but evidence remains which can still be seen in the present-day escarpments and occasional younger landscapes such as LS IIb1, which suggests that 'the full vigour of change ... was accomplished ... by scarp retreat and pedimentation' (L C King, 1962). In addition, the East African rift system has also affected the area significantly. It has resulted in the Tanganyika Basin; fault scarps and resultant lakes in the north; the intense dissection in the Luangwa Valley Land Province; the warping and tilting of the central plateau, producing such features as Lake Bangweulu and its incised valleys east of the lake, and drowned valleys on the west (the Chambeshi Floodplains); as well it is probably partly responsible for the Mpika-Isoka Ridge, the tilting of LS IIa1, and the Mushota back-swamps.

ENGINEERING ASPECTS

The section is mainly devoted to road construction, since roads play a large role in development of an area. It must be appreciated, however, that this record is only a by-product of the main agricultural survey and the descriptions are therefore largely qualitative. Furthermore, it was not possible to spend any time investigating remote land facets.

Road construction

Terrain geometry

The geometry of the terrain embraces location, gradients, radii of curvature, amount of cut and fill, number of river crossings, etc. Land system analysis gives an indication of these factors. They can be appreciated qualitatively from the block diagram and the description of general morphology, and quantitavely from the data listed at the beginning of each land system description.

Since most of the project area, particularly land regions Ia, IIa, IId and to a lesser extent IIc, consists of only very gentle slopes (Text Map 4-8), very little cut and fill will be necessary, and there will be not much difficulty in maintaining low gradients. The average number of stream crossings can be calculated from the stream frequency; thus, the number of stream crossings that can be expected in one kilometre of road will be the square root of the number of streams in a square kilometre. In most of the project area, but particularly in land regions Ia, IIa and IId, the stream frequency varies from about 0.08 to 0.3 streams per km^2 (0.2-0.8/mi^2). It should be noted, however, that whereas the stream frequency gives the *average* number of stream crossings in *any* direction, knowledge of the drainage pattern shows whether judicious route selection could eliminate a large number of crossings, eg by aligning the road as much as possible in the direction of a parallel drainage pattern. However, most of the project area possesses an angulate drainage pattern, so that road direction will not significantly affect the number of river crossings. Dambos will need to be traversed too: information on dambo widths can also be found in the land system descriptions.

Construction materials

Ideally, construction material should consist of a gravel of hard angular pebbles in a sandy matrix (R B King, 1964). Such a material is rarely found in practice, but approximations to it will suffice, depending on the foundation layer of the road and the local specifications. Roads are built of four main layers which from the bottom upwards are: formations or fill divided into *lower* and *upper sub-grade, sub-base* and *base-course.* The quantities needed (and therefore transportation cost) increase with the depth of layer but the textural plasticity and strength specifications correspondingly decrease. In addition, an aggregate is needed for the bitumen carpet, and concrete stone and sand for culverts and bridges.

Since smectoid (or more active) clays, which in the project area are only found in small pockets associated with basic rocks, are the only materials really unsuitable for fill, there will be no difficulty in finding materials for this layer. In this area of deep weathering, however, the materials for the upper layers will only be found where particularly resistant rock types have been revealed by erosion, or where material has been sorted by transportation, which is here largely alluvial. In areas of mature dissection, such as most of LS Ib3, there is usually little difficulty in finding material of the former category, but over most of the project area which consists of old planation surfaces with dissection varying between very little and little it will be necessary to look for isolated occurrences of resistant slopes, which are the result of local vertical incision or lateral corrasion. In addition, there are areas of irregular outcrop.

Inselberg

Inselbergs usually consist of rock outcrops or boulders overlying such outcrops. The lithology of most inselbergs consists of granite or quartzite and/or sandstone (see under 'Geology'). In areas of mixed granite and gabbro (eg LS IIIc5), however, most of the inselbergs, especially the larger ones, are composed of gabbro. Inselbergs occur as a dominant land facet in LS IIb1 and are characteristic of LS IIf2 and LS IIc5, particularly the latter. In all three land systems, the inselbergs have an igneous composition and can be used for sub-base, base-course and concrete stone.* Arenaceous (ie coarse-grained sedimentary) inselbergs can also be quarried for sub-base and base course, and the quartzitic ones can be used for concrete stone and as aggregate for the bitumen carpet (hereinafter referred to as 'chips').

Vein ridge

The vein ridge is a recurring land facet throughout much of the project area, and is particularly common in LS Ia10 and IIa2, where the ridges occur as very large features (Plate 8a), although elsewhere they are still large enough for a quarry (Plate 8b). They are composed of crystalline quartzite and sandstone impregnated with quartz veins, (Plate 4) and/or pure quartz usually at the ridge centre. They should prove suitable quarry sites for sub-base, base-course, concrete stone and chips; but their variable composition may preclude their use for chips without careful sorting.

Structural features

Structural features are the most likely sources of construction material in areas of sedimentary rock. The landform of these features will vary according to the dip of the rock: steeply dipping sedimentary rocks result in hogbacks; rocks without dip may produce mesas (see Volume 6). Furthermore each landform can be divided into a structurally controlled land element,eg a scarp or front slope and back or dipslope land elements (see Volume 6). The latter dipslope land element is usually preferred for quarrying because not only is the bedrock frequently overlaid by residual gravel, but also where the resistant bed is thin, the scarp face will be mostly composed of the underlying rock, which, being less resistant, is probably not suitable for road construction. In the project area, quartzite usually forms the resistant bed and since it is mostly thickly bedded, the latter situation does not normally arise; but in some areas, particularly LS Ia10 and IIa2, the resistant bed is often chert overlain by gravel which is probably very suitable for sub-base (since it does not need blasting) and possibly for base-course, though it may be only a metre or so thick (3-6 ft). In some areas, the resistant horizon is hardened plinthite and is probably very suitable for sub-base and base-course. Benches of hardened plinthite, called 'gallery laterite', are often found on the lower slopes of interfluves and piedmonts, a fine example of which can be seen in the main valley west of the Mpanda Hills near Isoka. Most of the zones of slope steepening at the contact between the interfluve and dambo land facets are probably due to hardened plinthite, although outcrops may not be visible (Plate 9).

Outcrops and sub-outcrops

In addition to areas where resistant rocks form definite landform features, outcrops of quartzite and sandstone may also form areas of irregular relief or microrelief in places

* Much of the information on the suitability of rock types for road building and foundations is taken from Floyd (1967)

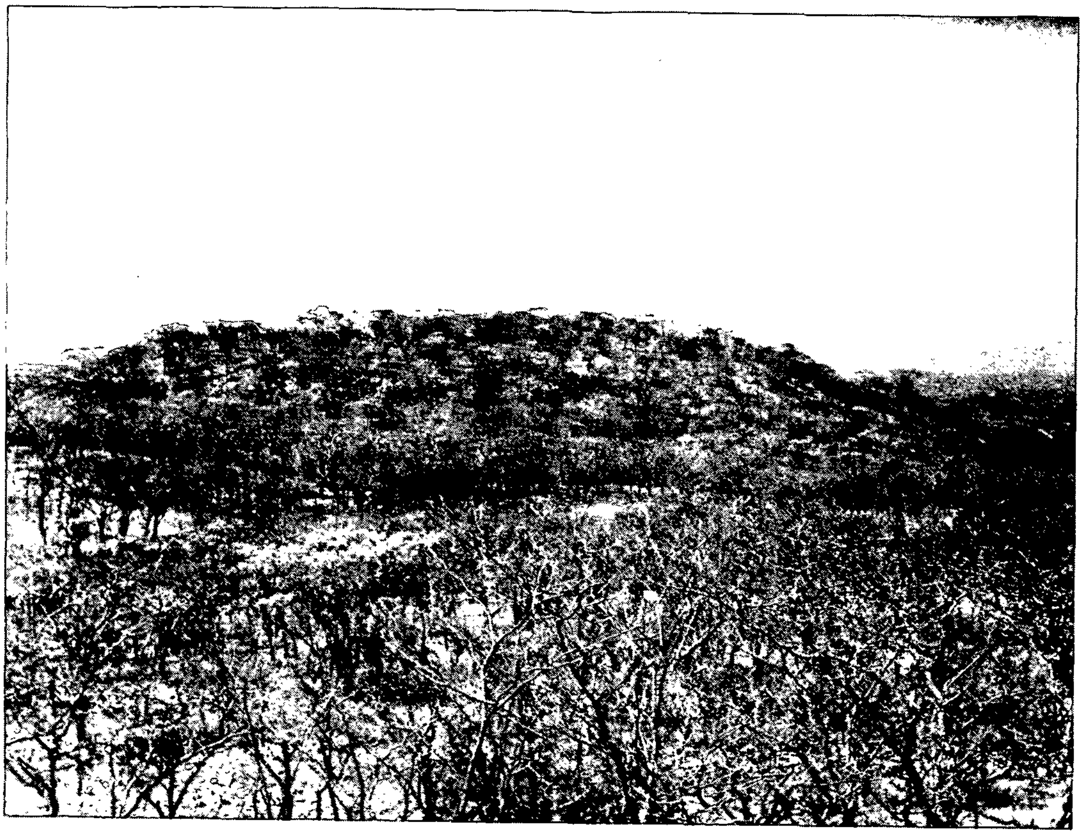


PLATE 8a Large vein ridge 37 km (23 mi) south-east of Mporokoso

PLATE 8b Vein ridge 14 km (9 mi) south of Kayambi

PLATE 9 Floodplain splay on the Chozi Floodplain. Note slope steepening at interfluve-floodplain boundary due to plinthite sub-outcrop

PLATE 10 Lumangwe Falls on the Kalungwishi River

associated with hanging dambos. The resistant layers do not always penetrate the land surface, but give rise to surface gravel or sand. This is particularly common along the alignment of an intermittent quartzite ridge. These ridges are also often surrounded by medium to coarse colluvial sand which, where present in sufficient quantity, is suitable as binder and, if coarse enough, as concrete sand. This sandy colluvium can usually be recognised on aerial photographs by high reflectance, but similar areas with the same high reflectance, especially far from ridges, may only consist of superficial quartz. Conglomerate horizons weather to a rounded quartzitic gravel in a sandy matrix, examples of which can be seen in the Ngona Valley just below the Muchinga Escarpment west of Kawambwa, and in the Mpika-Isoka Ridge Land Region, particularly near Mpika where a colluvial deposit of the gravel is being quarried. Plinthite is also a common sub-outcrop but it is very difficult to locate from aerial photographs.

Suitable materials for road construction can also be exhumed by local erosion. Valley incision, either by youthful vertical erosion or by the more mature lateral corrasion producing undercut slopes, has revealed, for example, fresh granite in LS IId3, fresh quartzite in LS IIg2 and plinthite in LS IIc5. Both abandoned and present-day lacustrine cliffs commonly show plinthite as well as the local rock type.

Transported material

There are four types of transported material in the project area: aeolian (windblown), colluvial, riverine and lacustrine.

The aeolian deposits consist of very scattered small dune fields of medium to coarse sand found along the shores of Lake Tanganyika and Lake Mweru Wantipa. They could probably be used as binder and concrete sand.

Debris slopes make up the colluvial deposits, usually consisting of boulders with an average diameter of about 1 m (3 ft). Since most of the scarps, or at least their upper horizons, are composed of quartzite, the boulders of the debris slope usually also consist of quartzite. It should, however, be realised that the debris slope may be shallow and quarrying might reveal softer material underneath.

Riverine deposits range from moderately sloping alluvial boulder cones (Volume 6) found in the Tanganyika Basin, to finer-grained deposits found on wide floodplains. The grain size of an alluvial fan deposit tends to decrease as the fan's catchment increases in area. Thus alluvial fans at the base of scarps consist of material as coarse as that comprising debris slopes. These fans are better quarry sites, however, because of the ease with which they can be worked, their smaller boulder size and their greater depth. The finer-grained material of the alluvial fans which have larger catchments is not however suitable for road construction. River terraces are also variable in composition, ranging from material too fine to be useful to rounded quartzite gravel, found along the Luwalisi and Kalungwishi Rivers in LS IIIa2 and Ia2 respectively. The coarsest material found on floodplains occurs in bars and to a lesser extent levées. These are usually sandy and can be used as binder and sometimes as concrete sand. Patches of medium coarse sand are also found on the backland (Volume 6), frequently as floodplain splays (Plate 9) but they are usually of too small a size to be economic.

Lacustrine bars and beaches, whether raised or not, consist of coarse sand, suitable as fine aggregate for concrete and as binder. Emergent shores, lacustrine terraces and plains, however are very variable in composition.

Foundation problems

Three main lithological units occur in the area (Text Map 4-5): quartzite and sandstone of the Kibaran System; siltstone, mudstone, shale and sandstone of the Kundelungu System; and granite. Although most of these rock types are deeply weathered, probably to a depth of the order of 50 m (150 ft), there is very little evidence of smectoid clays, and deep piling should therefore nor normally be necessary. Most of the Kibaran System contains good-quality rock, but care should be taken that the foundations do not lie in the rare argillaceous (shale, siltstone, mudstone or phyllite) or schistoze horizons.

TABLE 14 **Characteristics of the major rivers**

River	Geographical coordinates		Average width		Average depth		Banks				Dry season flow
							Composition	River sand	Height		
	S	E	m	ft	m	ft			m	ft	
Bemba	10° 36′	33° 28′	10	30	1	3	Alluvium over rock	Flaky cmf PA	4	12	Fast
Chambeshi	9° 49′	31° 41′	30	100	>4	>12	Alluvium	In bars	3	9	Slow
Chambeshi	10° 01′	32° 07′	40	130	>4	>12	Alluvium	m(F)	2	6	Fast
Chambeshi	11° 10′	30° 47′	100	330	>4	>12	Alluvium	m(F)	3	10	Fast
Choma	8° 29′	29° 40′	25	80	1	3	Alluvium	m-c(F)	1	3	Very slow
Kalungwishi	9° 33′	29° 26′	40	130	>4	>12	Alluvium	nil	0.6	2	Medium-fast
Kalungwishi	9° 03′	29° 02′	30	100	>4	>12	Alluvium	m	1	3	Fast
Lubansenshi	10° 28′	30° 25′	20	65	1-2	3-6	Rock and alluvium	nil	1	3	Fast
Lufubu	9° 05′	30° 20′	50	160	3-4	10	Alluvium and rock	cSPL	< 1	2-3	Medium-fast
Lufubu	10° 43′	29° 05′	15	50	1	3	Alluvium and rock	m(F)	1	3	Very slow
Lukutu	10° 49′	30° 34′	100	330	>4	>12	Alluvium	m(F)	1	3	Very slow
Luombe	10° 09′	30° 58′	25	80	3	10	Alluvium	Very little	0	0	Fast
Luongo	10° 44′	28° 53′	15	50	3	10	Alluvium	m(F)	1	3	Slow
Luongo	10° 41′	28° 43′	20	65	3	10	Alluvium	m(F)	1	3	Medium
Lwela	11° 54′	29° 01′	10	30	2	6	Alluvium	nil	2	6	Medium
Mansa	11° 12′	28° 52′	10	30	2	6	Alluvium and rock	nil	2	6	Medium
Mofwe	9° 08′	29° 14′	7	23	0.3	1	Alluvium	nil	2	6	Very slow
Mukubwe	9° 02′	29° 33′	10	30	>4	>12	Alluvium	cmf(F)	3	10	Medium
Mwambeshi	8° 50′	29° 55′	20	65	1	3	Alluvium	mSPL	4	13	Slow
Ngona	9° 49′	28° 46′	15	50	2	6	Boulders or alluvium	m-c(F)	2	6	Medium

c = coarse, m = medium, cmf = coarse, medium and fine, (F) = scattered over the floodplain, PA = patches
SPL = floodplain splay : see Plate 9.

Fresh bedrock is very rarely found in the Luitikila facies of the Kundelungu System (ie east of Lake Bangweulu), but it is more common in the Luapula facies in the Luapula Valley. The granite is usually deeply (but irregularly) weathered, but where fresh, it (together with other igneous rocks) should present few foundation difficulties. The rare occurrences of weathered basic igneous rocks may, however, contain smectoid clays.

Hydrology

Water is necessary for all engineering development; fortunately over most of the project area, there is an abundant supply (see Text Map 4-10). Furthermore in the Tanganyika Basin and the escarpment surrounding the Mbala-Kawambwa Plateau, there are several sites for hydroelectric power (Plate 10), three of which are already being exploited (on the Lunzua River near Mbala, the Luombe near Kasoma, and at the Musonda Falls on the Luongo north of Mansa). Rivers, however, not only provide water, but also have to be crossed and, in this connection stream frequencies and drainage patterns have already been discussed. The information given in Table 14 will be some guide to the sizes of the major rivers, and give some indication of bridging requirements.

Part 4

Soils

The principal determining factor in soil formation in Northern Zambia is the age of the land surface. The soils may be considered relict soils in that they are not the product of the present, but of previous, erosion cycles, in which wetter and warmer climates brought about the intense weathering and leaching of diverse parent materials to produce a relatively uniform soil over the gently undulating topography, now at a general level of 1 200-1 500 m (4 000-5 000 ft).

The influence of parent rock on soil type can be seen only by comparing the somewhat exceptional soils on parent rocks which have pronounced differences from 'average' rocks, eg soils over basic igneous rock should be compared with those over micaceous sandstones or granites. From our observations the relationship between an exceptional soil and a specific rock type is close; one exceptional soil is found over only one specific rock type except in areas of very steep slopes, and conversely one rock type only is found below each particular exceptional soil. This evidence suggests that the amount of reworking in these soils was limited and of local occurrence and unlikely to be of importance in the area.

The effect of man's activities on the soil has been to further deplete the already low nutrient reserves. The chitemene shifting ash-cultivation makes nutrients available which were previously held within the vegetation. These are removed by leaching and cropping; and the ever-increasing population pressure resulting in cultivation before adequate vegetation regeneration has taken place, is slowly leading to degeneration of the soil into an inert medium.

Estimates of the nutrient status of the top 50 cm of some of the soils (described in Appendix 1) are given in Table 15.

Soil morphology

UPLAND SOILS

Under this heading, all the soils within the survey area will be considered, except dambo, river valley and small floodplain soils, which were not surveyed; and those of the large floodplain areas which are dealt with separately. The soils are considered in terms of their morphological features, basically the presence or absence and degree of development of their three principal horizons.

The principal horizons formed have been termed the organic horizon, the upper subsoil and the lower subsoil. Horizon development is considered to have resulted from the removal of fine material from the upper horizons; but there is no evidence to suggest that clay enrichment has occurred in the lower subsoil. A soil having a coarse-textured organic horizon overlying a uniformly textured profile is therefore considered to lack an upper rather than a lower subsoil.

TABLE 15 **Nutrient cation content of the uppermost 50 cm of soil series, for the profiles described in Appendix (data from Mt Makulu Research Station)**

Soil series	Ca						Mg						K					
	kg/ha			lb/ac			kg/ha			lb/ac			kg/ha			lb/ac		
	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
Lungu**	751	–	–	670	–	–	164	–	–	146	–	–	144	–	–	128	–	–
Chishwishi*	3 265	–	–	2 913	–	–	224	–	–	200	–	–	240	–	–	214	–	–
Mabumba**	540	–	–	482	–	–	248	–	–	221	–	–	229	–	–	204	–	–
Lunzuwa	425	643	210	379	574	187	474	651	157	423	581	140	440	1 009	88	393	900	79
Nkolemfumu	263	409	117	235	365	104	104	142	62	93	127	55	277	309	248	247	276	221
Milima	460	622	298	410	555	266	235	242	228	210	216	203	312	477	147	278	426	131
Mululwe	5 071	8 273	3 066	4 524	7 381	2 735	1 666	2 640	1 125	1 486	2 355	1 004	1 035	1 853	328	923	1 653	293
Kaombe*	10 816	–	–	9 650	–	–	4 381	–	–	3 909	–	–	319	–	–	285	–	–
	11 943	–	–	10 655	–	–	4 538	–	–	4 049	–	–	524	–	–	468	–	–
Poorly	679	–	–	606	–	–	359	–	–	320	–	–	59	–	–	53	–	–
drained*	1 007	–	–	898	–	–	377	–	–	336	–	–	124	–	–	111	–	–
Imperfectly drained*	1 816	–	–	1 620	–	–	291	–	–	260	–	–	66	–	–	59	–	–

*Data from one profile only **Data from two profiles only

THE ORGANIC HORIZON

A dark-stained surface horizon several centimetres deep is ubiquitous. It is variable in texture, but is always the coarsest horizon of the profile, and in spite of the dark colouring is seldom high in organic matter.

Mean values of the chemical analyses for the soil series described subsequently, are given in Tables 16 and 17. The type and degree of structural development also varies, from structureless soil to a well-developed crumb in some undisturbed soils. The crumbs are often associated with roots, and although fragile to the touch, are resistant to breakdown on wetting. This characteristic is not related to texture, and some of the sandier soils have the most stable, though fragile, crumbs. Dry consistence is usually soft or slightly hard, and pore space which is predominantly interstitial is usually at a maximum for the profile.

The upper subsoil

This is that part of the profile between the bottom of the organic horizon and the point where the clay percentage reaches a maximum or where its rate of increase markedly diminishes. Soils with a uniform rate of clay increase throughout the profile are rare. The thickness of the upper subsoil is widely variable and the boundary with the lower subsoil may be abrupt or diffuse. These factors have been used to differentiate between most of the soils.

There is usually some organic staining at the top of the horizon, the depth to which this extends being related to the coarseness of the material. Confusion arises however when the upper subsoil of soil developed under chipya vegetation is considered. This vegetation is considered to be a fire-induced community developed from evergreen forest, and the soils are distinguished by a dark-coloured horizon extending to a variable and often considerable depth. This is not considered significant as the organic content is low and the physical characteristics of a true organic horizon are absent. The dark colour is possibly due to a stable and inert organic residue such as carbon.

Within any freely drained profile which contains iron in an oxidised form, colour appears to be related to clay content, so that clay increase with depth is usually reflected by increasing redness of hue and brightness of value and chroma. The lower boundary of the horizon can often be identified as the depth at which significant change of colour ceases, although where moister conditions occur at depth, yellower colour will be found.

TABLE 16 Means ($\bar{X}$) and standard deviations (S), by soil series, of Mt Makulu Research Station: upland soils only

Organic horizon

	OC(%) $\bar{X}$	OC(%) S	Ca (meq%) $\bar{X}$	Ca (meq%) S	Mg (meq%) $\bar{X}$	Mg (meq%) S	K (meq%) $\bar{X}$	K (meq%) S	CEC (meq%) $\bar{X}$	CEC (meq%) S	BS (%) $\bar{X}$	BS (%) S	pH $\bar{X}$	pH S
Lungu and Twingi	1.68	0.45	2.16	2.72	0.52	0.29	0.19	0.16	4.30	2.39	58.8	26.7	5.00	0.87
Chishwishi	1.80	0.79	1.10	0.72	0.76	0.44	0.14	0.11	5.21	1.73	37.49	24.00	4.89	0.28
Mabumba	1.34	0.60	1.30	0.99	0.46	0.23	0.11	0.05	3.42	1.08	54.30	20.63	4.94	0.36
Lunzuwa	1.89	0.66	1.56	1.50	0.80	0.67	0.24	0.16	7.05	3.82	34.00	17.26	4.82	0.48
Nkolemfumu	1.81	0.90	1.12	1.01	0.64	0.43	0.16	0.10	5.64	2.71	37.43	25.51	4.70	0.55
Milima	1.60	0.78	1.59	1.42	0.56	0.49	0.10	0.06	5.15	2.00	45.05	26.01	4.77	0.44
Mululwe	1.97	0.95	7.77	6.22	4.23	2.67	0.51	0.18	10.13	4.87	94.8	5.87	5.20	0.37
Kaombe*	2.03		7.70		4.70		0.26		19.00		66.63		5.05	
(2 samples)	2.69		8.40		4.70		0.67		21.00		64.95		5.45	
Poorly drained	2.28	0.87	2.11	1.00	0.81	0.40	0.08	0.04	6.14	4.05	53.97	17.73	5.01	0.41
Imperfectly drained	1.54	0.64	2.42	1.33	0.75	0.66	0.11	0.08	4.44	1.78	67.69	23.10	5.17	0.40

Upper subsoil horizon

	Ca (meq%) $\bar{X}$	Ca (meq%) S	Mg (meq%) $\bar{X}$	Mg (meq%) S	K (meq%) $\bar{X}$	K (meq%) S	CEC (meq%) $\bar{X}$	CEC (meq%) S	BS (%) $\bar{X}$	BS (%) S	pH $\bar{X}$	pH S
Lungu and Twingi	0.62	0.76	0.28	0.23	0.09	0.06	2.44	1.09	45.84	17.39	4.67	0.45
Chishwishi	0.33	0.47	0.32	0.17	0.11	0.10	3.80	1.88	21.96	17.45	4.49	0.27
Mabumba	0.34	0.31	0.30	0.13	0.10	0.04	2.13	0.42	35.67	14.15	4.66	0.48
Lunzuwa	1.73	1.69	0.47	0.45	0.22	0.21	6.63	2.64	16.23	12.39	4.45	0.43
Nkolemfumu	0.35	0.47	0.30	0.29	0.12	0.10	4.71	1.06	17.73	17.23	4.37	0.50
Milima	0.37	0.40	0.27	0.23	0.07	0.07	3.04	1.25	27.30	21.33	4.44	0.32
Mululwe	2.97	1.67	2.50	1.27	0.49	0.13	9.13	3.03	62.40	12.81	4.60	0.21
Kaombe*	7.50		4.95		0.10		19.80		63.38		4.50	
(2 samples)	7.30		3.80		0.13		17.60		63.81		4.95	
Poorly drained	0.39	0.22	0.31	0.18	0.04	0.04	2.31	1.27	37.89	19.26	4.58	0.43
Imperfectly drained	0.59	0.38	0.33	0.24	0.08	0.05	2.44	0.72	44.97	25.05	4.98	0.53

Sample of lower subsoil horizon having maximum clay above 125 cm

	Ca (meq%) $\bar{X}$	Ca (meq%) S	Mg (meq%) $\bar{X}$	Mg (meq%) S	K (meq%) $\bar{X}$	K (meq%) S	CEC (meq%) $\bar{X}$	CEC (meq%) S	CEC of clay (meq%) $\bar{X}$	CEC of clay (meq%) S	BS (%) $\bar{X}$	BS (%) S	pH $\bar{X}$	pH S
Lungu and Twingi	0.27	0.23	0.26	0.40	0.12	0.05	2.09	0.44	17.52	3.35	34.31	9.91	4.40	0.25
Chishwishi	0.22	0.28	0.33	0.24	0.20	0.11	5.36	2.25	10.11	2.55	16.53	8.62	4.38	0.24
Mabumba	0.35	0.33	0.48	0.50	0.22	0.12	4.11	1.67	12.09	4.67	24.84	12.51	4.46	0.23
Lunzuwa	0.36	0.45	0.64	0.63	0.20	0.16	5.56	3.44	12.17	7.27	21.37	19.98	4.69	0.58
Nkolemfumu	0.25	0.31	0.24	0.29	1.12	0.11	4.67	1.10	13.05	5.01	15.50	15.85	4.39	2.13
Milima	0.32	0.42	0.30	0.22	0.10	0.11	3.37	1.10	13.28	3.16	22.65	16.45	4.37	0.29
Mululwe	2.85	0.71	1.93	0.17	0.35	0.05	8.07	0.47	12.67	0.47	63.63	7.23	5.33	0.24
Kaombe*	6.70		4.70		0.06		19.20		30.09		59.69		4.55	
(2 samples)	8.60		5.90		0.08		19.20		37.07		75.94		5.35	
Poorly drained	0.34	0.24	0.18	0.09	0.04	0.03	3.35	1.54	13.28	2.76	22.49	15.98	4.32	0.33
Imperfectly drained	0.42	0.36	0.66	0.45	0.17	0.08	5.12	1.39	13.6	3.34	28.01	16.93	4.45	0.47

TABLE 17 Means ($\bar{X}$) and standard deviations (S), by soil series, of analysis data from the Tropical Soils Analysis Unit: upland soils only

Organic horizon

	OC(%) $\bar{X}$	OC(%) S	Ca (meq%) $\bar{X}$	Ca (meq%) S	Mg (meq%) $\bar{X}$	Mg (meq%) S	K (meq%) $\bar{X}$	K (meq%) S	CEC (meq%) $\bar{X}$	CEC (meq%) S	BS (%) $\bar{X}$	BS (%) S	pH $\bar{X}$	pH S
Twingi	0.94		3.00		1.30		0.50		5.10		96.00		6.60	
(2 samples)	0.47		1.00		0.40		0.20		2.40		67.00		5.70	
Chishwishi	1.23	0.78	3.03	3.72	0.83	0.55	0.23	0.02	5.48	3.77	59.00	25.60	5.88	0.20
Mabumba	0.85	0.25	1.73	0.98	0.38	0.04	0.15	0.05	3.20	1.34	70.25	11.54	6.05	0.18
Lunzuwa	0.98		1.10		0.50		0.20		3.70		49.00		6.10	
(2 samples)	0.88		0.40		—		0.30		4.00		18.00		4.50	
Nkolemfumu	1.54	0.66	0.90	0.46	0.84	0.89	0.22	0.04	6.98	3.41	37.00	24.3	5.22	0.62
Milima	0.96	0.46	0.04	1.61	0.52	0.32	0.17	0.06	4.63	2.52	59.80	21.10	5.79	0.36
Mululwe	2.87		9.70		3.10		0.60		15.60		86.00		6.20	
(2 samples)	1.43		6.50		1.60		0.40		9.40		90.00		6.00	
Kaombe (1 samples)	1.64		7.50		4.60		0.30		15.20		82.00		5.90	
Poorly drained (1 sample)	0.49		0.40		0.20		0.10		1.80		39.00		4.70	

Upper subsoil horizon

	Ca (meq%) $\bar{X}$	Ca (meq%) S	Mg (meq%) $\bar{X}$	Mg (meq%) S	K (meq%) $\bar{X}$	K (meq%) S	CEC (meq%) $\bar{X}$	CEC (meq%) S	BS (%) $\bar{X}$	BS (%) S	pH $\bar{X}$	pH S
Twingi	0.60		0.30		0.80		3.00		60.00		6.20	
(2 samples)	0.80		0.10		0.10		1.30		77.00		5.30	
Chishwishi	0.50	0.34	0.25	0.21	0.13	0.02	2.03	0.81	58.00	33.50	5.68	0.30
Mabumba	0.44	0.14	0.24	0.08	0.14	0.05	1.60	0.23	52.60	7.00	5.58	0.20
Lunzuwa	0.60		—		0.10		2.80		25.00		5.60	
(2 samples)	0.40		—		0.20		3.00		20.00		4.80	
Nkolemfumu	0.32	0.27	0.13	0.22	0.15	0.08	3.47	1.46	18.67	14.96	4.95	0.22
Milima	0.50	0.43	0.33	0.24	0.16	0.19	2.39	0.75	41.73	20.32	5.58	0.42
Mululwe	5.10		2.40		0.50		11.10		72.00		5.90	
(2 samples)	7.20		5.90		—		15.70		84.00		5.90	
Kaombe (1 samples)	7.30		4.90		0.20		17.40		72.00		5.90	
Poorly drained (1 sample)	0.50		0.20		0.10		1.30		62.00		5.60	

Sample of lower subsoil horizon having maximum clay above 125 cm

	Ca (meq%) $\bar{X}$	Ca (meq%) S	Mg (meq%) $\bar{X}$	Mg (meq%) S	K (meq%) $\bar{X}$	K (meq%) S	CEC (meq%) $\bar{X}$	CEC (meq%) S	CEC of clay (meq%) $\bar{X}$	CEC of clay (meq%) S	BS (%) $\bar{X}$	BS (%) S	pH $\bar{X}$	pH S
Twingi	0.40		—		0.20		2.00		14.81		30.00		5.10	
(2 samples)	0.60		—		0.10		1.30		11.40		54.00		5 20	
Chishwishi	0.33	0.20	0.40	0.22	0.35	0.23	3.30	0.99	6.73	1.44	38.25	28.37	5.55	0.67
Mabumba	0.56	0.38	0.40	0.29	0.28	0.07	2.84	0.73	8.68	1.55	46.80	27.07	5.48	0.47
Lunzuwa	0.40		—		0.10		2.80		5.65		18.00		4.90	
(2 samples)	0.30		—		0.30		3.00		6.59		20.00		4.30	
Nkolemfumu	0.22	0.29	0.05	0.11	0.13	0.14	3.00	0.85	7.73	1.22	10.33	11.30	5.07	0.50
Milima	0.25	0.22	0.20	0.25	0.15	0.20	2.11	0.48	8.60	2.14	29.18	19.53	5.24	0.41
Mululwe	4.40		1.70		0.40		8.80		11.40		74.00		6.00	
(2 samples)	3.60		1.30		0.30		6.30		8.71		83.00		5.70	
Kaombe (1 samples)	7.20		4.90		0.10		16.3		24.10		75.00		5.80	
Poorly drained (1 sample)	0.40		0.20		0.10		2.90		6.70		24.00		5.30	

The structure is usually at best weak subangular blocky, with fine-size units predominating; only a few exceptional soils have a better one. Consistence is usually friable when moist, and of variable hardness when dry, depending on the clay content; some soils are increasingly compact towards the bottom. Very small tubular pores are abundant.

The lower subsoil

Many of the properties of this horizon have already been mentioned comparatively. It is the horizon of maximum mean clay content, within which clay content may remain almost constant, increase slightly or decrease to a depth of several metres, although decreases very rarely occur.

Usually its upper boundary with the upper subsoil occurs within 50 cm of the surface, and is seldom found below 100 cm depth. Thereafter unless a limiting horizon of ironstone or gravel occurs, there is little change within the horizon down to 200 cm (80 in) depth.

Colour attains its reddest hue and brightest value and chroma in this horizon and varies little within it unless there is some drainage impedance, as may occur above a limiting horizon or in a low-lying area.

Changes in other properties also result from the increase in clay content. There is a slight improvement in the degree of structural aggregation at the top of the horizon, but still insufficient for it to rate as moderate in any but a few exceptional soils. This horizon, while friable when moist, becomes hard, very hard or extremely hard when dry, depending again to a certain extent on the clay content; and is often compact as well. This condition is most apparent in those soils with large, abrupt textural changes at the horizon's upper boundary, and in some instances incipient pale-coloured mottles are evidence of drainage restriction at this point. Towards the bottom of the profile a structureless condition is approached, consistence is usually friable to very friable, and the compaction has disappeared. Small tubular pores are again abundant.

An interesting corollary to these changes down the horizon is that field textural estimates often indicated a decreasing clay content with depth which was subsequently refuted by analytical data, suggesting that the resistance of micro-aggregates to disruption by standard field texturing techniques increases with depth.

DEPOSITIONAL SOILS

The broad lacustrine plains of Land Systems Ia4, Ia7, Ia8, IId2 and IId14, were surveyed where access permitted because of the large area of land concerned and their possible potential for specialised agriculture.

The soils of all the systems are largely depositional and are probably subject to flooding for a considerable part of the year. However, there is little evidence of material being laid down at present. The degree of profile development that has taken place is very variable between and within land systems. On the Chambeshi Floodplain (LS IId1) many of the soils have well developed textural profiles, similar to the upland soils, but with the grey colours of reduced iron. Massive or gravel ironstone was commonly found at depths of less than 2 metres and probably underlies a large part of the floodplain. In this connection it is interesting to note that the floodplain was flooded to a depth of 30-60 cm in December 1967 by the normal drainage of its tributary dambos, long before the river subsequently rose. The soils of LS IId14 are mainly sandy throughout. Textural layering is common, and profile development is restricted to iron segregation in some soils.

Much of LS Ia4, Ia7 and Ia8 are perennial swamp and little work was done on them. LS Ia4 appeared to have more silty soils than the others, and pit-digging was impossible using normal equipment due to the extreme hardness of the material. Surface salt efflorescence nearby indicate the possibility of salinity restriction to development. In LS IId2 and Ia7 small areas of soil were found with well-developed prismatic structure and cracks extending to considerable depth.

Pedological classification

The soils of the survey area have been classified into mutually exclusive series, the requirements of which are as follows:

1. They can be defined in terms of measurable soil parameters
2. They can be recognised in the field by a trained observer
3. They have significance with respect to agricultural potential
4. Wherever possible the definitive parameters should be consistent with the diagnostic criteria of the higher categories of the major international classification systems

During classification the major consideration was given to the deep, freely drained upland soils (the object of the survey), and little attention was paid to shallow and poorly-drained soils, which have been grouped according to these factors whatever their other characteristics. Dambos and local riverine areas were excluded from the survey and the larger areas of lacustrine plain have been treated separately. From the classification key in Appendix 1 it can be seen that provision has been made for further subdivision of series into depth, stone content and iron-segregation phases if required.

UPLAND SOILS: DEEP, FREELY DRAINED

The freely drained upland soils can be divided into two groups which are very significantly different from the agricultural point of view, with subgroups which conform with international classification practice:

Group 1 Chemically fertile soils with moderate or well developed macrostructure

Group 2 Chemically less fertile soils, without macrostructure below the organic horizon

Subgroup 2a Sandy soils
Subgroup 2b Soils with oxic horizons

The greater part of the survey area is covered by soils of Subgroup 2b, and only a relatively small area by soils of Group 1.

The colour and texture of the soils with oxic horizons are their principal variables. For any given clay content, colour differences are significantly related to differences of chemical and physical properties, but for a given colour, differences of clay content are related to much larger differences in the same properties. We have therefore used texture rather than colour as the primary basis for classification of these soils (see Table 18 for the dominant colours of the series defined). Northcote (1960) used the terms 'duplex', 'gradational' and 'uniform' to indicate respectively abrupt, gradual and zero changes of clay content with depth in the profile and we have used a similar method using definitions suited to the N. Zambia circumstances. But because accurate field estimation of clay content are required (in the absence of laboratory determinations) and such tests are difficult on soils of this group, the terms 'gradational' and 'uniform' were amalgamated, so that a distinction is made only between soils with and without an abrupt increase in clay content.

The series names adopted have been taken from localities where good examples of the soil in question are to be found. The use of names already adopted by the Soil Science section at Mount Makulu has been avoided. One or more possible equivalents from the existing Zambian classification have been given with each of the new soil series

TABLE 18 Colours of the lower subsoils of the main soil series; percentages of profiles observed within each group of hues

Hue	Lungu	Twingi	Chish-wishi	Mabumba	Lunzuwa	Nkole-mfumu	Milima	Mululwe	Kaombe	All main series+
Redder than 5YR	100*	0*	16	7	55	17	17	88	0	21
5 + 7.5/5YR	0*	35	44	55	26	39	30	12	100x	36
7.5 + 7.5/10YR	0*	22	30	21	15	35	29	0	0	27
10YR	0*	43	10	17	4	9	24	0	0	16
Total	100	100	100	100	100	100	100	100	100	100

* By definition, x Two profiles only, + This gives very roughly an estimate of the relative areas of soils with these hues within the project area

described, along with the group/subgroup of the USDA 7th Approximation and the soil unit(s) of the FAO/UNESCO system. A major disadvantage of the latter is the use of colour to subdivide the Ferralsol unit.

Group 1 Upland soils with moderate or well-developed macrostructure

Kaombe Series

A typical profile is as follows:

0-8 cm	Dark brown (5YR 3/3); loam; few concretions; medium subangular blocky structure
8-30 cm	Dark reddish brown (5YR 3/4); clay loam; few concretions; strong medium subangular blocky structure
30-140 cm	Yellowish red (5YR 4/8); clay; few to common concretions; strong subangular blocky structure; few cutans
140-200 cm +	Yellowish red (5YR 4/8); clay with abundant weathering rock

Samples from two profile pits located on the lower section of a piedmont traverse (669) south of Mpika on the Great North Road, were found to have a considerably higher nutrient status than any other soils found during the survey. This soil has a comparatively high CEC of clay with fairly high base saturation (Tables 16 and 17). Nutrient levels for calcium and magnesium are in excess of those for any other series (Table 15). Potassium, however, is deficient. Clay mineral analysis carried out by the Macaulay Institute for Soil Research attributed the high CEC to the presence of vermiculite or montmorillonite.

In the field, the soils are recognisable by their better structure, which with their 5 YR colour sets them apart. Texturally they have a duplex profile form (see section on duplex soils below) with clay textures below the duplex boundary. Fossil iron/manganese concretions were found in both profiles. These are probably samples of the soils referred to by Trapnell (1953) as Upper Valley soils. The associations of tree species described as occurring on such soils are to be found in the vicinity, but at the profile sites all vegetation had been cleared for cultivation. Their chemical properties would seem to indicate a younger soil formed on a youthful surface over underlying calcareous or feldspathic sandstone.

Equivalent series in *Soils in Zambia* (Yager, 1969)	–	Makeni
Category in 7th Approximation	–	Ustropept
FAO/UNESCO Soil Unit	–	Eutric Cambisol

Mululwe Series

A typical profile is as follows:

0-10 cm	Dark reddish brown (5YR-2.5YR 3/4); silty clay loam; strong fine granular structure becoming angular blocky
10-180 cm	Dark red (2.5YR or 10R 3/6); clay; moderate or strong medium subangular blocky structure becoming weaker below 60 cm; clay pellets and a few cutans present

The identification and separation of this series from apparently similar soils of the Lunzuwa Series should be an important part of any detailed soil survey. It is felt that the significance and indeed the existence of this type of soil is not fully appreciated.

Although not defined according to colour, only one example of this soil was found with a hue yellower than 2.5YR, and many soils were 10R. The texture of the upper subsoil can be sandy clay but is usually clay, while the structure is better than weak fine subangular blocky, thereby differing from that of the red Lunzuwa soils. The soils are derived from basic igneous parent materials and no catenary relationship was observed. It should be noted that examples having duplex textural differentiation (see Duplex Soils, below) within the clayey particle size classes were found.

Table 15 shows the position of the Mululwe Series with respect to the other series in terms of nutrient status; it will be seen to be less deficient in potassium than the Kaombe Series.

From Table 16, it can be seen that the CEC of the Mululwe Series is markedly lower than that of the Kaombe Series. Its relatively high nutrient status is due to its high clay percentage as well as its high base saturation. In Table 19, which compares Mululwe Series with Lunzuwa Series (the finest textured of the remaining series) this difference in clay content can be appreciated.

TABLE 19 Difference in clay content between the Mululwe and Lunzuwa Series

Series	Subsoil horizon of maximum clay % above 125 cm		
	Minimum %	Maximum %	Mean %
Mululwe	42.2	74.6	57.6
Lunzuwa	35.6	59.2	44.9

The data from the LRD Tropical Soils Analysis Unit however (Table 17), indicate that the CEC of the Mululwe Series is in fact greater than that of the Lunzuwa Series, and the difference in the base saturation figures is also greater, so that estimates of nutrient status based on those data would magnify the already considerable difference between the two.

Tables 20 and 21 emphasise the similarity to the Kaombe Series in terms of micronutrient and iron content, and in the case of the latter, indicate a possible means of separating the Mululwe and Lunzuwa Series when field examination has proved inconclusive and detailed analyses are not available.

The series is not widely distributed, but is found over considerable areas in the Mpika District and within an area west-south-west of Mbala. It is usually intensively cultivated.

TABLE 20 Micronutrient status of soil series: mean ppm of profiles analysed as check samples by the LRD Tropical Soil Analysis Unit

Soil series	Co	Cr	Cu	Mn	Ni	Zn
Twingi*	<50	<50	6	193	<50	8
Chishwishi	<50	<50	17	108	<50	24
Mabumba	<50	<50	10	55	<50	17
Lunzuwa*	<50	<50	12	506	<50	22
Nkolemfumu	<50	<50	11	151	<50	26
Milima	<50	<50	7	82	<50	15
Mululwe	95	<50	139	675	130	75
Kaombe	110	<50	70	770	169	77

* Data obtained from samples sent to TSAU for physical analysis

TABLE 21 Free iron and total iron of soil series

Soil series	Free iron, %			Total iron, %		
	Mean	Max.	Min.	Mean	Max.	Min.
Twingi	0.22	0.42	0.09	0.42	0.73	0.21
Chishwishi	2.07	3.01	0.54	3.12	4.00	1.57
Mabumba	0.55	0.64	0.40	1.05	1.40	0.77
Lunzuwa	2.56	4.08	0.66	3.72	5.60	1.53
Nkolemfumu	1.70	4.10	0.60	2.60	5.18	1.03
Milima	0.92	1.65	0.28	1.38	2.30	0.66
Mululwe	9.88	13.04	7.69	12.72	16.19	8.46
Kaombe	11.33	12.19	10.47	16.73	18.07	15.51

Equivalent series in *Soils of Zambia* — None
Category in 7th Approximation — Tropeptic Haplustox
FAO/UNESCO Soil Unit Rhodic Ferralsol

Group 2 Upland soils without macrostructure below the organic horizon
Subgroup 2a Sandy soils

These soils are by definition those which lack a horizon containing more than 15% clay through a depth greater than 30 cm. In view of the generally moderate silt content of most of these soils and in order to facilitate their field identification, the boundary between loamy sand and sandy loam has been regarded as constant at the 15% clay level.

Lungu Series

A typical profile is as follows:

0-10	Dark reddish brown (5YR 2/2) sand; granular structure
10-85 cm	Red (2.5YR 4/6) sand to loamy sand; very weak structure
85-190 cm	Red (2.5YR 4/6) loamy sand, massive

This series, whose subsoil hue is redder than 5YR in part, and its yellower relative, Twingi (described below) are the only series defined by colour. The justification in the case of the Lungu series is that as with the preceding series, its properties can be attributed to its formation from a common parent material, in this case ferruginous sandstone. It is very limited in extent occurring principally in steep and rocky areas, often on piedmonts, and particularly in the Mbala-Mpulungu and Isoka areas. For purposes of mapping and comparison it has been combined with Twingi series.

Equivalent series in *Soils of Zambia*	–	possibly a red variant of Kabuyu
Category in 7th Approximation	–	Typic/Oxic Quartzipsamment
FAO/UNESCO Soil Unit	–	Ferralic Arensol

Twingi Series

A typical profile is as follows:

0-5 cm	Dark brown (7.5YR 3/3); loamy sand; weak granular structure
5-22 cm	Dark yellowish brown (10YR 3/4-4/4); loamy sand to sandy loam, weak subangular blocky structure
22-90 cm	Strong brown (7.5YR 5/6) loamy sand to sandy loam, massive
90-195 cm	Reddish yellow (7.5YR 6/8) loamy sand to sandy loam, massive

This soil, having yellower hues than the Lungu series, is found throughout the survey areas. It is often associated with the sandstones and quartzites of steep and rocky areas, but is also found as the lower slope member of an interfluve catenary sequence on quartz-rich parent material, when the removal of clay from the profile has extended to greater depth than usual.

From Tables 16 and 17 this series can be seen to have a higher fertility status than would be expected for such a quartz-sandy soil, attributed to organic matter being leached and distributed throughout the profile.

Equivalent series in *Soils in Zambia*	–	Kabuyu
Category in the 7th Approximation	–	Typic/Oxic Quartzipsamment
FAO/UNESCO Soil Unit	–	Ferralic Arenosol

Group 2 Upland soils without macrostructure below the organic horizon
Subgroup 2b Soils with oxic horizons

These soils are defined in accordance with the diagnostic criteria of the oxic horizon of the USDA 7th Approximation, that is, they have a 30-cm deep horizon or subhorizon containing at least 15% clay which occurs at a depth less than 125 cm from the surface.

Division 1, Duplex soils

These series are defined as having an increase of clay content of 15% or more within a vertical distance of 20 cm in some part of the profile below the organic horizon and above 125 cm. The pedology of these soils is consistent with the genetic concept of the oxisols, but the clear textural boundaries are not normally admissible with the oxisol order.

Chishwishi Series

A typical profile is as follows:

0-10 cm	Black (N2/); loamy sand; very weak fine granular structure
10-50 cm	Brown (10YR 4/3); sand; very weak very fine granular structure
50-200 cm	Yellowish red (5YR 5/6); sandy clay; weak very fine sub-angular blocky structure

This series is defined as having a lower subsoil horizon (i.e. the horizon or sub-horizon immediately below the duplex boundary), with a sandy clay or finer texture. The textural change in clay content across the duplex boundary can be as low as the definitive level of 15% or as large as 49%, the largest encountered. The upper subsoil texture varies from sand to sandy clay loam, and further subdivision into textural phases may be desirable at some stage. The boundary normally occurs within 40 cm of the surface but can extend to the diagnostic level of 125 cm, while the extreme example quoted above occurred at 47 cm. Occasionally the simple horizon sequence of upper and lower subsoil below the organic layer is complicated by the presence of more than one abrupt increase in clay content.

Table 18 shows the largest proportion of these soils to be in the 5YR colour range. The sequence of colour changes down the profile is a reflection of the textural changes occurring, and the degree and rate of textural change can often be inferred from the pattern of increasing redness and brightness with depth.

During the dry season the lower subsoil becomes exceptionally hard and compact and difficult to auger. The few bulk-density determinations carried out were inconclusive, but relatively high bulk density is, nonetheless, probably the reason for this difficulty. A few of the more compact horizons exhibited incipient mottling at the top of the horizon, indicating a possible restriction in drainage. These soils are widely distributed, being the third most common series, covering 15% of the area according to the proportions of profile pits. They are most extensive in the Mansa area and occur on the Luapula Regional Research Station, (Republic of Zambia, Ministry of Agriculture, Soil Survey Report 3). They do not appear to occupy a definite position on the interfluve, and are often discontinuous in extent. More detailed work is required to locate and categorise the occurrence of these soils.

Equivalent series in *Soils in Zambia*	–	Kafulafuta or Mufulira sandy phase
Category in 7th Approximation	–	Psammentic and Typic Haplustox, accepting the defined duplex boundary as admissible within an oxisol. In the absence of any evidence of clay illuviation indicative of an argillic horizon, there is no acceptable alternative
FAO/UNESCO Soil Unit	–	Rhodic, Helvic and Ochric Ferralsols depending on colour

Mabumba Series

A typical profile is as follows:

0-10 cm	Dark grey (10YR 3/1-3/2); sandy loam, weak crumb structure
10-20 cm	Brown (10YR 4/3); sandy loam; weak structure
20-40 cm	Yellowish brown (10YR 5/4); sandy clay loam; weak subangular blocky structure
40-180 cm	Reddish yellow (7.5YR 6/6); sandy clay loam; massive structure

The lighter-textured duplex soil has a texture of sandy clay loam in the subhorizon below the duplex boundary, so that the upper subsoil cannot have a heavier texture than sandy loam. Its other properties are closely similar to those of the heavier Chishwishi series, with which it is often associated.

Equivalent series in *Soils of Zambia*	–	Kafulafuta or Mufulira sandy phase
Category in 7th Approximation	–	Psammentic and Typic Haplustox. Paradoxically the latter would be used for soils with the more sandy upper subsoils, which would not qualify as part of the oxic horizon
FAO/UNESCO Soil Unit	–	Rhodic, Helvic and Ochric Ferralsols

Division 2, Gradational Soils

These series may show quite large changes in clay content through the profile, but they are not abrupt enough to meet the definition of the duplex soil (15% clay over ≯20 cm).

Lunzuwa Series

A typical profile is as follows:

0-10 cm	Dark red (2.5YR 3/4); moderate granular structure
10-70 cm	Red (2.5YR 4/8); weak structure
70-180 cm	Red (2.5YR 4/6-4/8); clay; weak angular blocky structure

This, the finest textured of the gradational soils, having an upper subsoil of sandy clay or finer textured material, is also the most uniform series of the group, lacking the potential for large clay increases by definition. As it contains the highest clay percentage below the organic horizon of any series except for Kaombe and Mululwe, and as the latter series are very restricted in extent, Lunzuwa series soils are likely to be much sought after for development (see section on chemical properties).

They occur throughout the survey area, occupying 11% of it,according to the profile pit proportions, often in small pockets. They are rather rare in Luapula Province and considerably more extensive in a belt ranging north from Kasama, on the north-eastern boundary around Nakonde, and on the south-eastern edge of the survey area. In view of their significance for agriculture a rapid method of locating the occurrence and extent of these soils would be desirable, and Table 18 showing colour-series relationships suggests a way. It can be seen that 55% of Lunzuwa soils are redder than 5YR, and as many of the yellower soils are found in association with the red soils, a large proportion of this series can be located by examining red soils. As red soils account for only 21% (in terms of pit proportions) of the survey area, a very large part of it may be disregarded. A textural examination of the upper subsoil of red soils would then determine whether they were Lunzua series or some other. Lunzua series accounts for 29% of all red soils. In addition Mululwe series could also be located in this way.

The considerable similarity of the redder of these soils to Mululwe series has been mentioned. The presence or absence of macro-structure, generally fine subangular blocky, is usually apparent, but in doubtful cases a free or total iron determination will rapidly determine the issue. In support of the contention that the redder of these soils are preferable agriculturally to the yellow, it was found that the structural stability of the former was better than that of the latter. In terms of chemical fertility no difference was found, the exchange capacity being proportional to the clay content.

Lunzua soils can be found right across the interfluve, but not normally down to the dambo edge, and usually occupy the crest where they occur in association with soils of other series. Where they occur together the redder variant is usually found higher on the interfluve than the yellow.

Equivalent series in *Soils in Zambia*	–	Konkola and Mufulira series with sandy clay beneath the organic layer
Category in 7th Approximation	–	Typic Haplustox
FAO/UNESCO Soil Unit	–	Rhodic, Helvic and Ochric Ferralsol

Nkolemfumu Series

A typical profile is as follows:

0-10 cm	Dark brown (7.5YR 3/2); sandy loam, moderate crumb structure
10-30 cm	Dark brown (7.5YR 4/4); sandy clay loam; weak structure
30-180 cm	Yellowish red (5YR 5/6); sandy clay-sandy clay loam; massive structure

These soils defined as having an upper subsoil texture of sandy clay loam, are very extensively distributed throughout the survey area. The clay percentage may remain fairly constant down the profile or increase to sandy clay or clay.

The dominant colour is in the 5-7.5YR range (Table 18) and within the profile increasing redness of hue and brightness of chroma with depth reflect increasing clay percentage and decreasing organic matter/organic carbon content. Structure is no better than weak, usually fine, subangular blocky.

This series is representative of crests and upper slope sites of interfluves throughout the area, and together with its more sandy associate, Milima series, may be seen as the matrix of the area, within which other series occur in large or small pockets.

Equivalent series in *Soils of Zambia*	–	Konkola and Mufulira
Category in 7th Approximation	–	Typic Haplustox
FAO/UNESCO Soil Unit	–	Rhodic, Helvic and Ochric Ferralsols

Milima Series

A typical profile is as follows:

0-10 cm	Dark brown (10YR 3/2); sandy loam; moderate crumb structure
10-30 cm	Dark brown (7.5YR 4/4); sandy loam; weak structure
30-180 cm	Yellowish red to reddish yellow (5YR 4/6-5/8); sandy clay loam; massive structure

This is the most extensive series in the area, accounting for approximately 30% of the upland soils, and is defined as having an upper subsoil texture of sandy loam or coarser. The range in texture of the lower subsoil is wide: sandy loam occurs quite commonly; sandy clay loam is very extensive; and sandy clay and clay occur infrequently.

Colour frequency distribution is similar to the Nkolemfumu series, its more sandy texture reflected in the increased proportion of the series having a 10YR hue (Table 18).

Locally this soil may be found over large areas, extending right across the interfluve, but where found in association with Lunzuwa or Nkolemfumu series it is usually the foot slope member.

Equivalent series in *Soils of Zambia*	–	Misamfu
Category in 7th Approximation	–	Psammentic Haplustox
FAO/UNESCO Soil Unit	–	Acric, Rhodic, Helvic and Ochric Ferralsols

UPLAND SOILS: DEEP, POORLY DRAINED

Poorly-drained soils

These soils are defined solely on the presence of a gley-coloured matrix more than 30 cm thick occurring above 125 cm depth. A gley colour is regarded as having a hue yellower than 10YR or chroma $\leqslant 2$ with value >4. It is accepted that there are freely drained soils, particularly coarse-textured ones, which are so deficient in free iron that they meet the above requirements and are misplaced in the classification. It is accepted also that there are soils which do not satisfy the above conditions, although high water-table levels may occur within their profiles. The presence of such conditions is accepted as evidence of poor drainage.

Imperfectly drained soils

Being less poorly drained than the above, these soils have mottles of a similar colour through 75% of a layer >30 cm thick.

DEPOSITIONAL (LACUSTRINE PLAIN) SOILS

These are, by definition, the soils of the lacustrine plain areas which are flooded annually for extensive periods and whose vegetation is predominantly grassland.

Kaputa Series

These soils are identified by their well developed coarse prismatic structure. At the type location near Kaputa the prisms were so well developed that they constantly fell out of the profile face. They are of clay texture, and their faces are black in colour, being coated with organic matter, while internally they are variegated with no discernible matrix.

Chambeshi Series

This, the most extensive series, has a mean texture of the top 50 cm of sandy loam or coarser, i.e. not more than 20% clay.

Chozi Series

This series has a mean texture of the top 50 cm of sandy clay loam or finer, that is they comprise more than 20% clay.

Physical properties of the soils

The whole array of more or less freely drained soils, that is all the soils except those of the dambos and floodplains, can be divided into two main groups.

Group 1 soils consist of soils of two series, Mululwe and Kaombe, of very small total extent, which can be distinguished in the field by their well developed, fine angular and subangular blocky structure in the upper subsoil; and in the laboratory by their high content of free iron (rarely less than 8% in the topsoil and increasing downwards) reflecting their base-rich parent material.

Group 2 soils are composed of soils of the remaining seven freely-drained deep upland series (see Table 16), which cover the vast preponderance of Northern and Luapula Provinces. They are distinguished by their almost complete lack of macro-structure in the field, despite their naturally high porosity; and in the laboratory by the relatively low content of free iron (variable from nearly 0% to about 2% in the topsoil with increasing redness of hue). A few clayey soils at the red end of the array covered by Group 2 have properties transitional to those of Group 1, but their lack of macro-structure is diagnostic, and of primary importance.

Within Group 2, wide differences of organic matter content, texture, textural profile, (i.e. change of texture down the profile) and hue (reflecting as it does free iron content) occur, and their significance with respect to soil physical properties, especially structural stability, has been examined experimentally both in the field and the laboratory. For both Groups 1 and 2 the type of vegetation carried is reputed to have some effect, and differences between miombo-carrying soils, chipya soils and cultivated soils have also been examined.

In order to cover the wide variations within Group 2, sampling to examine differences in physical properties followed a partial factorial scheme, with colour (hue), texture (clay, silt and very fine sand, each considered independently) and vegetation or length of cultivation as factors (Table 22). Some combinations of factors were not found, others were rare, and the eventual sampling scheme was not a symmetrical partial replicate of the whole factorial scheme (Table 23). Analysis of variance was therefore only possible for parts of the scheme, and even then some missing values had to be substituted. On the other hand the distribution of samples over the whole range of combinations of factors observed forms a good basis for regression analysis.

Of the factors considered the following gave especial difficulty. Firstly, chipya vegetation variants were sometimes difficult to locate. Secondly, very short and relatively long period cultivation could be found for only a few combinations of factors, a fact which was of significance in itself, and the comparison eventually was only between cultivated and uncultivated. The distribution of profiles among the various factor combinations is in itself a useful commentary on certain aspects of the soils. In Table 24 for example the proportion of 'a' factor soils (soils with high clay content) is an increasing proportion of the total of all the texture factors with increasingly red hue (1:8, 1:5, 1:3, 1:2 in round figures as the hue reddens from 10YR to 2.5YR and more).

TABLE 22 Initial factorial scheme for examination of physical properties of Group 2 soils

Factor symbol	Description of factor	No. of levels	Factor levels			
			1	2	3	4
a	% clay (<2µ) in upper subsoil	2	<15	25-35*	–	–
b	% silt (2-50µ) in upper subsoil	2	<10	20-30	–	–
c	% v fine sand (50-100µ) in upper subsoil	2	<10	20-30	–	–
r,y	Hue of subsoil (50-125 cm)	4	10YR	7.5YR	5YR	2.5YR or redder
f	Vegetation or land use at soil site	4	Miombo	Chipya	Short cultivation	Long cultivation

*Clay contents of >35% were also compared but not included in the factorial scheme.

A partial replicate (¼) of the $2^3 \times 4^2$ arrangement was to be used.

Organic matter content was not considered among the factors because it was assumed that any effects would be closely correlated with the vegetation/land use effects. However when considered in subsequent multiple regression analysis its effects on physical properties (except possibly water-slaking stability) were generally not significant (see Table 29).

TABLE 23 **Final scheme showing factor combinations covered in the main set of observations of physical properties of Group 2 soils**

Texture factors*	Hue and site factors					
	Hue yellower than 5YR		5YR		Hue redder than 5YR	
	Miombo	Cultivation	Miombo	Cultivation	Miombo	Cultivation
(1)	x	x	x	x	x	x
c	x	x	x	x	x	x
b	void	void	x	x	x	void
bc	x	x	x	void	void	void
a	x	x	x	x	x	void
ac	void	void	x	x	void	x
ab	x	void	x	void	x	x
abc	void	x	x	void	x	void

a = clay (<2μ), 25-35%; b = silt, (2-50μ) 20-30%, c = very fine sand (50-100μ) 20-30%; where a factor is not mentioned the lower level is implied (a_o = <15%, b_o = <10%, c_o = <10%, (1) = a_o b_o c_o

Sufficient observations of chipya sites were also made to enable comparisons with miombo (see Table 24).

Length of cultivation was difficult to determine in practice, and the total number of cultivated sites too small to permit the long-short comparison.

Additional observations were made of soils in which there was an abrupt increase in clay content in the subsoil.

The physical factors examined were those thought to be important to agricultural land use in the survey area. From previous work, structural stability with its effects on aeration under cultivation seemed important, and observations of the onset of erosion under new open field cultivation demonstrated that it was perhaps more significant than any other hazard of cultivation. Drought during the growing season is always of importance, so that available water capacity was also considered. Chemical properties were not examined in the same way since the general relationships and the large order of within-class variations are well known.

A total of 75 sites were sampled, usually at two or three depths: topsoil, 0-10 cm; upper subsoil, 15-25 cm; and 50-60 cm. The following determinations were made:

1. Particle size distribution with and without dispersion using Ahn's (1968) method (Tables 25, 26)

2. Resistance to water-slaking of 4-6 mm peds (usually artificial) using Williams' methods (Williams and Cooke, 1961; Williams, 1963) (Table 27)

3. Free iron and total iron content (Table 28)

4. Bulk density and particle density to obtain total pore space (Table 29) (on about half the samples)

5. Water content at 0.1 and 15.0 atmospheres (field capacity approximately and wilting point) to determine available water capacity (on about 20 samples). In addition infiltration measurements were made at 30 sites and these are commented on in Volume 3 (Land Capability), under the index of erosion susceptibility

TABLE 24 Analysis by factors of profiles of Group 2 soils (initial factorial scheme) taken in 1968-9*

Site factors	Soil texture factors†	Hue (soil colour) factors				
		10YR	7.5YR	5YR	2.5YR	All
Miombo vegetation	(1)	47	43	32	10	132
	a	8	16	26	16	66
	b	5	7	4	2	18
	c	4	3	3	2	12
	ab	1	4	11	4	20
	ac	–	–	–	–	–
	bc	1	6	2	–	9
	abc	–	–	1	1	2
	All	66	79	79	35	259
Chipya vegetation	(1)	16	13	9	1	39
	a	5	4	5	4	18
	b	1	1	1	–	3
	c	–	–	–	1	3
	ab	–	–	–	1	1
	ac	–	–	–	–	–
	bc	–	1	2	–	3
	abc	–	–	–	–	–
	All	22	19	17	7	65
Cultivation (short or long period)	(1)	–	10	10	2	22
	a	1	5	6	2	14
	b	1	1	1	–	3
	c	1	–	–	–	1
	ab	–	2	3	2	7
	ac	1	–	1	–	2
	bc	–	–	–	1	1
	abc	–	–	–	–	–
	All	4	18	21	7	50
All sites	All	92	116	117	49	374*

† Notation as in Table 23

* This is less than the total number of profiles taken in 1968 and 1969; some profiles which were very shallow or for which part of the data was missing were omitted.

Most determinations were subjected to an analysis of variance with substitution for missing values. Significant main effects were found in most cases but relatively few interactions of significance. A series of multiple regressions have since been performed on most of the data and the analysis is presented elsewhere with the complete results. The main results have been interpreted subjectively in the light of field observations and some rather poor (variable) experimental results have been accepted as significant.

There is little difference between the physical properties of the two series which form Group 1; both within the group and within series, physical properties are relatively uniform, although vegetation cover has some modifying effects (see Effects of vegetation and cultivation on physical properties', below).

The physical properties of the soils of Group 2 however differ quite widely within series. The average difference between series may in fact be much less than the difference to be found within a series. It is therefore more efficient to describe the properties of soil types defined by combinations of texture and colour factors which will occur in several series. The explanation is that the soils of Group 2 form a very extensive continuum in which a number of factors affecting capability vary apparently randomly. The definition of units at series level has necessarily been arbitrary as few 'natural' groupings of factors appeared. Obviously, some of the factors affecting capability had to be omitted in series definition, to avoid the large number of units difficult to separate which would have resulted had a multi-dimensional classification been adopted. Physical properties and capability can therefore be more efficiently related to combinations of the soil factors influencing capability than the 'natural' series unit.

In the tables some of the physical determinations for topsoils are given and the main results are listed here, but the full data are available elsewhere.

DIFFERENCES BETWEEN THE SOIL GROUPS

Group 1 soils (Mululwe and Kaombe series) are clearly more favourable for agriculture in most characteristics than any of the other soils.

Group 2 soils are never as favoured as soils of Group 1, but increasingly favourable properties accompany redder hues. The major distinction is between soils of 5YR or redder hue, and those which are less red. This can be correlated with free iron content or the ratio of free to total iron (Table 28). There is reason to suppose that this is a direct causal relationship.

EFFECTS OF VARIOUS SOIL CONSTITUENTS

The *organic matter content* of the soils of Group 2 seems generally insignificantly correlated with favourable properties. The water-slaking stability data (Williams and Cooke, 1961; Williams 1963) do seem to show some effect due to organic matter content, but this tends to be refuted by other determinations and the structural development data of Table 30. Soils of Group 1 generally have much higher organic matter contents even under cultivation, which is probably partly responsible for their macro-structure.

In Group 2 *high percentages of silt* are associated with poor micro-aggregation (i.e. high proportions of water-dispersible clay). This also appears to be true of high contents of very fine sand, while by contrast *high percentages of clay* (sandy clay loam or more clayey textures) are associated with relatively marked micro-aggregation (Tables 25, 26, 27 and 29).

A few duplex profiles (from the Chishwishi and Mabumba series) in which there is an abrupt clay increase at depth were examined. Consistent evidence of increased bulk density or percentage of water-dispersible clay below the change in clay content was not found, although one example with a total pore space of 35% at 50 cm depth was the least porous of all the soils examined.

TABLE 25 Topsoil dispersions ratio (Middleton, 1930): the ratio of silt plus clay without dispersion to that determined during routine particle size analysis (data from Tropical Soil Analysis Unit, Reading)

Group 1 Soils						
Uncultivated 0.77			Cultivated 0.69			
Group 2 Soils						
Texture factors*	Hues yellower than 5YR		Hue 5YR		Hues redder than 5YR	
	Miombo	Cultivation	Miombo	Cultivation	Miombo	Cultivation
(1)	0.88	0.77	0.22	0.48	0.61	0.70
c	0.84	0.88	0.57	0.58	–	0.75
b	–	–	0.69	0.92	1.00	–
bc	0.81	0.83	0.96	–	–	–
a	0.77	0.61	0.46	0.77	0.57	–
ac	–	–	0.87	0.53	–	0.54
ab	0.93	–	0.83	–	0.50	0.87
abc	–	0.71	0.78	–	0.79	–

* Notation as in Table 23

Analysis of variance of these data using mean figures in the voids showed that factor b (silt) had a significant effect (probably highly significant) and its interaction with hue was probably also significant. Multiple regression analysis will be quoted in a subsequent publication.

This determination is a measure of the proportion of naturally occuring easily transported particles in the soil. Favourable figures are numerically low.

TABLE 26 Topsoil aggregation index: the ratio of coarse sand (>200μ) determined without dispersion to that determined during normal particle size analysis (Tropical Soil Analysis Unit)

Group 1 Soils						
Uncultivated 1.51				Cultivated 1.30		
Group 2 Soils						
Texture factors*	Hue yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Miombo	Cultivation	Miombo	Cultivation	Miombo	Cultivation
(1)	0.96	1.06	1.23	1.22	1.39	1.30
c	1.00	1.10	1.06	1.18	1.12	1.09
b	–	–	1.03	0.92	0.90	–
bc	1.00	1.07	1.00	–	–	–
a	1.27	1.11	1.25	1.12	1.40	1.09
ab	0.92	–	1.07	–	1.54	1.35
abc	–	1.28	1.20	–	1.46	–

* Notation as in Table 23

Analysis of variance of these data using mean figures in the void show that at least the hue and a texture (clay) factors were highly significant. Some interactions are probably also significant, but have been ignored because of the incomplete data. Multiple regression analysis will be quoted in a later publication.

This determination is a measure of the aggregation of the fine earth into moderately large, relatively less easily transported water stable aggregates. Favourable figures are numerically *high*, none in the table above is better than moderately favourable.

TABLE 27 Percentage stability of 4-6mm topsoil aggregates (Williams, 1963)

Group 1 soils						
Uncultivated 83				Cultivated 48		
Group 2 soils						
Texture factors*	Hue yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Miombo	Cultivation	Miombo	Cultivation	Miombo	Cultivation
(1)	41	–	52	40	76	–
c	28	73	60	20	49	5
b	24	–	28	20	17	–
bc	15	26	27	–	–	–
a	45	79	85	45	84	–
ac	–	–	65	39	–	41
ab	–	–	19	–	50	19
abc	–	–	27	–	75	–

* Notation as in Table 23

Analysis of variance of this incomplete matrix, substituting mean figures in the voids indicates significance for the a (clay), b (silt) and site (cultivation) factors.

This determination is a measure of the resistance of soil aggregates to slaking in water and is particularly suitable for fine differences within the less stable soils. High values near 100 are favourable.

TABLE 28 Soil free iron: total iron ratio in the topsoil and upper topsoil, means of groups (data from the Tropical Soil Analysis Unit)

Depth		Group 1 soils		Group 2 soils							
				10YR hue		7.5YR hue		5YR hue		2.5YR and 10R hues	
in	cm	Mean	Obs	Mean	Obs	Mean	Obs	Mean	Obs	Mean	Obs
0- 4	0-10	0.73	10	0.51	5	0.54	9	0.68	22	0.73	11
6-10	15-25	0.80	7	0.47	3	0.50	9	0.62	16	0.73	11
20-24	50-60	0.72	7	0.24*	2	0.46*	1	0.66	15	0.69	6

* Figures not considered reliable

TABLE 29 Total pore space of topsoil as a volume percentage

Group 1 soils						
Uncultivated 52			Cultivated 53			
Group 2 soils						
Texture factors*	Hues yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Miombo	Cultivation	Miombo	Cultivation	Miombo	Cultivation
(1)	46	40	45	43	53	48
c	–	49	47	53	–	–
b	–	–	–	42	46	–
bc	45	35	45	–	–	49
a	–	47	51	–	–	–
ac	–	–	44	–	–	–
ab	47	–	43	–	47	45
abc	–	–	47	38	48	–

* Notation as in Table 23

No rigorous analysis of variance has been attempted on these data because of (a) incompleteness and (b) the clearly wide variation of conditions of cultivated soil dependent on recent management.

Multiple regression analysis of the uncultivated soil determinations will be quoted in a later publication.

Pore space was calculated as $100\ (1-\frac{pb}{pp})$ where pb (bulk density) was determined on a large number of samples and pp (particle density) on sufficient samples to give a reliable value for each main parent material group (C of V pp$\simeq$3%).

SOIL: PHYSICAL PROPERTIES

Structural stability

Only soils of Group 1 have a well developed macro-structure, with natural aggregates larger than 4mm. For this reason, even where the micro-aggregation of Group 2 soils is not notably poorer than that of Group 1, among the redder clayey Group 2 soils, reduction of air and water permeability, surface capping and the transport of soil particles are more likely than among the Group 1 soils. Within Group 2, particle size and hue determine the relative stability of micro-aggregation, with the yellowest and most silty or very fine sandy poorest and the reddest and most clayey best. Observations of structural development (macro-structure) in organic horizons indicated that only about 15% of all profiles of Group 2 soils had moderate or strongly developed structure (Table 30). Again some correlation with subsoil hue was observed: 5YR soils had the largest proportion of well-structured topsoils and 10YR soils the lowest. It is clear that (predictably) clayey Group 2 soils have a higher proportion with 'good' structure but that hue is more significant than clay content, red soils with high clay and high silt (which are transitional to Group 1) have the highest proportion with 'good' structure, and 'good' structure is transient under cultivation in Group 2 soils.

Erodibility

Defined as the relative ease with which soil particles can be detached by moving water, erodability is obviously largely dependent on the stability of large aggregates and the ease with which their component micro-aggregates can be dispersed and therefore can be directly related to structural stability. Erosion by water is dependent on this factor and also the amount of water movement across the surface of the soil, which in certain circumstances is governed by infiltration rate (the rate at which water can enter the soil). Under well-developed natural vegetation, measured infiltration rates, although widely variable, were always high, often much greater than all but very rare rates of rainfall. Correlation of the infiltration rate with soil factors or series was not significant however. Under cultivation, even wider variability was found (see Tables 31 and 32),

TABLE 30 **Topsoil structural development of Group 2 soils: site, colour and texture factors and the development of good structure in the profiles considered in Table 24.**

Site factors	Texture factors*	Number of profiles									
		Hue 10YR		Hue 7.5YR		Hue 5YR		Hue 2.5YR		All hues	
		With good structure	All profiles	With good structure	All profiles	With good structure	All profiles	With good structure	All profiles	With good structure	All profiles
Miombo	(1)	2	47	4	43	7	32	2	10	15	132
	a	0	8	1	16	6	26	2	16	9	66
	b	1	5	1	7	1	4	0	2	3	18
	c	0	4	1	3	1	3	0	2	2	12
	ab	0	1	4	4	6	11	2	4	12	20
	ac,ab,abc	0	1	0	6	0	3	0	1	0	11
	all	3	56	11	79	21	79	6	35	41	259
Chipya	(1)	2	16	1	13	0	9	1	1	4	39
	a	0	5	1	4	0	5	0	4	1	18
	b	0	1	0	1	1	1	0	0	1	3
	ab	0	0	0	0	0	0	0	1	1	1
	c,ac,bc,abc	0	0	0	1	0	2	0	0	0	3
	all	2	22	2	19	2	17	1	6	7	65
Cultivation	(1)	0	0	1	10	1	10	0	2	2	22
	Others	0	4	0	8	1	11	0	5	1	28
	All	0	4	1	18	2	21	0	7	3	50
All sites	All	5	92	4	116	25	117	7	49	51	374

* Notation as in Table 23

The mean ratio of sites with 'good' structure topsoil to all sites is about 1:7. Soils of Group 1 are of 'good' structure even where cultivated.

TABLE 31 **Infiltration rates for the main soil series in Northern and Luapula Provinces (cm h^{-1})**

Soil group	Series	Uncultivated sites				Cultivated sites			
		No. of sites	Lowest rate	Mean rate	Highest rate	No. of sites	Lowest rate	Mean rate	Highest rate
1.	Mululwe	1	–	(7.7)	–	5	– 0	3.1	7.6
2.	Lungu	1	–	(15.8)	–	0		–	–
	Twingi	1	–	(35.4)	–	2	4.1	4.4	4.7
	Chishwishi	3	7.8	15.0	28.0	0	–	–	–
	Mabumba	0	–	–	–	1	–	(5.1)	–
	Lunzuwa	1	–	(13.1)	–	3	3.2	(10.9)	19.8
	Nkolemfumu	4	13.4	21.3	38.4	4	– 0	6.7	20.1
	Milima	4	10.1	23.5	41.0	10	0.8	8.4	15.1
	(Poorly drained)	1	–	(10.5)	–	0	–	–	–

Each observation is the mean of four measurements at each site, the highest and lowest of 6 measurements being rejected. Double-ring (25 cm and 60 cm) infiltrometers were used for the determinations, which took up to 6 h before equilibrium was reached.

The variability at each site is very large and no modal set of values can be produced.

Available water capacity

Available water capacity is discussed in Volume 3 (Land Capability) and methods of estimation are described. It appears that the Group 1 soils always have a substantial available water capacity. Group 2 soils with high percentages of coarse sand have low capacities and those with high percentages of very fine sand or silt have relatively high capacities, similar to those of Group 1 soils.

Hardness

Dry soils varied greatly in hardness, and penetrometer measurements were made in a few areas, but without accurate water-content measurements these are of little significance. However extreme the hardness, whether at the surface, or in the subsoil, it did not appear to persist in any form after the soil had been wetted. There was undoubtedly a greater tendency towards hardness in the soils with higher dispersion ratios and the hardest soils of all were the yellow duplex soils (Chiswishi and Mabumba series) found in Luapula Province. This suggests that some compaction, with an increase in bulk density has occurred, although direct (measured) evidence for this was not consistent and therefore not conclusive.

Summary

Thus, to summarise, the differences in physical properties between the soils in Groups 1 and 2 are as striking as their differences in chemical properties, the soils of Group 1 almost invariably being more favoured. Within Group 2 soil variation in physical properties again appeared to be correlated with soil hue and also with particle size. Unfavourable and unstable soil conditions were usually associated with high proportions of silt or very fine sand.

EFFECTS OF VEGETATION AND CULTIVATION ON PHYSICAL PROPERTIES

A comparison of the determinations made under miombo and chipya vegetation types is given in Table 33. Differences were generally insignificant and showed no underlying trend, the only really significant and obvious difference occurring in the structural development of Group 1 soils. Under chipya vegetation development of water-stable aggregates of coarse sand size was relatively quite markedly greater than under miombo vegetation.

The comparison of physical properties in cultivated and uncultivated soils is dealt with in more detail elsewhere. It is sufficient to say that most physical properties deteriorated under cultivation, but in most cases not very markedly, as can be seen from comparisons in Tables 25-30.

Chemical properties of the soils

Profile pits were sampled within natural horizons, at least every 30 cm (12 in) to a depth of 2 m (6 ft), and the samples were subjected to a routine chemical analysis at Mount Makulu Research Station. Every tenth pit was double-sampled and the duplicate samples were returned to the LRD Tropical Soils Analysis Unit (TSAU) at Reading for comparison. Tables 16 and 17 show the means and standard deviations by series of the data from each laboratory for the upland soils; certain differences in the results can be seen, the most striking being in the figures for CEC. This is partly due to the different estimates of clay, due to different mechanical analysis procedures used by the two laboratories. A small number of micro-nutrient analyses were carried out by the TSAU and the profile means, by series, are shown in Table 20. A complete account of analytical methods will be found in Appendix 1.

TABLE 32 Infiltration rates on varied sites on Milima Series at Misamfu, Lunzuwa and Milima Series at Mungwi and Mululwe Series at Mufubushi and Malashi (cm h^{-1})

Location and Series	Topographic position	Vegetation	Land use	Range of infiltration rates at one site*			Remarks
				Lowest	Mean	Highest	
Misamfu; Milima	Upper interfluve	Miombo	Windbreak	4.8	37.8	79.2	
			Woodland paddock	10.8	22.8	39.0	
			Ungrassed woodland	2.4	24.7	36.0	
		Cultivation	Stylo field	10.2	15.1	23.4	
			Grass fallow	0	0.8	11.6	High surface bulk density
			Grass paddock	0	7.6	17.2	
			Grass ley	0	1.3	4.0	High surface bulk density
			Continuous maize	5.2	10.9	14.4	
			Failed beans	12.8	17.1	24.0	No difference from good beans
		Plantation	1-yr-old conifers	7.2	14.3	31.8	
			2-yr-old eucalyptus	0.6	1.6	15.5	Poor surface structure
			7-yr-old eucalyptus	7.2	18.0	25.2	
			8-yr-old conifers	24.0	41.0	60.0	
Mungwi; Lunzuwa	Upper interfluve	Miombo	Windbreak	3.0	13.1	33.6	
		Short cultivation	Recently stumped	3.6	9.8	24.0	
		Long cultivation		0	3.2	22.8	
Mungwi; Milima	Lower interfluve	Miombo	Windbreak	6.6	13.7	39.6	
		Short cultivation	Recently stumped	0	6.5	21.6	Evidence of some degree of structure collapse
		Long cultivation		0	0.3	2.8	
Mufubushi; Mululwe	Incised valley upper slope	Short period cultivation	Maize	→0	→0	→0	Shallow profile
		Short period cultivation from chipya	Maize	→0	0.7	15	Shallow profiles but good surface structure
		Chipya		6.0	7.7	22.8	
Malashi; Mululwe	Incised valley upper slope	Miombo	(Regeneration)	2.0	7.6	30.8	
		Short period cultivation	Maize	→0	5.4	18.0	Shallow profile

* Six simultaneous measurements in an area of 1/70 ha (1/30 ac) in a pattern around a profile pit. The highest and lowest equilibrium rates and the mean of the four middle measurements are quoted here.

The first obvious point worthy of comment is that the variability of cultivated soils is relatively large and related to the time elapsed and weather since the last cultural operation.

The chipya site at Mufubushi is one of the rare examples of the highly organic surface horizons of good structure under chipya.

and the rate depended on the nature of the most recent cultural operation and amount of rain that had fallen since that operation, rather than on soil type. The infiltration rate decreased rapidly where rain had started the breakdown of surface roughness. It follows that the amount of erosive rainfall and the inherent erodibility of the soil is most important in determining the tendency to erode on cultivated land. Observations of erosion were few, since open cultivation is still not very common and slopes are mainly gentle. But in several areas, and notably at Chiundaponde and near Mufubushi quite spectacular rill and gully erosion was observed breaching well-made new ridges. A combination of silt texture, high dispersion ratios and a shallow soil overlying an impervious horizon were, it appeared, usually responsible.

TABLE 33 The effect of site vegetation: chipya compared with miombo

A. TOPSOIL DISPERSION RATIO (MIDDLETON, 1930)

Group 1 Soils						
Chipya 0.69			Miombo 0.77			
Group 2 Soils						
Texture factors	Hue yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Chipya	Miombo	Chipya	Miombo	Chipya	Miombo
(1)	–	–	–	–	0.71	0.70
a	0.55	0.77	0.62	0.57	–	–
ab	–	–	–	–	0.44	0.56

B. TOPSOIL AGGREGATION INDEX

Group 1 Soils						
Chipya 2.30			Miombo 1.24			
Group 2 Soils						
Texture factors	Hue yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Chipya	Miombo	Chipya	Miombo	Chipya	Miombo
(1)	–	–	–	–	1.06	1.39
a	–	–	1.1	1.25	–	–
ab	–	–	–	–	1.68	1.39

For texture factors, see Table 23

C. PERCENTAGE STABILITY OF 4-6 mm TOPSOIL AGGREGATES (WILLIAMS, 1963)

Group 1 Soils						
Chipya 57			Miombo 92			
Group 2 Soils						
Texture factors	Hue yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Chipya	Miombo	Chipya	Miombo	Chipya	Miombo
(1)	–	–	–	–	48	76
a	–	–	80	95	–	–
b	–	–	28	18	–	–

D. TOTAL PORE SPACE AS A VOLUME PERCENTAGE

Group 1 Soils						
Chipya 51			Miombo 47			
Group 2 Soils						
Texture factors	Hue yellower than 5YR		Hue 5YR		Hue redder than 5YR	
	Chipya	Miombo	Chipya	Miombo	Chipya	Miombo
(1)	45	48	–	–	46	53
a	–	–	41	51	–	–
ab	–	–	–	–	50	47

From the data it is evident that the freely-drained upland soils can be divided into two groups, Kaombe and Mululwe series having different characteristics from all the other series. In terms of actual nutrient status Table 15 emphasises the difference. Kaombe and Mululwe series both have relatively high chemical fertility, due basically to the high CEC of the clays of the former, and the higher clay percentage and high base saturation of the latter. The profiles of both series contain weatherable minerals (see Mineralogical Properties of the Soils below) so that a nutrient reserve is present. The chemical fertility of the remaining series is very low, and is concentrated in the small amount of surface organic matter, the mineral fraction having low base saturation. It is interesting to note the relatively high figures for the analytical data of the coarse textured soils (Tables 16 and 17), particularly that for CEC. This is attributed to organic matter having been carried down the profile by the very rapid internal drainage. In the absence of weatherable minerals the potential of this second group of series is measured in terms of their ability to retain fertiliser, which is reflected in the percentage of clay and reaches a maximum in the Lunzuwa series.

Free and total iron percentages again reflect the differences between the two groups of series (Table 21) and could possibly be used to classify heavy textured soils of uncertain identity.

Mineralogical properties of the soils

Grain counts were carried out on the 200-300 sieve mesh size fraction of selected soils by the Geological Survey of Zambia. The ratio of heavy to light mineral once again illustrates the division into the two groups of series (Table 34). Weatherable minerals are virtually absent from all but Kaombe and Mululwe series, the former having feldspars and epidote and the latter feldspars only.

Clay mineral analysis carried out by the Geological Survey of Zambia identified kaolinite as the major component with illite often present in varying amounts. Samples analysed by the Macaulay Institute for Soil Research, from the same profiles as the samples analysed in Zambia, contained only kaolinite and occasionally halloysite, with titanium in the form of anatase present in the clay fraction. The Kaombe profile was found to have a small amount of either vermiculite or montmorillonite, thus accounting for the higher CEC. The present of illite is in conflict with the low CEC of clay of those soils, suggesting that an alternative interpretation of the GSZ analysis is necessary.

Analysis of thin-sections of soils by petrographic microscope showed no evidence of clay translocation in any series.

TABLE 34 The two groups of soil series compared

Soil series	Profile number	Depth (cm)	$\frac{\text{Heavy mineral}}{\text{Light mineral}} \times 100$
Chishwishi	9	10-40	0.4
		140-170	0.7
Lunzuwa	539	9-39	0.2
		70-100	0.9
Lunzuwa	584	5-24	6.8
		120-150	5.5
Nkolemfumu	149	11-24	0.1
		80-110	0.6
Milima	569	11-41	0.1
		150-180	0.1
Mululwe	119	10-40	94.7
		210-235	65.0
		250-280	284.0
Kaombe	29	8-29	98.5
		120-150	135.7

Part 5

Ecology

THE VEGETATION OF THE PROJECT AREA

The vegetation of north-eastern Zambia can be broadly divided into two main types: *miombo* woodland which predominates on the plateau (Land Region IIa) and the Mpika-Isoka Ridge (Land Region IIg); and a mixture of *chipya* and dry evergreen forest which predominates over the Chambeshi-Bangweulu Plain (Land Region IId), an area previously known as the Lake Basin by Trapnell and other workers.

The early vegetation and soil survey by Trapnell *et al.* (1950, 1953) and Trapnell's (1959) review of the Ndola woodland burning experiments, together with Lawton's own long service, experience and publications (Lawton, 1963, 1964), have formed the background to this study. (The vernacular names which follow are defined below.)

Miombo is a single-storey woodland with a light closed canopy, dominated by trees of the genera *Brachystegia* and *Julbernardia*, which vary in height from 4 m to about 15 m (15-50 ft) (Plate 11). There are a few scattered shrubs under the canopy. The ground flora is a mixture of grasses and herbs that usually grow to a height of about 1m (3 ft) under the light woodland canopy.

Chipya varies from open herb/grass communities dominated by dense 2 m (6 ft) high colonies of *Aframomum biauriculatum, Pteridium aquilinum* (bracken) and grass of the genera *Andropogon* and *Hyparrhenia*, to open woodland communities with groups or scattered individual trees which attain a height of 15 m (50 ft) set in a matrix of smaller trees (Lawton, 1963, 1964; White, 1962) (Plate 12). The trees are fire-hardy.

Mateshi Within the chipya there are groups of dense dry evergreen forests, known in the vernacular as *mateshi* (Plate 13). The *mateshi* is frequently dominated by the fluted evergreen canopy tree *Marquesia macroura* that may attain a height of 25-30 m (82-98 ft) and a diameter at breast height of over 60 cm (24 in). The floristically rich patches of dry evergreen forest are too small to map individually. The dense vegetation of the evergreen forest patches exclude fire, but if the forest canopy is opened by exploitation or cultivation, then fire gains an entry and the forest is destroyed and replaced by chipya.

In addition to the main vegetation types, there is an area of low relief between Lake Tanganyika and Lake Mweru, known as the Mweru Depression (Land Region Ia), which is covered with a dry deciduous thicket called the '*Itigi*' thicket. The name *Itigi* originates from south-western Tanzania where this type of vegetation is widespread.

Aims of the vegetation survey

The aims of the vegetation survey are:

1. To determine the vegetative pattern by means of quantitative sampling and to investigate the dynamic relationships within the vegetation

2. To investigate the effect of fire and other human activities on the vegetation

3. To determine the significance of the vegetation pattern (including particularly soil-vegetation correlation) in site quality assessment for land-use purposes

4. To determine appropriate methods for forest production and conservation

5. To recommend the cultivation of certain minor crops, etc.

Survey methods and the collection of ecological data

Vegetation was sampled at 398 sites (Map 4-5) all of which, apart from 13, were located at a soil pit or soil auger boring to facilitate soil/vegetation correlation. These sites were chosen by studying the vegetation patterns on the air photographs at the soil sampling sites, and choosing those sites with the least disturbed vegetation.

The samples were 20 x 20 m (66 x 66 ft) quadrats in which all the woody growth was recorded. Tree height and diameter at breast height (d.b.h.) (130 cm (4 ft 3 in) above the ground) were measured with a Suunto hypsometer and diameter tape respectively. Plants under 2 m (6 ft) high or under 5 cm (2 in) d.b.h. were recorded and counted, but not measured. Coppice regrowth was counted in clumps or colonies; the individual shoots were not counted. The tree canopy is ecologically important, and a scale with five classes was used to assess the percentage canopy cover for each sample:

Class 1:	0-20%
Class 2:	21-40%
Class 3:	41-60%
Class 4:	61-80%
Class 5:	81-100%

Observations were made on the vigour of the vegetation and on any sign of damage by fire or frost, etc. Evidence of previous cultivation was noted, and the age of the regrowth was estimated, sometimes by ring-counts. Colour and black-and-white photographs were taken at many of the sampling sites, to illustrate both the vegetation and soil profile.

The integration of the vegetation sampling with the soil survey imposed some restriction on sampling and towards the end of the survey it was necessary to select 13 samples to cover types of vegetation which had not been adequately covered on the random soil traverses.

Definition of vernacular terms

Vernacular terms may be used to describe a number of the main vegetation types, which in their place of origin, have a precise meaning. But when they are more widely used this meaning may become obscure and it is therefore necessary to define each vernacular term. The South American word, 'savanna', is a good example of a word whose meaning has become so confused that Pratt and Greenway (1966) concluded 'savanna' was 'seldom correctly applied in East Africa and too much abused to be any longer of service for exact purposes'.

Miombo: the word originated in Tanzania. It is the Kinyamwezi word for *Brachystegia boehmii* (J E A Proctor, personal communication). Later it was used by the Germans to describe woodlands dominated by trees of the genera *Brachystegia* and *Julbernardia.*

Chipya: a Chibemba vernacular word meaning 'big fire'. It describes the state or condition of the habitat, that is, one where dry-season fires are fierce. Although chipya vary in composition, all the species are fire-hardy or fire-tolerant.

PLATE 11 A typical stand of *Brachystegia-Julbernardia* woodland. Luwingu District,9 October 1969

PLATE 12 Chipya after a recent fire. Nkolenfumu Kasama District, 5 September 1969

PLATE 13 Mateshi, a remnant patch of dry evergreen forest. Along the Luwingu-Chungu road, 3 October 1969

PLATE 14 Trees lopped and branches piled to make an ubukula. Mpika District, 19 September 1969

Mateshi: the patches of dry evergreen forest or thicket are known in Chibemba as *mateshi.* This is a precise term. All the species are fire-sensitive, evergreen trees, shrubs, scandent shrubs and climbers. In Katanga the term *muhulu* is used to describe patches of *mateshi.*

The use of vernacular names for plants may lead to confusion, because any particular vernacular name may refer to different plants in related languages. Some vernacular names yield useful autecological information, e.g. the small tree or shrub *Viridivia suberosa* is known as *mulyansefu,* which means 'the food of eland'. To help in the discussions throughout this section the Chibemba vernacular names have been listed in Lawton's Supplementary Report (in press).

HUMAN INFLUENCES ON THE VEGETATION

Fire

The climax vegetation has been modified by man's activities. Although natural fires may be caused by lightning, fires made by man have had the greatest effect on the vegetation. Early man used fire to hunt and to smoke out bees when collecting honey. The present inhabitants also used fire for the same purposes until quite recently. The time of burning has an important effect on the vegetation. Fires during the first half of the dry season, from May to early August, do little damage to the woody vegetation which is dormant at that time of the year. Fires during the second half of the dry season, from mid-August to the beginning of the rains, after the woody vegetation has flushed, may destroy the new growth and will eventually reduce the woodland to coppice (Trapnell, 1959). Hunters' fires early in the dry season would therefore favour the maintenance of a woodland canopy and late-season fires would destroy the woodland. In the past much of the woodland was probably burnt by hunters before late August, but during the past 30 or 40 years the scarcity of game has reduced the amount of hunting. Consequently much of the vegetation was not burnt until it was accidentally set alight late in the dry season.

In order to prevent large-scale destructive late dry-season fires, the government introduced a policy of early burning as much as possible of the fallow woodland areas each year. This policy was successful and was maintained from the early 1930s until the mid 1960s when it fell into abeyance. The destruction caused by the late dry-season fires that swept through parts of north-eastern Zambia were a feature of the late 1960s.

Iron-smelting

From early times, until about 60 years ago, man cut the forest and woodland to make charcoal for iron-smelting. Over the years, vast areas must have been cut for this purpose. The Balungu, a Bantu tribe that live in the northern and central parts of the plateau, are renowned for their skill as iron-smelters and they must have cut over much of the woodland in their area during the past 500 years. Frequent remains of smelters support this view.

Cultivation

Man's other major activity is cultivation. A large tribe, the Babemba, and a number of smaller related tribes, migrated into north-eastern Zambia from Katanga and the Congo Basin 200-250 years ago (Richards, 1951). The Bemba are forest cultivators and they settled in the mateshi or evergreen forest areas of the Chambeshi-Bangweulu Land Region, where they practised their own form of shifting cultivation, known as chitemene. The various systems of chitemene are discussed under "Traditional land use" in Volume 2.

A grassland system of cultivation practised by the Mambwe and described by Trapnell (1953), in which the tall perennial grasses are 'turned in' by hoe and mounded during the dry season, is worth further consideration. This system could replace chitemene in areas where the tree crop has been destroyed. The grasses provide organic matter and this probably helps to maintain soil fertility. The system has much to recommend it and its use should be extended. A fallow period, under grass, is required after a period of cultivation.

CLIMATIC FACTORS AND THEIR EFFECT ON THE VEGETATION

A number of climatic factors are of special ecological importance. Dry-season temperatures have an important effect on the vegetation; during the first half of the dry season when the temperatures are low and woody vegetation is dormant, some of the species shed their leaves, whilst others retain the old leaves for most of the cool season and are only deciduous for a very short period. As soon as the temperature rises from mid- to late August, the trees, shrubs and some of the perennial herbs flush and many of them also flower at this time. This is springtime in the dry tropics, although it occurs 2½ months before the beginning of the rains. Most of the trees and shrubs have deep root systems and some of the common species have been excavated (Savory, 1963). Some of the perennial herbs have extensive storage root systems (Lawton, unpublished).

Some species that grow on steep hillsides or escarpments, where the soils are shallow and dry, remain deciduous until the beginning of the rains e.g. *Brachystegia bussei*. On one typical site where *B. bussei* is growing on a deep plateau soil in association with other *Brachystegia* spp. (in particular, *B. floribunda*), it was observed that *B. bussei* remained dormant until the beginning of the rains, although *B. floribunda* and the other trees had flushed in August. This suggests that the ability to flush when the temperature rises may be a specific character.

While the average monthly rainfall and temperature broadly determine the type of vegetation in the area, the maximum and minimum monthly values for rainfall and temperature have a greater effect on the vegetation. The effects of a sharp frost can be seen for many years. An unusually heavy rainy season may so increase the height of the dry-season watertable that it will take a few years to fall to its usual dry-season level.

THE WOODLAND BURNING EXPERIMENTS

The importance of the effect of fire on the vegetation has been recognised for many years. A number of long-term woodland burning experiments have been established and a review of these experiments form an important part of the background to the ecological section of this reconnaissance survey.

Ndola woodland burning experiments

In 1933-4 the Forestry Department laid down a series of woodland burning experiments near Ndola. The primary aim was to investigate the effect of woodland burning, at different times of the year, on timber yields. In addition the experiments have yielded some useful autecological information on some of the woodland species.

Three series of plots were laid down at Ndola, in mature natural woodland of uneven age. Each plot is 0.4 ha (1 ac) and is separated from the next plot by a strip of woodland. In the first series, one plot is early-burnt each year, that is the grass is burnt as soon as possible in the dry season, some time in June or July. The second plot is late-burnt, that is burnt just before the beginning of the rains in October or November. The third and fourth plots have been completely protected from fire.

In the second series the woodland was felled; these are known as the coppice plots. The aim of the experiment is to compare the effect of fire at the different seasons on woodland regeneration after felling. The first plot was felled at breast height to simulate the local method of cultivation and its treatment has been annual early burning. The remaining plots were felled at ground level, one was early burnt, one late burnt and the remaining one completely protected from fire. The third series of plots is a replication of the coppice plots.

There was an initial enumeration of all the plots in 1933. All trees and saplings above 15.2 cm (6 in) girth at breast height were recorded in the woodland plots and all the stems of 20.3 cm (8 in) height were recorded in the coppice plots. A complete enumeration was done in 1944 and a re-measurement of recruitment was carried out in 1946. Trapnell made a visual appraisal of the plots in 1956 and reviewed the experiment in 1959. He grouped the species according to their degree of fire tolerance.

Fire-tolerant species

These are the species that occur repeatedly in several growth stages under both early- and late-burning treatments in both sets of plots. They are considered fire-resistant or fire-tolerant. Examples: *Parinari curatellifolia, Erythrophleum africanum, Pterocarpus angolensis, Anisophyllea boehmii, Diplorhynchus condylocarpon, Zanha africana, Strychnos innocua, Uapaca nitida, Maprounea africana, Hymenocardia acida, Syzygium owariense (S. guineense* subsp. *marcrocarpum), Strychnos cocculoides, Strychnos spinosa.*

Semi-tolerant species

These are the species that are only fire-tolerant under certain conditions. Examples: *Isoberlinia angolensis, Baphia bequaertii, Pseudolachnostylis maprouneifolia, Strychnos pungens, Uapaca kirkiana, Bridelia cathartica, Hexalobus monopetalus, Xylopia odoratissima, Uapaca pilosa.*

Fire-tender species

Although present in all the plots, the fire-tender species are unable to withstand fire during a stage of their development. There is a marked increase of these species in the plots under complete protection. Examples: the woodland canopy dominants, species of *Brachystegia* and *Julbernardia; Chrysophyllum bangweolense, Garcinia huillensis, Bridelia duvigneaudii.*

Intolerant species

The intolerant species are confined to the plots under complete protection and self-protected thickets in the early burnt plots. The intolerant species are not listed, but they include all the forest climbers and evergreen trees: *Entandrophragma delevoyi, Landolphia* spp. *Artabotrys monteiroae, Uvaria angolensis, Chrysophyllum magalismontanum (Bequaertiodendron magalismontanum), Opilia celtidifolia.*

Trapnell (1959) concluded that the woodland canopy species, *Brachystegia, Julbernardia* and *Isoberlinia* are fire-tender or at best only just semi-tolerant species, and that the woodland can be destroyed by consistent late burning. The concept of groups of species based on their response to fire has formed part of the background to this study, but the specific content of the groups sometimes differs from those of Trapnell.

1969 Ndola enumerations

It is realised that the Ndola woodland burning experiments create unnatural conditions. No single acre of woodland would be consistently early-burnt or late-burnt each year, or for that matter completely protected from fire for a period of 36 years (1933-1969), under natural conditions. This does not however detract from their value. Any species that has survived 36 years of annual late burning can be considered fire-tolerant, or fire-hardy. Species that are able to regenerate under an early-burning treatment are probably semi-tolerant or fire-tender and those species that are dominant in the complete protected plots are intolerant of fire, or fire-sensitive.

It was therefore decided to enumerate some 10 x 10 m random quadrats in the experimental plots and to use these lists as a nucleus for groups during this survey.

In the early-burnt woodland plots the canopy has been maintained (Plate 15). The enumeration records *Brachystegia spiciformis* as the main canopy species with some large *Erythrophleum africanum*, a fire-tolerant or hardy tree. The canopy has regenerated under the early-burning treatment in the coppice plot that was felled at breast height (Plate 16). In this plot *Isoberlinia angolensis, Julbernardia paniculata* and *Uapaca nitida* are the main canopy species. *Uapaca* spp. are also present in the coppice plot that has regenerated from felling at ground level. The presence of many *Baphia bequaertii* and the fire-sensitive *Bridelia duvigneaudii* indicates that fires are light in the early-burnt plots; this is partly because there is a light canopy covering 80-100% of each plot.

In the late-burnt woodland plot most of the species have been reduced to coppice (Plate 17). The woodland canopy species have survived as coppice, although they are unable to grow up through the sapling stage to form a canopy under this treatment. In the coppice plots the woodland has not regenerated (Plate 18), a few fire-damaged small trees of *Maprounea africana* and a sapling of *Pterocarpus angolensis* were enumerated. The common fire-hardy species that were enumerated include: *Chrysophyllum bangweolense, Diospyros virgata, Erythrophleum africanum, Combretum* spp., *Diplorhynchus condylocarpon, Hymenocardia acida, Hexalobus monopetalus, Ochna leptoclada, Ochna schweinfurthiana, Ochthocosmus lemaireanus, Maprounea africana, Parinari curatellifolia, Pterocarpus angolensis, Pseudolachnostylis maprouneifolia, Syzygium guineense* subsp. *marcocarpum, Strychnos* spp., *Xylopia adoratissima.*

A dense growth of shrubs and climbers has developed in the plots that have been completely protected from fire (Plate 19). A sapling of the evergreen forest emergent *Entandrophragma delevoyi* and the canopy tree *Marquesia macroura* were enumerated. The fire-sensitive or tender shrubs and climbers include: *Bridelia duvigneaudii, Canthium guenzii, Landolphia* spp., *Opilia celtidifolia, Artabotrys monteiroae, Uvaria angolensis.*

The presence of *Marquesia macroura* is of particular interest. It was recorded as a recruit in the completely protected coppice plot in 1946 (Trapnell, 1959) and by 1969 it had reached the canopy.

Kasama woodland burning experiments

In 1950, a similar series of woodland burning experimental plots were established in plateau woodland near Kasama. These were sample-enumerated in 1968 and they show the same response to fire as the Ndola plots. The number of plants over 2 m (6 ft) high is given in Table 35.

In the early-burnt plots species of the genus *Uapaca* have formed patches of light canopy at a height of about 3 m (10 ft). Under complete protection a dense *Uapaca* canopy has developed and the canopy species *Brachystegia floribunda* and *B. gladerrima* have emerged above the *Uapaca* canopy (Plate 20).

TABLE 35 Number of woody plants over 2 m (6 ft) high

Treatment	Coppice plots	Woodland plots
Late-burnt	2	2
Early-burnt	74	57
Complete protection	94	76

Nkolemfumu chipya burning experiments

In 1960 a series of plots were demarcated in chipya in the Nkolemfumu Protected Forest Area. The initial enumerations cannot be traced and the prescribed treatment of early burning and complete protection was only carried out for 8 years, that is until 1968. The experiment was then abandoned. The early-burnt plot has been maintained as coppice (Plate 21) with small trees of *Hymenocardia acida* and *Maprounea africana*, etc. Under the complete protection treatment the coppice has grown to a height of over 2 m (6 ft) (Plate 12) and is now beginning to suppress the dense grass

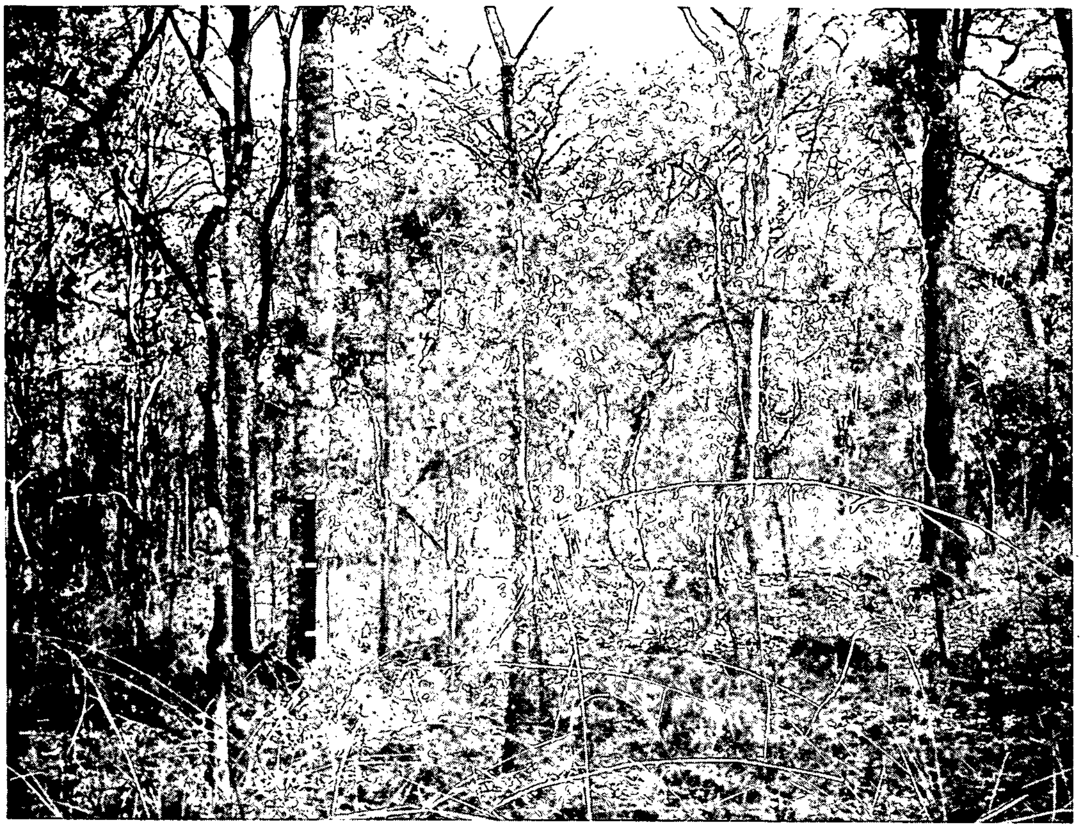


PLATE 15 An early-burnt woodland plot. Ndola woodland burning experiments, 24 September 1969

PLATE 16 An early-burnt coppice plot cut at breast height. Ndola woodland burning experiments, 24 September 1969

PLATE 17 A late-burnt woodland plot. Ndola woodland burning experiments, 24 September 1969

PLATE 18 A late-burnt *coppice plot cut at ground level.* Ndola woodland burning experiments, 24 September 1969

PLATE 19 Woodland plot completely protected from fire. Ndola woodland burning experiments, 24 September 1969

PLATE 20 Woodland plot completely protected from fire. A dense *Uapaca* canopy with emergent *Brachystegia floribunda* and *B. glaberrima.* Kasama woodland burning experiments, 30 October 1968

PLATE 21 An early-burnt plot maintained as coppice. Nkolemfumu chipya burning experiments, 4 September 1969

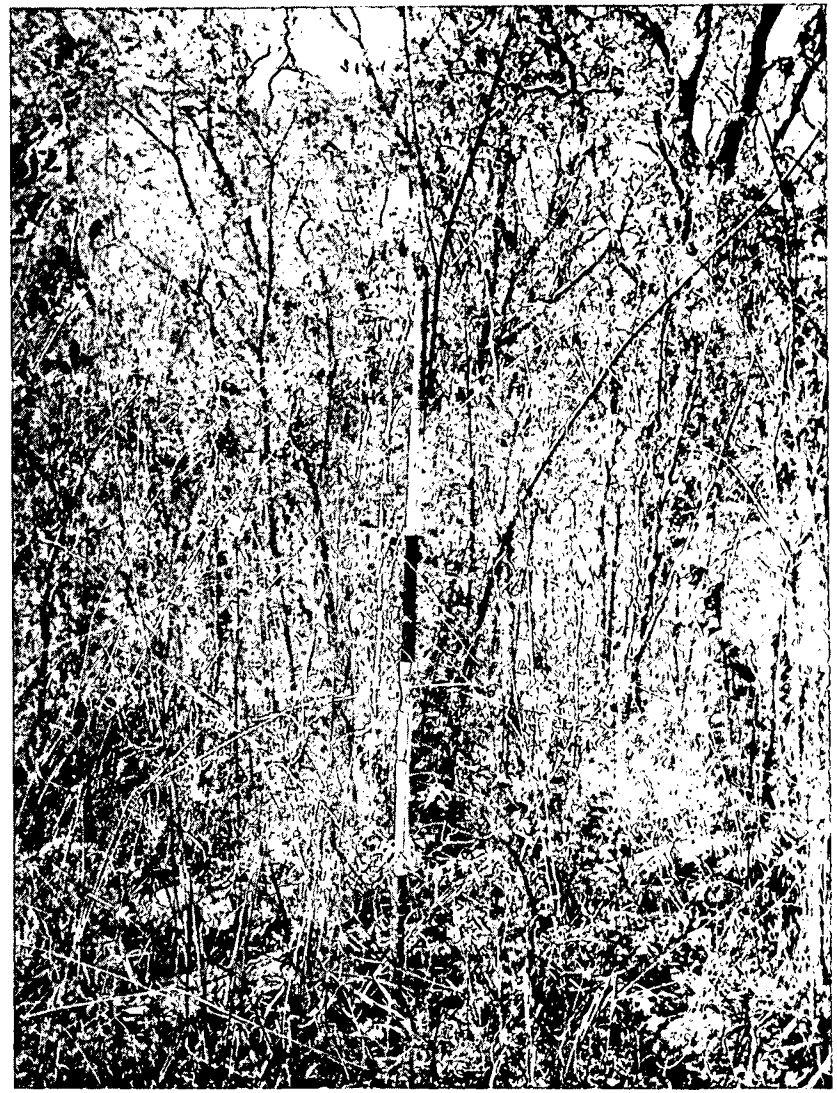


PLATE 22 Complete protection plot. Nkolemfumu chipya burning experiments, 5 September 1969

and bracken ground vegetation. Conditions have already become suitable for fire-sensitive evergreen climbers and *Canthium gueinzii, Bridelia duvigneaudii* and *Uvaria angolensis* were enumerated. The short-lived *Nkolemfumu* experiment, has suggested that if open chipya is protected from fire for a long enough period, it will be replaced by evergreen thicket, i.e. *mateshi.*

All the woodland burning experiments have clearly demonstrated that fire has an important effect on the vegetation. The time of burning, particularly in the *Brachystegia-Julbarnardia* woodland, is important. If the woodland grasses are burnt early during the dry season, the canopy is not destroyed and the woodland will even regenerate from coppice under an annual early-burning treatment. In chipya, a fire at any time of the dry season is destructive, but a period of protection from fire will lead to the replacement of open fire-hardy chipya by fire-sensitive evergreen thickets *(mateshi).*

It has been possible to compile lists of fire-hardy species and fire-sensitive evergreen species from the sample enumeration of the burning experiments. These lists have formed the basis of groups used in the analysis. Some dynamic relationships have also been revealed; for instance, the formation of patches of *Uapaca* canopy in the early burning and complete protection plots in the Kasama experiment with the emergence of the woodland canopy *Brachystegia* spp. above the Uapaca, suggests that the canopy species are protected from fire by the *Uapaca* as they grow through the sapling stage.

THE FORMULATION OF AN ECOLOGICAL CONCEPT

In natural vegetation, the distribution of species is usually non-random, that is, there is a pattern. It is the ecologist's task to determine the causes for the various patterns. In the past the vegetation was sometimes described in terms of long species lists that were often of little ecological value. The Zurich-Montpellier school, lead by Braun-Blanquet, compiled large abstract associations based on the floristic composition of the vegetation. In each association they recognised a number of 'faithful' species, that is, species with a narrow ecological range. Later Du Rietz replaced the 'faithful' species with ecological groups of species. He defined an ecological group as 'a group of species, which, in a particular set of ecological and geographical conditions, reaches maximum development and vitality, forms the characteristic core of the association, and usually fixes its physiognomy also'. (Du Rietz 1930, quoted by Poore, 1962). This rather narrow concept of an ecological group was modified by other workers, in particular Godron and his fellow workers at Montpellier. Godron (1967) recognised that ecological groups may overlap in space. The concept of overlapping, or imbricate ecological groups, is an important development in the recognition and determination of vegetative patterns and it has been used in this survey.

If the vegetation at each sample is considered an association, then the picture is confused and meaningless, but if the species with similar ecological affinities are grouped together, then a pattern emerges and it is possible to interpret the dynamic relationships within the vegetation. In a discussion on the ecology of a bird fauna, Moreau (1966) found that 'much of value and significance is lost if a bird fauna is dealt with en bloc'. By dividing the bird fauna into groups which are broadly ecological as well as taxonomic, Moreau found 'the comparisons revealed are enlightening in point after point'.

THE ECOLOGICAL GROUPS

From the discussion on the woodland burning experiments there are clearly two groups of species. There are the fire-hardy species that grow in an open habitat and can withstand intensive annual fires; these have been called the chipya ecological group. Secondly there are the fire-sensitive evergreen species, that occur in the patches of mateshi and in the complete protected plots; these have been called the dry evergreen forest ecological group.

The woodland canopy, mainly consisting of species of the genera *Brachystegia* and *Julbernardia*, has emerged as a group of special ecological significance. Species in this group require certain conditions for their establishment. This group is known as the *Brachystegia-Julbernardia* woodland canopy group.

Species of the genus *Uapaca* will later be shown to play an important role in the regeneration and establishment of the dry evergreen forest and *Brachystegia-Julbernardia* woodland canopies. The *Uapaca* spp. have been grouped together as a separate ecological group.

A number of species, some common, some rare, have a wide ecological range and these have been listed as the ubiquitous group of species.

The specific composition of all the groups is listed by Lawton in *J. Ecol.* They are the basic ecological groups that form the pool of species from which the species at each sample enumeration is drawn. The composition of each group at the enumeration level will vary, e.g. in one sample there may be 15 species belonging to the chipya group and in another sample there may also be 15 chipya group species, but only five of the chipya species may be common to both samples. Therefore the ecological groups, at the enumeration level, are usually non-specific.

Each sample usually contains species drawn from more than one ecological group and an interpretation of the dynamic relationship between the groups is the key to the history and ecology of the site.

Dynamic relationships within the vegetation

All the sample enumerations discussed in this and subsequent sections are given in *J. Ecol.* (Lawton, in press). Remnant patches of dry evergreen forest occur in Land Region 11d, the Chambeshi-Bangweulu Plain. In sample 277 (Plate 23) the evergreen forest remnant is surrounded by chipya. The closed forest canopy is dominated by *Marquesia macroura* and *Syzygium guineense* subsp. *afromontanum* at a height of 25-27 m (82-88 ft), with *Anisophyllea pomifera* and *Schrebera alata* occurring below the main canopy. Fire-sensitive evergreen shrubs and climbers are numerous and include *Artabotrys monteiroae, Bridelia duvigneaudii, Canthium gueinzii, Canthium schimperanum, Chrysophyllum (Bequaertiodendron) magalismontanum, Craterosiphon quarrei, Craterispermum laurinum, Erythroxylum emarginatum* and *Uvaria angolensis.*

One chipya group tree, *Erythrophleum africanum*, has grown up with the forest canopy. The chipya species *Diplorhynchus condylocarpon* occurs on the edge of the forest and *Hymenocardia acida* is noted as being 'old' under the forest canopy. A number of other chipya group species occur under parts of the forest canopy, e.g. *Chrysophyllum bangweolense, Hexalobus monopetalus, Garcinia huillensis, Ochthocosmus lemaireanus, Strychnos* spp. and *Xylopia odoratissima.* The presence of the chipya species suggests that part of what is now dry ever-green forest was open chipya in the past. The chipya species could not have become established under the forest canopy. The presence of two suppressed saplings of *Uapaca* spp. under the forest canopy probably represents the remains of a *Uapaca* canopy under which part of the forest canopy regenerated. The size of most of the *Marquesia macroura* indicates that they are young trees; their diameters range from 12 cm to 59 cm (5-23 in), with an average of 34 cm (13 in). Later samples will show how the *Marquesia* canopy regenerates under a *Uapaca* canopy.

A similar situation is illustrated in sample 394 where the evergreen forest canopy is dominated by *Brachystegia spiciformis, Marquesia macroura* and *Parinari curatellifolia.* The chipya tree *Combretum collinum* is just below the main canopy. Most of the other chipya group species occur as coppice under the forest canopy. The *Uapaca* group is again reduced to a little coppice, one sapling and a pollarded tree, probably the remnants of a *Uapaca* canopy. Some of the *Marquesia* are young trees which have only recently reached the canopy.

Sometimes *Brachystegia taxifolia* forms a canopy in the evergreen forest remnants, as illustrated by sample 398. This is located in Land Region 11d, the Chambeshi-Bangweulu Plain (see Map 4-5 for all the locations). The *B. taxifolia* canopy occurs at 20 m (66 ft) and a *Syzygium guineense* subsp. *afromontanum* also occurs in the canopy. A large *M. macroura* is noted outside the sample and some saplings occur in the sample. There are 81 coppice or coppiced seedlings of *B. taxifolia,* suggesting that the forest is probably spreading and colonising the surrounding chipya. Some of the main chipya group species are recorded as 'dying' or 'old', e.g. *Diplorhynchus condylocarpon, Maprounea africana,* and *S. g. macrocarpum*. Some other chipya species have grown up with the *Brachystegia taxifolia* canopy, e.g. *Erthrophleum africanum* and *Pericopsis angolensis. Uapaca nitida*, the only representative of the *Uapaca* group, is listed as 'edge' species.

If the evergreen forest is felled or cleared for cultivation, it is replaced by open chipya vegetation as illustrated by the foreground of Plate 23. Sample 163 is an extreme example where all the species belong to the chipya group. The most abundant species are *Diplorhynchus condylocarpon, Hymenocardia acida, Pericopsis angolensis, Pterocarpus angolensis, S. g. macrocarpum* and *Vitex doniana.*

The *S. g. macrocarpum* is forming patches of low canopy at a height of 4 m (13 ft). *V. doniana* grows to the same height, but its crowns are small and do not cast as much shade as the *Syzygium* crowns. The *S. g. macrocarpum* canopy partially suppresses the tall grasses and bracken of the chipya and under these conditions *Uapaca* spp. are established. *Uapaca* will not grow in the open chipya; it was absent in sample 163. In sample 370 *U. nitida* has grown up through the *S. g. macrocarpum* canopy (Plate 14). This sample is mainly open chipya and it is noted that *H. acida* and *M. africana* are recorded as healthy and vigorous. The *Syzygium* is also vigorous. There is a large *Parinari curatellifolia* (20 m, 66 ft), probably a remnant of the previous evergreen forest. (*Marquesia* occurs in the other samples along the traverse: see Map 4-5.)

The next stage of development is the formation of an *Uapaca* canopy as in sample 279 (Plate 29). The main *Uapaca* group species, *U. benguelensis, U. kirkiana, U. nitida* and *U. sansibarica* have formed a canopy at a height of 4-12 m (13-39 ft). The photograph (Plate 25) clearly shows that the ground vegetation has been reduced to a sparse short grass layer and most of it is covered with leaf litter. It had not been burnt in mid-October at the time of sampling and a fire would simply creep along the ground and do little damage. Under these conditions *Marquesia macroura* and the woodland canopy species *Brachystegia glaberrima* have regenerated. There are 43 seedlings or coppiced seedlings of *Marquesia* as well as a number of saplings and one young tree which has overtopped the *Uapaca. B. glaberrima* is represented by 40 seedlings or coppiced seedlings, some saplings and one 14 m (46 ft) tree. Some of the chipya species under the *Uapaca* canopy are noted as being 'moribund' or 'old' e.g. *Hymenocardia acida* and *S. g. macrocarpum.* This sample illustrates the concept of overlapping ecological groups. The chipya group is old and moribund and preceded the *Uapaca* canopy which is now well established. The evergreen forest canopy species and woodland canopy species are regenerating under the *Uapaca* canopy and growing up through the sapling stage to eventually overtop it. Once overtopped the *Uapaca* will die out and survive only as a fringe to the main *Marquesia* canopy (Plate 26).

So far the discussion has only covered samples on the Bangweulu-Chambeshi Plain, but there are also remnants of dry evergreen forest on the Mbala-Kawambwa Plateau (Land Region IIa). In sample 310 the dry evergreen forest canopy species *M. macroura* is associated with a small tree and saplings of *S. g. afromontanum*, and the forest shrubs or small trees; *Anisophyllea* spp., *Bequaertiodendron magalismontanum, Bridelia duvigneaudii* and *Uvariastrum hexaloboides*. The chipya group is large, although some species are noted as being 'old' or 'lacking vigour', e.g. *Hymenocardia acida* and *S. g. macrocarpum*. There is only one small tree and a sapling of *U. kirkiana* in the *Uapaca* group; this group is usually poorly represented under a forest canopy. In addition there is a *Brachystegia-Julbernardia* woodland canopy group on the plateau. In sample 310 *Brachystegia wangermeeana* and *Julbernardia globiflora* are in the canopy, and *Brachystegia spiciformis* has been included here because it is a little below the dry evergreen forest canopy. *B. floribunda* occurs as coppice and *Baphia bequaertii* occurs under the canopy.

Brachystegia floribunda, B. glaberrima and *B. wangermeeana,* sometimes with *B. utilis,* are often associated with *Marquesia macroura* on the main plateau (Land Region IIa). In sample 302 the *Marquesia* canopy at 20 m (66 ft) is the same height as *B. floribunda* with *B. glaberrima* and *Julbernardia globiflora* just below the canopy at 18 m (59 ft) and *B. wangermeeana* well below at 8 m (26 ft). The *Uapaca* group is mainly trees, indicating that it has been established for some time, and 1 specimen is noted as dying. Many of the chipya group species are coppice; it is suggested they have died back under the combined evergreen forest-woodland canopy, e.g. *S. g. macrocarpum* is recorded as 23 coppice clumps and *Hymenocardia acida* is moribund. The chipya group species will not thrive under a closed canopy. They only survive as coppice. If the canopy is opened again they will then respond to the increase in light, etc.

If the dry evergreen forest or mature woodland is cleared it may be replaced by chipya on the plateau (Land Region IIa). Sample 289 is all chipya group; *Aframomum biauriculatum* and *Pteridium aquilinum* suggest fierce dry-season fires. *Combretum* spp. are frequent and there is abundant *H. acida* with some small trees of 4 m (12 ft). *S. g. macrocarpum* is also represented by trees of 4-5 m (13-16 ft). Under groups of these trees the situation should now be suitable for the establishment of *Uapaca* spp., and this may be the next stage of development.

Sometimes *Marquesia macroura* is absent from remnant patches of evergreen forest on the plateau. This is probably because dry grass accumulates around the fluted base of the tree and each year fires damage the base until it is eventually burnt through and destroyed. In sample 269 *Brachystegia taxifolia* and *Syzygium guineense* subsp. *afromentanum* form a canopy at a height of 14-15 m (46-49 ft). There are some large *Bequaertiodendron magalismontanum* and *Bridelia duvigneaudii* and these are considered remnants of the old forest. The chipya group tree *Erythrophleum africanum* has also joined the forest canopy. The rest of the chipya species are largely coppice. It is interesting to note that *Uapaca* is absent from this sample as well as *Marquesia*. The woodland is also poorly represented. When the dry evergreen forest or *Brachystegia-Julbernardia* woodland is regenerating, *Uapaca* is usually well represented, often as coppice colonies in which the canopy seedlings are established (Plate 27) and as light canopy through which the canopy species saplings grow (Plate 28). In sample 346 there are remnants of the old forest crop, i.e. *Marquesia macroura* with DBH of 60 m (197 ft) or over, large *Anisophyllea pomifera, Craterosiphon quarrei* and *Uvariastrum hexaloboides,* and there are some young *M. macroura* suggesting a period of forest regeneration. There is a good *Uapaca* group canopy at a height of 8-14 m (26-46 ft) and under this canopy the *Marquesia* has regenerated. The chipya group takes the familiar pattern of coppice under the forest canopy. It is noted that the *Syzygium guineense* subsp. *macrocarpum* regrowth is from old stumps.

Many examples illustrate the role of *Uapaca* in the regeneration of forest or woodland canopies. In sample 389 *Brachystegia glaberrima* at 6 m (20 ft) is emerging above a canopy of *Uapaca kirkiana* at 4 m (13 ft). In sample 390, *U. robynsii* forms the main *Uapaca* canopy at 4 m (13 ft) and *B. glaberrima* and *Julbernardia paniculata* have emerged above it. The chipya group again shows a lack of vigour: *Hymenocardia acida, Maprounea africana* and *Syzygium guineense* subsp. *macrocarpum* are all old, moribund or dying, suggesting that they preceded the *Uapaca* and woodland phases. All the groups overlap in space.

In sample 367 coppice of *Marquesia macroura* is protected by coppice colonies of *Uapaca kirkiana*. There is a vigorous *Uapaca* group in this sample. The whole of the chipya group is coppice.

In the discussion on the samples, the dynamic pattern within the vegetation has been established. The ecological groups in each sample have been non-specific groups of species with a common ecological affinity, but in addition to these groups a number of specific groups have been recognised.

PLATE 23 Mateshi sample 277. Chunga road area, Luwingu District, 14 October 1969

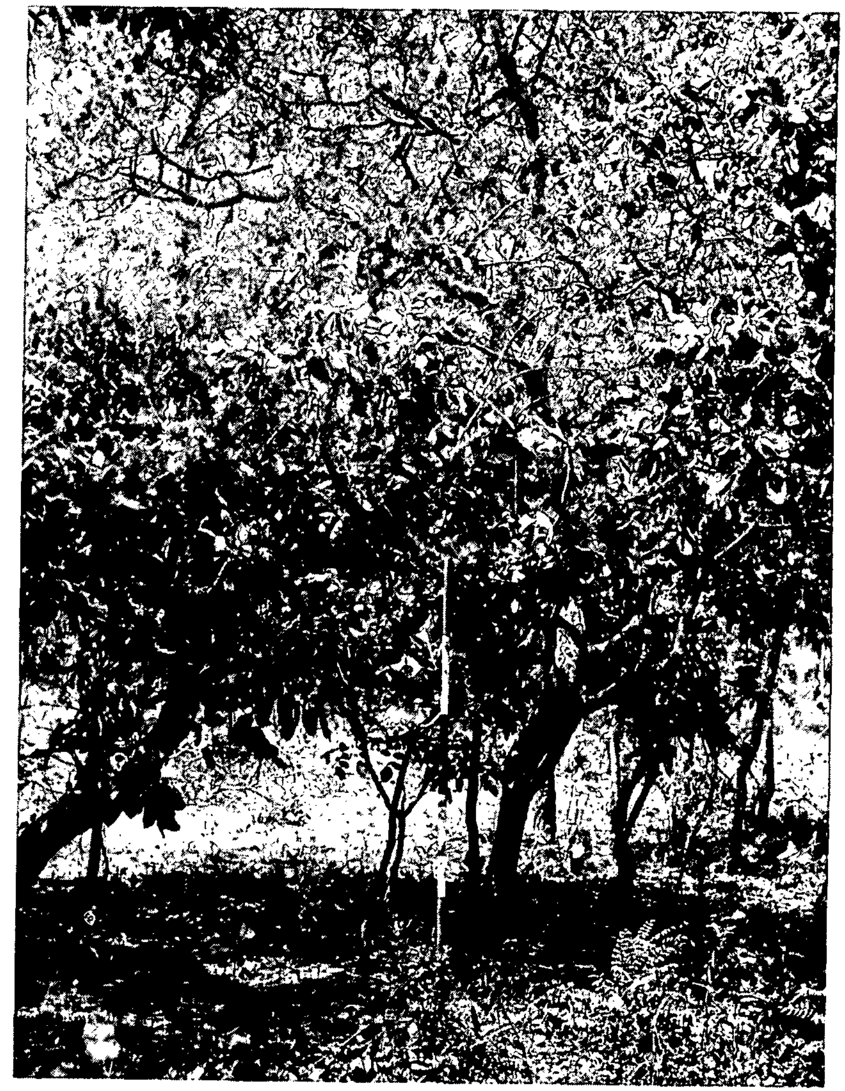


PLATE 24 *Uapaca nitida*, grown a canopy of *Syzygium guineense* subsp. *macrocarpum*. Sample 370, Katuta area of Luwingu District, 24 October 1970

PLATE 25 Sapling of *Marquesia macroura* below a *Uapaca* canopy of mainly *U. sansibarica.* Note the sparse cover of ground vegetation. Sample 279, Luwingu District, 14 October 1969

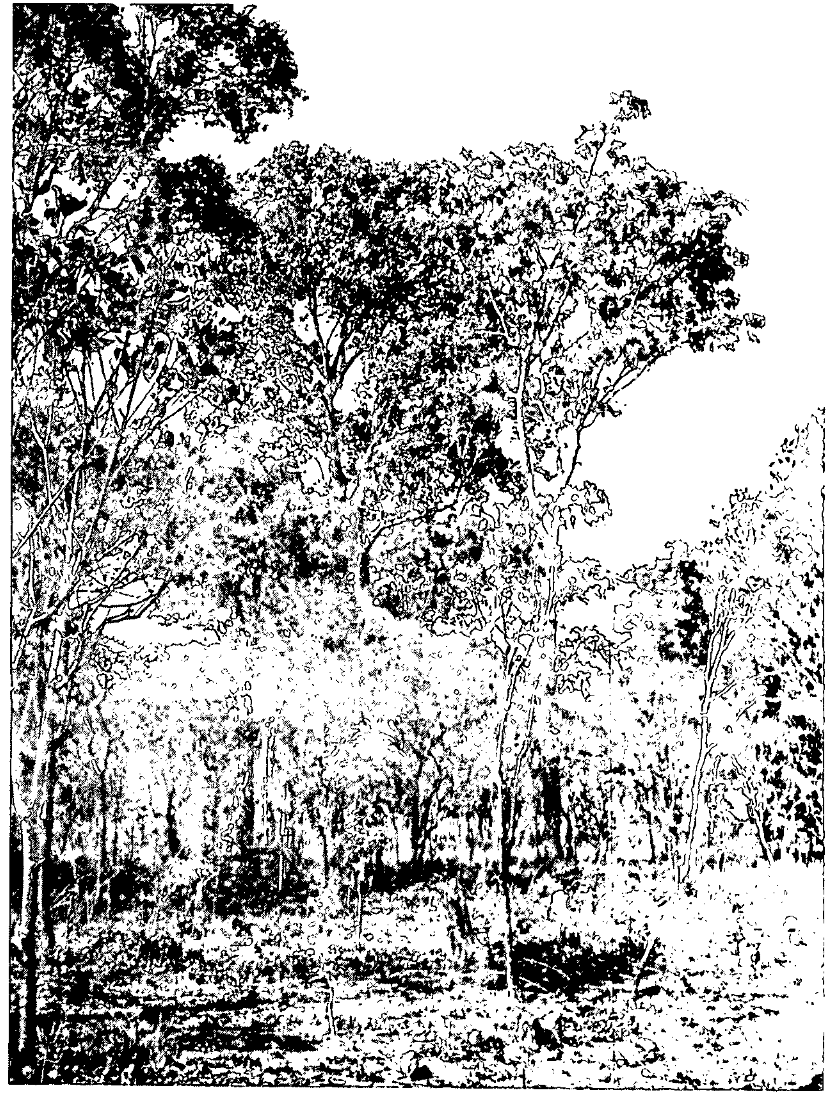


PLATE 26 A *Marquesia macroura* canopy with a fringe of *Uapaca.* Chunga road area, Luwingu District, 14 October 1969

PLATE 27 A sapling of *Brachystegia spiciformis* (to the right of the pole) regenerating in a colony of *Uapaca kirkiana* coppice. Mpika District, 18 September 1969

PLATE 28 A sapling of *Brachystegia glaberrima* emerging above a dense stand of *Uapaca sansibarica.* Kawambwa District, 20 September 1970

The specific ecological groups

A number of specific ecological groups, that is groups of shrubs, scandent shrubs or small trees, that occur together repeatedly, have been identified. These groups are indicators of definite sites or habitats. One group known as the *Bridelia cathartica* group (see Map 4-1 for its distribution) occurs east of the Chambeshi on the Mpika-Isoka Ridge (Land Region IIg), the Upper Luangwa Valley (Land Region IIIa), the Luangwa Valley Shoulder (Land Region IIIc) and the extreme north-eastern section of the Chambeshi-Bangweulu Plain (Land Region IId). The group consists of *B. cathartica, Flacourtia indica, Strychros innocua* and *Hippocratea parvifolia.* It is an indicator of a soil with a structureless upper horizon of sandy loam or loamy sand texture, followed by a compact horizon from a depth of about 10-15 cm of sandy clay loam or very fine sandy clay loam, with finally at a depth of 1 m or more there is an impermeable layer of either quartz, laterite, ferrous manganese concretions parent rock, or a gley horizon. The *Bridelia cathartica* group is associated with *Brachystegia allenii* on a shallow compact soil overlying quartz at 101 cm in sample 87. With *Brachystegia boehmii* and *B. manga* as the canopy species, the group indicates a shallow compact soil with mottling in sample 79 and laterite at 75 cm in sample 83. Where *B. floribunda* or *B. glaberrima* form the canopy the soil profile is usually deep, but there is often a compact horizon, as in samples 126 with *B. glaberrima* and sample 158 where *B. floribunda* is present as well as *B. glaberrima.* In sample 108 the *Bridelia cathartica* group is associated with a canopy of *Brachystegia glaberrima* and *B. manga* with coppice and pollarded stems of *B. allenii* and *B. boehmii.* The soil is recorded as having an increase in 'pellets' with depth and slight compaction. It is noted that *B. allenii, B. boehmii, B. manga* and *B. glaberrima* are most frequently associated with the *Bridelia cathartica* group and this group indicates soils that are often shallow and usually compact.

The *Bridelia duvigneaudii* group consists of *B. duvigneaudii, Craterosiphon quarrei* and *Uvariastrum hexaloboides.* It occurs mainly on the Chambeshi-Bangweulu Plain (Land Region IId) and the Mbala-Kawambwa Plateau (Land Region IIa). (See Map 4-1 for its distribution.) This group always indicates a deep freely drained soil that retains moisture during the dry season. It is usually part of an evergreen forest group as in sample 300. *Brachystegia wangermeeana, B. floribunda* and *B. glaberrima* may form a woodland canopy in association with this group, which can be considered an indicator of dry evergreen forest conditions and deep soils.

Another specific group has a restricted distribution in brown piedmont soils (see Map 4-1). The core of this group is formed by the small trees *Baphia bequaertii* and *Protea petiolaris* in association with the suffrutex *Salacia bussei.* To this group, known as the *Protea petiolaris* group, is sometimes added the small tree *Ochna pulchra* and the suffrutex *Hugonia gossweileri.* The group is sometimes associated with large *Anisophyllea pomifera* and evergreen forest and woodland groups as in samples 134, 183 and 185. In all samples the soils are deep, freely drained brown sandy loams to sandy clay loams at depth.

NOTES ON THE AUTECOLOGY OF SOME SPECIES

Apart from the ecological groups based on species with a common ecological affinity and the smaller specific groups of species that indicate definite habitats, a number of species may be of value as indicators of certain habitats. The ubiquitous *Parinari curatellifolia* would normally not be considered a species of ecological significance. It occurs as a shrub or small tree in many parts of Africa, but in north-eastern Zambia it grows to a height of 20-30 m (66-98 ft), with a clean straight bole that may be slightly buttressed. It has the habit or form of a forest tree and has been considered a canopy species in the dry evergreen forest, as in sample 331. This form of *P. curatellifolia* is considered a forest ecotype. In the same way, large *Brachystegia spiciformis* are considered forest ecotypes, e.g. sample 331.

A number of *Brachystegia* spp. are useful indicators. They can be divided into two main groups. One group includes all the species that may be associated with remnants of the *Marquesia macroura* dry evergreen forest; these are *Brachystegia floribunda, B. glaberrima, B. utilis, B. wangermeeana* and *B. taxifolia* (in fact considered part of the forest group). The second group include all the species that are usually not associated with evergreen forest remnants: these are *B. allenii, B. boehmii, B. bussei, B. manga* and *B. stipulata.* The ubiquitous *B. spiciformis* may be a component of both groups. *B. longifolia* is rare in north-eastern Zambia where it is mainly replaced by the closely related *B. glaberrima.*

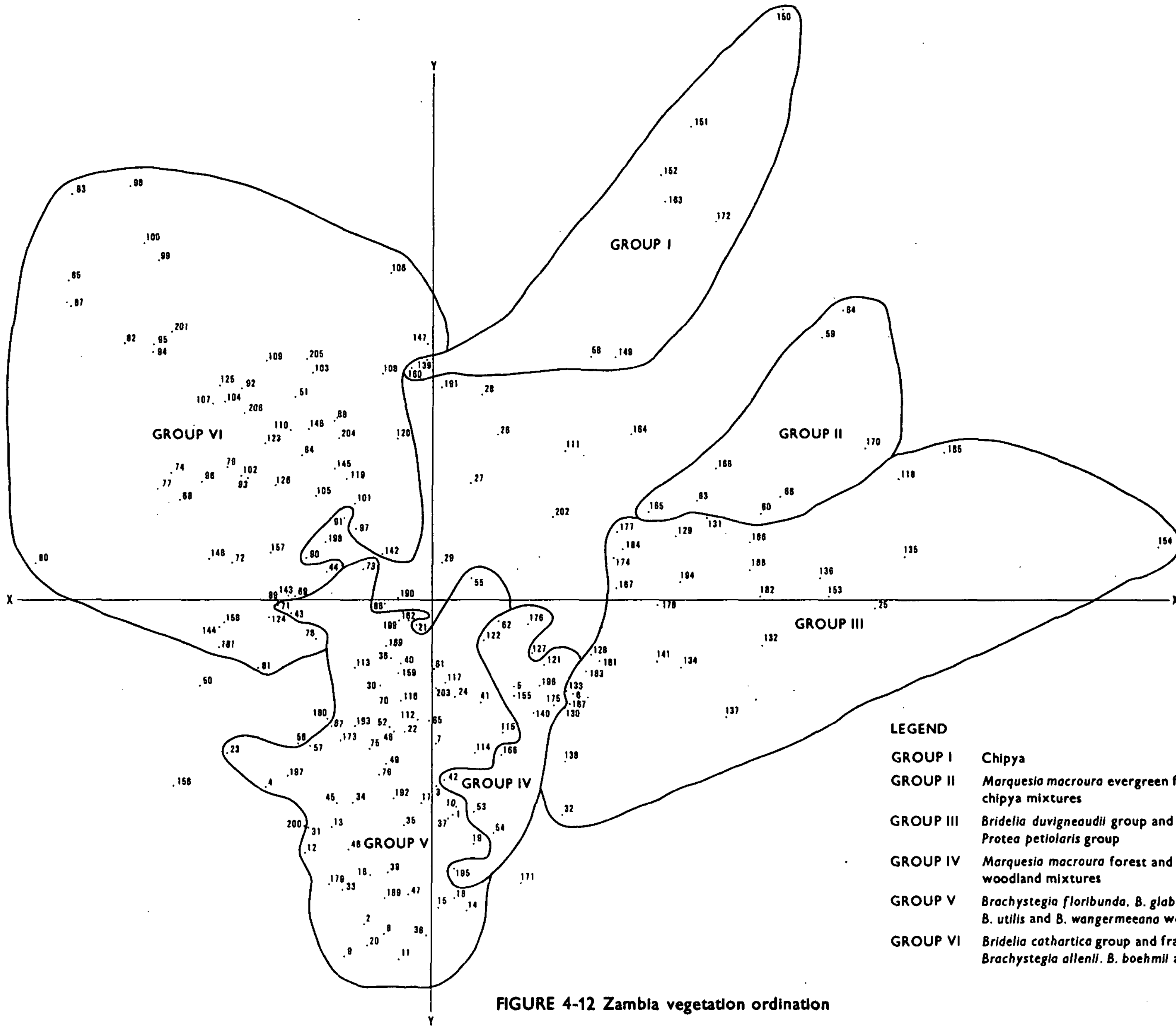
The first group generally indicate deep, freely-drained soils, that retain moisture during the latter half of the dry season and are mainly found in the central and western half of the Mbala-Kawambwa Plateau (Land Region IIa) and to some extent on the Chambeshi-Bangweulu Plain (Land Region IId). The second group indicate shallow, compact soils, often overlying a layer of laterite or parent rock. The soils dry out during the dry season, or they may be waterlogged during the rains. They occur in the drier north-eastern area, east of the Chambeshi on the Mpika Ridge (Land Region IIg), the Upper Luangwa Valley (Land Region IIIa) and the Luangwa Valley shoulder (Land Region IIIc), also in the Mweru Depression (Land Region Ia) and the Middle Luapula Valley (Land Region IIf), that is most of the land region surrounding the main Mbala-Kawambwa Plateau and the Chambeshi-Bangweulu Plain. The second group includes shallow soils on escarpments and rocky ridges.

Some *Brachystegia* spp. appear to occupy two different habitats, one on steep escarpments or rocky crests and the other on lower slopes near watercourses. In both habitats the soils are shallow. On the steep escarpments and crests the soils are physically shallow. On the lower slopes they are waterlogged for much of the season; they are therefore physiologically shallow.

B. beohmii is one of the indicators of shallow soils. It occurs on lower interfluve slopes where the soils are seasonally waterlogged as in sample 79, or perhaps where the water-table remains high through the dry season, e.g. sample 81. It also occurs on physically shallow upper slope soils, overlying laterite at 75 cm in sample 83, or laterite within the profile in sample 103. Another indicator of shallow soils is *B. bussei.* It may occur as almost pure natural stands on rocky escarpments as in sample 68, where the soil is only 20 cm, or on lower slopes where the soil profile is mottled at the base, e.g. sample 127.

Although a rare species, *B. stipulata* is a good indicator of shallow soils. It occurs on shallow lower slopes in the Chishinga area of the Mbala-Kawambwa Plateau and on shallow escarpment soils in the Mweru Depression, e.g. sample 318, and on the escarpment soils on the Isoka-Mpika Ridge. Apart from one recorded on Mbulu Island at the southern end of Lake Tanganyika, *B. allenii* is mainly found east of the Chambeshi. It is common on the lower escarpment soils of the Upper Luangwa Valley (Land Region IIIa), e.g. sample 100. *B. allenii* may be associated with *B. boehmii* and *B. manga* on shallow soils, e.g. sample 84.

From the other group that occur on deep soils, *B. floribunda* and *B. glaberrima* are the most widespread. *B. floribunda* is usually more frequent on the deep upper slope soils, e.g. sample 286 in which in fact *B. glaberrima* is also present. *B. glaberrima* is more frequent on the lower slopes as in sample 383. Both species are often associated with remnants of the dry evergreen forest. *B. utilis* is common on the shallow rocky soils of the Middle Luapula Valley, and occurs on soils with concretions in sample 69, and may also be associated with dry evergreen forest remnants. *B. wangermeena* is considered an indicator of moist habitats. It is one of the woodland canopy species most frequently associated with *Marquesia macroura,* e.g. sample 331. It frequently occurs with *Brachystegia floribunda* and *B. glaberrima,* e.g. samples 302, 310 and it has been noted on lower slopes near watercourses. The evergreen *B. taxifolia* is considered part of the dry evergreen forest, often forming a canopy as in sample 398. It may also form stands on lower woodland slopes and is a gregarious species. *B. microphylla* occupies rocky crests and upper slopes of escarpments but this rather specialised habitat has not been sampled during the survey.



LEGEND

GROUP I	Chipya
GROUP II	*Marquesia macroura* evergreen forest, forest and chipya mixtures
GROUP III	*Bridelia duvigneaudii* group and fragments of the group; *Protea petiolaris* group
GROUP IV	*Marquesia macroura* forest and *Brachystegia-Julbernardia* woodland mixtures
GROUP V	*Brachystegia floribunda, B. glaberrima, B. spiciformis, B. utilis* and *B. wangermeeana* woodland
GROUP VI	*Bridelia cathartica* group and fragments of the group with *Brachystegia allenii, B. boehmii* and *B. manga* woodland

FIGURE 4-12 Zambia vegetation ordination

Prepared by Directorate of Overseas Surveys 1974 from King (1964)

NUMERICAL ANALYSIS

Most ecological surveys are not considered complete without a statistical or numerical analysis. A principal component analysis using Orloci's formulae for similarity (Orloci, 1966) was used by the Statistical Branch of the Commonwealth Forestry Institute, Oxford, to analyse 206 samples. The plotting (Figure 4-12) divides the samples into a number of groups, but there is no clustering and a knowledge of the ecology of the vegetation is necessary to interpret the graph.

All the chipya samples occur in Group I; they represent samples where dry-season fires are intensive. Group II is a mixture of *Marquesia macroura* evergreen forest and forest/chipya mixtures, indicating the close relationship between forest and chipya. The *Bridelia duvigneaudii* group and *Protea petiolaris* group form Group III; these are on deep, freely drained soils. Group IV is a mixture of *Marquesia macroura* forest and *Brachystegia-Julbernardia* mixtures. This is followed by Group V which is *Brachystegia floribunda, B. glaberrima, B. spiciformis, B. utilis* and *B. wangermeeana* mixtures. These are usually on deep soils. The final group, Group VI, is the *Bridelia cathartica* group with *Brachystegia allenii, B. boehmii* and *B. manga* on shallow compact soils.

The continuous spread of the samples on the graph indicates that the vegetation is a continuum. This is so: there is an overlap of species and groups of species and the relationship between dry evergreen forest, chipya and woodland is complex. The principal component analysis confirms the conclusions reached in the discussion on dynamic relationships.

Part 6

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Appendix

Appendix

Representative profile descriptions

The 20 profile descriptions in this appendix are representative of the taxonomic units used in the report. They have been selected from a total of approximately 600 profiles described and analysed in detail. Copies of the other profile data will be available for inspection at Mount Makuku Research Station, Chilanga, together with copies of unpublished mineralogical data.

The methods of analysis used for the samples are described in Table A1.1 and its supplementary 'Procedural notes'. Methods used are described there but only results from determinations made at Mount Makulu are given in this appendix.

Index to the profiles described

FREELY DRAINED UPLAND SOILS

Group 1 Soils with moderate or well developed macrostructure.

Group 2 Soils without macrostructure below the organic horizon.

Subgroup 2a Sandy soils (less than 15% clay in any horizon).

1. Red colours (redder than 5YR): *Lungu Series,* profile 307.
2. Yellow colours (5YR or yellower): *Twingi Series,* profile 60.

Subgroup 2b Soils with oxic horizons

Division 1 Duplex soils (soils having an abrupt increase in clay content, defined as $\not<$15% within less than 20 cm).

1. Upper subsoil texture sandy clay or clay loam: *Chishwishi Series,* profile 9.
2. Upper subsoil texture sandy clay loam: *Mabumba Series,* profile 553.

Division 2 Gradational soils (not having an abrupt increase in clay content).

1. Upper subsoil texture sandy clay or clay: *Lunzuwa Series,* profiles 117 and 539.

2. Upper subsoil texture sandy clay loam: *Milima Series,* profiles 36, 68, 106 and 509.

3. Upper subsoil texture sandy loam or coarser: *Nkolemfumu Series,* profiles 17, 49, 58 and 149.

IMPERFECTLY AND POORLY DRAINED UPLAND SOILS

These have not been assigned series names; three profiles (540, 42 and 149) are given.

LACUSTRINE PLAIN SOILS

Some profiles were described but none is included in this appendix. They are available at Mount Makulu.

Identifications

Each profile description in the subsequent pages is headed by the sequential number used to identify uniquely the profiles taken by LRD in Northern and Luapula Provinces (e.g. PROFILE 29).

Immediately below this, LOCATION gives the (soil) sampling stratum number, an area identifier used on Maps 2, 3, 3A, 3B, 3D, etc. 'F' area 3 indicates that the sampling stratum is in area 3 for the calculation of the capability index 'F'.

This is followed by the traverse number, which uniquely identifies all the traverses inspected by LRD. Traverse start parts are shown on Map 2. The sequence of traverse numbers is such that numbers increase from west to east and north to south by ½ degree squares. Traverse 1 is in the north west cover of the survey area and traverse 700 in the south east.

The soil classifications referred to are:

1. a parametric classification used during the fieldwork

2. a post-routine analysis parametric used to decide on the samples required for special physical analysis, referred to under Soils in this volume

3. the series name finally adopted

TABLE A1.1 Analytical procedures

Type of analysis	Method of analysis of Mount Makulu Research Station	Method of analysis of LRD Tropical Soils Analysis Unit
Particle size analysis (Both American and International size fractions determined)	Dispersion by means of sodium hexametaphosphate using a top drive macerator. Clay and silt estimation by the Bouyoucos hydrometer method and sand fractions by sieving. Organic matter not destroyed.	Dispersion using calgon (sodium hexametaphosphate and sodium carbonate) and an ultrasonic generator. Clay and silt estimation by the pipette method and sand fractions by sieving. Organic matter removed with hydrogen peroxide.
Chemical analysis		
Organic carbon	Walkley-Black wet oxidation (Piper, 1950)	Walkley and Black oxidation without heating; the reduced chromium sulphate determined colorimetrically on the auto-analyser.
Total nitrogen	Kjeldahl method	Kjeldahl extraction using a selenium catalyst and a sodium sulphate to sulphuric acid ratio of 1:2 w/v. The ammonia determined as indophenol blue on the auto-analyser.
Exchangeable cations	Extracted with N ammonium acetate at pH 7. Calcium and magnesium estimated on the Perkin Elmer atomic absorption spectrophotometer and potassium on the flame photometer.	Extracted with N ammonium acetate at pH 7. Calcium and magnesium estimated on the Perkin Elmer atomic absorption spectrophotometer, using strontium to prevent interference from phosphorous. Sodium and potassium estimated on the Technicon auto-analyser, by flame emission spectroscopy, with an internal lithium standard.
Cation exchange capacity	Ammonium saturated soil from the previous determination leached with N NaCl and the displaced ions distilled.	Absorbed ammonia from the previous determination removed with N potassium chloride at pH 2.5 and estimated on the auto-analyser as indophenol blue.
Total exchangeable bases		Equals the sum of exchangeable cations
Saturation percentage	Calculated as $\frac{Ca + Mg + K \times 100}{CEC}$	Calculated as $\frac{TEB}{CEC} \times 100$
pH	Measured on a 1:5 soil in $\frac{M}{100}$ $Cacl_2$ suspension using a potentiometer with glass electrode.	Measured on a 1:5 soil in water suspension with a pH meter with dual toughened electrode.
Conductivity		Measured on a 1:5 soil in water suspension with a Mullard conductivity bridge.
Percentage moisture of air-dried soil		Air-dried fine soil (<2mm) placed in an oven at 105^{o} for 4h.
Bulk density of air-dried soil		Based on the mass of 10 ml of air-dried fine soil, i.e. passed through a 2 mm sieve.
Available phosphorus		Olsen's method, the extractant is 0.5N sodium bicarbonate at pH 8.5. Bray's method, the extractant is 0.03N ammonium fluoride and 0.1N hydrochloric acid. In both cases the final determination is colorimetric, based on molybdenum blue with ascorbic acid as a reducing agent.
Total elements		Extracted by digestion with 60% perchloric acid for 6h. Phosphorus, potassium and magnesium determined as previously stated. Cobalt, chromium, copper, manganese, nickel and zinc determined by atomic absorption spectrophotometry. Iron determined colorimetrically with 0-phenanthroline.
Free iron		Extracted by the citrate-dithionite method of Holmgren (1967) and determined as above.

PROCEDURAL NOTES (Table A1.1)

Physical analysis

Microaggregation. Particle size analysis with and without calgon dispersing agent into size fractions 2 000-500μ, 500-200μ, 200-50μ, 20-5μ, 5-2μ, <2μ. Bouyoucos hydrometer measurement of fractions smaller than 50μ and sieving of the remainder. Organic matter not destroyed. Carried out by the TSAU.

Structural stability (1) Williams and Cooke (1961) method measuring the collapse of a column of soil on slaking. Carried out in Tolworth Tower.

Structural stability (2) Williams method (1963) measuring the loss of pore space on slaking by comparing the amount of water extracted from a slaked soil with the amount extracted at the same pressure from a sample stabilised with perspex. Carried out by the TSAU, and at Misamfu.

Bulk density Determined by weighing 100 ml cores dried at 105°C. Carried out at Misamfu.

Particle density Volume of approximately 100 g of air-dried soil determined in a pycrometer at Misamfu.

Available water capacity Pressure plate extraction at 0.1, 0.33 and 15 atm. Difference in water content at 0.1 and 15 atm gives approximate value. Carried out by the Kafue Irrigation Research Station.

Mineralogical analysis

Total mineral analysis by the Geological Survey of Zambia. Wet sieving used to separate the +300 sieve mesh size fraction which is separated in bromoform into heavy and light fractions. The -200 +300 fraction of each then mounted in canada balsam and grain-counted, the heavy mineral fraction after extraction of magnetic minerals. Clay mineral identification on the 5 sample, obtained by sedimentation, by X-ray diffraction.

Clay mineral analysis by the Macaulay Institute for Soil Research. Sample ground to 2 mm in a Glen-Creston ball mill. Complete samples examined by differential thermal analysis and type samples then examined by X-ray diffraction.

Thin section analysis. Thin sections of soils on microscope slides were prepared by the Soil Science section at Mount Makulu and by staff of Rothamsted Experimental Station.

PROFILE 29

Location Sampling Stratum 11901, 'F' area, 3, Traverse 669

Site Lower convex slope about 2^{o}

Vegetation/land use Cultivation

Soil drainage Free

Soil classification 1. T 2. r-a b^{o}de 3. Kaombe series

Depth cm	Description
0-8	Reddish brown (5YR 4/3); clay loam; moderate medium granular structure; loose to slightly hard when dry; few coarse pores; many very fine and common fine fissures; common fibrous and few woody roots; no cutans; clear wavy boundary
8-29	Reddish brown (5YR 4/4 - 4/5); clay loam; moderate medium angular blocky breaking to strong fine sub-angular blocky structure; loose to slightly hard when dry; common fine pores, few medium and coarse pores; many very fine, common fine and few medium fissures; few fibrous and few woody roots; weakly developed thin clay cutans; few medium, hard, spherical, imperfect sesquioxidic concretions; diffuse smooth boundary
29-150	Yellowish red (5YR 4/6 - 4/8); gravelly silty clay loam becoming gravelly silty clay; moderate large breaking to strong very fine to fine angular blocky structure; slightly hard when semi-moist becoming very friable when moist; common very fine and fine pores, few medium and coarse pores; many very fine common fine and medium fissures; few fibrous and few woody roots; no cutans; few becoming common below 120 cm, medium hard, spherical imperfect sesquioxidic concretions; gradual irregular boundary
150-210	Yellowish red (5YR 4/6) and variegated colours of decomposing rock; gravelly silty loam; vestigial rock structure; friable when moist; common very fine and fine pores, few medium and coarse pores; common very fine and fine fissures; few medium fissures; few woody roots; no cutans; common medium, hard, spherical, imperfect, sesquioxidic concretions

ANALYSIS

	Sample depth (cm)						
	0-8	8-29	30-60	60-90	90-120	120-150	180-210
pH ($CaCl_2$)	5.04	4.50	4.55	5.10	5.40	5.65	5.70
Exch. bases meq %							
K	0.26	0.10	0.06	0.04	0.03	0.02	0.01
Mg	4.70	4.95	4.70	4.75	5.15	4.60	7.00
Ca	7.70	7.50	6.70	6.40	6.10	6.00	9.90
CEC meq %	19.00	19.80	19.20	15.80	16.80	17.80	23.00
Base saturation %	66.6	63.4	59.7	70.8	67.1	60.8	73.5
Organic C %	2.03	1.95					
Particle size %							
C Sand	16.8	9.4	5.8	5.6	5.3	7.2	4.8
F Sand	35.0	27.2	15.8	21.0	23.1	25.4	39.8
Silt	20.4	17.6	14.6	10.6	11.8	13.6	8.6
Clay	27.8	45.8	63.8	62.8	59.8	53.8	46.8

PROFILE 30

Location	Sampling stratum 11901, 'F' area, 3, Traverse 69
Site:	Slope about 2^{o}
Vegetation/land use	Cultivation
Soil drainage	Free
Soil classification	1. T 2. r - ab^{c}de 3. Kaombe series
Depth cm	**Description**
0-7	Dark brown (6.25YR 3/3); loam to clay loam; few small to medium hard, spherical, slightly imperfect sesquioxidic concretions; weak fine crumb above 1 cm to medium moderate sub-angular blocky below; hard when dry; moderately sticky; moderately plastic when wet; common very fine and fine fissures and pores, few medium pores; common fibrous and few woody roots; cutans not apparent; clear smooth boundary
7-24	Dark reddish brown (5YR 3/4); clay loam; common small to medium hard; spherical, slightly imperfect sesquioxidic concretions; moderate tending to strong medium sub-angular blocky structure; hard when dry, friable to firm when moist and moderately sticky and plastic when wet; many very fine and common fine pores and fissures, few medium pores; common fibrous and few woody roots; weakly developed thin clay cutans in pores and on vertical ped faces; clear smooth boundary
24-26	Yellowish red (5YR 4/8); gravelly clay; many small to medium, hard spherical, slightly imperfect sesquioxidic concretions; strong fine angular blocky structure; firm when moist, sticky and very plastic when wet; many very fine and common fine fissures and pores, few medium pores; common fibrous and few woody roots; cutans not apparent; clear smooth boundary
46-85	Yellowish red (5YR 4/8); gravelly clay; many small to medium, hard, spherical, slightly imperfect sesquioxidic concretions; common iron stained quartz and quartzite sub-angular stones; structure difficult to discern; friable when moist, sticky and very plastic when wet; many very fine and fine fissures, pores difficult to estimate; few fibrous and few woody roots; cutans not apparent; clear smooth boundary
85-115	Red to yellowish red (2.5YR 5/8 to 5YR 5/8); gravelly clay; many small to medium, hard, spherical, slightly imperfect sesquioxidic concretions; strong fine angular blocky structure; hard when dry, friable when moist and sticky, very plastic when wet; many very fine and common fine fissures and pores; few fibrous and few woody roots; weakly developed clay cutans; gradual smooth boundary
115-160	Various red, yellow, black colours associated with the constituent minerals of weathering rock

ANALYSIS

	Sample depth (cm)					
	0-7	7-24	24-46	46-85	85-115	125-150
pH ($CaCl_2$)	5.45	4.95	5.35	5.70	5.80	6.15
Exch. bases me %						
K	0.67	0.13	0.08	0.07	0.04	0.03
Mg	4.70	3.80	5.90	5.40	6.50	5.00
Ca	8.40	7.30	8.60	6.30	8.00	10.00
Cation exchange capacity me %	21.20	17.60	19.20	18.80	20.40	26.20
Base saturation %	64.95	63.81	75.94	64.61	71.24	57.37
Organic carbon %	2.69	0.94				
Total P ppm	11.0					
Particle size %						
C Sand 2.0-0.2 mm	22.0	20.8	11.2	24.6	15.2	9.6
F Sand 0.2-0.02 mm	30.8	28.0	30.4	16.2	22.4	30.0
Silt 0.02-0.002 mm	25.4	23.9	6.6	9.4	23.6	10.6
Clay - 0.002 mm	21.8	27.3	51.8	49.8	38.8	49.8

PROFILE 59

Location	Sampling stratum 14801, 'F' area, 3, Traverse 136
Site	Lower convex slope about 2^{o}
Vegetation/land use	Cultivation
Soil drainage	Free
Soil classification	1. T 2. rya $\frac{o}{-}$de 3. Mululwe series
Depth cm	**Description**
0-6	Dark reddish brown (5YR 3/4)½ silty clay loam; strong fine granular becoming sub-angular blocky structure; hard when dry; moderately sticky, moderately plastic when wet; common very fine pores, few fine, medium and coarse pores; many very fine, common fine and few medium fissures; many fibrous and many woody roots; no cutans; common medium, soft to moderately hard spherical to irregular clay concretions; gradual wavy boundary
6-44	Dark red (10R 3/6); clay; weak large breaking to strong fine to medium sub-angular blocky structure; hard when dry; very sticky, moderately plastic when wet; common very fine pores, few fine, medium and coarse pores; many very fine fissures, few fine and medium fissures; common fibrous and woody roots; weakly developed thick clay cutans coating horizontal ped faces and lining pores; common medium, moderately hard, spherical imperfect clay concretions; diffuse smooth boundary
44-190	Dark red (10R 3/6); clay; moderate large to very large breaking to strong medium sub-angular blocky structure; hard when dry; very sticky, moderately plastic when wet; common very fine and fine pores, few medium pores; common very fine and fine fissures, few medium and coarse fissures; few woody roots; no cutans; common medium, moderately hard, spherical, imperfect clay concretions

ANALYSIS

	Sample depth (cm)				
	0-6	10-40	44-74	90-120	150-180
pH ($CaCl_2$)	5.60	4.90	5.30	5.50	5.60
Exch. bases me %					
K	0.62	0.67	0.51	0.30	0.11
Mg	8.00	4.30	2.00	2.00	2.10
Ca	16.50	5.30	3.40	3.80	4.50
Cation exchange capacity me %	17.00	13.00	13.00	8.40	9.80
Base saturation %	100.0	79.0	45.5	72.6	68.5
Organic carbon %	3.00	0.87			
Particle size %					
C Sand	8.7	3.2	2.5	2.6	2.0
F Sand	44.7	20.6	18.2	21.2	20.8
Silt	18.9	1.6	7.6	5.6	6.6
Clay	27.7	74.6	71.6	70.6	70.6

PROFILE 307

Location	Sampling stratum 08101, 'F' area, 3, Traverse 349
Site	Mid-lower pediment
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1. uCr 2. r-- ^{o}-^{o}-^{o}-- 3. Lungu series

Depth cm	**Description**
0-10	Dark reddish brown (5YR 2/2); loamy sand; organic stained patches; very weak fine angular blocky structure; soft to slightly hard when dry; non sticky and slightly plastic when wet; common very fine pores; common fibrous and common woody roots; cutans not apparent; diffuse wavy boundary
85-190	Red (2.5YR 4/6); sandy loam to loamy sand; massive structure; hard when dry to slightly moist; non sticky and slightly plastic when wet; common very fine and few fine pores; frequent fibrous and frequent woody roots; cutans not apparent

ANALYSIS

	Sample depth (cm)				
	0-10	10-40	50-80	100-130	140-170
pH ($CaCl_2$)	4.25	4.10	4.20	4.25	4.25
Exch. bases me %					
K	0.10	0.04	0.01	0.02	0.01
Mg	0.50	0.10	0.10	0.10	0.10
Ca	1.60	0.20	0.40	0.40	0.50
Cation exchange capacity me %	7.80	4.20	3.80	3.00	2.40
Base saturation %	28.21	8.09	13.42	17.33	25.42
Organic carbon %	2.51	1.41	-	0.57	0.38
Particle size %					
C.Sand 2.0-0.2 mm	58.2	53.3	57.3	49.9	50.9
F.Sand 0.2-0.02 mm	34.2	32.1	30.1	34.9	33.4
Silt 0.02-0.002 mm	3.6	3.6	2.1	2.1	2.6
Clay -0.002 mm	4.0	9.0	10.5	13.1	13.1

PROFILE 60

Location	Sampling stratum 13601, 'F' area, 3, Traverse 58
Site	Lower convex slope about 0^{o} 20'
Vegetation/land use	Miombo. Trees and tall grass
Soil drainage	Free
Soil classification	1. uCy 2. -y-^{o}bc- - 3. Twingi series
Depth cm	**Description**
0-5	Dark brown (7.5YR 3/3); loamy fine sand; weak fine granular structure; dry, soft; wet, non sticky, non plastic; common very fine and common fine pores and fissures; many fibrous and common woody roots; cutans not apparent; clear smooth boundary
5-22	Dark yellowish brown (10YR 3/4-4/4); loamy fine sand, fine sandy loam; weak medium sub-angular blocky structure; dry, soft; wet, slightly sticky, non plastic; common very fine and few fine pores; common fibrous and common woody roots; cutans not apparent; clear smooth boundary
22-90	Strong brown (7.5YR 5/6-7.5YR 5/6-6/8); fine sandy loam; massive structure; dry, slightly hard; wet non sticky, non plastic, many very fine and common fine pores, few medium; few fibrous and few woody roots; cutans not apparent, diffuse smooth boundary
90-128	Reddish yellow (7.5YR 6/8); fine sandy loam to loamy fine structure; dry, slightly hard; wet, non sticky, non plastic; many very fine, common fine pores, few medium; few fibrous roots; cutans not apparent; gradual smooth boundary
128-195	Reddish yellow (7.5YR 6/8); common, fine to medium, distinct, irregular, soft to moderately hard R_2O_3 concretions of strong brown to yellowish red (7.5YR 4/8 - 5YR 5/8); loamy fine sand - fine sandy loam; massive structure; dry, slightly hard; wet, non sticky, non plastic; many very fine, common fine pores, few medium; few fibrous roots; cutans not apparent

ANALYSIS

	Sample depth (cm)				
	5-22	22-52	52-82	90-120	140-170
pH ($CaCl_2$)	5.20	5.00	5.45	4.40	4.10
Exch. bases me %					
K	0.20	0.17	0.23	0.11	0.19
Mg	0.90	0.70	0.80	0.60	0.25
Ca	2.10	0.70	0.50	0.60	0.40
Cation exchange capacity me %	3.00	2.20	2.40	2.40	2.40
Base saturation %	100	71.4	63.8	54.6	35.0
Organic carbon %	0.57	0.19			
Particle size %					
C.Sand 2.0-0.2 mm	1.6	1.4	1.3	1.1	1.2
F.Sand 0.2-0.02 mm	79.8	82.5	79.1	85.8	81.7
Silt 0.02-0.002 mm	10.4	6.9	5.4	3.9	5.9
Clay -0.002 mm	8.2	9.2	14.2	9.2	11.2

PROFILE 9

Location:	Sampling stratum 12203, 'F' area, 3, Traverse 698
Site:	Upper interfluve. Slope about 1°30′
Vegetation/land use	Miombo
Soil drainage	Free. Moderately rapid to rapid infiltration
Soil classification	1. dAy 2. - - - o - - 3. Chishwishi series

Depth cm	**Description**
0-1	Black (N2/); sand; very weak, very fine granular structure; slightly hard when dry, loose when moist; and non sticky, non plastic when wet; few very fine and fine fissures, few very fine and common fine pores; many fibrous and woody roots; cutans not apparent; clear wavy boundary
6-47	Brown (10YR 4/3 - 7.5YR 5/4); sand; very weak very fine granular structure; hard to slightly hard when dry, very friable when moist, and non sticky, non plastic when wet, common very fine and fine pores, few very fine fissures; common fibrous and common woody roots; cutans not apparent; clear to abrupt smooth boundary
47-200	Yellowish red (5YR 5/6); sandy clay loam to sandy clay; few medium faint yellow mottles; weak to moderate very fine sub-angular blocky structure; hard to very hard when dry, friable when moist and very sticky, moderately plastic when wet; many very fine, common fine and few medium pores; few fibrous and woody roots; cutans not apparent

ANALYSIS

	Sample depth (cm)					
	0-6	10-40	60-90	100-130	140-170	170-200
pH ($CaCl_2$)	5.50	6.10	6.20	6.15	5.40	5.10
Exch. bases me %						
K	0.17	0.07	0.44	0.72	0.73	0.31
Mg	0.95	0.15	0.65	0.55	0.25	0.25
Ca	9.30	1.20	0.80	0.90	0.80	0.70
Cation capacity me %	13.00	1.40	4.40	4.00	3.60	4.20
Base saturation %	80.15	100	42.95	54.25	39.44	30.00
Organic carbon %	5.72	0.39				
Particle size %						
C.Sand 2.0-0.2 mm	44.5	44.3	28.2	25.2	28.9	29.1
F.Sand 0.2-0.02 mm	40.3	46.5	20.6	31.6	30.7	31.0
Silt 0.02-0.002 mm	8.2	3.7	7.2	4.1	3.3	2.8
Clay -0.002 mm	7.0	5.5	44.0	39.1	37.1	37.1

PROFILE 553

Location	Sampling stratum 110033, 'F' area, 3, Traverse 509
Site	Lower plane slope about 1°
Vegetation/land use	Cultivation
Soil drainage	Free
Soil classification	1. dBy 2. -$\overset{c}{y}$-b- - e 3. Mabumba series
Depth cm	**Description**
0-8	Very dark grey (10YR 3/1); sandy loam; weak very fine crumb structure; slightly hard when dry; slightly sticky, slightly plastic when wet; common very fine and fine pores; common very fine fissures, many fibrous and few woody roots; no cutans; abrupt smooth boundary
8-17	Brown (10YR 4/3); sandy loam; weak fine crumb becoming sub-angular blocky structure; hard when dry; slightly sticky, slightly plastic when wet; many very fine pores, few fine and medium pores; few very fine fissures; common fibrous and few woody roots; no cutans; abrupt smooth boundary
17-27	Yellowish brown (10YR 5/4); sandy clay loam; weak fine sub-angular blocky structure; very hard when dry; slightly sticky, slightly plastic when wet; many very fine pores, very few fine and medium pores; few very fine fissures; common fibrous and few woody roots; no cutans; diffuse smooth boundary
27-128	Reddish yellow (7.5YR 6/6); sandy clay loam; massive structure; extremely hard when dry becoming very friable when moist; very, becoming moderately, sticky, slightly plastic when wet; common very fine pores, very few fine and medium pores; few very fine fissures; few fibrous and few woody roots; no cutans; clear wavy boundary

ANALYSIS

Chemistry	Sample depth (cm) 0-8	8-17	17-27	30-60	80-110	130-160
pH ($CaCl_2$)	4.90	4.45	4.35	4.30	4.20	4.20
Exch. bases me %						
K	0.07	0.05	0.06	0.10	0.12	0.11
Mg	0.70	0.30	0.30	0.30	0.10	0.00
Ca	1.40	0.20	0.15	0.15	0.10	0.10
Cation exchange capacity me %	4.00	2.00	2.20	3.40	3.40	3.60
Base saturation %	54.3	27.5	23.2	10.3	0.4	5.8
Organic carbon %	1.91					
Particle size %						
C.Sand	32.6	31.0			20.8	
F.Sand	55.7	52.8			39.0	
Silt	6.7	6.2	5.7	5.2	5.2	5.7
Clay	5.0	10.0	15.0	30.0	35.0	35.5

PROFILE 117

Location	Sampling stratum 06001, 'F' area, 3, Ngoli Coffee Scheme
Site	Interfluve, half way between crest and dambo Less than 1^{o} slope
Vegetation/land use	Proposed coffee. Presently grass and maize
Soil drainage	Well drained. Moderate to rapid permeability
Soil classification	1. uAr 2. rya — —^{o}∓ e 3. Lunzua series
Depth cm	**Description**
0-10	Dark red (2.5YR 3/4-3/6); clay; moderate very fine granular structure; soft when dry, moderately sticky and moderately plastic when wet; many very fine and common fine fissures and pores; common fibrous and few woody roots; cutans not apparent; gradual smooth boundary
10-65	Red (2.5YR 4/8); clay; weak large prismatic breaking to moderate fine sub-angular blocky structure; slightly hard to hard when dry, moderately sticky and moderately plastic when wet; common very fine fissures and pores; common fibrous and common woody roots; cutans not apparent; diffuse smooth boundary
65-117	Red (2.5YR 4/6-4/8); clay; moderate medium subangular blocky structure; loose to soft when slightly moist, moderately sticky and moderately plastic when wet; common very fine fissures and pores, few large fissures; thin cutans of clay in pores; common fibrous and common woody roots; diffuse smooth boundary
117-138	Dark red (2.5YR 3/6); clay; 10% to 20% hard, rounded, polished concretions and stones, 2-20 mm in size; weak large prismatic breaking to moderate fine sub-angular blocky structure; soft when slightly moist, very sticky and moderately plastic when wet; common very fine and fine fissures and pores, few larger fissures; thin cutans of clay in pores; common fibrous and common woody roots, abundant at depth
138+	Dense layer of iron manganese concretions

ANALYSIS

	Sample depth (cm)			
	0-10	25-55	80-110	117-138
pH	4.40	4.50	4.50	4.70
Exch. bases me%				
K	0.11	0.12	0.07	0.07
Mg	0.60	0.65	0.40	0.55
Ca	0.30	0.35	0.20	0.60
Cation exchange capacity me%	6.40	6.40	5.20	5.40
Base saturation%	15.78	17.50	12.89	22.60
Organic carbon %	0.23			
Total N %	0.042			
Total P ppm	2.00			
Particle size %				
C.Sand 2.0-0.2mm	12.1	12.5	7.2	7.2
F.Sand 0.02-0.002mm	32.9	31.5	28.6	31.3
Silt 0.02-0.002mm	9.3	6.8	10.4	7.8
Clay -0.002mm	45.7	49.2	53.8	53.7

PROFILE 539

Location	Sampling stratum 11002, 'F' area, 3, Traverse 520
Site	Upper convex slope about 0^{o} 30′
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1. Ay 2. $-ya\,\frac{o}{-}\,\frac{o}{-}\,-\,-$ 3. Lunzua series
Depth cm	**Description**
0-9	Very dark greyish brown (10YR 3/2); sandy clay loam; moderate fine crumb structure; slightly hard when dry; slightly sticky, slightly plastic when wet; few very fine pores; few very fine fissures; many fibrous and few woody roots; no cutans; abrupt smooth boundary
9-104	Strong brown (7.5YR 5/6); sandy clay loam; moderate fine sub-angular blocky structure; very hard when semi-moist; slightly sticky, slightly plastic when wet; common very fine pores, very few fine pores; few very fine and fine fissures; few fibrous and few woody roots; no cutans; diffuse smooth boundary
104-168	Strong brown (7.5YR 5/8); sandy clay loam to sandy clay; weak fine to medium sub-angular blocky structure; hard to very hard when semi-moist; moderately sticky, slightly plastic when wet; common very fine pores; very few fine pores; few fibrous and few woody roots; no cutans

ANALYSIS

	Sample depth (cm)				
	0-9	9-39	40-70	70-100	110-140
pH ($CaCl_2$)	4.50	4.20	4.25	4.40	4.45
Exch. bases me%					
K	0.07	0.01	0.01	0.01	0.01
Mg	0.50	0.10	0.10	0.10	0.15
Ca	0.70	0.10	0.20	0.20	0.40
Cation exchange capacity me%	4.40	4.00	4.60	3.60	5.00
Base saturation%	28.9	5.3	6.7	8.6	11.2
Organic carbon%	2.03				
Particle size %					
C.Sand					
F.Sand					
Silt	7.2	5.2	4.2	4.7	5.3
Clay	19.8	39.8	46.8	47.8	51.3

PROFILE 36

Location	Sampling stratum 09503, 'F' area, 3, Traverse 622
Site	Lower interfluve slope about 1^{o}
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1. d By/Cy 2. –y–$\underline{o}$–––– 3. Milima series
Depth cm	**Description**
0-13	Very dark greyish brown (10YR 3/2); loam sand; moderate medium crumb to weak fine sub-angular blocky structure; slightly hard – hard when dry and non sticky, slightly plastic when wet; voids not recorded; many fibrous and few woody roots; cutans not apparent; clear smooth boundary
13-38	Strong brown (7.5YR 5/6 approx.); sand; massive structure; very hard when dry, compact when moist and non sticky, non plastic when wet; many very fine, common fine and few medium pores. Few very fine fissures; common fibrous and common woody roots; cutans not apparent; gradual smooth boundary
38-84	Strong brown – yellowish red (7.5YR 5/6); loamy sand; massive structure; very hard when dry, compact when moist, non sticky and slightly plastic when wet; many very fine, very few fine and medium pores. Few very fine and fine fissures; common fibrous and few woody roots; cutans not apparent; gradual smooth boundary
84-190	Yellowish red (5YR 5/7); sandy clay loam, massive structure; very hard when dry, compact when moist, slightly sticky, moderately plastic when wet; many very fine, very few fine and mediumpores. Few very fine and fine fissures; few fibrous and few woody roots; cutans not apparent.

ANALYSIS

	Sample depth (cm)				
	0-13	13-38	40-70	90-120	140-170
pH ($CaCl_2$)	5.10	4.60	4.80	5.05	4.65
Exch. bases me%					
K	0.06	0.04	0.06	0.21	0.18
Mg	0.30	0.20	0.30	0.50	0.40
Ca	1.60	0.60	0.30	0.80	0.60
Cation exchange capacity me%	2.60	1.00	1.20	2.80	2.40
Base saturation%	75.38	84.00	55.00	53.93	49.17
Organic carbon%	0.70	0.16			
Total P ppm	6.3				
Particle size %					
C.Sand 2.0-0.2mm	19.9	19.8	18.4	17.3	17.4
F.Sand 0.2-0.02mm	72.9	71.5	70.4	56.5	58.4
Silt 0.02-0.002mm	2.2	2.2	2.2	2.2	3.2
Clay -0.002mm	5.0	6.5	9.0	24.0	21.0

PROFILE 68

Location	Sampling stratum 03901, 'F' area, 3, Traverse 57
Site	Upper interfluve. Slope less than 1^{o}
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1.K(M) 2. ———^{o}—c—— 3. Milima shallow phase
Depth cm	**Description**
0-7	Dark yellowish brown (10YR 3/4); loamy sand; weak medium crumb and granular structure; loose when dry; many very fine and fine pores, common medium pores. Few very fine, fine and medium fissures; many fibrous and few woody roots; cutans not apparent; clear smooth boundary
7-21	Dark yellowish brown (10YR 4/4); loamy sand; many fine distinct yellowish brown mottles (10YR 5/8); weak medium granular to weak fine sub-angular blocky structure; loose when dry; many very fine and fine pores; common medium pores. Few very fine and common fine fissures; many fibrous and few woody roots; cutans not apparent; gradual smooth boundary
21-65	Yellowish brown (10YR 5/8); loamy sand-sand loam; many fine distinct strong brown mottles (7.5YR 4/8); weak medium sub-angular blocky structures; soft when dry; common very fine, fine and medium pores, few medium fissures; few fibrous and few woody roots; cutans not apparent; gradual smooth boundary
65-83	Strong brown (7.5YR 5/8); sandy loam; many fine distinct yellowish red mottles (5YR 5/8); weak medium angular blocky structure; slightly hard when dry; common very fine and fine pores, few medium pores. Few very fine, fine and common medium fissures; few fibrous roots; cutans not apparent; abrupt smooth boundary
83-150	Yellowish red (5YR 5/8); stony sandy loam; many small irregular, imperfect, hard sesquioxidic concretions; large stones and boulders present derived from weathering rock at 150 cm; felspar mineral grains present; structure, voids and consistency difficult to determine; roots absent, cutans not apparent

ANALYSIS

	Sample depth (cm)				
	0-7	7-20	20-50	65-80	90-120
pH ($CaCl_2$)	4.20	4.05	4.00	3.85	4.10
Exch. bases me%					
K	0.15	0.14	0.24	0.34	0.25
Mg	0.80	0.70	0.20	0.40	0.30
Ca	0.80	0.70	0.20	0.40	0.30
Cation exchange capacity me%	3.20	2.60	2.80	2.00	3.20
Base saturation%	54.7	59.2	22.9	57.0	26.6
Organic carbon%	1.35	0.36			
Particle size %					
Gravel 2cm-2mm	29				56.8
C.Sand 2.0-0.2mm	29.1	27.1	26.7	24.5	35.4
F.Sand 0.2-0.02mm	60.5	61.0	57.9	55.1	44.2
Silt 0.02-0.002mm	4.3	3.8	2.8	2.8	4.8
Clay –0.002mm	6.1	8.1	12.6	17.6	15.6

PROFILE 106

Location	Sampling stratum 00305, 'F' area, 3, Traverse 113
Site	Lower convex slope about 1^{o}
Vegetation/land use	Miombo. R_1 tall trees, ground cover thick about 2 ft high
Soil drainage	Free
Soil classification	1. By 2. r———c—— 3. Milima series
Depth cm	**Description**
0-8	Dark brown (10YR 3/2-3/3); sandy loam; weak fine crumb structure; slightly moist, loose; wet, slightly sticky, non-plastic; many very fine and fine pores and fissures; common fibrous roots; cutans not apparent; clear smooth boundary
8-24	Dark brown (7.5YR 4/4); sandy clay loam; weak medium sub-angular blocky breaking to weak fine granular structure; slightly moist, soft to slightly hard; wet, moderately sticky, moderately plastic, many very fine and common fine pores and fissures; common fibrous and common woody roots; cutans not apparent; gradual smooth boundary
24-45	Yellowish red (5YR 4/6-4/8); sandy clay loam; weak fine to medium sub-angular blocky structure; slightly moist, hard; wet, moderately sticky, moderately plastic; many very fine and few fine pores and fissures; few woody roots; cutans not apparent; diffuse smooth boundary
45-180	Reddish yellow (5YR 6/8-5/8); sandy clay loam; weak large prismatic breaking to weak fine sub-angular blocky structure; slightly moist, soft to slightly hard; wet, moderately sticky, moderately plastic; many very fine and fine pores, few fine fissures; few woody roots to 180 cm; cutans not apparent

ANALYSIS

	Sample depth (cm)				
	0-8	8-24	25-45	60-90	120-150
pH($CaCl_2$)	4.3	4.20	4.15	4.15	4.20
Exch. bases me%					
K	0.23	0.15	0.15	0.13	0.13
Mg	0.55	0.30	0.15	0.10	0.15
Ca	0.40	0.10	0.20	0.15	0.20
Cation exchange capacity me%	6.80	4.80	5.00	4.80	4.80
Base saturation	17.35	11.46	10.00	7.29	10.00
Organic carbon%	0.86				
Total N%	0.056				
Total P ppm	5.00				
Particle size %					
C.Sand 2.0-0.2mm	6.5	4.7	3.4	2.5	1.9
F.Sand 0.2-0.02mm	76.5	72.3	66.1	61.0	62.1
Silt 0.02-0.002mm	5.1	4.6	4.1	4.1	2.0
Clay -0.002mm	11.9	18.4	26.4	32.4	34.0

PROFILE 509

Location	Sampling stratum 15401, 'F' area, 3, Traverse 196
Site	Upper convex slope about 0^{o} 20'
Vegetation/land use	Cultivation
Soil drainage	Free
Soil classification	1. By 2. —y—$\frac{o\ o}{}$de 3. Milima series
Depth cm	**Description**
0-15	Black (10YR 2/1); sand to loamy sand; very weak fine crumb to massive structure; loose to slightly hard when dry; non-sticky, non-plastic when wet; very few pores and fissures; many fibrous and few woody roots; no cutans; abrupt smooth boundary
15-100	Dark greyish brown to brown (10YR 4/2-5/3) becoming brown to yellowish brown (7.5YR-10YR 5/4); loamy sand to sandy loam becoming sandy loam; massive structure; very friable when moist; slightly sticky, slightly plastic when wet; very few pores and fissures; few fibrous and few woody roots; no cutans; gradual smooth boundary
100-192	Brown becoming reddish yellow (7.5YR 5/5-6/6); sandy loam; massive structure; very friable when moist; slightly sticky, slightly plastic when wet; very few pores and fissures; few fibrous and few woody roots; no cutans

ANALYSIS

	Sample depth (cm)				
	0-15	15-45	50-80	100-130	140-170
pH ($CaCl_2$)	4.00	4.20	4.20	4.30	4.30
Exch. bases me%					
K	0.03	0.01	0.01	0.01	0.01
Mg	0.05	0.00	0.00	0.00	0.00
Ca	0.10	0.10	0.10	0.10	0.10
Cation exchange capacity me%	5.80	4.20	3.60	2.80	2.80
Base saturation%	3.10	2.61	3.05	3.93	3.93
Organic carbon%	1.79				
Particle size %					
C.Sand	47.0	44.3	41.1	42.6	40.1
F.Sand	36.5	34.2	36.7	33.7	35.7
Silt	4.9	4.4	3.3	3.8	3.3
Clay	11.6	17.1	18.9	19.9	20.9

PROFILE 17

Location	Sampling stratum 11801, 'F' area, 3, Traverse 566
Site	Interfluve, halfway between crest and dambo Slope about 3°
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1. uBr 2. ry—b——— 3. Nkolemfumu series
Depth cm	**Description**
0-4	Yellowish red (5YR 4/6); sandy loam; carbon fragments present; very weak fine sub-angular blocky and weak fine crumb structure; slightly hard when dry; slightly sticky and slightly plastic when wet; pores and fissures not apparent; common fibrous and common woody roots; cutans not apparent; abrupt smooth boundary
4-18	Red (2.5YR 4/6); sandy loam; weak fine sub-angular structure; hard when dry; compact when moist; slightly sticky and moderately plastic when wet; common very fine pores; common fibrous and few woody roots; cutans not apparent; clear smooth boundary
18-195	Red (2.5YR 4/7); sandy clay loam; few hard sandy clay loam lumps; structure not apparent; friable to very friable when slightly moist to moist; slightly sticky and moderately plastic when wet; common very fine pores; common fibrous and few woody roots; cutans not apparent

ANALYSIS

	Sample depth (cm)			
	4-18	18-48	60-90	120-150
ph ($CaCl_2$)	4.25	4.35	4.30	4.35
Exch. bases me%				
K	0.10	0.07	0.06	0.08
Mg	0.10	0.05	0.05	–
Ca	0.10	0.20	0.10	0.10
Cation exchange capacity me%	3.80	3.20	3.80	2.80
Base saturation%	7.89	10.00	5.35	–
Organic carbon%	0.55	0.19		
Particle size %				
C.Sand 2.0-0.2mm	15.8	15.1	12.7	11.9
F.Sand 0.2-0.02mm	56.0	52.7	53.1	54.4
Silt 0.02-0.002mm	9.8	8.8	8.8	8.8
Clay –0.002mm	18.4	23.4	25.4	24.9

PROFILE 49

Location	Sampling stratum 00205, 'F' area, 3, Traverse 125
Site	Lower convex slope about 2°
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1. uBy 2. –y—o— 3. Nkolemfumu series
Depth cm	**Description**
0-3	Very dark grey (10YR 3/1); dense mat of roots; abrupt smooth boundary
3-27	Brown (10YR 4/3-5/3); organic stained; sandy loam to sandy clay loam; weak fine sub-angular blocky structure; hard when dry; slightly sticky, slightly plastic when wet; common very fine pores, very few fine pores; few fibrous and common woody roots; no cutans; gradual smooth boundary
27-76	Strong brown (7.5YR 5/6); slight organic staining; sandy loam to sandy clay loam; weak fine sub-angular blocky to massive structure; slightly hard when dry; slightly sticky, slightly plastic when wet; many very fine pores, very few fine pores; few fibrous and common woody roots; no cutans; diffuse smooth boundary
76-200	Strong brown to reddish yellow (7.5YR 5/6-6/6); sandy loam to sandy clay loam becoming sandy clay loam; massive structure; slightly hard when dry becoming semi-moist; many very fine pores, very few fine pores; few fibrous and few woody roots; no cutans

ANALYSIS

	Sample depth (cm)				
	3-27	27-57	76-100	100-150	160-190
pH ($CaCl_2$)	3.90	3.95	3.95	3.95	4.00
Exch. bases me%					
K	0.05	0.04	0.02	0.02	0.02
Mg	0.05	0.05	0.10	0.10	tr.
Ca	0.10	0.30	0.10	0.15	0.20
Base saturation%	3.80	2.00	2.40	2.16	0.80
Organic carbon%	1.06				
Particle size %					
C.Sand	39.5	41.1	31.7	35.8	33.6
F.Sand	32.7	32.1	36.5	32.4	35.5
Silt	4.6	2.6	3.0	3.0	3.1
Clay	23.2	24.2	28.8	28.8	27.8

PROFILE 58

Location	Sampling stratum No. 13501, 'F' area, 3, Traverse 50
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	i. Ay ii. r-a ——— iii. Nkolemfumu series
Depth cm	**Description**
0-5	Dark brown (7.5YR 4/4-3/2); sandy loam; moderate fine crumb structure; dry, slightly hard; wet, slightly sticky, slightly plastic; many very fine pores, many fine fissures; many fibrous, few woody roots; cutans not apparent; abrupt smooth boundary
5-21	Dark brown (7.5YR 4/4); sandy clay loam. weak medium sub-angular blocky structure; dry, very hard; wet, slightly sticky, slightly plastic; many very fine, common fine and few medium and coarse pores; few fibrous and common woody roots; strongly developed thick organic cutans in pores; gradual smooth boundary
21-188+	Yellowish red (5YR 5/6); sandy clay loam, massive structure; dry, very hard to hard; moist, compact at top; wet, very sticky, slightly plastic; many very fine and fine pores; few fibrous and common woody roots; cutans not apparent

ANALYSIS

	Sample depth (cm)				
	5-21	21-51	70-100	120-150	150-180
pH ($CaCl_2$)	3.80	3.90	3.90	3.90	3.90
Exch. bases me%					
K	0.22	0.15	0.11	0.08	0.08
Mg	0.10	0.06	0.10	Trace	Trace
Ca	Trace	Trace	0.10	0.10	0.06
Cation exchange capacity me%	4.20	3.80	3.00	2.80	3.40
Base saturation%	7.6	5.3	10.3	6.4	3.8
Organic carbon%	0.57				
Particle size %					
C.Sand 2.0-0.2mm	16.9	12.4	12.5	12.6	13.5
F.Sand 0.2-0.02mm	50.5	48.5	49.9	51.3	51.9
Silt 0.02-0.002mm	0.5	3.5	2.4	1.9	1.9
Clay –0.002mm	32.1	35.6	35.2	34.2	32.7

PROFILE 149

Location	Sampling stratum 00208, 'F' area, 3, Traverse 221
Site	Lower plane slope about 1^{o}
Vegetation/land use	Miombo
Soil drainage	Free
Soil classification	1. uBy/Ay 2. ——— o —— 3. Nkolemfumu series
Depth cm	**Description**
0-11	Black (10YR 2/1); sandy clay loam; moderate very fine granular structure; slightly hard when semi-moist; moderately sticky, slightly plastic when wet; common very fine and fine pores; many very fine fissures; dense mat of fibrous and common woody roots; no cutans; clear irregular boundary
11-24	Very dark greyish brown (10YR 3/2); sandy clay loam; weak fine to very fine granular structure; slightly hard when semi-moist; moderately sticky, moderately plastic when wet; common very fine and fine pores, few medium pores; many very fine fissures; common fibrous and common woody roots; no cutans; diffuse smooth boundary
24-69	Yellowish brown (10YR 5/4); fine sandy clay loam; weak medium to fine sub-angular blocky structure; firm when moist; very sticky, moderately plastic when wet; common very fine and fine pores, few medium pores; common very fine fissures; few fibrous and common woody roots; no cutans; gradual smooth boundary
69-170	Yellowish brown (10YR 5/6); fine sandy clay loam; weak medium to fine sub-angular blocky structure; firm when moist; very sticky, moderately plastic when wet; common very fine and fine pores; common very fine fissures; few fibrous and common woody roots; no cutans

ANALYSIS

	Sample depth (cm)			
	0-11	11-24	30-60	80-110
pH ($CaCl_2$)	4.00	4.10	4.10	4.20
Exch. bases me%				
K	0.23	0.11	0.05	0.04
Mg	0.25	0.05	0.00	0.10
Ca	0.20	0.10	0.20	0.10
Cation exchange capacity me%	14.40	8.80	5.80	4.60
Base saturation%	4.7	2.8	4.3	5.2
Organic carbon%	2.69			
Particle size %				
C.Sand	43.9	40.5	33.5	26.9
F.Sand	34.2	32.6	33.1	30.2
Silt	6.1	6.1	4.1	4.0
Clay	15.8	20.8	29.3	38.9

PROFILE 540

Location	Sampling stratum 11002, 'F' area, 3, Traverse 520
Site	Lower concave slope about $1^{o}40'$
Vegetation/land use	Dambo edge. Trees
Soil drainage	Imperfectly drained
Soil classification	1. dzF 2. ——o—o 3. Imperfectly drained soil group
Depth cm	**Description**
0-13	Dark grey to very dark grey (10YR 4/1-3/1); sand; weak fine crumb to massive structure; slightly hard when dry; non-sticky, non-plastic when wet; pores and fissures not recorded; many fibrous and few woody roots; no cutans; smooth boundary
13-79	Greyish brown becoming pale brown (10YR 5/2-10YR 6/3); sand becoming loamy sand; massive structure; hard becoming very hard when dry; non-sticky, becoming slightly plastic when wet; many very fine pores, few fine pores; few fibrous and common woody roots; no cutans; clear smooth boundary
79-119	Light yellowish brown (10YR 6/4); sandy clay; massive structure; extremely hard when semi-moist; moderately sticky, moderately plastic when wet; many very fine pores, few fine pores; few fibrous and few woody roots; no cutans; clear smooth boundary
119-155	Light yellowish brown (10YR 6/4); sandy clay; common becoming many distinct medium white mottles (2.5YR 8/1); massive structure; extremely hard when semi-moist; moderately sticky, moderately plastic when wet; many very fine pores; few fine pores; few fibrous and few woody roots; no cutans

	Sample depth (cm)				
	0-13	13-43	43-73	80-110	120-150
pH ($CaCl_2$)	5.50	5.70	5.60	4.40	4.30
Exch. bases me%					
K	0.03	0.02	0.02	0.09	0.12
Mg	0.40	0.30	0.25	0.80	0.70
Ca	2.30	0.90	0.50	0.65	0.40
Cation exchange capacity me%	3.60	1.60	1.40	3.60	4.40
Base saturation%	75.8	76.3	55.0	42.8	27.7
Organic carbon%	1.99				
Particle size %					
C.Sand					
F.Sand					
Silt	3.7	3.7	4.2	5.2	3.7
Clay	6.4	5.9	6.9	30.0	38.0

PROFILE 42

Location	Sampling stratum 09501, 'F' area, 3, Traverse 551
Site	Lower concave slope about 0°20'
Vegetation/land use	Trees and short grass
Soil drainage	Poorly drained
Soil classification	1. ugH 2. —y$^{\underline{oo}}$— 3. Poorly drained soil group
Depth cm	**Description**
0-8	Very dark grey (10YR 3/1); sand to loamy sand; very weak very fine granular structure; slightly hard when dry; non-sticky, non-plastic when wet; many very fine pores, common, fine pores, few medium and coarse pores; few very fine and fine fissures; many fibrous and common woody roots; no cutans; clear smooth boundary
8-22	Light brownish grey (10YR 6/2); loamy sand; very weak very fine granular structure; slightly hard when dry; non-sticky, non-plastic when wet; common very fine pores; few fine and medium pores; few very fine fissures; common fibrous and few woody roots; no cutans; gradual smooth boundary
22-81	Pinkish grey (7.5YR 7/2); loamy sand; common distinct medium reddish yellow mottles (5YR 6/8); very weak fine granular structure; slightly hard when dry; non-sticky, non-plastic when wet; common very fine pores, few fine pores; few woody roots; no cutans; gradual smooth boundary
81-175	Pinkish grey (7.5YR 7/2); loamy sand; common becoming many distinct medium becoming coarse reddish yellow becoming strong brown mottles (5YR 6/8-7.5YR 5/8); massive structure; loose when moist; non-sticky, non-plastic when wet; common very fine pores; few woody roots; no cutans

ANALYSIS

	Sample depth (cm)					
	0-8	10-20	30-60	80-110	120-150	150-175
pH ($CaCl_2$)	4.75	4.20	4.10	4.10	4.10	4.30
Exch. bases me%						
K	0.16	0.02	0.02	0.01	0.01	0.01
Mg	0.85	0.45	0.25	0.35	0.25	0.25
Ca	2.50	0.50	0.20	0.10	0.10	0.10
Cation exchange capacity me%	6.00	2.00	1.20	1.20	1.20	1.20
Base saturation%	58.5	48.5	39.2	46.7	30.0	30.0
Organic carbon%	2.74	0.59				
Particle size %						
C.Sand	39.8	38.8	33.5	30.2	30.2	30.5
F.Sand	52.1	56.6	54.9	54.7	55.2	55.9
Silt	4.9	2.9	2.4	2.9	1.4	1.4
Clay	3.2	7.7	9.2	12.2	13.2	12.2

PROFILE 159

Location Sampling stratum 00104, 'F' area, 3, Traverse 239

Site Lower concave slope about 2^{o}

Vegetation/land use Miombo

Soil drainage Poorly drained

Soil classification 1. gL 2. r—$\underline{ooo}$—— 3. Poorly drained soil group

Depth cm	Description
0-4	Dark grey (10YR 4/1); loamy sand; massive structure; loose becoming soft when semi-moist; non-sticky, non-plastic when wet; common very fine pores; many very fine fissures; common fibrous and few woody roots; no cutans; clear smooth boundary
4-48	Greyish brown becoming light brownish grey (10YR 5/2-6/2); coarse sandy clay loam; weak medium sub-angular blocky structure; firm when moist; very sticky, slightly plastic when wet; common very fine pores; common very fine fissures; common fibrous and few woody roots; weakly developed thin clay cutans lining pores; clear smooth boundary
48-81	Pinkish grey (7.5YR 6/2); sandy clay loam becoming sandy clay; few to common coarse distinct reddish yellow mottles (7.5YR 6/8); massive structure; firm when moist; very sticky, moderately plastic when wet; common very fine pores; common very fine fissures; few fibrous and few woody roots; weakly developed thin clay cutans lining pores; gradual smooth boundary
81-110	Pinkish grey (5YR 6/2); coarse sandy clay; common coarse distinct light grey mottles (N7) and common coarse distinct light red mottles (2.5YR 6/8); massive structure; very firm when moist; moderately sticky, moderately plastic when wet; common very fine pores; few very fine fissures; roots absent; moderately developed thin clay cutans lining pores; gradual smooth boundary
110-155	Pinkish grey (5YR 6/2); coarse sandy clay; many coarse distinct light grey mottles (N7) and common coarse distinct reddish yellow mottles (5YR 6/8); massive structure; very firm when moist; very sticky, very plastic when wet; common very fine pores; few very fine fissures; roots absent; no cutans

ANALYSIS

	Sample depth (cm)				
	0-4	10-40	50-80	81-110	120-150
pH ($CaCl_2$)	5.10	4.80	4.20	4.10	4.10
Exch. bases me%					
K	0.06	0.04	0.06	0.08	0.08
Mg	0.35	0.40	0.30	0.10	0.15
Ca	0.60	0.40	0.10	0.10	0.20
Cation exchange capacity me%	2.80	2.20	4.40	4.80	4.20
Base saturation%	36.1	38.2	10.5	5.8	10.2
Organic carbon%	1.41				
Particle size %					
C.Sand	68.5	60.5	42.1	39.8	42.9
F.Sand	21.1	22.6	18.0	17.8	17.1
Silt	2.6	2.1	3.1	2.1	3.0
Clay	7.8	14.8	36.8	40.3	37.0

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1 map