A

T H E S I S

entitled

DISPERSION OF COPPER AND ASSOCIATED TRACE ELEMENTS IN A KALAHARI SAND ENVIRONMENT, NORTHWEST ZAMBIA.

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ABSTRACT

In north-west Zambia, Kalahari Sand of aeolian origin forms a cover of varying thickness on residual latosols. Sedimentological and mineralogical characteristics indicate that the Sand is similar to Kalahari Sand occurring elsewhere in southern Africa, and to aeolian sands in general.

Geochemical sampling at 9 inch depth on residual soil defines Cu anomalies overlying Cu mineralisation in bedrock.

At two localities, the surface Cu anomalies have been extended into Kalahari Sand overburden by the use of the silt fraction for analyses. In both areas, Cu anomalous Sand overlies poorly mineralised bedrock. The Cu, Fe, Mn and Zn content of Kalahari Sand is considerably lower than in soil. Metal patterns in the Sand appear to be epigenetic and reflect variation in bedrock content.

Lateritic horizons are widely developed in the residual soils, Kalahari Sand and dambo sediment, and result in concentrations of Fe, Cu, Mn, Zn and other trace elements. In the absence of laterite development, the distribution of metals in Kalahari Sand and some soil profiles displays an upward increase in content. This, together with the epigenetic anomalous patterns, is believed to result from seasonal upward migration of metal-bearing moisture during the dry season.

Analyses of grain size fractions of residual soil, Kalahari Sand and dambo sediment indicate that metal content increases with decreasing grain size. Maximum Cu contrast occurs in the silt fraction. Metal values in humus are

generally similar to overburden values but greater than the vegetation content. Metal values of termitaria are similar to A horizon values of the overburden.

A geobotanical survey reveals no significant variation in tree frequency related to Cu anomalous overburden. Randomly selected common tree species reveal a Cu correlation with surrounding Kalahari Sand values, with maximum content and contrast in bark.

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INTRODUCTION

The early primitive metal workers probably arrived in Zambia before 500 A.D. and produced copper on a very limited scale until the sixteenth century when increased trading with the coastal areas stimulated production. This early copper was dug from pits, smelted in small clay kilns in the forests using the local charcoal as a fuel, and the purified metal was worked into ornaments and wire (Clark, 1957; Dart, 1967).

European prospectors entered Zambia in 1895 and pegged the initial copper claims at Roan Antelope and Bwana Mkubwa in 1902. In 1923 Rhodesia Congo Border Concessions Limited was registered to explore the area along the Congo border as far west as Angola (Mendelsohn, 1961), and as a result of this work the copper occurrences at Lower Kamwedgi (M.O.150) and at Mufumbwe (M.O.21 and M.O.152)* were noted. In the latter area shafts and trenches were excavated but were later abandoned during the depression of the early thirties. Interest in the area by Roan Selection Trust (formerly Rhodesian Selection Trust) began in 1954 with extension of the pitting at Mufumbwe.

Mineral exploration by geochemical methods has been pioneered in Zambia by Roan Selection Trust since the early fifties. Detailed research, with subsequent improvement of the techniques employed, was carried out on copper dispersion in soils and stream sediments by the Applied Geochemical Research Centre of Imperial College, and in particular by Tooms (1955) and Govett (1958). Subsequently extensive

*Rhodesia Congo Border Concessions Mineral Occurrence number.

areas of Zambia covered by residual soils have been successfully investigated by several prospecting companies. In 1960 Roan Selection Trust began stream sediment and soil sampling in the Mufumbwe area, extending westwards beyond the Kamwedgi dambo. Large tracts covered by Kalahari Sand overburden were encountered and these areas did not respond to the standard geochemical nor geophysical techniques. Although occasional Cu anomalies were located in stream sediments, geochemical soil sampling failed to reveal any extensions of these anomalies in Kalahari Sand terrain.

The Applied Geochemistry Research Group was invited to investigate the problem of prospecting through a transported aeolian overburden in areas of low drainage density. Although the problem has a world wide application, it has previously been neglected, and to-date little documented work exists on geochemical prospecting in aeolian sand.

At the commencement of this study, mineralisation beneath Kalahari Sand was unknown. The copper mineralisation at Mufumbwe and at Lower Kamwedgi occurs in areas of residual soil and are some distance from the Kalahari Sand cover. Anomalous Cu values of unknown origin in dambo sediment were known at Jijombo and at Middle Kamwedgi, draining areas of Kalahari Sand.

The initial work of this project attempted, by field analyses, to trace the Cu soil anomaly at Mufumbwe into Kalahari Sand. During this phase, 1550 analyses for total Cu were carried out under field conditions and although traced for a distance of over 5000 feet, the anomaly swung

away from the Sand contact. At Jijombo subsequent to the promising results of the initial exploratory sampling programme of the first field season, power-auger drilling by Roan Selection Trust intersected mineralised bedrock beneath anomalous dambo sediment; this anomaly extends laterally for 300 feet under Kalahari Sand on the west bank of the dambo.

During the following field season, at Lower Kamwodgi near surface sampling was successful in tracing the Cu anomaly from residual soil into a Kalahari Sand cover.

At Middle Kamwedgi, use was made of RST pits which were sampled in an area of dambo sediment in Kalahari Sand with a Cu anomaly of unknown origin.

The presentation of the thesis is as follows.

Following the introductory chapter, the second chapter considers the various aspects of the Kalahari System. In particular, the physical characteristics of the Kalahari Sand and of associated soils and sediments of the area are investigated with a view to establishing diagnostic differences.

The third chapter is purely descriptive and contains the various results of the geochemical studies for Cu, Fe, Mn and Zn in residual soil, Kalahari Sand and dambo sediment at the various study localities.

The fourth chapter is a discussion of the various factors influencing the dispersion of the four elements studied in the various environments of the area. The problem of the inadequacy of the standard techniques in obtaining a reasonable detection of Cu in Kalahari Sand samples is

studied by the application of various sample attacks and different types of determination techniques; also by the effectiveness of the attacks on the various size fractions of the samples. In addition, the detection of mineralisation depends on deriving a suitable contrast between the anomaly value and the upper limit of background fluctuation (threshold). Thus the maximum contrast is discussed in relation to the type of extraction of Cu, the size fraction analysed and the soil horizon sampled. The possible use of associated trace-elements and metal ratios as a guide to mineralisation is discussed.

The fifth chapter investigates the effect of Cu mineralisation on the vegetation of the area. This involves both the distribution of vegetation and also the uptake of Cu, Fe, Mn and Zn by common species in relation to underlying overburden content.

The study covers 4 areas which lie approximately in a south-west line:

(1) Mufumbwe area where chalcopyrite-pyrite mineralisation occurs in shales and quartzites overlain by residuum, 8 miles north-east of the Kalahari Sand contact

(2) Jijombo area where Cu mineralised bedrock underlies dambo sediment and Kalahari Sand, and is separated from (1) by 12 miles of residuum and Kalahari Sand overburden

(3) Middle Kamwedgi dambo where a Cu anomaly is located in a tributary dambo draining Kalahari Sand and is separated from (2) by 14 miles of Kalahari Sand

(4) Lower Kamwedgi Prospect area where malachite-impregnated quartzite outcrops through residuum 2200 ft. south of the Kalahari Sand boundary,and is separated from (3) by 9 miles of Kalahari Sand and residuum.

CHAPTER I DESCRIPTION OF THE AREA

1. LOCATION

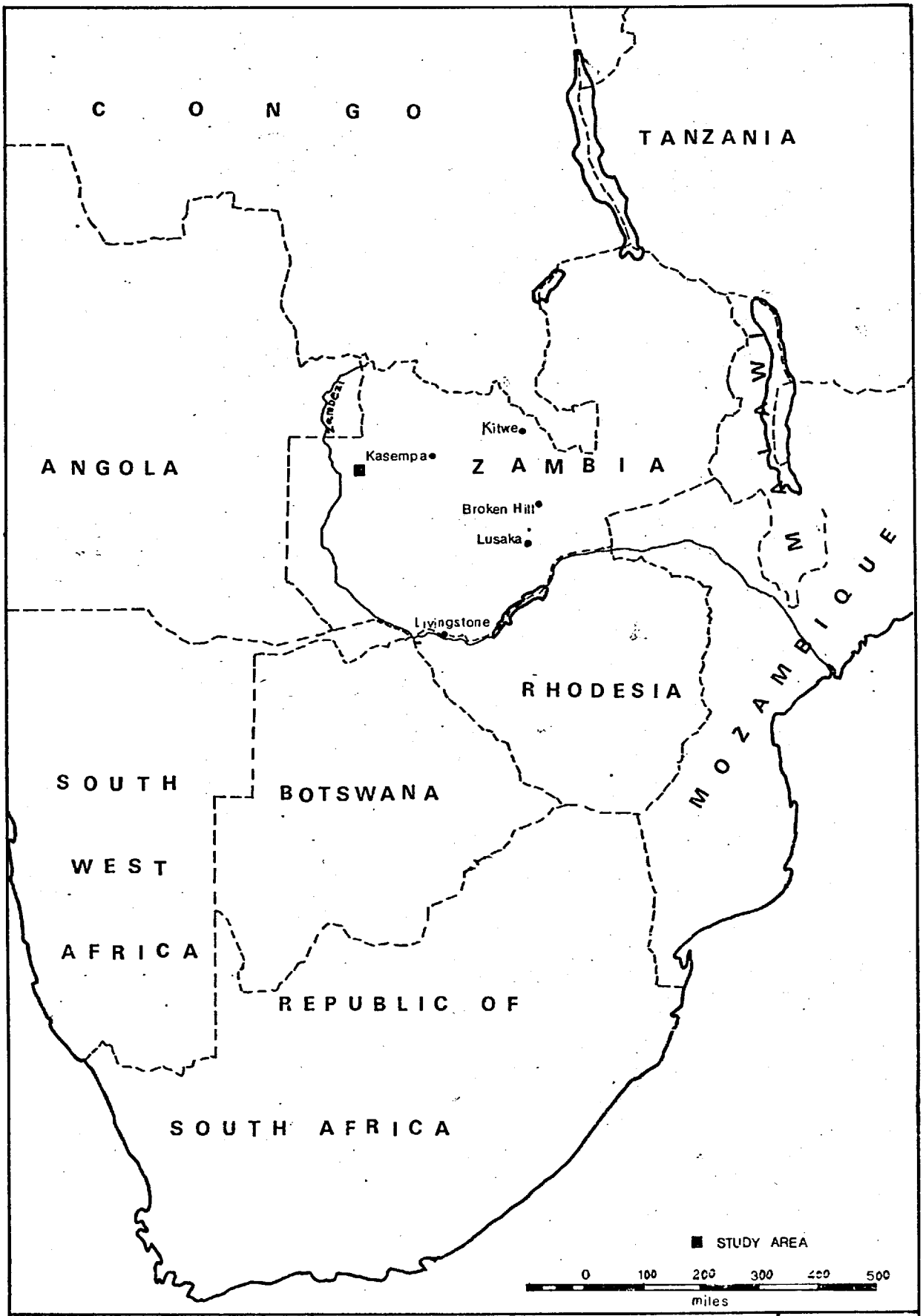
The field area is in the North Western Province of Zambia (13°30-48' South; 24°17-48' East), (Fig.1), 300 miles west of Kitwe on the Zambian Copperbelt; it lies astride the boundary between the Kabompo and Kasempa Administrative districts. A fair-weather track links Mufumbwe Camp with the townships of Kabompo, 75 miles to the west, and Chizela, 50 miles to the north-north-east. Dry season tracks within the field area link Mufumbwe with Jijombo, Middle Kamwedgi and Lower Kamwedgi, and also with Kalengwa Mine Camp, 30 miles to the north-east (Fig. 2).

Access in the dry season can also be gained to Mufumbwe by light plane from the Copperbelt, whilst the minor camps are serviceable throughout the year by field helicopter.

2. GEOLOGY

(a) Introduction

The geology of the North Western Province of Zambia is imperfectly known and little has been added to the regional maps produced by Rhodesia Congo Border Concessions Ltd. in the early nineteen fifties. Other maps produced in the past show considerable variation. Thus the Carte Geologique et Miniére of Southern Equitorial Africa (1931) depicts the Mufumbwe area as underlain by mixed rocks of the Archaen and Muva-Ankole Systems while continental Cainozoic rocks extend south-westwards into Barotseland. The 1:1,000,000 geological map of Zambia (Reeve, 1963) indicates clippes of Lower Kundulungu limestone, dolomite and shale appearing at Mufumbwe, Jijombo and Lower Kamwedgi through a cover of both Karroo and Kalahari sediments.



Location of Zambia and study area

Fig.1.

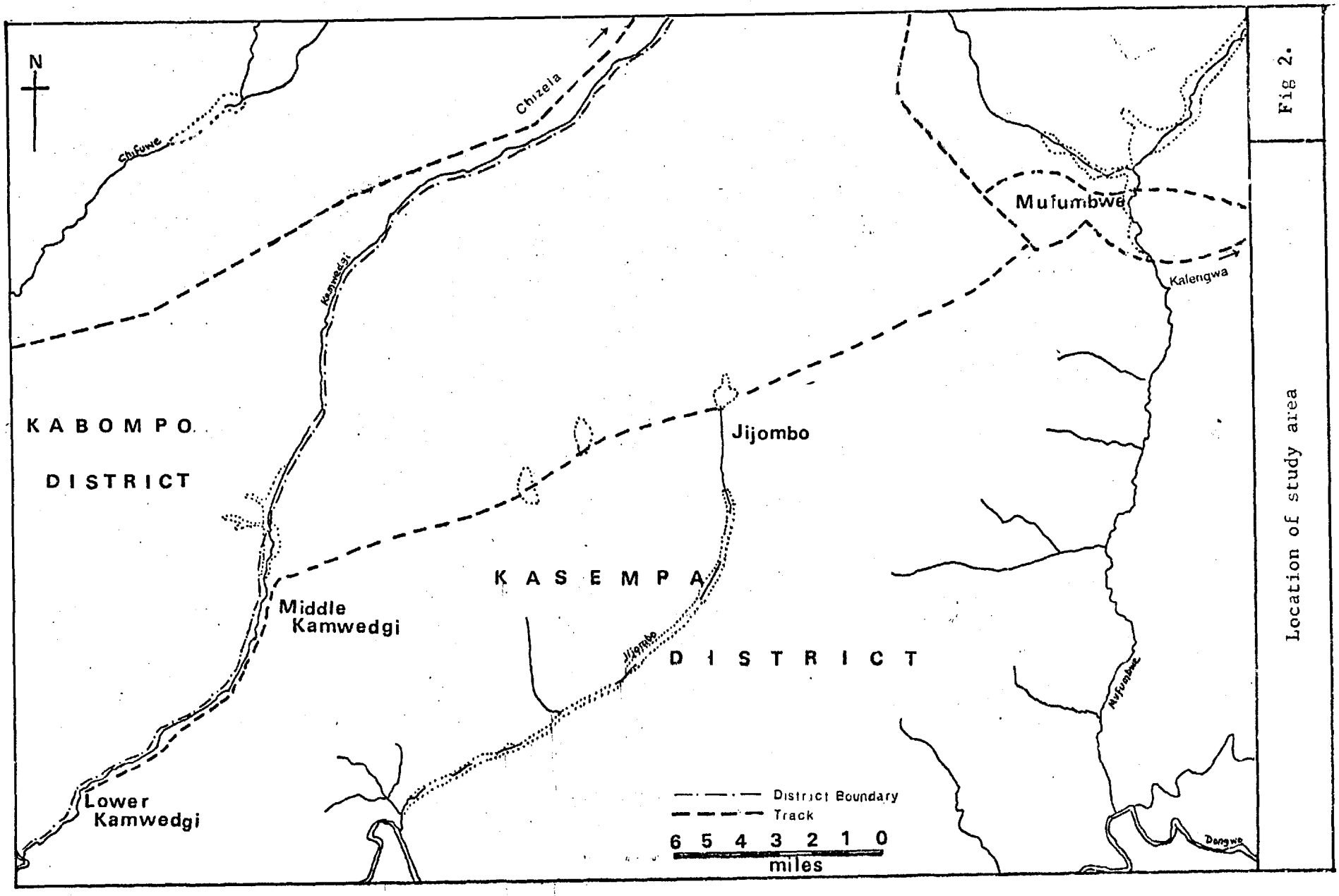


Fig 2.

Location of study area

(b) General geology

The generalised geology succession of northern Zambia is given in Table 1.

Table 1 Geological subdivisions of northern Zambia

Thickness(ft)	Stratigraphic Unit			Rock-type
?	Kalahari System			sand
<13,000	Karroo System	Upper Karroo		sandstone
		Lower Karroo		mudstone
3,000-20,000	Katanga System	Kundulungu Series	Upper	shale
			Middle	sandstone
			Lower	limestone, dolomite, shale, tillite
500-2,000		Mine Series	Mwashia Gp.	carbonaceous shale, sandstone.
1,500-2,000			U. Roan Gp.	dolomite, argillite.
0-3,000			L. Roan Gp.	quartzite, conglomerate, argillite.
3,600-13,000	Basement Complex	Muva System (1200-1400m.y)		quartzite, schist, conglomerate
?		Lufubu System (2650m.y)		schist, gneiss
-		Old Granite		granite

The geology of the north-west region is normally correlated with the type successions of the Copperbelt and consequently a brief review of the Copperbelt is presented (after Mendelsohn, 1961).

The Lufubu System is the oldest recognisable formation and comprises mica schists, micaceous quartzites, and gneisses. These are widely intruded by a number of granitic masses which are grouped together as the Old Granite, and although varying in content, are regarded as compositional phases of a granite of both granitisation and magmatic origin; these masses include grey granite of alkali to tonalite composition, red microcline granite and the Muliashi adamellite granite gneiss.

The Muva System unconformably overlies the Lufubu System and comprises a lower rudaceous group of conglomerates and mica schists, a middle arenaceous group of micaceous to glassy quartzites, and an upper argillaceous group of schists.

The Katanga System is associated with the ore deposits of the Copperbelt and is well documented. The Lower Roan Group of the Mine Series is a feldspathic conglomeratic to arenaceous unit and is the main ore horizon. The Upper Roan comprises a dolomite-argillaceous sequence with intercalated quartzites. The Mwashia Group is dominantly argillaceous with typical carbonaceous shale, conglomeratic and limestone horizons.

The base of the Kundulungu Series is a tillite, overlain by the Kakontwe limestone (1500 ft.) and shales. The Middle and Upper Groups do not show the division of the type succession of the Congo and comprise a thick shale sequence with minor quartzites.

The Karroo System of Zambia is virtually absent from the central plateau area of Zambia and only occurs in depressions and rift valleys where it has been protected from erosion. The Lower Karroo is a dominantly argillaceous sequence whilst the Upper Karroo is arenaceous. Similarly, the Kalahari System of loose sand and consolidated sandstone only appears in the west of Zambia.

(c) North-west Zambia

Although the regional trend of the Katanga sediments appears to continue westwards from the Copperbelt to the Angolan border, rapid changes of facies and the increase in grade of metamorphism westwards, renders the identification of equivalent formations in the west difficult (de Swart et al., 1964; Reeve, 1963). The major subdivisions of the Copperbelt have been recognised between the Solwezi and Mwombeshi Basement domes (Garlick, 1939) and appear to extend into the Mwinilunga area (McGregor, 1960).

The Kundulungu Series on the Copperbelt is dominantly argillaceous but westwards becomes more calcareous (Reeve, 1963) or arenaceous (Brock, in de Swardt, 1964). The persistent Kakontwe limestone of the Copperbelt cannot be identified, although at Solwezi the Chafugoma carbonate is equated with the limestone (Hatfield, in Reeve, 1963). Generally the basal Kundulungu is represented by conglomerates with interbedded grey shales and sandstones, and is overlain by arkoses and sandstones which form hill features (de Swardt, 1964).

(d) Local Successions.

Between the Dongwe and Lulafuta rivers a local Katanga succession has been identified (Taylor, Lyall and Oston, 1962):

Sandstone
Shale-siltstone
Motoma basalt
Limestone-dolomite

At the Kalengwa Mine, 20 miles north-east of Mufumbwe, the succession in 900 ft. of Katanga rocks is:

Recent or Tertiary sandy clay and rubble
Sandstone with shale bands (4-25 ft.)
Silty dolomite
Calcareous dolomite
Albite-chlorite intrusive.

The similarity with the Kundulungu Series, and the lack of regional metamorphism suggests that these horizons at Kalengwa are younger than the Lower Katanga copper-bearing strata of the Copperbelt. The structure at the Kalengwa Mine indicates a north-east strike parallel to the regional trend, with a 50-70° dip to the north-west. Although major folds are not identified, the minor fold axial planes are horizontal (Ellis and McGregor, 1967) and suggest intense deformation.

(e) Geology of the study area (Fig.3)

The area has been geologically mapped by geologists of the Rhodesia Congo Border Concessions Ltd. who indicate an 8 mile wide band of Kundulungu quartzites striking generally southwestwards and dipping subvertically, occurring between Kalengwa Mine and Mufumbwe. This band extends a further 1½ miles south-west of the Mufumbwe camp beyond which the bedrock type is inferred from surface float material.

Geological mapping during the present survey of the sparse outcrop, trench, pit and drillhole cuts, reveals that

N

CHIFUWE

Kalahari Sand

Karroo

Kundulungu

Granite

Study area

road

clearing

track

0 ½ 1 1½ miles

Middle Kamwedgi

KAMWEDGI

Lower Kamwedgi

Jijombo

JIJOMBO

Mufumbwe

MUFUMBWE

DONGWE

24° 30′

40′

13° 50′

after R.C.B.C. sheet No 5

FIG. 3 GEOLOGY OF THE STUDY AREA.

the lithology at Mufumbwe is interbedded metamorphosed quartzites and shales. The quartzites are pink to colourless, contain gritty horizons and frequently display current bedding and specularite banding. They form ridge features and are normally the only outcropping rocks. Interbanded shales are green, with pyritic relics when unweathered, but near surface oxidation produces a red colouration. The assemblage is tentatively correlated with the Kundulungu Series on a lithological basis.

Study of aerial photographs reveal large-scale isoclinal folding between Mufumbwe and Kalengwa. At Mufumbwe two areas of better exposure were studied in detail in the field and intense small-scale folding is apparent. The quartzites appear to have acted as competent horizons while the shales have intensely deformed producing isoclinal and disharmonic folding. Axial plane cleavage can be pervasive, often co-planar with bedding, and may replace bedding in sheared out folds. The fold axes indicate a constant north-east trend with axial plunge both to the north-east and south-west.

At Jijombo both quartzites and limestones of Kundulungu age are noted by the RCBC geologists. Within the study area a single outcrop of pink-brown quartzite occurs to the north on the dambo margin. The quartzite contains quartz-specularite veining and current bedding which are similar to structures found in the Mufumbwe quartzites. The rock strike is 355° north-west with a 20° easterly dip.

No outcrop appears at Middle Kamwedgi, but Karroo sandstone and limestone have been noted one mile to the north-west, while Kundulungu quartzites appear again two miles south.

The Lower Kamwedgi area lies in a band of interbedded quartzites and shales of probable Kundulungu age where the riverbed is eroded into the sub-Kalahari floor. The lithology is similar to Mufumbwe. Although the regional trend is north eastwards, the local strike is northerly and the dip sub-vertical.

Karroo rocks have been noted in patches along the Dongwe and Kamwedgi rivers but no outcrops of this System appear in the study areas.

The Kalahari System is extensively discussed in Chapter II.

(f) Mineralisation

On the Copperbelt no major copper ore occurrences appear in the pre-Katanga rocks. The ore horizon is limited to the argillite of the Lower Roan where disseminated copper appears predominantly as chalcopyrite but also as bornite and chalcocite (Mendelsohn, 1961). Oxidation occurs down to a depth of 300-400 ft.

The copper deposit at Kalengwa is believed to lie in a belt of strata-bound, northwestwards trending, disseminated copper sulphides which extend from the Kafue Hook. Primary mineralisation occurs mainly in calcareous conglomerate often concentrated in scour holes, and suggests a syngenetic origin. The overlying sandstones are poorly mineralised. Primary minerals are bornite, chalcopyrite, pyrite and chalcocite. Decomposition of bedrock has led to extensive supergene enrichment with replacement of the carbonate matrix by malachite and chalcocite with additional digenite, cuprite, melaconite, native Cu, covellite, chrysocolla, libethenite

and cornetite. Some 300,000 tons of ore containing 2% Cu has been outlined (Ellis and McGregor, 1967).

At Mufumbwe, malachite stained shales outcrop and the oxidised mineralisation follows bedding, joints and axial plane cleavage. Results from initial drillholes indicate relatively high grade Cu mineralisation with mainly primary chalcopyrite and pyrite. The sulphides occur at 200-400 ft. above the quartzite contact in shales. Oxidation of the sulphides occurs down to 100 ft. depth.

At the Lower Kamwedgi Prospect, malachite staining appears on mixed shale and quartzite outcrops. Initial drill-hole results indicate good chalcocite mineralisation.

3. PHYSIOGRAPHY

(a) Climate

The North Western Province enjoys the subtropical climate typical of the plateau country of Zambia, with the year divisible into three distinct seasons. A cool, dry winter extends from April to August with a mean temperature maximum of 77-81 °F and an easterly airstream of 4-13 knots prevails. A short, dry, hot season follows with temperatures rapidly increasing to 90-95°F. The wet season is longer than in the rest of Zambia and extends from late September until March; the daily mean temperature is over 80°F and 40-50 ins. of rain fall, mostly as violent rainstorms. A light wind of 4-8 knots blows from the north-west during this season.

Monthly rainfall-temperature data for Mwinilunga, 130 miles north of Mufumbwe are presented in Fig. 4.

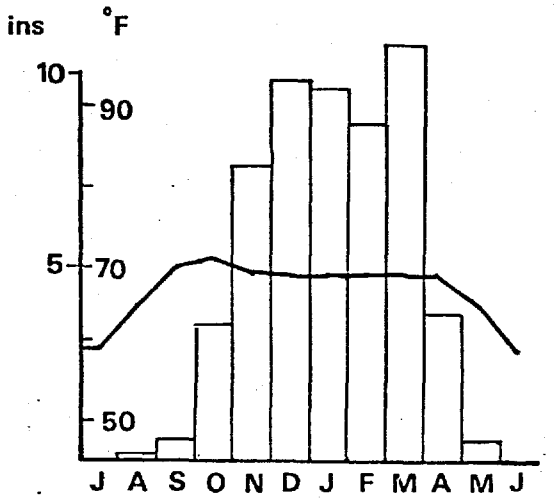


Fig.4 Temperature-rainfall data for Mwinilunga.

(b) Geomorphology

Much has been written on Central African geomorphology mainly by Dixey (1938, '42, '43, '44, '45,), King (1949, '50, '51), Cahen and Lepersonne (1952, '54), Mabbutt (1957), Flint (1959) and Bond (1963).

Although opinions conflict on the significance and origin of certain geomorphological features, there is a general agreement on the overall physiographic surfaces. The Zambian plateau is a composite feature and may locally contain any of the following erosional surfaces:

1. Sub Plateau Surface
2. Sub Karroo Surface
3. Late Jurassic Peneplain (7,000-7,500 ft. elevation)
4. Early Cretaceous Cycle
5. Late Cretaceous, Vipya or Gondwanaland peneplain (5,200-5,500 ft.)
6. Mid Tertiary or Miocene or African Surface (4,200-4,800ft.)
7. End Tertiary Cycle (3,000-4,400 ft.)
8. Early Pleistocene or Victoria Falls Cycle (1,200-3,000 ft.)
9. Mid to Upper Pleistocene Cycle.

The development of the present landscape began at the close of the Karroo epoch (end-Triassic) (Table 2) with widespread erosion which reduced southern Africa to a vast near-level surface (Dixey, 1945); concomitant isostatic uplift formed a basin of the interior of the continent and allowed depositional phases to occur (Mabbutt, 1957). In north-west Zambia post-Karroo warping developed the Congo-Zambezi watershed along an upfold, and the earliest recognisable

Table 2 GEOLOGICAL TIME-SCALE

GEOLOGICAL DIVISION		AGE	DURATION
QUATERNARY			
	HOLOCENE	10,000	10,000 yrs.
	PLEISTOCENE	1m.-10,000	1 million yrs.
TERTIARY			
	PLIOCENE	11m.-1m.	10m. yrs.
	MIOCENE	25m.-11m.	14m. yrs.
	OLIGOCENE	40m.-25m.	15m. yrs.
	EOCENE	70m.-40m.	30m. yrs.
CRETACEOUS		135m.-70m.	65m. yrs.
JURASSIC	KARROO SYSTEM	180m.-135m.	45m. yrs.
TRIASSIC	KARROO SYSTEM	225m.-180m.	45m. yrs.

surface is the Vipya or Gondwanaland Surface: this occurs along the Congo-Zambia border as flat topped, steep sided monadnocks of 5,200-5,300 ft. elevation, 800-1,000 ft. above the younger Miocene Surface (Fig. 5).

The mid-Tertiary, Miocene, or African Surface is very extensive in Zambia and is equivalent to the Tanganyika plateau and to the high veld of Rhodesia (Dixey, 1945; King, 1951). This surface lies at 4,200-4,800 ft. and in the north-west of Zambia slopes southwards off the Congo-Zambesi watershed. This is in the direction of Miocene drainage which included the Zambesi River.

The end-Tertiary Surface was eroded into the Miocene Surface according to the resistance of the underlying formations. It is typified by broad shallow erosion basins of which the Barotse Kalahari Sand Basin is an example.

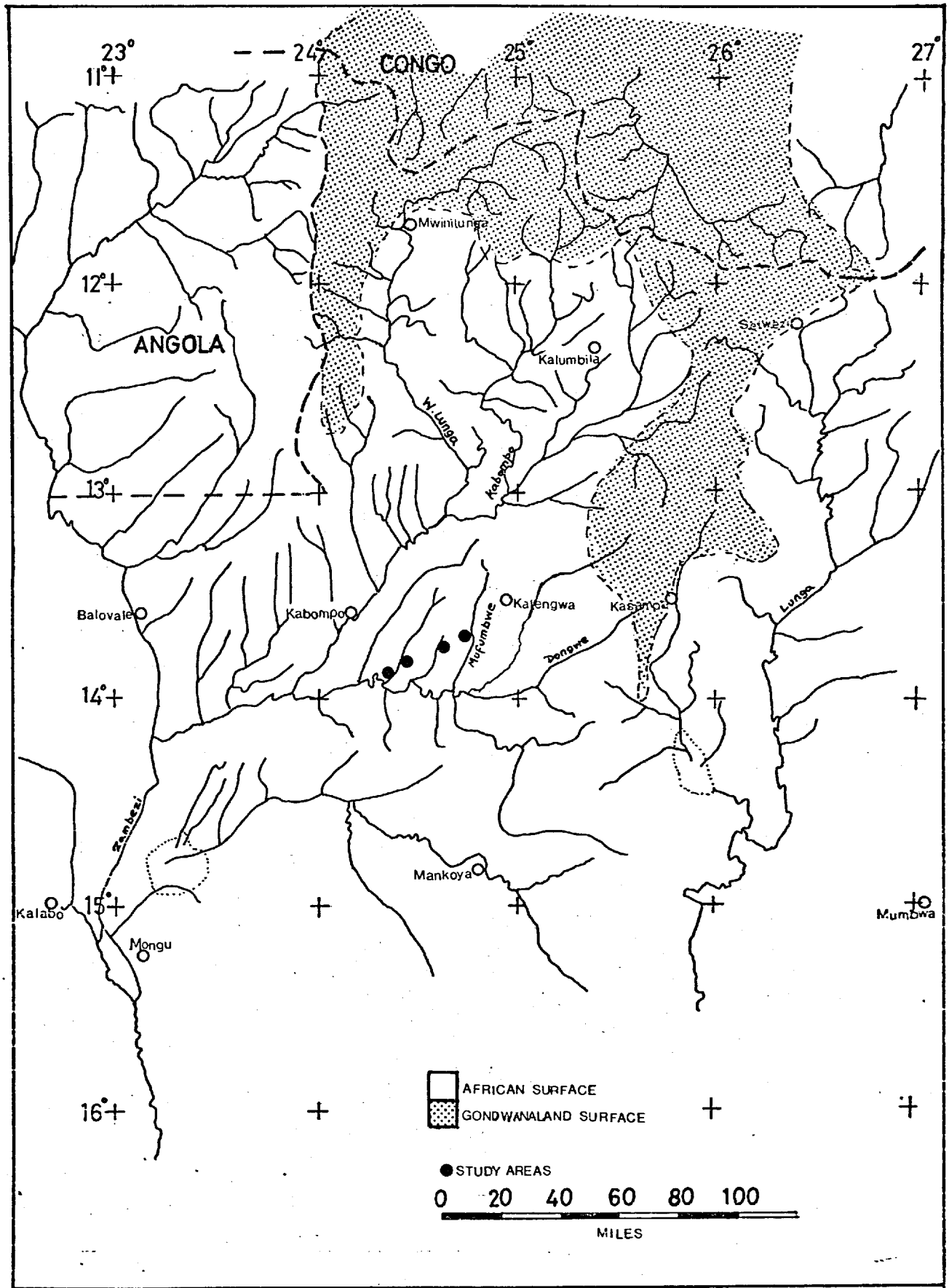


Fig.5 Geomorphological surfaces in northwest Zambia.

Since the end of the Tertiary Period, north-west Zambia has been little deformed but subjected to both erosion and deposition. However, as the surfaces were generally flat and gradients low, little erosion is considered to have taken place (Flint, 1959), although Bond (1963) has calculated that the main rivers have cut down 150 ft. since the Pleistocene. Three main Quaternary climatic cycles have resulted in three pluvial periods followed by three drier interpluvials; the former have led to river erosion and river gravel terrace deposits, while the latter have given rise to ferricrete formation followed by deposition or redeposition of aeolian sand (Clark, 1957). Away from the main river channels the eroded, level land surface has given rise to sluggish seasonally swampy drainage. This is known in Zambia as dambo drainage. Later gradual uplift or warping has rejuvenated the drainage system causing rivers to cut back towards the head water dambos.

Within the study area, the topography is fairly level with a gentle slope to the south-west. The three main rivers, the Mufumbwe, Jijombo and Kamwedgi are consequent on this slope. Towards the east the river system is incised and of a dendritic pattern but within the area it is diffuse and streams are less frequent. This effect becomes more marked west of the area because of the increased cover of Kalahari Sand. The rivers have large tracts of dambo development of both headwater and river dambo types; the latter are parallel to the riverbed. Minor tributaries may be entirely dambo-type drainage. These dambos are wide, shallow,

grass-covered, treeless valleys with sublevel floors and poorly defined axial water courses. They result from poor drainage and excess sedimentation on peneplained surfaces.

(c) Overburden

The study area lies on the fringe of an eastern extension of the Kalahari Sand of the Barotse Basin. East of the Mufumbwe River (Fig.6) the soils are predominantly Plateau Soils (Trapnell et al., 1957). Apart from a lobe of Plateau Soil which extends for 9 miles south-west of Mufumbwe towards the Jijombo River, the area west of Mufumbwe is extensively covered by Kalahari Sand. Only locally along the upper Jijombo and the lower river courses, is the Sand thin and gives way to Plateau Soil. The exposure of the residual soil in these river valleys is in part due to the wetter conditions since the Kalahari epoch, with increased river dissection of the overburden. Rejuvenation of the river has added to the river erosion.

The soils of the area have been studied by Trapnell et al. (1957) and the following soil descriptions are a result of their findings (Fig.6).

(1) Plateau Soils, equivalent to Ferruginous Laterite Soils of the Transvaal (van der Merwe, 1941), to the Plateau Soils of East Africa (Anon, 1936), and to the ferralitic soils of the Copperbelt (Tooms, 1955), are described as coarser to finer grained, sandy to sandy clay eluvial soils formed by long periods of seasonal leaching on maturely eroded topography. These are the residual soils referred to in this thesis. According to Trapnell et al. (1957) the normal soil profile comprises a brown-grey

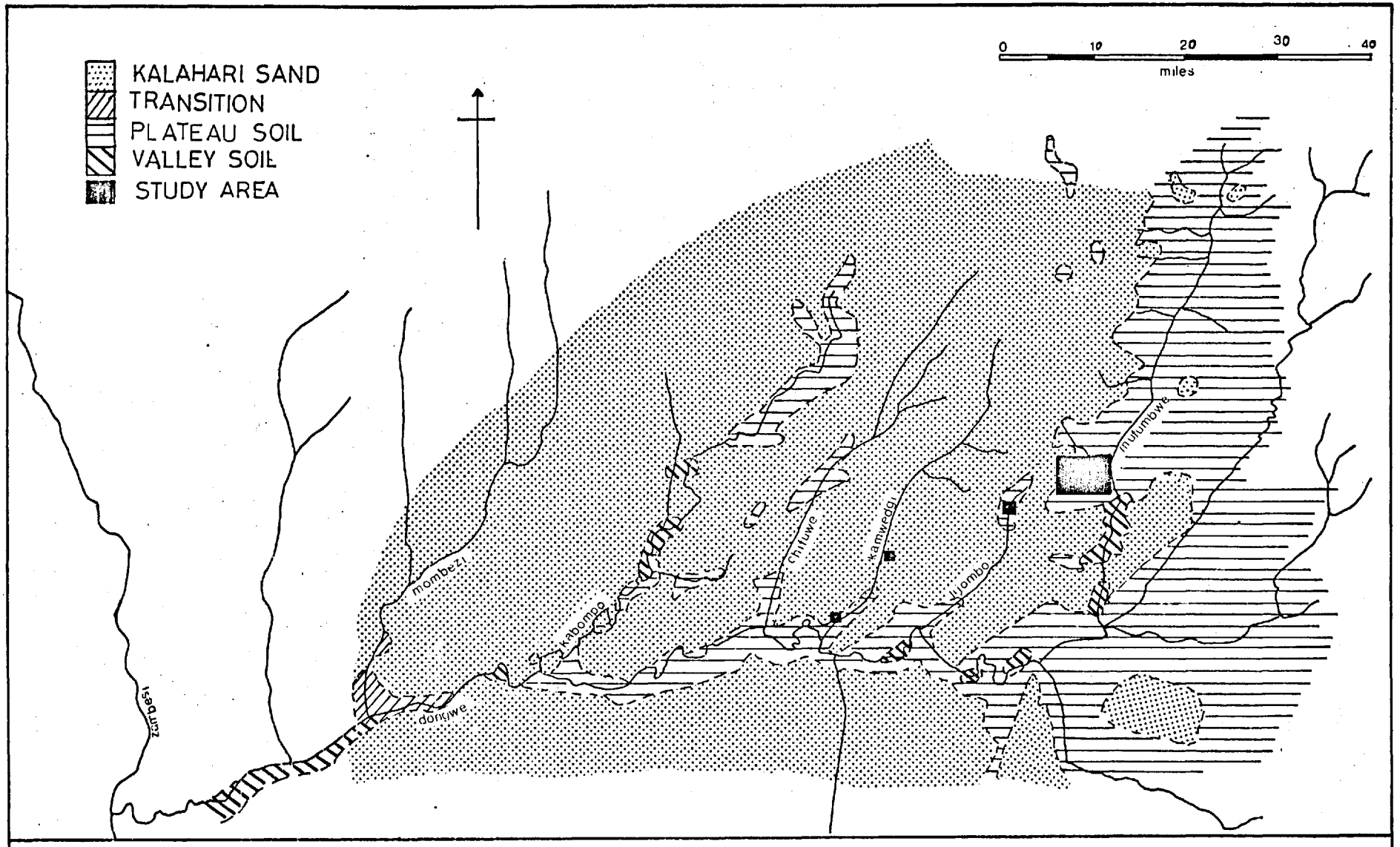


Fig.6 Overburden of the study area.

organic top-soil, grading down to a raw ochrous subsoil, granular in structure and plastic when wet. Pronounced nodular lateritic concentrations occur in the lower subsoil which grades into the underlying rotted rock. These lateritic formations may be due to impeded drainage caused by low relief and seasonal downpours. The soil is acid (pH 5.0-5.5), low in soluble minerals, and has a low cation exchange capacity (2-10 meq/100 gm; Hawkes and Webb, 1965) and are very low in exchangeable bases. The soil is also low in nitrogen, phosphate and organic matter and has a low primary mineral content.

Much literature has been published describing laterite and lateritic soils and will be considered later in this section.

(2) Kalahari Sands comprise pure quartz grains which are markedly rounded and frosted. The colour is normally white, while grey varieties are due to organic colouring. Fe staining causes a red to gold colouration. Profiles are seldom developed. The Sand tends to be acid (pH 4.5-5.5), with a low clay content; the clay content increases with depth.

(3) Transitional or Contact Kalahari Sands are a mixture of the previous two types. They are generally grey or brown with 40-70% coarse sand and 1-3% clay. The acidity is lower than in Kalahari Sand (pH 5.3-6.3).

(4) River valleys tend to be filled with younger regraded soils which may be seasonally wet varieties of the former types. Two diagnostic flood plain soil types are formed:

(i) Grey Clays, equivalent to the grey non-calcareous clays of East Africa, and to glei and glei podsols, have a brown-grey superficial layer over a mottled clay sand. They tend to be sandier and more acid than Black Clay. They are inert and non-cracking with a lower zone of rusty or glei limonitic concretions and mottles. The cation exchange capacity of 15-25 meq/100 gm (Hawkes and Webb, 1965), is relatively low.

(ii) Black Clays, equivalent to the Subtropical Black Soils of the Transvaal and to the Black Calcareous Clays of East Africa, are black to brown in colour, near neutral to basic (pH 6.2-9.0), deep-cracking, siliceous and may locally contain calcareous nodules. These clays are markedly base-rich with Ca, Mg and Na salts and are organic poor (1-3%). When dry the clay tends to be hard and impervious when wet. These properties are due to excess silica and bases received in solution from surrounding areas. The upper horizons tend to be more acid due to leaching. The upper reaches of dambos are more acidic due to the proximity of residual soils.

Black dambo soils have been variously described as pedocals, black earths, vlei clay, cotton soil, regur, grumosol, tirs, rendzina and badob (Hessayon and Hutton, 1954; Oakes and Thorp, 1950). The black colouration has been ascribed to montmorillonite plus carbon material (Lozet, 1955), clay-organic complexes (Singh, 1956) or anaerobic bacteria in montmorillonite clay (Hessayon et al., 1954) while Mohr and van Baren state that the colour is due to the Ca and Mg of the montmorillonite (1954). The high exchange capacity of the sediment has been ascribed either to the montmorillonite or to the carbon content. With continued

leaching and more acid conditions the montmorillonite can be converted to kaolinite and the soil can become lateritic (Lozet, 1955; Mohr and van Baren, 1954). No montmorillonite was found during the present survey in dambo sediment.

The residual (Plateau) soils of the study area are lateritic soils. In addition, the Kalahari Sand frequently has laterite horizons, and would with time and a continuation of the present climate develop certain characteristics of lateritic soil. A great amount of literature has been written on laterite horizons and lateritic soils. The term 'laterite' has been used in the past to describe material of a widely diverse chemical composition and origin. The term has been applied to material from different climates, geology, geomorphology, drainage and vegetation conditions and thus virtually all aspects of laterite development and composition are disputed. A comprehensive resume of the subject is presented by Maignien (1966) and the following conclusions, on the Fe-rich variety of laterites and lateritic soils are mainly drawn from his work.

The soil formed during the process of lateritisation has been termed latosol, kaolisol or ferrallitic soil. These soils are normally red in colour, dependent on the hydration of the Fe oxides, while Mn imparts a purple colour. They are deep (up to 20 m), and apart from the concretionary zone, show little horizon differentiation; they may not have a true textural B horizon. These soils are intensely altered so that little residual material is recognisable. The extensive alteration causes loss of bases (K_2O,Na_2O,CaO) and also of Mg^{++} and K^{+} with marked accumulation of Fe sesquioxides.

The exchange capacity of the laterite profile is low, as exchangeable and total cations are low; absorbing complexes of the profile are extremely unsaturated. The pH of the profile is acidic (pH 4.5-5.5) but increases in alkalinity in the C horizon, and also at surface where vegetation may increase the pH to 7. The surface content of organic material (2%), nitrogen and clay are low, and the humic matter does not extend below 20 cms.

Commonly a concretionary, Fe-rich (Fe<10-80%), Al-poor, Si-poor (<20%) horizon of variable thickness and depth is developed. It may have the form of isolated pisolitic concretions, densely-packed, hardened concretions, or, a massive indurate zone. This zone is now generally described by the term 'laterite'. The zone may be illuvial, the accumulation of Fe resulting from leaching from above or from lateral migration from outside the profile. Alternatively the laterite may be a remnant formation in situ, and results from the leaching out of other minerals.

The laterite horizon, may be indurate at depth, or may harden and darken on exposure, partly through oxidation and dehydration of the ferruginous material. The difference between the soft and crust types of laterite appears to depend not on the absolute content of Fe but on the crystallinity of the Fe oxides.

The laterite horizon comprises mainly the Fe sesquioxides goethite ($\alpha Fe_2O(OH)$) and hematite (Fe_2O_3) with kaolinite ($(OH_4)Al_2Si_2O_3$), Mn oxides and the rarer Al sesquioxides, gibbsite ($\gamma Al(OH)_3$) and boehemite ($\gamma AlO(OH)$). Cryptocrystalline

goethite retains variable water and gives rise to amorphous limonite. Clays may also include illite. In addition residual and detrital material appear. Silica may occur as residual quartz, or secondary chalcedony, opal or colloidal silica.

The migration of Fe in the laterite profile is conjectural. Although ferric Fe is almost insoluble in tropical pH conditions, the ferrous ion is appreciably soluble. Electropositive ferric Fe in the profile may attach itself to clay and be leached out with the clay: or ferric and ferrous ions may form electronegative complex ions with substances in the soil and be leached out. Ferric Fe may also be converted to ferrous Fe by bacteria or organic matter. The soluble Fe then migrates in ionic, complex or chelate form depending on the conditions in the environment. Movement of Fe and other elements, within the profile may be in part capillary for a height of 2-2.5m in the zone of temporary saturation at the fringe of the water-table. Movement is probably mainly related to the fluctuation of the water-table between wet and dry seasons. As the water-table recedes in the dry season, the ferrous Fe which was in solution in the zone of saturation, is converted to insoluble ferric Fe through oxidation by aeration; this process is aided by coarse

material which allows more rapid oxidation. The depth of penetration of oxygen in the profile limits the downward development of Fe accumulation even after the water-table has fallen below this level. In the permanently waterlogged horizons, the reducing conditions produce glei horizons with Fe mottles, rather than laterite. If the base level of the water-table permanently recedes, these mottles give rise to concretions.

Within the study area, the residual soils are lateritic, and commonly have a concretionary horizon occurring at a variable depth. This normally rests immediately over bedrock or decomposed bedrock. Since the Tertiary Period, the rejuvenated drainage system has lowered the landscape and locally exposed the lateritic B horizons. These exposed cemented horizons are impervious and cause seasonal water-logging. Such surface pavements (equivalent to the Murram of East Africa) are often marked by substantial clearings in the otherwise evenly canopied woodland.

Within the Kalahari Sand profiles, lateritic horizons are sporadically developed. The horizons may be more frequent but have not been intersected in the relatively shallow pits. They may be loose, concretionary Fe nodules or indurate, compact horizons. The cementing Fe normally contains a matrix of Sand grains. In time, lateritic development might become more pervasive, and the Sand would develop lateritic soil characteristics.

(d) Vegetation.

The vegetation cover of Zambia is controlled by climate, soil types and depth, drainage and seasonal fires. The close correlation between soil and vegetation has long been recognised in Zambia and has been used extensively in the interpretation of geology of the Copperbelt on the ground and from aerial photographs (Mendelsohn, 1961).

Trapnell et al. (1957) described the vegetation of the study area during a country wide survey. They note that the plateau soils east of the Mufumbwe River carry a mixture of Northern and Central Brachystegia-Julbernardia paniculata* "miombo" woodlands. The Northern type is typified by medium to tall woodlands with Julbernardia paniculata,* Brachystegia longifolia, Brachystegia floribunda, Isoberlinia angolensis,* Brachystegia boehmii* and Brachystegia hockii merging into poor scrublands of Brachystegia boehmii or Julbernardia paniculata and Uapaca spp. on shallower soils overlying laterite sheets. The Central type comprises medium woodlands of simpler composition, with predominantly Julbernardia paniculata and also Brachystegia longifolia, Brachystegia boehmii and Uapaca spp. This type can tolerate Kalahari

* marked species have been altered from the original nomenclature of Trapnell, with reference to reclassification of the vegetational species by Fanshawe (1965)

Sand but on shallow lateritic soils tends to give way to scrublands with Parinari and Diplorhynchus.

A botanical survey was carried out during the present project. The vegetation on the residual soils in the study area forms a tall woodland with trees of 40-60 ft. and a limited understorey. In the Mufumbwe vicinity the vegetation comprises Julbernardia paniculata, Brachystegia boehmii and Brachystegia longifolia, with Isoberlinia angolensis, Ochna pulchra, Faurea sp., Pseudolachnostylis maprouneifolia and Parinari excelsa (Plate 1).

At Lower Kamwedgi, the assemblage on residual soil includes Julbernardia paniculata, Brachystegia boehmii and Brachystegia longifolia with less abundant Brachystegia spiciformis. In addition Cryptosepalum pseudotaxus and Isoberlinia angolensis appear. The middle storey vegetation comprises Diplorhynchus condylocarpon, Ochthocosmus lemaireanus and Monotes sp.

On the Contact Soils, Trapnell notes Julbernardia and Brachystegia with additional Erythrophleum africanum, Pterocarpus angolensis, Diplorhyncus and Diospyros batocana. This vegetation type is gradational into areas of deeper Kalahari Sand where denser forest cover of Cryptosepalum and Baikiaea predominate, together with an understorey of Baphia, Bauhimia, Paropsia and ground shrubs.

During the present study, it was noted that the transgression to Kalahari Sand is frequently marked by a thinning and stunting of the vegetation (Plate 2).

West of Mufumbwe, the common species on Kalahari Sand

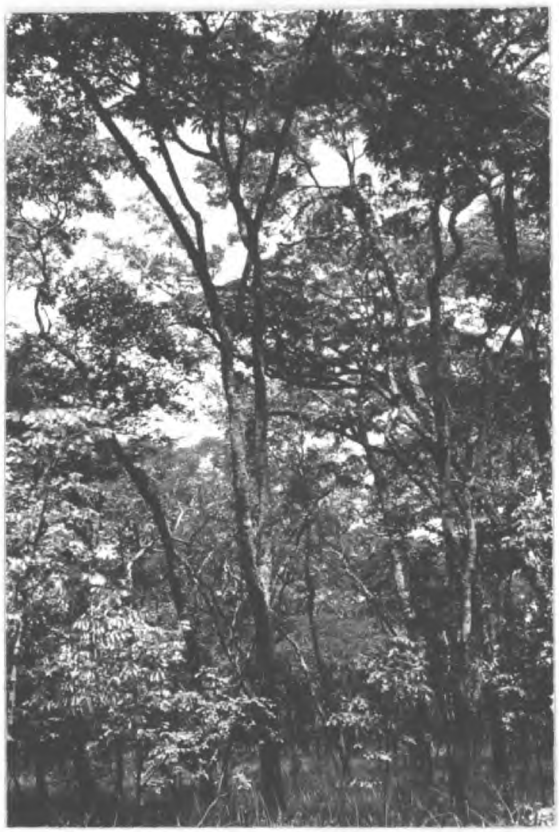


Plate 1. Upper storey (50 ft.) Brachystegia longifolia, B. boehmii and Julbernardia paniculata on residual soil.



Plate 2. Middle storey Brachystegia longifolia, Isoberlinia angolensis and Julbernardia paniculata on Kalahari Sand.

are Afrormosia angolensis, Brachystegia spiciformis and Isoberlinia angolensis with an understorey of Pseudolachnostylis sp., Monotes sp., Afzelia quanzensis, Swartzia madagascarensis and Lannea discolor.

At Jijombo the upper storey trees on Kalahari Sand include Julbernardia paniculata, Cryptosepalum pseudotaxus, Brachystegia longifolia, Isoberlinia angolensis, Ochna pulchra, Combretum molle, Monotes sp. and Ochthocosmus lemaireanus; the lower storey vegetation includes Diplorhynchus condylocarpon and Pseudolachnostylis spp. At Middle Kamwedgi a similar assemblage is found with additional Pterocarpus angolensis and Diospyros batocana. Cryptosepalum pseudotaxus is only common towards the dambo margin.

At Lower Kamwedgi on Kalahari Sand, the upper storey comprises Julbernardia paniculata, Brachystegia longifolia and Erythrophleum africanum. The lower storey includes Diplorhynchus condylocarpon, Pseudolachnostylis spp. and Combretum molle while the ground plant Landolphia kirki is common.

Thus the typical Cryptosepalum-Baikiaea forest of the Kalahari regions to the west in Barotseland do not encroach into the study area.

Dambo floors are usually devoid of trees and carry only a grass coverage (Plate 3). This feature has been attributed to a lack of nitrogen in the dambo clay (Duvigneaud, 1958) or to the lack of oxygen in the ground water (Tooms, 1955) but may be due to the seasonal



Plate 3. Treeless dambo in miomba woodland savanna.

waterlogging. Trapnell notes that the black dambo clays support the tall grass Hyparrhenia rufa and the tussocky Setaria phragmistoides and Setaria ciliolata; the sandier dambos of the Kalahari tend to contain Trichopteryx Hitchcockii and Themada trianda. Most dambos are fringed by "mishitu" evergreen thickets.

A marked pecularity of the normal vegetation cover is the occurrence of natural clearings occurring in the woodland covers. These clearings are due to two causes. The most frequent type of clearing is under-floored by hardpan laterite which occurs either immediately below the thin soil cover, or outcrops as a barren indurate pavement (Plate 4). The absence of trees is probably due to the inability of the roots to penetrate the laterite carapace. The second type of clearing is the "copper clearing" overlying copper mineralisation (Plate 5); here the absence of trees has been ascribed to the poisoning of seeds by the high copper content of the soil (Mendelsohn, 1961) or to the absence of nitrogen as a result of excess copper (Duvigneaud, 1958).

Occurring in the Mufumbwe copper clearing is the small ground shrub Becium obovatum*, known in Zambia as the "copper flower". This was first studied in Zambia by Woodward in 1949 when its association with copper deposits was noted, and has since been described as a widespread geobotanical indicator of copper deposits in Zambia (Horizon Magazine , 1959; Mendelsohn, 1961; Cornwall,1969).

A complete list of the species located in the study area is noted in Appendix I.

* previously known as Becium homblei de Wild.



Plate 4. Laterite clearing in Brachystegia - Julbernardia woodland.



Plate 5. Mufumbwe Main Copper Clearing with abundant flowering Becium obovatum.

CHAPTER II KALAHARI SYSTEM AND ASSOCIATED SEDIMENTS

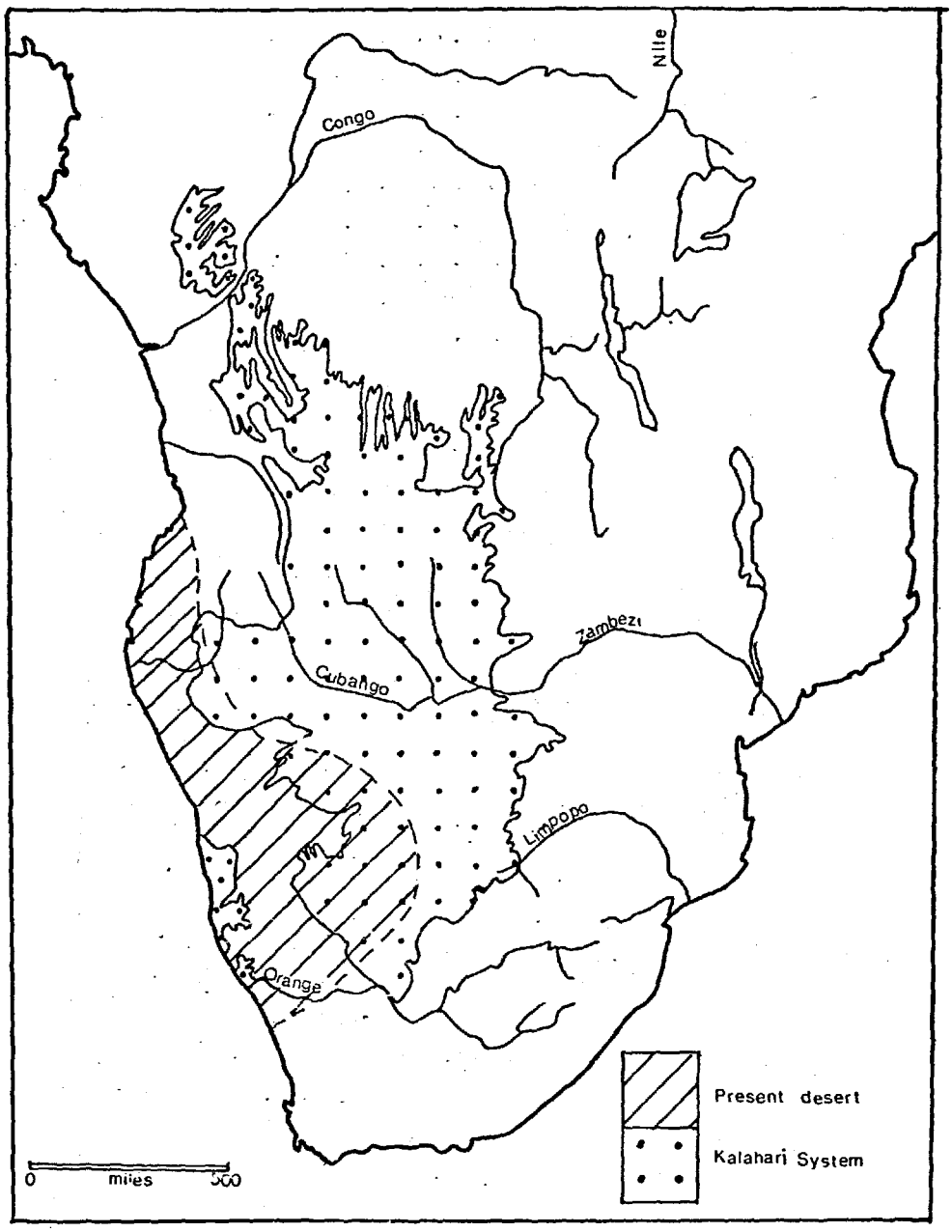
SECTION I KALAHARI SYSTEM (PREVIOUS WORK)

1. INTRODUCTION

Under existing climatic conditions, the present Kalahari Desert is limited to Botswana and South West Africa, but in the past, during more arid epochs, Kalahari deposits have extended from 30° South to 1° North: these deposits are found in South Africa, Rhodesia, Angola, Zambia and the Congo (Fig.7).

The overall correlation of the Kalahari System of southern Africa is extremely tentative. Two schools of study have emerged with diverging conclusions, the Belgian and French in the Congo and the English speaking scientists of southern Africa. Most of the work in the Congo has been done by Maufe (1929), Polinard (1932), Veatch (1935), Jamotte (1940), Lepersonne (1945), Cahen and Lepersonne (1948, '52, '56), de Ploey (1963) and de Ploey, Lepersonne and Stoops (1968). The various areas south of the Congo have been studied dominantly by Passarge (1904), Maufe (1929), du Toit (1954), McGregor (1947), Clark (1950, '55), Cooke (1952, '57), Dixey (1945) and Bond (1946, '48, '57, '63).

Much of the previous work has attempted to correlate local successions with the type sections of either the Congo or of southern Africa, which are not similar nor necessarily contemporaneous: The terminology, including "Kalahari Sands" and "Kalahari Beds", is often loose and as it is variously dependant on lithological, pedological, palaeoclimatical, geomorphological or archaeological



Cooke, 1957

Fig.7 Distribution of the Kalahari System.

interpretation, correlation is extremely complicated. Correlation of the different sedimentary facies depends on dating river gravel deposits, erosion surfaces, aeolian sands, laterite horizons, fossils, human artefacts and cultural horizons. Difficulties arise in the identification of erosion surfaces, in relating laterite horizons, by the reworking of aeolian sand and river deposits, and by restricted occurrences of fossil or human evidence which is limited to river or lacustrine deposits. The aeolian sand rarely contains fossils as a result of either the inhospitable climate during the deposition of the sand, or of the subsequent poor preservation through initial oxidation and later decay in the acidic environment of the sand.

2. STRATIGRAPHY

Two separate type successions are used for the Kalahari System, one from the Congo and the other from the Upper Zambezi Valley; the equivalence of the two is still in doubt (de Ploey, Lepersonne and Stoops, 1968).

(a) Congo Type Succession.

In the Congo, the succession is divided into 3 series (Cahen and Lepersonne, 1956):

Name	Sediment Type	Depth(ft)	Age
1. Upper Series.	ochre sand	<330	Miocene or early Pliocene
	mid-Tertiary(African)Surface		
2. Middle Series.	pale sand, silicified sandstone and limestone	<300	early Tertiary
	Upper Cretaceous(Gondwanaland)Surface		
3. Lower or Kamina Series.	sands, sandstone and gravels	<33	early Cretaceous

The Lower Series is peculiar to the Congo.

The Middle Series has been variously equated with the "grès polymorphes" of the Congo; the Silicrete, Botletle Beds (Passarge, 1904) or Kalahari Beds of Southern Africa; or the Ka_1 sandstone of Angola (Stanton, 1963). South of the Congo the age is generally regarded as Pliocene to lower Pleistocene and the deposits are not related to the Gondwanaland erosion Surface. (Clark, 1950).

The Upper Series has been called the Kalahari Sands, the "sable ocre" or Plateau Sands of the Congo, or the Ka_p of Angola. South of the Congo, the Series is regarded as Middle Pleistocene to Holocene and postdates the end-Tertiary surface.

(b) Zambian type succession

As the deposits of the Cainozoic indicate varying climatic conditions, the beds of the Kalahari System are equated to climatic episodes. Three major cycles of wetter pluvials and drier interpluvials with two subsequent short pluvials have been postulated for southern Africa since the Tertiary (Table 3). The succession for the Upper Zambezi Valley (Victoria Falls area) is summarised in Table 4; this succession has datable river gravel deposits with limited interbedded aeolian sand.

Table 3. Correlation of the climatic, geological and archaeological events of the Kalahari System of southern Africa.

Age Yrs B.P.	Period	CLIMATE	ZAMBESI VALLEY.	TRIBUTARY STREAMS	CULTURE	CONGO BASIN	SOUTH AFRICA
0-6800	2nd Post Pluvial	Semi arid	Erosion to present contours and formation of low sand islands. Formation of low level degradation terraces & abandoned channels. Black alluvium. Erosion.		Upper Northern Rhodesian Wilton	Downcutting to present contours	
11,240	-	arid	Accumulation of dirty wind-blown Sand. Formation of calc-tufa.				
12,970	1st post Pluvial wet phase	semi arid wet	Aggregation of sandy calcareous alluvium forming 15-10ft. terrace. Minor erosion of Kalahari System. forming scarps. Erosion of Older and Younger Gravels.		Lower Northern Rhodesian Wilton	Sands	
	-	arid	Redeposition of Kalahari Sand II by wind.		Rhodesian Magosian		Aeolian sand
30,500	3rd Pluvial (Gamblian)	semi arid wet wet semi arid	Calcreting of Younger Gravels and sands Erosion Erosion Temporary living sites on eroded Sand slopes	Kunkar formation. Formation of Younger Gravel III and Alluvium III. Erosion. Kunkar formation. Aggragation of sands and Younger Gravels II and Alluvium II.	Rhodesian Stillbay Rhodesian proto-Stillbay	gravels and sands of lower terraces of the Kasai.	Grits, sands and clays
41,000		wet semi arid wet semi arid	Erosion Redistribution of Kalahari Sand on scarp slopes and nodules of Ferricrete. Temporary living sites. Erosion Formation of ferruginised scarp rubble.	Erosion Kunkar formation. Aggragation of earlier Younger Gravels over 15-20ft. terrace Younger Gravels I and Alluvium I. Erosion Formation of ferricrete.	Upper Rhodesian Sangoan Lower Rhodesian Sangoan	Erosion Red Sands Sandy Clays gravels erosion and formation of the high-level terrace of Kasai. Ferruginisation	Erosion Red aeolian sand Calcified sand Youngest Gravel Erosion
			Commencement of removal of Kalahari Sand				
57,000	Inter-pluvial	very arid	Land rubble. Deposition of Kalahari I under desert conditions of long duration; small tributaries dry up. ? ferricrete formation.			Kalahari Sand	Kalahari Sand Calcification
	2nd Pluvial (Kamasian)	arid semi arid wet semi arid very wet semi arid	Formation of calc-tufa and Kunkar. Deposition of Older Gravels II on 15-20ft. terrace. Erosion Ferruginisation of Older Gravels Deposition of Older Gravel I on 45ft. terrace Erosion of Pipe Sandstone, Chalcedony. Induration of Pipe Sandstone and formation of siliceous ferricrete on upper surfaces		Late Rhodesian Acheulian **Middle Rhodesian Acheulian** Hope Fountain Early Rhodesian Acheulian Rhodesian Chellean	Sand and clays High level Kamoa gravels	
		very arid wet	Silicification of Pipe Sandstone ? Gentle warping Deposition of freshwater limestone, and later Sand				
		very arid	Silicification of limestone and associated sandstones, by conversion to chalcedony.			Kalahari Sand Earth movement	Kalahari Sand
	1st Pluvial (Kageran)	semi arid very wet	Deposition of freshwater limestone and sands. Deposition of scattered pebbles. Erosion and formation of the end-Tertiary surface peneplain.		No Culture	Plateau Gravels	Older gravels Basal Older Gravels Peneplanation

modified from Clarke (1950).

Table 4. Kalahari System succession of the Victoria Falls area

1st post-Pluvial	windblown sands with calc-tufa sandy calcareous alluvium	RECENT
	Kalahari Sand II	UPPER PLEISTOCENE
3rd Pluvial	Younger Gravels and sands	UPPER PLEISTOCENE
	Kalahari Sand I	MIDDLE PLEISTOCENE
2nd Pluvial	Older Gravels and sands	MIDDLE PLEISTOCENE
	Pipe Sandstone	LOWER PLIOCENE
1st Pluvial	Chalcedony(silicified limestone)	LOWER PLIOCENE
	High Level Gravels	LOWER PLIOCENE

(after Clark, 1950)

(c) Kalahari Beds

The Kalahari Beds comprise the High Level Gravels, the Chalcedony, Pipe Sandstone and the Older Gravels. In Zambia these are preserved in depressions in the Upper Cretaceous and mid-Tertiary erosion surfaces (Cahen and Lepersonne, 1956).

(i) High Level Gravels

Following the peneplanation forming the end-Tertiary surface, the deposition of the Gravels suggest the wetter conditions of the 1st Pluvial period. Similar deposits are reported in the Congo (Plateau Gravels), Angola and South Africa (Older Gravels).

(ii) Chalcedony

Freshwater sandy limestone, varying from 0 to 5 ft. in thickness and deposited in the late Tertiary or

early Pleistocene were silicified soon after deposition. They occasionally contain the fossil gastropods Viviparus sp., Limnea sp., Planorbis sp., and Isodora, and seeds of the aquatic plant Chara. Similar deposits are noted in the Congo, Botswana, Rhodesia, South Africa, Angola and Mozambique.

(iii) Pipe Sandstone

This formation is uniform and widespread in Zambia (Clark, 1950). It comprises a white sandstone with an opaline cement, 0-12 ft. thick. Fossils recorded include Limnea sp., Cypris sp., Planorbis sp. and Chara sp. The vertical pipes are believed to be remnant reeds. Similar rocks are found in the Congo, Rhodesia and Mozambique.

(iv) Older Gravels

A gravel terrace, 1 to 2 ft. thick, locally overlies the Pipe Sandstone and indicates the wetter conditions of the 2nd Pluvial period.

(d) Kalahari Sand

(i) Introduction

The aeolian sands are the most widespread unit of the Kalahari System. They underlie 60,000 square miles of western Zambia to a depth of 200 ft.; they also cover 12% of Rhodesia up to a depth of 200 ft., 85% of Botswana (Clark 1957) and areas of the Congo, Angola (Stanton, 1963; Janmart, 1953; Leakey, 1949), Mozambique (Bosazza, 1957), South West Africa and South Africa (Fig. 7). As previously stated, correlation of the Sand* horizons is difficult and has only been achieved near river channels.

* "Sand" is used throughout this thesis for Kalahari Sand.

(ii) Successions

Three major accumulations have been proposed for Zambia (Clark 1950):

(1) Kalahari Sand I

During the arid phase following the 2nd Pluvial, the major windblown deposits formed. Although only 10 ft. thick at the Victoria Falls, elsewhere this unit is up to 200 ft. Cahen and Lepersonne reinterpret these Sands as pre-dating the end-Tertiary surface (1956).

(2) Kalahari Sand II

After the river terrace gravels of the 3rd Pluvial, a further arid phase resulted in a second deposit of Kalahari Sand. At the Victoria Falls this Sand section is only 40 ft. thick.

(3) Reworked Sand

During the post 3rd Pluvial period, Sands deposited during the earlier phases were redeposited.

(iii) Age

The age of the Sand is disputed. Janmart (1953) states that the age of the Sand should be the age of the last movement, whilst other investigators date the Sand as the age of the origin of the Sand. As the earliest deposits of Kalahari Sand have never been lithified, there has been considerable redistribution without detectable change, often on to lower topographic benches.

Several authors suggest a Tertiary age. Hence Mabbutt (1957) considers the age of the original Sand as Upper Tertiary. Cooke (1957) regards the Sand of South

Africa as Pliocene while the lowest Sand of the Congo preceeds the end-Tertiary surface (Cahen and Lepersonne, 1952). Savory (1965) indicates that the Sand of the Sesheke area of Zambia originated in the Pliocene.

Other authors suggest a Quaternary age. Wayland (1953) considers the Sands in Botswana to be Quaternary, while Clark (1957) regards the Sands of southern Zambia as post-end Tertiary, similar to the age of the Upper Series Sand of the Congo (Cahen and Lepersonne (1952). In Angola, a Pleistocene age is postulated for the Ka_1 Sands (Stanton, 1963), while a middle Pleistocene age is suggested for the lowest Sand horizon (Leakey, 1949; Janmart, 1953); a similar middle Pleistocene age is proposed for the first Sand in the Zambesi Valley (Clark, 1950; Bond, 1957) and for Rhodesia (Bond, 1946).

(iv) Origin

The Sand is generally believed to be aeolian and derived by long aerial erosion in an arid environment with little removal of the detritus by river action.

McGregor (1947) argues that the vast quantity of Sand was derived from the exposed sea floor during the Pleistocene Ice Age and that the Sand was transported on to land by easterly winds. Bond (1948) indicates by a heavy mineral study that the Sand of Rhodesia is of local origin, eroded from pre-Karroo rocks near the Zambesi Valley. Du Toit (1954) suggests South West Africa as the general area of origin while Flint (1959) favours local derivation from underlying Kalahari Beds. Savory (1965) suggests that the Sand of the Sesheke area of Zambia is of local origin

from the underlying Upper Karroo Sandstone.

The "sable ocre" of the Congo, equated with the Kalahari Sand, was previously regarded as aeolian (Cahen 1954). Recent work tentatively suggests that the Sand may be fluviatile in origin (de Ploey, Lepersonne and Stoops, 1968), while the underlying "grès polymorphes" has mixed aeolian and lacustrine horizons.

SECTION 2 SEDIMENTARY ANALYSES

(1) Method of Study

(a) Granulometry

After disaggregation of the sample using 1% Calgon and ultrasonic vibrations, the -200#* material (Table 5) was separated into silt and clay fractions by sedimentation, and the weight of each calculated by the Bouyoucos hydrometer method. The +200# material was subdivided into fractions by wet sieving and each separated fraction weighed.

Several different classifications of soil particle size exist, and many ways of recording the results are employed. The system adopted is based on Wentworth's scale using the phi scale adaption of Krumbein (1938) (Fig.8 and Table 6). This produces equal log size class intervals which aids data plotting.

The phi unit is defined as $-\log_2$ of the particle diameter size in millimetres.

Using the size frequency data, cumulative frequency curves are constructed and the following four parameters, which measure the symmetry of the curve, are deduced:

1. Phi Median diameter (Md_ϕ)
2. Phi Quartile Deviation (QD_ϕ) where

$$QD_\phi = \frac{75\% \text{ quartile} - 25\% \text{ quartile}}{2}$$

this measures the average spread of the curve and for zero deviation, $QD_\phi = 0$

3. Sorting Coefficient (So)

* # is used throughout this thesis for "sieve mesh size". A minus sign implies "size less than" while a positive sign indicates "size greater than".

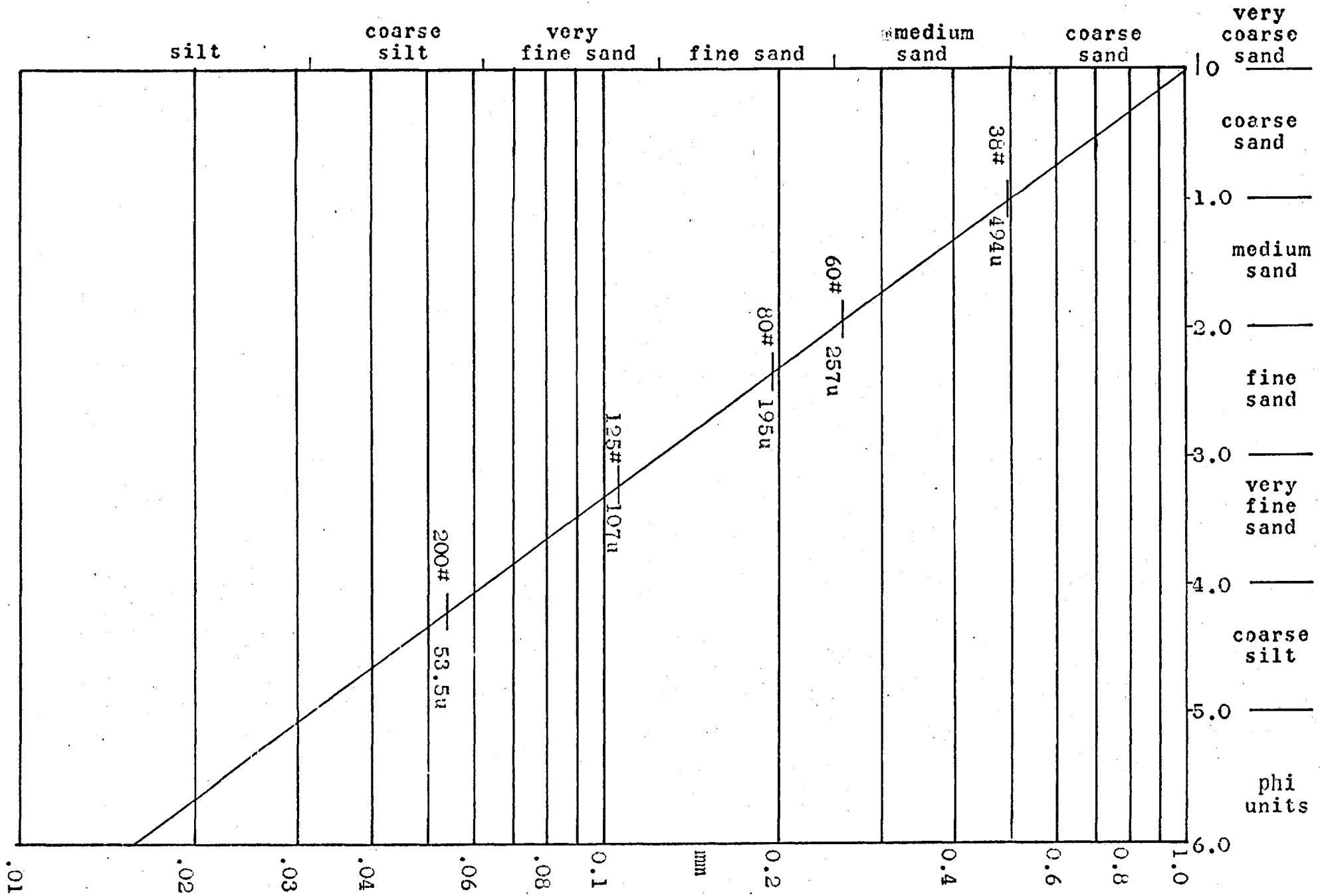


Fig.8 Millimetre-phi unit conversion chart.

Table 5. Sieve Mesh size (mm)

Mesh size# (B.S.S.)	Diameter (mm)	Sediment
2	2.0	
20	1.040	very coarse sand
38	0.494	coarse sand
60	0.257	medium sand
80	0.195	fine sand
125	0.107	
200	0.054	very fine sand
Sedimentation	0.054-0.002	silt
	<0.002	clay

Table 6. Wentworth's scale-phi unit correlation

Phi Unit (ø) diameter	Wentworth's scale diam. (mm)	Sediment	Sieve mesh# (approx.)
0-1	$1-\frac{1}{2}(1.0-0.5)$	coarse sand	-20+38
1-2	$\frac{1}{2}-\frac{1}{4}(0.5-0.25)$	medium sand	-38+60
2-3	$\frac{1}{4}-\frac{1}{8}(0.25-0.125)$	fine sand	-60+125
3-4	$\frac{1}{8}-\frac{1}{16}(0.125-0.063)$	v. fine sand	-125+200
4-8	$\frac{1}{16}-\frac{1}{256}(0.063-0.004)$	silt	-200
>8	$<\frac{1}{256}$ (<0.004)	clay	

where So = $\text{antilog}_2 QD_\phi$, and for convenience is derived from a conversion chart (Fig. 9). The sorting classification is based on Trask with a range of values from:-

1.2 - 1.7	well sorted
1.7 - 2.0	moderate sorting
2.0 - 3.0	poor sorting
>3.0	very poor sorting

4. Phi Quartile Skewness (SKq_ϕ), where

$$SKq_\phi = \frac{25\% \text{ quartile} + 75\% \text{ quartile}}{2} - Md_\phi$$

This measures the asymmetry of the curve, so that with zero skew, $SKq_\phi = 0$; a positive value is an overabundance of fine material and a negative value a high coarse material content.

(b) Microscopy

The various size fractions of the disaggregated samples were studied using a binocular microscope under low power to determine morphological grain features such as colour, rounding, sphericity, surface texture, inclusions and bulk composition. Thin sections were examined of a limited number of samples for evidence of regrowth and other internal features.

(c) Heavy Minerals

Heavy mineral separation was effected by tetrabromoethane (S.G. 2.8) with subsequent examination of the heavy mineral suites. The heavy minerals were counted by microscopic traverses of the mounted sections, and the frequency of the grains was noted.

(d) X-ray diffraction analyses

Samples of the sand, silt and clay sized material were separated by sedimentation and mounted for scanning

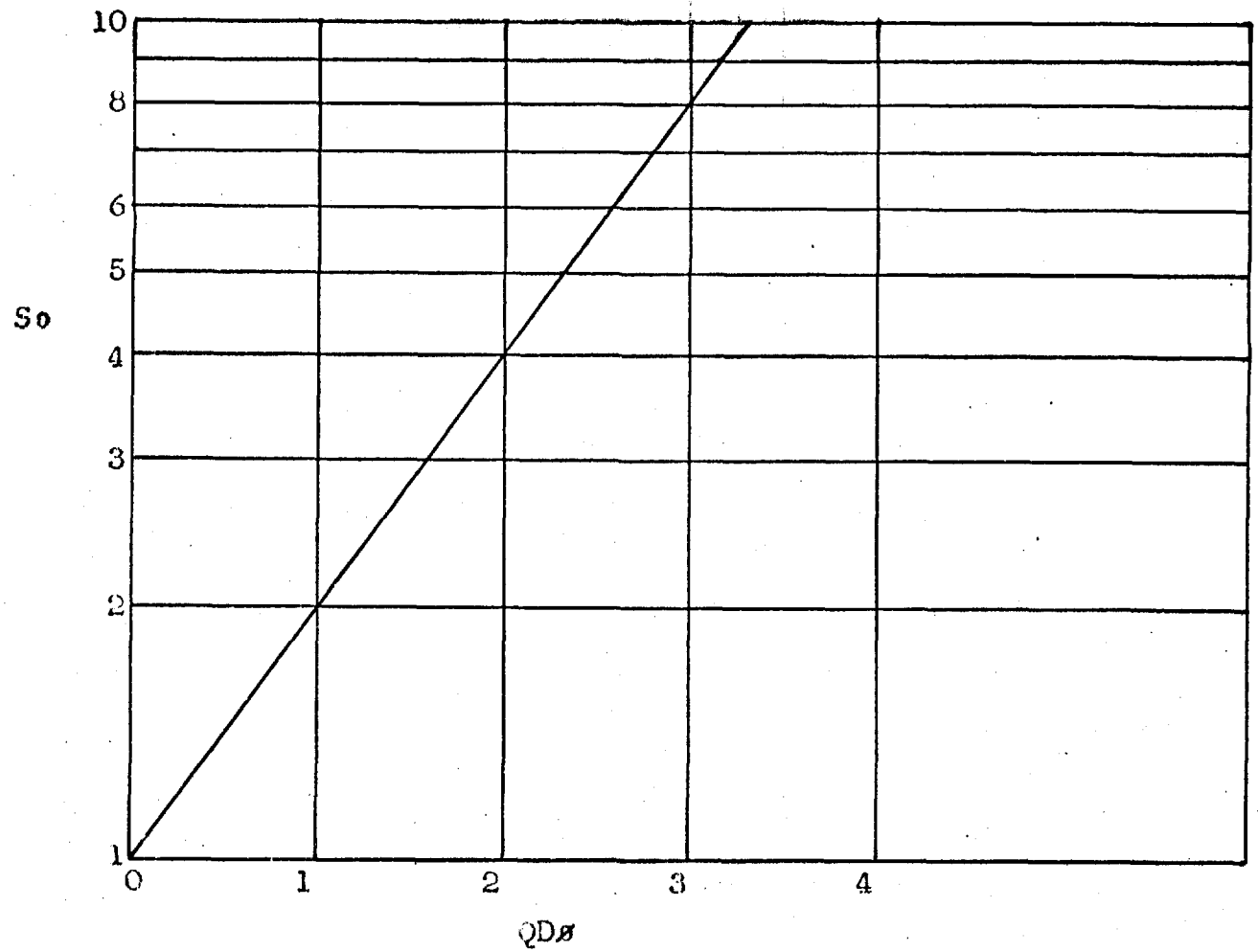


Fig.9 Quartile deviation-sorting coefficient conversion chart.

with a Phillips X-ray diffractometer. Additional heating and glycerol techniques were applied to differentiate the clay minerals.

(2) Results of Analyses

(a) Kalahari Sand

(i) Granulometry

Samples selected from widely scattered areas of Kalahari Sand are moderately representative (Fig.10 and Table 7). Samples indicate:

Near surface (9 in. depth) from west of Mufumbwe(samples 1-3)

phi median diameter (Md_ϕ) 1.68 to 1.99 (0.313-0.253mm)

phi quartile deviation (QD_ϕ) 0.70 to 0.95

sorting coefficient (So) 1.62 to 1.96

phi quartile skewness (SKq_ϕ) 0.12 to 0.19

Sand at depth, west of Mufumbwe (samples 4-5):

MD_ϕ	2.30 (0.203mm)
QD_ϕ	0.88 to 0.97
So	1.84 to 1.96
SKq_ϕ	0.08 to 0.12

Near surface Sand, Jijombo area (samples 6-8):

MD_ϕ	1.95 to 2.28 (0.257 to 0.205mm)
QD_ϕ	0.71 to 1.25
So	1.63 to 2.36
SKq_ϕ	0.21 to 0.50

Near surface Sand, Lower Kamwedgi (samples 9-14):

MD_ϕ	2.15 to 2.36 (0.225 to 0.196mm)
QD_ϕ	0.65 to 0.71
So	1.57 to 1.64
SKq_ϕ	-0.01 to 0.06

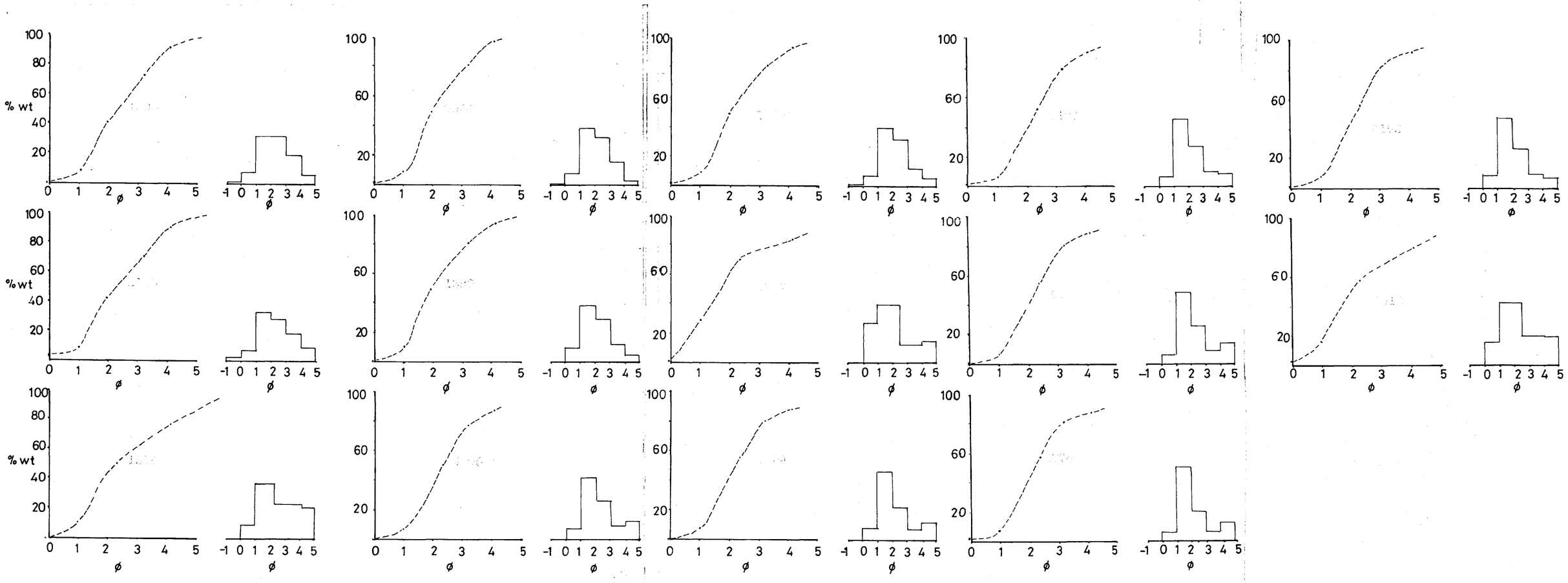


FIG. 10 GRAIN SIZE CUMULATIVE CURVES FOR KALAHARI SAND.

Table 7. Granulometric Statistics of Kalahari Sand

SAMPIE	LOCATION	COLOUR	% wt. +20#	-20 +38#	-38 +60#	-38 +80#	-60 or -80 +125#	-80 or -125 +200#	silt	clay	MDø	Q1ø	Q3ø	QDø	So	SKqø
	MUFUMBWE															
1. (0707)	(228/W7/57/9in.)	orange brown	0.4	28.4	-	41.5	-	13.5	2.6	13.1	1.68	0.85	2.74	0.95	1.93	0.12
2. (1389)	(228/26/15/9in.)	buff orange	0.1	10.3	39.1	-	30.8	13.7	5.7		1.97	1.35	2.94	0.80	1.74	0.18
3. (1869)	(Namsimba Rd/10/2-3ft)	buff	1.8	7.0	40.1	-	32.4	12.8	5.9		1.99	1.48	2.88	0.70	1.62	0.19
4. (1805)	(Chizera Rd/16-20ft.)	orange brown	0.9	7.7	32.5	-	31.9	19.2	8.0		2.30	1.50	3.25	0.88	1.84	0.08
5. (2125)	(228/26/6/11"-3')	orange brown	1.6	7.2	33.5	-	28.4	19.5	9.7		2.30	1.45	3.38	0.97	1.96	0.12
	JIJOMBO															
6. (2064)	(A/9in.)	buff	0.9	8.5	39.9	-	32.6	16.0	3.8		1.95	1.45	2.86	0.71	1.63	0.21
7. (2012)	(A/4/9in.)	buff	0.4	15.7	-	42.4	-	21.0	6.9	13.5	1.95	1.20	3.70	1.25	2.36	0.50
8. (1304)	(1/5ml NE/9in.)	buff	0.4	11.6	-	39.6	-	25.7	5.5	17.4	2.28	1.41	2.92	1.25	2.36	0.39
	LOWER KAMWEDGI															
9. (4804)	(RN/-5/9in.)	orange brown	0.15	8.6	-	47.5	23.8	8.5	6.1	5.3	2.15	1.50	2.91	0.71	1.63	0.06
10. (4806)	(RN/-6/9in.)	orange brown	0.05	7.4	-	43.8	26.5	9.9	5.8	6.5	2.36	1.68	3.05	0.69	1.62	0.02
11. (4194)	(RN/4/9in.)	orange brown	0.05	6.7	-	45.2	27.9	10.7	4.4	4.9	2.28	1.60	3.01	0.71	1.63	0.03
12. (4193)	(RN/5/9in.)	orange brown	0.2	8.2	-	47.7	26.8	9.4	2.9	4.7	2.18	1.52	2.82	0.65	1.57	0.01
13. (4778)	(KN/-5/9in.)	orange brown	0.1	6.5	-	51.8	21.7	6.8	5.1	8.0	2.19	1.58	2.89	0.66	1.58	0.05
14. (4780)	(KN/-4/9in.)	orange brown	0.1	6.3	-	48.3	25.2	8.8	5.8	5.4	2.25	1.56	2.99	0.72	1.64	0.03

The results show that Sand at 9 in. depth west of Mufumbwe, has the coarsest median size (medium sand), moderate deviation, moderate to good sorting, and a slight skew towards the fine material.

The Sand at depth from the same area is slightly finer (fine sand), has more deviation and a moderate sorting, with a very slight skew to the fine grades.

The Sand from Jijombo is similar in grain size to the former group (fine sand), with less sorting and a higher skew to the fine grades.

The Sand from Lower Kamwedgi displays consistent parameters. The grain size range is narrow (fine sand) sorting is good and the skewness is minimal.

In all samples, less than 2% of the Sand is greater than 20# (1.040 mm), and the largest individual grain measured was 3.5 x 1 mm. The dominant grain size is the 1-2ϕ (0.25-0.5 mm) class.

In these Sand samples, clay is more abundant than silt, but the percentages of both vary considerably. Generally the combined value is below 20% of the total sample.

(ii) Morphology

(1) Colour

The individual Sand quartz grains are clear or milky in colour but are generally coated with a red clay, Fe-rich pellicle. The intensity of colouration of the pellicle results in the variation of colouration of the Kalahari Sand in the different areas, and in depth.

(2) Rounding and sphericity (Plate 6).

The +20# (>1.040 mm) fraction of samples comprises rounded quartz grains of irregular to subspherical shape; the roundness corresponds to the "rounded" classification of sedimentary particles (Powers,1953). The grains of the -20+38# fraction (1.040-0.494 mm) are all rounded and sphericity is generally oval to spherical. The -38+80# material contains over 80% well-rounded, millet-seed type quartz grains which classify as "low to highly rounded" (Powers, ibid.); the remainder of this fraction is poorly rounded while sphericity is similar to the previous fraction. The -80+125# material has only 60-70% rounded grains while the remainder are subangular; sphericity is less well developed. In the -125+200# fraction both rounding and sphericity of the quartz are poor and angular grains are common. Grains are markedly angular in the -200# fraction.

(3) Frosting.

Minute pitting and curved scarring of the grain surface, commonly referred to as frosting, is found on all grains greater than 0.494 mm diameter. This frosting also appears in fracture clefts in the grains. Between the 0.494 mm and 0.107 mm grain sizes, the frosting is progressively less developed and many grains are highly polished. Few grains in the 0.107-0.054 mm class are frosted, while all grains less than 0.054 mm diameter have polished surfaces.

Thin section microscopy indicates that the frosted grains show no evidence of surface growth, while marginal fracturing is a common feature.

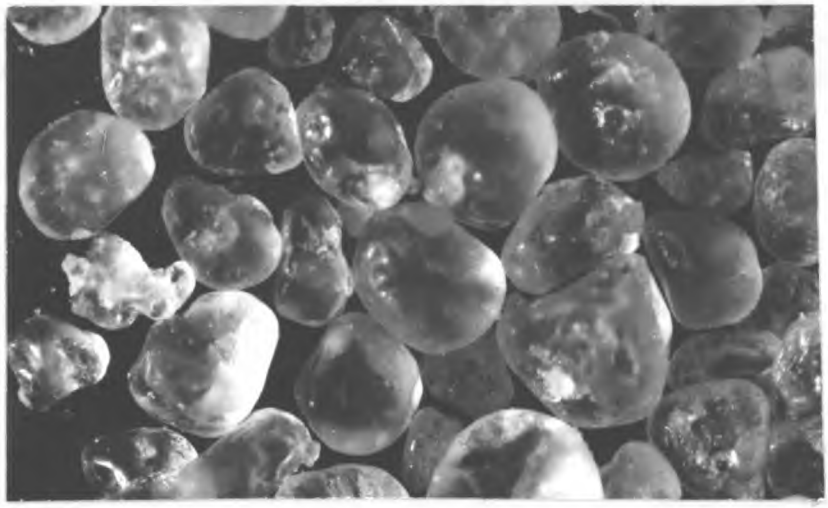


Plate 6. Kalahari Sand grains, Middle Kamwedgi, line 4, pit 17, 1-5 ft. depth. (c. x90)

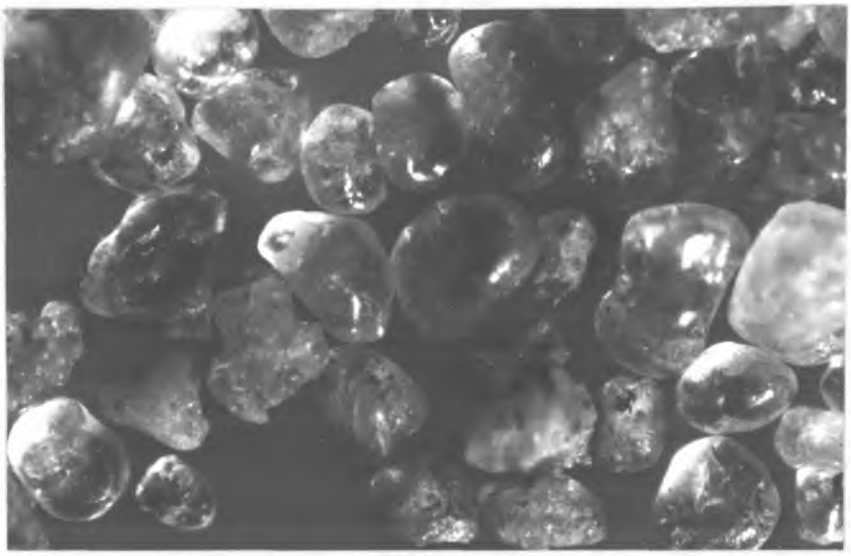


Plate 7. Contact Kalahari Sand grains, Mufumbwe, Block 228, line 8, pit 0, 1-2 ft. depth. (c. x60)

(iii) Light fraction composition

The light fraction (S.G < 2.8) of all fractions is predominantly quartz of clear and opaque varieties. In -125# material, opaque kaolinite aggregates are prominent. Mineral intergrowth aggregates are rare but occasional quartz-specularite, or quartz-felspar aggregates are noted.

(iv) Heavy Mineral Analyses

Brief descriptions of the heavy minerals identified follows:

Apatite: euhedral, hexagonal, colourless to green.

Augite: irregular, anhedral, non-pleochroic, green.

Epidote: irregular, subrounded, pale lime green to brown.

Garnet: irregular, pale to clear yellow, isotropic (grossularite).

Hornblende: anhedral, rounded to spherical, green to brown, pleochroic; occasional subhedral laths.

Kyanite: irregular, rounded or prismatic laths with stepped cleavage, clear to blue-tinted; abundant inclusions; occasional euhedral prisms.

Monazite: irregular to squat rounded, yellow with brown discolouration, weakly pleochroic.

Riebeckite: subrounded, oval to spherical, deep blue, pleochroic.

Rutile: irregular to elongate, well rounded, yellow to red; occasionally euhedral, prismatic with geniculate twinning.

Staurolite: oval, well rounded, pale yellow-pink-brown, pleochroic; occasional euhedral laths.

Tourmaline: anhedral, rounded, blue green to pink pleochroic; frequent inclusions; occasional euhedral laths.

Zircon: oval, well rounded, clear; also prismatic pyramidal grains with inclusions; rarely purple.

Opaque minerals: mainly red-brown hematite, brown-black ilmenite and blue-black magnetite. These minerals are not easily differentiated and consequently are grouped together.

The heavy mineral fractions examined from the five samples (Table 8) were in the following size ranges:

(1) - 60 + 125#
(2) -125 + 200#
(3) -200#

The -125 +200# is the optimum size for examination. In the coarser fraction, the grains are generally opaque and difficult to identify, and heavy minerals are less abundant.

The frequency of the heavy minerals occurring in the samples is presented in Table 8; the number of both anhedral and euhedral grains are given. The frequency of minerals, as a percentage of the total minerals counted per sample, is plotted in Fig 11.

The heavy mineral fraction forms less than 1%, and often less than 0.5% weight of the sample in each grain size. Opaque minerals are predominant, and are mainly hematite and ilmenite with accessory magnetite. The dominant non-opaque heavy minerals are kyanite, rutile and zircon; hornblende, staurolite and tourmaline are intermediate in frequency

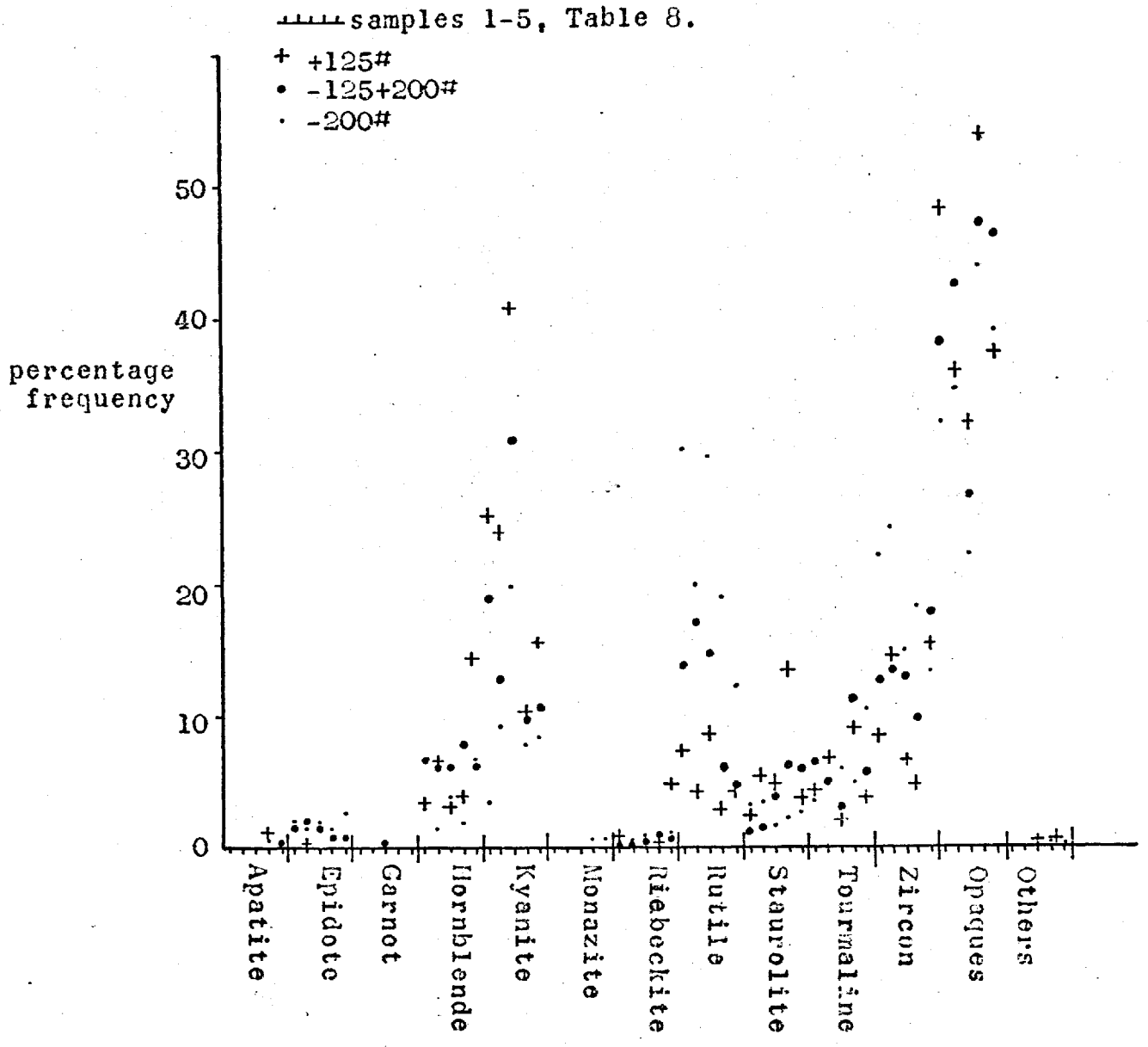


Fig.11 Heavy Mineral percentage frequency of Kalahari Sand.

Table 8. Frequency counts of heavy minerals in fractions of Kalahari Sand

SAMPLE NO.	SIZE FRACTION	Apatite	Augite	Epidote	Garnet	Hornblende	Kyanite	Monazite	Riebeckite	Rutile	Staurolite	Tourmaline	Zircon	Opaques	Others
2125	A(-200#)	0	0	11-0	0	17-0	20-0	0	2-0	166-10	18-1	20-1	111-19	190	0
	B(-125 +200#)	0	0	8-0	0	35-0	90-9	0	1-0	67-5	7-0	33-1	61-5	205	0
	C(-60 +125#)	0	0	0	0	10-0	78-4	0	2-0	23-1	9-0	13-1	27-1	159	0
1805	A	0	0	7-0	0	6-0	36-3	0	2-0	88-1	15-0	10-0	91-17	166	0
	B	0	0	8-0	0	25-1	48-6	0	0	71-1	5-1	21-0	55-2	180	0
	C	0	0	1-0	0	14-0	57-2	0	1-0	10-0	12-0	15-0	32-0	81	0
1869	A	0	0	9-2	0	23-0	78-41	0	4-1	169-13	10-0	31-4	79-9	135	0
	B	0	0	9-0	1-0	34-0	132-44	0	1-0	81-3	22-0	16-1	70-3	156	0
	C	0	0	0	0	14-0	161-30	0	0	42-0	22-1	19-0	28-1	150	1
2064	A	0	0	9-0	0	12-0	47-3	4-1	0	121-0	15-0	27-4	117-0	283	1
	B	0	0	2-0	0	26-0	32-0	0	3-0	20-0	21-0	34-3	32-0	155	1
	C	2-0	0	0	0	7-0	17-1	0	1-0	5-0	24-0	17-0	9-0	96	1
1389	A	0	1-0	12-0	0	19-19	26-23	3-0	4-0	68-4	15-0	44-16	70-8	225	1
	B	1-0	0	7-0	0	46-1	55-24	0	6-0	34-2	42-2	40-8	123-7	342	0
	C	0	0	0	0	16-0	17-0	0	5-0	5-0	4-0	4-2	16-1	42	0
Mean % frequency in samples(fraction B)		-	-	1.3	-	6.6	16.5	-	0.4	11.2	3.8	6.5	13.2	40.2	-
% frequency range in samples(fraction B)		-	-	0.6-4.9	0.2	6.0-7.9	9.7-30.9	-	0.2-0.9	4.5-14.7	1.3-5.9	3.0-11.2	9.7-17.6	26.7-47.2	

first figure - irregular grains second figure - euhedral grains

while epidote and riebeckite, though widespread, are uncommon. Augite, apatite, garnet, monazite and anatase are rare accessories. The grains are predominantly rounded, although kyanite, rutile and zircon often occur as euhedral laths.

There is a difference in the distribution of the minerals per grain size. Epidote, rutile and zircon are most abundant in the finest fraction; kyanite, staurolite and the opaque minerals are more common in the coarser grades, while tourmaline is evenly distributed between each size fraction.

In the samples examined, the heavy minerals are similar in type and abundance. In the -125 +200# size fraction, the following heavy mineral frequency ranges occur:

Epidote	0.6-1.9%
Hornblende	6.0-7.9%
Kyanite	9.7-30.7%
Riebeckite	0-0.9%
Rutile	4.5-14.7%
Staurolite	1.3-6.3%
Tourmaline	3.0-11.2%
Zircon	9.7-17.6%
Opaques	26.7-47.2%

(v) X-ray diffraction analyses

The silt fractions of 15 samples of Sand from Mufumbwe, Jijombo, Upper and Lower Kamwedgi have been analysed by x-ray diffraction to determine their mineral content. Quartz and kaolinite are abundant, with accessory illite, and a little chlorite. Crystalline iron is in the form of goethite and hematite. Trace feldspar appears.

Sand occurring near the Kalahari Sand-residual soil contact contains an increase of illite.

Analyses of different grain size fractions of the same sample, indicate that the coarser fractions are almost monomineralic quartz. With decrease towards the 0.05 mm size class, illite, goethite and hematite slightly increase. The silt fraction comprises abundant quartz, little kaolinite and chlorite, while the clay fraction contains abundant kaolinite with amorphous Fe, sparse illite and little quartz.

(b) Residual Soil

(i) Granulometry

Four of the samples selected(Fig.12 and Table 9) are C horizon soils, containing decomposed bedrock detritus (samples 1-4) collected at depths of 1-20 ft. below surface from Mufumbwe, and west of Mufumbwe. The remainder are A horizon soils at 9 in. depth collected from west of Mufumbwe and Lower Kamwedgi (samples 5-11).

A horizon soil (9 in. depth) from Mufumbwe (sample 5):

MD_ϕ	3.65 (0.08 mm)
QD_ϕ	>1.50
So	>2.8
SKq_ϕ	>-0.15

C horizon soil from Mufumbwe (samples 1-4):

MD_ϕ	<0 to 2.25(>1.00-0.21 mm)
QD_ϕ	1.53 to >1.79
So	>2.8 to >3.43
SKq_ϕ	-0.28 to <0.49

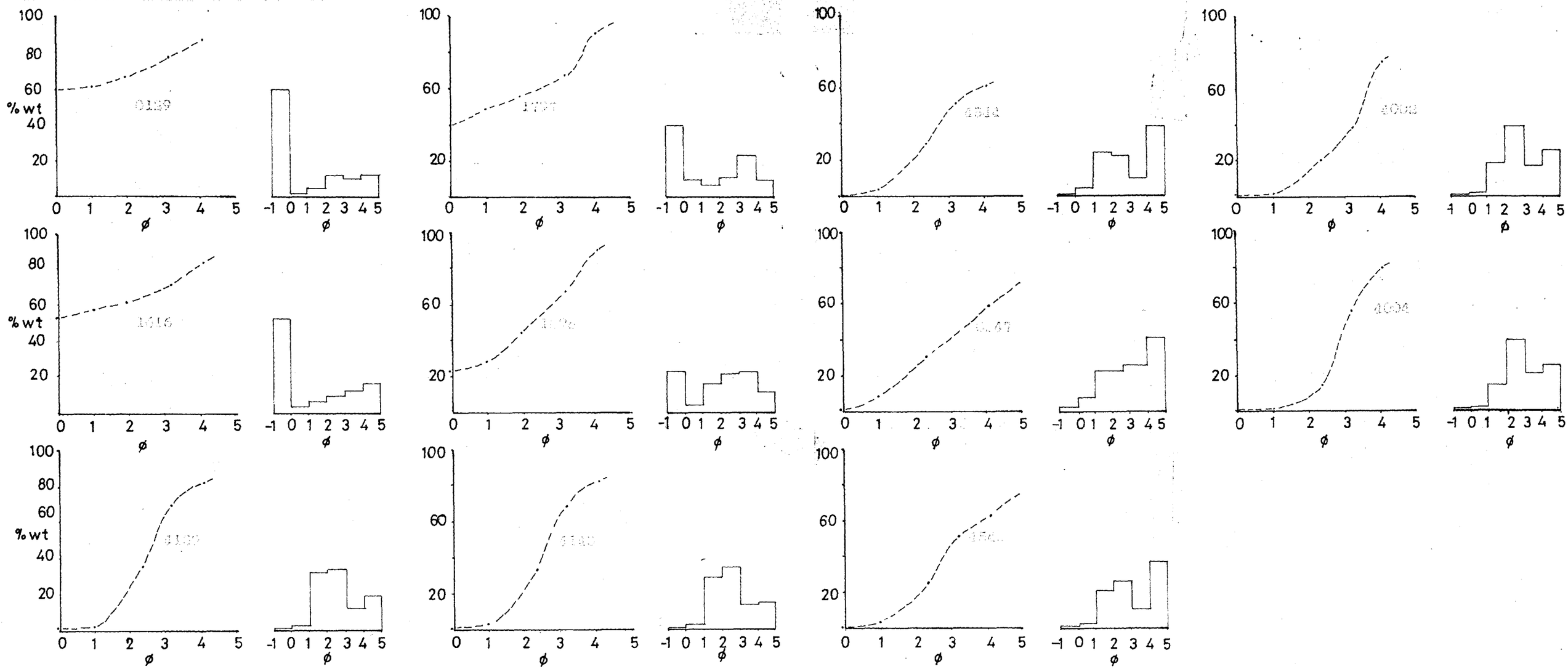


FIG.12 GRAIN SIZE CUMULATIVE CURVES FOR RESIDUAL SOIL.

Table 9. Granulometric Statistics of Residual Soil.

SAMPLE	LOCATION	COLOUR	% wt. +20#	-20 +38#	-38 +60#	-38 +80#	-38 or +80 -125#	-80 or +125 +200#	silt	clay	Mdø	Q_1ø	Q_3ø	QDø	So	Skqø
	MUFUMBWE															
1.(0129)	East trench/1-2ft.	brown	59.8	1.8	4.5	-	11.5	10.0	12.4		<0	<0	2.95	>1.50	>2.80	-
2.(1616)	(229/11/19/4-14ft.	red	53.7	3.8	4.2	-	9.1	12.4	16.8		<0	<0	3.48	>1.74	>3.32	-
3.(1797)	(229/34/19/12-16ft.	maroon	39.3	9.3	6.6	-	11.8	23.2	9.7		1.3	<0	3.58	>1.79	>3.43	<0.49
4.(1898)	(250/20/27/16-20ft.	red brown	23.5	5.2	16.1	-	22.0	23.3	11.4		2.25	0.44	3.50	1.53	2.89	-0.28
5.(0247)	(229/34/23/9in.)	red brown	1.4	7.9	-	22.4	-	26.8	41.8		3.65	2.00	>5.00	>1.50	>2.80	>-0.15
	LOWER KAMWEDGI															
6.(4139)	(KN/3/9in.)	red brown	0.2	2.7	-	32.8	33.1	12.3	11.2	7.6	2.63	2.06	3.44	0.69	1.61	0.12
7.(4140)	(KN/4/9in.)	orange brown	0.2	3.3	-	29.6	35.0	14.2	11.6	6.0	2.78	2.11	3.47	0.68	1.59	0.01
8.(4542)	(C/-4/9in.)	brown	0.5	3.2	-	21.3	26.2	11.3	21.7	15.8	3.18	2.35	5.00	1.33	2.48	0.50
9.(4544)	(C/-5/9in.)	orange brown	0.1	4.1	-	24.5	22.9	9.5	15.8	23.0	3.12	2.20	>5.00	>1.40	>2.62	>0.48
10.(4002)	(C/2/9in.)	red brown	0.3	1.4	-	18.3	38.2	16.8	16.1	8.9	3.51	2.66	4.10	0.72	1.64	-0.13
11.(4004)	(C/4/9in.)	yellow brown	0.4	1.0	-	14.0	39.9	19.4	16.4	9.0	3.08	2.64	3.85	0.61	1.52	-0.33

A horizon soil (9 in. depth) from the Lower Kamwedgi (samples 6-11):

MD_ϕ	2.63 to 3.51 (0.163-0.089 mm)
QD_ϕ	0.61 to >1.40
So	1.59 to >2.62
SKq_ϕ	-0.33 to 0.50

The A horizon residual soil at 9 in. depth from Mufumbwe exhibits a very fine sand median size, a large deviation and very poor sorting. The C horizon material from the same area has a variable coarse to fine sand median size, a large deviation, very poor sorting and a probable coarse skew.

The residual soil at 9 in. depth at Lower Kamwedgi has a fine to very fine median sand size, little deviation and moderate to very poor sorting. The skew is variable towards both fine and coarse material.

The +20# fraction of the A horizon soil examined, forms less than 2% of the total sample. In C horizon soil, this fraction may be at least 60% of the total sample. In A horizon soil, the silt content is greater than clay and the combined silt and clay content forms 18-41% of the total sample.

(ii) Morphology

(1) Colour

The colour of the individual grains or fragments in residual soil is more varied than in Kalahari Sand. Rock fragments reflect the colour of the bedrock, while the quartz is frequently coloured due to inclusions. The colour of the residual soil is a result of the Fe oxide content, and variations in amount and oxidation of the Fe affect the soil colour.

(2) Rounding and sphericity (Plates 7 and 8)

The quartz grains are predominantly angular, while rounded, subspherical millet-seed, quartz grains occur sporadically in all coarser size fractions. These latter grains are more abundant in samples of contact residual soil. Below the 125# fraction, all quartz grains are angular.

Similar millet seed quartz grains are located in underlying decomposed bedrock, but not in fresh bedrock.

(3) Frosting

Frosting is restricted to the millet seed grains of rounded, subspherical quartz. The frosting of these grains decreases in the -125# fractions and is not apparent in grains of -200# fraction.

(iii) Light fraction composition

The light fraction is variable in composition. The coarser material may contain abundant fragments of the bedrock together with coarse angular quartz and laterite material (Plate 8). The finer size fractions have a preponderance of quartz with occasional rock fragments and lateritic fragments, and sparse but widespread mica. The finest fractions comprise entirely quartz, with occasional mica flakes.

(iv) Heavy Mineral Analyses

The heavy minerals, although derived from soils developed on bedrock varying from shale to quartzite, belong to a similar heavy mineral suite. (Table 10, Fig.13). Opaque minerals are common. The dominant non-opaque minerals are kyanite, zircon and rutile, with additional hornblende, staurolite, tourmaline and rare apatite, riebeckite,

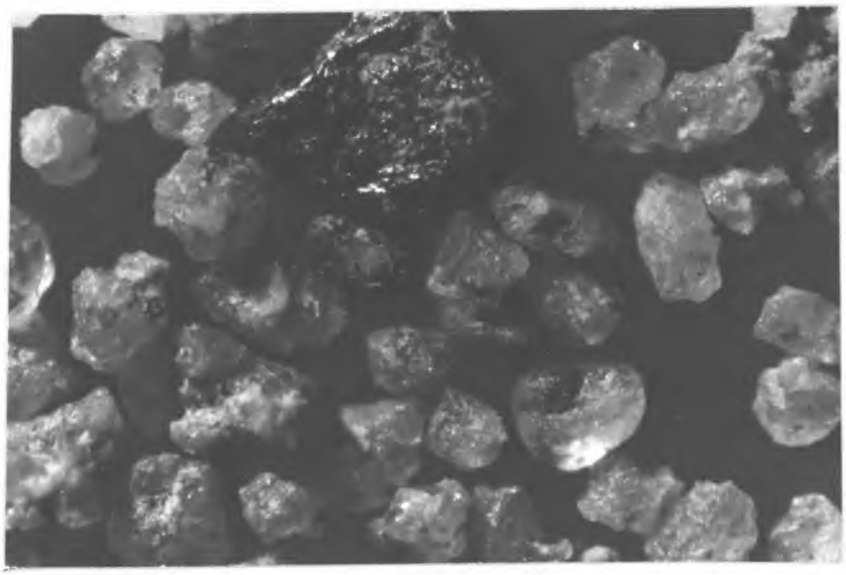


Plate 8. Residual soil grains, Lower Kamwedgi, line C, peg 1, 9in. depth (c. x60).

andalusite and acmite. There is a variation in the frequency range of the heavy minerals between the individual samples, but the overall percentage distribution is similar(Fig.13). Zircon, epidote and rutile tend to be more common in the fine grades, while kyanite is more abundant in coarser fractions.

Most of the heavy minerals are rounded to some extent and only zircon is commonly euhedral.

(v) X-ray diffraction analyses

Analyses of the silt fraction of a variety of soils reveals that quartz is dominant, with accessory kaolinite and illite. Goethite, hematite and feldspar are present together with trace chlorite. Boehmite and gibbsite were not observed.

Samples from near the Kalahari Sand contact show a reduced illite content and an increase in kaolinite.

Different grain size fractions of the same sample comprise predominantly quartz in the coarser grades, while kaolinite, illite and chlorite increase in content with decrease of grain size. The clay fraction is mainly kaolinite with accessory illite, hematite, goethite, chlorite and amorphous silica; the quartz content is low.

(c) Dambo alluvium.

Only four samples have been analysed and cannot be regarded as representative of the wide range of sediment obtainable. The following properties indicate some of the variation which occurs:

Table 10. Frequency counts of heavy minerals in fractions of residual soil

Size Fraction	Sample No.	Apatite	Augite	Epidote	Garnet	Hornblende	Kyanite	Monazite	Riebeckite	Rutile	Staurolite	Tourmaline	Zircon	Opaques	Others
A(-200#)		0	0	15-2	0	5-1	10-0	0	0	51-3	0	18-1	46-21	43-0	0
B(-125+200#)	0129	0	0	2-0	0	18-0	18-0	0	0	5-0	2-0	14-1	16-2	28-0	1
C(-60+125#)		0	0	0	0	1-0	0	0	0	0	0	0	0	0	0
A		0	0	7-0	0	19-0	172-15	0	1-0	64-0	15-0	22-2	59-5	60-0	1
B	1898	0	0	4-0	0	12-0	122-5	0	1-0	113-0	12-0	4-0	92-12	180-0	0
C		0	0	6-0	0	11-0	109-2	0	0	40-0	9-0	11-0	17-0	84-0	0
A		0	0	7-0	0	5-2	14-2	0	0	42-9	2-0	4-5	51-20	82-0	1
B	1797	0	0	2-0	0	8-0	28-1	0	0	11-0	2-0	9-0	29-2	51-0	0
C		0	0	0	0	0	10-0	0	0	0	0	1-1	1-0	7-0	0
A		1-0	0	5-0	0	0	5-0	0	0	25-2	0	1-1	84-37	7-0	1
B	1616	0	0	0	0	28-0	16-3	0	1-0	23-4	7-0	37-3	14-3	33-0	0
C		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mean % frequency in samples(fraction B)		-	-	2.7	-	10.2	17.3	-	0.4	12.0	2.4	11.1	16.6	28.1	-
% frequency range in samples(fraction B)		-	-	1.4-4.2		2.1-16.4	11.0-21.2	-	0.2-0.5	4.6-20.0	1.4-4.1	0.7-23.2	9.8-21.7	19.2-35.7	-

first figure - irregular grains
second figure - euhedral grains

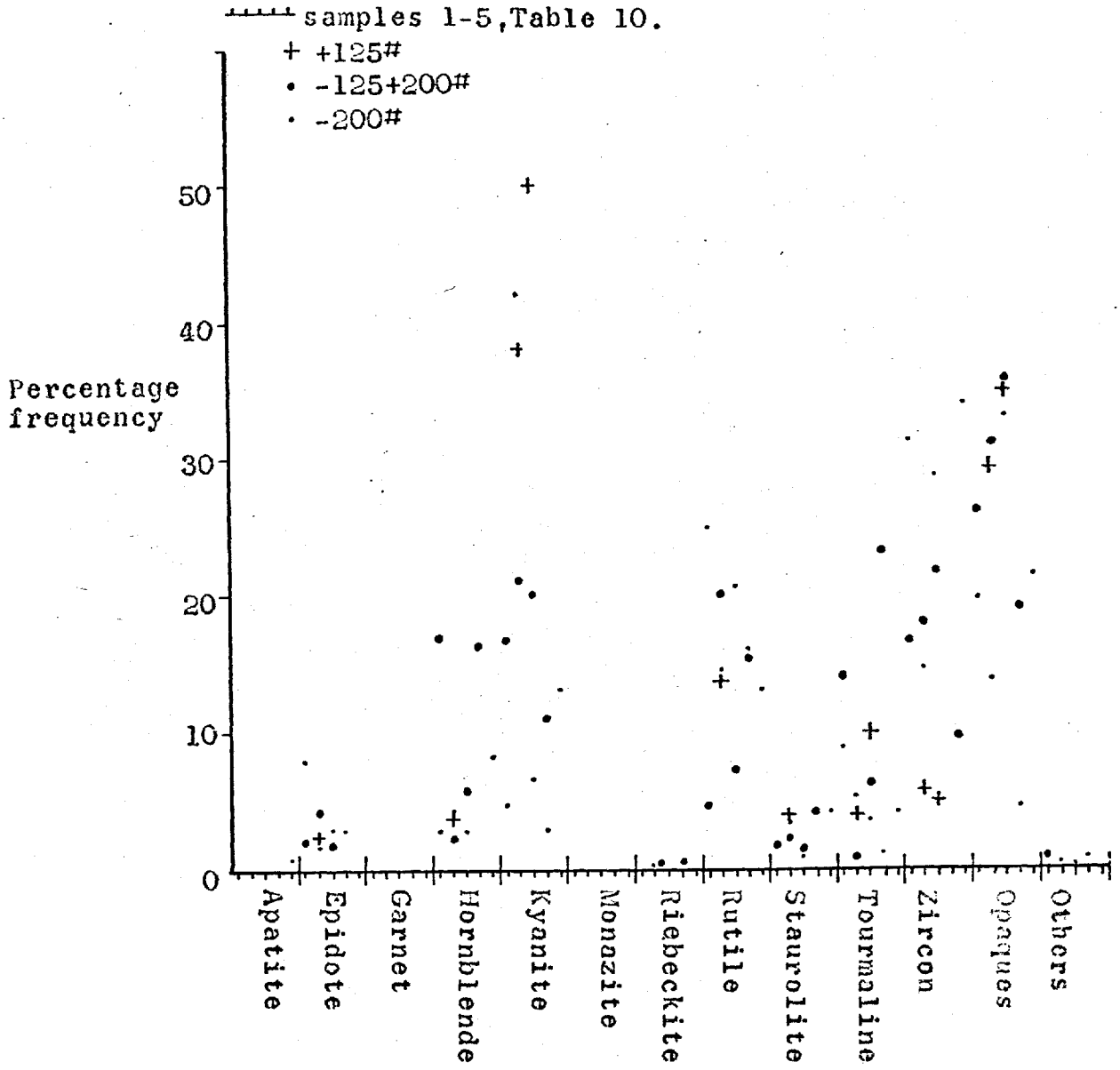


Fig.13 Heavy Mineral percentage frequency of residual soil.

(i) Granulometry (Fig.14, Table 11)

Clay-rich sediment (sample 2):

MD_ϕ	4.5(0.043 mm)
QD_ϕ	>1.4
So	>2.62
SKq_ϕ	>-0.9

Clay-sandy horizon (samples 1,3):

MD_ϕ	2.89 to 3.68(0.135-0.079 mm)
QD_ϕ	0.89 to >1.19
So	1.85 to >2.28
SKq_ϕ	-0.12 to >0.14

Pebbly zone (sample 4):

MD_ϕ	<0(>1.0 mm)
QD_ϕ	>1.18
So	>2.25

The clay-rich horizon has a silt median grain size with poor sorting and little skew. The clay-sand horizon has a fine to very fine sand median size, moderate to very poor sorting and a variable skew. The pebble zone has a very coarse sand median grain size, and poor sorting.

The amount of material greater than 2mm is extremely variable. Further, the combined silt and clay content can have a wide range and in the samples examined, it formed up to 57% of the total sample.

(ii) Morphology

(1) Colour

The individual quartz grains display a wide colour range.

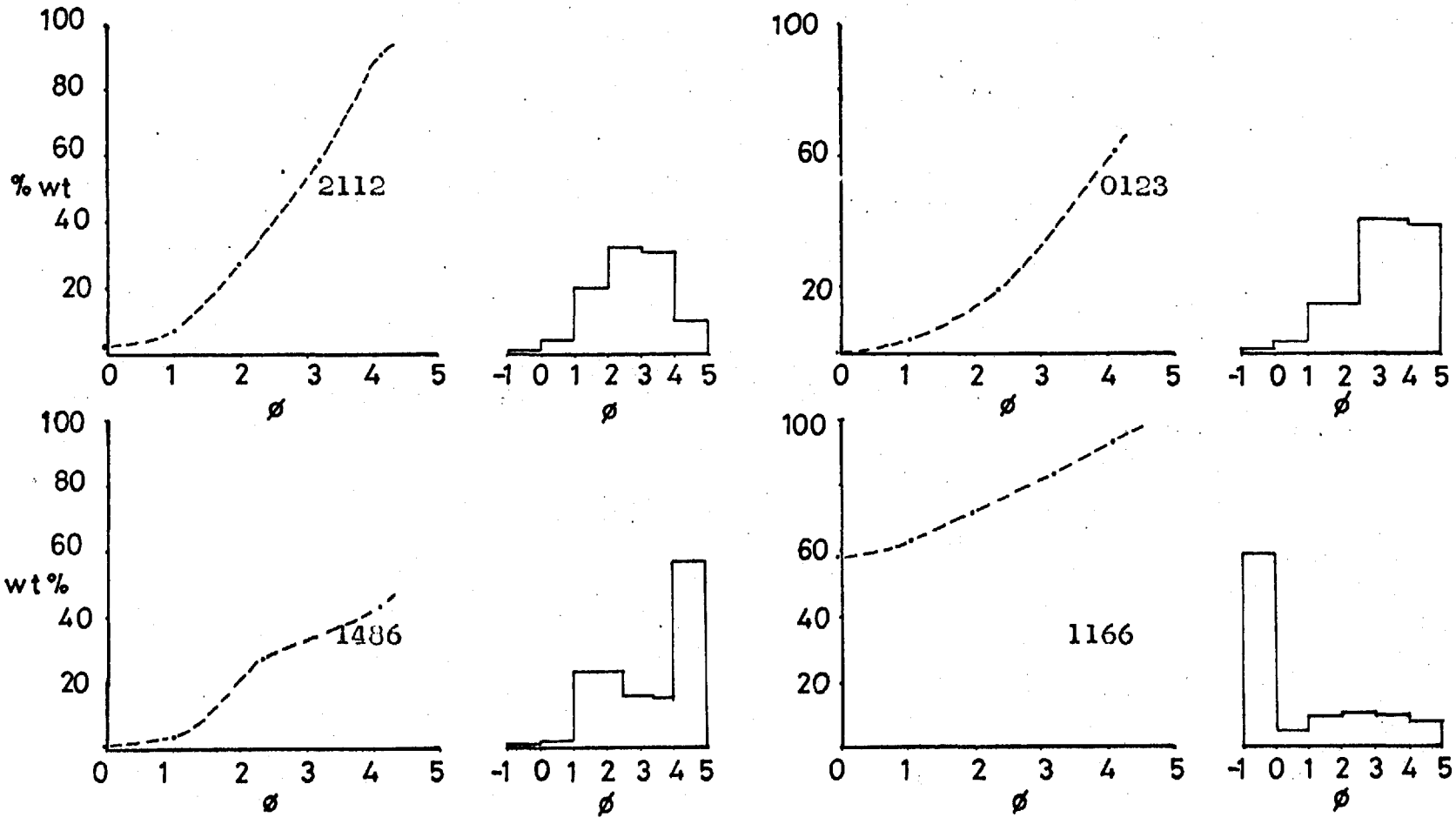


FIG. 14 GRAIN SIZE CUMULATIVE CURVES FOR DAMBO SEDIMENT.

Table 11. Granulometric Statistics of Dambo Sand

Sample	Location	Colour	% wt. +20#	-20 +38#	-38 +60#	-38 +80#	-60 or -80 +125#	-80 or -125 +200#	silt	clay	Mdϕ	$Q_1\phi$	$Q_3\phi$	$QD\phi$	So	$SK_g\phi$
	MUFUMBWE															
1. (0123)	(B/1/3/0-3ft.)	white	0.6	3.3	-	15.3	-	41.9	12.9	26.0	3.68	2.63	>5	>1.19	>2.28	>0.14
2. (1486)	(82/DH/1/5/5in.-2ft.)	yellow	1.1	2.6	-	23.9	-	15.5	19.0	38.0	4.5	2.20	>5	>1.4	>2.62	>-0.9
3. (2112)	(M4/2/1-2ft.)	grey	2.6	4.5	19.9	-	32.2	31.1	9.9		2.89	1.88	3.66	0.89	1.85	-0.12
	JIJOMBO															
4. (1166)	(F/9/6-7ft.)	grey	58.2	4.3	9.4	-	10.9	9.9	7.6		<0	<0	2.35	>1.18	>2.25	-

(2) Rounding and sphericity

In coarser fractions, quartz grains of both rounded and angular form occur. In the Jijombo and Middle Kamwedgi dambos, which drain areas of Kalahari Sand, millet seed rounded grains are common. Below 125#, all quartz grains are angular.

(3) Frosting

This characteristic is restricted to millet seed, rounded quartz grains belonging to the +125#. In the Mufumbwe dambo, the frosting on similar grains is greatly reduced.

(iii) Light fraction composition.

In addition to quartz grains, rock fragments are common. In areas of Kalahari Sand, dambo sediment may contain predominantly quartz grains. Mica occasionally occurs.

(iv) Heavy Mineral analyses

Only two samples have been analysed and the results are shown in Table 12. Opaque minerals are abundant. The non-opaque minerals are mainly zircon and rutile with accessory hornblende, kyanite, staurolite and tourmaline. The grains are dominantly rounded.

(v) X-ray diffraction analyses

Silt samples from dambos draining areas of residual soil and Kalahari Sand contain mainly quartz, with kaolinite, illite, and poorly developed chlorite, goethite and hematite. In the clay fraction kaolinite and illite predominate, while quartz is scarce. Montmorillonite was not identified in any of the samples.

Table 12. Frequency counts of heavy minerals in fractions of dambo sediment

Size Fraction	Sample No.	Apatite	Augite	Epidote	Garnet	Hornblende	Kyanite	Monazite	Riebeckite	Rutile	Staurolite	Tourmaline	Zircon	Opaques	Others
A(-200#)		4-1	0	0	0	11-2	12-0	2-0	2-0	58-4	6-3	31-10	46-8	34-13	1-0
B(-125+200#)	2112	2-0	0	1-0	0	19-6	30-0	3-0	3-0	16-1	6-0	30-15	14-3	21-28	2-0
C(-60+125#)		0	0	2-0	0	9-0	56-0	1-0	4-0	16-0	16-0	19-3	8-0	86-27	0
A		0	0	5-0	0	3-0	11-0	0	0	51-6	5-0	4-0	127-16	52-0	1-0
B	1166	0	0	2-0	0	16-0	42-0	0	0	18-0	38-0	12-0	88-2	160-0	1-0
C		0	0	0	0	17-0	33-0	0	0	8-0	17-0	9-0	19-0	150-0	1-0
Mean % frequency in samples(fraction B)		-	-	0.3	-	8.3	13.2	0.5	0.8	6.6	6.5	12.8	16.1	34.8	-
% frequency range in samples(fraction B)		-	-	-	-	4.2-12.4	11.1-14.9	-	-	4.8-8.4	3.0-10.0	3.2-22.3	8.4-23.8	24.3-45.3	-

first figure - irregular grains
second figure - euhedral grains

3. DISCUSSION

Differentiation of highly weathered quartz-rich residual soils from Kalahari Sand, when both are subjected to a sub-tropical climate, can be difficult in the field. Consequently the diagnostic properties of the Sand must be defined. In addition, the origin of the Sand has a critical bearing on any geochemical dispersion patterns developed and must be established.

Thus the following section discusses:

(i) recognition of diagnostic sediment type properties, and

(ii) suggested origin of the Kalahari Sand of the study area.

The grain size of the local Sand has an average median diameter of 0.228 mm with a narrow range of 0.196-0.313 mm. The median diameter of the residual material has a wide range from 0.08 to >1 mm, and is dependant on the degree of weathering. Dambo sediment also has a wide range of at least 0.043 to >1 mm.

The median diameter of the Sand compares with the values of 0.2-0.4 mm suggested for the Kalahari Sand of north-east Angola (Stanton, 1963) and in South Africa of 0.15-0.4 mm (du Toit, 1954) and 0.215 mm (2.2ϕ; Goudie, 1969). The values compare with aeolian sand in general, as a median diameter for the latter is quoted as 0.44 mm (Bagnold, 1965), 0.15-0.30 mm (Hills, 1966), 0.15-0.35 mm (Seppala, 1969), and 0.2 mm (Philip et al., 1968).

The combined clay and silt fraction of Kalahari Sand shows considerable variation. The local values are 3.8-22.9%, while in Zambia, in general a silt-clay content of 2-9% is quoted (Trapnell, 1947), at Sesheke 4.5-10%

(Savory, 1965), in Rhodesia 4-14% (Bond, 1968) and 1-12% (Flint and Bond, 1968), in South Africa 5-43% (Bossaza, 1957) while in the Congo the "sable ocre" contains 13-70% and the "grès polymorphes" have 8-43% (de Ploey, Lepersonne and Stoopes, 1968).

The residual soils of the study area contain a higher proportion of silt and clay than Kalahari Sand with between 9.7-41.8%, of which 6-23% is clay. This compares with 23-40% clay in the ferralic soils of the Copperbelt (Tooms, 1955), 20-30% clay in the Plateau soils of Tanganyika (Muir et al., 19-) and 45-68% clay in the latosoils of the Congo (Kellog et al., 1949).

The Sorting coefficient of the local Sand ranges from 1.57 to 1.96 with a single sample of 2.35. This indicates a moderate to good sorting. The coefficient for the residual soil varies from 0.52 to >3.43 and has thus a wider range and a generally poor sorting. Similarly the dambo sediments reveal a large range of sorting, depending on the nature of the sediment, and may vary between 1.85 to >2.62. Savory (1965) suggests a sorting coefficient of 1.7 for the Sands at Sesheke in Zambia while values for aeolian sand in general are 1.22 (Bagnold, 1965), 1.20-1.30 (Sindowski, 1961) and 1.24-1.55 (Seppala, 1969). The slightly poorer sorting of the Kalahari Sand of the study area compared with other aeolian sand may be in part due to deep, post-depositional, subtropical weathering with introduction of clays.

The skewness of the Sands is almost symmetrical (-0.01 to 0.39) with a slight tail towards the fine material. The skew range of the residuum is greater and varies from

coarse to fine, depending on the stage of weathering (-0.33 to 0.50). Dambo sediment has a wide skew range and values vary with the type of sediment from coarse in the pebble horizons, to fine in the clay-rich zones. The value of the skew of Kalahari Sand may be affected by post-depositional diagenises with introduction of clay, thus producing a bias towards the fine material.

Rounding and sphericity of the individual grains are a marked feature of the Sand. Rounding of all grains occurs from the coarsest down to the 0.1 mm size but below this the rounding decreases with decreasing size; below 0.05 mm diameter the grains are angular. Sphericity is poor in the coarse material but reaches maximum development at the 0.25-0.50 mm size class. Above this size the grains are increasingly irregular to elongate.

The rounding and sphericity in grains of residuum are only applicable to grains of clear or opaque quartz which, in coarser fractions, show frosting. These grains comprise a small proportion of residual material and show identical morphological variation relative to grain size as the Kalahari grains. The majority of quartz grains in residual soils are angular and elongate. It is suggested that the frosted millet seed grains in residuum are admixed Kalahari Sand grains, derived from a former pre-existing Sand cover. They have been mixed into all levels of the residuum, including locally decomposed bedrock, partly by burrowing fauna, such as termites and worms. In addition, the rounded, subspherical shape of the grains will aid downward movement through the soil profile. It is noted that the residual soil

nearest to the Kalahari Sand contact comprises a greater proportion of rounded and spherical grains. Dambo sediments in residual soil areas comprise mainly angular and unspherical quartz grains but in Sand areas contain a high proportion of rounded grains; this proportion is dependent on the type of terrain crossed by the dambo.

A similar decrease in rounding of grains with decreasing grain size is noted in the Kalahari Sands at Sesheke (Savory, 1965), in Rhodesia (Bond, 1948), Botswana (Poldervaart, 1955) and South Africa (Bosazza, 1957).

A higher degree of rounding is regarded as distinguishing windblown from river and glacial sands (King, 1951). Pettijohn (1957) notes that rounding is a feature of prolonged transport and multicycle sands. Kuenen (1959) has shown by experimentation that river action produces negligible chemical or mechanical rounding, while aeolian transport over a few hundred kilometres produces well rounded coarse sand and subrounded fine sand with a lower abrasion limit of 0.05 mm. Rounding and sphericity have been attributed to solution (Kuenen, 1959) but such a process would tend to round grains of all sizes and possibly to produce complex grains with solution cavities. Bond (1954), and Ingerson and Ramisch (1942) suggest that sphericity in quartz grains is inherited, dependent on the form of the quartz in the parent rock and that quartz sphericity is aided by fracturing parallel to rhombohedral faces.

Frosting of the quartz grains is evident in the local Sand on grains from the coarsest to the 0.05 mm size. Between 0.5 and 0.05 mm the grains are progressively less

frosted with decreasing grain size and below 0.05 mm the grains have a polished, unfrosted surface. Similar frosting in residual soils is only found on the rounded, spherical quartz grains of >0.05 mm size, while in the dambo sediments, frosting is restricted to similar millet seed quartz grains, and only in samples derived from the smaller dambos crossing Kalahari Sand. Millet seed grains in the major Mufumbwe dambo sediments are only slightly frosted. The frosted grains in residual soils and dambo sediments are regarded as originating from the Kalahari Sand.

Frosting is a widely noted feature of the Kalahari Sand of southern Africa, and decreasing frosting with decreased grain size has been noted (Savory, 1965; Poldervaart, 1955). Bond (1954) notes that aeolian grains are polished below 0.3-0.4 mm size while sand grains under a river regime polish below 0.4-0.7 mm size. Kuenen (1959) notes that aeolian sands are frosted while river sands are polished; he has found that in test conditions abrasion produces polishing. Bond (ibid) notes that frosted grains in a river regime become smooth and polished.

Frosting has been attributed to aeolian abrasion (Walker, 1957), to differential solution of sand grains by percolating waters (Pettijohn, 1957; Walker, 1957), incipient secondary quartz overgrowths (Roth, 1932; Walker, 1957; de Ploey et al., 1968) or to carbonate replacement of quartz along grain boundaries (Walker, 1957). As frosting does not occur below 0.15 mm, frosted and unfrosted grains in the same sample have been attributed to two different regimes (Keunen, 1959).

The frosted grains in the present area show no marginal growth in thin section, and reveal frosting in fracture and conchoidal surfaces. In addition they appear to be restricted to Kalahari Sand. It is suggested that the frosting is typical of the aeolian sand but is due to surface chemical action in the desert regime. Keunen (1959) also invokes the action of dew to explain frosting. Transport of the Sand grains in the larger dambos appears to remove the frosting.

The light fraction composition of the Sands of the study area is almost monomineralic and comprises clear quartz grains; opaque and colourless to rose coloured varieties of quartz also occur. Rare fragments of intergrown quartz-specularite, quartz-felspar, or lateritic fragments may be of local origin. The kaolinite content is probably post-depositional in formation. Mica is notably absent (cf Bond, 1948). The residual soils of the C horizon contain abundant rock fragments while the highly weathered A horizon soil has abundant angular quartz with only occasional detrital fragments; feldspar, mica, and laterite fragments are common to both soil horizons. Dambo material comprises mainly angular or rounded quartz. Rock fragments and pebbles are variable in frequency and content and depend on the type of bedrock traversed by the dambo, or to sediment sorting action of the water.

The heavy mineral fraction of the local Sand forms 0.5-1% weight of the finer fractions and comprises mainly kyanite, rutile, zircon and opaque minerals with accessory hornblende, staurolite and tourmaline. Garnet is virtually absent. There is a variation in frequency in some minerals

between size fractions, but the overall range of percentage frequency for a mineral is relatively constant in the samples studied. The heavy mineral suite of residual soil is analogous to that of the Sand. Variations occur in mineral frequency per size fraction, but the variation is similar to the Sand. The soils appear to have a greater proportion of hornblende and tourmaline while opaque minerals are more common in the Sand. The degree of anhedrality is similar in the soil and Sand. The heavy mineral suite of the dambo sediment shows no marked differences, as the sediment is mainly derived from the local soil and Sand.

At Sesheke, Savory (1965) notes that heavy minerals form 0.14-1.30% weight of the Sand and comprise mainly magnetite, zircon, rutile, sphene and kyanite; he suggests a local Upper Karroo Sandstone derivation for the Sand. In Rhodesia, heavy minerals form <0.5% weight of the Sand (Bond, 1948); zircon, tourmaline, rutile, staurolite, kyanite are dominant with additional epidote, brookite, apatite and sphene. Garnet is absent. Bond suggests that kyanite and staurolite indicate a short 200 mile transport, and defines a local pre-Karroo schist derivation. In Botswana, Poldervaart (1955) notes a non-opaque residue of mainly zircon, tourmaline, staurolite, kyanite and rutile. The heavy minerals form 0.1-0.3% weight of the sample. In the Congo, the dominant heavy minerals of the "sable ocre" and the "grès polymorphes" are opaque minerals, zircon, tourmaline, rutile, staurolite and kyanite (de Ploey et al., 1968).

The heavy mineral suite of the Kalahari Sand of the study area is thus similar to that of Rhodesia, Botswana

and possibly the Congo. The minerals are indicative of a metamorphic provenance supplying abundant kyanite and staurolite but lacking garnets. The marked rounding of the heavy mineral grains may not be the result of aeolian transport as the heavy minerals of the residual material are also markedly rounded. The effect may be due to post-depositional solution. The similarity of the heavy mineral suite of the Kalahari Sand, with that of residual soil suggests a similar origin. The Sand may be derived from a bedrock facies similar to the Kundulungu rocks of the area. Alternatively the Sand could be derived from a younger formation such as Karroo Sandstone, in turn derived from underlying Kundulungu rocks. However as a Kundulungu-type lithology appears to cover much of western Zambia at least, the source of the Sand need not be local.

Clay fractions are similar in content in both the Kalahari Sand and residual soils, and comprise dominantly kaolinite and illite, with goethite and hematite. In residual soil the clay minerals are the result of extreme weathering in situ in a subtropical climate with acidic soil conditions. The occurrence of similar clay minerals in the Kalahari Sand of dominantly quartz composition, is probably the result of post-depositional diagenesis with introduction of the clay minerals derived from deep weathering action on underlying soil or rock formations. In the Congo, the "sable ocre" is reported to contain kaolinite, goethite, hematite and trace spasmodic gibbsite and halloysite, while the underlying "grès polymorphes" has kaolinite, goethite and

hematite. There, the clays, together with the Fe pellicles of the quartz grains, are suggested as post-depositional features (de Ploey, Lepersonne and Stoopes, 1968).

The age of the Kalahari Sand is difficult to determine. No fossils nor human artefacts were located in the Kalahari Sand. Laterite horizons in the Sand appear to be related to the present subtropical climatic drainage conditions, and locally are currently forming. In addition no definite erosion surface underlying the Sand was identifiable. Consequently no estimation of the age of the deposits is proposed.

In conclusion, the Kalahari Sand of the area is similar to the Kalahari Sand described elsewhere in southern Africa. It can be differentiated from local residuum and fluviatile sediment, and regarded as aeolian in origin on the following features:

	Kalahari Sand	Residual Soil	Dambo Sediment
1. Median grain size	Consistent(0.228mm)	Variable (0.08->1.0mm)	Variable (0.04->1mm)
2. Sorting	Moderate to good (1.5-2.0)	Poor (0.5 ->3.4)	Poor (1.8 ->2.6)
3. Skew	Small skew to fine grades (-0.01 to 0.39)	Variable (-0.3 to 0.5)	Very Variable
4. Rounding	Good, decreasing with decreasing grain size	Nil	Variable
5. Sphericity	Good, maximum in 0.2-0.5mm size. decreases with decreasing grain size	Dependant on host rock	Variable
6. Frosting	Prevalent, decreasing with decreasing grain size	Nil	Nil
7. Bulk composition	Mono-mineralic quartz, rare rock fragments, no mica	Variable. Abundant rock fragment mica.	Variable. Abundant rock fragments, mica
8. Profiles in overburden	Structureless. Occasional laterite zone.	A, B. C horizons	Pebble, clay, or laterite bands.

Recently reworked Kalahari Sand may occur as present dambo sediment. This reworked Sand can be recognised as the dambo drainage channels are obvious from the present day topography.

CHAPTER III OBSERVED TRACE ELEMENT DISPERSION

1. MUFUMBWE AREA

(a) Previous Work

Following the abandonment of the diggings in the early nineteen thirties, R.S.T. renewed interest in the area in 1954 with an exploration programme which included geochemical soil sampling. Results indicated a soil Cu anomaly of over 60 ppm (-80# D, colorimetric)* extending southwestwards, from the Mufumbwe East Trenches area to the western margin of Prospect Block 229 (Fig. 15). The anomaly attains a peak value of 250 ppm Cu in the vicinity of the Main Clearing and decreases westwards. At the western edge of Block 229, the anomaly is broad and diffuse, with sporadic values of up to 180 ppm. This loss of definition of the anomaly westwards was partly attributed by R.S.T. geologists to soil dilution by Kalahari Sand.

Follow-up power auger drilling located Cu anomalous bedrock values of over 1000 ppm underlying the soil anomaly. Peak values occur at the East Trenches and at the Main Clearing. This bedrock anomaly becomes weaker and very erratic west of the Main Clearing. Subsequently, a diamond drill programme has revealed relatively high grade mineralisation at the East Trenches and at the Main Clearing in steeply dipping shales in a dominantly shale-quartzite succession of possible Kundulungu age (Company data).

(b) Residual and Contact Soil

West of Block 229 no bedrock is exposed and no previous exploration work had been carried out prior to the present survey. The topography is flat, and drainage negligible

* D signifies dry sieved.

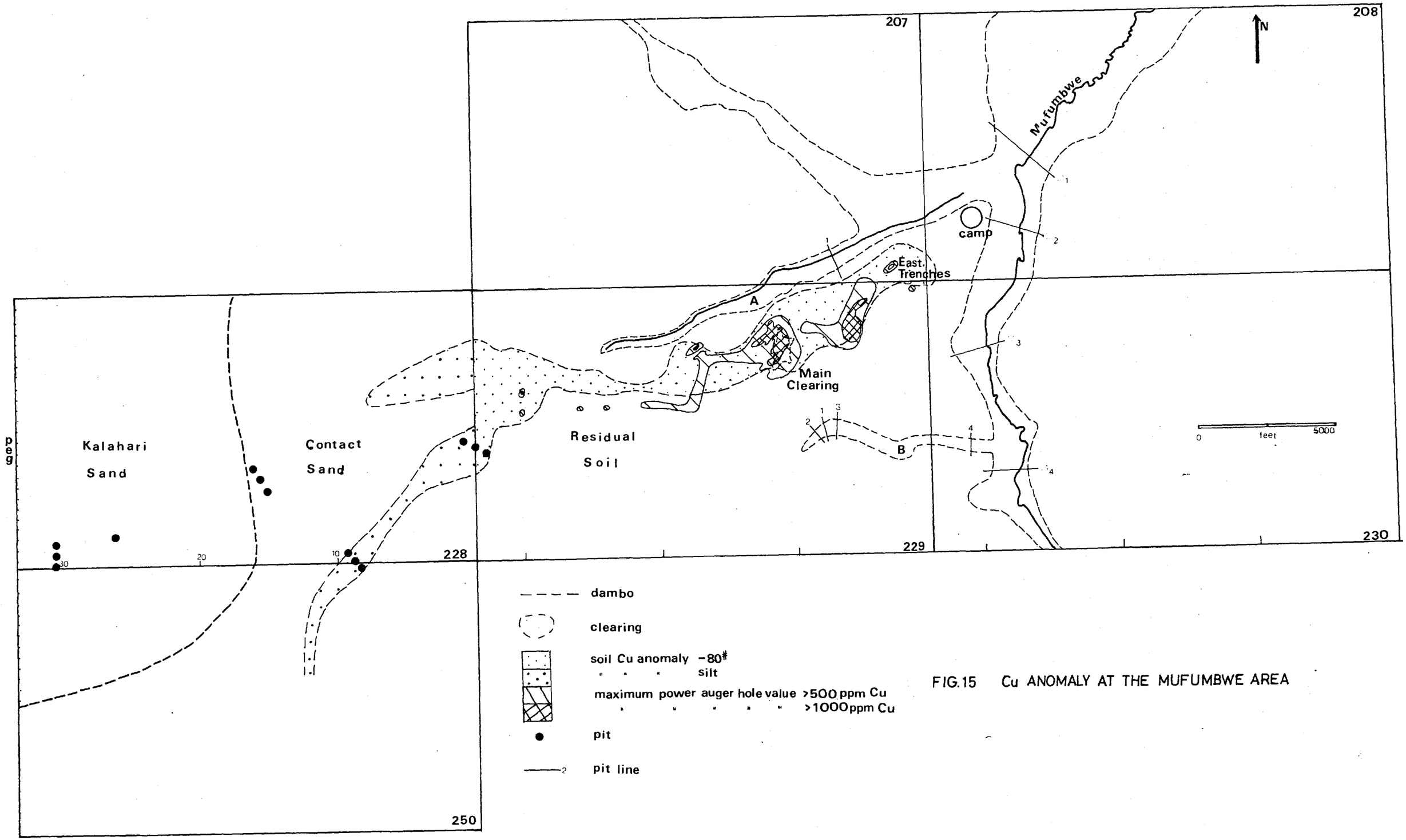


FIG.15 Cu ANOMALY AT THE MUFUMBWE AREA

with a few isolated waterholes.

Although the overburden in the east of Block 228 is a uniform, ochre red, clay-rich freely-drained soil, there is a considerable proportion of Sand in the upper zones and this amount increases westwards.

(i) Surface dispersion

The extension of the Mufumbwe soil Cu anomaly was initially traced in the field using a -80# dry sieved soil fraction and a potassium bisulphate fusion attack.*

From the west margin of Block 229, a northern branch of the anomaly extends only 4000 ft. westwards where values decrease to background (30 ppm, -80#D). A southern branch extends for 11,300 ft. southwestwards in contact soil, where the anomaly peak is 110 ppm Cu with a background threshold of 30 ppm (-80#D).

Re-analyses of the samples using the silt fraction and a nitric-perchloric acid attack with atomic absorption element determination, produces a higher average extraction (+65%) due to the finer size fraction.

The content of Fe in near surface samples in Blocks 228 and 250 has an overall range of 2.5-6.6% with no enhancement in the Cu anomalous zone. The Mn content ranges from 200-500 ppm and shows a slight correlation with Cu. Zn (15-40 ppm), Co (6-20 ppm), Ni (25-60 ppm) and Pb (20-40ppm) are consistent in level and show no secondary dispersion pattern which correlates with Cu (Tables 13 and 14).

* unless otherwise stated, all analyses of overburden have been carried out on the silt fraction, using a nitric-perchloric acid extraction and atomic absorption metal determination.

Table 13. Trace element content in contact residual soil (9 in. depth)(Block 250),(silt fraction, nitric-perchloric attack).

	Cu	Zn	Co	Ni	Pb	Fe%	Mn
Background Range(ppm) (16 samples)	31-62	23-37	6-13	36-59	20-37	3.7-6.4	290-500
Anomaly Range(ppm) (4 samples)	65-150	24-32	6-7	34-43	24-30	6.1-6.6	450-560

(ii) Vertical dispersion

Three soil pit profiles in the anomaly zone (Block 228, line 0, pegs 19NW, 19, 19SE) (Figs. 15 and 16) indicate that the bedrock of interbedded grey quartzite and maroon shale, which occurs at 5-12 ft. depth, is similar to the lithology found elsewhere at Mufumbwe. It is overlain by 2-5 ft. of C horizon soil containing decomposed bedrock fragments. Lateritic nodules, or a laterite zone occur in the B horizon, and are succeeded by a homogeneous, structureless, ochre red-brown, A horizon soil. The humic Ao zone is thin. Cu values increase down-profile into the lateritised rubble and underlying bedrock, where the peak value is 920 ppm (pit 0/19). Fe, Mn and Zn show concentrations in the Ao and laterite zones, while bedrock may be further enriched in Fe and Mn (e.g. pit 0/19).

Pits located 6500 ft. to the south-west (Block 228, line 8, pegs ONW, 0, OSE) contain bedrock quartzite at 9-17 ft. depth, overlain by 1½-6 ft. of indurate laterite, followed by red-brown, homogeneous contact residual soil (Fig. 16). Cu values increase below the Ao horizon and

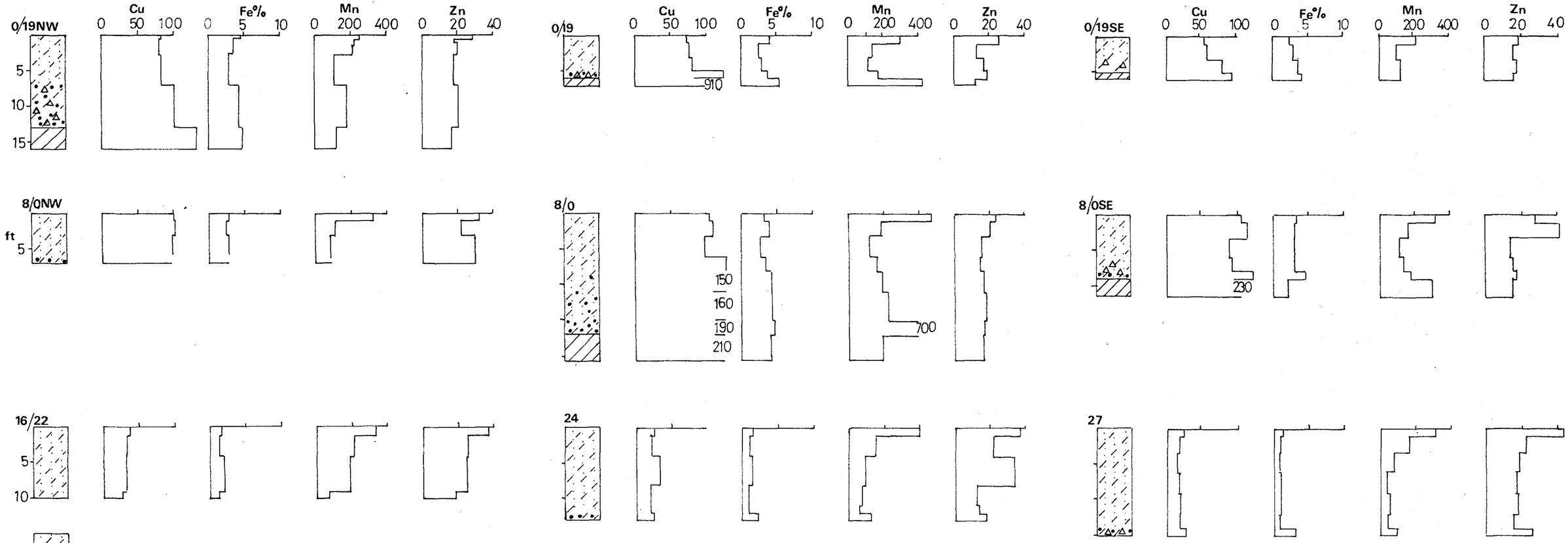


FIG. 16 CONTACT SOIL PIT PROFILES, BLOCKS 228 & 229, MUFUMBWE (ppm).

Table 14. Trace element content of contact residual soil (9 in. depth) Mufumbwe, Block 250. (optical spectrometry).

Sample No.		Element														
		Pb	Sn	Ga	Bi	V	Mo	Cu	Zn	Ti	Ag	Ni	Co	Mn	Cr	Fe_2O_3%
880	background	13	5	30	5	130	2	60	50	8500	0.2	40	13	400	50	8
884		8	5	16	5	160	2	41	50	8500	0.2	30	13	400	60	14
889		8	5	20	5	200	2	52	50	8500	0.2	30	13	400	160	15
898	anomalous	10	5	16	5	200	2	90	50	8500	0.2	16	13	400	60	17
899		10	5	16	5	200	2	90	50	8500	0.2	20	10	400	60	18

concentrate in the laterite. A peak value of 230 ppm Cu occurs in bedrock quartzite (pit 8/OSE). Fe values decrease down to 5 ft. but then increase towards the laterite zone. Mn and Zn values are lower with depth but are enriched in the laterite zone.

Fe, Mn and Co, and to a lesser extent Cu, are concentrated in B horizon lateritic nodules (Table 15).

Table 15. Trace element concentration in lateritic nodules. (ppm).

	Cu	Fe%	Mn	Zn	Ni	Co
Contact Soil(anomalous)	150	6.5	450	24	43	7
average of approximately 20-30 nodules from soil	160	52.7	1800	-	46	34
Contact Soil (background)	43	3.7	290	31	53	9
average of approximately 20-30 nodules from soil	120	46.2	1800	39	160	66

Pits located at line 16 (Block 228, pegs 22-27) near the Kalahari Sand boundary (Figs. 15 and 16) have profiles of homogeneous, orange-brown, Sand-rich, contact soil. Lateritisation occurs at 12-15 ft. depth. Cu values tend to decrease down-profile and show a slight concentration in the lateritised contact soil. Fe, Mn and Zn values are enriched at surface. In depth Fe is variable but shows enrichment in the lateritised zone. Mn and Zn values decrease down-profile but increase in the laterite horizon.

(c) Kalahari Sand

(i) Surface dispersion

Westwards from Block 229, a gradual physical change occurs in the overburden over a distance of 16,000 ft. due

to an increasing Sand content. Approximately 7000 ft. west of Block 229, the overburden alters to an orange-brown contact Kalahari Sand. A further 3,000 ft. southwestwards (line 20) the overburden is a loose-textured, buff-orange Kalahari Sand.

A regular trace element variation is found relative to the overburden change (Table 16).

Table 16. Trace element content in relation to soil-Sand variation (ppm) Block 228 (silt fraction)

Line	0	5	10	14	16	20	26	30
overburden type	contact residual soil					Kalahari Sand		
Soil colour	red brown	red brown	red brown	orange brown	orange brown	yellow brown	buff orange	buff orange
Cu peak	135	46	37	56	35	38	19	18
background	40	40	30	30	30	30	15	15
Fe% peak	5.6	5.0	3.9	3.4	2.7	1.9	1.4	1.3
background	3.0	4.3	3.1	2.5	1.8	1.2	1.2	1.2
Mn peak	420	460	600	520	450	330	360	420
background	240	250	300	290	200	200	200	200
Zn peak	60	38	30	40	35	32	26	25
background	30	30	30	30	30	30	25	25
Co peak	18	27	26	22	21	22	14	12
background	17	18	20	15	15	15	15	10
Ni peak	-	37	38	44	35	-	-	-
background	-	35	35	35	25	-	-	-

From line 8 (Block 228) westwards, no Cu anomaly is apparent and the background values gradually decrease from 40 to 15 ppm over a distance of 15,000 ft. Fe, Zn, Co and Ni values reveal a similar impoverishment into the Kalahari

Sand. This is a direct result of the original low metal content of the Sand. The Mn content remains relatively high in near surface Kalahari Sand. This is believed to be due to a correlation between Mn and organic debris. A variable organic content in near surface samples thus produces fluctuations in Mn values.

(ii) Vertical dispersion

At line 26, peg 6 (Block 228) (Fig. 17) the overburden profile comprises structureless, orange-brown Sand with indurate, lateritised Sand at 9 to 11 ft. Beneath the laterite zone, contact Soil and residual soil containing Fe pisolites extend to 24 ft. The metal content generally increases downwards due to enrichment in the laterite zone. In the underlying contact residual soil the Cu, Fe, Mn and Zn values are higher than in the overlying Sand.

Profiles 2,000 ft. westwards (Block 228, line 30, pegs 0, 2, 4) (Fig. 17) comprise orange-buff Kalahari Sand, bleached at depth, with a hard, lateritised horizon at 17-19 ft. The bleaching probably results from seasonal reduction of Fe by water-table fluctuations. Cu values are at maximum at the surface and show little variation in depth. Enrichment of Cu occurs in the laterite zone (e.g. pit 30/4). Fe, Mn and Zn generally decrease down-profile, but tend to have concentrations in the lateritised Sand. (e.g. pit 30/4).

Two profiles in Kalahari Sand, in randomly selected background areas, are located 2.4 and 4.5 miles north-west of Block 229 (Fig. 17). Little pedological differentiation occurs and the overburden comprises orange-brown and buff Kalahari Sand with cream coloured, bleached patches below

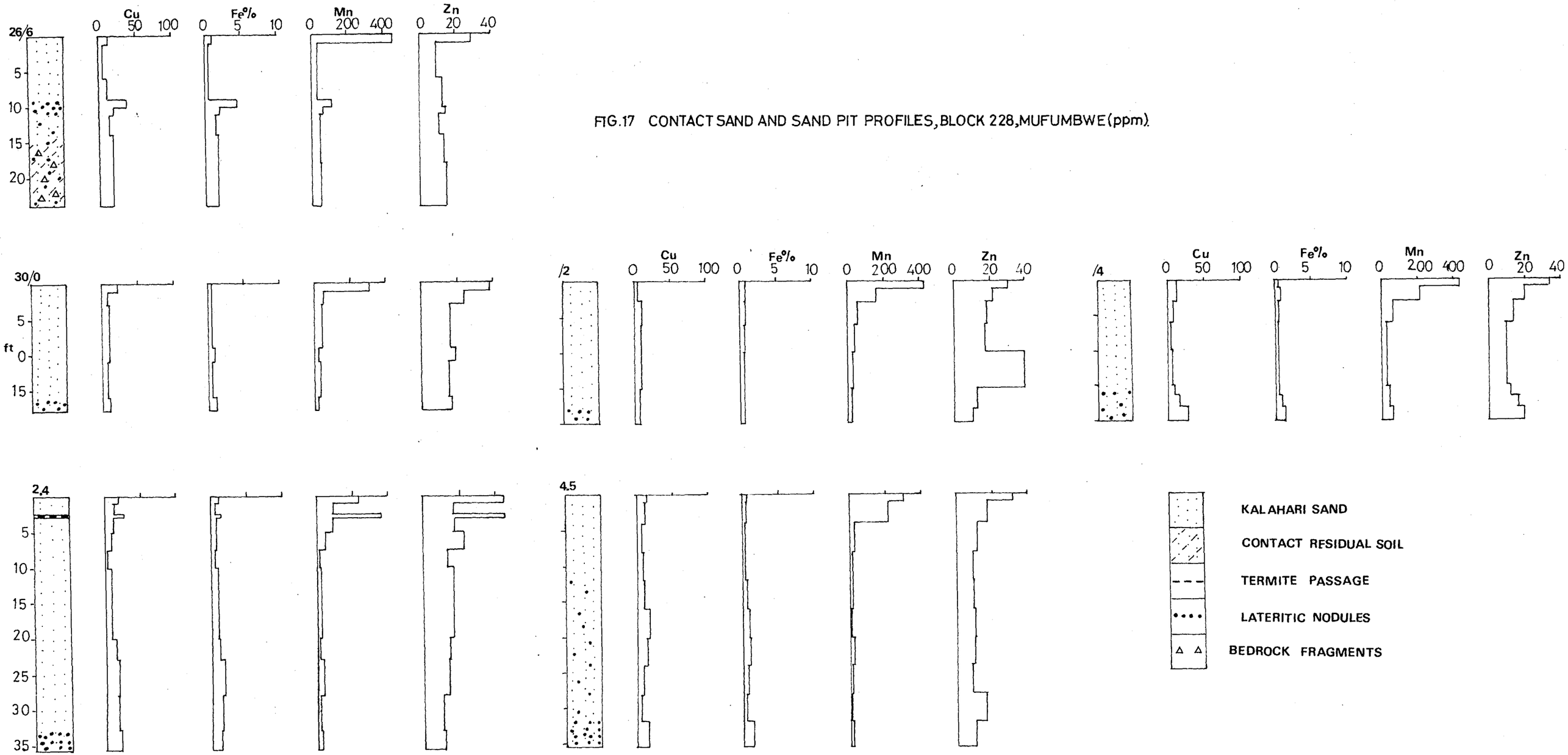


FIG.17 CONTACT SAND AND SAND PIT PROFILES, BLOCK 228, MUFUMBWE (ppm).

20 ft. Laterite concretions only appear below 33 ft. in one profile, but are spasmodically developed in the second from 12 to 33 ft. depth. Local intense lateritisation has resulted in coarse nodules of Fe cemented Sand, several inches in diameter. Cu values in the profiles decrease downwards to 10 ft. Below this depth, the Cu content appears to fluctuate in Fe stained or Fe pisolitic Sand. The Fe, Mn and Zn trends are similar to the Cu, although Mn and Zn are markedly concentrated in the Ao horizon. A termitaria passageway at 2½ ft. depth in one pit contains significant enrichment of each element.

Ten randomly selected sections through Kalahari Sand at 1 mile intervals on the Chizera Road, 10 miles north-west of Mufumbwe, display consistent ranges of trace element content with depth, over a wide area (Table 17).

Table 17. Trace element content range in Kalahari Sand, 10 miles N.W. of Mufumbwe. (ppm).

Depth	Cu	Fe%	Mn	Zn	Co
0-3ins.	8-33	0.3-1.1	84-800	14-68	3-11
3ins.-1ft.	4-19	0.3-1.0	17-170	7-25	3-11
1-2ft.	4-15	0.3-1.2	11-180	5-19	3-10
2-3ft.	5-13	0.3-1.0	11-210	8-19	4-9
3-4ft.	5-13	0.3-1.2	11-130	7-23	4-8

The Sand profiles are similar in structure. A 0-3 in. dark, humic Ao horizon, is underlain by a 9 in. transition zone and 3 ft. of loose, buff Kalahari Sand. Fe staining is virtually absent. The metal content level in each profile

is similar, and a consistent decreasing downward trend for each element occurs. Mn, and to a lesser degree Cu and Zn, are enriched in the Ao horizon.

(d) Dambo Sediments

(i) Background area

Three separate tributary dambos of the Mufumbwe River, occur 4, 12 and 14 miles north and upstream of the Mufumbwe area respectively, (dambos 82/DH, 82/DI and 81/DA) and drain areas of residual soil. Previous Company stream sampling data indicate that these dambos contain background Cu values. Overburden profile pits were aligned across the dambo axis, $\frac{1}{4}$-$\frac{1}{2}$ mile upstream of the dambo confluence with the Mufumbwe River to eliminate possible contamination by flooding of the main river. One pit was sited in the water course (Fig. 18, pit 3), one at the break of slope on either bank of the dambo (Fig. 18, pits 2 and 4), and one beyond each dambo margin (Fig. 18, pits 1 and 5).

The profiles exhibit a catena from partly residual material beyond the dambo margin, through partially drained exotic material on the dambo fringe, to the normally water-logged glei profiles of the dambo channel. Profiles beyond the dambo margin (pits 1 and 5) have a brown to black, humic topsoil overlying orange-brown to grey sandy clay. This is underlain by a grey-brown clay horizon with occasional yellow Fe mottle and lateritic development, and may overlie bedrock rubble and bedrock horizons. Cu profiles are variable (4-26 ppm) but values generally increase downwards with higher values in the lateritic zones. The Fe dispersion is similar to the Cu with up to 5% Fe in the

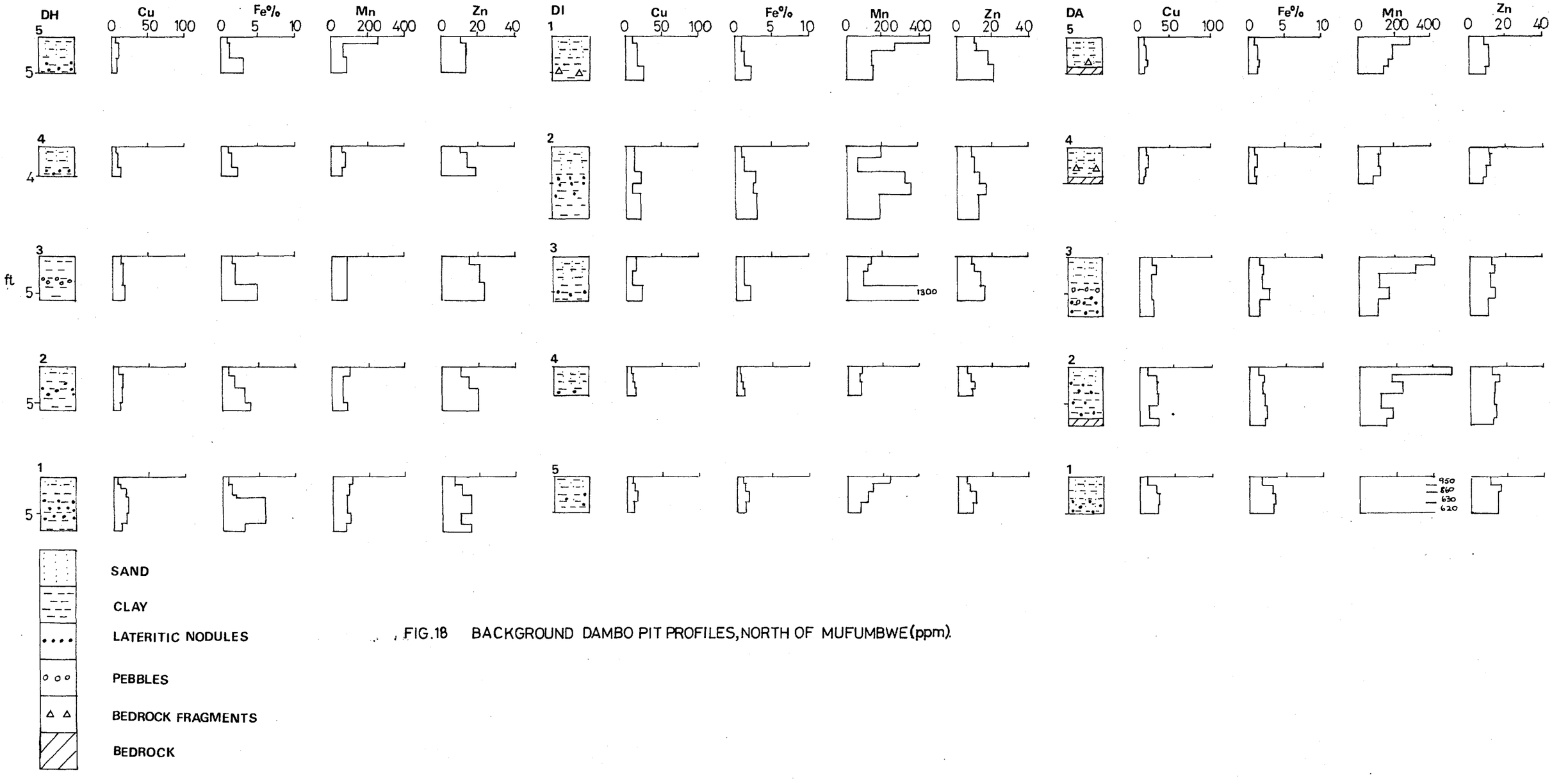


FIG.18 BACKGROUND DAMBO PIT PROFILES, NORTH OF MUFUMBWE (ppm).

lateritic clay zone. Mn values decrease with depth but are locally enhanced in the lateritic zones (e.g. pit DH5). The Zn content generally increases with depth.

Profiles on the dambo margin (pits 2 and 4) contain a grey-black to brown, humic Ao zone overlying a grey, clay-rich, glei horizon with abundant orange Fe mottles and occasional soft lateritic pisolites. These pisolites harden on exposure. The Cu content in the profiles is again variable (4-25 ppm) but concentration occurs in the lateritic zones. Fe consistently increases down-profile, while Mn values fluctuate with concentrations in the Ao and laterite zones (e.g. pit DI/2). The Zn profile is variable.

In the dambo channel (pit 3), a thick, black-brown, humic horizon overlies a well developed glei zone containing grey clay with yellow Fe mottles and black Fe pisolites. The Cu content in profile (7-23 ppm) is enhanced in the Fe mottle zones. Fe increases downwards, while Mn is locally strongly concentrated in the lateritic zones (e.g. pit DI/3). The Zn content tends to increase with depth.

In conclusion, in each dambo profile, similar trace element profiles appear. The Cu content varies from 4 to 26 ppm and is generally low in the Ao horizon and enhanced in lateritic zones. Fe ranges from 0.3 to 5.3% and increases down-profile. The Mn content is variable (25-1400 ppm). High values occur in the Ao and lateritic zones while there is a weak tendency for values to decrease in depth. Zn (5-22 ppm) generally increases with depth.

(ii) Anomalous area

Two tributary dambos (Fig. 15, dambos A and B) drain the predominantly residual soil cover of the Mufumbwe

mineralisation. Dambo B is located to the south, and dambo A to the north. The main drainage from the mineralisation is southwards, and consequently the stronger drainage anomaly appears in dambo B.

In dambo B, the pit profiles of line 2 (Fig. 15), are sited upstream of the mineralised surface water seepage channel (Fig. 19, line 2, pits 1-5). An Fe mottled sandy-clay and clay A horizon overlies a zone of pallid clay, or alternatively a rubble zone containing rounded and angular quartzite and vein quartz material. The rubble zone normally contains Fe pisolitic development. Decomposed bedrock shale occurs at 8 ft. depth in the dambo centre. The Cu content varies from 10-89 ppm and is concentrated where Fe mottle, Fe pisolitic and pebble horizons occur (e.g. pit 2/3). Values generally increase down-profile while bedrock values are low (35 ppm). These values, together with the values in background dambos, suggest a local Cu threshold of 50 ppm in clay-sand, but may be 50% greater in lateritic zones. The Fe content increases with depth although it is low in pallid zones. Mn varies in distribution but is higher in rubble and pisolitic zones (e.g. pit 2/2). Zn tends to increase in content down-profile.

A line of pits (Fig. 19, line 1, pits 1-7) sited opposite a drainage channel from the Main Clearing have sandy-clay profiles with locally intense lateritic development at 3-5 ft. depth. Pebble horizons containing rounded, water-worn pebbles of up to 4 ins. diameter occur between 5 and 10 ft. depth. Bedrock quartzite is found at 10 ft. depth under both banks. The Cu content is highest in lateritic

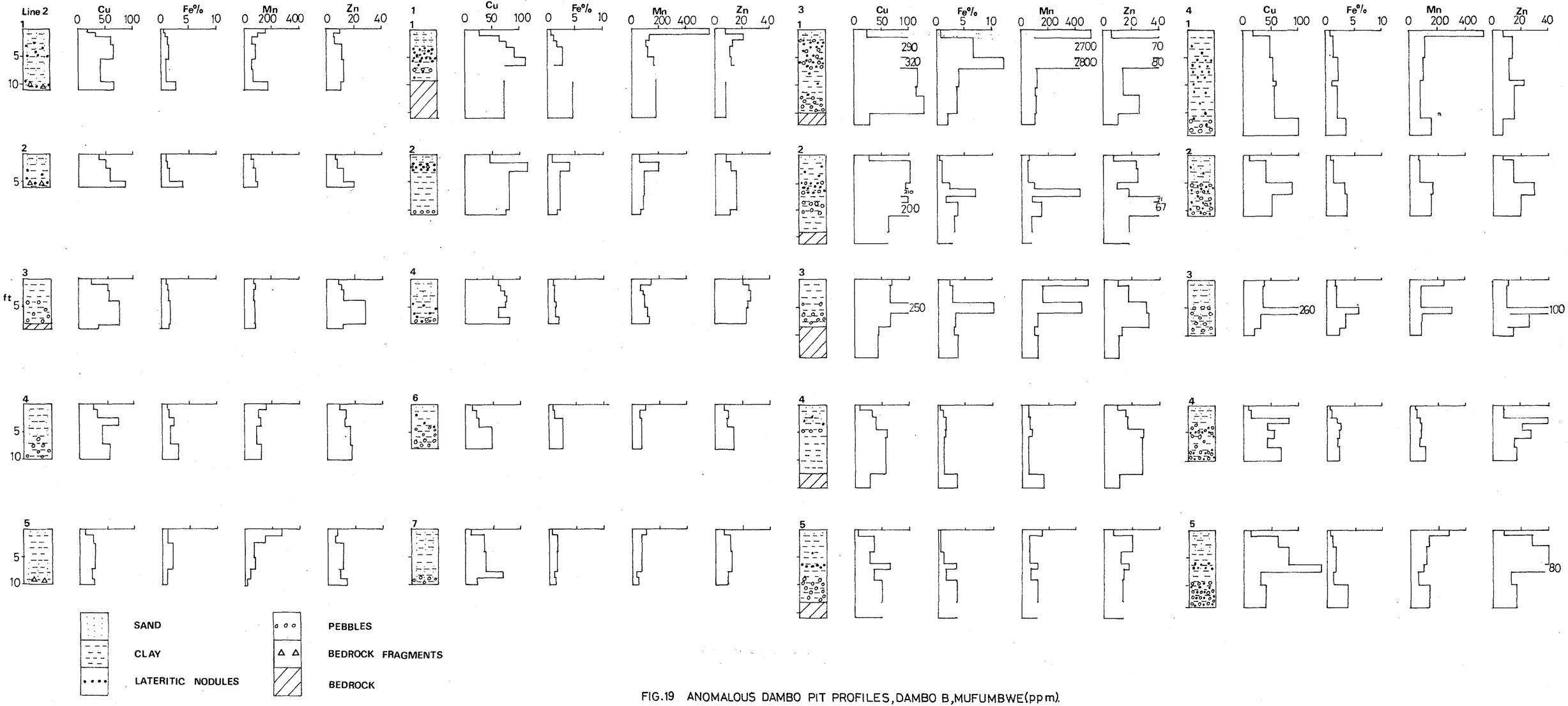


FIG.19 ANOMALOUS DAMBO PIT PROFILES, DAMBO B, MUFUMBWE (ppm).

and pebble horizons, and generally increases with depth. On the northern side of the dambo, nearest to the drainage channel (pits 1-4), values are generally anomalous throughout the profile, with peak values of 110-120 ppm in Fe mottled and Fe pisolitic zones (pit 1/2). The Ao horizon is Cu enriched only in the dambo centre, which may be due to deposition of Cu where Cu bearing groundwater reaches surface. Fe values tend to increase slightly with depth, while Mn and Zn are variable in depth with local Mn enrichment in Fe pisolitic zones (e.g. pit 1/2).

Opposite the main drainage from the mineralisation (Fig. 19, line 3, pits 1-5), the sediment profiles are basically similar to those occurring upstream. Several zones of coarse, rounded pebbles of up to 6 in.-1ft. diameter occur with attendant lateritisation and overlie decomposed quartzite at 9-15 ft. This quartzite locally decomposes to a grey clay. Cu values on the south side of the dambo (pits 4 and 5) are low, variable (8-65 ppm) and within the background range, but from the dambo channelway to the north bank, values are generally anomalous (22-330 ppm). Marked concentrations of Cu occur in the pebble and lateritised pebble zones (e.g. pit 3/2). Ao horizon Cu values are only enriched at the dambo channelway. Fe generally increases in content with depth with high concentrations in the pebble zones. Mn and Zn have a similar tendency to concentrate in the pebble zones (e.g. pit 3/1).

Pits sited 4600 ft. further downstream (Fig. 19, line 4, pegs 1-5) show similar sedimentological features with clay

sand passing downwards to mottled and lateritised clay. Zones of fine to coarse grained pebbles appear in the lower part of the profiles. Cu values are variable (9-260 ppm), but are generally anomalous with a slight tendency to increase with depth. Maximum values appear in the pebble (e.g. pit 4/3) and lateritic zones (e.g. pit 4/5) while surface values are low except in the dambo channelway. The Fe, Mn and Zn values are high in the pebble and lateritic zones, while Mn is locally concentrated in the Ao horizon. Zn is slightly enriched in the Ao horizon of the dambo channelway.

Minor drainage from the Mufumbwe mineralisation enters dambo A. Profiles in the dambo (Fig. 15, line 1; Fig. 20) comprise grey-orange sandy clay with pisolitic and pebble bands overlying decomposed quartzite at 16 ft. Below the Ao horizon, the Cu content is anomalous (11-290 ppm) and maximum values are associated with the laterite and pebble zones, especially in midchannel (e.g. pit 1/3). Ao horizon values are low with maximum values in the channelway. The Fe distribution appears erratic with concentrations in laterite and pebble zones (e.g. pit 1/3). There is a slight tendency for Fe to increase with depth. Mn, Zn and Co values are high in the pebble and pisolite zones. There is a marked correspondence between the Co and Mn dispersions (e.g. pit 1/4).

Thus in dambos A and B, the Cu distribution is dependent on the type of sediment in the profile and is frequently enriched in the pebble, Fe mottled and lateritic zones. Pebble zones appear to be conducive to the development of

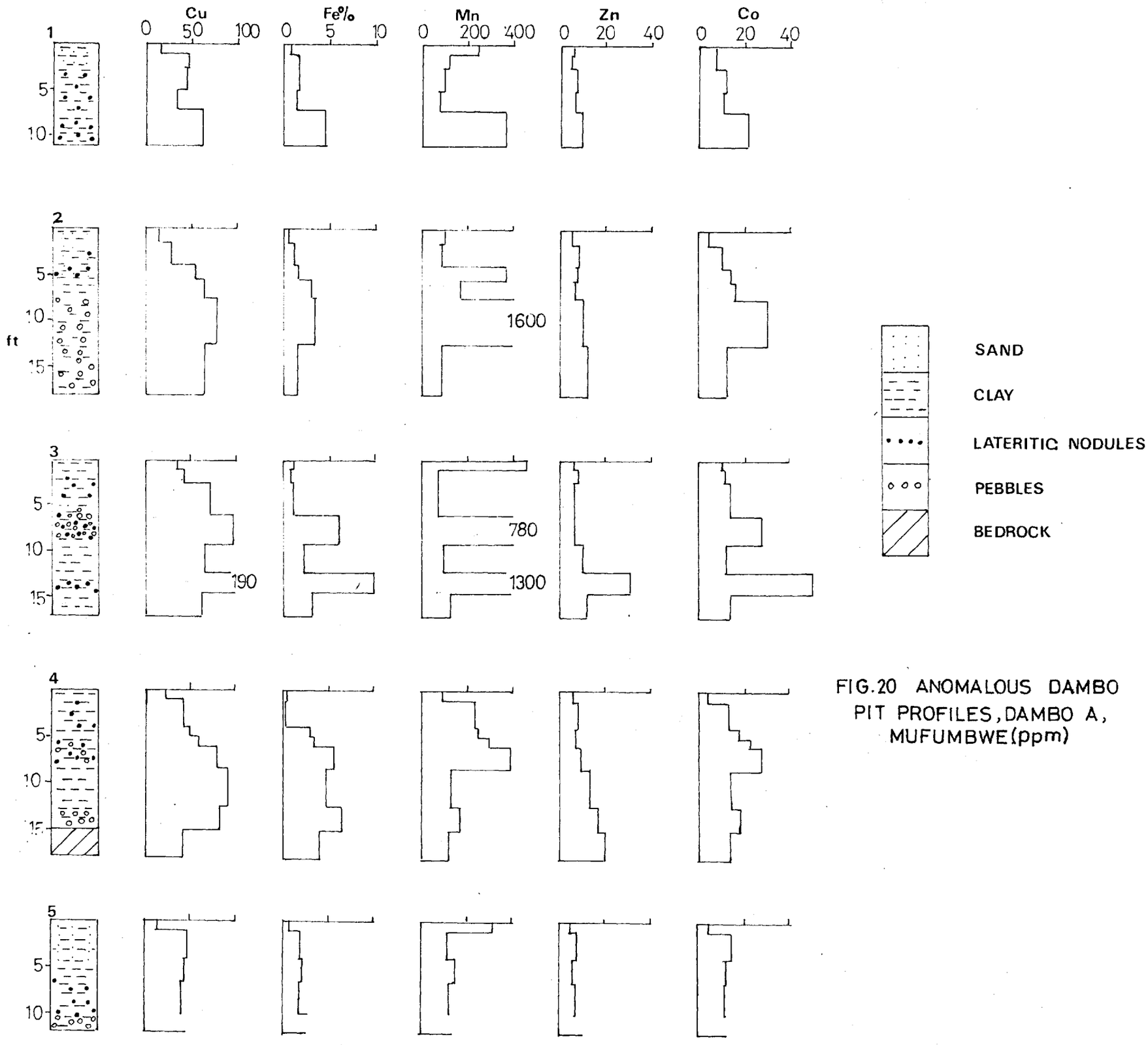


FIG.20 ANOMALOUS DAMBO PIT PROFILES, DAMBO A, MUFUMBWE (ppm)

laterite pisolites, possibly due to increased aeration and oxidation. The Cu content of the profiles is generally anomalous (>50 ppm), irrespective of the sediment type, although in the Ao horizon, values are low and below the threshold value. Only in the dambo channelway are Ao values slightly enriched, but are still below threshold value of the remainder of the profile.

(iii) Mufumbwe Dambo

At Mufumbwe, the Mufumbwe dambo should receive anomalous amounts of Cu from the probable eastward extension of the Cu mineralisation beneath the dambo, from the anomalous sediment of the tributary dambos A and B, and from groundwater emanating from the mineralised residual soil between dambos A and B (Fig. 15).

Pits sited across the wide flood-plain, 1400 ft. upstream of the tributary dambo A (Fig. 21, line 1, pits 1-5) reveal short glei profiles above the near-surface dry season water-table. The profiles comprise a dark, organic Ao horizon, over grey-brown clay with orange Fe mottle and occasional Fe pisolite development. Cu values range from 16-63 ppm and are occasionally at the upper limit of threshold. The higher values are associated with a high Fe content (e.g. pit 1/5). Fe and Zn values increase down-profile while Mn values are high in the Ao horizon.

Below the confluence of tributary A (Fig. 21, line 2, pits 1-5) Cu values are low (11-50 ppm). Fe and Zn increase with depth while Mn is more erratic.

Although anomalous Cu probably enters the Mufumbwe dambo in groundwater from the residual soil of the western

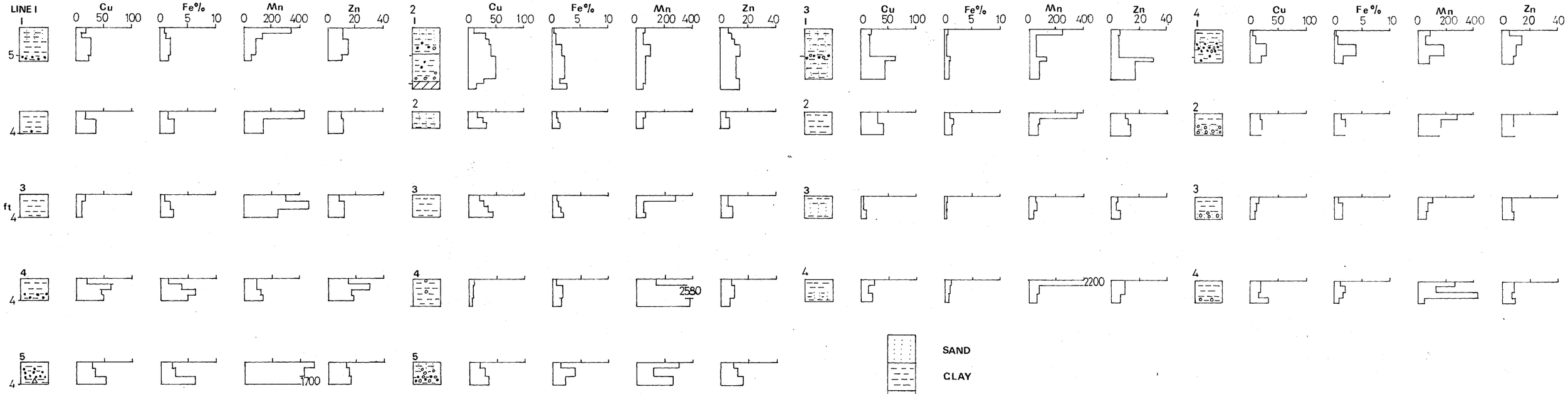


FIG.21 MUFUMBWE DAMBO PIT PROFILES(ppm).

bank between dambos A and B, no detectable Cu enrichment (3-62 ppm) is located in the sediment (line 3). The highest Cu value occurs in a lateritic pebble zone.

Similarly, dambo sediment from 600 ft. downstream of the confluence of tributary dambo B (Fig. 15, line 4) contains no anomalous Cu content (5-29 ppm).

Thus barren material, transported down the main Mufumbwe dambo, appears to dilute or swamp any anomalous Cu introduced from both tributary dambos or from anomalous groundwater entering from the anomalous soils.

2. LOWER KAMWEDGI AREA

(a) Previous Work (Fig. 22)

Following the discovery of outcropping Cu mineralisation between 1920-25, pits and trenches were dug by R.S.T. in the Prospect Block during 1959, and several bands of Cu mineralisation were intersected in an interbedded quartzite and shale succession. The Prospect Block was soil sampled in 1968, when a north-south trending anomaly was outlined for 1200 ft., extending from the trenches southwards to the Kamwedgi River. A peak value of 160 ppm Cu (-80# D)was located at peg C3, downslope of the sub-outcropping mineralisation. A local soil threshold of 60 ppm was indicated (company data).

Follow-up power auger drilling within the Prospect Block in 1968, revealed anomalous Cu values of 2500 ppm in bedrock at a depth of 22-27 ft. at peg C3. Further power auger holes were sited to the north of the Prospect Block, on the northward extrapolation of the anomaly. Shales with 300 ppm Cu were intersected at peg HN4 at 17-22 ft. depth under a surface soil value of 140 ppm. Northwards at peg KN4, shale

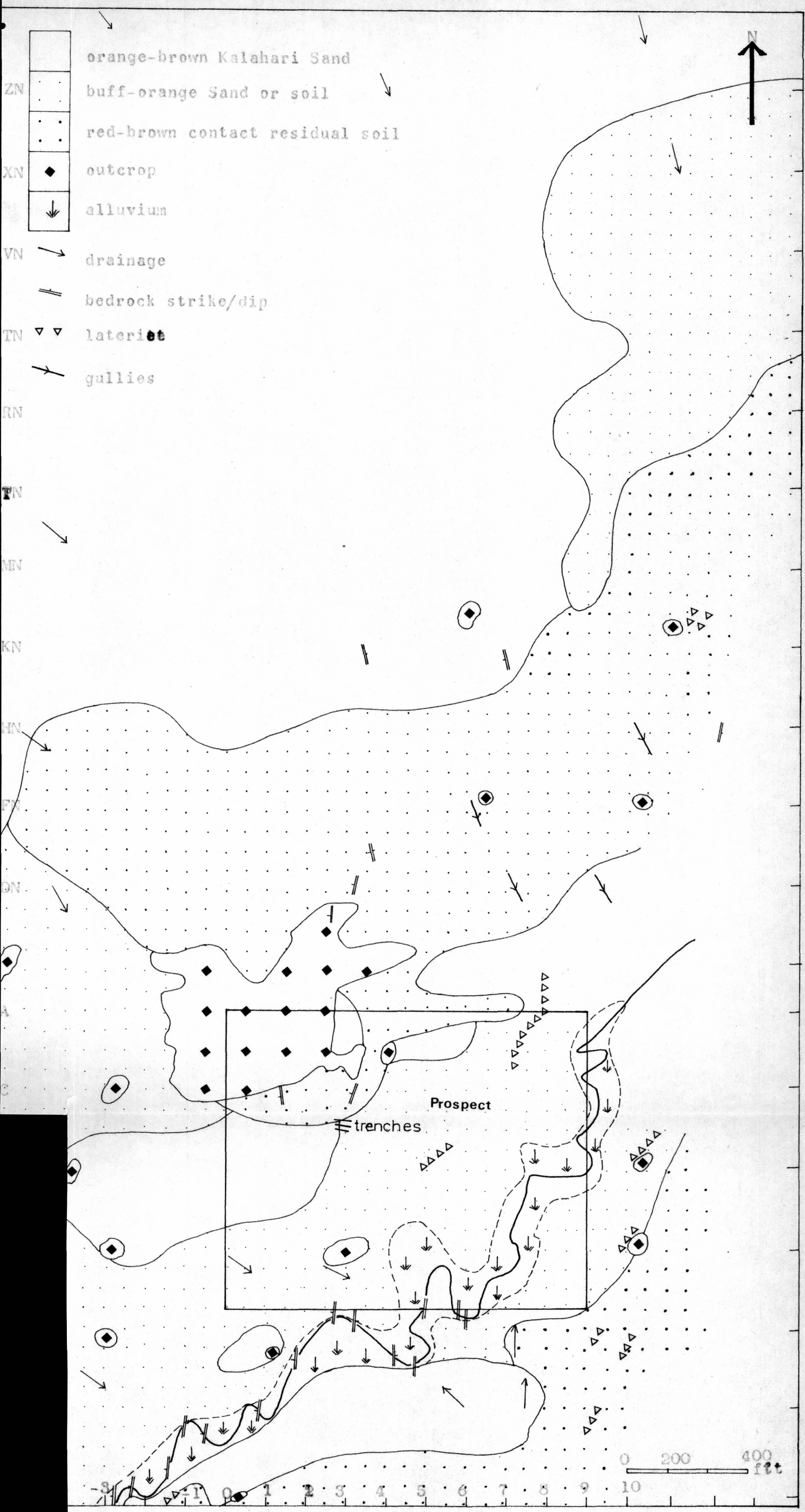


Fig.22 Geology and overburden of the Lower Kamwedgi area.

at 67-72 ft. depth contains 310 ppm Cu under a surface contact-soil value of 60 ppm. No further northwards extension of the anomaly could be traced.

Subsequent diamond drilling in 1968 within the Prospect area at peg C3, proved relatively high grade Cu mineralisation at a depth of 130 ft. This mineralisation is mainly in the form of disseminated chalcocite in subvertical quartzite in a quartzite-shale succession. Bornite, chalcopyrite, malachite and chrysocolla are also noted, and mineralisation is sporadic.

In the primary trace element distribution in bedrock, only Co indicates a slight correlation with Cu mineralisation (Table 18).

Table 18. Trace element content of bedrock (ppm), Lower Kamwedgi, peg C 3. (hydrochloric-perchloric attack - company data).

Depth(ft.)	Lithology	Cu	Co	Ni	Zn	Fe%	Pb
0-2	residual soil	120	-	20	<20	1.0	-
2-7	quartzite	140	-	20	<20	1.0	-
7-12	"	150	20	20	<20	1.5	-
12-17	"	400	-	20	<20	1.5	-
17-22	"	640	28	16	6	1.5	12
22-27	"	3,500	40	20	24	2.0	32
27-32	"	2,450	56	24	14	2.0	32
27-32(Bit sample)	"	2,850	48	22	12	2.5	32
	Background bedrock from several drill holes.	20-50	10-40	10-40	20-30	1.0-3.5	-

(b) Geology and residual soil (Fig. 22)

The most representative exposures of bedrock in the area are found in the Kamwedgi River and comprise inter-bedded, current-bedded quartzite and shale horizons probably of Kundulungu age. The rocks have a consistent northerly strike and a subvertical dip. Beyond the river, quartzite is intermittently exposed as far north as line KN, where the strike remains northerly. Beyond line KN there is no outcrop.

Residual soils occur on both banks of the Kamwedgi River and extend northwards to the Kalahari Sand boundary which occurs between pegs FN-6 and TN 16. The soil is a brown-buff colour and contains a proportion of admixed Kalahari grains which becomes more prevalent northwards. It is probable that formerly the Kalahari Sand and residual soil overburden were more extensive, but have been partly removed by the drainage system of the Kamwedgi River. The depth of residual soil varies between 0 and 15 ft., partly due to the uneven, underlying bedrock surface.

The present land surface is relatively even and the slope within the Prospect is moderate (3°) but northwards the gradient is low ($<1^{o}$). Drainage is south-southeasterly towards the Kamwedgi River.

(i) Surface dispersion

A broad zone with higher Cu values (50-100 ppm) extends in a north-east direction through the Prospect Block, and is believed to reflect the higher metal content of the relatively shallow contact-residual soils (Fig. 23). Superimposed on this zone, a north-south trending anomaly extends northwards from the Prospect Block and develops

Cu ppm

<50

50-100

100-150

150-300

>300

Sand boundary

floodplain

pit

N

0 200 400
ft

-3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13

ZN XN VN TN RN PN MN KN HN FN DN EN A C

Fig.23 Cu dispersion at 9in.,Lower Kamwedgi.

northern and north-easterly branches 1,400 ft. north of the Prospect boundary. The anomaly peak occurs in the Prospect Block between lines E - G, pegs $2\frac{1}{2}$-$3\frac{1}{2}$ (350-450 ppm), and lies to the south of the outcropping mineralisation. Power auger and diamond drill results indicate the strongest mineralisation in bedrock at peg C3, to the north of the soil peak. Consequently the displaced surface enrichment may be the result of a combination of a downslope clastic soil wash and saline dispersion. A further soil peak (240 ppm) at peg HN 3 overlies indicated minor bedrock mineralisation (250 ppm) at 12-17 ft. depth. It is possible that higher grade mineralisation occurs at a greater depth.

The anomaly branch in the north-east has a peak value of 200 ppm Cu at peg MN 9, overlying Cu enriched bedrock (900 ppm; Fig. 28).

The Fe distribution in soil (Fig. 24) displays a zone of over 3% Fe to the north of the Prospect Block, with two broad areas of over 4%. Maximum enrichment in soil occurs in the east where Fe-rich bedrock (10-20% Fe) is near surface. A marked decrease of Fe content is observed along the surface residuum-Kalahari Sand boundary.

A further zone of high values (>4%) occurs in the south-east of the Prospect Block, in thin residual soil overlying laterite-capped bedrock. This may be a continuation of the Fe-rich bedrock directly north of the river. The peak value of this zone ($5\frac{1}{2}$%) is located in colluvium immediately below a lateritic scarp. The soil of the Prospect Block contains low Fe values (2-3%), which extends to the south-west. This zone cross-cuts the rock strike and may be related to

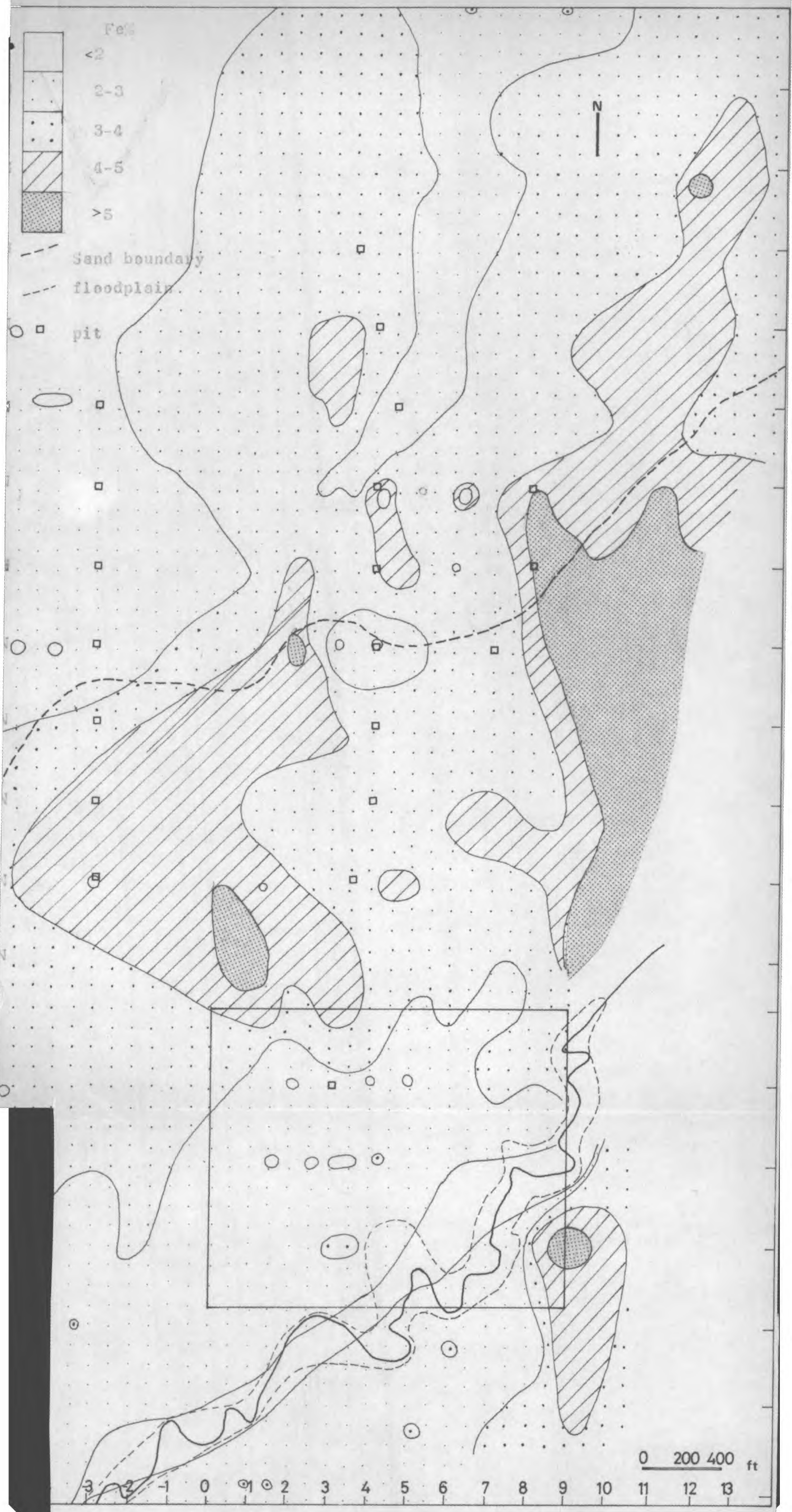


Fig.24 Fe dispersion at 9in.,Lower Kamwedgi.

increased leaching of the surface soils due to stronger drainage conditions on the increased ground slope.

The general northerly trend of the Fe zones possibly reflects bedrock strike.

The Mn distribution (Fig. 25) has a wide zone of higher values (>200 ppm) to the north of the Prospect Block. Values increase eastwards and attain a peak of over 600 ppm in the north-east, near the sand boundary with the residual soil. This area overlies Mn rich bedrock (8800 ppm; Fig. 28). In the south-east of the Prospect Block, a zone of Mn enrichment coincides with the zone of high Fe values. The peak value occurs in colluvium below the lateritic outcrop. The soil of the Prospect Block is generally low in Mn (<200 ppm).

Zn distribution in the soil (Fig. 26) indicates a broad anomaly to the south-east of the Prospect Block on thin soil on the exposed laterite-capped bedrock. The highest concentration (280 ppm) is again in the colluvium below the laterite outcrop. A northerly trending enriched zone occurs north-east of the Block, and is possibly the extension of the previous zone. Bedrock contains up to 540 ppm Zn at pit MN10 (Fig. 28).

Thus in the residual and contact residual soil, the following surface dispersion zones can be differentiated:

(1) a north trending Cu anomaly with poor Mn-Zn association, related to bedrock mineralisation.

(2) marked Fe-Mn-Cu-Zn enrichment at pegs MN-KN/9-11 associated with bedrock enriched in these metals.

Mn ppm
<100
100-200
200-300
300-400
400-500
>500
Sand boundary
floodplain
pit
N
0 200 400
ft
-3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13

Fig.25 Mn dispersion at 9in., Lower Kamwedgi.

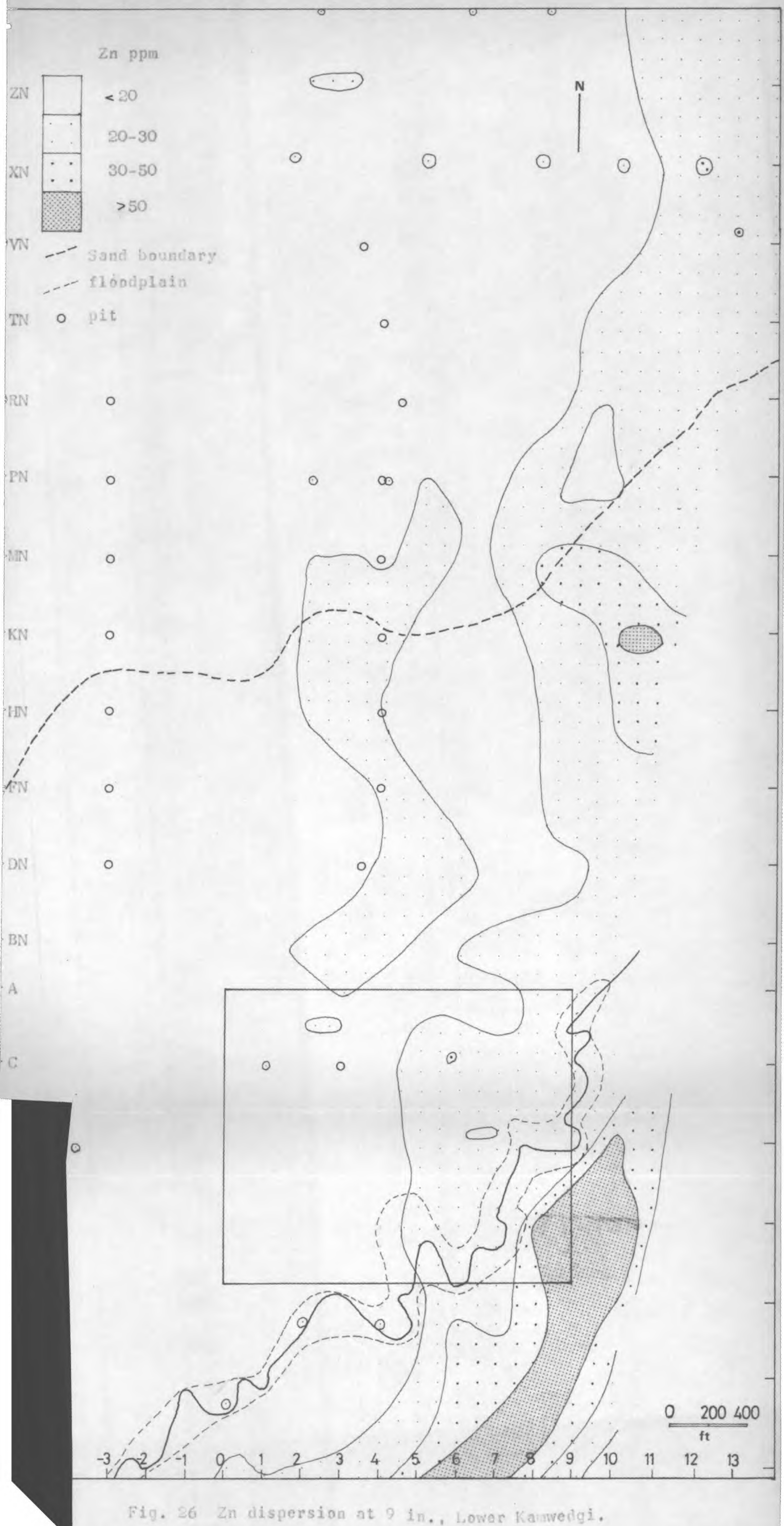


Fig. 26 Zn dispersion at 9 in., Lower Kamwedgi.

(3) a zone of high Zn-Mn-Fe values, south-east of the Prospect Block, in thin soil on outcropping lateritic-capped quartzitic bedrock and may be a continuation of zone (ii). The peak value of each element occurs in colluvial soil below the laterite and may result from hydromorphic concentration. The extension of the Zn anomaly on to the flood-plain probably reflects the high mobility of Zn in saline dispersion.

(4) low Mn and Fe content of the soil of the Prospect Block and to the south-west of the Block, possibly due to increased leaching through stronger drainage associated with the increased slope angle.

(ii) Vertical dispersion

Soil profiles in residuum vary in thickness from 0 to 17 ft. The profile (Fig. 27) normally comprises a 2 in. surface Ao horizon, underlain by a 3-6 in. transition zone with a downward decreasing humic content. This overlies both A and B horizons which comprise up to 10 ft. of red-brown, homogeneous soil containing predominantly fine-grained, angular quartz with associated kaolinite clay. The C horizon is up to 5 ft. thick, and contains abundant fragments of the underlying decomposed bedrock. Weathering of the bedrock is extensive, and shales are frequently reduced to a red clay with relic structures while quartzite can become extensively friable. Laterite is frequently developed, in the base of the B horizon, forming an indurate or loose layer of Fe pisolites in various stages of development. This zone frequently extends into the C horizon where the heterogeneous matrix aids oxidation and deposition of Fe. Silicification may occur with the lateritisation.

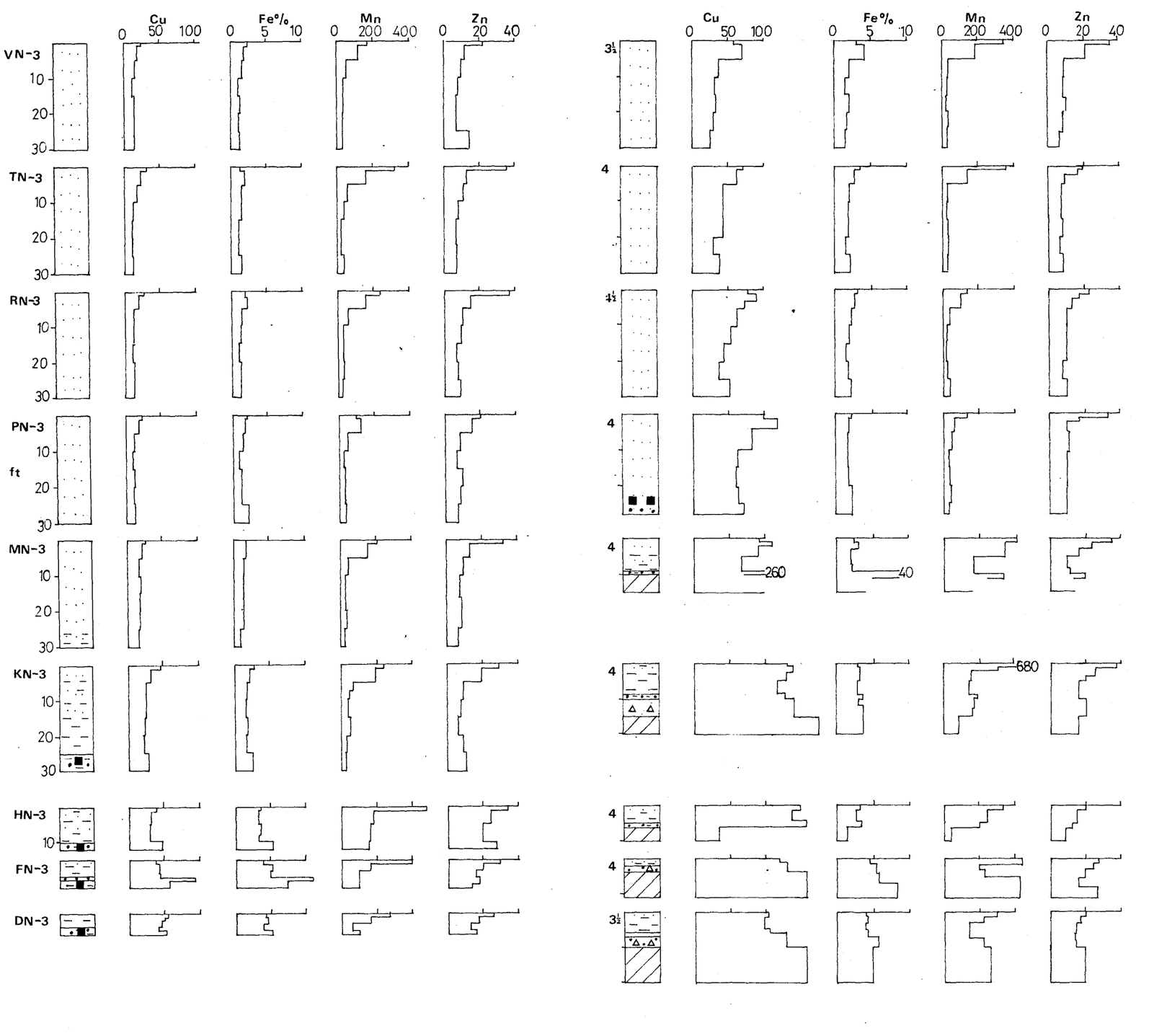
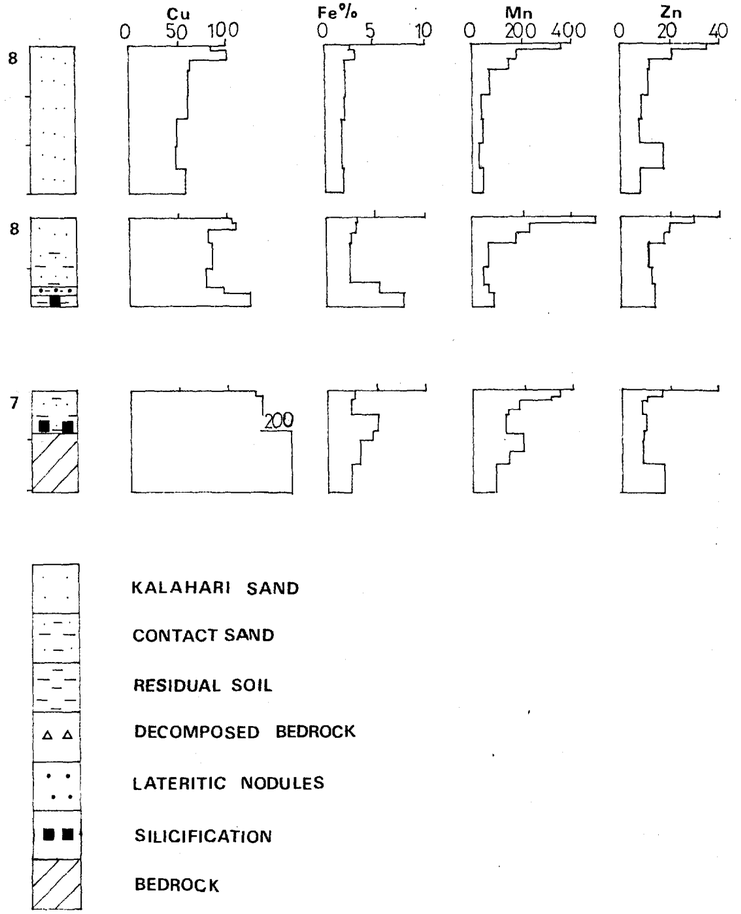


FIG.27 OVERBURDEN PIT PROFILES, LOWER KAMWEDGI (ppm).



The Cu content of the Ao horizon is erratically higher or lower than in the underlying soil. Cu values tend to decrease down-profile in the thin A horizon. Concentration of Cu frequently appears in the lateritic and C horizons, and bedrock may be further enriched (e.g. pit DN $3\frac{1}{2}$). In background areas, profile values range from 29-100 ppm while in the anomalous zone the range is 67-1400 ppm. The peak value (1400 ppm) occurs at pit C3 in C horizon rubble, directly overlying bedrock containing 1200 ppm Cu. The threshold is 100 ppm in the A horizon but is slightly greater at depth, and may be 50% higher in laterite zones. Although the Cu content varies in depth, the Cu contrast of equivalent depth horizons shows little variation. As the Cu content of the Ao, lateritic and rubble zones can be more variable, the Cu contrast in A horizon material is the most consistent.

Fe values are variable in trend in the A horizon below sporadic Ao enrichment. Marked concentration of Fe occurs in the C horizon and pisolitic zones (e.g. pit KN4). The Mn content decreases markedly below the Ao horizon, while the content in the C horizon tends to reflect the bedrock content. The Zn distribution is similar to Mn.

The organic carbon content of soil profiles varies from 0.8-1% at the surface to 0.3% at 10 ft. depth, irrespective of lateritic development.

(c) Kalahari Sand

(i) Surface dispersion (Fig. 22)

The Kalahari Sand is orange-brown in colour and increases rapidly in thickness northwards from the contact residual soil boundary; it is over 30 ft. deep at peg PN4 and 55 ft. deep at peg PN-4.

The Cu distribution (Fig. 23) reveals a broad, enriched zone extending along the Sand-soil boundary with a superimposed north-trending anomaly. Local background values decrease northwards from 50 to 25 ppm, while the anomaly peak decreases from 185 to 52 ppm. Below the Sand anomaly at peg PN5, and beneath an overburden of 30 ft. of Kalahari Sand, the bedrock contains 400 ppm Cu at 110 ft. depth (Fig. 28).

The Cu contrast in the Sand is consistently 2 to 3 if calculated by comparing anomalous values to the immediate local background values. If a -200# dry sieved fraction is employed, the anomaly is not defined northwards beyond line RN as the Cu contrast of this fraction is lower than the silt contrast.

The Fe distribution (Fig. 24) exhibits two broad zones of enrichment. In the east, a zone of >4% Fe extends northwards from pegs RN 12-14. A second weaker zone with values of >3% follows the Cu anomaly. The general range of Fe in the Kalahari Sand is 2.5-3.5%.

The Mn content of the Sand decreases westwards, from 400 to <200 ppm (Fig. 25). A broad band of higher values (> 300 ppm) extends northwards from pegs RN/12-14.

Zn values (Fig. 26) show a similar pattern to the Mn, and values in the Sand tend to be below 20 ppm.

Thus in the Kalahari Sand, two zones of trace element enrichment appear:

(1) a central Cu-Fe zone extending northwards and overlying Cu enriched bedrock at peg PN5.

(2) a Fe-Mn-Zn zone in the east, extending northwards, and may be a northerly extension of the bedrock enriched in these metals at pegs MN9-10.

(ii) Vertical dispersion

Profiles of Kalahari Sand (Fig. 27) typically display 30 ft. of homogeneous, orange-brown, loose-textured Sand. This Sand comprises abundant rounded, frosted, quartz grains with a kaolinite, Fe hydroxide-rich matrix. Towards the contact-residual soil boundary, the Sand contains Fe pisolites and is occasionally silicified at depth. The silicification results in loosely cemented nodules, several inches in diameter, or indurate silicification with chert development. At peg MN4, the Sand cover is less than 10 ft. in depth, but thickens to over 55 ft. at peg PN-4.

The distribution of Cu in profile (Fig. 27) is consistent in all pits. In background localities, maximum values occur in the Ao horizon (21-28 ppm) with a regular decrease with depth to 10-13 ppm at 30 ft. In anomalous zones, the corresponding values are 57-100 ppm and 27-69 ppm respectively. In both cases, the higher values appear southwards towards the contact-residual soil boundary. Pisolitic zones show slight Cu concentrations (e.g. pit PN4). The Cu contrast between corresponding horizons is approximately 3, although the value in the Ao horizon tends to be more variable. The Fe distribution is relatively consistent in all sections. Maximum values may occur in the Ao horizon (1.5-3.5%) and decrease to 1.0-2.0% at 30 ft. depth. Near the residual soil boundary, values near the base of the profile are over 2%, and indicate admixed residuum or lateritisation (e.g. pit PN4). The Mn content reveals an abrupt 4-10 fold decrease from the Ao horizon to 5 ft. depth, where the range is 34-69 ppm. At 30 ft. depth, the values range from 20 to 40 ppm.

The Zn dispersion is similar to Mn, with a marked enhancement in the Ao horizon (20-37 ppm). Values rapidly decrease to 7-10 ppm at 30 ft. depth.

In order to establish the cause of the surface anomalies in the Kalahari Sand, power auger drill holes were subsequently sited at 3 localities (Fig. 28):

(1) Contact-residual soil Cu-Fe-Mn-Zn anomaly (pegs MN9 and MN10)

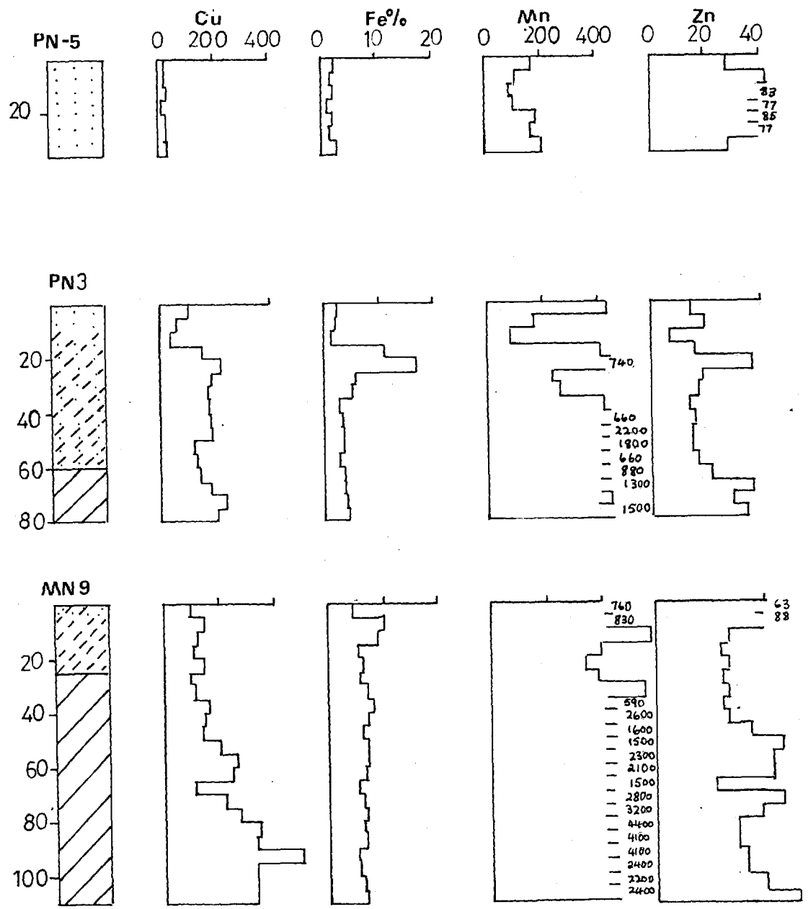
(2) Kalahari Sand Cu anomaly (pegs PN 3, 4 and 5)

(3) Kalahari Sand background (pegs PN-4 and -5)

(1) Contact residual and residual soil extends for 10 to 25 ft. down to quartzite bedrock. The bedrock is enriched in Cu (920 ppm), Fe (20%), Mn (8800 ppm) and Zn (540 ppm), which account for the high soil and Sand values of this area.

(2) The overburden consists of 5-45 ft. of Kalahari Sand with silicification zones, 5-55 ft. of contact Kalahari Sand overlying quartzite at 30 ft. at peg PN5 and 60 ft. at peg PN3. Cu values are high in bedrock with 255 ppm at peg PN3 and 430 ppm at peg PN5. In the overlying overburden high Cu values occur in the silicification and laterite bands. Bedrock enrichment is thus reflected in the overlying Sand values. Mn is also high in bedrock (2200ppm at peg PN3) and correspondingly enriched at surface, although surface values of the drill samples are considerably higher than near-surface sampling values. This is partly explained by the fact that the surface 5 ft. sample of the power auger drill includes the Ao horizon material.

(3) Kalahari Sand is over 55 ft. thick and is lateritised at depth. Cu values throughout the profile are



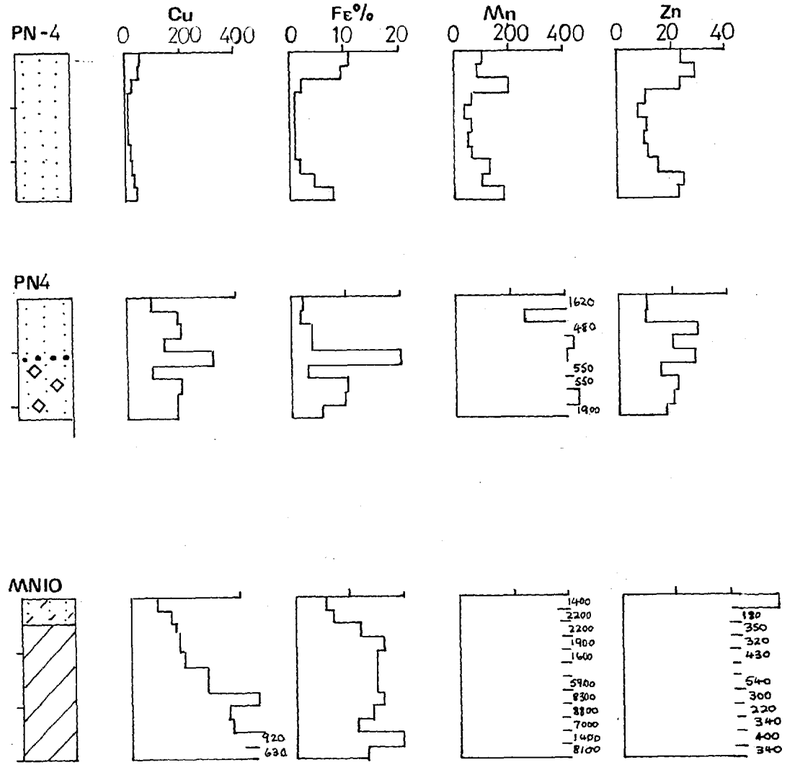
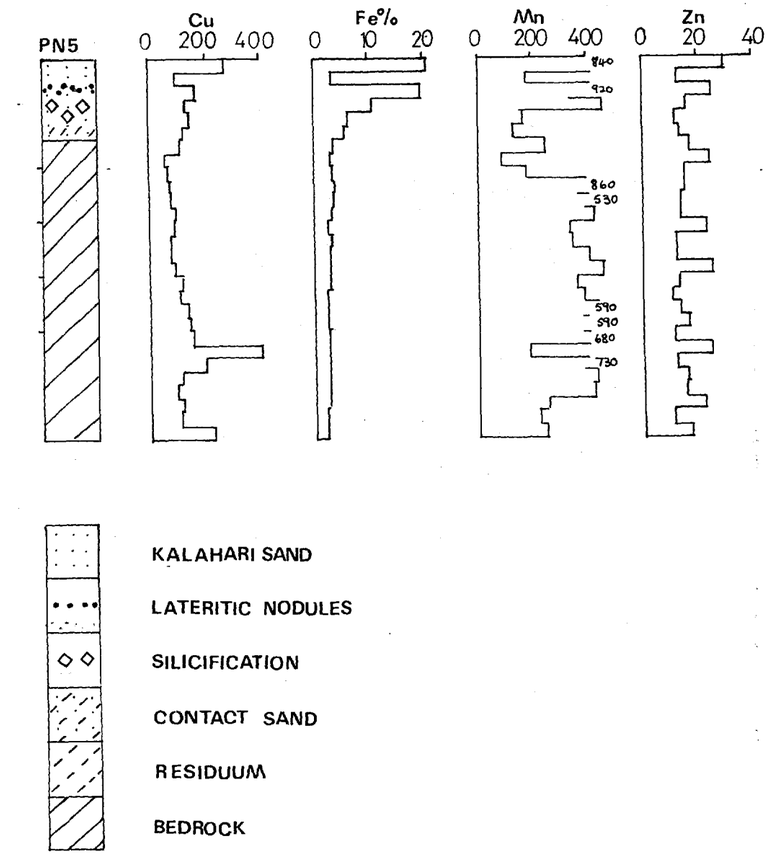


FIG. 28
WAGON DRILL PROFILES,(ppm)

LOWER KAMWEDGI



low and fluctuate slightly with depth (20-27 ppm at peg PN-5). At peg PN-4, the Cu values at surface are slightly higher, probably due to the associated higher Fe content.

The organic carbon content of Kalahari Sand is greater than in residual soil. The value at surface is 1.2-1.6% and drops to <0.2% at 10 ft. depth. The value thus decreases more rapidly with depth in Kalahari Sand than in soil. This may be the result of decreased biological activity in the Sand and in particular to termite activity. Termitaria are not apparent in Kalahari Sand areas while they are abundant in residual soil. Consequently reworking of the soil by termites may carry carbonaceous material down-profile, decreasing the content at surface and increasing the content at depth.

(d) Dambo Sediment

(i) Flood-plain alluvium.

The sediment of the Kamwedgi River flood-plain is a humic, black to brown, silt or silty sand. Cu values in the sediment (Fig. 23) reflect the values of the surrounding residual soil. The extension of the Cu anomaly into flood-plain alluvium may be due to saline dispersion. The Fe (<2%) and Mn (<100 ppm) contents of the alluvial plain are low (Fig. 24 and Fig. 25). The Zn content (Fig. 26) varies from 16-27 ppm, and values tend to reflect the residual soil distribution.

The river alluvium is unlikely to be of local origin. The river extends for 40 miles upstream and consequently during the Rains, the entire flood-plain is covered by several feet of fast flowing water, and considerable reworking of the sediment is likely to occur. In addition, the river flood-plain represents an area of redeposition by a meandering river. The lower contents of Fe and Mn in the sediment may reflect

the lower average composition of the exotic alluvium, while the continuation on to the sediment of the local soil Cu and Zn patterns, may be a result of the saline dispersion of these relatively mobile elements.

(ii) Stream sediment

Samples of fine river sand, collected from the active stream bed, have a Cu dispersion similar to that of the flood-plain alluvium and residual soil. Upstream of the anomaly, the Cu content is <50 ppm but immediately opposite the soil anomaly, the river sand value increases to 170-290 ppm. For a further 2200 ft. downstream of the anomaly the content of the sand is below 60 ppm. The Fe values of the river sand are variable from 1.7 to 6.3%, and do not correlate with the alluvium or soil Fe values. Mn in the river sand is generally <100 ppm, and similar in content to the alluvium values. The Zn content in the sand is below 50 ppm.

The river sand is partly of local origin, and is derived from the sporadic outcrop in the river bed. Consequently metal values in the Sand will tend to be erratic. Cu mineralised bedrock is well exposed in the river bed, and gives rise to a clastic dispersion of limited extent in the sand.

3. MIDDLE KAMWEDGI AREA

(a) Previous Work

The area is covered by a considerable thickness of Kalahari Sand which is locally over 80 ft. deep. Bedrock and residual soil have not been intersected. A minor westward flowing dambo drains into the main Kamwedgi dambo (Fig. 29). During a regional stream sediment sampling programme in 1957

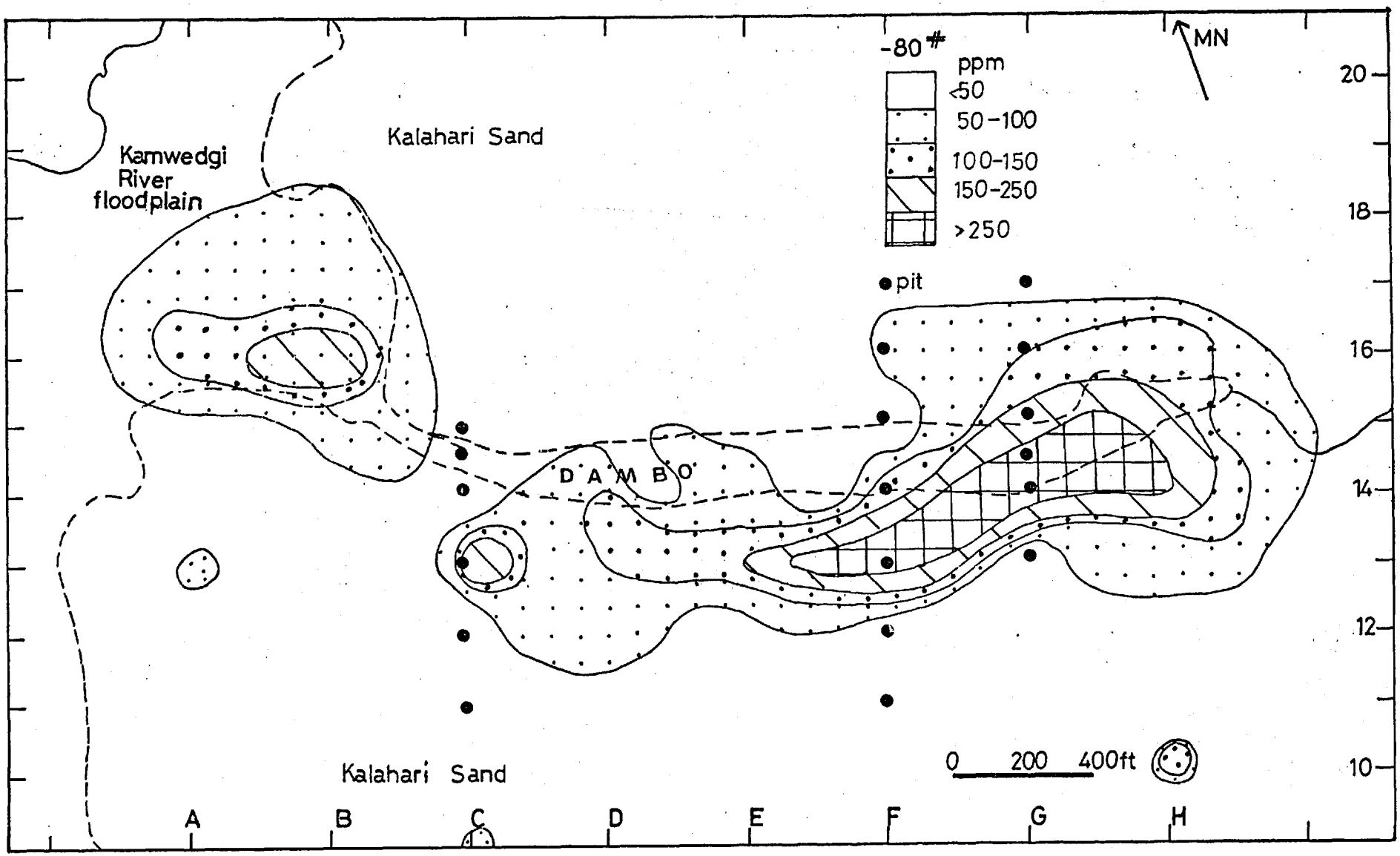


Fig 29. Cu anomaly at Middle Kamwedgi
(company hand auger data).

by R.S.T., a Cu anomaly of 450 ppm (-80#D, dithizone) was detected in the Kamwedgi dambo immediately downstream of the tributary. Later soil sampling in the vicinity of the tributary in the same year, outlined the probable source of Cu as the Middle Kamwedgi anomaly (150 ppm), occurring 2000 ft. east of the Kamwedgi River margin. A follow-up hand auger and pitting programme in 1968 in the minor dambo indicated a maximum peak of 800 ppm Cu (chromatography) with a background of 50 ppm.(company data).

(b) Kalahari Sand

(i) Surface dispersion

The head of the tributary lies 6000 ft. south-east of the Kamwedgi River, and cuts a small depression in the widespread, buff coloured Kalahari Sand overburden. Similar Sand flanks both banks of the lower dambo zone of the tributary. The Cu anomaly occupies a zone on the southern fringe of the dambo and extends into the Kalahari Sand beyond the south bank with a peak value of 800 ppm (chromatography) at peg F13. Upstream, and within the drainage basin, values are consistently below 50 ppm.

(ii) Vertical dispersion (Fig. 30)

The Sand overburden is locally over 80 ft. thick, and comprises a homogeneous, structureless, cream to buff Sand which becomes pallid at depth. Fe forms occasional orange mottling in profiles upstream of the dambo, while lateritic zones occur in the Sand profiles on either bank of the dambo where the water-table is relatively shallow. Silicification zones, up to 5 ft. thick, comprise nodules of silica-cemented Sand grains, in a Sand matrix and harden on exposure.

FIG.30 PIT PROFILES, MIDDLE KAMWEDGI (ppm)

KALAHARI SAND

LATERITIC NODULES

SILICIFICATION

RIVER PEBBLES

HUMIC SEDIMENT

The Cu content of profiles upstream of the dambo shows regular decreasing content with depth. (Fig. 30, line Q). The content range decreases from 14-62 ppm in the Ao horizon to 8-36 ppm at 5 ft., and 4-12 ppm at 30 ft. depth. Near the dambo, enrichment of Cu is associated with Fe mottled and lateritic horizons (e.g. pits F11 and G13): in the latter, values of up to 230 ppm Cu are noted in the crushed laterite material.

The Fe content is low with a regular variation of 0.28-0.76% in the Ao horizon to 0.15-0.55% at 30 ft. Fe enrichment is associated with Fe pisolitic zones (e.g. pits F12, G13) and to a lesser extent with silicification (e.g. pit F12).

Mn may exceed 230 ppm in the Ao horizon, but drops abruptly to 30 ppm at 5 ft. and to 3-13 ppm at 30 ft. depth. Higher values are associated with the pisolitic (e.g. pit F11) and silicification zones (e.g. pits G13, G17).

The Zn dispersion is similar to Mn with a range of 11-33 ppm in the Ao horizon, decreasing to 5-8 ppm at 10 ft., and 4-6 ppm at 30 ft. depth. Zn is similarly enriched in the silicification (pits F12, F13) and lateritic zones (pits F11, G13).

The organic carbon content in Kalahari Sand decreases from 1.11-1.38% in the Ao horizon to below 0.1% at 10 ft. depth.

(c) Stream sediment

In the upper reaches of the tributary, the profile contains possibly reworked, buff Kalahari Sand, which extends in depth to 82 ft. In the area of the present-day dambo, and extending beneath both banks, the dambo sediment profile is mainly a buff Kalahari Sand redeposited as a stream sediment

with occasional detrital pebbles. Pebble zones occur spasmodically throughout the profile and quartz pebbles of up to 6 in. diameter indicate former active stream conditions. Fe mottle and pisolitic horizons occur.

A marked feature of the profiles is a 6 in. to 2 ft. thick, black to brown, humic, silty band occurring at 2-5 ft. depth below the present surface. This zone extends laterally below both banks.

The vertical Cu dispersion in the upper reaches of the tributary illustrates a decrease with depth from 23-29 ppm at surface to 11-12 ppm at 25 ft., and erratic variation (11-27 ppm) to a depth of 82 ft. In profiles in the lower dambo, the Cu dispersion is dominated by the subsurface humic zone, in which values of up to 2,600 ppm occur. The concentration of Cu in this humic horizon shows a direct relationship to the organic carbon content (Table 19, Fig. 30). Where the humic zone merges upwards and downwards into buff sand, the Cu values decrease to background levels (Table 20). In general the dambo profile values decrease with depth, but mottle, pebble and pisolitic zones cause local concentrations.

Table 19. Trace element content (ppm) relative to organic carbon content (%) Middle Kamwedgi dambo profile.

Depth	Description	Cu	Fe%	Mn	Zn	C%	pH
0-2"	Ao horizon	560	2.8	120	21	1.39	5.47
2"-1'2"	transition zone	920	3.0	25	16	1.36	5.04
1'2"-2'6"	mottled sand	270	2.3	21	6	0.08	5.68
2'6"-3'6"	humic zone	1300	1.6	12	19	1.26	5.24
3'6"-4'6"	humic zone	1600	0.5	12	19	1.37	5.10
4'6"-5'6"	pale purple sand	87	0.2	16	4	0.14	5.61
5'6"-9'	buff sand	31	0.2	12	6	<0.01	4.87

Table 20. Trace element composition of buried humic horizon, Middle Kamwedgi (ppm).
(-80# dry sieved, atomic absorption - company data.)

Pit	Depth(ft.)	Cu	Co	Ni	Zn	Fe%
F14	0-2	140	-	10	<20	0.5
	2-4	300	-	10	<20	0.5
G15	2-4	200	-	10	<20	0.1
H15	4-6	320	-	10	<20	0.1
	6-8	350	-	10	<20	0.1
Sediment background range		10-20	30	10-30	20-60	0.1-1.0

Similar tributary dambos, occurring 3 miles north and 2 miles south, drain similar Kalahari Sand environments, and display analogous Cu trends. Enrichment to 230 ppm Cu is found in subsurface humic zones, while values in underlying buff sand are less than 30 ppm.

At Middle Kamwedgi, in the upper tributary, Fe values in the profile tend to decrease with depth. In the lower dambo the values are variable, but are generally below 1%. Concentration of Fe occurs in pebble and pisolitic zones. The Fe content of the humic zone is low.

The Mn content in profiles in the upper tributary decreases initially with depth but shows a slight tendency to increase below 30 ft. In the lower dambo, values are variable but are generally less than 25 ppm beneath the Ao horizon. The subsurface humic zone is not enriched and contains 6-13 ppm Mn.

In profile, Zn shows a weak tendency to decrease with depth and values are 5-10 ppm below the Ao horizon. Values

in the humic zone indicate a slight concentration with up to 19 ppm. In the stream sediment, the organic carbon is generally enriched at surface (1.00-1.78%) and decreases with depth. The subsurface humic zone contains a maximum of 1.48% organic carbon, and values depend on the gradation with surrounding sediment. Above and below the humic zone, values in buff sand are less than 0.05%C.

The Cu anomaly is thus coincident with a subsurface humic horizon in the dambo profile. The high organic content of the zone suggests that it is a former, swampy, dambo meander, slightly offset from the present dambo course. This zone has acted as a trap for Cu transported downstream. Similar dambos, occurring to the north and south, with similar Cu-enriched, humic zones, suggest the origin of the Cu may be from a source located within the watersheds of the three dambos.

4. JIJOMBO AREA

(a) Previous Work (Fig. 31)

In the study area, regional stream sediment sampling by R.S.T. in 1957 detected a Cu anomaly of 60-250 ppm (chromatography) on the western side of the Jijombo dambo. The background threshold is 50 ppm. Subsequent soil sampling detailed an area in the dambo sediment with up to 230 ppm Cu (chromatography). Cu values of 10-20 ppm were located beyond the west bank, and 10-30 ppm beyond the east bank. Later hand-auger sampling outlined the anomaly between lines C and D in the dambo sediment but failed to locate any extension of the anomaly beyond the dambo margin. In 1968 during the present study, after positive indications of anomalous Cu in termitaria samples from west bank Kalahari Sand, power auger

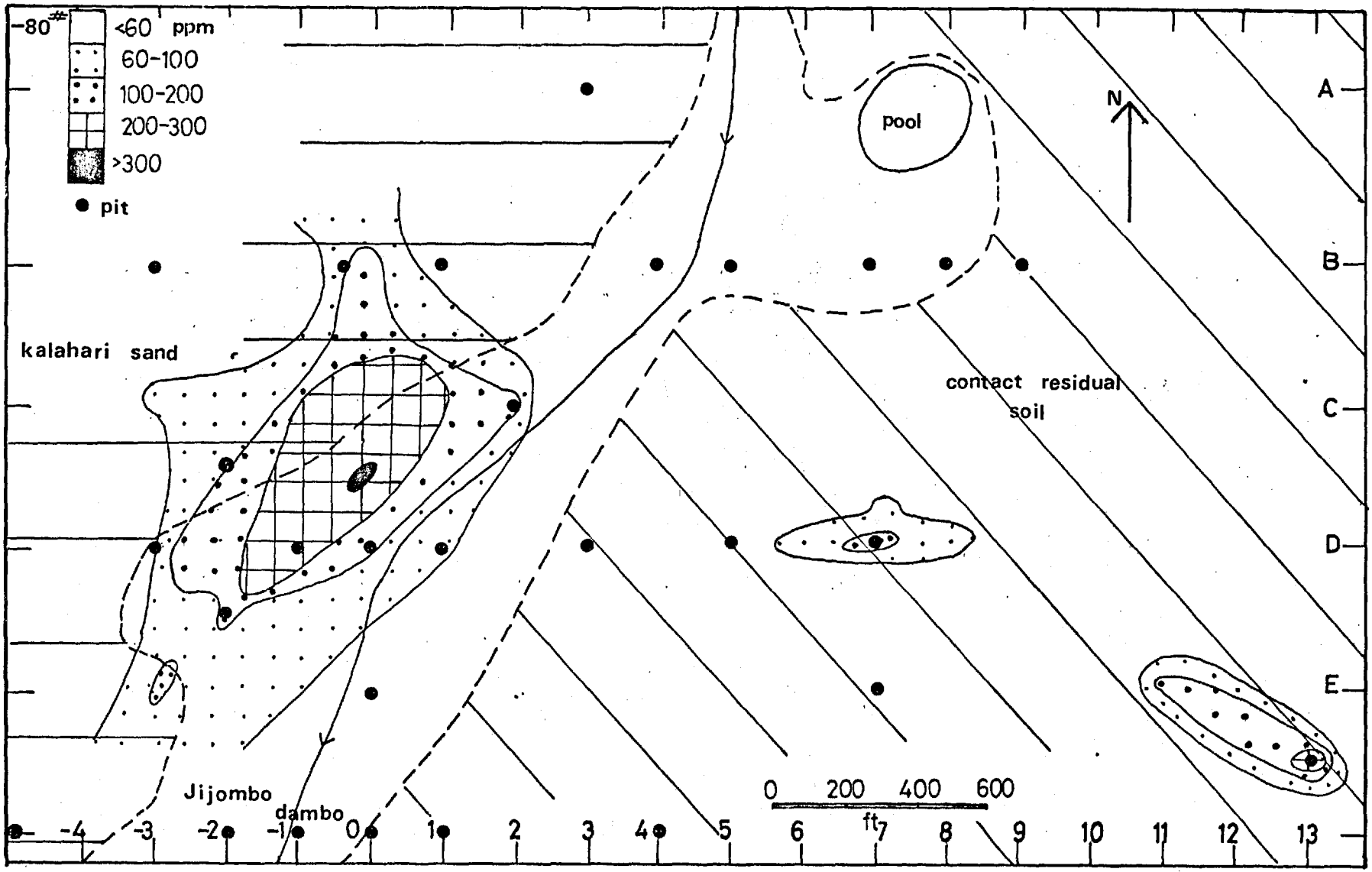


Fig.31 Cu anomaly at Jijombo area (company machine auger data).

drilling outlined Cu enrichment in the bedrock. Up to 350 ppm Cu (hydrochloric-perchloric acid extraction) occurs at peg C½9 in mudstone below dambo sediment, with an extension beneath the west bank Kalahari Sand at 37 ft. depth in mudstone (Fig. 31, peg C10; Fig. 32 - company data).

(b) Contact-residual Soil

Power auger drilling has revealed that bedrock is on average less than 10 ft. below the surface beyond the east bank and the overburden is a yellow to orange-brown contact-residual soil overlying residual soil. The C horizon contains bedrock fragments and is lateritised.

(i) Vertical dispersion (Fig. 32).

In background areas, the Cu values in the A horizon range from 14-22 ppm and increase in the lateritic zones with values up to 50 ppm (e.g. pit F8). In bedrock, the Cu range is 15 to 30 ppm with 160 ppm in anomalous areas (e.g. pit E½-4).

The Fe dispersion in the A and B horizons ranges from 0.4-3.6% with enrichment in the Fe pisolitic zones. Values in bedrock vary from 3.4 to 13.4% Fe.

Mn displays a marked enrichment in the Ao horizon (170-610 ppm) but the content decreases rapidly in the A horizon. Values in bedrock vary from 240-950 ppm.

Sparse data on the Zn dispersion indicates values of 14-17 ppm in the C horizon while bedrock contains 32-75ppm. SoilCo values are low (6-15 ppm), with enrichment in Fe pisolitic zones (e.g. pit F8).

(c) Kalahari Sand (Fig. 33).

On the west bank of the dambo, the overburden is a grey-white Kalahari Sand, which increases in depth from 27 ft. on

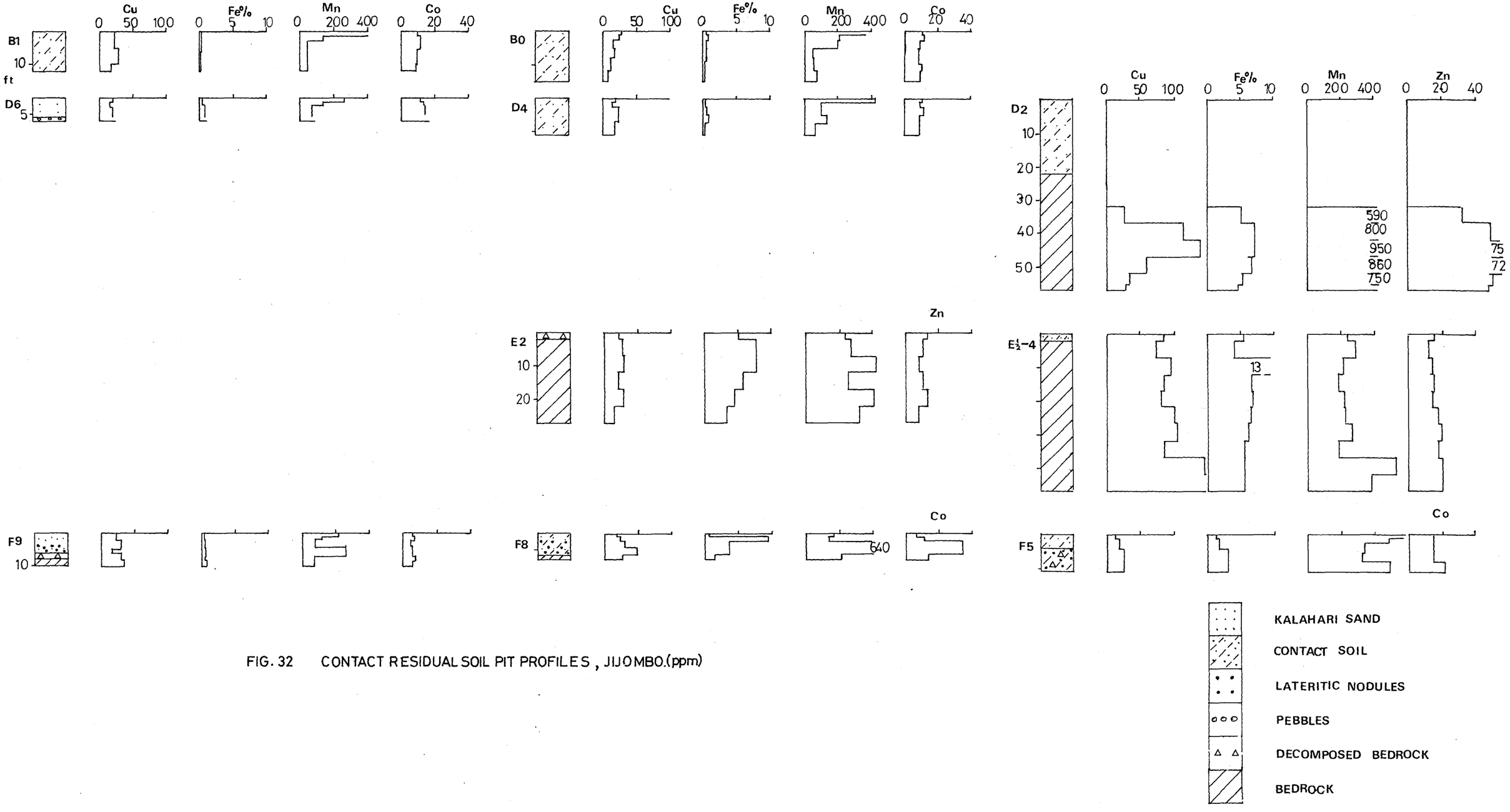


FIG. 32 CONTACT RESIDUAL SOIL PIT PROFILES , JIJOMBO.(ppm)

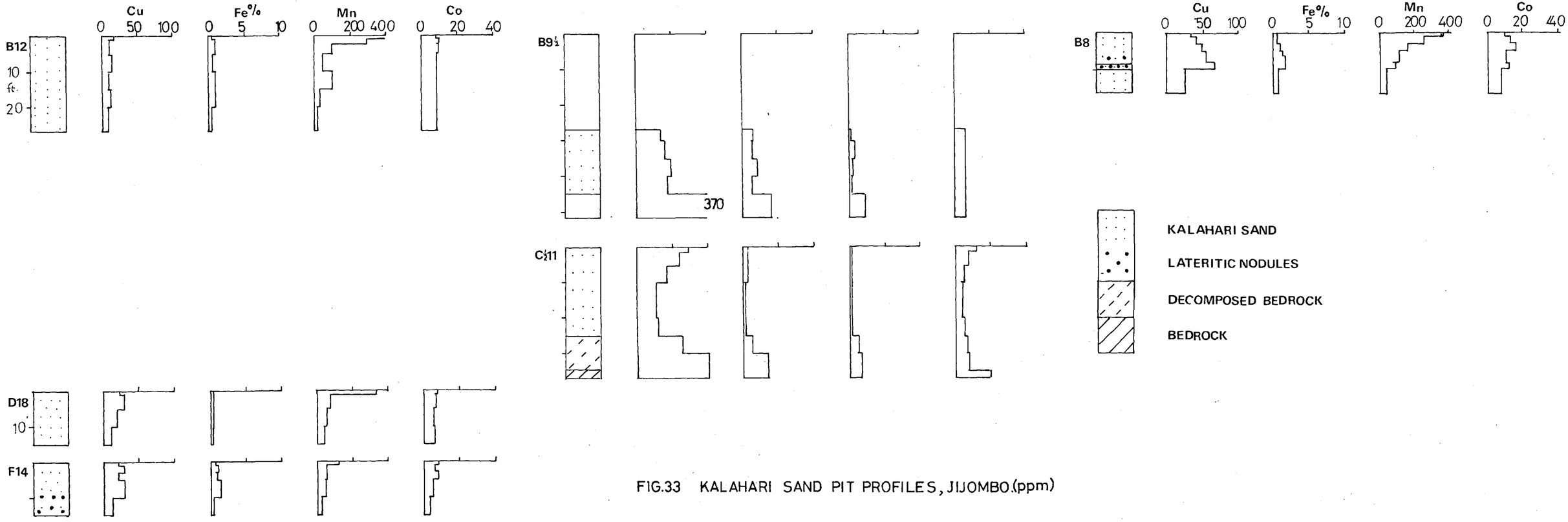


FIG.33 KALAHARI SAND PIT PROFILES, JIJOMBO.(ppm)

the dambo margin to over 170 ft. westwards (peg D13). The Sand overlies bedrock quartzite and shale.

The near-surface Cu dispersion exhibits a background range of 20-30 ppm with an anomalous peak of 70 ppm near peg C10. This anomaly is not indicated on analysis of the -80# D Sand fraction.

(i) Vertical dispersion

In depth, the Sand profile is structureless and comprises white to buff Sand containing sporadic Fe mottle and pisolitic development (Fig. 33). The vertical Cu dispersion is variable but tends to decrease with depth. In background localities, the value range is 7-49 ppm. In anomalous areas (e.g. pits $B9\frac{1}{2}$, $C\frac{1}{2}11$) the range in profile is 28-73 ppm, while the bedrock contains up to 380 ppm.

The near-surface Fe dispersion ranges from 0.3 to 0.8%. In depth, Fe values tend to increase in the upper 20 ft. with concentrations in Fe pisolitic zones. Bedrock has over 3½% Fe. Mn is high in the Ao horizon (130-610 ppm) and decreases with depth. Bedrock contains over 70 ppm Mn.

The near-surface Zn content is 10-20 ppm. In vertical profiles, values are less than 16 ppm, with up to 20 ppm in bedrock. The Co content in profiles is low (4-12 ppm).

(d) Stream Sediment (Fig. 34)

The sediment of the Jijombo dambo in the study area is mainly redeposited Kalahari Sand with occasional pebbles or rock fragments. The sediment profile comprises a dark brown to black Ao horizon, overlying a cream or grey clay or sand zone, with sporadic brown Fe mottle. A pale grey glei clay or sand horizon occurs immediately above the water-table.

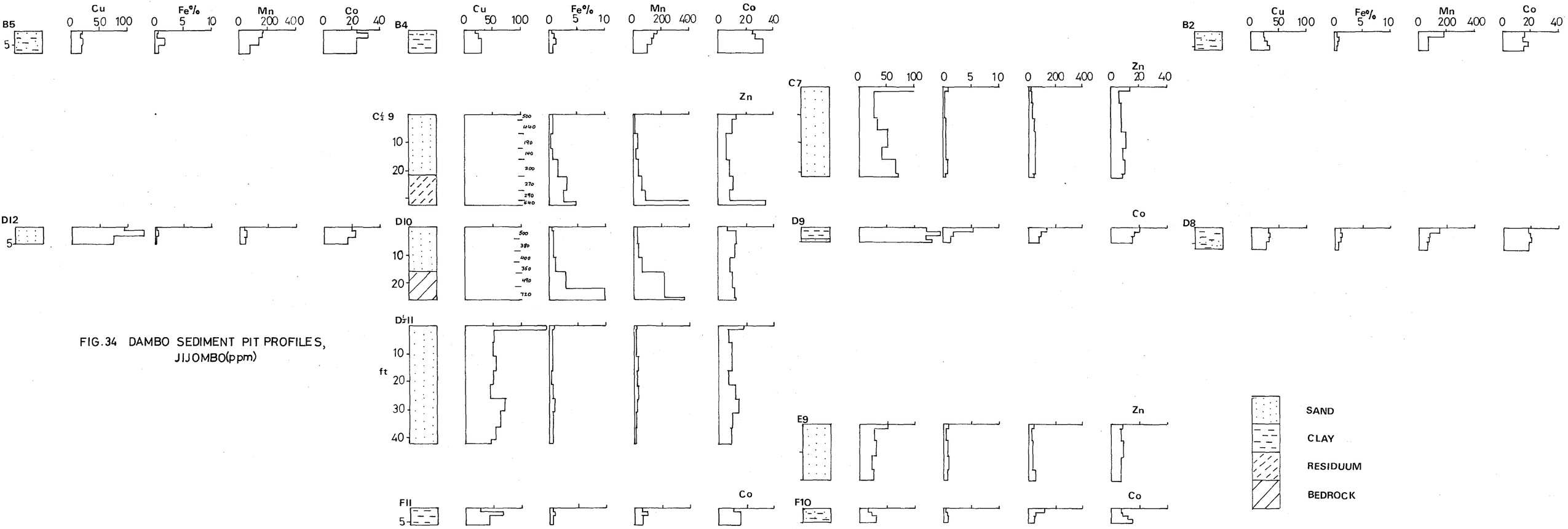


FIG. 34 DAMBO SEDIMENT PIT PROFILES, JIJOMBO(ppm)

(i) Vertical dispersion

In background areas, upstream of the anomaly (Figs. 31 and 34, line B), the vertical dispersion of Cu has a range of 18-32 ppm, and the content decreases with depth. At, and downstream of the anomaly, Cu values increase to 600 ppm at surface (pit C½9). Values decrease with depth, while in bedrock, values are high. There is no apparent association of Co, Ni nor Zn with the Cu mineralisation in bedrock (Table 21).

Table 21. Trace element content of bedrock (ppm), Jijombo area (peg D/10) (-80# dry sieved, hydrochloric-perchloric attack, company data.)

Depth(ft.)	Description	Cu	Co	Ni	Zn	Fe%
0-2	Dambo sand	250	-	30	<20	0.5
2-7	" "	180	-	30	<20	0.5
7-12	" "	160	-	30	<20	0.5
12-17	Bedrock	200	-	30	<20	0.5
17-22	"	230	-	30	<20	0.5
22-27	"	130	10	30	<20	0.5
22-27(bit sample)	"	400	10	30	<20	0.5
Background bedrock		10-50	10-30	10-60	<20-50	0.5-10.0

The Fe distribution varies (0.3-1.8%) and concentration appears in Fe mottle zones. Bedrock contains over 2% Fe.

The Mn content is enriched in the Ao horizon but is variable with depth (10-170 ppm). Bedrock contains up to 1000ppm. Zn (6-14 ppm) and Co (7-32 ppm) are variable in profile, while bedrock values of 7-32 ppm Zn and 8-12 ppm Co respectively occur.

5. CONCLUSIONS

The following conclusions may be drawn from the observed data of the four study areas:-

(a) Bedrock

(i) No significant primary dispersion correlation with Cu mineralisation has been found for:

(1) Fe, Zn, Co, Ni at Lower Kamwedgi.

(2) Fe, Zn, Co, Ni at Jijombo.

(ii) Bedrock comprises interbedded quartzites and shales and contains a higher metal content than residual soil or Kalahari Sand. The following ranges occur (Table 22):-

Table 22. Trace element ranges in bedrock (ppm)

	Mufumbwe	L. Kamwedgi	M. Kamwedgi	Jijombo	Average* sandstone
Cu	6-920	60-1200	-	26-720	10-40
Fe%	0.7-6.6	2.3-20.0	-	0.7-13.4	3.1
Mn	6-420	23-8600	-	59-1200	390
Zn	6-27	6-560	-	7-50	5-20
Co	6-28	-	-	7-14	1-10
No. of Samples	19	62	-	30	

*after Hawkes and Webb, 1965.

(b) Residual and contact-residual Soil

(i) Trace element values are impoverished by dilution through admixtures of Kalahari Sand. Virtually all present-day surface soil in the study area has some contamination by Kalahari Sand.

(ii) There is no significant trace element secondary dispersion correlation with Cu. In Cu anomalous soil, Fe and Mn are locally enriched.

(iii) Soils at 9 in. depth have the following ranges (Table 23):-

Table 23. Trace element ranges in residual and contact-residual soil at 9 in. depth. (ppm).

	Mufumbwe	L. Kamwedgi	M. Kamwedgi	Jijombo	Average* soil
Cu(background)	10-40	24-100	-	10-30 (chromatography)	20
Fe%	2.5-6.6	1.8-8.8	-	0.2-3.6	1.4-4.0
Mn	200-500	60-630	-	45-640	850
Zn	15-40	12-30	-	-	50
Co	16-20	-	-	8-34	8
Ni	25-60	-	-	-	40
Pb	20-40	-	-	-	10

*after Hawkes and Webb, 1965.

(iv) Local Cu background threshold in A horizon soil varies between 40 ppm at Mufumbwe and 100 ppm at Lower Kamwedgi. The threshold may be 50% higher in lateritic horizons.

(v) The vertical dispersions of metal shows considerable variation due to the short profiles and proximity of bedrock, and to the sporadic development of laterite horizons, which vary in depth and in intensity of development. The vertical dispersions of metals are also influenced by rubble and silicification zones. The following variations occur (Table 24):-

Table 24. Trace element variation with depth in residual and contact-residual soil

	Maximum value in Ao horizon	Variation of content with depth	Approximate concentration in lateritic zones
Cu(background)	erratic	variable	(x1.5)
(anomalous)	erratic	increase	
Fe	erratic	variable	(x10)
Mn	maximum	decrease	(x4-6)
Zn	maximum	decrease	(-)
Co	maximum	-	(x5)

(vi) Anomalous Cu values in soil are related to Cu enriched bedrock at Mufumbwe, Lower Kamwedgi and at Jijombo. At Mufumbwe relatively high grade bedrock mineralisation produces a soil value (9 in. depth) of 250 ppm (-80#D) while at the Lower Kamwedgi similar bedrock mineralisation underlies a soil value (9 in. depth) of 160 ppm (-80#D) or 240 ppm (silt).

(vii) Fe, Mn and Zn contents in soils show a direct relationship to bedrock enrichment at Lower Kamwedgi.

(c) Kalahari Sand

(i) Metal values are lower in Kalahari Sand than in soils and display the following ranges at 9 in. depth (Table 25):-

Table 25. Trace element variation in Kalahari Sand at 9in. depth (ppm).

		Mufumbwe	L. Kamwedgi	M. Kamwedgi	Jijombo
Cu	background range	4-19	10-50	(9-40(silt) (14-50(chrom-atography)	8-30
	peak value	-	54-190	430	70
	contrast	-	2.0-3.8	10.8	2.3
Fe%		0.3-1.3	2.5-3.5	0.3-3.0	0.3-0.8
Mn		20-420	100-400	6-140	30-90
Zn		7-25	12-20	9-17	10-20
Co		3-12	-	-	4-12

(ii) The content of Mn at 9 in. depth may be similar to the levels in residual soil due to Mn-rich organic matter contamination.

(iii) Metal values exhibit a systematic decrease with depth, and have similar ranges in each area (Table 26):-

Table 26. Trace element variation with depth in Kalahari Sand (ppm).

	Depth	Mufumbwe	L.Kamwedgi	M.Kamwedgi	Jijombo
Cu(background)	Ao	8-33	21-28	14-62	15
	30ft.	10-22	10-13	4-12	7
Fe%	Ao	0.3-1.2	1.5-3.5	0.3-0.8	0.3-0.8
	30ft.	0.6-2.0	1.0-2.0	0.2-0.6	0.4
Mn	Ao	84-800	100-300	230	90-600
	30ft.	20-34	20-40	3-13	17
Zn'	Ao	14-68	20-37	11-33	10-20
	30ft.	9-16	7-10	4-6	-

(iv) The Ao horizon shows considerable enrichment for Mn (3 fold), Zn (2 fold) and Cu from background areas (1½ fold). Laterite, which can develop in pisolitic form, over a depth of at least 21 ft., Fe mottle and silicified zones, generally result in increased metal values, and may exert an influence throughout the profile. Cu-Fe and Mn-Zn associations appear in profile.

(v) Cu anomalies in Kalahari Sand resulting from Cu enriched bedrock can be successfully detected, using the silt fraction of the Sand for analyses. Anomalies are detectable through Sand overburden of 30 ft., with bedrock mineralisation at 110 ft., at Lower Kamwedgi. Similar anomalies are found through 47 ft. of Sand on bedrock at 52 ft. in the Jijombo area. Coarser Sand fractions (e.g. -80#D) comprise

predominantly quartz grains and analyses of the fractions are insufficiently sensitive to detect Cu anomalies of low contrast.

(d) Dambo sediment

(i) Dambo sediment may be composed of residual soil or Kalahari Sand of local origin, or of exotic alluvium.

(ii) Trace metal values are generally low in dambo sediments (Table 27):-

Table 27. Trace element ranges in dambo sediment(below Ao)ppm.

	Mufumbwe	L.Kamwedgi	M.Kamwedgi	Jijombo
Cu(background)	4-50	22-50	<50	18-32
Fe%	0.3-12.0	1.1-1.9	0.2-1.3	0.3-1.8
Mn	25-2800	29-98	7-90	10-170
Zn	5-110	19-27	5-30	7-14
Co	5-98	-	-	-

The following variations in metal content with depth occur (Table 28):-

Table 28. Trace element variation with depth in dambo sediment

	Variation in depth (draining residuum)	Variation in depth (draining Kalahari Sand)
Cu anomalous	increase	decrease
background	variable	decrease
Fe	increase	variable to decrease
Mn	decrease	variable to decrease
Zn	increase	variable to decrease
Co	increase	-

(iii) Laterite, Fe mottle and pebble zones are generally enriched in trace elements. Mn, Zn and Co show coprecipitation effects, while Cu may show a correlation with Fe, Mn and C contents.

CHAPTER IV DISCUSSION OF THE FACTORS CONTROLLING THE SECONDARY DISPERSION OF COPPER AND ASSOCIATED ELEMENTS

1. PRIMARY METAL DISPERSION

The distribution of Cu in the bedrock is the primary factor controlling secondary dispersion values. In addition, the relative abundance of associated metals in the bedrock may produce diagnostic trends in the overlying overburden. The various rock types tend to have significant and differing contents of metal. The average metal content of sandstone and shale, the metamorphosed equivalents of which appear to underlie much of the study area, are shown in Table 29.

Table 29. Average metal contents of rock types (ppm)

Rock Type	Cu	Fe%	Mn	Zn	Co	Ni
acid igneous	7.0*	4.6*	1000*	80*	10	0.1
sandstone	10-40+	3.1+	385+	5-20+	1-10+	60
shale	30-150+	4.3+	-	50-300+	10-50+	20-100+

*after Clarke, 1924; +Hawkes and Webb, 1965.

Sandstone and quartzite generally contain a lower trace element content than argillaceous rocks. Analyses of quartzite and shale derived from throughout the study area (Table 30), illustrate a slight tendency for enrichment in the shales. There is considerable local metal varation within individual rock types, and this may be the result of extensive oxidation and leaching of metal ions in near-surface bedrock by the processes of intensive weathering.

In general the trace element content of residual soils reflects the primary dispersion of elements. Where the soils are immature and the minerals composing the soil are relatively unaltered, the similarity is most apparent. Even in the maturely-weathered latosols of the Copperbelt, a four

Table 30. Metal content of bedrock from the study area

Rock-type	Area		Cu Range(Mean)	Fe% Range(Mean)	Mn Range(Mean)	Zn Range(Mean)	Co Range(Mean)	No. of Samples
Quartzite	Mufumbwe	Mineralised	52-1100(480)	2.5-7.3(5.1)	105-420(252)	10-16(13)	9-20(13)	5
		Background	6-70(32)	0.7-5.3(2.9)	70-180(144)	7-27(12)	6-19(10)	12
	L.Kamwedgi	Mineralised	160-1100(488)	3.7-8.3(4.6)	38-430(203)	7-20(15)	-	6
	Jijombo	Background	26-32(29)	0.7-1.6(1.2)	57-100(80)	12-18(15)	7-12(10)	2
Shale	Mufumbwe	Mineralised	135-2500(1310)	4.8-5.9(5.3)	120-250(183)	11-17(14)	8-15(12)	2
		Background	35	1.7	73	11	9	1
	Jijombo	Mineralised	160-540(360)	4.3-5.5(4.8)	7-1200(567)	21-91(48)	-	3
		Background	15-100(49)	2.0-4.7(3.4)	73-640(281)	8-46(22)	-	4

fold Cu enrichment in soils overlying shales in a quartzite environment has been noted (Tooms, 1955) although the mechanical composition of A horizon soils over shales is more clay rich (Hawkes and Webb, 1965), which may in part explain the metal variation. In the study area, interbanded shale and quartzite underlie the soils at Mufumbwe, Jijombo and Lower Kamwedgi and no soil secondary dispersions can be related to bedrock geology except over a band of Fe-Mn-Zn enriched quartzite at Lower Kamwedgi. This lack of correlation is probably the result of the poor initial metal variation in the local shales and quartzites. In addition, the subsequent intense and deep weathering would destroy relic minerals and mobilise metal ions in the soil profile, thus tending to modify any variation. It is interesting to note that even immature soils in southern Zambia, overlying lithologically differing biotite gneiss and mixed schist, have similar Cu, Zn and Co values (Harden, 1962), suggesting a homogenisation of the metal content in the soils. The relative mobility of Cu in the secondary environment in the study area also accounts for the greatly reduced soil Cu anomaly compared with the primary bedrock anomaly.

Concentration of a single element in mineral deposits is rare. The ore minerals of the study area are derived mainly from the supergene zone of oxidation where secondary malachite ($(Cu_2(CO_3)OH_2)$), chrysocolla ($CuSiO_3.2H_2O$), chalcocite (Cu_2S), pyrite (FeS_2), bornite (Cu_5FeS_4) and cuprite (Cu_2O) have developed (company data). These minerals suggest only a Cu-Fe correlation. Copper is a chalcophile element, and in sulphide deposits is commonly associated with other chalcophile trace elements such as Zn and Pb. Analyses of mineralised and

background bedrock from Mufumbwe and Jijombo (Tables 31 and 32) indicate a possible parallel enhancement of Fe, Mn and subsidiary Mo, Ag and Hg. (The high Hg values may result from sulphur vapour from sulphide minerals which can interfere with Hg determination when using a vapour technique). Further data from Lower Kamwedgi illustrate similar results (Table 18).

2. NATURE OF THE OVERBURDEN

(a) Residual soil

In subtropical climates, with heavy seasonal rainfall and high average temperature, weathering is intense and of a chemical nature. Although the effect tends to decrease with depth, permeable soils allow deep weathering. In addition, the present landsurface has been subjected to weathering since the mid-Tertiary Period, and consequently the weathered overburden is up to tens of feet thick. Locally, bedrock is commonly decomposed for many feet below bedrock surface. With the absence of relief, mechanical attrition is at a minimum, and only in the vicinity of the Kamwedgi River at Lower Kamwedgi has there been removal of surface residuum. Water is the essential element of chemical weathering. Rain water in Uganda has been noted as acid (Clews, 1962), and in percolating through the soil tends to be further activated, mainly by the addition of dissolved oxygen, carbon dioxide, humic complexes and bacteria. Furthermore, the groundwater tends to be markedly acidic in areas of oxidising sulphides through the addition of sulphur.

The intense chemical weathering and leaching of the original coarsely crystalline quartzites and micaceous shales, has resulted in a soil of fine-grain, irrespective of host-type, with no distinct textural horizon above the laterite

Table 31. Trace element content of bedrock (Optical spectrometry-ppm)

	Rock-type	Pb	Sn	Ga	Bi	V	Mo	Cu	Zn	Ti	Ag	Ni	Co	Mn	Cr	Fe_2O_3%
Background																
Jijombo	quartzite	8	<5	16	<5	600	<2	30	<50	8500	<0.2	40	13	50	130	2.5
Anomalous																
Mufumbwe	quartzite	10	<5	6	<5	1600	2	1000	<50	3000	<0.2	16	5	600	30	16.5
	quartzite	16	<5	16	<5	600	2	300	<50	6000	<0.2	30	30	1600	60	14.0
Kalengwa Mine	chalcocite	8	<5	6	<5	130	8	>>1%	<50	6000	6.0	13	<5	300	60	-

Table 32. Trace element content of bedrock (nitric-perchloric extraction-ppm).

	Rock-type	Cu	Fe%	Mn	Zn	Co	Ni	Pb	Mo*	Hg+ ppb
Background										
Mufumbwe	quartzite	4	0.6	70	7	6	20	14	2.4	-
	quartzite	3	6.1	62	11	5	20	23	0.2	-
Jijombo	quartzite	32	8.8	70	19	7	20	23	<0.1	>40
	quartzite	92	8.6	210	18	14	60	33	<0.1	>40
Anomalous										
Mufumbwe	quartzite	900	5.8	420	12	9	-	-	3.3	-
	quartzite	1100	15.1	9300	18	120	74	61	3.4	-
	quartzite	1000	7.3	100	14	10	24	-	<0.1	50
	shale	2500	6.0	250	11	8	41	33	1.6	40
Jijombo	shale	530	4.7	1200	32	-	-	-	-	-
Mineralisation										
Mufumbwe	quartzite	1400	6.2	160	13	10	30	23	-	-
Kalengwa Mine	chalcocite	4.2%	8.1	350	37	9	34	23	-	-
	chalcocite	5.3%	7.2	52	10	7	14	33	-	1000
	chalcocite	4.4%	4.4	115	10	6	24	23	3.2	90

*Colourometric analyses
+Vapour method analyses

zone. The absence of bedrock fragments in the upper zones reflects the maturity of the soil. The diminution of soil grain size has led to an increased surface area of material, which is conducive to increased chemical reaction.

A stable mineralogy has been developed composed of quartz, kaolinite and hematite with minor goethite and illite; the illite may be either residual from an argillaceous host rock, or from incomplete weathering of feldspar. However, with greater leaching illite normally alters to kaolinite (Hawkes and Webb, 1965). Gibbsite, although relatively common in similar latosols in the Congo, (Kellog et al., 1949) has only been noted in trace amounts in the study area which may result from the less wet conditions in Zambia.

In the study area, the Cu dispersion in background areas is variable in depth and illustrates a strong correlation with the Fe distribution. Where Fe fluctuation in the profile is absent, the Cu dispersion in the A and B horizons in background areas increases or decreases down-profile below erratic enrichment in the Ao horizon (Table 24). Where enrichment occurs in the Ao horizon, this may be the result of Cu fixation by organic-rich material. Similarly, Govett (1958) observed a correlation between Cu and organic content in latosols on the Copperbelt, which he ascribed to the high cation exchange capacity of humic material.

The Cu dispersion below the humus zone can be attributed to several complex and interacting factors. During the wet season, the soil moisture content, with a pH between 4 and 6, will increase markedly, and will consequently cause solution or suspension of bedrock Cu, which may then migrate in the profile. With the ensuing 6 months dry season and loss of soil moisture by evaporation and plant transpiration, Cu will be

reprecipitated in various forms and with time and dessication, the deposited Cu will tend to become more firmly bonded. Such bonding will include absorption in, and adsorption on clays and ferric hydroxides. This Cu will be only partially dissolved during the following wet period and will therefore tend to concentrate. In addition, variation of Cu in the soil profile will be affected by the decrease of organic material with depth, although the low content of carbon below 5 ft. depth probably has a minimal affect on the Cu dispersion. The upward increase of pH and Eh in the profile is also conducive to increased Cu deposition in upper zones. It is noted that lower acidity leads to increased adsorption of Cu by kaolinite (Hawkes and Webb, 1965). Cu is markedly concentrated in the clay fraction of the soil (see section 4(a)), and in the soils of the study area the percentage of clay appears to increase with depth. Maignien (1966) reports a higher clay content with depth in latosol profiles.

Cu notably attains a peak content at the top of the B horizon, especially where laterite is developed (cf. Tooms, 1955; Webb, 1964). As there is no marked increase in pH associated with this horizon, the enrichment is a direct result of sorption by hydrous Fe oxide in the zone of oxidation immediately above the water-table. Laterite nodules are markedly Cu enriched (Table 14).

In areas of Cu anomalous soil, the Cu content generally increases with depth. The Ao horizon is erratically enriched either as a result of a variable quantity of Cu-rich organic material, or to the variable fixation of Cu by the humus. Significant enrichment of Cu of a relatively firmly bonded nature occurs in the B horizon, as a result of sorption by Fe

hydroxides, and in the C horizon; the latter is a reflection that the primary bedrock Cu content is normally greater than the soil content.

In conclusion, it is therefore suggested that the major influence on Cu distribution in the residual soil profile is the dispersion of Fe, which forms coatings on clay minerals and concentrates in Fe hydroxide zones. Cu in lateritic zones is reported as less readily-extractable than soil Cu (Govett, 1958) and will thus tend to accumulate during seasonal fluctuations at the expense of the more soluble forms of Cu in the profile. It is stated that in a subtropical climatic regime, continuous leaching of the upper part of the soil profile by downward percolating rainwater, progressively removes loosely bonded Cu, Zn, Co and Ni. This produces a relative increase of Cu content with depth, although no illuvial horizon is developed (Clews, 1962). In the study area the lower content of Cu in the A horizon is unlikely to be the result of leaching or downward concentration by illuviation, as the Cu dispersion in nearby Kalahari Sand has the reverse trend. It is very probable that similar weathering processes of leaching apply to both types of overburden.

The overall Fe content of the residual soils of the study area is above average (Table 23), and the degree of oxidation is responsible for the prevalent red-brown colouration. Fe is not enriched at surface. This is a result of various factors, including the relatively low uptake of Fe by vegetation, and the subsequent low retention of Fe by the humus. In addition, humus helps to reduce Fe^{3+} to more mobile Fe^{2+} (Stobbe and Wright, 1959). Fe variation in depth (Table 24) is erratic, and much of the Fe is sorbed on clay minerals. As the

dominant clay mineral is kaolinite, Fe will form coatings on the clay micelles (Carroll, 1958). A marked concentration of Fe is present at the top of the B horizon, and normally constitutes a lateritic zone. The laterite varies from soft Fe concretions to hard pisolites which may become pervasive and form a massive, indurate zone, generally gradational into the soil above and below. The pisolites tend to harden on exposure and it has been suggested that the induration of laterite is a result of a mineralogical rearrangement of the Fe oxides rather than due to oxidation (Maignien, 1966). Frequently, the laterite development is superimposed on C horizon soil containing abundant bedrock fragments, and extends into the decomposed bedrock surface.

The formation of the sesquioxide zone has been attributed to the introduction of ferrous cations or colloidal Fe by the groundwater, with subsequent precipitation of ferric Fe in the zone of oxidation created as the water-table drops during the dry season (Fig. 35)(Hawkes and Webb, 1965). The presence of water is regarded as essential to active oxidation and consequently the optimum position for deposition of Fe and Mn hydroxides is immediately above the water-table (ibid., 1966). Deposition may be aided by soil bacteria. The thickness of the zone of lateritisation is dependent on the fluctuations of the water-table, while progressive thickening can occur as the water-table gradually drops in response to the lowering of the land surface by erosion (Tooms, 1955). Laterite development is also enhanced by the removal of soil Si with resulting concentration of Fe in situ. The mobility of Si is indicated by the development of secondary silica minerals. Fe can be concentrated in the profile by illuviation but since laterites

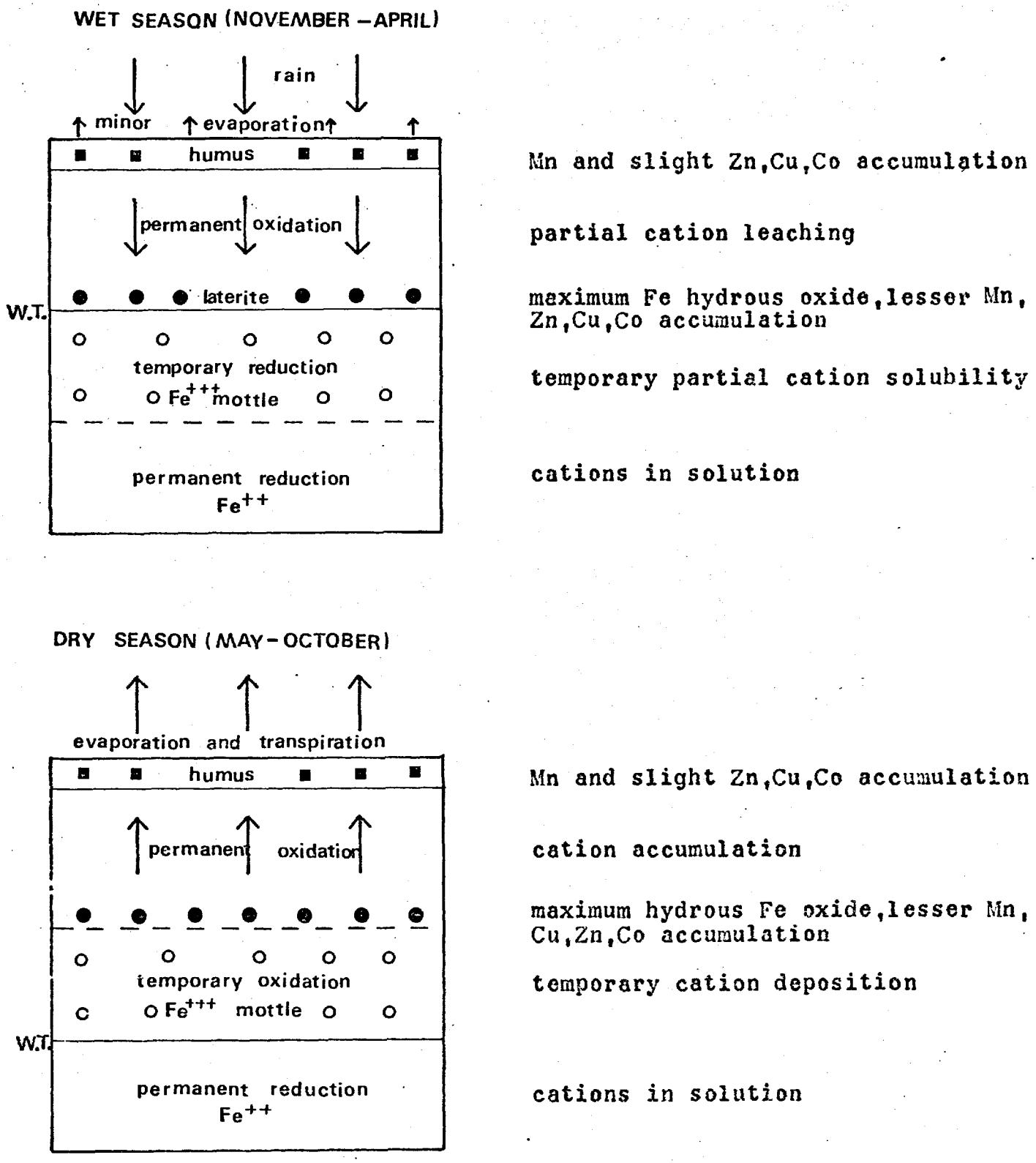


Fig.35 Diagramatic seasonal moisture movement in residual soil and Kalahari Sand.

develop in Kalahari Sand, which are generally more deficient in Fe than soils, it is more likely that the process involves enrichment via the groundwater.

It is observed in the study area that laterite is often coextensive with C horizon soil zones containing bedrock fragments, and in dambo sediments where pebble horizons occur. This suggests that the hydrous Fe oxides are deposited as a direct result of increased soil aeration. Subsequent to the development of incipient pisolites, the resulting heterogeneous soil is conducive to further precipitation of Fe through increased aeration. Although the zone at the top of the water-table has a high redox potential, no increased pH values, which would aid deposition, were noted in the B horizon. This contrasts with results in similar horizons on the Copperbelt (Tooms, 1955).

The Mn content of the residual soils is similar to the Clarke for soils (Table 23). There is a marked concentration of Mn at surface where values are double the A horizon content. Although Mn is not concentrated in the vegetation, (see Chapter V), it appears to form stable metallo-organic compounds in the humic zone. In profile, the Mn content decreases in depth probably as a result of the parallel decrease of organic matter, although in soil much of the Mn is associated with clay minerals.

In the laterite zone, frequent enrichment of Mn occurs, but is less marked than in the Ao horizon. Furthermore, the Mn concentration is much lower than Fe (Table 24). The Fe and Mn probably precipitate simultaneously in the zone of oxidation above the water-table forming Fe-Mn rich nodules (Table 14). The process of accumulation of the hydrous Mn oxide is probably similar to that of Fe with the introduction

of soluble Mn^{2+} cations and Mn colloids from the weathered bedrock and C horizon material via the groundwater. The greater mobility of Mn^{2+} relative to Fe^{2+} may result in the lower Mn deposition.

Zn and Co show similar dispersions in profile. Zn, and to an extent Co, are feebly enriched in the humus zone which may be a result of accumulation through vegetation decay, increased surface alkalinity (pH 5.6-6.3) or the scavenging effects of Mn; the low Co enhancement relative to that of Mn in humus does not indicate a strong correlation with Mn. Zn and Co values are lower in the A horizon where the metals are mainly concentrated in the clay fraction. They are enriched in the lateritic zone where concentration is probably associated with Fe and Mn hydroxides by surface adsorption or internal lattice absorption. In Zambian soils Co and Mn have been shown to have a close relationship (Jay, 1959; Harden, 1962).

The trace element content of the residual soil decreases where admixing with Kalahari Sand occurs. As the original distribution of the Sand was aeolian, the surface boundary between soil and Sand is gradational. Considerable mixing of the overburden by organic activity has obscured any sharp vertical pedological or chemical change from residual soil to Sand.

(b) Kalahari Sand

The Kalahari Sand was originally deposited under arid conditions but today the widespread vegetation cover aids stabilisation of the Sand, and little redeposition occurs. Under the present subtropical climate, the overburden experiences extensive chemical weathering and the permeability

of the Sand aids the depth of penetration of the weathering.

Only a rudimentary pedological profile is developed. Below the humus-rich Ao horizon, which may be 6 inches thick, a structureless Sand profile exists to the underlying residuum boundary. Lateritic horizons may develop and vary from segregated pisolites which may extend for up to 20 ft. down-profile, to hard Fe cemented nodules several inches in diameter or indurate bands. At least two laterite zones can occur in the same profile (Fig. 30, pit G14) as a result of local drainage conditions. The laterite zone is a B horizon, marking a zone of Fe concentration. Consequently the Sand between the laterite and the humus zone is a developing A horizon. Locally the silica has been remobilised and has been deposited to form siliceous nodular horizons (Fig. 30), and cherty vugs and fillings, often associated with the laterite zone.

The Sand is composed predominantly of quartz grains which display typical aeolian grain-surface textures and indicate subsequent minimal chemical alteration. The Sand is of similar grain size to Kalahari Sand in arid areas elsewhere in southern Africa, and the quartz has not been reduced to the grain size of the residual soil quartz. This probably reflects the relative immaturity of the Sand quartz with regard to chemical weathering, as the age of deposition of the Sand is probably less than one million years. The clay matrix of the Sand is essentially kaolinite with minor illite. The origin of the kaolinite is not believed to be due to decomposition of original alumino-silicate minerals as no microscopic trace of such host minerals exists, and no reference to similar minerals in Kalahari Sand elsewhere is recorded. In addition, the Sand has a high Fe oxide content which gives the Sand its

common reddish hues. It is unlikely that the Fe has been derived from the breakdown of Fe-rich, heavy minerals, as the heavy minerals do not notably display solution features. The low Fe content of Sand at Middle Kamwedgi and Jijombo, where the Sand is over 80 and 150 ft. thick respectively, together with areal variation of content at Mufumbwe away from the residual soil contact (Table 16), indicate that the overall Fe content of Sand profiles is related to the depth of the Sand cover. Local profile enrichments can be directly correlated with Fe-rich bedrock (Fig. 28, pit MN 10). The Fe dispersion in Kalahari Sand is thus a post-depositional feature.

Under the existing climate, the area has 6-7 months of dry season during which considerable surface evaporation and plant transpiration occurs. An upward migration of moisture in the profile to replace the surface loss will result during this period (Fig. 35). Effective capillary rise of groundwater carrying heavy metals for 50 ft. vertically over a period of a year has been reported in a clay-rich matrix (Bischoff, 1954; Ginzburg, 1960). Upward movement above the capillary fringe more probably involves migration of water, and dissolved and suspended material, on the surface of minerals (Marshall, 1959; Hawkes and Webb, 1965). It is likely that following deposition, mineral bonding is enhanced during the period of aridity and dehydration, and becomes sufficiently stable to withstand solution during the temporary downward movement of moisture during the ensuing Rains. It is suggested, therefore, that the clay and Fe content of the Sand is derived from the underlying residual soil or bedrock, and the elements have been transported upwards into the Kalahari Sand by soil moisture and deposited when the moisture evaporates.

In the Congo, similar kaolinite-Fe oxide cement in Kalahari Sand has been attributed to post-depositional introduction from underlying formations (de Ploey et al., 1968). It is interesting to note that the clay of the Kalahari Sand of the Congo may comprise kaolinite and gibbsite (ibid., 1968) suggesting a pedogenic rather than an aeolian origin for the clay.

The trace element content of Kalahari Sand is low (Tables 25 and 33), but distinct epigenetic patterns are developed which show a direct correlation with underlying bedrock metal content.

In both background and anomalous areas, the Cu content systematically decreases in depth. Local enrichment in the surface humus horizon may be the result of the uptake of Cu by vegetation with subsequent accumulation in the Ao zone. In addition, the Sand profile is more alkaline towards surface where the pH is 5.3-6.5. This alkalinity may be the result of the loss of CO_2 in the near surface moisture (Clews, 1962) or to the alkalinity of the humus material. The pH conditions are thus conducive to increased Cu deposition towards surface.

In the Sand the Cu is concentrated in the clay fraction, either adsorbed on the kaolinite or associated with Fe on the kaolinite. Due to the affinity of Cu with Fe hydroxides, the occurrence of lateritic development can influence the distribution of Cu in much of the profile. Thus erratically high surface values may be due to the proximity of laterite to the surface.

The amount of Cu in the Sand profile is proportional to the Cu in bedrock. In areas of high Cu, anomalous values extend throughout the Sand profile and extend into the

Table 33. Kalahari Sand trace element content (optical spectrometry) - silt ppm.

	Sample No.	Pb	Sn	Ga	Bi	V	Mo	Cu	Zn	Ti	Ag	Ni	Co	Mn	Cr	Fe_2O_3%	lithology
Mufumbwe area	1811	6	<5	4	5	30	<2	8	<50	3000	<0.2	16	6	600	16	1.3	Sand
	2150	10	<5	4	5	50	<2	3	<50	4000	<0.2	20	13	600	20	1.4	Sand
	2157	8	6	10	5	400	<2	20	<50	8500	<0.2	20	20	160	13	9.7	lateritised Sand

underlying residuum and bedrock. PH measurement at the base of 30 ft. profiles indicate relatively acid values of 4.0-4.5. It is proposed that Cu is leached from the underlying bedrock or residual soil by groundwater, which will be further acidified in areas of sulphide mineralisation, and is carried above the water-table by ascending moisture for at least 50 ft. during dry seasons. In the moisture phase, the Cu may be in solution, suspension, colloid or complex form, and is deposited in the profile mainly in association with Fe hydroxides and clay minerals. In the profile Cu may also be deposited as insoluble salts and complexes, soluble Cu carbonates and sulphates (Hawkes and Webb, 1965). Cu adsorption on kaolinite will increase with concentration of the metal in the moisture phase (Richardson and Hawkes, 1958) which will develop through evaporation. Also Cu adsorption on kaolinite is aided by increased alkalinity (Heydemann, 1959), and both concentration and alkalinity will increase towards surface. Most of the Cu associated with the kaolinite is probably associated with the Fe oxide coatings of the clay. The higher ratio of cx/Total Cu in Sand as compared with soil (see section 4(b)) is a further indication that the Cu is hydromorphically introduced. It is possible that a minor part of the dispersion of Cu is from the derivation of metal from deep-rooted vegetation.

The Fe distribution in the Sand indicates a peak value below the Ao horizon at 1 to 2 ft. depth. Although the initial uptake of Fe by vegetation is relatively low, the subsequent retention of Fe by humus is also low, and maximum accumulation occurs below the humus zone. In the A horizon, Fe is mainly associated with the clay fraction as coatings on

kaolinite. Although laterite horizons have not been encountered in all 30 ft. profiles, this may be due to the greater depth to the water-table in areas of Kalahari Sand. The laterite zone represents the area of oxidation at the surface of the water-table where colloidal Fe sesquioxide, carried in the groundwater, is deposited. In addition, colloidal silica is similarly introduced, and silicification is often coextensive with lateritisation.

The Mn enrichment in the humus horizon is more marked than in residual soil and correlates with the abrupt decrease of organic carbon with depth in Kalahari Sand (see section 5). Below the humus horizon, the Mn content consistently decreases with depth. Minor fluctuations in the trend occur in Fe mottle zones and in lateritic zones, where the Mn content may be double, implying related deposition of Fe and Mn hydroxides. But as in the residual soil, the Mn hydroxide deposition is considerably lower than Fe, possibly denoting the greater mobility of the Mn^{2+} ion.

The average Mn content is lowest at Middle Kamwedgi and Jijombo, where Kalahari Sand is deeper, while at Mufumbwe the content decreases in the deeper Sand (Fig. 17). These observations suggest that the Mn content of the Sand below the Ao horizon is related to the depth to bedrock. In addition, local high bedrock Mn content is reflected in the Mn content of Sand profiles at Lower Kamwedgi (Fig. 28, pit MN10). Thus the dispersion of Mn in the Sand is mainly epigenetic and the main factors influencing the accumulation of Mn in the profiles are the organic content and laterite development.

Zn and Co are similar in dispersion and generally decrease with depth. The accumulation in the humus horizon

may be due to organic complexing or to near surface alkalinity. Coprecipitation with Fe and Mn hydroxides results in slight enrichment in the laterite zones (Fig. 30, pit F11). There is a tendency for generally lower values to appear in areas of deeper Kalahari Sand (Tables 16 and 26).

In summary, the content of Cu, Fe, Mn, Zn and Co in Kalahari Sand of the study areas may bear a direct relationship with values in underlying bedrock or residual soil. In such circumstances, the dispersions of these trace elements in the Sand is epigenetic and has originated from moisture migrating upwards from the water-table during the dry season.

(c) Dambo Sediment

Dambos in the Copperbelt area are considered to advance at the expense of residual soil, and are consequently composed of residual soil in situ underlying a veneer of transported material (Tooms, 1955; Govett, 1958). In the study area, the dambo material at depth is transported, and is derived from the hinterland. Sections of dambo sediment in residual soil and Kalahari Sand areas, reveal horizons of water-worn pebbles in which individual pebbles of several inches in diameter can occur, often interbedded with fine sediment. Former fluctuating climatic conditions are responsible for the zonal sediment, and periods of considerable stream flow are indicated by the pebble zones. The sediment of dambos reflects the sediment of the immediate hinterland, and in areas of Kalahari Sand, the dambo sediment is dominantly reworked Sand. The dambos are seasonal and are only waterlogged for half of the year, during which reducing conditions prevail in the underlying sediment. During the dry season, the water level in the minor dambos (e.g. Middle Kamwedgi) may be below 30 ft. and

oxidising conditions exist in the overlying sediment. In the larger dambos (e.g. Jijombo and Mufumbwe), the dry season water-table is only a few feet below surface and the near surface profile is moist, indicating marginal oxidising or reducing conditions.

Sedimentary profiles in dambos ideally display an organic-rich horizon, overlying grey-black clay, which is underlain by a pallid glei horizon with abundant brown Fe mottle. The higher content of organic material in the surface horizon relative to interfluve overburden, is a result of the decreased breakdown of vegetation by oxidation due to the waterlogged conditions. The fluctuation of the water-table produces temporary oxidation conditions. This results in ferric oxide mottle or Fe pisolitic development, with intervening pallid patches where the Fe may be in a reduced state. Bloomfield (1963) explains the lack of colouring above the water-table as due to colourless ferric oxide.

Within the lower zone of groundwater fluctuation, prevalent reduction of Fe to the ferrous state may produce a uniform pallid colour in the clay. At the top of the water-table, and often coextensive with zones of pebbles, laterite commonly develops (Fig. 19) forming one or more horizons. As all stages of laterite development occur, from incipient pisolites to indurate bands, it is probable that the dambo lateritisation is a continuing process, and thus the laterite zone may have a wide age range.

In the profile, the acidity conditions are variable (pH 4.5-6.5), with no systematic variation with depth. No montmorillonite has been detected and the dominant clay mineral is kaolinite. This may be partly derived from

surrounding soils but is mainly due to the overall acidity of the profiles and to adequate leaching.

The trace element distribution in dambo sediments is affected by the metal content of both groundwater solutions, and surface waters. The metal may be in solution, suspension or colloidal form. The depositional environment of the dambo is thus complex, with factors such as pH, Eh, metal solubility, coprecipitation, saturation level and organic complexing, affecting metal content of water and sediment. Consequently only a few empirical distributions are noted, and conclusions are restricted by the limited observational data.

The trace element content is generally lower than in soil or Kalahari Sand (Table 34) which may indicate the greater leaching capacity of the dambo groundwater.

The Cu content in sediment profiles of dambos draining residual soils is variable with depth. In anomalous areas, values generally increase with depth. The Ao horizon is enriched only in the dambo channelway which has been attributed to deposition from groundwater, which approaches the surface in the dambo channelway (Tooms, 1955; Govett, 1958). In dambos draining areas of Kalahari Sand, the Cu content tends to decrease with depth. Higher values are associated with lateritic zones probably due to coprecipitation with Fe hydroxides, or to the greater groundwater flow through lateritic zones. In addition, heterogeneous pebble horizons create increased aeration, or allow increased passage of water, and are conducive to Cu deposition. There is no apparent correlation of Cu with pH or C trends and maximum deposition is on clays or Fe hydroxides associated with the clay (see section 4). Govett (1958) correlates the Cu content in dambos

Table 34. Trace element of dambo sediment (optical spectrometry) - ppm silt

	Sample No.	Pb	Sn	Ga	Bi	V	Mo	Cu	Zn	Ti	Ag	Ni	Co	Mn	Cr	Fe_2O_3%	lithology
Background																	
Jijombo	1163	10	<5	5	<5	85	<2	20	<50	6000	<0.2	20	10	130	60	1.5	sand
Anomalous																	
Mufumbwe	0715	8	<5	6	<5	85	<2	60	<50	5000	<0.2	30	10	40	50	3.0	sand
	0719	8	<5	8	<5	600	<2	60	<50	6000	<0.2	40	10	85	85	8.8	pebble zone

with the carbon content, but his profiles do not contain lateritic zones. Local correlation of Cu with organic carbon does occur, and the Cu anomaly of the Middle Kamwedgi dambo is restricted to a buried humus horizon which has acted as a trap for Cu transported down the former dambo.

The Fe content of dambo sediment is generally lower than surrounding soil but similar to surrounding Sand values. In profile, the Fe generally increases in depth in areas of residual soil, but is more erratic in a Kalahari Sand dambo. Fe hydroxide enrichment above the water-table results in lateritic formation due to increased oxidation. Mn is enriched in the humus horizon and tends to decrease with depth. This decrease in depth may be related mainly to the decrease of carbon with depth, with minor Mn content fluctuations caused by the variation in pH. Mn deposition in the zone of lateritisation is erratic and may be high (Figs. 18 and 20), and is usually associated with an accumulation of Co. In areas of residual soils, the Zn content increases downwards in dambo sediment, but decreases in depth in Kalahari Sand dambos. This may be partly due to the irregularity of dambo pH values.

3. HYDROGEN ION POTENTIAL

Determinations of the pH of profiles in residual soil, Kalahari Sand and dambo sediment were carried out in the laboratory nine months after collection. Although drying of samples affects element bonding, while the amount of water added to dried samples during pH measurements affects the values obtained (Jackson 1958), the standardised method employed is generally accepted as indicative of pH conditions in situ.

In residual soils (Table 35), maximum pH values occur in

Table 35. pH values in soil, Sand and dambo sediment profiles.

Residual Soil

	Mufumbwe			L.Kamwedgi				Jijombo
Pit No.	34/19	34/19NW	0/8NW	DN/3½	DN-3	KN7	MN8	F5
Ao horizon	5.3	4.9	5.6	5.4	5.8	6.3	6.0	5.6
A horizon	4.9	4.5	4.5	4.5	5.7	5.2	5.2	5.1
B horizon(laterite)	-	-	4.6	4.9	4.4	5.3	5.2	-
C horizon	4.5	4.5	4.5	4.7	-	4.8	5.0	4.5
D horizon	-	4.2	4.4	4.5	-	4.7	-	-

Kalahari Sand

	Mufumbwe				L.Kamwedgi						M.Kamwedgi			Jijombo
Pit No.	2.1uml	26/6	30/2	30/0	MN-3	MN4	RN4½	RN-3	VN3½	VN-3	J14	F17	E11	D18
Ao horizon	-	6.0	5.9	6.5	5.8	6.2	5.1	5.8	5.9	5.3	5.2	6.3	5.6	-
1-5ft.	4.8	4.7	4.7	.4.7	4.6	5.7	4.5	4.8	4.7	5.3	4.4	4.9	4.9	4.6
5-10ft.	4.7	4.6	4.9	4.5	4.4	5.0	4.5	4.6	4.7	5.1	4.6	4.6	-	4.4
10-15ft.	6.5	4.6	4.4	4.4	4.4	-	4.6	4.6	4.5	5.1	4.0	4.8	4.4	4.5
15-20ft.	4.3	4.3	4.5	-	4.5	-	4.4	4.6	4.4	4.9	4.2	4.8	4.3	-
laterite zone	-	4.9	-	4.0	-	5.2	-	-	-	-	-	4.5	-	-

Dambo Sediment

	Mufumbwe										M.Kamwedgi			Jijombo			
Pit No.	B/4/3	B/4/4	B/4/2	B/4/5	B/4/1	B/1/2	B/1/1	M2/1	M2/2	M2/3	M2/5	G14	E13	C4½	F10	D9	B4	F9
Ao horizon	5.7	5.9	5.9	5.5	6.2	4.7	6.2	5.3	4.8	5.5	5.4	5.5	5.4	6.1	5.9	4.8	6.0	5.9
transition	6.2	5.4	4.8	4.9	5.6	4.4	5.5	4.7	4.8	5.3	5.0	5.0	5.2	4.9	5.5	4.6	5.2	5.3
1-3ft.	5.7	-	5.7	5.0	4.2	-	4.8	4.6	5.2	5.3	5.2	-	5.1	5.0	4.9	6.3	5.1	4.6
3-6ft.	-	-	-	-	-	-	-	-	-	-	-	5.6	-	4.8	5.3	6.6	5.1	-
pebble zone	6.3	6.5	6.6	6.5	6.3	5.2	-	5.6	-	-	-	-	-	4.5	-	-	-	6.5
laterite zone	-	-	-	6.4	5.2	5.1	5.7	-	-	-	-	4.5	-	4.8	-	-	-	-

the Ao horizon (4.9-6.3) which may be due to humic alkaline complexes, and to bases derived from decayed vegetable matter (Mohr and von Baren, 1954). The acidity increases with depth which relates to the increased soil CO_2 content with depth, and to removal of bases by leaching. No consistent increase was found in the B horizon sesquioxide zone, while the C horizon is generally acidic (pH 4.5-5.0). Value ranges are similar to those of latosols in the Copperbelt (Tooms, 1955; Govett, 1958) while Tooms (1955), and Kellog (1949) in Congo latosols, note upward increasing alkalinity. The upward increase in alkalinity is conducive to greater metal deposition towards surface.

A similar trend is observed in Kalahari Sand (Table 35). The pH values in the Ao horizon (5.1-6.5) are generally similar in level to residual soils, and there is a considerable drop in pH value below the humus horizon, which would suggest a correlation of alkalinity with humus. Plant material may accumulate bases or produce bases by vegetation decay. The Sand is slightly more acid with depth where an increase in CO_2 content, and increased leaching of bases will occur. The lateritic horizon indicates no systematic increase in pH values.

The pH values of dambo profiles are erratic and no consistent trend is apparent. Values in the Ao horizon range from 4.7-6.2, with similar values in the A horizon. Conditions in the pebble horizons appear to be less acid. The value range is in accord with values in dambos on the Copperbelt although Tooms (1955) and Govett (1958) noted downward and upward increase in pH respectively.

All profiles are therefore slightly acidic. The upward increase in alkalinity values in both soil and Sand agrees

with the observed upward increase in the metal content. The variable trend of acidity in dambos may partly explain the poor trace element patterns developed in dambo profiles.

Table 36. pH of hydrolyses of metals

Cu++	Fe++	Co	Zn	Mn++
5.3	5.5	6.8	7.0	8.5

(after Britton, 1942)

The pH ranges of the profiles are, in the absence of other factors, particularly critical for Cu and Fe (Table 36). But many competing factors are present in profiles, and strict adherence to these values alone is unrealistic (Hawkes and Webb, 1965).

4. MECHANICAL COMPOSITION

(a) Grain size fraction metallic content

Samples of residual soil, Kalahari Sand and dambo sediment were divided into specific size fractions both by dry sieving, and by a combination of wet sieving and sedimentation. With both techniques a similar partitioning of metal content per size fraction is apparent, and the metal content increases with decreasing grain size (Table 37). The trend is subdued with the dry sieved samples, as the fine material including clays, which contain the greater proportion of the metals, is present in coarser fractions adhering to, or cementing, individual grains. A more complete tabulation of size fraction analyses of the three sediment types for Cu, Fe and Mn is presented in Appendix III.

Table 37. Comparison of dry and wet sieved fraction Cu analyses (ppm)(nitric-perchloric acid attack)

Overburden type	Sieve method	Size fraction					
		+38#	-38 +80#	-80 +200#	Silt	-200#	Clay
Residual Soil	Dry	76	53	71		85	
	Wet	18	6	9	84		170
Kalahari Sand	Dry	15	9	11		23	
	Wet	3	3	2	18		120
Dambo sediment	Dry	14	10	10		18	
	Wet	1	1	2	18		52

(i) Residual Soil

The distribution of Cu, Fe and Mn in size fractions of residual soil from Mufumbwe and Lower Kamwedgi (Fig. 36) show similar and consistent variation. Slightly erratic high values of each element occur in the +38# material, possibly due to metal-rich bedrock or laterite fragments. Values are at a minimum between -38# and +200#. A notable concentration occurs in the silt fraction for Cu (10 fold), Fe (6 fold) and Mn (4 fold), with a further but lower increase in the clay fraction, especially in anomalous material.

The silt fraction has a mineralogical composition of quartz, Fe hydroxide and oxide, and minor clay minerals, while the clay fraction comprises predominantly kaolinite with Fe hydroxide and oxide and subsidiary quartz, illite and possible organo-minerallic colloids. In the silt fraction, Cu may be sorbed by Fe hydroxide, while in the clay fraction the Cu may be sorbed by Fe hydroxide and organo-minerallic colloid. Kaolinite has a low cation exchange capacity, but has a large surface area which is conducive to coating by Fe (Jenne, 1968),

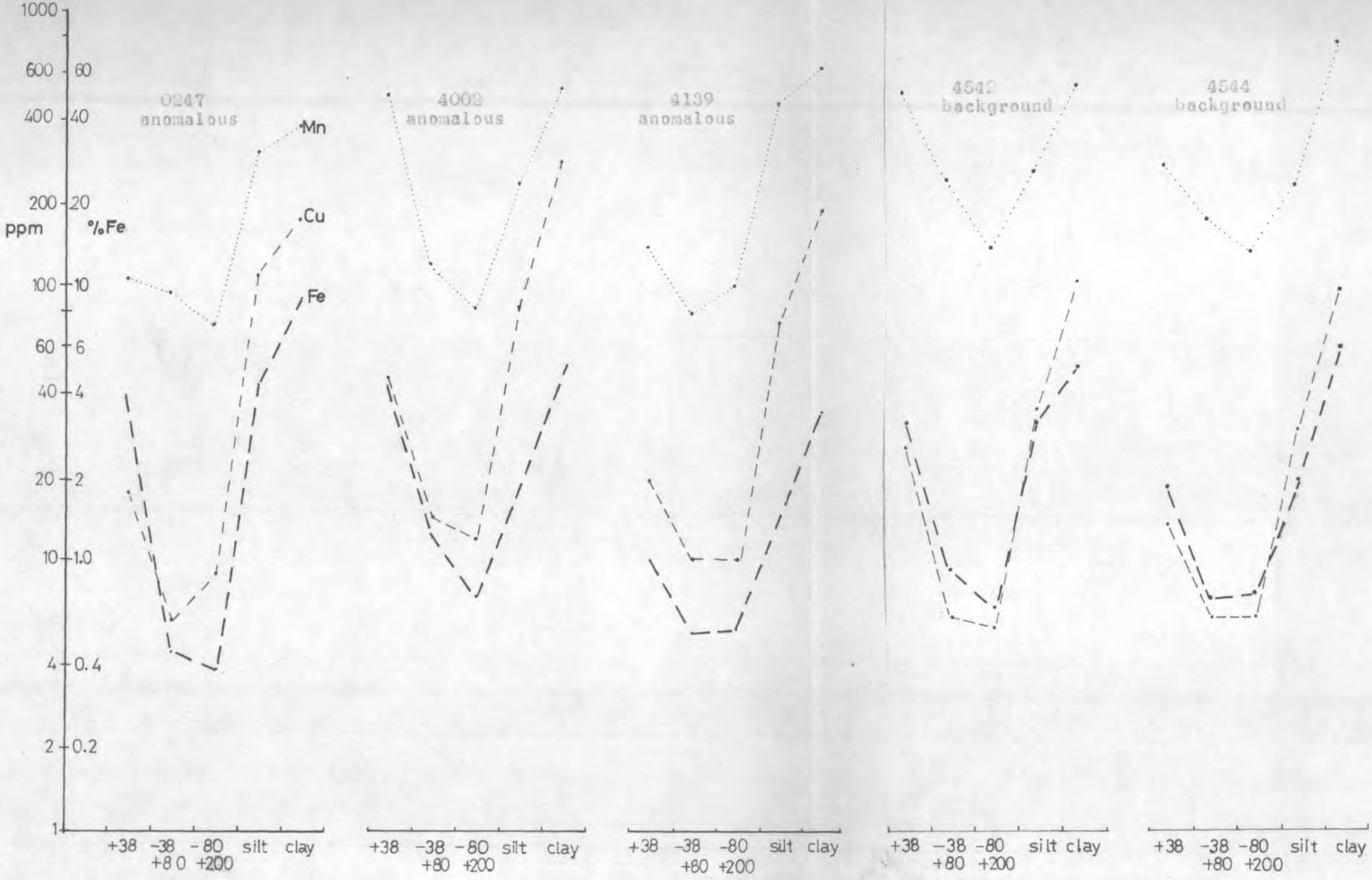


Fig.36 Distribution of Cu,Fe and Mn between size fraction residual soil.

which would in turn sorb Cu. The Fe and Mn association in fractions appears to be an accumulation of the hydroxides in the fine grades, and an adsorption of hydroxides on clay minerals. An intimate Fe-kaolinite association in laterite soil is noted by Maignien (1966).

Similar distribution of Cu per size fraction has been noted in latosols by Tooms (1955) and Govett (1958), although the latter states that the Cu is equally distributed between silt and clay. In immature soils in Uganda, Clews (1962) notes that 85% of Cu occurs in the silt-clay fraction, while the Fe content of the clay fraction of all samples is consistent (2.9%Fe). Band (1969) has observed similar trends for Cu, Ni, Fe and Mn in the B horizon of podsols in Norway, and relates the Ni in silt to hydrous Fe oxides, while the Ni in clays is associated with Fe-rich, organo-minerallic colloids.

(ii) Kalahari Sand

The metal partitioning per grain size in Kalahari Sand is similar to that in residual soils (Fig. 37), but with a more marked increased content with decreasing grain size. High values in the +200# material are more sporadic and are indicative of the low incidence of lateritic fragments with high metal content. The low values of the +200# fractions are due to the monomineralic quartz composition. Marked enrichment occurs in the silt fraction for Cu (20 fold), Fe (9 fold) and Mn (5 fold) with a proportionately lower enrichment in clay; this is more pronounced in anomalous material. Mineralogically, the silt and clay fractions are very different. The former comprises fine quartz and Fe and Mn hydroxides and oxides; the latter is mainly kaolinite, with Fe and Mn hydroxides and oxides, and possible organo-minerallic colloids. The cation

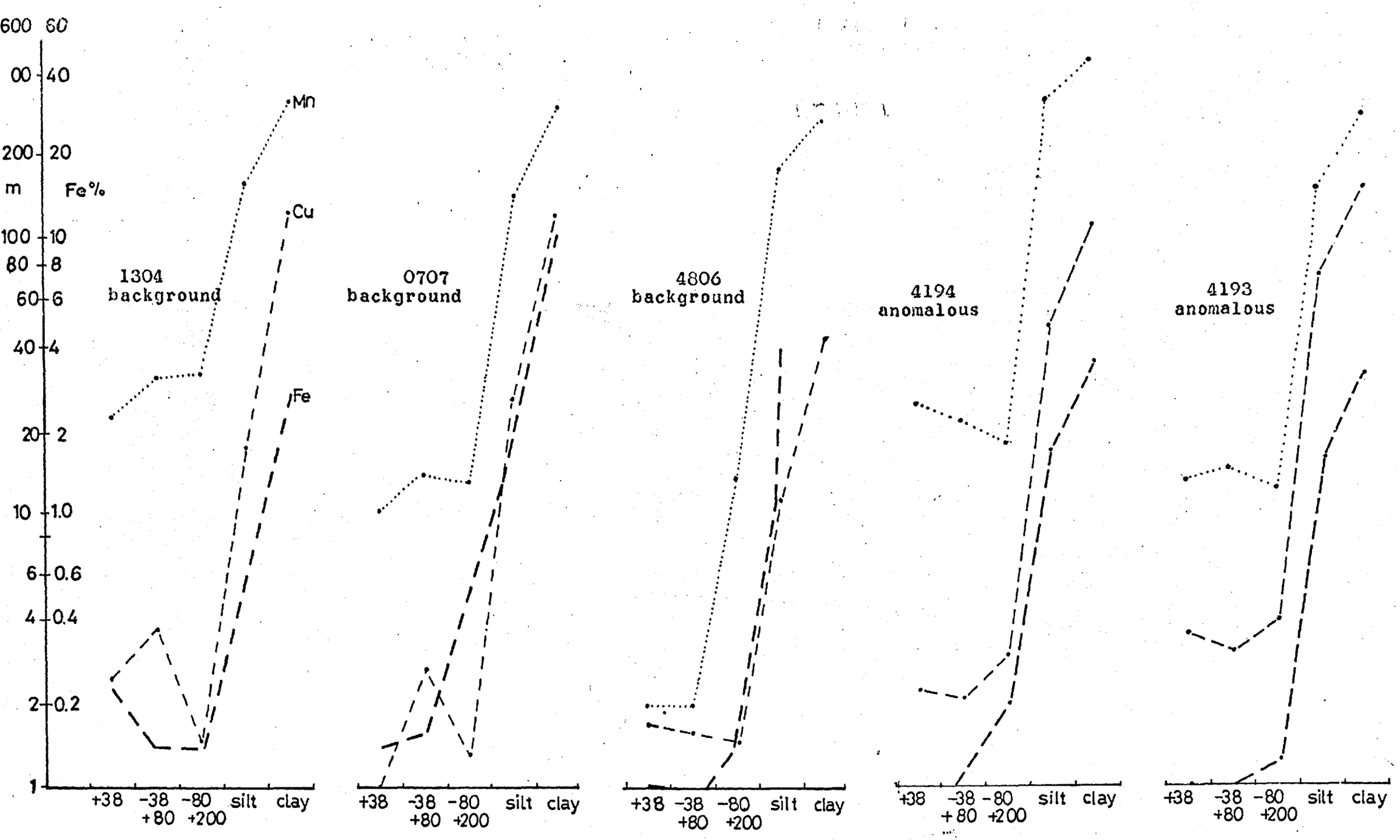


Fig.37 Distribution of Cu,Fe and Mn between size fractions, Kalahari Sand.

exchange capacity of both quartz and kaolinite is low, although Fe is probably associated with the kaolinite. The fine quartz of the silt fraction is capable of adsorbing Fe and Mn hydroxides, which will in turn sorb Cu. The bonding of the Cu is weaker in the silt fraction which is of considerable significance when contrast of anomalous to background samples is considered (See Table 38).

(iii) Dambo sediment

The dambo sediment is mostly derived from soil or Kalahari Sand although not necessarily of local origin, and consequently the partitioning of metals in soil and Sand is influenced on entering the dambo environment by mechanical factors such as stream sorting, and by chemical factors of solution and redeposition. Nevertheless, the metal content per grain size is similar to soils and Sand (Fig. 38). Values in the +38# fraction are variable and result from the inclusion of rock or laterite fragments. The silt fraction contains a pronounced accumulation of Cu (17 fold), Fe (12 fold) and Mn (6 fold). In the clay fraction, Fe is further enriched, while Cu and Mn values indicate a relatively poorer enhancement, especially in anomalous material. Mineralogically the silt and clay fractions are similar to the equivalent fractions of the soil and Sand. Consequently a strong correlation between Cu, Fe hydroxides or oxides and fine quartz is suggested in the silt fraction, and between Cu, Fe hydroxides or oxides and kaolinite in the clay fraction. It is interesting to note that Govett (1958) found the maximum exCu content in the silt fraction of Copperbelt dambo sediments, although he correlat the Cu content with organic carbon. In addition, Harden (1962) notes maximum Cu, Zn, Co and Ni values in the silt fraction of

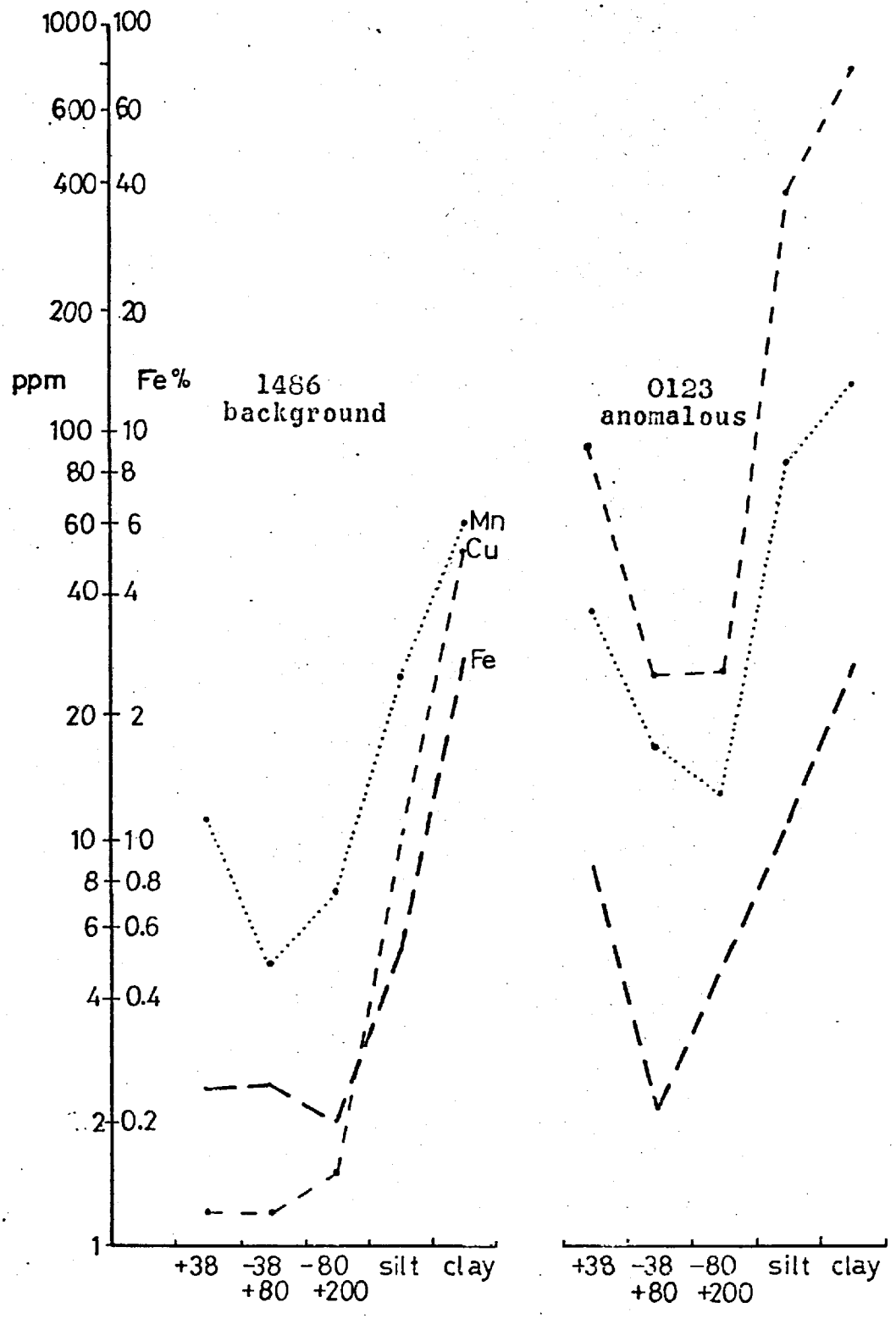


Fig. 38 Distribution of Cu, Fe and Mn between size fractions, dambo sediment.

dambo sediments in southern Zambia although in that area the sediment is immature. Band (1969) observed maximum Cu values in Norwegian stream sediments in the clay fraction, and maximum Fe and Mn values in the silt; he suggests that the Fe content in soil clay is related to organic-mineralic colloids which breaks down in the oxidising environment of the stream and are dispersed, resulting in low Fe in stream sediment clay. In the study area, the Fe appears to be adsorbed on kaolinite both in the soils and dambo sediment. The Fe content in dambo sediment is generally lower than in soil and Sand, both in silt and clay fractions, indicating a removal of Fe in the stream environment by reduction either in suspension or in solution.

(b) Differential Metal Extraction

The techniques of partial extraction of metals, or the extraction of different forms of metal, can be successfully applied to ascertain origins of metal in overburden. Five extractants, ammonium acetate, dithizone, warm 0.5M hydrochloric acid, potassium bisulphate and nitric-perchloric acid were applied to the various size fractions of residual soil, Kalahari Sand and dambo sediment (APPENDIX III, Tables 68-72). The ammonium acetate and dithizone techniques are cold extractants and only remove weakly bonded metals. Hydrochloric acid and potassium bisulphate are stronger attacks which are effective on mature sediment but are selective on immature material containing fresh rock minerals (Harden, 1962; Clews, 1962). Nitric-perchloric acid extracts over 90% of metal from all sediment types, and the attack can be regarded as total in mature sediment.

Each attack produced similar results to those observed in the above section. This is not unexpected as the material of the overburden is predominantly the end product of an intensive chemical weathering regime. Consequently a minimum of fresh bedrock material occurs and the metals are in a secondary form. Weak attacks would therefore produce similar trends to stronger extractants. With the ammonium acetate and dithizone extractions, results are more erratic as values are generally near the detection limit of the methods. In addition, the high Fe content of the samples tends to interfere with the colouration of the dithizone. The weaker attacks are relatively more effective in Kalahari Sand and dambo sediment than in residual soils, and indicate that Cu in these sediments is in a more readily extractable form. This is further indicated by a comparison of exCu (dithizone)/Total Cu (nitric-perchloric) between the three sediment types (Table 38).

Table 38. ex (dithizone)/Total (nitric-perchloric)Cu% in overburden per size fraction

Overburden type		Sieve method	size fraction					
			+38#	-38 +80#	-80 +200#	-200#	Silt	Clay
Residual soil	(anomalous)	Dry	0.3	0.4	0.3	0.6	-	-
		Wet	0.6	6.6	4.4	-	<0.1	<0.1
Kalahari Sand	(background)	Dry	6.7	3.3	5.5	2.6	-	-
		Wet	6.7	6.7	10.0	-	7.2	3.9
	(background)	Dry	4.0	4.0	3.0	1.2	-	-
		Wet	20.0	10.0	30.0	-	2.0	0.6
Dambo Sediment	(background)	Dry	3.6	2.0	3.0	2.8	-	-
		Wet	10.0	10.0	5.0	-	4.5	5.0
	(anomalous)	Dry	5.0	4.3	4.1	5.5	-	-
		Wet	1.7	7.2	4.2	-	8.0	4.3

The lowest ratio values, and hence the most firmly bonded Cu, occur in the residual soil. In residual soil, the Cu of the silt and clay fractions appear relatively firmly bonded. The higher ratio values for the +200# wet sieved fractions, are probably due to analytical error as values are near the detection limit of the dithizone method, and precisiion is liable to be low. In the clay fraction interference of colour by clay occurs and may also cause error. The ratio values of the Kalahari Sand and dambo sediment are of similar and greater magnitude, and imply that the Cu is more loosely bonded. It is probable that the Cx/Total ratio values are high in the wet sieved fractions as dithizone values are again near the detection limit. The Cu of the silt fraction is more extractable than the Cu of the clay. In Zambia, the cx/Total Cu ratio has beenmoted as higher in dambo sediment than in latosols (Govett, 1958; Coope and Webb, 1963). Govett relates the high cxCu to carbon content while Clews (1962) in stream sediments in Uganda correlates high cxCu with sorption effects on clay.

A comparison of HCl extractable Cu, Fe and Mn relative to total content in residual soil and Kalahari Sand is shown in Table 39. In residual soil the Cu values are similar for all fractions and suggests that HCl extractable Cu is in a similar form in each fraction. The marked fluctuation of Cu in the +200# fraction in Kalahari Sand probably reflects experimental error due to the low Cu extraction in the +200# fraction. Values are generally higher in Kalahari Sand than in the residual soil indicating the general looser bonding of the Cu in Kalahari Sand.

Table 39. HCl/Total% metal ratio per size fraction(wet sieved)

	Overburden type		-38 +38#	-80 +80#	-125 +125#	+200#	Silt	Clay
Cu	Residual Soil	(anomalous)	17.5	14.9	19.6	17.2	17.0	14.5
		(background)	20.0	21.7	25.6	18.5	21.7	19.2
	Kalahari Sand	(anomalous)	35.7	18.1	9.7	13.9	27.7	26.3
		(background)	26.3	45.5	35.7	38.4	35.7	27.8
Fe	Residual Soil	(anomalous)	30.3	30.3	27.0	25.6	27.8	32.3
		(background)	26.3	22.2	30.3	25.0	18.2	18.5
	Kalahari Sand	(anomalous)	20.0	22.2	26.3	23.3	18.1	22.2
		(background)	21.3	26.3	29.4	17.9	20.8	12.8
Mn	Residual Soil	(anomalous)	66.6	100	100	100	90.9	90.9
		(background)	100	100	100	100	83.3	90.9
	Kalahari Sand	(anomalous)	55.6	38.5	100	100	100	90.9
		(background)	100	100	76.9	66.7	90.9	83.3

The amount of HCl extractable Fe in residual soil and Kalahari Sand is of similar magnitude to the Cu. The lack of trend in either soil or Sand suggests that in all size fractions, the Fe is in a similar form either adsorbed on quartz or clay. HCl extractable Mn is virtually total Mn in both soil and Sand. The correspondence in ratio level between Cu and Fe extractions, and the contrast with Mn, suggests that there is an intimate association between the Cu and Fe in all size fractions, and probably reflects the Fe hydroxide coatings on quartz grains or kaolinite.

(c) Metal association per size fraction

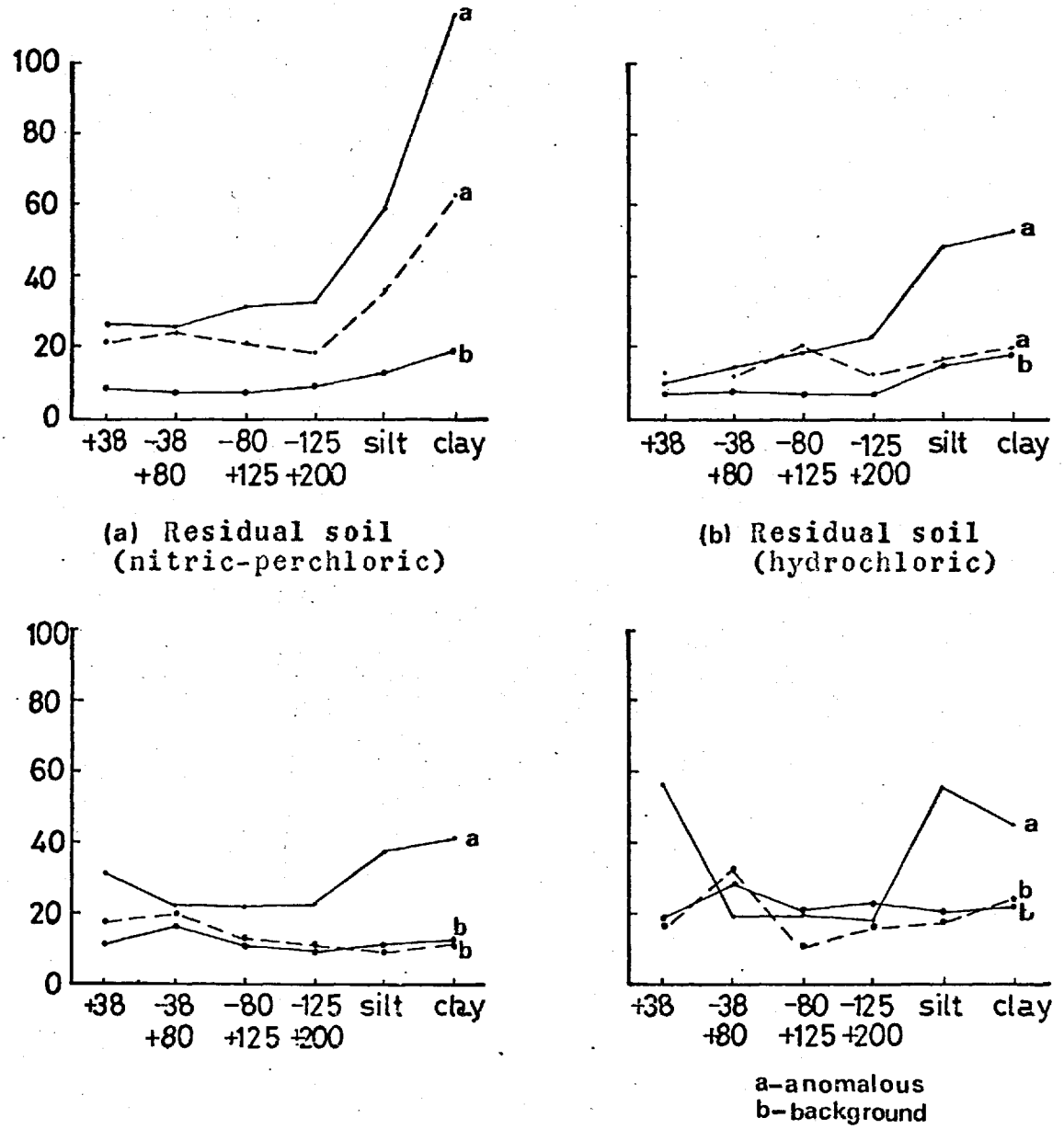
(i) Cu-Fe

The ratio of total Cu to Fe per size fraction in soils (Fig. 39a) illustrates that in background and anomalous areas, the value increases with decreasing grain size. In anomalous soil, Cu is in greatest excess of Fe in the clay fraction. The HCl extractable metal ratio for the soil (Fig. 39b) illustrates a similar but subdued trend and values for the silt and clay fractions are of equal magnitude. This difference between the attacks in the silt and clay fractions, suggests that a proportion of the Cu in the clay is more strongly bonded than in the silt fraction.

In Kalahari Sand in background areas (Fig. 39c) the total ratio value is similar for all fractions while in anomalous samples, a general increase occurs with decreasing grain size. The value for the silt fraction is similar to the clay. With an HCl extraction, background values are equal while in anomalous Sand the silt value is greater than the clay. This suggests that in anomalous areas, the greatest excess of Cu to Fe is in the silt and clay, and Cu is looser bonded in silt.

(ii) Cu-Mn

The ratio of total Cu to Mn per size fraction of residual soil (Fig. 40a) increases with decreasing grain size. A similar trend occurs with HCl extractable metal (Fig. 40b). With both attacks the trends are greater in anomalous areas. In Kalahari Sand, values are erratic in the coarser fractions; possibly due to the low extraction of metal. Values generally indicate a similar trend with both total and HCl soluble metal, and increase in silt and clay. As HCl soluble Mn is virtually equivalent to total extraction, trends for both attacks should be similar.



(a) Residual soil (nitric-perchloric)

(b) Residual soil (hydrochloric)

(c) Kalahari Sand (nitric-perchloric)

(d) Kalahari Sand (hydrochloric)

Fig.39 Cu/Fe% ratio per grain size fraction, residual soil and Kalahari Sand.

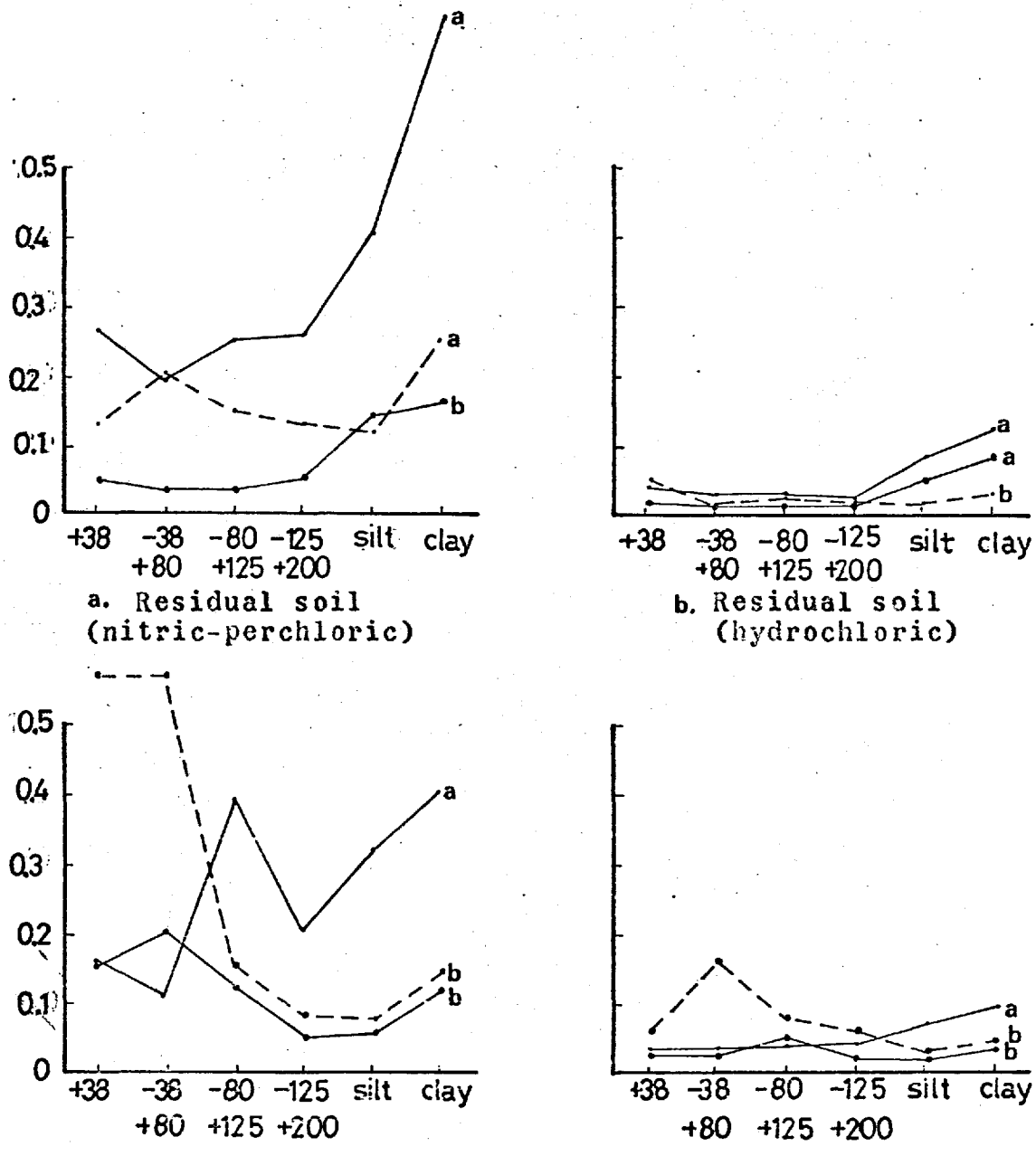


Fig.40 Cu/Mn ratio per grain size fraction, residual soil and Kalahari Sand.

(d) Contrast

Detection of the maximum contrast between anomalous and background metal content is the aim of a prospecting technique, and most variations in technique attempt to enhance this contrast, whether by use of a particular sediment type, metal extractant, pathfinder element or metal ratio. The contrast of different size fractions of the same sample is now considered, as metal content of different grain size fractions of overburden has been shown to vary (Figs. 36-38).

(i) Residual Soil (Table 40)

The maximum total Cu contrast occurs in the silt and clay fractions, while values in dry sieved samples are notably low. The trend is similar with HCl soluble Cu, but the values are more erratic where they are near the detection limit of the method. The sporadic high values in the +38# fraction result from occasional lateritic or rock fragments containing anomalous metal content.

The Fe and Mn contrasts for the same size fractions are illustrated in Tables 41 and 42 respectively. Fe or Mn enrichment is not necessarily associated with Cu mineralisation or Cu enrichment in the soils of the study area, and where Fe or Mn is greater in Cu anomalous areas and lower in Cu background areas, contrast values in Tables 41 and 42 are marked positive (+); where the reverse association occurs, the contrast values are reciprocals and are marked negative (-). In residual soils, the maximum total Fe contrast occurs in the silt and clay fractions, while the maximum Mn contrast is more erratic, but tends to occur in the silt fraction.

Band (1969), working on Norwegian soils, records maximum Cu and Mn contrasts in silt, while maximum Fe, Ni and Co

Table 40. Cu contrast values in overburden per size fraction.

Overburden type		Sample	Wet sieved						Dry sieved	
			+38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	-80#	-200#
Residual soil	Total Cu	(1)	2.7	2.5	2.6	2.0	2.6	3.3	1.9	2.1
		(2)	1.3	1.8	2.0	1.7	2.1	1.9	1.3	1.4
		(3)	0.8	1.2	-	1.4	2.6	1.8	-	1.7
	HCl Cu	(1)	4.0	1.9	1.5	1.7	2.1	2.5		
		(2)	1.0	1.2	2.2	1.8	1.6	1.5	1.2	-
		(3)	0.1	0.5	-	1.2	0.8	4.3	-	0.4
Kalahari Sand	Total Cu	(4)	2.4	1.8	2.1	2.8	3.8	2.7	2.4	3.4
		(5)	1.8	1.8	2.2	3.3	5.1	3.2	3.4	4.4
		(6)	5.0	0.8	-	3.0	4.1	1.1		
		(7)	1.2	0.6	-	2.6	3.5	1.7		
	HCl Cu	(4)	2.7	0.7	0.6	1.0	2.8	2.8	1.4	-
		(5)	2.8	0.8	0.8	1.2	4.0	3.2	2.3	-
		(6)	11.0	0.1	-	0.3	5.5	4.6		
Dambo sediment	Total Cu	(7)	49.7	31.4	-	13.8	42.2	13.9		15.3
	HCl Cu	(7)	7.4	5.9	-	4.5	5.0	5.5		12.4
	cxCu	(7)	20.1	22.0	-	14.0	65.3	13.1		32.0

Table 41. Fe contrast values in residual and Kalahari Sand per size fraction

Overburden type		Wet sieved						Dry sieved		
		+38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	-80#	-200#	
Residual soil	Nitric-perchloric acid	1.2	0.9	0.8	0.7	0.6	0.7	0.6	0.6	(-)
		0.5	0.6	0.8	0.9	0.7	0.6	0.7	0.5	(-)
	Hydro-chloric acid	2.5	1.4	0.7	0.6	0.8	1.0			(-)
		0.4	0.7	0.8	1.1	1.4	1.4	1.0		(-)
Kalahari Sand	Nitric-perchloric acid	0.8	1.1	1.2	1.0	1.2	0.9	0.9	1.2	(+)
		1.0	1.3	1.0	1.2	1.4	0.9	1.3	1.3	(+)
	Hydro-chloric acid	1.0	1.0	1.0	1.7	1.0	1.3	0.8		(+)
		0.7	1.0	1.0	1.3	1.3	1.7	0.9		(+)

Table 42. Mn contrast in residual soil and Kalahari Sand per size fraction

Overburden type		Wet sieved						Dry sieved		
		+38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	-80#	-200#	
Residual soil	Nitric-perchloric acid	0.8	0.4	0.4	0.5	0.8	0.7	0.5	0.7	(-)
		0.5	0.3	0.5	0.8	2.4	1.3	0.8	1.6	(+)
	Hydro-chloric acid	1.1	0.5	0.4	0.7	0.8	0.7	-		(-)
		0.3	0.5	0.5	0.9	2.7	1.5	0.9		(+)
Kalahari Sand	Nitric-perchloric acid	2.3	2.3	0.6	0.6	0.8	0.9	1.1	0.9	(+)
		5.3	10.5	1.0	1.2	1.4	1.2	1.7	1.2	(+)
	Hydro-chloric acid	0.7	0.6	1.1	0.8	0.8	0.9	1.5		(+)
		3.0	4.0	2.7	2.4	1.7	1.4	2.3		(+)

contrasts appear in the clay fraction. The maximum Cu contrast value in the silt fraction of the soils of the study area is probably related to the fact that maximum exCu and ex/Total Cu occur in the silt fraction of latosols (Govett, 1958). The silt fraction comprises fine quartz with Fe hydroxide and oxide and is similar in composition to coarser fractions of the soil. It is possible that the Cu in silt is associated with the very fine quartz, and in particular with Fe hydroxide coating the quartz. In areas of mineralisation during weathering, original Cu minerals are altered or decomposed, and the remobilised Cu, together with hydromorphically introduced Cu from the water-table, may be weakly sorbed on to the Fe-coated fine quartz.

(ii) Kalahari Sand

The maximum Cu contrast (Table 40) for both total and HCl soluble Cu occurs consistently in the silt fraction, and values are greater than in residual soils; the Fe and Mn contrasts are low (Table 41 and 42) and show no consistent trend. The silt fraction of Kalahari Sand is mineralogically similar to coarser grain size fractions, and comprises fine quartz, Fe hydroxide and oxide and minor kaolinite. The clay fraction is predominantly kaolinite with Fe hydroxide and oxide. Thus in the silt fraction, Cu will be sorbed mainly by the Fe hydroxide and oxide associated with the quartz. The marked increase in Cu content which occurs in the silt fraction (Fig. 37) no doubt relates to the concurrent increased Fe content; the relatively greater increase of Cu in silt in Cu anomalous areas where the Fe content is not necessarily increased, and where the Cu is more readily leached (Govett, 1958), may be due to some relatively loosely

bonded association with the fine quartz, or fine quartz coated with Fe hydroxide and oxide. Furthermore, in areas of mineralisation, the anomalous Cu may be in an association in the groundwater which tends to concentrate in the silt fraction in the overburden.

(iii) Dambo sediment

Maximum Cu contrast occurs in the silt fraction. The cxCu contrast occurs in the same fraction but is of greater magnitude. Similar results in dambo sediment are recorded by Govett (1958). Although factors controlling the dispersion of Cu in dambo sediment appear to be more complex than in the soil or Sand, and insufficient data has been collected covering the various influences, it seems probable that the general similarities of Cu distribution per size fraction, and Cu contrast per size fraction, with soil and Sand indicate a similar control of Cu.

5. INFLUENCE OF ORGANIC MATERIAL

Decaying vegetation comprises much of the Ao horizon of subtropical soils, and contains both altered residues (humus) and relatively unaltered, unhumified plant fibre. Because of the high temperatures, vegetation is rapidly decomposed and oxidised mainly to carbon dioxide and water. This results in a reduced amount of intermediate humic compounds. In addition, occasional bush fires convert surface vegetable material to carbon.

(a) Humus fractionation

Ao horizon humic matter was divided into a coarse, unhumified fraction containing twigs and leaves, and a fine fraction comprising mostly humified material.

Table 43. Humus fractionation trace element content (ppm).

		Residual Soil						Kalahari Sand					
Cu	overburden silt	78	70	36	24	60	62	15	185	110	10	12	19
	humus coarse	81	79	38	40	58	60	24	34	76	30	28	30
	humus fine	68	73	40	38	78	60	29	46	98	17	16	15
	Average vegetation range and mean	4.5-12.4 (7.2)											
Fe%	overburden silt	1.2	1.9	3.1	1.9	1.9	1.8	1.5	5.5	4.2	1.1	1.3	2.6
	humus coarse	0.1	0.6	1.0	1.2	1.0	0.8	0.4	0.3	0.6	0.7	0.7	0.7
	humus fine	1.8	0.9	2.1	2.5	2.0	1.5	1.6	0.9	1.8	1.4	1.4	1.3
	Average vegetation range and mean	12.0-18.0 (5.6)											
Mn	overburden silt	240	190	290	230	460	770	370	150	270	170	160	150
	humus coarse	-	470	570	540	920	860	520	720	630	760	370	700
	humus fine	460	340	530	550	560	580	920	710	620	560	460	420
	Average vegetation range and mean	32-630 (229)											
Zn	overburden silt	22	20	15	15	20	20	14	22	20	16	20	13
	humus coarse	43	48	34	34	50	42	49	44	51	61	55	56
	humus fine	12	13	16	18	26	22	35	32	41	20	17	28
	Average vegetation range and mean	4-26 (15)											

The Cu content of the two fractions is similar (Table 43) over either residual soil or Kalahari Sand, and displays similar variations to the content in the underlying sediment. Both fractions show enrichment of the Cu content relative to vegetation (10 fold). The Fe content is enriched in the fine humus, is of a similar level to the underlying soil or Sand content, and is considerably enhanced relative to vegetation values (200 fold). The variation of Fe content in overburden is not reflected in the humus values. The Mn content of the two fractions is similar and is higher than the Mn values of the soil or Sand; the humus Mn values tend to reflect the overburden pattern, while they are greater than the values in vegetation (2 fold). Zn is enriched in the coarse humus, while the Zn content of fine humus is similar to the overburden content. The Zn content of humus is double the vegetation value (2 fold).

Although of rather a rudimentary nature, these results indicate that the metal content of even coarse, relatively unhumified plant debris in the Ao horizon differs considerably from the metal content in surrounding vegetation. The humus tends to accumulate trace elements, possibly by metal insolubility, and attains metal levels more equivalent to soil values.

Humus is reported to be a dark coloured, complex organic substance with a high total exchange capacity with which the less soluble constituents of plant decay tend to accumulate. It has a high adsorptive capacity for cations, and Cu is strongly chelated (Boyle, 1969); in addition Cu is strongly sorbed by unhumified plant material (Bloomfield, 1963).

Some authorities consider that metals, and in particular Cu, form stable complex metallo-humics by chelation (Duvigneaud and Denaeyer, 1963; Malyuga, 1964) and are irreversibly fixed and accumulated (Ginzburg, 1960). Others suggest that Cu tends to stabilise in non-soluble metallo-organic complexes but that the bonding is extremely variable resulting in both readily-extractable or firmly bonded metal (Hawkes and Webb, 1965). In Zambian soils, Govett (1958) maintains that Cu in the humus horizon is more readily-extractable than at 18 ins. depth.

(b) Ao horizon metal content

In the study area the organic carbon content in residual soils decreases from surface (0.8-1.0%) to the A horizon (0.3%) and remains relatively constant into the C horizon irrespective of laterite development. In Kalahari Sand the surface organic carbon is more concentrated (1.1-1.6%) and decreases rapidly to 5 ft. (0.2-0.4%) and is less than 0.2% down to 20 ft.

In the study area in both background and anomalous soils, Cu values in the Ao horizon are variable but generally lower than in soil at 9 in. depth (Table 44), and especially in anomalous areas. The Ao humus horizon is enriched in Mn (+70%) and Zn (+25%) but impoverished in Fe (-18%) in comparison with the values at 9 in. depth. Although vegetation has a low uptake of Fe, the lower Fe value in humus may also be due to organic reduction of Fe^{3+}, or to the prevention of flocculation of colloidal ferric hydroxide by humic substances (Oborn, 1960).

In Kalahari Sand areas with background Cu values, there is a marked enrichment of Cu in the Ao horizon compared with underlying Sand (+29%). In anomalous areas, the humus zone

Table 44. Humus horizon trace element enrichment

Overburden type	element	Anomalous Ao	9in.	Enrichment (Ao/9in.)	*	Background Ao	9in.	Enrichment (Ao/9in.)	*
Residual soil	Cu	183.1	220.7	-15%	(11)	28.8	29.9	-1%	(5)
	Fe%					1.8	2.1	-18%	(16)
	Mn					340.7	200.5	+70%	(16)
	Zn					24.0	19.0	+26%	(16)
Kalahari Sand	Cu	78.4	86.6	-11%	(5)	26.6	20.6	+29%	(29)
	Fe%					1.2	1.3	-7%	(31)
	Mn					207.0	71.5	+190%	(31)
	Zn					34.0	16.1	+111%	(31)

* No. of samples

is impoverished. As the Cu content of Kalahari Sand is low, biochemical enrichment may be more significant than in residual soil. Moreover, the Ao horizon is generally more organic-rich and alkaline than over residual soil. The deficiency of Cu in humus in anomalous Sand may reflect a greater hydromorphic concentration of Cu in the silt and clay fractions of Sand than by vegetation. Mn (+190%) and Zn (+111%) values are notably enhanced in Sand humus while Fe values are lower (-7%). The Mn and Zn are more enriched than in residual soil humus which may reflect the higher carbon content and alkalinity of the Kalahari Ao horizon compared with residual soil.

Cu enrichment in humic horizons is reported in various European and Canadian soils (Duvigneaud and Denaeyer, 1963; Hornbrooke, 1969). Humus is used as a successful prospecting

technique in areas of transported overburden (e.g. Canada; Boyle and Dass, 1967) or where the humus metal is of a higher concentration than in the underlying soil. In the study area humus sampling is less effective than soil or Sand sampling. Although the areal trace element pattern of the soil is reflected in the humus, the generally lower values of Cu in humus would result in a lower contrast between anomalous and background areas. In addition, Cu values are more variable in the humus horizon.

(c) Middle Kamwedgi anomaly

The anomalous Cu at Middle Kamwedgi is restricted to a zone of brown-black, humic dambo sediment in which the organic carbon content rises to over 1%. A typical profile is presented in Table 45. The zone is coextensive with the

Table 45. Trace element content (ppm) relative to carbon content (Middle Kamwedgi, pit G14)

Depth(in.-ft.)	Description	organic carbon %	Cu	Fe%	Mn	Zn	pH
0-2"	dark brown humus	1.4	560	3.0	120	21	5.5
2"-1'2"	brown humus	1.4	920	3.0	25	16	5.0
1'2"-2'6"	buff sand	0.1	270	2.3	21	6	5.7
2'6"-3'6"	black humic sand	1.3	1300	1.6	12	19	5.2
3'6"-4'6"	black humic sand	1.4	1600	0.5	12	19	5.1
4'6"-5'6"	brown sand	0.1	90	2.0	16	4	5.6
5'6"-9'	buff sand	<0.1	30	2.3	12	6	4.9

anomalous Cu zone outlined in Fig. 29 and occurs under the southern fringe of the present-day dambo. This position, together with the existence of pebble horizons lower in the profile (Fig. 30), suggest that it is the Ao horizon of a buried former dambo meander. The former climatic conditions, existing when the humus was formed, may have been considerably wetter than the present day climate, as evidenced by pebble zones. Consequently, the horizon may have been similar to humus horizons in present day dambos, or to more permanent swamp conditions which have a lower redox potential. Seepage Cu anomalies are common in present day dambo humus zones (Tooms, 1955; Govett, 1958) and in temperate swamps (Hawkes and Webb, 1965). If the anomaly was due to metal concentration in a swamp environment from a background source, Zn would tend to precipitate in a similar manner. The absence of Zn accumulation at Lower Kamwedgi may be due to post-depositional solution of the more mobile Zn, or alternatively suggests that the anomalous concentration of Cu alone, reflects a Cu-rich, Zn-poor source upstream.

6. BIOGENETIC FACTORS

(a) Termitaria

(i) Introduction

Termitaria are common features in the study area and develop on residual and contact soil, dambo sediment and in Kalahari Sand near dambos. The structures are of two types:

(1) small cylindrical knobs, 6 in. to 1 ft. in diameter and 1-2 ft. in height.

(2) large conical mounds with a base of up to 60 ft. in diameter; the lower older base is typically surmounted by a younger pinnacle with a height of up to 30 ft.

The mound generally contains about 300 tons of material.

The large structures (2) were the object of investigation as they represent a considerable amount of reworked overburden material with possible disruption of soil and geochemical profiles. Similar termitaria have been investigated on the Copperbelt where the termite species is believed to be Termes bellicosus (Arnold is Mendelsohn, 1961). Termite activity has been noted on the Copperbelt to depths of 20 ft., and may be deeper if the termites obtain moisture from the water-table.

The termitaria in the study area reflect the soil colour. On residual soil the general frequency is 1 per acre, but in areas of contact soil are less common and the termitaria are flatter in outline. In areas of Kalahari Sand, they occur only on the fringes of dambos. Although Tooms (1956) suggests that termitaria only occur on well aerated soils, it is probable that excessive depth to the water-table, or the poor water-retention qualities of the overburden, as in areas of Kalahari Sand, is prohibitive, either to the existence of the termites, or to the construction of termitaria. Within the dambo flood-plains, the semi-permanent water-logging of the sediment restricts the activity of the termites.

(ii) Residual Soil

Termitaria tops and bases together with adjacent soils were sampled and the -80# dry sieved fraction analysed (Fig. 41). The soil Cu anomaly is displayed in the termitaria material. The Cu contents of the tops and bases of the termitaria are of similar magnitude but are consistently greater than the soil values. This apparent increase in the Cu content of the termitaria is a result of the higher proportion

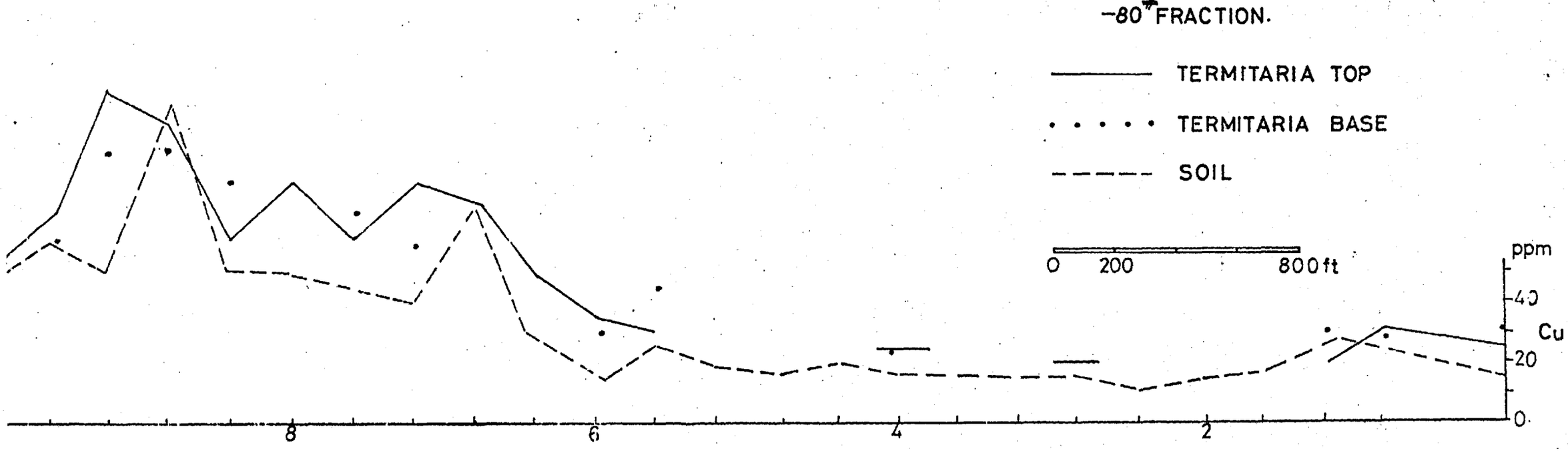


FIG.41 TERMITARIA AND RESIDUAL SOIL Cu CONTENT, MUFUMBWE.

of -200# material in termitaria (Table 46) with a higher metal content associated with the fines. Reanalyses of the samples using a similar silt size fraction (Fig. 42) indicates very similar Cu, Fe, Mn, Zn and Co values for the two parts of the termitaria and suggest a similar origin for the material for both parts.

In comparison with the soil results, the metal dispersion in the termitaria is identical to the soil, and values except for Cu are of equal magnitude; the Cu is slightly enriched in the termitaria. This random sampling of the termitaria indicates an overall consistency of metal content within the termitaria, although locally a range of values may occur within a single termitaria (Tooms, 1955).

(iii) Kalahari Sand

At Jijombo, large termitaria occur within half a mile of the dambo margin. Company data of 9 in. and hand-auger sampling in the Kalahari Sand on the west bank of the dambo, adjacent to the dambo anomaly (Fig. 31), had indicated consistent background values of 40 ppm Cu (-80#D). Resampling of the Sand during the present study indicated low background values of 4-11 ppm Cu (Fig. 43a; -80#D, potassium bisulphate extraction). Analyses of -80#D fractions of adjacent termitaria illustrate a significant anomalous zone, with a peak value of 43 ppm and a background range of 4-20 ppm (Fig. 43b). Subsequent power auger drilling at this anomaly has confirmed mineralised mudstone at 52 ft. depth, overlain by Kalahari Sand. Comparative mechanical analyses of the Sand and termitaria material (Table 46) indicate a markedly higher content of -200# material in termitaria than in Sand which would account for the variation in magnitude of Cu

SILT

TERMITARIA TOP

TERMITARIA BASE

SOIL

0 200 500ft

Cu ppm 100 80 60 40 20 0

Fe % 4 3 2 1 0

Mn ppm 200 100 0

Zn 30 20 10 0

Co 10 5 0

10 8 6 4 2

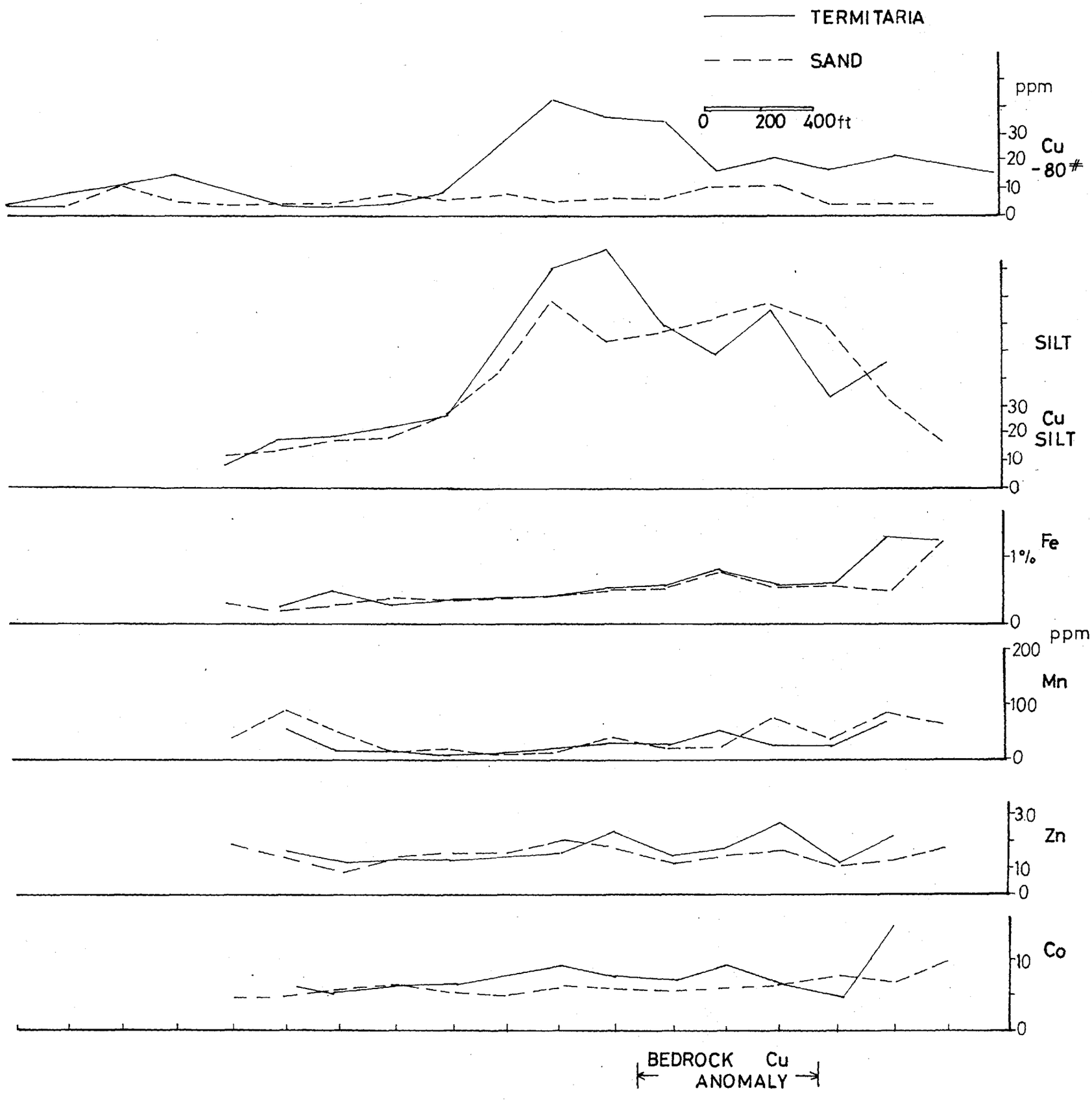


FIG.43 TERMITARIA AND KALAHARI SAND Cu,Fe,Mn,Zn,Co CONTENT, JIJOMBO.

Table 46. Mechanical analyses of termitaria and adjacent overburden.

	Location	Type	% weight per size fraction +20#	-20+38#	-38+80#	-80+200#	-200#
Residual soil	Mufumbwe	Termitaria	1.7	2.8	10.5	24.1	60.9
		Residual soil	1.4	7.9	22.4	26.8	41.8
Kalahari Sand	Mufumbwe, Nansimba Rd.	Termitaria	0.3	11.3	28.0	5.2	55.2
		Kalahari Sand	0.3	13.9	43.8	15.0	27.0
	Jijombo	Termitaria	0.8	15.3	30.2	15.9	37.8
		Kalahari Sand	0.4	15.7	42.4	21.0	20.6

between the termitaria and Sand samples. This is illustrated if analyses of the silt fraction of both Sand and termitaria are compared (Fig. 43b). The Cu, Fe, Mn, Zn and Co metal content of both sample types is similar. The anomalous Cu zone is outlined by the silt fraction of both types of sample.

A comparison of trace element values in termitaria and in adjacent residual soil profiles (Table 47) indicates that the Cu, Fe and Mn values in termitaria are similar to soil values at 10 ft. depth, while Zn and Co values correlate with any depth below the Ao horizon. A similar comparison in a Kalahari Sand environment (Table 47) illustrates that the metal content of the termitaria equates with values in near-surface horizons and in particular above a metal enriched laterite zone (pit B8, 8-12 ft. depth). These results, together with the overburden and termitaria data in Figs. 42 and 43, suggest that termitaria material is derived from relatively near-surface overburden. The results are in accord with Tooms (1955), who suggests that termitaria material is derived from the A horizon.

In conclusion, although termites probably burrow through overburden to a considerable depth, the general consistency of geochemical soil profiles implies that little disruption is caused. Moreover, termitaria are mainly constructed from nc surface overburden which would not involve contamination by material from depth. As a prospecting technique, the metal content of termitaria is similar to that of surrounding overburden, although the greater proportion of fine material in

Table 47. Comparison of termitaria and overburden profile metal content (ppm)

Residual soil (Mufumbwe)						Kalahari Sand (Jijombo)						
Termitaria	Cu	Fe%	Mn	Zn	Co	Termitaria	Cu	Fe%	Co	Cu	Fe%	Co
Top	160	3.1	150	16	9	Top	45	0.9	9	13	0.6	6
Base	160	3.8	190	17	10	Base	51	0.9	9	17	0.7	7
Pit 22E/8/0 Depth(ft.)						Pit B8 Depth(ft.)						
0-0.2	105	3.2	460	24	10	0-0.3	34	0.7	10	15	0.5	9
0.2-1	120	3.5	250	20	10	0.3-2	44	0.9	13	10	0.7	10
1-3	110	2.9	180	16	10	2-5	52	1.3	16	11	0.6	9
3-6	95	2.7	120	15	9	5-8	54	1.7	11	12	0.7	9
6-9	130	3.2	160	17	10	8-12	69	2.6	12	10	0.7	8
9-11	160	4.4	200	17	10	12-18	28	1.0	9	12	0.6	9
11-14	160	4.2	220	18	10	18-26				7	0.4	9
14-17	210	4.1	200	17	28							

termitaria is an aid where coarse material sampling (-80#D) is employed; this effect is most marked in Kalahari Sand areas where termitaria sampling is superior to Sand sampling, if a coarse sieve fraction is used for analyses. Unfortunately in Kalahari Sand areas, the distribution of termitaria is limited to the environment of dambos, which are notably infrequent in these areas.

CHAPTER V BIOCHEMICAL PROSPECTING

1. Introduction

The detection of mineralisation by the observation of plants was first reported by Agricola (1556). Early research in the application of vegetation to geochemical prospecting was carried out by Goldschmidt (1937), Fersman (1939) and Brundin (1939). Since then a great amount of literature on the subject has been written both in the western hemisphere and in the U.S.S.R.

Early workers in the U.S.S.R. include Malyuga (1947,'63), Ginzburg (1957), Vinogradov (1954), and Tkalich (1952); in Canada much work has been done by Warren and associates, and papers include Warren and Delavault (1948), Warren and Howatson (1947); in the U.S.A. early researchers include Bateman and Wells (1917), Cannon (1952), Lovering et al. (1950); in Europe initial experiments were carried out by Rankama (1940), Vogt (1942), Millman (1953); and in Africa preliminary research was carried out by Millman (1953) with references by Wilding (1965) and Jay (1959).

The use of vegetation has a particular appeal in areas of transported overburden and has been applied successfully where overburden of 50 ft. of glacial drift or swamp sediment occurs (Webb, 1953). Various authors have discussed the use of biogeochemistry in arid environments; these include the prospecting for Cu (Malyuga, 1954; Lovering et al., 1950); for U and V (Cannon, 1952; Botova et al., 1963; Kurbatov (in Grabovskaya, 1965)) and for Hg (Saukov, 1950).

General biogeochemical methods in arid areas are noted by Khamrabaev and Talipov (1960), Vinogradov et al., (1958)

and Viktorov (1960). Most of the described arid areas experience a desert climate but the overburden is residual soil, or thin mantles of aeolian sand. Research on deep transported sand covers has not been located during the present research.

In the study area Kalahari Sand overburden is locally over 100 ft. thick but may be in excess of 200 ft. In addition the climate is subtropical and epigenetic anomalies are able to develop through the Sand profile. Elsewhere in southern Africa, where areas of Kalahari Sand experience a semi-arid climate, lack of moisture may prohibit the development of a saline anomaly in the Sand, and surface sampling might be ineffective. In such areas, in order to penetrate the Sand cover, deep sampling would be necessary. But techniques such as machine auger drilling, on a grid sampling basis, would be extremely time-consuming and costly. Alternatively, regular sampling of vegetation has been used for detection of deeply buried anomalies, and the method depends on the root penetration of local plant species.

Species of short desert plants and shrubs are reported to have root systems of up to 100 ft. in order to reach the water-table (Grabovskaya, 1965; Malyuga, 1964) while in arid zones in California juniper roots are recorded at depths of several hundred feet (Cannon and Starrett, 1956). The vegetation of the study area is typical of the subtropical woodland savanna of northern Zambia. As the plants do not rely solely on water from the water-table, and as the water-table is relatively shallow in comparison with desert areas, the root system may be comparatively shallow. Nevertheless,

the vegetation is subjected to a 7 month drought and certain upper storey Zambian tree species are known to have a well developed tap root system (Fanshawe, 1962).

In plant metal associations, two main divisions are recognised:

(a) Indicator or overt plants which form about 8% of reported cases (Carlisle and Cleveland, 1958) and whose distribution or morphological condition is altered by the excess or deficiency of metal content in the soil; this category is further divided into (i) specific indicators, which require a specific element distribution for normal growth, and, (ii) symptomatic indicators which display deformed morphological features such as abnormal colour, shape or flowering time as a result of metal toxicity.

This category of overt plants is also divided into local and universal indicators.

(b) covert or tolerant plants, which show no outward indication of variable metal content and represent 92% of reported cases (ibid.,1958). This group includes the "accumulator" plant which is capable of accepting above-average levels of metal concentrations in its tissues (Webb and Millman, 1951; Malyuga, 1964). It is suggested that almost all plants may reflect mineralisation (Warren and Delavault in Carlisle et al., 1958) but high Cu content is harmful to organisms (Day, 1965). The effect of different concentrations of metal in the soil may affect the floristic ecological assemblage.

The association of specific plants with Cu deposits is well known. These plants are mainly herbaceous and generally belong to the families Caryophyllaceae and Labiatae, and to

the Bryophyte mosses (Grabovskaya, 1965). Of the family Labiatae, two species are found in close association with Cu deposits in the Katanga Province of the Congo, namely Becium obovatum* and Acrocephalus robertii (Duvigneaud, 1958): the former is reported to grow on soil containing over 5000 ppm Cu, while the tolerance of the latter is very high and in the Congo has never been found outside Cu outcrops (Hawkes and Webb, 1965).

In addition many cases are cited of the covert type of plant, whereby the only indication of soil Cu mineralisation is in the abnormal level of Cu in the plant tissues. There is considerable disagreement on the factors controlling the metal content in plant tissues. Metal variation has been attributed to the species of the plant, the part of the species, the age of the species, the age of the part, the type of soil, the availability of metals in the soil, the soil pH, microorganisms or organic matter in the soil, the climate, season, rainfall, amount of light, and the direction to which the sample part is directed. Although these factors may be important locally, standardised biogeochemical surveys have proved successful in a wide variety of geological environments, soil types, climates and plant assemblages.

The average metal concentration in plants is given in Table 48.

* originally known as Ocimum homblei, later reclassified as Becium homblei de Wild, but in fact is Becium obovatum (Dr. Launert, personal communication).

Table 48 Comparison of average metal content (ppm) in plants and substratum.

	Rock	Soil	Plant(ppm-ash)	Plant(ppm dry wt.-approx)
Cu	100+,40*	20+*	200+*	8
Fe	5%+	3.8%+	1%+	400
Mn	900+	850+	7500+	300
Zn	50+,80*	50+*	900+,300*	36, 12

(+ after Grabovskaya, 1965)
(* after Malyuga, 1964)

2. Previous work in Central Africa

The observation of treeless patches in otherwise normal bush cover and association with high soil Cu content, has been noted in Katanga since 1914 (Ball and Shaler, 1914). In 1949 on the Zambian Copperbelt, the association between the small mauve flowering plant Becium homblei de Wild.,* locally known as the "copper flower", and Cu mineralisation was established by Woodward, although it was recognised in the Katanga at the beginning of the century (Wildeman, 1921). The plant may differ by flower and leaf characteristics from a similar species Becium obovatum E. Mey known as the "pseudo-copper flower" which is widespread on unmineralised areas (Mendelsohn, 1961). The "copper flower" is a specific indicator, requiring a high Cu level in the soil of over 100 ppm to above 5000 ppm Cu (Hawkes and Webb, 1965): the plant tissues may contain a high content of Cu, occasionally over 1000 ppm Cu (ash). In addition Cryptosepalum sp., although a widespread species in northern Zambia, grows in greater profusion on Cu mineralised soils, a feature which has also been noted in the Congo (Mendelsohn, 1961).

* in fact Becium obovatum.

In clearings found in association with Cu rich soils, the normal tree growth is replaced by low shrubs and grass, often accompanied by "copper flowers". The absence of trees in these copper clearings is considered due to the Cu toxicity of the soil (ibid.,1961) or the excessive leaching of nutrients due to soil acidity (Hawkes and Webb, 1965) or to a lack of nitrogen in the soil (Duvigneaud, 1958). In the Congo a peculiar Cu-tolerant flora has been noted on copper outcrops. In such areas of high mineralisation and a Cu content in soil of toxic quantity, the normal forest vegetation gives way to peculiar herbaceous "copperphytes" or to stunted vegetation belonging to the families Labiatae (which includes the genera Becium and Acrocephalus), Compositae, Scrophulariaceae, Cyperaceae, Commelinaceae and Gramineae. (Duvigneaud, 1958).

The Co and Cu content of the twigs and leaves of several common Zambian tree species have been analysed (Jay 1959; Wilding, 1965). Wilding noted that no geobotanical assemblage variation could be correlated with Cu mineralisation at Kalumbila in north-west Zambia, and the vegetation produced no chemical anomaly. The Cu content in Brachystegia boehmii and Julbernardia paniculata bark ash is 100-200 ppm (2.7-5.4 ppm dry weight) and in Diplorhynchus mossambicensis leaf ash is 200-300 ppm (7.8-11.7 ppm dry weight).

At the Mangula Copper Mine in Rhodesia (Jacobsen, 1967), a zonation of the vegetation correlates with mineralisation. The widespread Brachystegia boehmii-Julbernardia globiflora-

Diplorhynchus condylocarpon-Monotes engleri assemblage gives way to a more Cu tolerant assemblage of Euphorbia matabelensis, Tapiphylum velutinum, Olax obtusifolia, and Combretum zepheri. The following average values occur (ppm dry weight):-

	Soil	Twig
Anomaly peak	1360	45
Background	50	17

Reilly (1967) studied several Zambian Cu clearings and noted 4 herb indicators: Becium homblei,* Vernonia glaberima, Triumfelta welwitschii and Cryptosepalum maraviense. He noted that the trees Combretum sp. and Pterocarpus angolensis prefer non-mineralised areas. Becium obovatum and B. angustifolium*, closely related species of Beciuun homblei*, were found to be intolerant of soil containing over 20-40 ppm Cu. Becium homblei* from several localities was found to have a range of Cu in its tissues (32-324 ppm dry weight).

3. Geobotany

A geobotanical survey was carried out at Lower Kamwedgi. Transects were laid out on residual soil, contact and Kalahari Sand in both background and anomalous areas. On a line transect, at 200 ft. intervals, the total tree and shrub population was counted within demarked 100 sq. ft. quadrates. With the exception of Landolphia kirki, the ground vegetation of herbs and grasses was excluded. (For full details of vernacular and botanical names, see Appendix I).

* all species probably Becium obovatum.

Aerial photography indicates even vegetation cover with no obvious variation.

On residual soil at line C (Table 49, Fig.23) the dominant tree species is Julbernardia paniculata, subordinated by Cryptosepalum pseudotaxus, Brachystegia boehmii, B. longifolia, Combretum mechowianum and Brachystegia spiciformis. These trees form a 40-50 ft. canopy. Common lower storey species (20 ft.) include Diplorhynchus condylocarpon, Ochthocosmus lemaireanus, Monotes spp. and Pseudolachnostylis sp. Where quartzite outcrops, or is near surface, trees are sparser with the significant exception of Uapaca kirkiana and U. nitida, while lateritic rubble is associated with Monotes spp.

The Cu soil anomaly occurs at peg C3 (240 ppm) where Pterocarpus angolensis, Olax obtusifolia, and Ochna pulchra are more abundant than average. Brachystegia spp. are sparse.

On residual soil at line DN (Table 50) the upper storey is dominated by Julbernardia paniculata with occasional Brachystegia boehmii and B. spiciformis. The shorter trees comprise mainly Ochnocosmus lemaireanus, Monotes spp., Pseudolachnostylis spp. and Diplorhynchus condylocarpon. The soil Cu anomaly peak occurs at peg DN4 (139 ppm) with a spread from DN3 to DN5. Julbernardia paniculata, Olax obtusifolia and Monotes spp. are more abundant over the anomaly.

At line KN, in contact soil, near the surface boundary between residual soil and Kalahari Sand, (Table 51) the tall canopy is dominated by Julbernardia paniculata, with

Table 49. Tree species frequency per quadrate, Lower Kamwedgi, line C. (* Soil Cu anomaly)

Peg No.	C6	C4	C3*	C2	C1	CO	C-1	C-2	C-3	C-4	C-5	C-6
No. of Trees	78	95	89	67	113	29	92	68	85	97	238	143
Afrormosia angolensis	-	3	1	-	-	-	1	-	1	1	-	2
Albizia zygia	-	-	-	-	-	-	2	1	4	-	-	-
Amblygonocarpus andongensis	-	-		-	-	-	-	-	-	-	1	-
Anisophyllea spp.	-	1	1	-	1	-	-	1	5	-	-	-
Brachystegia boehmii	7	2	-	2	9	1	3	-	2	4	10	4
Brachystegia longifolia	-	5	1	7	5	-	4	3	2	4	-	7
Brachystegia spiciformis	5	3	-	3	2	-	6	4	7	2	2	6
Combretum mechowianum	-	3	2	-	2	6	3	-	1	1	6	3
Commiphora mollis	-	-	-	-	2	1	1	-	-	-	-	1
Cryptosepalum pseudotaxus	-	9	4	8	6	-	7	3	3	12	-	2
Diospyros batocana	-	1	1	-	-	-	-	-	-	1	2	-
Diplorhynchus condylocarpon	1	7	3	4	7	8	2	7	7	3	4	1
Eriosema spp.	-	-	-	-	-	-	-	-	1	-	-	-
Erythrophleum africanum	-	-	-	-	3	3	-	-	-	-	-	1
Faurea spp.	2	2	2	1	5	1	4	15	-	4	24	13
Hexalobus monopetalus	-	-	-	-	-	-	-	-	1	-	-	-
Julbernardia paniculata	19	19	22	4	18	5	13	4	18	2	84	82
Landolphia kirki	-	Rare	Rare	Rare	Rare	Rare	Rare	Rare	Rare	Rare	Rare	Rare
Monotes spp.	32	3	-	1	1	-	3	4	9	18	43	-
Ochna pulcra	1	1	11	1	-	-	-	-	-	-	-	-
Ochthocosmus lemaireanus	5	13	7	3	5	-	1	4	5	3	5	2
Olax obtusifolia	-	4	11	-	-	-	3	8	-	21	1	-
Parinari excelsa	-	4	-	-	-	-	-	-	-	-	1	-
Pseudolachnostylis maprouneifolia	-	2	-	-	4	1	-	-	-	1	-	1
Pseudolachnostylis sp.	-	1	-	11	18	-	2	2	3	-	-	-
Pteolopsis spp.	-	-	-	-	-	-	-	-	2	-	-	-
Pterocarpus angolensis	-	3	12	14	-	-	-	1	-	-	-	2
Steganotaenia araliacea	-	-	-	-	-	-	-	-	1	-	-	-
Strychnos spinosa	-	-	1	-	-	-	-	-	-	-	-	-
Swartzia madagascariensis	-	3	1	1	6	-	-	1	1	-	2	2
Uapaca kirkiana	1	3	-	-	-	-	10	4	2	5	-	-
Uapaca nitida	4	1	2	-	-	1	13	-	2	6	6	1

Table 50. Tree species frequency per quadrate, Lower Kamwedgi, Line DN. (*Soil Cu anomaly)

Peg No.	DN10	DN9	DN8	DN7	DN5	DN4*	DN3	DN2	DN-3	DN-4	DN-5	DN-6
No. of Trees	79	61	52	102	70	67	138	64	50	88	100	77
Afrormosia angolensis	-	1	-	-	1	-	1	2	1	-	-	-
Afzelia quanzensis	-	-	-	-			-	-	-	1	1	-
Albizia zygia	1	1	-	-	-	3	-	-	1	1	2	1
Amblygonocarpus andongensis	-	-	-	-	-	-	-	-	-	-	-	-
Anisophyllea spp.	1	1	-	-	4	1	-	-	-	-	-	-
Brachystegia boehmii	2	4	3	3	5	10	6	6	-	8	7	10
Brachystegia longifolia	3	5	2	3	4	-	1	2	-	1	-	1
Brachystegia spiciformis	-	2	4	7	3	-	1	2	3	8	3	1
Combretum mechowianum	-	-	-	-	1	-	-	-	-	-	1	-
Combretum molle	2	2	3	1	1	1	-	-	-	-	1	1
Commiphora mollis	2	1	1	-	3	-	-	-	-	1	4	5
Cryptosepalum pseudotaxus	-	4	-	-	-	1	2	5	1	9	1	-
Diospyros batocana	-	-	-	-	-	-	-	-	-	-	-	-
Diplorhynchus condylocarpon	10	4	2	5	2	3	1	3	6	7	11	15
Eriosema spp.	-	-	-	-	-	-	-	-	-	-	-	-
Erythrophleum africanum	-	-	-	-	-	-	-	-	-	-	-	-
Faurea spp.	-	2	5	14	1	1	3	-	-	2	-	-
Gardenia subacaulis	-	1	1	4	-	-	-	-	-	-	-	-
Hexalobus monopetalus	-	-	-	-	-	-	-	-	-	2	2	1
Julbernardia paniculata	18	12	21	26	32	23	54	20	9	5	21	5
Landolphia kirki	Rare	Rare	Rare	Rare	Rare	Rare	-	-	-	-	-	-
Lannea discolor	-	1	-	-	-	-	-	-	-	-	-	-
Monotes spp.	-	1	-	16	2	7	34	13	4	12	-	3
Ochna pulcra	10	-	-	1	-	1	1	-	1	10	7	5
Ochthocosmus lemaireanus	1	3	-	6	4	-	3	2	5	2	4	1
Olax obtusifolia	-	-	5	5	1	-	22	3	6	3	1	-
Parinari excelsa	-	1	-	-	1	-	-	1	1	-	-	-
Piliostigma thonningi	11	-	-	-	-	-	-	-	-	-	-	-
Pseudolachnostylis sp.	12	6	1	-	-	12	1	-	7	11	22	5
Pteolopsis spp.	-	-	-	-	-	-	-	-	-	2	-	-
Pterocarpus angolensis	-	-	-	-	-	-	-	-	-	-	1	1
Steganotaenia araliacea	-	-	-	-	-	-	-	-	-	-	-	1
Strychnos spinosa	-	-					-	-	-	-	-	-
Swartzia madagascariensis	3	2	1	-	-	-	1	-	-	-	3	4
Uapaca kirkiana	-	-	-	-	-	-	-	-	-	-	-	-
Uapaca nitida	-	2	-	-	-	-	1	-	-	-	-	-

Table 51. Tree species frequency per quadrate, Lower Kamwedgi, line KN. (*Sand Cu anomaly).

Peg No.	KN10	KN9	KN8	KN7	KN5	KN4	KN3	KN2	*KN-3	KN-4	KN-5	KN-6
No. of Trees	74	83	59	109	83	107	150	137	70	85	151	125
Afrormosia angolensis	1	–	2	–	–	–	1	–	2	–	–	–
Afzelia quanzensis	–	–	–	–	–	–	–	–	–	–	–	–
Albizia autunesiana	–	2	–	–	–	–	–	–	–	–	–	–
Albizia zygia	1	1	–	–	1	1	–	–	–	–	1	1
Ambylgonocarpus andogensis	–	–	–	–	–	–	–	–	–	–	–	–
Anisophyllea spp.	–	–	–	–	–	–	2	–	–	–	–	–
Brachystegia boehmii	–	10	12	9	10	6	34	19	–	–	–	–
Brachystegia longifolia	8	3	2	1	–	1	2	2	5	6	15	7
Brachystegia spiciformis	4	5	4	2	5	6	2	3	4	5	–	8
Combretum mechowianum	–	1	–	–	–	–	–	–	–	–	–	–
Combretum molle	–	1	2	–	1	1	–	1	4	4	8	4
Commiphora mollis	–	1	1	–	–	1	5	4	4	2	–	1
Cryptosepalum pseudotaxus	6	–	–	–	3	6	7	3	–	–	–	–
Diplorhynchus condylocarpon	7	10	6	6	5	3	1	4	12	14	22	21
Eriosema spp.	–	–	–	–	–	–	–	–	–	–	–	–
Erythrophleum africanum	–	1	2	–	–	–	–	–	3	5	9	1
Faurea spp.	1	–	–	–	5	1	1	–	–	–	–	–
Gardenia subacaulis	–	–	–	–	–	–	–	–	–	–	–	–
Guibourtia coleosperma	–	–	–	–	–	–	–	–	3	6	4	1
Hexalobus monopetalus	1	–	–	–	–	–	–	–	1	4	–	1
Julbernardia paniculata	5	11	9	86	22	48	82	52	4	7	2	6
Landolphia kirki	–	–	–	–	–	–	–	–	–	–	3	Abund.
Lannea discolor	–	1	–	–	–	–	–	1	–	–	1	–
Monotes spp.	9	3	3	2	15	3	6	14	6	–	6	–
Ochna pulcra	2	2	–	–	–	1	–	5	–	5	3	3
Ochthocosmus lemaireanus	5	1	1	–	1	–	9	7	–	–	–	–
Olax obtusifolia	6	–	–	1	9	17	1	–	–	–	–	–
Parinari excelsa	–	–	–	–	–	–	–	–	–	–	–	–
Piliostigma thonningi	–	–	–	–	–	–	–	–	–	–	–	–
Pseudolachnostylis maprouneifolia	–	1	3	–	1	1	2	–	5	3	6	12
Pseudolachnostylis sp.	10	20	16	–	–	–	–	17	14	15	51	38
Pteolopsis spp.	–	–	–	–	–	–	–	–	–	–	–	2
Pterocarpus angolensis	–	2	–	–	–	–	–	–	3	1	1	1
Steganotaenia araliacea	–	–	–	–	–	–		–	–	–	–	–
Strychnos spinosa		–	–	–	–	–	–	–	–	–	–	–
Swartzia madagascariensis	–	1	–	2	–	1	–	3	–	–	–	–
Uapaca kirkiana	1	–	–	–	–	–	–	–	–	–	–	–
Uapaca nitida	6	–	–	–	–	–	3	–	–	–	–	–

Table 52. Tree species frequency per quadrate, Lower Kamwedgi, line PN. (* Sand Cu anomaly)

Peg No.	PN9	PN8	PN7	PN6	PN4*	PN3	PN2	PN1	PN-3	PN-4	PN-5	PN-6
No. of Trees	114	155	129	158	167	90	172	120	107	111	164	107
Aformosia angolensis	-	1	-	-	-	-	1	-	-	-	-	-
Afzelia guanzensis	-	-	-	-	-	-	-	-	-	-	-	-
Albizia autunesiana	-	-	-	-	-	-	-	-	-	-	-	-
Albizia zygia	2	1	1	1	1	-	-	-	-	-	4	-
Amblygonocarpus andongensis	-	-	-	-	-	-	-	-	-	-	-	-
Anisophyllea spp.	-	-	-	-	2	-	-	-	-	15	-	-
Brachystegia boehmii	-	-	-	-	-	-	-	-	-	-	-	-
Brachystegia longifolia	3	1	3	2	4	3	3	4	5	8	5	7
Brachystegia spiciformis	4	7	10	4	2	5	4	7	5	2	2	5
Combretum mechowianum	-	2	1	-	-	-	-	-	-	-	-	-
Combretum molle	4	7	9	9	-	2	3	7	3	4	4	5
Commiphora mollis	-	2	1	2	-	-	-	-	-	-	-	-
Cryptosepalum pseudotaxus	2	-	8	-	1	3	3	2	-	-	-	-
Diospyros batocana	3	1	2	6	2	3	1	1	-	-	-	-
Diplorhynchus condylocarpon	26	33	11	9	8	10	16	12	16	20	28	9
Eriosema spp.	-	-	-	-	-	-	-	-	-	-	-	-
Erythrophleum africanum	11	5	3	14	60	5	15	4	2	6	11	1
Faurea spp.	-	-	-	-	-	-	-	-	-	-	-	-
Gardenia subacaulis	-	-	-	-	-	-	-	-	-	-	-	-
Guibourtia coleosperma	-	1	-	-	-	-	1	1	3	2	1	2
Hexalobus monopetalus	-	-	-	1	2	1	1	1	2	1	-	-
Julbernardia paniculata	5	8	-	9	10	3	6	15	5	5	43	14
Landolphia kirki	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Abund.	Abund.	Abund.
Lannea discolor	-	-	-	-	-	-	-	-	-	-	4	-
Monotes spp.	2	-	5	1	3	3	2	-	-	1	-	6
Ochna pulcra	2	3	4	1	3	4	28	4	1	-	1	-
Ochthocosmus lemaireanus	1	3	1	-	3	-	-	-	-	-	-	-
Olax obtusifolia	-	-	-	-	-	-	-	-	-	-	-	-
Pariani excelsa	-	-	-	-	-	-	-	-	-	-	-	-
Piliostigma thonningi	-	-	-	-	-	-	-	-	-	-	-	-
Pseudolachnostylis malprouneifolia	1	5	2	1	3	-	2	6	3	2	2	4
Pseudolachnostylis sp.	30	55	50	86	46	32	59	50	43	30	45	42
Pteolopsis spp.	-	-	-	-	2	2	-	-	2	-	-	-
Pterocarpus angolensis	2	2	1	-	-	4	4	15	1	9	8	7
Steganotaenia araliacea	-	-	-	-	-	-	-	-	-	-	-	-
Strychnos spinosa	-	-	-	-	-	-	-	-	-	-	-	-
Swartzia madagascariensis	2	1	-	-	4	-	1	-	-	1	1	-
Uapaca kirkiana	-	-	-	-	-	-	-	-	-	-	-	-
Uapaca nitida	-	-	-	-	-	-	-	-	-	-	-	-

Table 53. Tree species frequency per quadrate, Lower Kamwedgi, line VN. (* Sand Cu anomaly).

Peg No.	VN10	VN9	VN8	VN7	VN4	VN3	VN2	VN1 *	VN-3	VN-4	VN-5	VN-6
No. of Trees	174	156	144	179	254	201	145	162	139	170	118	147
Afrormosia angolensis	1	-	-	-	-	-	-	-	-	-	-	-
Afzelia quanzensis	-	-	-	-	-	-	-	-	-	-	-	-
Albizia autunesiana	-	-	-	-	-	-	-	-	-	-	-	-
Albizia zygia	-	1	5	3	-	-	1	1	2	1	-	-
Amblygonocarpus andongensis	-	-	-	-	-	-	-	-	-	-	-	-
Anisophyllea spp.	-	-	-	-	-	-	-	-	-	-	-	-
Brachystegia boehmii	-	-	-	-	-	-	-	-	-	-	-	-
Brachystegia longifolia	11	11	3	10	9	9	6	10	8	17	8	12
Brachystegia spiciformis	4	3	2	6	11	6	16	3	1	5	3	6
Combretum mechowianum	-	1	-	-	1	-	-	-	-	-	3	-
Combretum molle	13	10	28	23	44	55	4	11	6	4	10	13
Commiphora mollis	-	-	-	-	-	-	-	-	2	-	-	-
Cryptosepalum pseudotaxus	-	-	1	-	1	-	-	-	1	2	2	1
Diospyros batocana	2	-	2	4	1	-	2	-	-	10	-	2
Diplorhynchus condylocarpon	16	25	27	26	26	16	13	9	8	16	15	14
Eriosema spp.	-	-	-	-	-	-	-	-	-	-	-	-
Erythrophleum africanum	7	6	7	8	8	10	5	12	12	3	2	2
Faurea spp.	-	-	-	-	-	-	-	-	-	-	-	-
Gardenia subacaulis	-	-	-	-	-	-	-	-	-	-	-	-
Guibourtia coleosperma	2	2	3	-	-	2	2	-	-	1	-	2
Hexalobus monopetalus	-	-	-	-	-	-	1	-	-	-	1	-
Julbernardia paniculata	10	12	8	9	29	32	20	14	15	16	5	46
Landolphia kirki	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.	Com.
Lannea discolor	1	-	-	-	-	-	-	-	-	-	-	-
Monotes spp.	-	1	8	-	1	-	-	-	4	-	-	-
Ochna pulcra	10	4	3	14	10	7	11	8	3	5	7	5
Ochthososmus lemaireanus	1	-	1	-	-	-	-	-	-	-	-	-
Olax obtusifolia		-	-	-	-	-	-	-	-	-	-	-
Parinari excelsa	-	-	-	-	-	-	1	-	-	-	-	-
Piliostigma thonningi	-	-	-	-	-	-	-	-	-	-	-	-
Pseudolachnostylis sp.	46	35	42	63	57	31	29	72	50	42	47	32
Pteolopsis spp.	-	-	-	-	-	-	-	-	-	-	-	-
Pterocarpus angolensis	6	16	1	4	-	2	3	-	5	6	1	1
Steganotaenia araliacea	-	-	-	-	-	-	-	-	-	-	-	-
Strychnos spinosa	-	-	-	-	-	-	-	-	-	-	-	-
Swartzia madagascariensis	3	4	-	-	1	-	-	-	-	1	-	2
Uapaca kirkiana	-	-	-	-	-	-	-	-	-	-	-	-
Uapaca nitida	-	-	-	-	-	-	-	-	-	-	-	-

Brachystegia longifolia, B. boehmii and B. spiciformis. The shorter trees include Diplorhynchus condylocarpon, Monotes spp. and Pseudolachnostylis sp. Near a quartzite outcrop (peg KN10) Uapaca Kirkiana and U. nitida occur. The Cu anomaly is located at peg KN2 (125 ppm) but ranges from pegs KN2-9. Julbernardia paniculata, Olax obtusifolia and Monotes spp. again show increased frequency.

At line PN in Kalahari Sand (Table 52) Julbernardia paniculata, Brachystegia spiciformis and B. longifolia are dominant in the upper storey. Brachystegia boehmii is absent. Middle storey Diplorhynchus condylocarpon, Erythrophleum africanum, Pseudolachnostylis sp., Combretum molle, and Pterocarpus angolensis are common. The Cu anomaly peak occurs at peg PN4 (185 ppm) where Erythrophleum africanum is locally abundant.

In Kalahari Sand at line VN (Table 53) the dominant upper storey trees are Julbernardia paniculata, Brachystegia longifolia, B. spiciformis and Combretum molle. Common lower storey trees include Diplorhynchus condylocarpon, Pseudolachnostylis sp., Erythrophleum africanum, Pterocarpus angolensis and Ochna pulchra. The Cu anomaly peak occurs at peg VN1½ (64 ppm) where no species is significantly more abundant.

In conclusion, there is a considerable vegetational change from south to north in the area studied. This is partly related to the change from residual soil to Kalahari Sand as bedrock geology, soil acidity and drainage are essentially similar within these areas. Some species are restricted on the residual soil and include Brachystegia

boehmii, Olax obtusifolia, Faurea spp., Uapaca kirkiana and Uapaca nitida. Other trees which appear more frequently on residual soils are Monotes spp., Cryptosepalum pseudotaxus, Ochthocosmus lemaireanus and Combretum mechowianum. Other species appear restricted to the Kalahari Sand and include Combretum molle. Trees more abundant on the Kalahari Sand are Pseudolachnostylis maprouneifolia, Diplorhynchus condylocarpon, Brachystegia longifolia, Erythrophleum africanum, Pseudolachnostylis sp., and Ochna pulchra.

The ground plant Landolphia kirki was included in the survey and because of its high frequency, only a qualitative abundance is noted. The species does occur on residual soil but is more abundant on Kalahari Sand.

The total number of trees per quadrate is greatest in the Kalahari Sand partly because species tend to be shorter and smaller. There is more variety of species on residual soil and this variation is probably due both to the better physical rooting capacity and to the more varied chemical nutrients of the soil.

The frequency of trees is not apparently influenced by the Cu content of the overburden. No species is consistently more abundant in anomalous areas; the local sympathetic abundance of Julbernardia paniculata, Olax obtusifolia and Monotes spp. may be coincidental although Olax obtusifolia is noted in Rhodesia (Jacobsen, 1967) and in the Congo (Duvigneaud and Deneayer-de-Smet (1963) as being more Cu tolerant. This lack of correlation or lack of obvious abnormality related to the Cu probably results from the

very low content of anomalous Cu in the overburden. The maximum soil value encountered is 240 ppm Cu in the silt fraction or 160 ppm in the -80# dry sieved fraction. This low content contrasts with areas of obvious vegetation abnormalities such as the copper clearings at Mufumbwe and Kalengwa Mine where soil Cu values of 250 and 800 ppm are reported respectively for the -80#D fraction (Company data), and at Fitula on the Copperbelt where clearings and "copper flowers" occur on soils with 500-5000 ppm Cu (-80#D) (Cornwall, 1969).

The "copper flower" Becium obovatum occurs on residual soil in the vicinity of the outcropping mineralisation at peg C3 (Fig.22). The plant is herbaceous and morphologically similar to the "copper flower" growing at the mineralisation of the Mufumbwe East Trenches. Both these varieties differ from the shrubby "copper flower" occurring in the Mufumbwe Main Clearing (Plates 9 and 10) and compare well with the "pseudo-copper flower" collected from a background locality (Plate 11). All appear to belong to the same species, namely Becium obovatum.

There is considerable confusion on the identification and taxonomy of the Zambian "copper flower" Becium obovatum, and the following discussion is the result of information supplied by Dr. E. Launert ('Prodromus of a Flora of South West Africa'; in prep.). Original independent classification of the species occurred in north-east Africa (Becium Knyanum Vatke) and in South Africa (Becium obovatum); the latter classification has been accepted. Wildeman (1921) working on a limited number of specimens from Cu



Plate 9. "Copper flower" (Becium obovatum) from Mufumbwe Main Clearing.



Plate 10. Flower of "copper flower".



Plate 11. "Pseudo copper flower" (Becium obovatum).

mineralisation in the Congo, created a new species Becium homblei de Wilde which became accepted as the "copper flower", while Becium obovatum was regarded as the "pseudo-copper flower" (Mendelsohn, 1961). These two varieties are now regarded as belonging to the species Becium obovatum as both have the species characteristic of a gland at the base of the flower stalk. In addition varieties of "copper flower" and "pseudo-copper flower" from the study area, together with many specimens from Zambia have been examined by Dr. Launert, who concludes that they all belong to Becium obovatum. Variations of features of the plant, such as leaf width and serration, and hairy calyx are not species differences (Horizon, 1959; Mendelsohn, 1961) but are ecologically induced variations within the species. As yet no diagnostic characters can be ascribed to all examples of the "copper flower" from Cu localities, and differences that appear to occur, related to mineralisation, may be a local effect which differs in different areas.

This "copper flower" may be a specific indicator and appears to be abundant in areas of high soil Cu content. The tolerance of the plant is variable and quotes of over 5000 ppm Cu (Hawkes and Webb, 1965) and 35-71,000 ppm exCu (Reilly, 1967) are given, while in Katanga the soil may be locally too Cu-rich and prohibits the growth of the plant (Mendelsohn, 1961). It is unlikely that the Cu-tolerant variety of the species will occur on areas of Kalahari Sand even where anomalous concentrations of Cu will be of a low order, and insufficiently toxic for the replacement of the universal Becium obovatum. Furthermore, the use of the

indicator as a prospecting tool is restricted as the flowering period, which is necessary for identification, is short and lasts for only 4 weeks during October - November. During the major part of the year the herb is withered.

4. Biogeochemistry

(a) Introduction

In the absence of overt indicator plants, the use of covert plants as a guide to mineralisation was investigated, and the geochemical technique is analogous to soil sampling.

Six species common to both the residual and Kalahari Sand overburden, were selected in the Lower Kamwedgi area (Table 54).

Table 54. Vegetation species selected for sampling

	Average height (ft.)	Bole diameter	
Upper Storey trees			
Brachystegia longifolia	30-50	1ft.	(Plate 12)
Julbernardia paniculata	30-50	1ft.	(Plate 13)
Brachystegia spiciformis	30-50	1ft.	(Plate 14)
Middle Storey trees			
Diplorhynchus condylocarpon	15-25	9in.	(Plate 15)
Pseudolachnostylis sp.	15-25	9in.	(Plate 16)
Ground Storey plant			
Landolphia kirki	4in.-1ft.	-	(Plate 17)

The three upper storey tree species occur throughout Central Africa in miombo-type woodlands. They are semi-deciduous, reaching a height of 80-100 ft. and have a maximum bole diameter of 3-4 ft. Brachystegia longifolia attains



Plate 12. Brachystegia longifolia (c. 40 ft.)



Plate 13. Julbernardia paniculata. (c. 40 ft.)



Plate 14. Brachystegia spiciformis (c. 40 ft.)



Plate 15. Diplorhynchus condylocarpon (c. 20 ft.)



Plate 16. Pseudolachnostylis sp. (c. 12 ft.)



Plate 17. Landolphia kirki. (c. 3 ins.)

maximum growth on sandy soils, and develops an extensive tap root system with lateral roots extending 40 ft. from the tree. Julbernardia paniculata is a highly adaptable species, and produces one or several tap roots, with a lateral root system radiating 20 ft. from the tree. Brachystegia spiciformis grows best on sandy soils, and displays a well developed tap root with laterals extending 40-50 ft. (Fanshawe, 1962; Savory, 19 -).

Upper storey trees were selected as they probably develop the maximum root capacity and consequent depth of penetration. They are presumably the best indicators of chemical variation at maximum depth in Kalahari Sand. The middle storey trees with shallow root systems are selected for comparative purposes while the ground plant reflects the near-surface conditions.

In order to standardise the method, average-sized trees were selected where possible. Lichen-free bark, second year twigs and fresh leaves were sampled. As the species were locally scarce only one specimen, with the exception of the ground plant, was sampled per location.

Several methods of vegetation analyses are mentioned in the literature, and for comparison the samples were prepared by three methods:

(i) dried vegetation subjected to a nitric-perchloric-sulphuric digestion (10:4:1),

(ii) dried vegetation homogenised in a vegetation mill, and subjected to a nitric-perchloric-sulphuric digestion,

(iii) pulverised vegetation ashed for 10 hrs. in a muffle furnace at 435°C, and the ash subjected to a nitric-perchloric digestion.

Trace element determination was, in each case, by atomic absorption spectrometry. Ashing concentrates the metal content. In order to compare the metal values per dry weight with ash, the following local conversion factors were applied.

Leaf ash is 3.9% of dry weight - concentration factor 25.6

Twig ash is 3.7% of dry weight - concentration factor 27.0

Bark ash is 2.7% of dry weight - concentration factor 37.0

A good correlation is found between the dry weight methods for Cu, Mn and Zn although Fe is more variable (summarised Table 55; for full details see Appendix III). This indicates that pulverisation is unnecessary; similar results were found by Provan (1965). Values for the ashing method are lower for Mn and Cu and generally more variable, which may be the result of incomplete ashing, volatisation effects, or conversion of the trace elements to relatively insoluble salts (Smith, 1954).

(b) Observed trace element distribution

(i) Residual soil

At Lower Kamwedgi the overburden at line C is less than 10 ft. thick and thus the rooting capacity of upper or middle storey vegetation is not critical. Moreover Landolphia kirki is rare. Trees from only two locations were sampled and the data is thus limited.

Table 55. Comparison of wet chemical and ashing techniques in Brachystegia longifolia (average of 4 samples)

		Cu			Fe			Mn			Zn		
		Mean unpulverised (ash equivalent)	Mean pulverised (ash equivalent)	Mean ash	Mean unpulverised (ash equivalent)	Mean pulverised (ash equivalent)	Mean ash	Mean unpulverised (ash equivalent)	Mean pulverised (ash equivalent)	Mean ash	Mean unpulverised (ash equivalent)	Mean pulverised (ash equivalent)	Mean ash
Sector PN-6 to PN-3	leaf	240	220	130	1580	2100	1200	17000	16000	700	650	570	460
	twig	150	170	130	580	1300	1100	4000	4000	850	310	280	290
	bark	380	300	370	6000	4000	5000	9000	6000	3000	190	170	220
Sector PN7 to 10	leaf	210	210	170	1400	1400	900	14000	17000	1800	490	490	470
	twig	200	180	160	510	1200	1100	3700	3600	840	280	260	240
	bark	400	340	250	10400	12000	7900	3700	5800	2400	160	190	110
Sector PN2 to 5	leaf	250	230	180	1400	1700	830	25000	21000	1000	550	550	550
	twig	160	190	160	540	1600	1800	5600	4500	1900	330	310	290
	bark	500	400	590	4600	4000	6500	6900	6500	5500	130	130	170

The mineralised Cu soil values (Table 56) are reflected by the three sampled parts of Brachystegia longifolia and Diplorhynchus condylocarpon. Only the leaves of Julbernardia paniculata indicate sympathetic concentration. The vegetation content of Cu is low. The contrast between mineralised and background areas is considerably lower than the soil.

Table 56. Trace element content in vegetation(ppm dry weight) on residual soil, Lower Kamwedgi, line C.

	Anomalous(peg C/3)			Background(peg C/-1)		
	Leaf	Twig	Bark	Leaf	Twig	Bark
Cu Soil(silt)		240			70	
(1)Brachystegia longifolia	9.8	7.7	16.8	7.6	4.4	1.0
(2)Julbernardia paniculata	8.6	6.7	2.4	8.2	10.6	3.3
(3)Diplorhynchus condylocarpon	8.8	6.5	3.4	7.4	6.1	2.6
Fe Soil(silt)		2.3%			2.8%	
(1)	34.6	32.0	220	44.0	6.2	8.1
(2)	64.4	23.5	25.0	53.5	20.9	15.4
(3)	47.4	18.5	28.6	53.5	16.1	32.5
Mn Soil(silt)		75			200	
(1)	438	122	288	550	25.9	88.0
(2)	101	37.0	32.4	34.6	24.1	24.2
(3)	815	18.0	260	196	22.6	97.3
Zn Soil(silt)		18			17	
(1)	21.4	12.2	2.9	14.6	7.4	1.0
(2)	12.5	11.8	2.0	17.2	14.8	4.3
(3)	16.4	6.8	4.5	17.7	13.0	4.4

Soil Fe is slightly enriched at peg C-1, while the twigs of all species, the bark of Brachystegia longifolia and Julbernardia paniculata, and the leaves of Julbernardia paniculata illustrate the reverse. The general content of Fe in the trees is markedly lower than the soil content. Soil Mn is similarly enriched at peg C-1 while the correlation of tree parts is antipathetic. The highest Mn content occurs in the leaf, and the leaf content is generally enriched relative to the soil content. Soil Zn values at the two pegs are similar. The values for each part per tree is consistent. Zn uptake is greatest in the leaves of each species and of similar magnitude to the soil content.

(ii) Kalahari Sand.

The leaves, twigs and bark of the six species were sampled at 12 points along transect PN, Lower Kamwedgi (Fig.22) in Kalahari Sand. The Cu anomaly peak in the overburden occurs at peg PN4 (185 ppm)(Fig.44). Of the upper storey trees, the Cu content of bark and twig produce a similar variation while the results for leaves are more variable. The middle storey trees produce a good correlation with the Sand values for all three parts. The ground plant shows no sympathetic variation. Maximum correlation with the Sand variation is found in the tree bark, in which 4 of the 5 trees have maximum values at peg PN4. By averaging the Cu values of the four trees per block (Table 57), which eradicates local erratic values, the Cu content of the bark and twigs in 4 out of 5 species correlates with the soil anomaly; only 1 out of 5 leaf values shows a similar correlation. The highest Cu content is consistently in the bark (Table 58).

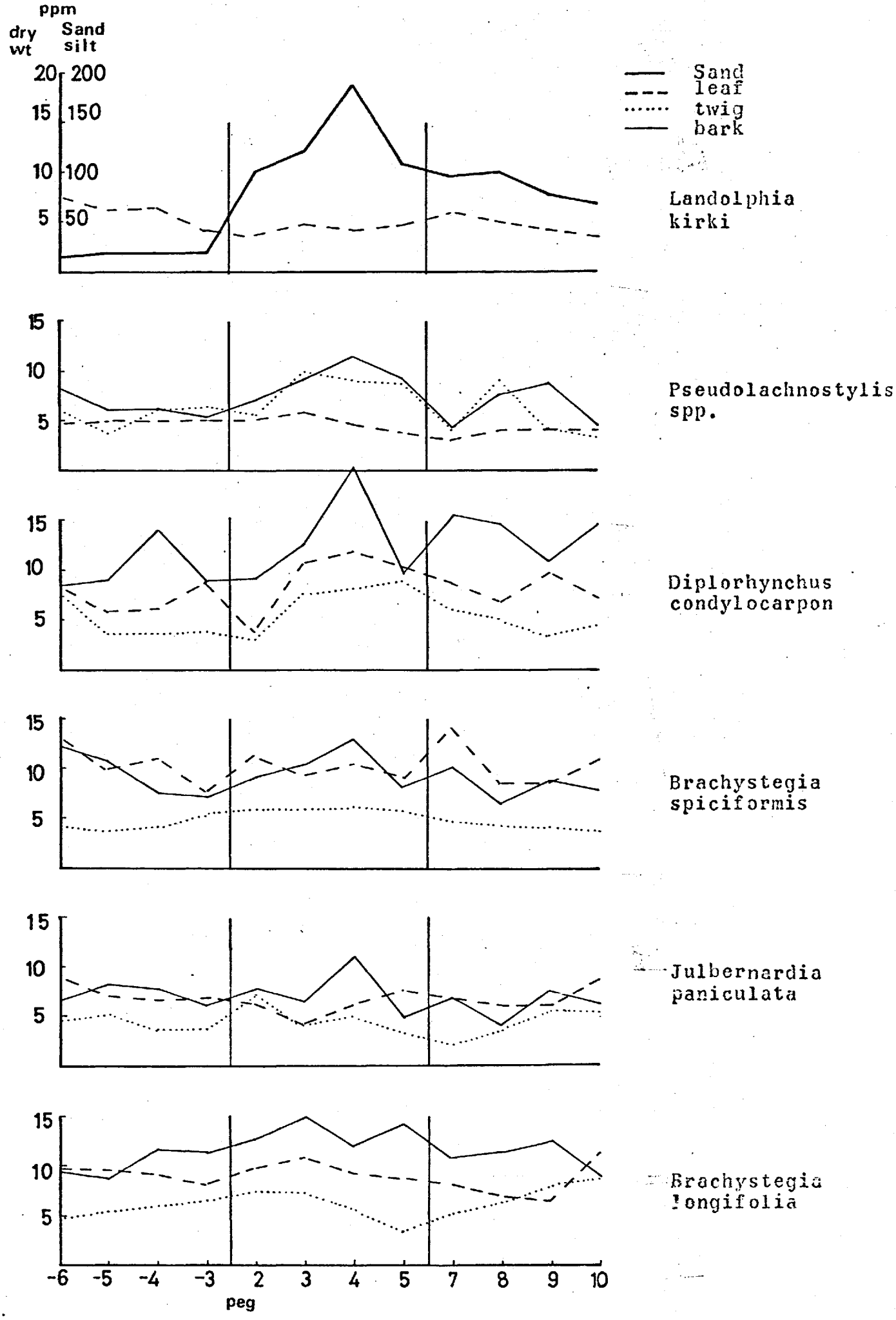


Fig.44 Variation of Cu content in leaves, twigs and bark relative to Kalahari Sand Cu content.

Table 57. Average Metal values per species per block(ppm, dry weight), Kalahari Sand

		Cu						Fe						Mn						Zn					
	Tree	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
PN-6 to-3	Leaf	9.2	7.4*	10.5	7.4	5.0*	6.1*	58	28	24	29	32	60	650	130	440	530	260	220	25	19	21	24	12	21
	Twig	5.5	4.3	4.4	4.5	5.5	-	22	13	10	14	23	-	160	44	140	100	68	-	12	19	21	29	9	-
	Bark	10.3	7.3	9.4	10.1	6.1	-	160	70	100	80	70	-	240	80	100	70	33	-	5	5	5	37	4	-
PN4	Leaf	9.2	6.2	10.5	11.9	4.7	4.2																		
	Twig	5.7	5.0	6.1	8.1	9.2																			
	Bark	12.1	11.1	13.0	21.5	11.5																			
PN2 to 5	Leaf	9.9*	6.2	10.2	9.1*	4.9	4.4	56	29	32	23	66	46	960	120	530	670	220	350	21	16	16	15	11	12
	Twig	6.0	5.0*	6.0*	6.9*	8.3*	-	20	13	14	13	20	-	210	80	130	170	64	-	11	32	18	11	7	-
	Bark	13.5*	7.6*	10.1*	13.2	9.3*	-	120	140	61	83	90	-	190	100	110	110	37	-	4	3	4	11	4	-
PN7 to 10	Leaf	8.2	7.0	10.6*	8.2	3.9	4.9	52	28	42	26	26	100	560	90	380	610	240	250	19					
	Twig	7.2*	4.2	4.2	4.9	5.3	-	41	10	11	14	14	-	140	49	120	140	70	-	10					
	Bark	10.8	6.2	8.3	14.0*	6.2	-	280	89	69	100	29	-	100	68	75	80	27	-	4					

Tree
1. Brachystegia longifolia
2. Julbernardia paniculata
3. Brachystegia spiciformis
4. Diplorhynchus condylocarpon
5. Pseudolachnostylis sp.
6. Landolphia kirki

*maximum value per part per species.

Table 58. Average metal values (ppm, dry weight) per part per tree.

	Cu						Fe						Mn						Zn					
Tree	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Leaf	9.0	6.8	10.4*	4.6	4.6	5.1	55*	26	33	26	42	69	701*	111	450	633	237	267	22*	17	17	19	11	15
Twig	6.3	4.5	4.8	5.5	6.4*	-	28*	12	12	13	19	-	169*	58	133	133	68	-	11	24*	18	19	7	-
Bark	11.5	7.1	9.3	12.4*	7.2	-	188*	98	76	88	64	-	177*	83	95	86	32	-	4	5	4	26*	4	-

Tree
1. Brachystegia longifolia
2. Julbernardia paniculata
3. Brachystegia spiciformis
4. Diplorhynchus condylocarpon
5. Pseudolachnostylis sp.
6. Landolphia kirki

* maximum value per part.

Table 59. Comparison of vegetation and Kalahari Sand Cu contrast values

		Background mean	Anomaly high	Contrast
Brachystegia longifolia				
	leaf	9.2	10.7	1.2
unpulverised	twig	5.7	7.3	1.3
(dry weight)	bark	10.3	14.9	1.5
	leaf	8.6	9.6	1.2
pulverised	twig	6.2	8.6	1.4
(dry weight)	bark	8.1	12.7	1.4
ashed	leaf	134	213	1.5
(ash weight)	twig	129	233	1.8
	bark	373	690	1.8
Julbernardia paniculata				
(dry weight)	leaf	7.4	6.2	0.8
	twig	4.3	5.0	1.2
	bark	7.3	11.1	1.5
Brachystegia spiciformis				
(dry weight)	leaf	10.5	10.5	1.0
	twig	4.4	6.1	1.4
	bark	9.4	13.0	1.4
Diplorhynchus condylocarpon				
(dry weight)	leaf	7.4	11.9	1.6
	twig	4.5	8.1	1.8
	bark	10.1	21.5	2.1
Pseudolachnostylis sp.				
(dry weight)	leaf	5.0	4.7	0.9
	twig	5.5	9.2	1.7
	bark	6.1	11.5	1.9
Soil (silt)		18	185	6.2

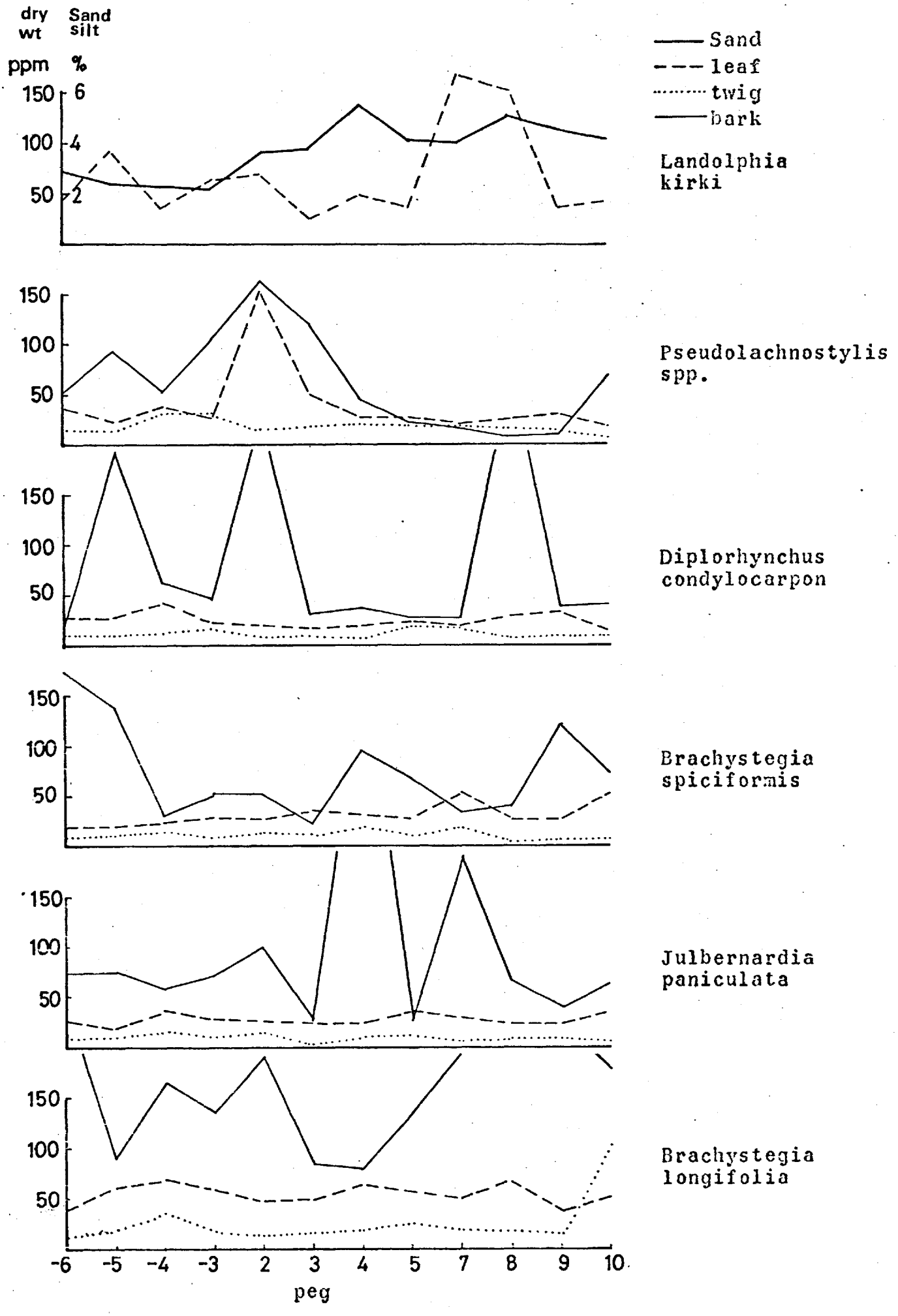
The accumulation of Cu by the vegetation is lower than the Sand content especially in the anomalous zone. The contrast is approximately 25% of the soil value and is consistently greatest in the bark, with maximum values in middle storey trees (Table 59).

Maximum Sand Fe values occur at pegs PN4 and PN8 with a general enrichment from pegs PN 2-10 (Figs. 24 and 45). Neither trees nor ground plant indicate a related trend. The Fe uptake of the twigs and leaves of the tree species are generally similar, while bark values are higher and more erratic. The vegetation values are up to a thousand fold lower than the Sand values (Table 58). Maximum Sand Mn content occurs at peg PN10 with a general decrease of values eastwards (Figs. 25. and 46). Vegetation values show no similar correlation. Maximum Mn content occurs in the leaves while the twigs and bark have lower and similar values. Generally only the leaf Mn values are above the Sand content (Table 58). The Zn values of the Sand transect have a consistent content with a minor peak at peg PN4 (Figs. 26 and 47). Vegetation values tend to be higher in the west from pegs PN-3 to -6. Leaves tend to be more enriched than woody parts although locally twig values are erratic and high. Vegetation Zn values are generally slightly lower than Sand values.

(c) Discussion

The four elements analysed are all minor but essential elements in plant metabolism (Mitchell, 1955; Jackson, 1958). Of the 4 elements, only the Cu content of the vegetation of the study area, both in residual soil

Fig.45 Variation of Fe content in leaves, twigs and bark relative to Kalahari Sand Fe content, Line PN, Lower Kamwedgi.



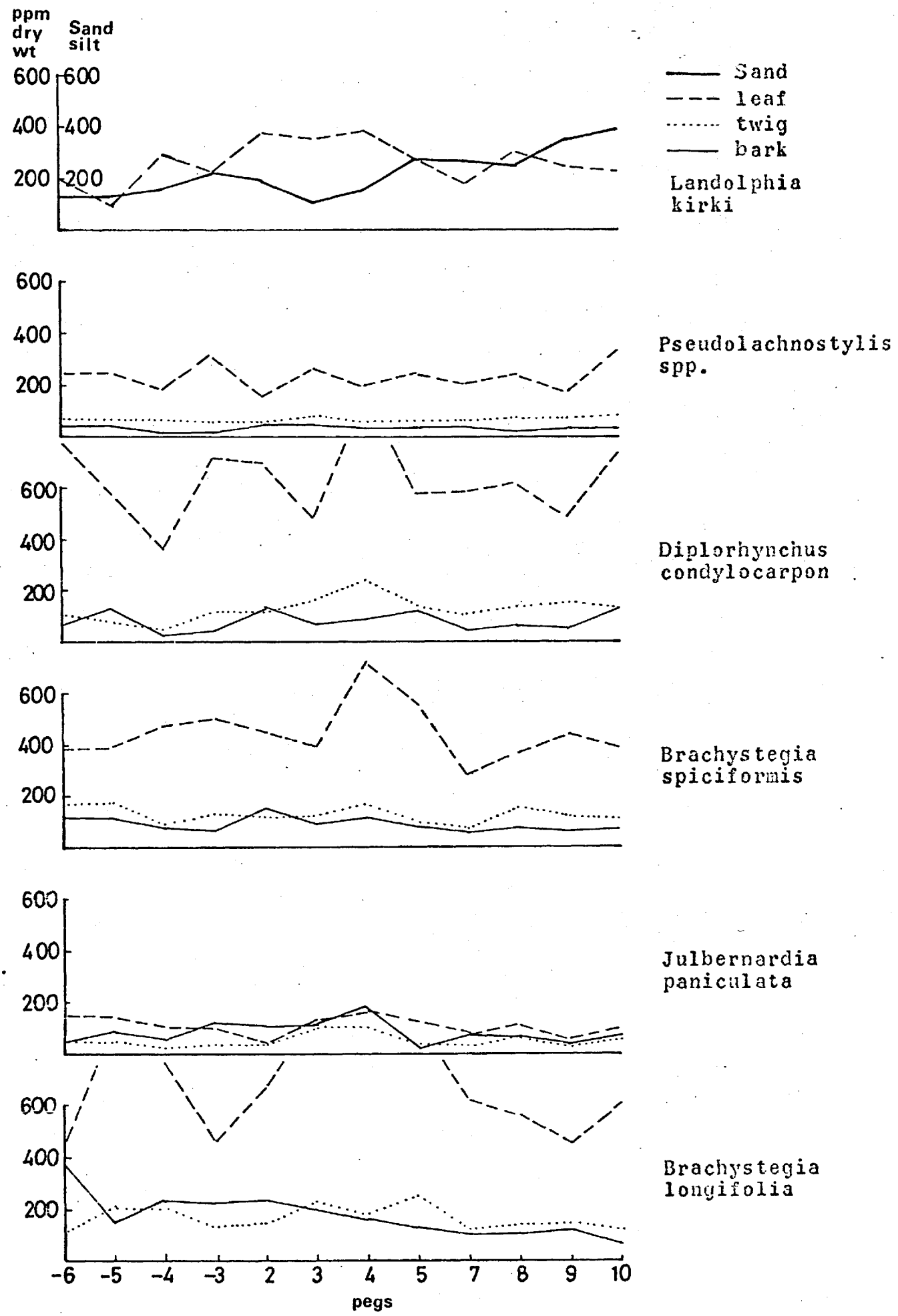


Fig.46 Variation of Mn content in leaves, twigs and bark relative to Kalahari Sand Mn content. Line PN, Lower Kamwedgi.

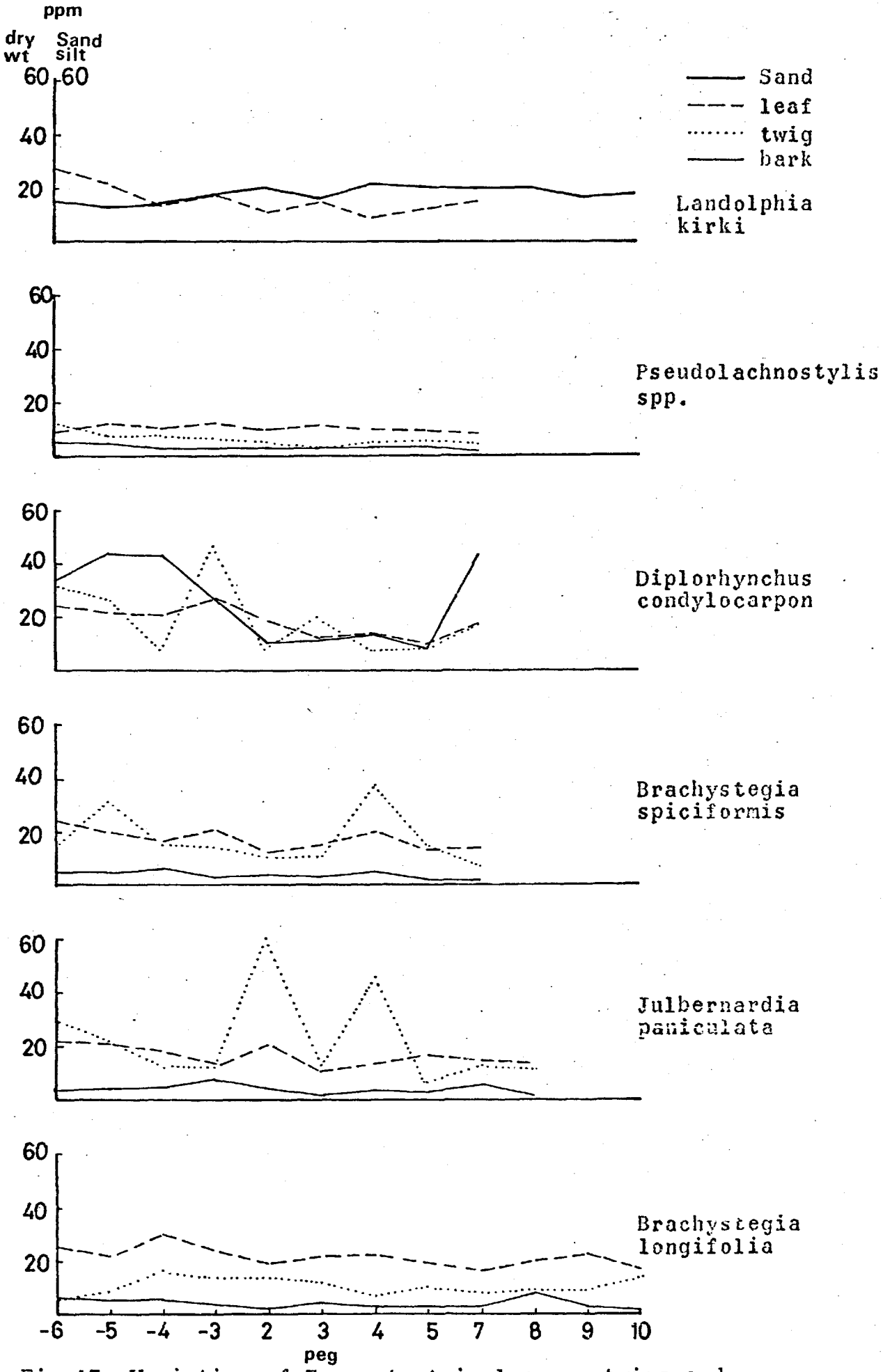


Fig.47 Variation of Zn content in leaves, twigs and bark relative to Kalahari Sand Zn content.

and Kalahari Sand, illustrates an analogous trend to the overburden variation. Although the amount of Cu in the overburden, even in anomalous areas is low, the vegetation uptake and distribution in the various plant parts is sufficiently sensitive to duplicate the overburden trend. This sensitivity in the vegetation at low Cu concentrations agrees with the results of Lunblad et al. (1949), who noted in Sweden that ground vegetation was sensitive to low range Cu variation in soil, while with higher soil Cu content, plant intake is apparently restricted and does not exceed a certain level. The results do not agree with Provan (1965) who observed no significant Cu enrichment in Australian herbs and grasses until a soil Cu level in excess of 600 ppm was encountered.

Woody parts indicate the best correlation of Cu with the overburden, with the highest uptake in the tree bark. The contrast between anomalous and background areas is consistently greatest in the bark and twigs especially in the middle storey species, while leaf values are erratic (Table 59). The contrast is considerably less than in the overburden, and is generally less than 2. These results may be attributed to the fact that the woody parts of trees are more mature and chemically more stable than in the young growing leaves where metabolism is greatest and chemical content more changeable (Carlisle and Cleveland, 1958). This high metabolism in growing parts would also help to explain the lack of Cu correlation in Sand with the ground plant, the leaves of which were sampled. The low Cu contrast in the vegetation is in accord with the findings of other authors

who note contrast values of between 25% and 300% (Harbaugh, 1950; Malyuga, 1964; Riddell, 1952; Warren et al., 1952). These low contrast values, irrespective of the overburden contrast, suggest that the vegetation generally tends to suppress a high intake of anomalous Cu.

Bark sampling has a distinct advantage over leaves and twigs as the former can be collected without the need of felling trees, necessary for leaf or twig samples.

The middle storey trees, with a probable less extensive root system derive an amount of Cu from the overburden, comparable to the deep rooted species, and are equally sensitive to Cu variation in the overburden. This implies that the Cu is accessible to a similar degree throughout the profile. In the Kalahari Sand the metal dispersion throughout the profile is saline and in a relatively accessible form. In residual soil with more firmly bonded metals, it has been found that resistant minerals and primary silicates are attacked by vegetation through a process probably involving high acidity at the root tips (Lovering, 1959).

The intake of Cu varies in the part of the tree sampled, but a general trend is apparent. (Table 60). Within the individual species a considerable variation in content occurs for any part (Table 58) and considering the low contrast values in vegetation, a separate Cu threshold must be calculated for each species and for each separate plant part.

Table 60. Relative metal uptake per tree part

Cu	bark	>	leaf	>	twig
Fe	bark	>	leaf	>	twig
Mn	leaf	>	twig	≥	bark
Zn	leaf	>	twig	>	bark

The ranges obtained in the area are slightly higher than the results of Wilding from the Kalumbila area of north-west Zambia (1966), who noted the background bark ash content of Brachystegia boehmii and Julbernardia paniculata as 100-200 ppm (approximately 2.7-5.4 ppm dry weight).

The uptake of Fe, Mn and Zn by the vegetation does not reflect the overburden content. Fe and Mn have been reported as being more variable than Cu and Zn in plants (Warren and Delavault, 1952) and are regarded as more indicative of soil pH and climatic conditions (Warren, 1962). The content of Fe is greatest in the bark (Tables 60 and 61) and the dilution relative to the overburden silt is in the order of 500-1000 fold. Mn is notably more abundant in the leaves where the concentration is similar to the overburden silt.

Table 61. Metal range per tree part (ppm, dry wt.).

	leaf	twig	bark	approximate concentration relative to overburden silt
Cu	4.6-10.4	4.5-6.4	7.1-12.4	5-50%
Fe	26-69	12-28	64-190	0.05-0.08%
Mn	110-700	58-170	32-180	100%
Zn	11-22	11-24	4-26	100%

Zn is concentrated in the leaves, and values for the vegetative parts are generally similar to those for overburden silt.

The general content of the elements in the trees is in the order:

Mn > Fe > Zn > Cu, whereas the overburden content is in the order Fe > Mn > Cu > Zn. Consequently the relative uptake of metals by the plant is not a simple function of concentration in the overburden. The similarity of the sequence in vegetation with the mobility series of the metals suggests a possible correlation.

It has been observed that in areas of Cu mineralisation where the uptake of Cu or Zn is variable according to individual plant requirements, the relative uptake of Cu to Zn will be similar. Thus the Cu/Zn ratio in the vegetation may be more regular than individual metal values, and more related to soil mineralisation. Values of over 0.36 are quoted for Cu mineralisation (Warren et al., 1949 ; White, 1950; Usik, 1969). A similar comparison of ratio values of the 5 species at Lower Kamwedgi (Table 62) shows no similar consistent trend of higher ratio values over mineralisation with the possible exception of Diplorhynchus condylocarpon. Consequently a ratio pattern is less useful in this area than the values of Cu alone.

Table 62. Cu/Zn ratio of tree parts.

		Brachystegia longifolia			Julbernardia paniculata			Brachystegia spiciformis			Diplorhynchus condylocarpon			Pseudolachnostylis sp.		
		Leaf	Twig	Bark	Leaf	Twig	Bark	Leaf	Twig	Bark	Leaf	Twig	Bark	Leaf	Twig	Bark
Pe6	PN-6	.39	.78	1.60	.39	.16	1.68	.54	.24	2.48	.39	.22	.25	.48	.51	1.33
	-5	.44	.59	1.72	.34	.23	2.65	.50	.12	2.12	.27	.13	.20	.39	.57	1.22
	-4	.30	.36	1.93	.37	.28	1.56	.65	.26	1.07	.30	.44	.34	.48	.74	1.70
	-3	.34	.46	2.85	.54	.32	0.80	.36	.32	2.33	.32	.08	.34	.39	.92	1.77
	2	.51	.54	4.30	.30	.12	1.98	.87	.60	2.30	.19	.33	.92	.51	.92	1.78
	3	.49	.61	2.98	.40	.30	3.25	.59	.49	3.37	.70	.40	1.02	.48	.31	3.10
	4*	.40	.81	4.03	.45	.11	2.78	.53	.17	2.17	.82	1.01	1.15	.47	1.15	2.88
	5	-	.32	4.67	.45	.53	1.63	.71	.41	4.10	.94	1.00	1.04	.39	.97	2.30
	7	.50	.66	3.60	.45	.10	1.20	1.0	.59	5.00	.49	.33	.36	.35	.86	2.15

*Sand Cu peak

In conclusion, it is apparent that vegetation analyses of randomly selected common species of trees growing in an area of Kalahari Sand where anomalous Cu is of low magnitude, reflect the overburden Cu variation. Although the contrast obtained is considerably lower than in the overburden analyses, it is conceivable that analyses of a more Cu-tolerant species with a higher uptake of Cu, or of an accumulator species, would result in greater Cu contrast between vegetation growing on anomalous and background areas.

CHAPTER VI SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

1. SUMMARY OF CONCLUSIONS

(CHAPTER I)

(1) Bedrock outcrop throughout the study area is extremely limited. Quartzite and shale horizons at Mufumbwe, Jijombo and Lower Kamwedgi appear to belong to a similar lithological sequence of possible Kundulungu age. Malachite mineralisation is exposed at Mufumbwe and Lower Kamwedgi, overlying sulphide mineralisation at depth. Copper mineralisation has also been intersected at depth at Jijombo.

(2) The climate of the area is subtropical with six month wet and dry seasons.

(3) The topography of the area is moderately level with a gentle regional slope to the south-west. Drainage becomes less frequent westwards in areas of thick Kalahari Sand overburden.

(4) The area lies on the eastern fringe of the Kalahari Sand belt of the Barotse Basin. In the east of the Mufumbwe area, the overburden comprises residual and contact-residual latosols. Westwards, the Kalahari Sand overburden is pervasive with local exposures of the underlying residuum along the river banks, revealed by river erosion.

(5) The vegetation is dominantly moderately dense, tall, Brachystegia-Julbernardia miombo woodland.

(CHAPTER II)

(6) As the identification of lithological units of the Kalahari System is dependant on lithological, pedological, palaeoclimatical, geomorphological and archaeological factors, the correlation of the System in southern Africa is

complicated and tentative. In addition, the widespread aeolian Sands rarely contain fossil evidence and have been subjected to considerable reworking.

(7) No occurrence of the Kalahari Beds was located in the study area, although the river gravels intersected in dambo profiles may represent these horizons.

(8) Due to the intense chemical weathering of the sub-tropical climatic regime, distinction of Kalahari Sand and residual soil can be difficult in the field.

(9) The Kalahari Sand is similar to Kalahari Sand occurring elsewhere in southern Africa and may be distinguished from residual soil and dambo sediment of the study area on most of the following characteristics:

(i) consistent median diameter (0.23mm); residual soil and dambo sediment have a wider range of median diameter.

(ii) moderate to good sorting (sorting coefficient 1.57-1.96); the sorting coefficient of residual soil and dambo sediment have a wider range. The slightly poorer sorting of Kalahari Sand compared with other aeolian sand may be due to the deep, post-depositional, subtropical weathering with the introduction of clays from underlying soil or bedrock.

(iii) small skew in grain size frequency distribution towards the fine grade. The skew of residual soil and dambo sediment are variable. This parameter may also be affected by post-depositional weathering.

(iv) good rounding of grains down to 0.1mm diameter. Below this size rounding decreases with decreasing grain size. Below 0.05mm diameter, the grains are angular.

(v) good sphericity of grains with maximum sphericity in the 0.25-0.50mm size class.

(vi) prevalent frosting of grain surfaces, in grains of over 0.05mm diameter. The frosting decreases with decreasing grain size. Transport of Kalahari Sand in large rivers appears to remove the frosting of the grains. As frosting is developed on conchoidal and fracture surfaces, the origin of the frosting is suggested as due to the chemical action of desert dew. Frosted, rounded quartz grains, which form a minor proportion of residual soils and dambo sediments, are believed to be of Kalahari Sand origin.

(vii) the light fraction of the Sand is almost monomineralic and comprises colourless quartz. Kaolinite, with minor illite, appear in the clay fraction but may be post-depositional in origin. The clay minerals are similar to the residual soil clay suite.

(viii) the heavy mineral fraction forms less than 0.5-1.0% weight of the Sand and comprises mainly kyanite, rutile, zircon and opaque minerals. The heavy mineral composition of residual soils is similar. This suggests derivation of the Sand from a similar metamorphic provenance to the parent bedrock of the residual soils.

(10) Apart from the occasional development of laterite horizons, the Kalahari Sand profiles are structureless with no clay, pebble nor rock fragment horizons. The colour of the Sand varies locally from white to red-brown; the redness is due to a higher iron oxide content. It is possible that the intensity of colour may reflect the proximity of underlying residual soil or bedrock.

(CHAPTER III)

(11) In bedrock, there is no apparent primary metal association with Cu mineralisation.

(12) In the overburden there is no prevalent associated secondary metal dispersion with Cu.

(13) Virtually all surface residual soil has some contamination by Kalahari Sand. Westwards from Mufumbwe, and northwards from the Lower Kamwedgi Prospect, residual soil is progressively covered by a thickening Kalahari Sand cover. Concurrent with the pedological change, a decrease in the trace element content appears in the overburden.

(14) In residual soils, near surface metal values vary locally. The Cu threshold varies from 40 ppm (silt) at Mufumbwe to 100 ppm at Lower Kamwedgi. The range of metals in residual soil at 9 in. depth is:- Fe 2-9%, Mn 60-640 ppm, Zn 15-30 ppm, Co 10-35 ppm, Ni 25-60 ppm and Pb 10-40 ppm.

(15) Vertical distribution of elements in residual soil shows considerable variation due to the development of a laterite horizon. Marked increases of Cu, Fe, Mn and Zn content may occur in these laterite zones, and may affect the entire profile. Laterite nodules contain considerable concentrations of trace elements.

(16) The trace element content of Kalahari Sand is lower than in residual soil. The Cu background range is generally less than 50 ppm (silt).

The metal content range of Kalahari Sand varies from area to area, and the following metal ranges occur at 9 in. depth:- Fe 0.3-3.5%, Mn 20-420 ppm, Zn 7-25 ppm, Co 3-12 ppm.

(17) The Mn content of near-surface samples of Kalahari Sand and residual soil may be of similar level. This is

possibly due to a correlation between Mn and organic matter in near-surface overburden.

(18) In Kalahari Sand, metal values in vertical profile decrease in depth. Mn in particular shows marked enrichment in the Ao horizon. Concentrations of the metals may occur in Fe mottle, laterite and silicification zones.

(19) The silt fraction of Kalahari Sand has been successfully used to detect anomalous Cu through 30 ft. of Sand at Lower Kamwedgi, and 47 ft. of Sand at Jijombo. The Cu anomaly at Lower Kamwedgi extends into Sand overburden in excess of 30 ft. depth.

(20) Dambo sediment may comprise reworked residual soil or Kalahari Sand of local origin, or may include exotic alluvium. The dominant clay mineral is kaolinite.

(21) The background threshold for Cu in dambo sediment in the area is 50 ppm. The Cu content of dambo sediment shows marked variation according to sediment type. Cu is enriched in Fe mottle, laterite and pebble bands. Enrichment of Cu at surface in anomalous areas only occurs in the dambo channelway, and values may be below the sediment threshold value.

(22) Trace element values in dambo sediment are generally lower than in residual soil.

(23) Although the major Mufumbwe dambo probably flows across the extension of the Mufumbwe mineralisation and receives Cu anomalous sediment from two tributary dambos at Mufumbwe, this anomalous material is swamped in the Mufumbwe dambo by barren material.

(CHAPTER IV)

(24) Variation in bedrock lithology is not reflected by metal concentration variation in the secondary environment for the metals studied.

(25) The intense chemical weathering of the subtropical climate has resulted in a stable mineralogy of quartz, kaolinite and hematite with minor illite and goethite in both residual soil and Kalahari Sand.

(26) Seasonal moisture movement controls the vertical trace element dispersion patterns of Kalahari Sand, and to a lesser extent of residual soil. During the 6 months of the wet season, movement of moisture and metals in solution or suspension is downwards, but during the 6 months dry season, movement is upwards. Metals deposited in the profile during the dry season, are only partially removed in solution during the ensuing wet season. Consequently an upward increase in metal content results. In addition, higher pH and Eh conditions, and increased organic material occur towards surface, and aid deposition of metals near-surface.

(27) Laterite horizons are developed at the top of the water-table fluctuation. It is probable that on account of the low Fe content of Kalahari Sand, the Fe required for laterite development is mostly introduced from ferrous or colloidal Fe in the groundwater, and oxidised and immobilised at the top of the water-table. Cu and occasionally Mn, Zn and Co attain peak values in the laterite zones. Accumulation of Cu, Zn and Co is due to sorption by the hydrous oxides. The dispersion of Fe throughout profiles has a marked influence on the Cu dispersion.

(28) The content of Cu, Fe, Mn, Zn and Co in Kalahari Sand locally bears a direct relationship to values in underlying bedrock, or in underlying residual soil. The dispersion of these elements in the Sand is mainly epigenetic.

(29) Dambo profiles have complex Eh, pH and lithological

conditions. Consequently trace elements distribution is complex and variable.

(30) The Cu, Fe and Mn content of residual soil, Kalahari Sand and dambo sediment increase with decreasing grain size. The silt fraction, which is dominantly quartz and Fe hydroxide and oxide, and the clay fraction of mainly kaolinite, Fe hydroxide and oxide, are particularly enriched. In the silt fraction, the Cu may be adsorbed on Fe hydroxide and oxide, and on fine quartz, or quartz coated with Fe hydroxide or oxide. In the clay fraction, Cu may be adsorbed on Fe hydroxide or oxide and on organo-minerallic colloids. Although kaolinite has a low cation exchange capacity, the surface area of the clay is great and it may be coated by Fe, which is thus conducive to Cu adsorption.

(31) Weaker metal extraction techniques are relatively more effective in Kalahari Sand and dambo sediment than in residual soil. The ex/Total Cu values are lowest in residual soil.

(32) With HCl/Total extraction ratios per grain size, Cu and Fe trends are similar. These metals are only partially HCl extractable. This contrasts with Mn, which is virtually totally HCl extractable. Consequently, a strong Cu-Mn hydroxide association is unlikely to occur in the overburden.

(33) In residual soils, maximum Cu contrast occurs in the silt and clay fractions, and values are greater in wet sieved as compared with dry sieved material. Maximum Fe and Mn contrasts occur in similar fractions. In Kalahari Sand, maximum Cu contrast occurs consistently in the silt fraction. It is suggested that this maximum contrast is due to the accumulation of anomalous Cu in silt by association with fine

quartz, or quartz coated by Fe hydroxide or oxide.

(34) The Cu content of coarse and fine Ao humus material shows a similar trend to that in underlying soil, and is considerably enriched relative to the Cu content of surrounding vegetation. The Fe content of humus does not reflect the Fe distribution in soil and is greatly enhanced relative to vegetation Fe values. The Mn content of humus tends to reflect soil Mn values, and is double the Mn value of vegetation. The Zn content of humus is double the vegetation Zn content. Thus, even coarse, relatively unhumified, vegetation litter accumulates trace elements, and attains levels equivalent to those in underlying soil.

(35) The Cu content of humus is generally lower than that in underlying soil, while Mn and Zn values are enriched and Fe values impoverished, relative to soil content. In Kalahari Sand, the Cu content is enriched in humus relative to Sand values in background areas only. The Mn and Zn contents of humus are enriched, and Fe impoverished, relative to Sand values.

(36) Humus analyses for Cu produce lower and more erratic values, and would produce a lower contrast than Sand analyses.

(37) The Middle Kamwedgi anomaly is restricted to a buried former Ao horizon of a dambo meander, and probably reflects a former seepage anomaly.

(38) Termitaria contain a higher proportion of -200# material relative to surrounding soil and Kalahari Sand. Consequently, analyses of a -80#D fraction of termitaria produce a higher metal content than in an adjacent overburden sample. Comparison of similar silt size fractions of

termitaria and overburden, produce identical metal values. If a -80#D fraction is employed, termitaria sampling is considerably better than overburden sampling in areas of Kalahari Sand. On Kalahari Sand, termitaria are limited to the environment of dambos.

(39) Termitaria appear to be constructed from material derived from the A horizon. Little disruption of geochemical profiles is apparent in overburden near termitaria, and minimal metal contamination from underlying horizons occurs through the action of the termites.

(CHAPTER V)

(40) The frequency and species of tree occurring in the study area is partly controlled by the overburden type. No significant correlation of tree frequency nor physical abnormality is noted at Lower Kamwedgi in relation to Cu mineralisation. This is probably due to the low content, and low toxic effect, of anomalous Cu in the Sand. Although at Mufumbwe, a vegetation clearing occurs in residual soil which probably results from Cu toxicity, it is unlikely that Cu will reach similar toxic level in Kalahari Sand. Consequently, geobotanical surveys are unlikely to be useful in prospecting for Cu in Kalahari Sand.

(41) The intake of Cu in parts of randomly selected trees reflects the underlying Sand Cu distribution, and indicates a sensitivity of the trees at low overburden Cu concentrations. Tree woody parts give the best correlation with the overburden, and the highest Cu content occurs in bark. The Cu contrast of the vegetation is less than 2. Because of variability of intake between tree species and tree parts, a separate threshold must be calculated for each species and part.

Analyses of ground vegetation do not show any trend corresponding to the Sand Cu values.

(42) The Fe, Mn and Zn contents of selected tree species do not reflect Sand values. Fe is concentrated in the bark of trees, while Mn and Zn accumulate in the leaves.

2. RECOMMENDATIONS FOR FUTURE RESEARCH

1. The effectiveness of the silt fraction for Cu analyses in the Kalahari Sand, within the limitations of the study area, has been demonstrated. As epigenetic trace element patterns are now known to develop in aeolian Kalahari Sand, and are of detectable magnitude, it is now necessary to extend the research into the wider context of aeolian Sand in a desert area. Limiting factors for the technique may be (i) depth of Sand (ii) arid conditions.

(i) It is conceivable that in the vicinity of Lower Kamwedgi, the Sand may attain a depth of over 100 ft., while westwards, towards the Barotse Basin, the depth may be several times greater. The effectiveness of the technique with increasing depth of overburden could thus be studied.

(ii) The development of the Cu anomalies in the Kalahari Sand of the study area is a direct result of present climatic conditions with abundant rainfall and evaporation. In areas of aridity, overburden profiles tend to be alkaline, and saline dispersions of metals are severely restricted. It is possible that in such areas, past climatic fluctuations may have produced temporary wetter conditions, during which, saline dispersions of metals developed in the overburden. Relic dispersion patterns may still survive a reversion to arid conditions.

2. It is possible that silt analyses may be effective in locating saline dispersions in other types of transported overburden (e.g. glacial, colluvial) where vertical transportation of metal in solution has been effective.

3. A major influence on geochemical profiles in latosols is the development of lateritic zones. Where intense lateritisation occurs, marked trace metal concentrations result from sorption by the hydroxides. These metals may have been initially introduced via the groundwater from a considerable distance. Subsequent to the laterite formation, weathering processes, including leaching by upward and downward movement of soil moisture, result in a metal enriched profile. In Kalahari Sand which contains a low metal content in the profile, this alteration of the geochemical profile by metal from accumulations in laterite zones is most apparent. Consequently, identification of near-surface metal anomalies resulting from laterite is necessary, possibly by study of associated minor elements only concentrated by lateritisation. An estimation of the trace element enrichment factor resulting from laterite would be useful.

4. Although no obvious associated pathfinder element (including Hg) was found occurring with Cu, further study of these minor elements in an aeolian environment are necessary, especially of gaseous phase elements.

5. In areas of Kalahari Sand, dambo drainage is infrequent and widely spaced. In addition, the few streams capable of crossing expanses of Sand are likely to be of major size. It was found at Mufumbwe that Cu anomalous sediment from the minor tributaries was swamped by barren material transported down the main Mufumbwe dambo, and no anomalous material was

detectable in the main dambo. Further research should include detailed investigation of movement of anomalous material in the major dambos with a view to successful routine sampling of these dambos. It is possible that the humus Ao zone in the dambo centre may produce better results than sediment at depth.

6. Maximum Cu contrast was found in residual soil, Kalahari Sand and dambo sediment in the silt fraction. In addition, this fraction has the maximum cx/Total Cu ratio. The actual form of the Cu in this fraction, and its association with the Fe oxide and hydroxide, or with quartz, is an essential study for the understanding of the fixation of anomalous Cu in overburden.

7. Geobotanical investigations in the study area suggest no obvious correlation with mineralisation. A more comprehensive study, including the ground vegetation, may produce a geobotanic indicator. Further statistical investigations are necessary on possible varieties of Becium obovatum to indicate:-

(a) diagnostic morphological features associated with Cu mineralisation, and

(b) the upper and lower limits of Cu toxicity of the species.

8. In the study area the Cu intake by vegetation, although sensitive to overburden Cu variation, was low and produced a Cu contrast of between 1 and 2. Species were selected, which were common in the area. It is possible that further research might locate a species which accumulates Cu, and would produce a higher Cu contrast.

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APPENDIX I. VEGETATION BOTANICAL AND VERNACULAR NOMENCIATURE

Botanical Name	Vernacular Name				KALAHARI SAND	RESIDUAL SOIL	CONTACT KALAHARI
	Kaonde	Luvale	Lunda	Bemba			
Acacia albida	Lukuku					A	
Afrormosia angolensis	Mubanga	Mubambo	Mubanga	Mubanga	+	+	+
Afzelia quanzensis	Nkulakazhi	Mwalato		Mupapa	+	+	
Albizia autunesiana	Munkwasenge	Mulungu		Musase	+		+
Albizia zygia	Mweyeye		Mweyeye		+	+	
Amblygonocarpus andongensis	Kapapata	Kapapata	Kapapata			+	
Anisophyllea spp.	Mufungo	Mfuko	Mfunu		+	+	+
Bousanthus speciosus	Mumpunzhu	Musungu	Mupunzhu			+	+
Brachystegia boehmi	Musamba	Musamba	Musamba			+	
Brachystegia floribunda			Musompa		+		+
Brachystegia longifolia	Musamba	Musamba	Musamba		+	+	+
Brachystegia speciformis	Manga	Mumanga	Manga			+	+
Combretum mechowianum	Mufuka	Mufuko	Mufuka		+	+	
Combretum molle	Mulama	Mulamata	Mulama		+	+	

Botanical Name	Vernacular name				KALAHARI SAND	RESIDUAL SOIL	CONTACT KALAHARI
	Kaonde	Luvale	Lunda	Bemba			
Comiphora mollis	Musangaluembe	Musangalembe	Nsangalembe		+	+	+
Craterosiphon quarrei				Mukolo		A	
Cryptosepalum pseudotaxus	Mukwe	Mukwe	Mukunu		+	+	+
Desmodium spp.				Kalambatila		A	
Diospyros batocana	Muntukufita	Munjongolo			+	+	
Diplorhynchus condylocarpon	Mwenge	Muli	Mwengi		+	+	+
Eriosema spp.	Kikombabazhike	Muhuhu	Kalalila			+	
Erythrophleum africanum	Kabulwebulwe	Musese	Musese	Mukoso	+	+	+
Faurea spp.	Musokoto	Musunge		Saninga	+	+	
Ficus fischeri		Mutata					+
Garcinia huillensis				Musongwa	+		
Gardenia subacaulis				Chiwowo		+	
Guibourtia coleosperma	Kapepe	Mushibi	Kapepe		+	+	
Hexalobus monopetalus	Kalendeshi		Kalendeshi		+	+	

Botanical Name	Vernacular name				KALAHARI SAND	RESIDUAL SOIL	CONTACT..KALAHARI
	Kaonde	Luvale	Lunda	Bemba			
Hymenocardia acida	Kapempe				+	+	
Isoberlinia angolensis	Mutobo		Mutobo		+	+	+
Julbernardia paniculata	Mutondo	Munyumbe			+	+	+
Landolphia kirki	Mubungo	Mubungo	Mubungo		+	+	+
Lannea discolor	Mowombwo		Nakabumbu		+		+
Monotes spp.	Kipampa	Chipampa	Chipampa		+	+	+
Ochna pulcra	Musengu	Musengo	Musenu		+	+	+
Ochthocosmus lemaireanus	Mulumbwelumbwe		Mulumbwelumbwe		+	+	+
Olax obtusifolia	Mwalu	Mukunyasefu	Mwalu		+	+	+
Parinari excelsa	Mupundu	Mutongo	Mupundu		+	+	+
Parinari polyandra	Mukuwe					+	
Piliostigma thonningi	Kifumbe					+	
Pseudolachnostylis maprouneifolia	Kabalabala				+	+	+

Botanical Name	Vernacular Name				KALAHARI SAND	RESIDUAL SOIL	CONTACT KALAHARI
	Kaonde	Luvale	Lunda	Bemba			
Pseudolachnostylis sp.	Kachiwa				+	+	+
Pteleopsis spp.		Mufunji			+	+	
Pterocarpus angolensis	Ndombe	Mukula	Ndombe		+	+	+
Steganotaenia araliacea	Lumonokyulu					+	
Strychnos spinosa	Kapwi	Makolo	Kapwi			+	
Swartzia madagascariensis	Ndale	Mutete	Ndali		+	+	+
Syzygium cordatum		Musombo	Mufinsa		+		
Syzygium guineense macrocarpum				Musafwa	+	+	
Terminalia sericea			Chibumbu		+		

Botanical Name	Vernacular name				KALAHARI SAND	RESIDUAL SOIL	CONTACT KALAHARI
	Kaonde	Luvale	Lunda	Bemba			
Uapaca kirkiana	Mukusu	Mudengo	Mubula			+	
Uapaca nitida	Musokobele	Ndengondengo	Musokobele			+	+
Ximenia americana				Mulobe	+	+	+

Footnote: A = Anthill

Workmen for the project were derived from the local tribes of the Kaonde from the Kasempa area to the east, the Luvale-Luchaze from Balovale in the west, and the Lunda-Luba from Mwinilunga in the north. Some Bemba employees were brought from the Copperbelt. Consequently the vernacular names of the vegetation were derived from men from these various tribes.

The botanical classification is based on Fanshawe (1965).

APPENDIX II SAMPLING AND ANALYTICAL TECHNIQUES

1. SAMPLE COLLECTION

(a) Surface Soil and Sand.

Ao humus samples were collected by scraping the surface organic litter. Soil and Sand samples were taken at 9 in. depth in the A horizon by means of a small native hoe. Care was taken to exclude Ao contamination of the sample. At each locality the samples were transferred to prenumbered kraft sample packets (5 in. x 3 in.) and the overburden type, colour, granularity and peculiar geomorphological, geological, drainage or vegetational features noted. Area surveys involved systematic sampling on a closely spread grid system. Starting from company survey base-lines, further sample lines were set out by compass and tape, and lines were marked by stakes and tree blazes. Along the lines, set at right angles to the presumed anomaly trend, samples were generally collected at 200 ft. intervals, with closer sampling in areas of interest. Sample intervals along lines were made by compass and pacing.

(b) Profiles in Soil and Sand.

Profile samples were collected by hand augering, pitting, trenching and power augering.

A steel hand auger with a 3 in. diameter hollow bit was employed to collect samples down to a depth of 4 ft. Samples were collected according to the horizon intervals but averaged one per foot depth. It was found impractical to core clay-rich samples by this method in the dry season as the ground was too hard.

Circular pits of 2½ ft. diameter were dug to bedrock if possible, with a maximum depth of 30 ft. Indurate lateritic crusts were occasionally impenetrable. The pits were sampled by cutting a continuous 1 in. deep groove into the wall of the pit and collecting a continuous channel sample from bottom upwards to minimise contamination. The sample interval was dependant on the horizons intersected by the pits and at least one sample was collected per horizon. Company dug trenches were similarly sampled. For deep profiling, a limited use of a truck-mounted power auger was available. Depending on the overburden conditions, profiles of 70-180 ft. were intersected, although in Kalahari Sand depth of penetration was disappointing, perhaps due to the clay content at depth. Samples were collected at 5 ft. intervals and were thus a mixture of the material in the 5 ft.

(c) Dambo sediment.

Dambos were sampled in a similar manner to the soil and Sand. Locally stream sediment was collected from active stream channels.

(d) Rocks

Samples of rock and indurate laterite were collected from surface and from pits by hammer. Care was taken to collect as fresh a specimen as possible.

(e) Termitaria

Large termitaria were sampled in two parts. The lower, wide basal plinth and the upper pinnacle section were each sampled by digging 6 in. into the termitaria to expose unweathered material.

(f) Vegetation

(i) Survey

At 200 ft. intervals along the sample transect line, quadrats with 100 ft. sides were set up centred on the transect peg. The quadrate boundaries were marked out by blazing trees and clearing the lower vegetation. Each tree and shrub within the quadrate was identified by vernacular name and counted.

(ii) Sampling

A suitable tree was selected nearest to the transect peg. As the upper storey trees were 40-50 ft. in height and devoid of lower branches, each tree was felled. Lichen free bark was chipped off by axe, care being taken to avoid areas of termite passageways. Second year twigs, randomly selected from the tree, were cut into convenient lengths by secateurs, while leaves were hand stripped. Each part was individually packeted in a kraft sample packet (5 in. x 3 in.).

2. SAMPLE PREPARATION

(a) Drying

All samples were sundried in the packets. Oven drying was necessary in periods of high humidity during the Rains.

(b) Dry sieving

Soil, Sand or dambo sediment was lightly ground in a porcelain mortar, care being taken not to pulverise mineral grains. This results in a crude disaggregation but does not effectively break up cemented material or separate grains from coatings. Rock and laterite material were washed by deionised water to clean off soil coatings and were then crushed by mortar.

Sieves were constructed of plastic holders with nylon bolting cloth screens. During initial field work, a -80# size fraction was used for analyses and this was achieved by hand sieving of the total sample.

For a more complete size fraction separation, a nest of plastic sieves of various sizes (20#, 38#, 80#, 125#, 200#) were employed, and shaken for a specified period. Ten minutes is regarded as adequate (Milner, 1962). Sieves were thoroughly cleaned by a brush between sieving.

Dry sieving was also applied to the dry coarse material derived from a wet dispersion technique.

(c) Wet sieving.

This technique ensures a more complete separation of mineral grains from adhering silt, clay and oxide coatings.

Following dispersion [see section (d)] the sample material was hand sieved through each size of sieve separately, starting with the coarsest. Shaking was aided by washing

material through the sieve into a beaker with a jet of deionised water from a wash bottle. The material in the beaker, plus the water, were then sieved through the next finest sieve. It was impractical to wet sieve below 200# due to surface tension effects.

(d) Wet dispersion

The method employed is based on Piper (1950) and is a modification of Bouyoucos (1935). 150 ml of 1% Calgon solution (sodium hexametaphosphate) at 20°C were added per 100 gm of sample in a beaker. The mixture was stirred and placed in an ultrasonic tank (Electrosonic H110 ultrasonic cleaner) for 60 minutes. The dispersed slurry was then transferred to a 100 ml measuring cylinder (over 30 cm in height) and the volume was made up to 1000 ml with deionised water. A uniform suspension was obtained by turning the cylinder end over end. The material was then allowed to settle. A Bouyoucos hydrometer was placed in the suspension and the calibration and temperature noted after 5 minutes.

After applying a temperature correction, this reading gave the silt plus clay percentage in suspension. The clay percentage was derived from the hydrometer reading after 5 hours of settling. The silt content was calculated by subtraction. For the separation of silt and clay, the topmost 10 cm of suspension was drawn off by suction pump after 5 minutes of settling. The cylinder was topped up to 1000 ml with deionised water and the process repeated till no suspension appeared in the top 10 cm. The clay was separated from the silt in a similar manner after an elapse of approximately 5 hours, depending on the temperature.

The silt and clay were then derived from suspension by slow evaporation or by centrifuging.

(e) Silt extraction

This method is based on the beaker method of Piper (1950). Approximately 20 gm of sample were added to a 100 ml beaker and topped up with 1% Calgon. The slurry was dispersed in an ultrasonic tank for 30 minutes with occasional stirring. The sample was then wet sieved through a 200# nylon sieve into a beaker. The -200# material was stirred and allowed to settle for 8 hrs during which time the silt settled to the bottom. The liquid phase containing the clay in suspension was then siphoned off by suction pump and discarded. The silt was oven dried at 60°C.

(f) Heavy mineral separation

Clean, dispersed size fractions were added to separating funnels containing tetrabromoethane (sp gr 2.8). The denser heavy minerals settled to the bottom of the funnels and were drained off after 30 minutes. The process was repeated 3 times to ensure complete separation. The tetrabromoethane was then removed from the minerals by acetone. The magnetic fraction of the heavy minerals was separated by hand magnet. The heavy minerals were then mounted on a slide, and identified and counted microscopically.

(g) Vegetation

After oven drying, vegetation samples were prepared in 3 ways:-

(i) Bark was broken into small pieces and 2 gm were weighed into a pan balance. Twigs were cut into small

pieces and similarly weighed into a pan balance (2 gm). Leaves were hand crushed and weighed (3 gm).

(ii) Bark, twigs and leaves were individually fed into a vegetation grinding mill and pulverised. The pulverised material was weighed as above.

(iii) 10 gm of both pulverised and unpulverised samples were ashed in porcelain crucibles for 10 hrs in a muffle furnace at 435°C. Initial care is necessary to allow ignition without loss of material, or contamination through draught. The white ash was then weighed by torsion balance (0.2 gm).

3. ANALYTICAL TECHNIQUES

(a) Attack

(i) Citrate Extraction

Reference: Holman, 1956.

Technical Communication 25 (A.G.R.G.)

Procedure:

Weigh 0.2 gm sample into a test-tube (18 x 180 mm) and add 5 ml buffer solution (pH 4.5). 2 ml of 0.001% dithizone (diphenylthiocarbazone) in purified benzene is added, and the tube is then shaken vigorously for 3 minutes. The colour of the organic phase is then compared with a set of prepared standards.

If the colour of the sample exceeds the colour of the highest standard, a further 2 ml of 0.001% dithizone in benzene is added and the test-tube is shaken for a further 2 minutes. This can be repeated till the sample colour matches the standard colour range.

Standards:

To eleven test-tubes containing 5 ml of buffer solution, add 0, 0.5, 1.0, 1.5, etc., to 4.0, 4.5, 5.0 ug of copper. Add 5 ml of 0.001% dithizone, cork and shake tubes for 3 minutes.

Reagents:

1. Buffer solution: dissolve 100 gm tri-ammonium citrate and 100 gm hydroxylamine hydrochloride in 500 ml water. Extract with approximately 50 ml portions of 0.01% dithizone in carbon tetrachloride until free from Cu, and then remove the excess of dithizone by extraction with carbon tetrachloride. Dilute the aqueous phase to 1 litre with water.

2. Dithizone solution in benzene:

(a) 0.01% dithizone in benzene: dissolve 40 mg in 400 ml of benzene and store in a vacuum flask

(b) 0.001% dithizone in benzene: dissolve 40 ml of the 0.01% solution in benzene with 360 ml of benzene and store in a vacuum flask.

3. Benzene: Shake 1 litre of crystallisable grade with 10 ml of 5% potassium dichromate, discard the aqueous phase, and wash the benzene 4 times with 500 ml quantities of water. Pass the benzene through a filter paper to remove water.

4. 0.5 M hydrochloric acid: mix 20 ml of the acid with 420 ml water.

5. Standard Cu solution.

100 ug of Cu per ml - dissolve 200 mg of cupric sulphate crystals in 0.5 M hydrochloric acid and dilute to 500 ml.

5 ug of Cu per ml - dilute 5 ml of the 100 ug per ml solution to 100 ml with 0.5 M hydrochloric acid

cx Cu ppm = weight factor x dilution factor x standard concentration (ug)

= ml dithizone x ug of matching standard.

Discussion:

Several metals react with dithizone to form primary dithizonates and selectivity of the metallic ion depends on the pH of the solution. The reagent is unstable in direct sunlight and heat.

(ii) Ammonium acetate extraction

Reference: Bray and Willhite, 1929.

Clews, 1962.

Procedure:

Weigh 0.25 gm of sample into a test-tube (18 x 180 mm) and add 10 ml of M ammonium acetate (pH 7.0). The tube is corked and shaken mechanically for 20 minutes: this has been found to be an adequate extraction time (Wilding, 1965, Fig.16). The sample is then centrifuged for 5 minutes at 2000 rpm and the fluid phase is used for metal determination

Discussion:

This attack measures the amount of exchangeable metal cations, which are replaced by strongly charged NH_4^+ ions (Wilding, ibid), and is regarded as effective for clays (Bray and Willhite, 1929)

(iii) Hydrochloric Acid extraction

Reference: Clews, 1962.

Procedure:

0.25 gm sample is added to a test-tube (18 x 180 mm) and heated with 5 ml of 0.5 M HCl for 60 mins. at 80°C in a water bath. The solution is centrifuged for 40 mins. at 2000 rpm and the clear solution used for determination.

Reagents:

0.5 M hydrochloric acid: dilute 20 ml of concentrated hydrochloric acid with 420 ml water

Discussion:

The sample is partially decomposed by hydrochloric acid producing soluble metal chlorides. Results of the

overburden of the study area indicate that the more loosely bonded Cu and Fe minerals are leached while virtually all the Mn is in HCl soluble form.

(iv) Potassium Bisulphate Fusion

References: Almond, 1955.

Technical Communication 23 (A.G.R.G.).

Stanton, 1966.

Procedure:

0.1 gm sample is weighed into a test-tube (16 x 150 mm) with approximately 0.5 gm potassium bisulphate. The mixture is fused on a primus stove and the melt dissolved in 5 ml of M hydrochloric acid and 5 ml of deionised water.

A variation of this procedure was used in the RST laboratory in Kalulushi. Following the bisulphate fusion, the sample was further attacked by a weak hydrochloric-perchloric acid mixture, and then filtered.

Discussion:

Metal sulphides, sulphosalts, most clay minerals and weathered silicates are believed to be attacked by this method (Wilding, 1965). The attack is less effective on fresh silicates and some oxides (Harden,1962). The attack is virtually total in maturely weathered sediments, and in the study area results are comparable with the nitric-perchloric attack.

The attack was not found to be effective for vegetation.

(v) Nitric-Perchloric Acid extraction

Reference: Technical Communication 50 (A.G.R.G.).

Procedure:

0.25 gm sample is weighed into a wide-rimmed test-tube (16 x 150 mm) and 5 ml of acid mixture added. This is evaporated to dryness at an initial temperature of 80°C for 3 hours to drive off the nitric acid, followed by 200°C until the sample is dry. The dry material is leached with 5 ml of M HCl on a warm sand tray.

Reagents:

Acid mixture: mix concentrated nitric acid with perchloric acid (60%) in the ratio 4:1.

Discussion:

Perchloric acid is a powerful oxidising agent. Organic matter is eliminated, while silicates are decomposed and the metals form perchlorates. The extraction is 90% total, although Band (1969) states that in weathered material the attack is total but less effective on fresh silicate lattices. In the highly weathered overburden of the study area, the attack is essentially total.

(vi) Nitric-Perchloric-Sulphuric Acid extraction

Reference: Smith, 1954.
Jackson, 1958.
Piper, 1950.

Procedure:

3 gm of dried vegetation is weighed into a conical flask. Concentrated nitric acid is added (5 ml/gm) and evaporated to dryness. Acid mixture is then added (concentrated nitric: perchloric: sulphuric = 10:4:1) at 5 ml/gm. This is again evaporated to dryness on a hot plate at 200°C. Further additions of acid mixture may be necessary if the vegetation is not fully decomposed to a white evaporite. The evaporite is then dissolved in 20 ml warm M HCl.

Discussion:

Because perchloric acid is a powerful dehydrating agent, explosive activity can occur with vegetation samples, and the initial addition of nitric acid precludes rapid oxidation. The wet ashing is preferable to dry ignition as the process is more rapid, and complex insoluble silicates, which retain trace elements, are not formed. In addition the weight of ash derived from dry matter is dependant on temperature (Carlisle et al., 1958).

(b) Estimation of Elements

(i) Colorimetric

(1) Dithizone

Procedure:

The method is described in the citrate extraction method (see section 3(a)(i). The tint of the dithizone phase is compared with prepared standards.

Reagents:

As described in the citrate extraction method.

Discussion:

The leached Cu ions form a coloured primary dithizonate complex with the dithizone. The colour range is from green through grey to mauve (strong metallic ion concentration). The visual detection limit is 0.1 ug/ml concentration. As several other metals react similarly with dithizone, selectivity of Cu is achieved by pH control. Dithizone has the disadvantage of decomposition in strong light or high temperatures, and care is required in hot climates. In addition dithizone may be oxidised by ferric iron, and colour interference may occur in Fe rich material.

(2) Biquinolyl

Reference: Technical Communication 23 (A.G.R.C.)
Almond, 1955.
Stanton, 1966.

Procedure:

A 2 ml aliquot of the sample solution is pipetted into a test-tube and 10 ml buffer solution added. After a 2 ml addition of 0.02% 2.2-biquinolyl solution, the test-tube is shaken for 30 seconds and compared with a prepared set of standards. If the colour is above the top standard, a further 2 ml of biquinolyl is added. The sample is shaken and the coloured phase again compared with the standards.

Reagents:

Buffer solution: dissolve 200 gm of sodium acetate (trihydrate), 100 gm of potassium sodium tartrate, (tetra-hydrate) and 20 gm of ascorbic acid in water, and dilute to 1 litre. Extract with 0.01% dithizone until free from copper, and then remove the excess of dithizone by extraction with carbon tetrachloride.

0.02% 2.2-biquinolyl solution: dissolve 40 mg in 200 ml of amyl alcohol.

Standard Copper solutions: as per citrate extraction (section 3(a)(i)).

Standards: To 20 test-tubes containing 10 ml buffer solution add 0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10, 12, 14, 16, 18, 20 ug copper. Dilute to 12 ml with 0.5 M hydrochloric acid, add 2 ml of biquinolyl solution, and shake for 30 seconds.

Copper (ppm) = weight factor x dilution factor x biquinolyl factor x standard concentration (ug)

Discussion:

Cuprous copper reacts with normally colourless 2.2-biquinolyl to give a pink complex, which is stable for weeks provided the solvent is free of oxidising impurities. The reaction is virtually specific for cuprous ions and is recommended for tropical soils. The visual detection limit is 0.1 ug/ml concentration.

(c) Mo Analyses

Reference: Technical Communication 56 (A.G.R.C.)
Stanton and Harwick (1967)

Procedure:

0.25 gm sample is weighed into a test-tube (16 x 150 mm) and fused with 1 gm of potassium bisulphate. The sample is then leached with 5 ml of 6 M hydrochloric acid and after the addition of a further 5 ml of acid, is allowed to settle. A 5 ml aliquot is pipetted into a test-tube and 2 ml of reducing solution added. The mixture is allowed to settle for 2 minutes. 2 ml of potassium iodide solution and 1 ml of dithiol solution are added and the mixture is allowed to stand for 2 minutes before an addition of 2 ml of petroleum spirit. The tube is stoppered with a silicone bung and the mixture is shaken for 90 seconds. The organic coloured phase is compared with prepared standards.

Reagents:

Reducing solution: dissolve 75 gm of citric acid and 150 gm of ascorbic acid in water and dilute to 1 litre.

Potassium iodide solution: dissolve 500 gm of potassium iodide in 500 ml of water and store in a dark bottle.

Dithiol solution: add 2 ml of ethyl alcohol to 0.3 gm of zinc dithiol. Add 4 ml of water, 2 gm of sodium hydroxide and 1 ml of thioglycollic acid. Mix well and when clear dilute to 50 ml with water, when the solution will become cloudy again. Mix this solution with 50 ml of potassium iodide solution and store in a refrigerator.

Iron solution: dissolve 5 gm of ammonium ferric sulphate crystals in 500 ml of 6M hydrochloric acid.

Standard molybdenum solutions: 100 ug of Mo/ml - dissolve 126 mg of sodium molybdate in 6M hydrochloric acid and dilute to 500 ml with this acid.

10 ug Mo/ml - dilute 10 ml of the 100 ug/ml solution to 100 ml with 6M hydrochloric acid.

Discussion:

During the fusion, molybdenum is converted to water soluble molybdate. With dithiol, molybdenum forms a green complex which is extracted into the amyl acetate layer.

(d) Mercury analyses

Reference: Technical Communication 55 (A.G.R.C.).
James and Webb (1964).

Procedure:

A double beam mercury vapour meter was employed. Care was taken to select samples which had undergone no heating with subsequent loss of volatile mercury. The sample

were chosen from the weathered zone as sulphur from sulphide mineralisation may cause contamination in the determination stage. The precision level at the low content range of Hg in the soils and Kalahari Sand samples (10 - 40 ppb) is ± 80% at the 95% confidence level.

(e) Organic Carbon analyses

Reference: Technical Communication 32 (A.G.R.C.). Schollenberger, 1927.

Procedure:

0.3 gm of sample is weighed into a conical flask (250 ml) and 10 ml of 0.4 N potassium dichromate added, followed by 10 ml of concentrated sulphuric acid. This is lightly heated for 25 seconds, cooled and 100 ml of 5% ammonium fluoride solution added. The solution is titrated against standardised 0.2 N-ferrous ammonium sulphate solution using diphenylamine as an indicator.

Reagents:

0.4 N potassium dichromate solution: dissolve 19.6147 gm of potassium dichromate in water and dilute to 1 litre.

0.2 N ferrous ammonium sulphate solution: dissolve 78.6 gm of the hexa-hydrate in 1 litre of water containing 20 ml of concentrated sulphuric acid. Standardise by titrating against 10 ml of 0.4 N potassium dichromate solution.

5% ammonium fluoride solution: dissolve 50 gm in 1 litre of water.

Diphenylamine solution: dissolve 0.5 gm in 100 ml of concentrated sulphuric acid and dilute by pouring into 20 ml of cold water.

Discussion:

The dichromate solution produces chromic acid which with sulphuric acid oxidises the organic carbon. The excess unreduced chromic acid is back titrated against standardised ferrous ammonium sulphate. Results are lower than those obtained by the combustion method.

(f) pH analyses.

Procedure:

A mains Pye pH meter was used in the laboratory to determine the pH of soil, Sand and dambo sediment samples. 5 gm of sample were mixed in a beaker with 12.5 ml of water of pH 7.0 and allowed to stand for 30 minutes. This allows the soil and water to attain equilibrium (Jackson, 1958). The Pye meter is calibrated against prepared solutions of known pH and the electrode washed in water (pH 7.0) before immersion in the sample slurry. The readings were taken twice over an interval of 15 minutes, and the mean of the two readings was taken.

(g) Atomic Absorption

A Perkin Elmer Atomic Absorption double beam Spectrophotometer (Model 303) with a combined Perkin-Elmer digital concentration readout accessory (DCR-1) was used for the majority of trace element determinations in London.

The sample material in weak acid solution is atomised in a acetylene-air flame and the absorbance of any particular element is determined by use of the corresponding spectral lamp. Both Boling and single slot burners were used.

Procedure:

Standard solutions, covering the range of values for each element, are aspirated every 10 sample solutions. The trace element concentration of the samples is derived from a calibration curve of the standard solutions. A new curve is plotted when machine variation occurs.

The operational data for the various elements are given in Table 63.

Table 63. Operating conditions of Atomic Absorption apparatus

	Wavelength (Å)	Slit	Gain	Standards (ug/ml)
Cu	3250 uv	4	3	0.2-50
Fe	3720 uv 3868 uv	3	5	10-300 50-500
Mn	4030 vis	4	3	25-200
Zn	2138 uv	5	6	0.5-5.0
Pb	284 uv	4	5	1.0-5.0
Co	2407 uv	3	5.5	0.5-20
Ni	2320 uv	3	6	0.25-20

Discussion:

The lower detection limit for the apparatus for Cu is a 0.2 ug/ml concentration. Using the factor outlined in the nitric-perchloric extraction, with a 0.25 gm sample weight and a 10 ml acid leach, this limit is equivalent to 8 ppm Cu.

By altering the sample weight and the leach solution volume, the detection limit can be reduced. Although an increased sample weight for the same acid leach volume may produce a decreased metal extraction, this is not believed to be applicable in the Kalahari Sand where the total level of soluble salts is low. In addition the Cu content of Kalahari Sand is generally in excess of 10 ppm if a silt fraction is analysed.

(h) Optical Spectrometer analyses

Reference: Nichol and Henderson-Hamilton (1965).

Procedure:

Samples were analysed by the spectrographic laboratory of the Geochemical Research Centre. Samples were ignited in silica crucibles at 400 - 500°C for 3 hours to oxidise organic matter and to eliminate water. The samples were homogenised with a 1:1 mixture of lithium carbonate and carbon containing germanium, the internal standard. The mixture was arced for 90 seconds and the concentrations of the elements in the sample were estimated by comparing the spectra of the sample with spectra on a standard plate.

Specifications of the machine and method are listed in Table 64.

Table 64. Operating conditions of optical spectrometer.

Source Unit	Hilger FS 131
Spectrograph	Hilger Large Quartz FS 55
Arc Stand	Hilger FS 56
Comparator	Hilger JA Co L90
Wavelength Range (Å)	2800-4950
Emulsion	Ilford N30
Anode	Morganite SG 305H-5mm carbon, crater diam. 2.91mm, depth-5mm.
Cathode	Morganite SG 305H-flat ended
Exposure	20 seconds
Gap	3 mm
Arc Current	12.5 amps
Slit	15 u
Collimator	Internal
Step sector	2 steps giving 3 intensities in proportion of 1:¼:1/16

Spectrographic analyses have the advantage of a wide range of element coverage from a single sample, and a permanent record of the analyses. The method has the disadvantage of a lower precision than the Atomic Absorption method. Moreover variations in the bulk chemical composition matrix can affect the reliability of results. Comparison between spectrometry and Atomic Absorption data for the same routine samples indicates that the spectrographic method has a tendency for low Cu, higher Fe and similar Mn and Co.

(i) X-ray diffraction analyses

Procedure:

Initial samples were finely ground in an agate mortar and the powder mounted on an X-ray slide cavity mount. In later studies the powdered sample was drawn on to a ceramic disc from suspension by means of a suction pump. A Phillips Proportional Counter X-ray diffractometer with a wide angle goniometer and Cu-Kα radiation was used for mineral determination. The samples were scanned as mounted. In order to identify certain clay minerals, samples were heated to 550°C for 1 hour. This causes evaporation of water molecules, which with certain minerals, causes a lattice change by collapse (e.g. montmorillonite). Treatment by glycerol produces in certain minerals swelling by lattice expansion (e.g. chlorite). For minute quantities of sample, a smear mount was used.

The operating conditions of the apparatus are presented in Table 65.

Table 65. Operating conditions of x-ray diffraction apparatus

Counter type	Scintillation
Slit width	0.1 mm
Range	4-60 (2θ)
Scale factor	16 x 1
Time constant	1 or 2 second
Divergence (α)	1°
Scan speed	2° (2θ) per minute

The maximum Bragg reflections of the main minerals from the study area are listed with the corresponding d spacings (Table 66).

Table 66. d spacing of minerals.

Mineral	D spacing (Å)
1. Chlorite-Montmorillonite Group	14
2. Mica-Illite Group	10
3. Kaolinite-Serpentine Group	7.15
4. Talc Group	9.3
5. Gibbsite	4.82
6. Goethite	4.18
7. Quartz	3.30
8. Hematite	2.69

4. PRECISION

Reference: Technical Communication 46 (A.G.R.C.). Craven, 1953.

In Zambian A horizon latosols the sampling error has been demonstrated to be insignificant compared with analytical error (Tooms, 1955; Jay, 1959).

The analytical error was evaluated during routine sample analyses by inserting artificially prepared soil standards with a range of Cu similar to the samples. Precision was then calculated by the method of Craven (1953).

An alternative evaluation of precision was obtained by at least 5 replicate analyses of the same sample. For the latter method the mean percentage precision at the 95% confidence level is

$$\pm \frac{2D \times 100}{\text{mean}} \quad \text{where } D = \sqrt{\frac{\Sigma x^2 - N.\bar{x}^2}{N-1}}$$

N = number of repeats
$\bar{x}$ = mean value
x = sample value

Various precisions obtained during analyses are presented in Table 67.

Table 67. Mean % Precision at the 95% confidence level.

Metal	Extraction	Statistical method	Value range (ppm)	Mean % Precision(±)
Cu	NH_4 Acetate dithizone	Standard series Standard series	0.5-10 0.5-30	52 41
Cu	0.5 M HCl	Standard series	5-300	33
Cu	bisulphate fusion	Standard series	10-400	15
Cu	Nitric-perchloric	Standard series	10-80	10
Cu	dithizone	Standard series	0.2-1.0	30-45
Cu	0.5 M HCl	Standard series	0.5-4.0	52
Cu	Nitric-perchloric	Replicates	85	21
Fe	Nitric-perchloric	Replicates	4%	33
Mn	Nitric-perchloric	Replicates	290	35
Zn	Nitric-perchloric	Replicates	25	21
Co	Nitric-perchloric	Replicates	15	25

The mean precision is dependant on the element analysed in any sample, on the sample attack employed, on the metal range in the samples and on the grain size. Thus the Craven method gives the average precision over a range of values, while the replicate method produces a value for a certain content level. In general the precision for Cu can be seen to improve with a stronger extraction, and best precision is derived with a nitric-perchloric attack and an Atomic Absorption determination. Fe and Mn extraction is more erratic than Cu within the same sample, while the precision of any element is lower towards the detection limit.

APPENDIX III ANALYTICAL DATA OF OVERBURDEN AND VEGETATION

Table 68. Cu, Fe and Mn content of residual soil (anomalous) (ppm) per size fraction for various extractants

Reagent		Sieve	+38#	-38 +80#	-80 +200#	silt	-200#	Clay	Detection limit
Cu	Ammonium acetate	Dry	<0.1	<0.1	<0.1		<0.1		3.0
		Wet	<0.1	0.4	0.4	<0.1		<0.1	
	Dithizone	Dry	0.2	0.2	0.2		0.5		0.16
		Wet	0.1	0.4	0.4	<0.1		<0.1	
	Hydro-chloric acid	Dry	5.5	2.4	1.1		2.8		2.5
		Wet	<0.1	0.6	1.6	5.8		8.2	
	Potassium bisulphate	Dry	93	73	83		130		1.0
		Wet	28	10	22	125		210	
	Nitric-perchloric	Dry	76	53	71		85		2.0
		Wet	18	6	9	84		170	
Fe%	Hydro-chloric acid	Dry	2.4	3.0	3.0		4.2		
		Wet	1.4	1.0	0.7	3.7		6.8	
	Nitric-perchloric	Dry	6.4	3.4	4.3		6.3		
		Wet	3.8	1.0	0.4	3.9		8.9	
Mn	Nitric-perchloric	Dry	320	220	230		360		
		Wet	110	94	71	300		370	

Table 69. Cu, Fe and Mn content of Kalahari Sand (background) (ppm) per size fraction for various extractants

Reagent		Sieve	+38#	-38 +80#	-80 +200#	silt	-200#	clay	Detection limit
Cu	Ammonium acetate	Dry	<0.1	<0.1	<0.1		<0.1		3.0
		Wet	<0.1	0.4	<0.1	<0.1		0.4	
	Dithizone	Dry	1.0	0.3	0.6		0.6		0.16
		Wet	0.2	0.2	0.2	1.3		4.8	
	Hydrochloric acid	Dry	1.8	2.4	<0.1		3.0		2.5
		Wet	<0.1	0.5	0.1	13		29	
	Potassium bisulphate	Dry	14	10	18		27		1.0
		Wet	1	1	1	27		91	
	Nitric-perchloric acid	Dry	15	9	11		23		2.0
		Wet	3	3	2	18		120	
Fe%	Hydrochloric acid	Dry	0.6	0.3	0.3		0.9		
		Wet	0.1	0.1	0.1	0.8		1.6	
	Nitric-perchloric acid	Dry	0.6	0.4	0.4		2.2		
		Wet	0.2	0.1	0.1	0.6		2.3	
Mn	Nitric-perchloric acid	Dry	65	46	92		110		
		Wet	23	31	33	150		310	

Table 70. Cu, Fe and Mn content of Kalahari Sand (background) (ppm) per size fraction for various extractants

Reagent		Sieve	+38#	-38 +80#	-80 +200#	silt	-200# clay	Detection limit
Cu	Ammonium acetate	Dry	<0.1	<0.1	<0.1	<0.1		3.0
		Wet	<0.1	<0.1	0.4	<0.1	<0.1	
	Dithizone	Dry	0.2	0.2	0.3	0.3		0.16
		Wet	0.2	0.3	0.3	0.5	0.8	
	Hydro-chloric acid	Dry	0.7	<0.1	<0.1	3.6		2.5
		Wet	<0.1	2.8	1.6	3.1	7.6	
	Potassium bisulphate	Dry	8	7	11	32		1.0
		Wet	1	1	1	12	76	
	Nitric-perchloric acid	Dry	5	5	10	25		2.0
		Wet	1	3	1	25	120	
Fe%	Hydro-chloric acid	Dry	0.3	0.3	0.5	1.0		
		Wet	0.1	0.1	0.2	0.4	1.6	
	Nitric-perchloric acid	Dry	0.7	0.7	1.2	3.0		
		Wet	0.1	0.2	0.5	2.5	10.6	
Mn	Nitric-perchloric acid	Dry	45	32	55	85		
		Wet	11	13	13	140	190	

Table 71. Cu, Fe and Mn content of dambo sediment (background) (ppm) per size fraction for various extractants

	Reagent	Sieve	+38#	-38 +80#	-80 +200#	silt	-200# clay	Detection limit
Cu	Ammonium acetate	Dry	<0.1	1.2	<0.1	<0.1		3.0
		Wet	0.4	<0.1	1.2	<0.1	0.4	
	Dithizone	Dry	0.5	0.2	0.3	0.5		0.16
		Wet	0.1	0.1	0.1	0.5	2.6	
	Hydrochloric acid	Dry	0.6	2.8	4.3	3.0		2.5
		Wet	<0.1	0.1	<0.1	3.2	14.6	
	Potassium bisulphate	Dry	22	14	12	32		1.0
		Wet	1	2	1	14	60	
	Nitric-perchloric acid	Dry	14	10	10	18		2.0
		Wet	1	1	2	11	52	
Fe%	Hydrochloric acid	Dry	0.8	0.7	0.6	1.4		
		Wet	0.2	0.2	0.2	0.8	2.6	
	Nitric-perchloric acid	Dry	1.6	0.8	0.9	1.2		
		Wet	0.3	0.3	0.2	0.6	2.9	
Mn	Nitric-perchloric acid	Dry	28	23	30	43		
		Wet	12	6	7	25	60	

Table 72. Cu, Fe and Mn content of dambo sediment (anomalous) (ppm) per size fraction for various extractants

	Reagent	Sieve	+38#	-38 +80#	-80 +200#	silt	-200# clay	Detection limit
Cu	Ammonium acetate	Dry	1.2	1.6	3.2	2.8		3.0
		Wet	2.8	<0.1	0.8	2.4	3.6	
	Dithizone	Dry	8.3	6.7	8.3	15.4		0.16
		Wet	1.6	1.8	1.1	31.4	33.6	
	Hydrochloric acid	Dry	27	26	35	60		2.5
		Wet	13	10	7	24	90	
	Potassium bisulphate	Dry	160	150	140	300		1.0
		Wet	68	54	39	360	530	
	Nitric-perchloric acid	Dry	170	160	200	280		2.0
		Wet	94	25	26	390	780	
Fe%	Hydrochloric acid	Dry	0.6	0.4	0.6	1.1		
		Wet	0.5	0.2	0.2	1.1	1.4	
	Nitric-perchloric acid	Dry	1.3	0.7	0.6	1.1		
		Wet	0.9	0.2	0.1	1.2	2.8	
Mn	Nitric-perchloric acid	Dry	60	74	58	92		
		Wet	38	17	13	83	130	

Table 73. Cu content of residual soils (ppm) per size fraction.

	Sample No.	Location	Wet sieved +38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	Dry sieved -80#	-200#
Nitric-perchloric acid	Anomalous	L.KAMWEDGI								
	4002	C2	45	14	12	12	80	290	38	80
	4004	C4	67	15	13	15	88	360	51	110
	4139	KN3	19	10	10	11	72	190	31	70
	4140	KN4	36	12	10	12	63	190	31	51
	Background									
	4542	C-4	25	6	5	6	35	100	25	47
	4544	C-5	16	6	5	7	29	94	23	42
Hydrochloric acid	Anomalous									
	4002	C2	17	3	2	2	17	43		
	4004	C4	-	2	2	2	13	51		
	4139	KN3	3	2	4	2	11	26	5	
	4140	KN4	4	1	2	2	11	29		
	Background									
	4542	C-4	5	1	1	1	7	15	4	
	4544	C-5	4	1	1	1	7	23		7

Table 74. Fe content of residual soils (%) per size fraction.

	Sample No.	Location	Wet sieved +38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	Dry sieved -80#	-200#
Nitric-perchloric acid	Cu-Anomalous	L.KAMWEDG-I								
	4002	C2	4.3	1.2	0.8	0.7	1.9	5.1	1.2	2.3
	4004	C4	1.6	0.4	0.3	0.3	1.2	2.9	0.7	1.2
	4139	KN3	1.0	0.4	0.5	0.6	1.9	3.4	1.2	1.2
	4140	KN4	1.6	0.5	0.5	0.6	1.8	2.7	1.1	1.5
	Background									
	4542	C-4	3.1	0.9	0.6	0.7	3.1	5.0	1.6	2.8
	4544	C-5	1.8	0.7	0.7	0.8	1.9	5.9	1.7	2.8
Hydrochloric acid	Anomalous									
	4002	C2	1.6	0.4	0.2	0.1	0.5	1.2		
	4004	C4	-	<0.1	0.1	<0.1	0.2	0.7		
	4139	KN3	0.3	0.1	0.1	0.2	0.7	1.6	0.4	
	4140	KN4	0.3	0.2	0.2	0.2	0.6	1.2		
	Background									
	4542	C-4	0.9	0.2	0.2	0.1	0.5	1.1	0.4	
	4544	C-5	0.4	0.2	0.2	0.2	0.4	1.0		0.9

Table 75. Mn content of residual soils (ppm) per size fraction

	Sample No.	Location	Wet sieved +38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	Dry sieved -80#	-200#
Nitric-perchloric acid	Cu-Anomalous	L.KAMWEDGI								
	4002	C2	500	120	86	82	240	520	150	330
	4004	C4	150	58	34	41	190	360	120	180
	4139	KN3	140	79	120	79	460	620	200	420
	4140	KN4	270	43	41	110	770	1000	180	640
	Background									
	4542	C-4	500	240	140	130	260	460	250	360
	4544	C-5	270	170	160	120	230	750	250	330
Hydrochloric acid	Anomalous									
	4002	C2	450	120	82	85	220	500		
	4004	C4	-	61	44	89	140	330		
	4139	KN3	170	110	110	120	430	640	200	
	4140	KN4	56	65	56	110	750	1000		
	Background									
	4542	C-4	510	220	180	140	280	350	220	
	4544	C-5	280	170	160	120	160	760		310

Table 76. Cu content of Kalahari Sands (ppm) per size fraction

	Sample No.	Location	Wet sieved +38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	Dry sieved -80#	-200#
Nitric-perchloric acid	Anomalous	L. KAMWEDGE								
	4194	RN4	3	2	3	4	48	112	13	34
	4193	RN5	4	2	3	5	73	150	20	70
	Background									
	4780	KN-4	1	1	1	2	14	45	7	16
	4778	KN-5	1	1	2	2	17	39	6	14
	4806	RN-4	2	2	2	2	11	43	5	13
	4804	RN-5	2	1	1	1	12	39	4	12
Hydrochloric acid	Anomalous									
	4194	RN4	0.5	0.5	0.1	0.5	10	24	2	
	4193	RN5	1.5	0.5	0.5	1	24	45		
	Background									
	4780	KN-4	0.1	0.5	0.5	0.5	5	14	2	
	4778	KN-5	0.5	0.5	0.5	1	7	11		
	4806	RN-4	0.5	0.5	0.5	0.5	4	9	1	
	4804	RN-5	0.5	0.5	0.5	0.5	5	12		

Table 77. Fe content of Kalahari Sand (%) per size fraction.

	Sample No.	Location	Wet sieved +38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	Dry sieved -80#	-200#
Nitric-perchloric acid	Cu-Anomalous	LKAMWEDGI								
	4194	RN4	<0.1	<0.1	0.2	0.2	1.7	3.6	0.7	1.5
	4193	RN5	0.1	<0.1	0.1	0.2	1.6	3.2	0.7	2.3
	Background									
	4780	KN-4	0.1	<0.1	0.1	0.2	1.3	4.1	0.7	1.6
	4778	KN-5	0.1	<0.1	0.1	0.2	1.4	3.4	0.7	1.6
	4806	RN-4	<0.1	<0.1	0.1	0.2	1.1	4.2	0.5	1.5
	4804	RN-5	0.1	<0.1	0.1	0.2	1.3	3.5	0.5	1.4
Hydrochloric acid	Anomalous									
	4194	RN4	<0.1	<0.1	<0.1	<0.1	0.3	0.7	0.1	
	4193	RN5	<0.1	<0.1	<0.1	<0.1	0.3	0.5		
	Background									
	4780	KN-4	<0.1	<0.1	<0.1	<0.1	0.3	0.7	0.1	
	4778	KN-5	<0.1	<0.1	<0.1	<0.1	0.3	0.5		
	4806	RN-4	<0.1	<0.1	<0.1	<0.1	0.2	0.4	0.1	
	4804	RN-5	<0.1	<0.1	<0.1	<0.1	0.3	0.5		

Table 78. Mn content of Kalahari Sand (ppm) per size fraction

	Sample No.	Location	Wet sieved +38#	-38 +80#	-80 +125#	-125 +200#	silt	clay	Dry sieved -80#	-200#
Nitric-perchloric acid	Cu- Anomalous	L.KAMWEDGI								
	4194	RN4	25	22	12	24	230	450	100	200
	4193	RN5	16	19	6	22	150	280	58	180
	Background									
	4780	KN-4	9	6	9	37	240	300	41	130
	4778	KN-5	9	6	20	37	370	470	100	280
	4806	RN-4	2	2	9	16	170	270	52	160
	4804	RN-5	6	2	9	22	160	330	42	150
Hydrochloric acid	Anomalous									
	4194	RN4	23	15	23	32	290	450	82	
	4193	RN5	1	1	8	15	190	230		
	Background									
	4780	KN-4	20	15	15	28	200	290	56	
	4778	KN-5	15	3	13	32	390	490		
	4806	RN-4	1	1	3	8	150	210	35	
	4804	RN-5	8	3	8	11	140	260		

Table 79. Total-HCl soluble trace element ratios

			Sample	+38#	-38 +80#	-80 +125#	-125 +200#	silt	clay
Total/HCl Cu	Residual soil	Anomalous	4002	3.4	6.0	6.8	6.6	5.6	6.9
		Anomalous	4139	8.0	7.4	3.5	5.0	6.2	6.9
		Background	4542	5.0	4.6	3.9	5.4	4.6	5.2
	Kalahari Sand	Anomalous	4194	2.8	5.5	10.3	7.2	3.6	3.8
		Background	4780	3.2	2.0	2.1	2.6	2.7	3.4
		Background	4804	4.3	2.4	3.5	2.5	2.8	3.8
Total/HCl Fe%	Residual soil	Anomalous	4002	1.8	3.1	4.1	4.5	4.3	4.1
		Anomalous	4139	4.7	3.5	3.2	3.3	2.9	2.1
		Background	4542	3.8	4.5	3.3	4.0	5.5	5.4
	Kalahari Sand	Anomalous	4194	5.0	4.5	3.8	4.3	5.5	4.5
		Background	4780	6.0	4.0	3.2	7.0	4.5	6.7
		Background	4804	3.3	3.5	3.5	4.2	5.0	8.9
Total/HCl Mn	Residual soil	Anomalous	4002	1.1	1.0	1.0	1.0	1.2	1.1
		Anomalous	4139	1.8	1.0	1.0	1.0	1.0	1.0
		Background	4542	1.0	1.0	1.0	1.0	1.2	1.1
	Kalahari Sand	Anomalous	4194	1.8	2.6	1.0	1.0	1.0	1.1
		Background	4780	1.0	1.0	1.0	1.2	1.0	1.0
		Background	4804	1.0	1.0	1.5	1.9	1.1	1.3

Table 80. Comparison of Cu content (ppm) of unpowdered, powdered and ash analyses of Brachystegia longifolia

	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash
	PN-6							PN-5							PN-4							PN-3						
Leaf	5855	-	9.8	250	9.1	230	140	5871	3.7	9.6	250	9.0	230	130	5887	-	9.1	230	9.2	240	130	5903	-	8.2	210	7.2	180	150
Twig	5856	3.3	4.7	130	4.9	130	150	5872	2.8	5.3	140	5.7	180	140	5888	3.8	6.1	160	6.0	160	130	5904	3.3	6.5	180	7.1	180	98
Bark	5857	5.4	9.6	360	7.4	270	110	5873	1.4	8.6	320	7.4	270	450	5889	2.5	11.6	430	7.4	270	180	5905	1.5	11.4	420	10.0	370	560
	PN2							PN3							PN4							PN5						
Leaf	5919	4.2	9.7	250	8.7	220	170	5935	-	10.7	270	9.6	250	210	5951	3.9	9.2	240	8.7	220	160	5967	-	-	-	-	-	-
Twig	5920	5.2	7.5	200	6.2	170	110	5936	3.2	7.3	200	8.6	230	230	5952	3.5	5.7	150	6.2	170	160	5968	4.7	3.5	95	6.7	180	130
Bark	5921	-	12.9	480	9.0	330	320	5937	1.4	14.9	550	12.7	470	690	5953	1.2	12.1	450	10.0	370	710	5969	1.4	14.0	58	11.0	410	620
	PN7							PN8							PN9							PN10						
Leaf	5983	3.4	8.0	210	7.6	200	170	5999	4.4	6.9	180	6.2	160	170	6015	4.1	6.7	170	7.9	200	150	6031	3.8	11.0	280	10.7	270	210
Twig	5984	-	5.3	140	5.2	140	230	6000	3.2	6.7	180	5.3	140	150	6016	3.7	8.0	220	8.0	220	170	6032	-	8.9	240	8.3	220	-
Bark	5985	-	10.8	400	5.9	220	110	6001	2.9	11.4	420	12.5	460	360	6017	3.4	12.5	460	8.9	330	320	6033	2.8	8.6	320	9.7	360	310

Table 81. Comparison of Fe content (ppm) of unpowdered, powdered and ash analyses of Brachystegia longifolia.

	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash
	PI-6							PN-5							PN-4							PN-3						
Leaf	5855	-	40	1000	80	2000	1100	5871	3.7	60	1500	71	1800	2200	5887	-	70	1800	80	2000	330	5903	-	61	1600	92	2400	1300
Twig	5856	3.3	13	350	36	970	2600	5872	2.8	20	540	120	3200	630	5888	3.8	33	890	36	1000	710	5904	3.3	20	540	40	1100	570
Bark	5857	5.4	250	9100	230	8500	2600	5873	1.4	93	3400	120	4400	7500	5889	2.5	170	6200	50	1900	-	5905	1.5	140	5100	80	3000	5300
	PN2							PN3							PN4							PN5						
Leaf	5919	4.2	50	1300	56	1400	1000	5935	-	50	1300	80	2000	1200	5951	3.9	68	1700	65	1700	300	5967	-	-	-	-	-	-
Twig	5920	5.2	13	350	42	1100	1800	5936	3.2	20	540	56	1500	1700	5952	3.5	20	540	65	1800	2200	5968	4.7	27	730	80	2200	1700
Bark	5921	-	190	7100	100	3800	3600	5937	1.4	87	3200	71	2600	5700	5953	1.2	80	3000	130	4800	9500	5969	1.4	130	4920	130	5000	7200
	PN7							PN8							PN9							PN10						
Leaf	5983	3.4	50	1300	58	1500	330	5999	4.4	70	1800	62	1600	1500	6015	4.1	40	1000	42	1100	530	6031	3.8	50	1300	54	1400	430
Twig	5984	-	20	540	50	1400	-	6000	3.2	20	540	21	570	710	6016	3.7	17	460	62	1700	1500	6032	-	110	2900	160	4200	-
Bark	5985	-	400	15000	320	12000	6000	6001	2.9	270	10000	360	13000	5200	6017	3.4	240	9000	250	9400	5700	6033	2.8	210	7900	400	15000	14600

Table 82. Comparison of Mn content (ppm) of unpowdered, powdered and ash analyses of Brachystegia longifolia

	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash
	PN-6							PN-5							PN-4							PN-3						
Leaf	5855	-	440	11300	550	14000	250	5871	3.7	900	23000	850	21700	1700	5887	-	770	20000	700	17800	450	5903	-	470	12000	430	11000	500
Twig	5856	3.3	100	2800	170	4500	1100	5872	2.8	210	5700	140	3900	850	5888	3.8	200	5400	180	4800	360	5904	3.3	140	3700	110	3000	1200
Bark	5857	5.4	370	13500	190	680	2600	5873	1.4	160	5700	150	5600	3900	5889	2.5	240	8700	190	7100	-	5905	1.5	220	8000	160	5900	2100
	PN2							PN3							PN4							PN5						
Leaf	5919	4.2	670	17200	620	15900	790	5935	-	1000	25000	860	2200	1700	5951	3.9	1200	32000	950	24000	520	5967	-	-	-	-	-	-
Twig	5920	5.2	160	4300	130	3500	2500	5936	3.2	230	6200	200	5400	1500	5952	3.5	180	5000	160	4200	1600	5968	4.7	260	6900	170	4600	1800
Bark	5921	-	240	8800	210	7800	3100	5937	1.4	190	7100	190	7000	11500	5953	1.2	180	-	180	6500	5100	5969	1.4	140	5100	130	4700	2300
	PN7							PN8							PN9							PN10						
Leaf	5983	3.4	610	16000	590	15100	2000	5999	4.4	560	14000	570	14500	1200	6015	4.1	470	12000	670	17200	2300	6031	3.8	600	15400	770	20000	1800
Twig	5984	-	130	3400	110	3000	-	6000	3.2	140	3900	130	3400	700	6016	3.7	160	4200	160	4200	1000	6032	-	130	3400	140	3700	-
Bark	5985	-	100	3700	120	4300	1500	6001	2.9	110	4000	120	4300	1800	6017	3.4	130	4600	280	10400	2500	6033	2.8	71	2600	120	4300	4000

Table 83. Comparison of Zn content (ppm) of unpowdered, powdered and ash analyses of Brachystegia longifolia

	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash	Sample	Ash %wt.	Unpowdered vegetation	Equivalent ash wt.	Powdered vegetation	Equivalent ash wt.	Ash
	PN-6							PN-5							PN-4							PN-3						
Leaf	5855	-	25	540	24	610	490	5871	3.7	22	560	21	540	240	5887	-	30	770	27	690	600	5903	-	24	610	17	440	510
Twig	5856	3.3	6	160	8	220	240	5872	2.8	9	240	9	240	190	5888	3.8	17	460	15	410	340	5904	3.3	14	380	10	270	400
Bark	5857	5.4	6	220	6	220	140	5873	1.4	5	190	5	190	310	5889	2.5	6	220	4	150	-	5905	1.5	4	150	3	110	200
	PN2							PN3							PN4							PN5						
Leaf	5919	4.2	19	490	17	440	450	5935	-	22	560	23	590	640	5951	3.9	23	590	24	610	570	5967	-	-	-	-	-	-
Twig	5920	5.2	14	380	14	380	250	5936	3.2	12	320	12	320	360	5952	3.5	7	190	9	240	250	5968	4.7	11	300	11	300	270
Bark	5921	-	3	110	3	110	110	5937	1.4	5	190	5	190	250	5953	1.2	3	110	3	110	170	5969	1.4	3	110	3	110	150
	PN7							PN8							PN9							PN10						
Leaf	5983	3.4	16	410	17	440	510	5999	4.4	20	510	17	440	270	6015	4.1	23	590	26	670	640	6031	3.8	17	440	16	410	460
Twig	5984	-	8	220	7	190	600	6000	3.2	10	270	8	220	250	6016	3.7	9	240	9	240	230	6032	-	14	380	14	380	-
Bark	5985	-	3	110	4	150	67	6001	2.9	9	330	9	260	110	6017	3.4	3	110	7	260	150	6033	2.8	2	74	3	110	130

Table 84. Cu content of vegetation (ppm, dry weight) on transect PN, Lower Kamwedgi

SPECIES	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
	PN-6 (soil silt 16)						PN-5 (20)						PN-4 (19)						PN-3 (19)					
Leaf	9.8	8.6	12.9	8.4	4.8	7.7*	9.6	7.2	10.0	5.9	5.1	6.1	9.1	6.7	11.1	6.2	5.0	6.3	8.2	6.9	7.8	8.9	5.1	4.3
Twig	4.7	4.7	4.1	7.2	6.1		5.3	5.1	3.8	3.6	4.0		6.1	3.6	4.2	3.5	6.0		6.5	3.9	5.5	3.8	6.5	
Bark	9.6	6.7	12.4	8.5	8.0		8.6	8.3	10.6	8.9	6.1		11.6	7.8	7.5	14.4	5.1		11.4	6.4	7.0	8.7	5.3	
	PN2 (100)						PN3 (120)						PN4 (185)						PN5 (110)					
Leaf	9.7	6.3	11.4	3.7	5.1	3.7	10.7	4.4	9.5	10.5	5.8*	4.9	9.2	6.2	10.5	11.9*	4.7	4.2	7.7	9.2	10.4	3.9	4.9	
Twig	7.5	7.1*	6.0	3.0	5.5		7.3	4.2	5.9	7.6	9.8*		5.7	5.0	6.1*	8.1	9.2		3.5	3.7	5.8	9.0*	8.8	
Bark	12.9	7.9	9.2	9.2	7.1		14.9*	6.5	10.1	12.6	9.3		12.1	11.1*	13.0*	21.5*	11.5*		14.0	4.9	8.2	9.4	9.2	
	PN7 (95)						PN8 (100)						PN9 (80)						PN10 (70)					
Leaf	8.0	6.8	14.0*	8.8	3.2	6.2	6.9	6.1	8.6	6.7	4.2	5.2	6.7	6.4	8.6	9.9	4.2	4.4	11.0*	8.7*	11.0	7.4	4.3	3.7
Twig	5.3	2.3	4.7	6.2	4.3		6.7	3.6	4.2	5.2	9.2		8.0	5.5	4.1	3.5	4.1		8.9*	5.5	3.6	4.6	3.6	
Bark	10.8	7.2	10.0	15.5	4.3		11.4	4.0	6.6	14.8	7.8		12.5	7.5	8.7	11.0	8.4		8.6	6.3	7.9	14.5	4.3	

* Highest values per part per species

1. Brachystegia longifolia 2. Julbernardia paniculata 3. Brachystegia spiciformis 4. Diplorhynchus condylocarpon
5. Pseudolachnostylis sp. 6. Landolphia kirki.

Table 85. Fe content of vegetation (ppm, dry weight) on transect PN, Lower Kamwedgi

SPECIES	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
			PN-6 (soil silt 2.8%)						PN-5 (2.4%)						PN-4 (2.2%)						PN-3 (2.3%)					
Leaf	40	29	20	26	37	46	60	20	20	23	24	91	70*	36	25	44*	38	38	61	27	30	24	29	68
Twig	13	9	8	12	15		20	13	11	11	13		33	18*	16	13	32		20	10	8	18	33*	
Bark	250	73	170*	22	50		93	75	140	200	90		170	60	31	66	52		140	74	54	47	100	
			PN2 (3.7%)						PN3 (3.8%)						PN4 (5.5%)						PN5 (4.2%)			
Leaf	50	25	25	23	150*	72	50	26	38	18	53	26	68	25	34	24	30	48		38*	30	26	28	38
Twig	13	18*	13	9	17		20	5	10	13	19		20	13	21	9	22		27	14	11	22*	21	
Bark	190	100	53	230	170*		87	29	26	34	120		80	380*	100	38	48		130	26	68	26	25	
			PN7 (4.1%)						PN8 (5.2%)						PN9 (4.6%)						PN10 (4.2%)			
Leaf	50	32	56*	21	22	170*	70*	21	28	31	28	150	40	21	30	36	34	38	50	37	54	15	20	45
Twig	20	7	22*	22*	20		20	10	5	7	16		17	13	8	11	14		110*	9	7	14	6	
Bark	400*	190	36	26	21		270	60	41	290*	9		240	40	120	36	14		210	65	75	42	70	

* Highest values per part per species

1. Brachystegia longifolia 2. Julbernardia paniculata 3. Brachystegia spiciformis 4. Diplorhynchus condylocarpon

5. Pseudolachnostylis sp. 6. Landolphia kirki

Table 86. Mn content of vegetation (ppm, dry weight) on transect PN, Lower Kamwedgi

SPECIES	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
	PN-6 (soil silt 150)						PN-5 (130)						PN-4 (170)						PN-3 (230)					
Leaf	440	150	400	780	250	200	900	140	390	580	250	100	770	110	480	380	190	290	470	110	510	720	330*	230
Twig	100	55	170	110	71		210	51	180*	87	74		200	28	95	57	70		140	43	130	120	57	
Bark	370*	55	130	78	49*		160	85	120	130	48		240	57	73	32	18		220	130	74	45	18	
	IN2 (200)						PN3 (110)						PN4 (150)						PN5 (270)					
Leaf	670	40	450	690	160	380	980	140	400	490	260	360	1200*	170*	720*	1000*	200	390*	-	120	570	560	250	280
Twig	160	53	130	110	58		230	110*	120	160	76		180	110	180	240*	60		260*	46	100	150	62	
Bark	240	100	150*	140	48		190	72	90	73	44		180	190*	110	88	26		140	32	90	130	29	
	PN7 (270)						PN8 (260)						PN9 (360)						PN10 (390)					
Leaf	610	83	280	590	210	190	560	120	380	620	250	300	470	60	440	490	180	260	600	100	400	740	390	230
Twig	130	25	85	100	65		140	72	160	150	69		160	30	130	160	73		130	69	110	130	84*	
Bark	100	71	77	56	28		110	76	80	72	19		130	47	66	56	31		71	79	76	150*	28	

* Highest value per part per species

1. Brachystegia longifolia 2. Julbernardia paniculata 3. Brachystegia spiciformis 4. Diplorhynchus condylocarpon

5. Pseudolachnostylis sp. 6. Landolphia kirki

Table 87. Zn content of vegetation (ppm, dry weight) on transect PN, Lower Kamwedgi

SPECIES	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
			PN-6	(soil silt 15)					PN-5			(13)			PN-4			(14)			PN-3			
Leaf	25	22*	24*	25	10	28*	22	21	20	22	13	20	30*	18	17	21	11	14	24	13	21	28*	13*	18
Twig	6	29	17	32	12*		9	22	32	27	7		17*	13	16	8	8		14	12	17	47*	7	
Bark	6	4	5	34	6*		5	4	5	44*	5		6	5	7*	42	3		4	8*	3	26	3	
			PN2			(20)			PN3			(16)			PN4			(22)			PN5			(20)
Leaf	19	21	13	19	10	12	22	11	16	15	12	15	23	14	20	14	10	9	-	17	13	11	10	13
Twig	14	60*	10	9	6		12	14	12	19	3		7	46	37*	8	8		11	7	14	9	9	
Bark	3	4	4	10	4		5	2	3	12	3		3	4	6	13	4		3	3	2	9	4	
			PN7			(20)			PN8			(20)			PN9			(17)			PN10			(18)
Leaf	16	15	14	18	9	16	20	14					23						17					
Twig	8	24	8	19	5		10	11					9						14					
Bark	3	6	2	44*	2		9*	2					3						2					

*Highest values per part per species

1. Brachystegia longifolia 2. Julbernardia paniculata 3. Brachystegia spiciformis 4. Diplorhynchus condylocarpon
5. Pseudolachnostylis sp. 6. Landolphia kirki