THE GEOMORPHOLOGY AND SURFICIAL GEOLOGY OF THE KOIDU AREA, SIERRA LEONE

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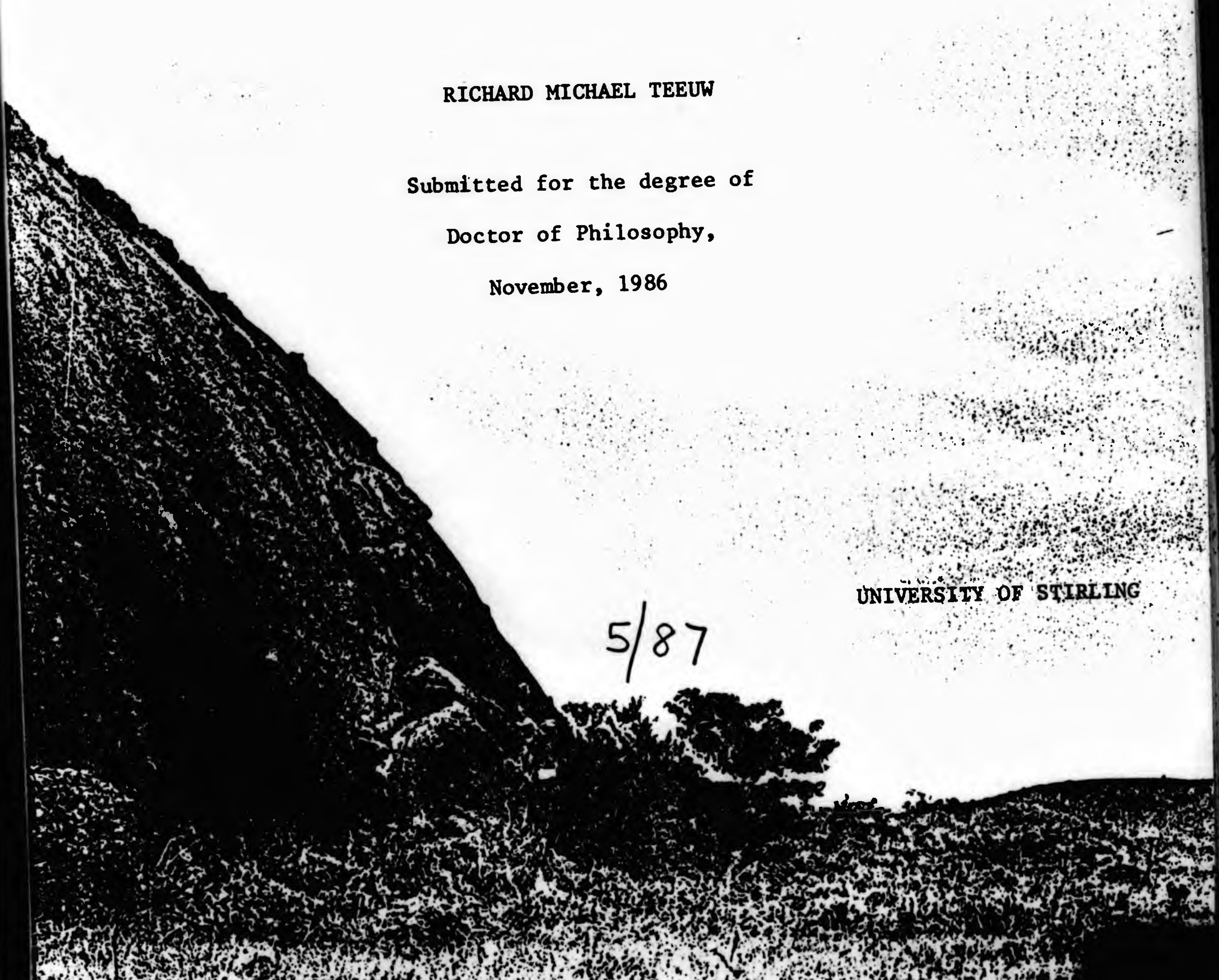

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ABSTRACT

The objectives of this study were to produce a landscape development model for a 400 km^2 granitoid basin in the West African forest/savanna zone, and to test whether variations in landsurface morphology can be related to surficial geology. Each Unit Landform identified by morphological mapping was found to have a characteristic Morphofacies Type on the basis of slope angle, depth to topgravel, presence of unconformities or palaeosols and depth to saprolite. Textural and micromorphological analyses confirmed the distinctiveness of each Morphofacies Type. Variations in 'stoneline' petrography provided insights into contemporary morphodynamics. Three Process Domains (Residual, Colluvial and Fluvial) apparently interact across the landscape to produce a unique set of stratigraphic and material indicators for each Morphofacies Type. The presence of relict indicators, such as fluvially-rounded pebbles in the residual interfluve gravels, points to extensive landscape modification.

Of the detailed study areas, Kania is classified as a 'Saprolite-mantled Etchplain' with extensive near-planate interfluves; whereas Yengema is a 'Partially-stripped Etchplain' with numerous rock outcrops and residual hills. This is partly explained by lithological differences, but the main cause appears to be drainage modification. Yengema's drainage was apparently captured by a regional trunk river during the early Quaternary, resulting in drainage reversal, fluvial incision and soil/saprolite stripping. Consequent extensive bedrock exhumation has made Yengema more sensitive to environmental instabilities than Kania (which escaped similar drainage disruption). Supportive evidence comes from the infilled Late-Quaternary valleyhead extensions and relatively deep profiles at Kania, versus the rocky valleyheads and shallow profiles characteristic of Yengema. 3000 years of farming and deforestation have caused soil/saprolite stripping, with 1-2m of colluvium filling valley swamps.

ACKNOWLEDGMENTS

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On the Sierra Leonean side, thanks must go to the directors of NDMC and to Mr. Keith Mantell, the General Manager at Yengema, for giving me permission to work on the Yengema lease and as much assistance as possible. The support of the Sierra Leone Geological Survey and the Ministry of Agriculture and Natural Resources in providing access to maps, reports and airphotos is also much appreciated. In the field, Chris Clements and Malcolm Bannister taught me a lot about both the geology of the Koidu area and methods of mineral exploration. Of the Prospecting Dept. staff Alieu Mahdi, George Dunbar, John Bangura and "M.G." Kamara were particularly helpful.

Back in Scotland, the thin sections were prepared and analysed under the direction of Dr. E.A. Fitzpatrick of the Soil Science Dept., Aberdeen University; whilst the Image Analyser was made available by Professor Adrian Curtis of Glasgow University, Cell Biology Dept. Many thanks go to the staff and fellow students of Stirling University who have assisted me, particularly Mrs.Mary Smith for help and advice over diagrams, and Mrs. Ina Mack for ably typing this thesis. Finally, I am indebted to both the University of Stirling and, particularly, the Natural Environment Research Council for providing the "onshore" funds for this project.

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CHAPTER ONE

INTRODUCTION

This thesis concerns the geomorphology and surficial geology of a small area (400 km^2) in eastern Sierra Leone, centred on the town of Koidu, a centre for alluvial diamond mining since the 1930's. Two detailed study areas of 1-5 km^2 each with markedly different terrain types, were intensively mapped and sampled in an attempt to explain the geomorphological evolution of this area, as well as to test whether land form can be related to surficial geology.

Sierra Leone is situated on the north-western coast of Africa, between longitudes 14 to 10° West and latitudes 7 to 10° North with a monsoonal climate dominating the coastal plains and a progressively drier savanna climate near the Guinea border (Figure 1.1). Koidu lies in the forest/savanna transition zone and has probably experienced numerous bioclimatic fluctuations since the Tertiary era, ranging from perhumid rainforest to semi-arid vegetation. The geology of the Koidu area consists of relatively homogeneous Archaean "Basement Complex" granitic gneisses, with a few thin strips of supercrustal rocks less than 1 km wide. The area is highly faulted, with numerous kimberlite dykes and occasional dolerite dykes, all of which exert a strong control over local drainage patterns.

Aims, concepts, and organisation of thesis

The aims of this study were threefold:

Firstly, to map and describe the land forms and surficial materials of the study sites, using a geomorphological, rather than a geological or pedological rationale.

Secondly, to test for relationships between land form and surficial materials.

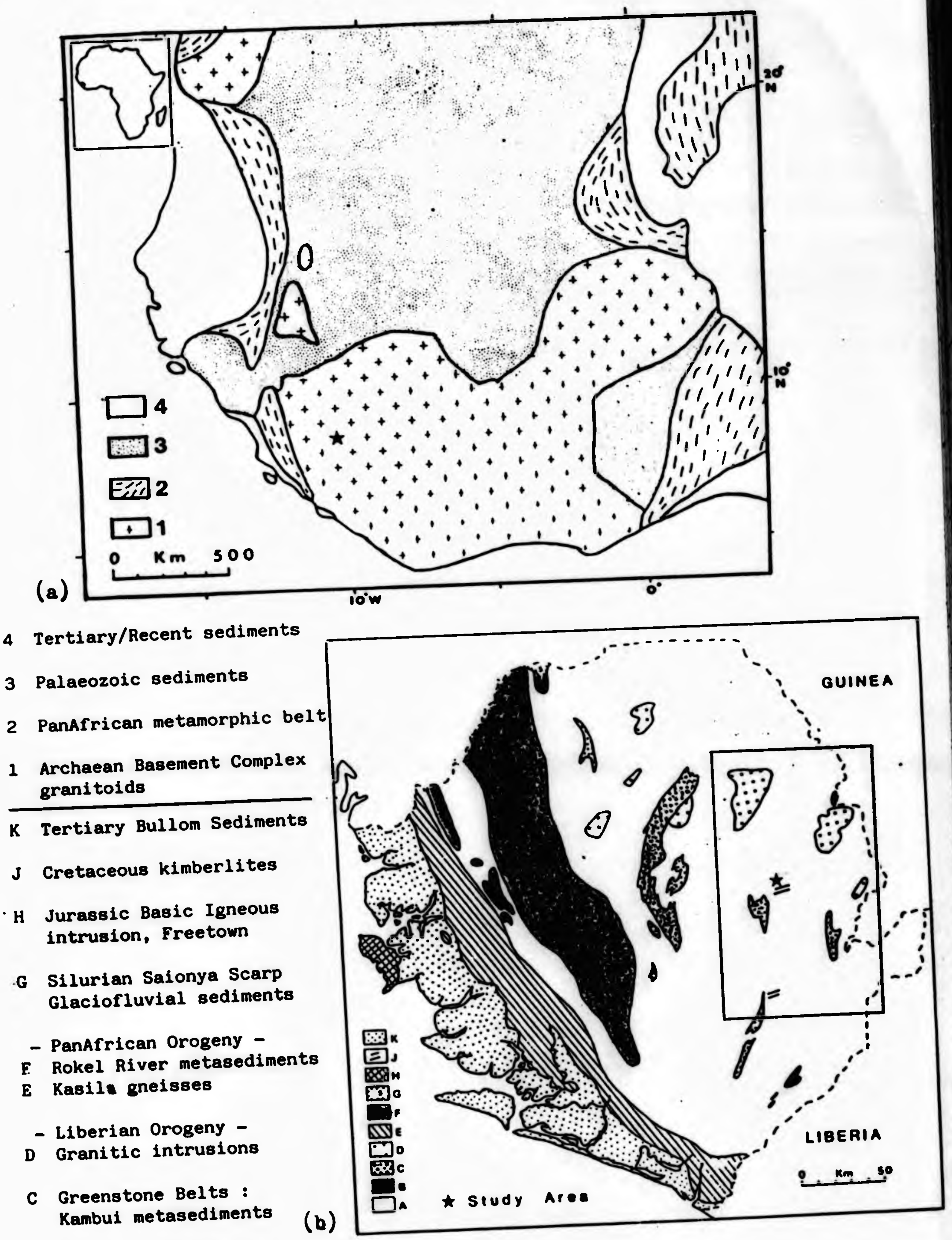
Thirdly, to provide a model of landscape development for the Koidu region.

The use of a sampling system based on traverses from interfluve crests to valley floors allows variations in land form and surficial materials to be studied (i) along toposequences; (ii) downwards to the regolith/rock interface; and (iii) in plan form by considering results from all the traverses at each study area.

Data from this sampling scheme were analysed to determine how texture and micromorphology varied between landform units. Variations in surficial materials were then related to inferred formative processes, be they past or present.

The remainder of this introductory chapter concentrates on the regional setting of the study area with regard to its climate, vegetation, soils, geology, and geomorphology. The second chapter is a review of literature concerning the relationships between (a) land form and materials and (b) the processes operating on both land forms and materials. Chapter three presents the research strategy and methods used in this study. Results are presented in chapters four and five: Chapter four dealing with the geomorphology of the Koidu region, particularly the Kania and Yengema study areas; and chapter five concentrating on the surficial geology of the Kania and Yengema study areas. In chapter six these results and those of comparable studies are discussed and a model of landscape development is proposed for the Koidu region.

A glossary of terms used in the text is given in the Map Pocket at the back of this thesis.



4 Tertiary/Recent sediments

3 Palaeozoic sediments

2 PanAfrican metamorphic belt

1 Archaean Basement Complex granitoids

K Tertiary Bullom Sediments

J Cretaceous kimberlites

H Jurassic Basic Igneous intrusion, Freetown

G Silurian Saionya Scarp Glaciofluvial sediments

– PanAfrican Orogeny –

F Rokel River metasediments

E Kasila gneisses

– Liberian Orogeny –

D Granitic intrusions

C Greenstone Belts : Kambui metasediments

B Archaean granulites

A Basement Complex : migmatitic gneisses

Inset : area covered by Figure 1.2

Figure 1.1 (a) The West African geological setting (b) The major lithological units of Sierra Leone.

1.1 GEOLOGY

A full understanding of the varied geology of Sierra Leone can only be gained by viewing its rock types and structures from a large-scale perspective both in terms of global geological events and in terms of time, as some of the "Basement Complex" rocks in the study region are over 3000 million years old (Beckinsale et. al., 1981, p.89).

There is strong geological evidence (summarised in Windley, 1977) that the West African continental shelf was formerly joined to that of the Guyanas and Brazil, forming a section of the "Gondwanaland" supercontinent. The formation of Gondwanaland during the Precambrian, its break-up during the Mesozoic, and contemporaneous geological units now in West Africa and northern South America can be explained in terms of global plate tectonics.

Research by Burke and Dewey (1973, p.1041) indicates that between 850 and 400 million years ago three continental plates collided with the West African craton, causing the "Pan-African" orogenic events: Sierra Leone apparently lay on the west side of a triple junction between the Guyanan plate and the North American plate. Between 230 and 180 million years ago these Gondwanaland sutures were arched to form a series of domes. This doming caused crustal tension, leading to triple-junction fracturing, doleritic dyke swarms, rift valley formation, and finally sea-floor spreading to form the Atlantic Ocean (Wilson, 1965; Le Bas, 1971).

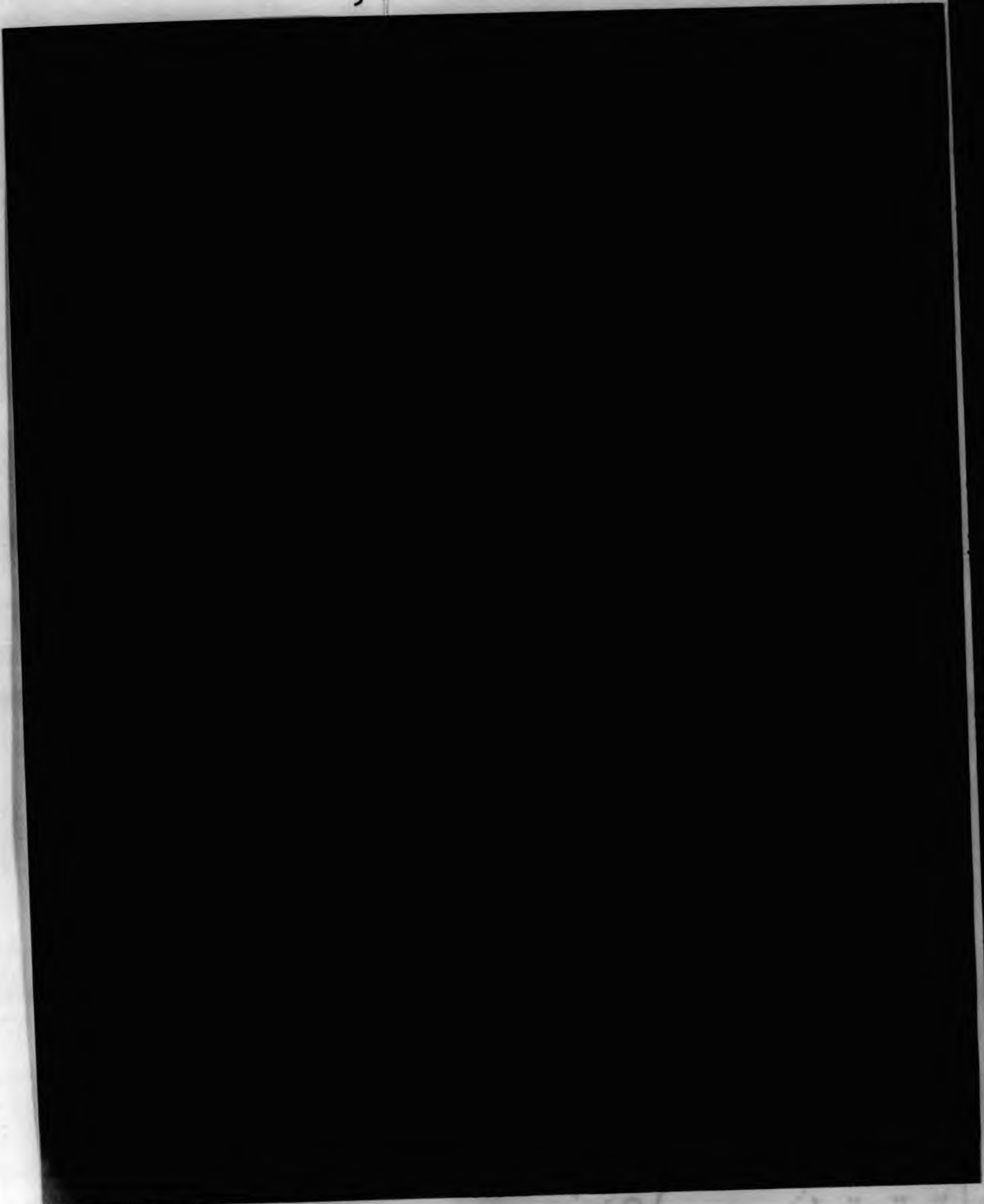
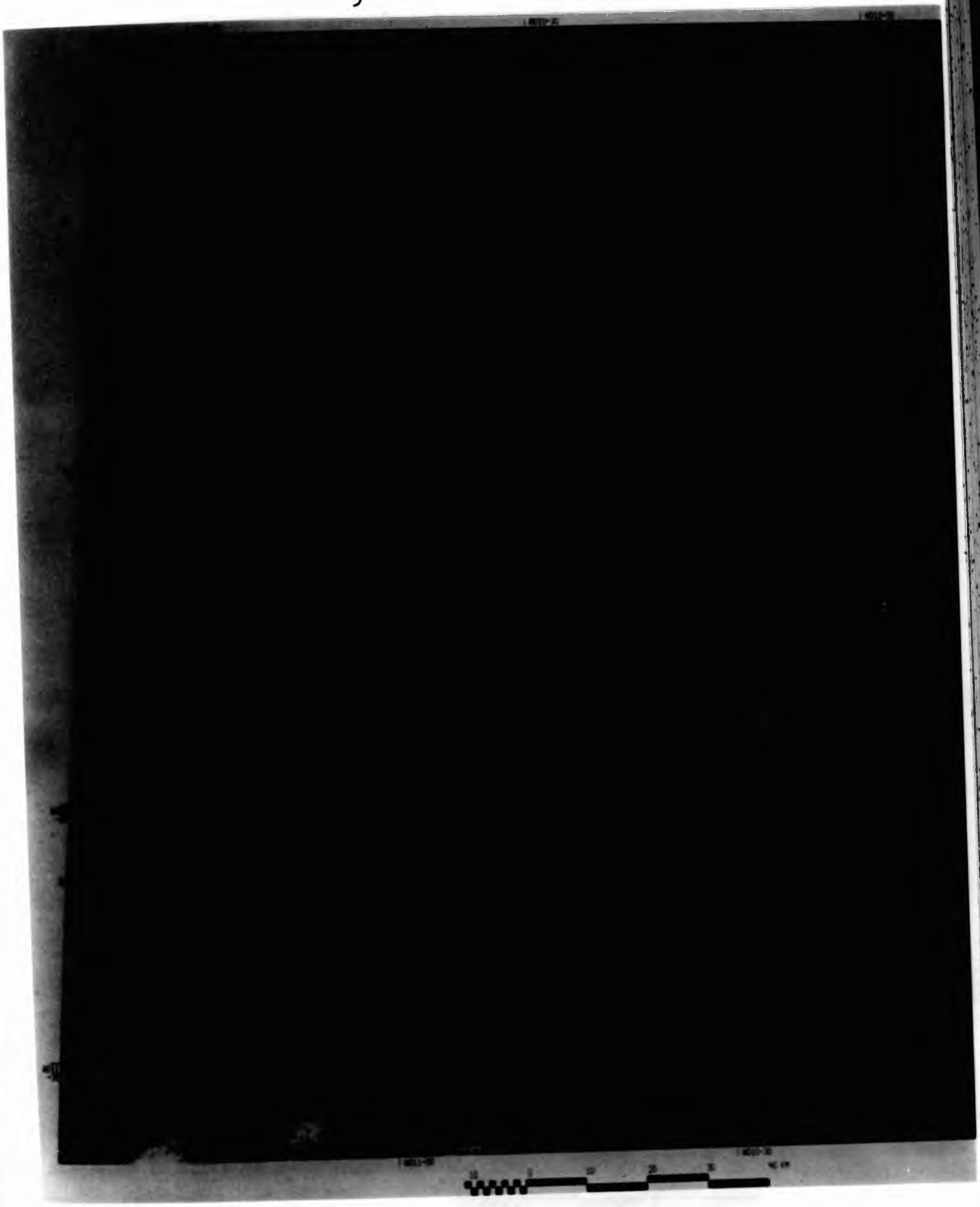


Plate 1.1 LANDSAT image of eastern Sierra Leone and southern Guinea. A false-colour, near-infra red image (MSS Bands 4, 5 and 7); 6th January, 1974. Forest=red, grassland and shrubs=blue/olive grey. The Koidu area is highlighted by the tracts of alluvial mining (white), centre-left of the image.



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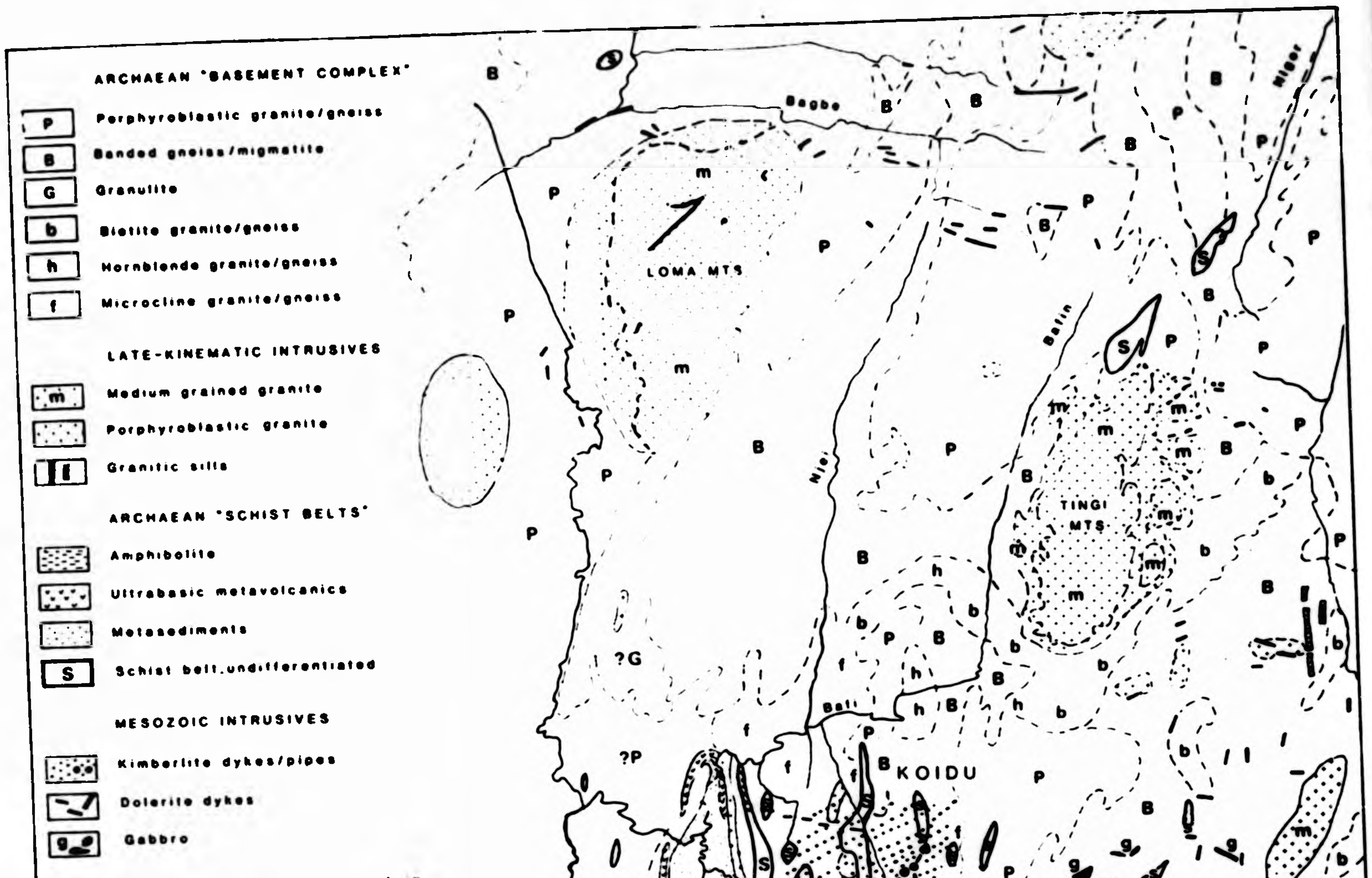


Figure 1.2 EASTERN SIERRA LEONE : LITHOLOGICAL UNITS

The geology of the study area is shown in its West African and Sierra Leonean context in Figure 1.1 and the geological history is summarised in Table 1.2. The rest of this section will concentrate on the geology of eastern Sierra Leone, particularly the Koidu area, as shown in Figure 1.2 and Plate 1.1.

The Basement Complex

The Archaen granitic and migmatitic gneisses which form the Basement Complex are the basis of the West African craton and underlie most of eastern Sierra Leone. The Basement Complex was formed during at least two orogenies, the Liberian (2700-2750 Ma) and the Leonean (2750-2950 Ma), with a few dates indicating Pre-Leonean orogenic activity between 3100 and 3600 Ma (Beckinsale et al., 1981, p.89).

The rocks of the Basement Complex consist of granitoids with fabrics ranging from granitic to migmatitic; textures ranging from medium-grained to porphyroblastic, and compositions ranging from granitic to granodioritic. Garret and Nichol (1967, p.19) stated that the properties of the Basement Complex appear to be "essentially homogeneous" within 160 km^2 of the Nimini Hills (Figure 1. 2). However, mining operations near Koidu have revealed large amounts of amphibolitic gneiss occurring as frequent small inclusions and strips (often less than 1m wide) within the Basement Complex, indicating parts of it may have a highly heterogeneous nature when examined in detail (M.B. Thorp, pers.comm., 1985).

Granitization during the Leonean orogeny produced granodioritic, biotite-rich rocks foliated with an E-W trend. Beckinsale et al. (1981, p.93) dated a gneiss from Kenema, 100 Km south of Koidu, at 2980±80 Ma. However, any Leonean foliations in the Koidu area appear to have been totally deformed during the Liberian orogeny, as no E-W foliations have been recorded in that region (re. Table 1.1).

Table 1.1: **Basement Complex foliations in the Koidu area**

Lineation Direction	% of observations	Sources (n = 150)	n
E-W	0	S.L.G.S. (1:250000 Provisional Map)	113
N-S	86	N.D.M.C. (Gregory, 1971)	15
NW-SE/WNW-ESE	14	This study	22

The dominant foliation in the Koidu area is the general N-S trend of the Liberian orogeny. Radiometric dating of gneisses has given the Liberian orogeny a range of 2750 to 2700 Ma (MacFarlane et al., 1981, p.41). Late-Liberian dislocations and metasomatism produced granitic gneisses with orthoclase/microline porphyroblasts: this is the dominant rock type of the Koidu area.

Liberian age late-kinematic activity also produced the granitic plutons of the Loma, Tingi, Kongotan, Kabala and Gbengbe "inselberg massifs" (Figure 1.6). These plutons have dominantly coarse-grained cores with alkali-feldspar porphyroblasts, and migmatitic margins (MacFarlane et al., 1981, p.14-15). Late-kinematic pegmatites were intruded in the Koidu area, with a quartz-specularite pegmatite occurring in the Kania study site; with epidotic pegmatites at Yengema; and with a tin-bearing pegmatite on the northern rim of the Nimini Hills (Garrett & Nichol, 1967, p.102).

Precambrian supracrustal rocks

The oldest mappable units of supracrustal rocks in the Koidu area occur as small roof-pendants, often less than 1 km wide, with a low relief which is virtually indistinguishable from that of the Basement Complex. These supracrustals consist of talc-actinolites with amphibolitic margins, and quartzite/banded iron formations (Gregory, 1971). They probably correlate with the early Archaean Loko Group of MacFarlane et.al., (1981, p.17).

Larger strips of late Archaean Kambui schists form steep-sided ridges, such as the Dowadu Hills between Koidu and Yengema. The largest supracrustal belts in the region are the Nimini and Gori Hills. These two schist belts have lithologies and structures similar to many other greenstone belts: rims of psammitic and pelitic metasediments with metavolcanic (amphibolitic) cores (viz. Figure 1.2). Late-Liberian kinematic activity led to partial melting and mineralisation in the Nimini, Gori, and Kambui hills. Garrett and Nichol (1967, p.99-102) recorded anomalously high concentrations of Ca, Cr, Mn, Ni, Sn, Ti, V and Zn from these areas relative to the Basement Complex.

The Rokelide Event (850-550 Ma)

After the Liberian orogeny, no significant thermotectonic events affected Sierra Leone until the Rokelide Event, some 2000 million years later (Hurley et. al., 1971 p.3484). Rokelide deformations produced NW-SE and WNW-ESE lineaments, accounting for 14% of the foliations measured in the Koidu area (Table 1.1). Late Rokelide deformations have been dated at ca.550 Ma by MacFarlane et.al., (1981, p.41). During these deformations the Kasila granitoids were partially remelted to form the present Kasila gneisses (Hurley et.al., 1971, p.3485 and viz. Figure 1.1b).

Palaeozoic cover rocks

The only cover rocks of probable Palaeozoic age in Sierra Leone are the volcaniclastic glaciofluvial rocks of the Saionya Scarp (Figure 1.1b). These are thought to lie uncomformably over the Rokel River Group and be lateral equivalents of the Gres Silicieux Horizontaux of Guinea, which are conformably overlain by Silurian graptolitic shales (Reid and Tucker, 1972,).

MacFarlane et al., (1981, p.8) consider the Saionya Scarp sequence to be an upfaulted continuation of the Precambrian Rokel River Series, as they could find no evidence of an unconformity during fieldwork. However, evidence of an extensive cover of lower Palaeozoic cover rocks over much of northern Sierra Leone has recently been found in the Koidu area. A set of pelitic and psammitic sediments occur as xenoliths in the Koidu No. 1 Kimberlitic pipe. An organic-rich mudstone xenolith gave an Ordovician to Devonian age range - probably lower Silurian (Wenlock) - from micropalaeontological analyses (Hubbard, 1983, P.67-69). It now appears likely that the Saionya Scarp sequence is all that remains of sediments that extended from the Bove/Conakry Basin of Guinea to the Koidu region (Figure 1.1), during the late stages of the Saharan Glaciation. The basal tillite and dominantly glaciofluvial nature of the Saionya Scarp sediments supports this hypothesis (Culver et al. 1978, p.49).

Mesozoic Igneous Activity

During early Mesozoic times Sierra Leone again experienced deformations, block-faulting and igneous activity with the Karoo thermotectonic event and the break-up of Gondwanaland. During this period two sets of tholeiitic dolerite dykes were intruded (viz. Figure 1.2):

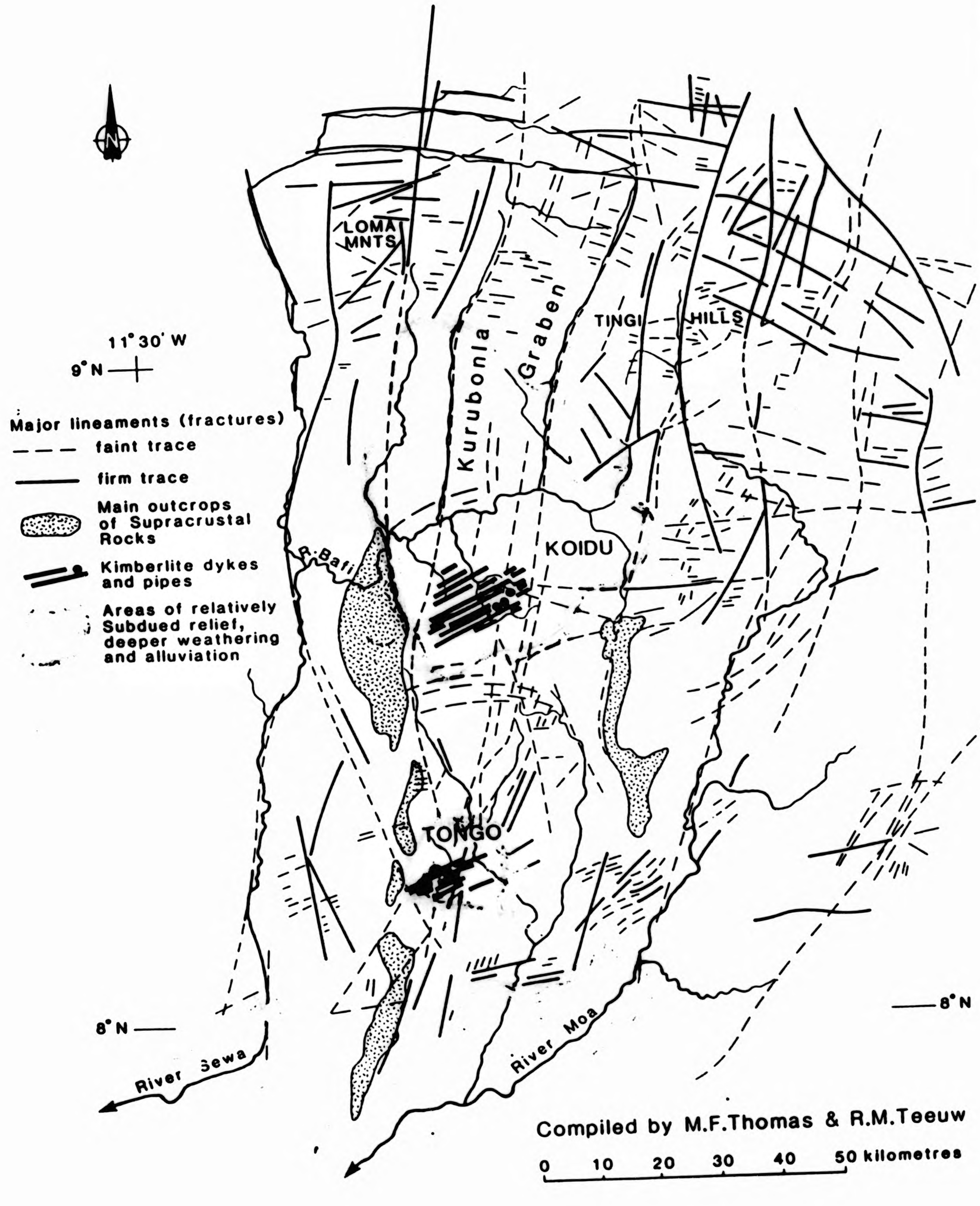


Figure 1.3 Eastern Sierra Leone : major lineaments.

(i) N-S to NE-SW trends (355° to 050°): as in the Koidu area

(ii) E-W to NW-SE trends (090° to 130°): as in the Tongo area.

Various radiometric dates have been determined for these dykes, ranging from 235±10 Ma (Beckinsale et.al., 1981, p.90) to 169±10 Ma (Morel, 1979, p.1571). These dates coincide with the dates for the intrusion of the Freetown layered basic igneous complex, ranging from 193±3Ma (Beckinsale et. al., op.cit.) to ca. 180 Ma (Windley, 1977, p.213). Kimberlite dykes and stringers cut and therefore postdate both sets of dolerite dykes (Figure 1.2). The kimberlitic dykes of the Koidu area have an EWE (065° to 075°) trend and have formed three small kimberlitic pipes with areas of between 0.2 ha and 0.45 ha, where fractures trending 007° intersect them. Radiometric ages for these kimberlites range from 145±5 Ma for one of the Tongo dykes near Panguma, 55 km south of Koidu (Beckinsale et.al., 1981, p.91), to ca.92 Ma for Koidu No. 1 pipe (Bardet & Vachette, 1966; cited by King 1972, p.9). Amongst the xenoliths described by Hubbard from the Koidu No. 1 kimberlitic pipe are amygdoloidal basaltic lavas, indicating lava flows in the Koidu area during the Cretaceous period (Hubbard, 1983, p.69).

Mesozoic Faulting and Structures

The Koidu region is dominated by two sets of regional faults (Figure 1.3). The Oyie-Shongbo and Njei fault zones trend NNE-SSW (010°); whilst the Meya-Moinde fault zone trends NNW-SSE (340°). The Kurubonla "Graben", lying between the upfaulted Loma and Tingi Mountains, may well extend southwards, the downfaulting explaining the preservation of the Koidu and Tongo kimberlitic dyke swarms (viz. Figure 1.3; also MacFarlane et.al., 1981, p.8). At a more detailed level, around Koidu and Yengema, five main fault trends occur:

(1) Meya-Moinde trend: 340^{o}

(2) Oyie-Shongbo trend: 010^{o}

(3) Gaiya trend: 315^{o}

(4) Liberian trend: 355^{o}-005^{o}

(5) Kimberlitic trend: 065^{o}-075^{o}

Interpretation of Landsat-2 and SLAR images has revealed a more extensive system of annular fault patterns than was previously reported (MacFarlane et.al., 1981, p.8), indicating phases of local updoming with a progressive shift northwards from a dome centred about Tongo/Panguma, to a larger dome centred near Koidu. Crustal updoming is known to be associated with alkali igneous activity and may well explain the occurrence of kimberlites (Le Bas, 1980). The relative radiometric ages of kimberlites from Tongo (145 ± 5 Ma) and 55 Km to the North at Koidu (ca. 92 Ma) indicate the presence of a lithospheric "hotspot" over which this section of the African continental plate drifted (at a rate of ca. 1cm/year), producing the Tongo, and later the Koidu, kimberlites during two periods of relative continental "standstill". A shift in the direction of continental drift to a westward direction would explain the occurrence of kimberlities 80 Km to the east of Koidu in Upper Guinea, which appear to be younger than the more deeply eroded Koidu kimberlites (Sutherland, 1984, p.99, and Vink et al, 1985).

Cainozoic to Recent Sediments

Substantial coastal downwarping during the Tertiary led to the deposition of a succession of marine and estuarine sediments, the Bullom Series (viz. Figure 1.1b), dipping gently seawards and probably reaching a thickness of "several thousand metres" offshore (Sheridan et al,1974, p.2515).

The base of this series has been dated at Eocene from fossil fish and shells (Sierra Leone Geological Survey, 1955, p.3). Lignites from a cyclothem sequence near the top of this series have given C14 ages of between 30250+690y and 34840±1200y (Strasser-King, 1979, p.337). The Bullom Series is still forming, with the silting-up of mangrove swamps and the deposition of sand bars along over 100 Km of the coast. A summary of Cainozoic events and deposits is given in Table 1.2.

M. Yr. B.P.	GUYANAS[1]	Sea[2] level	SIERRA LEONE	SENE-GAMBIA[3]
		+/- -	Cut-and-fill episodes	
0.01	Cut-and-fill episodes			
0.10		+/-	Poorly lateritized "Bullom surface" and Koidu glacis.	Lower Glacis } pedi-sediments
0.50		-	Lateritized glacis	Middle Upper-Glacis
1	"Mazaruni surface"		Freetown and Kasewe Hills.	
2	* * EROSION * *	-	* * EROSION * *	* * EROSION * *
4	"Rupunini Surface" DEEP WEATHERING	+	"Interior Lowland Surface" DEEP WEATHERING	DEEP WEATHERING ATLAS MTS OROGENY[5]
6	EROSION * Detrital Sands	-	* * EROSION * *	
8	"LTII Surface" Sedimentary hiatus	+ -	Detrital Bullom sediments * * EROSION * *	Detrital sediments
10	DEEP WEATHERING EROSION * Detrital sands	+		DAKAR VOLCANISM[5]*
20	BASALTIC VOLCANISM[4]	-	* * EROSION * *	
30	EPIEROGENY * *		"Intermediate surfaces"	"Intermediate surfaces"
	"LTI" or "Kaiteur" surface	+	DEEP WEATHERING	Marine sediments DEEP WEATHERING
40	DEEP WEATHERING	-	EROSION * Detrital sediments Tonkolili Ironstone[10]	"Continental Terminal" sediments ARIDITY* EROSION* Bichemical sediments
	ALKALI IGNEOUS	++	DEEP WEATHERING	
60	INTRUSIONS (Brazil)[4]		Bullom fluviomarine sediments[9]	DEEP WEATHERING
70	EPIEROGENY **	- +	* * EROSION * *	EPIEROGENY*
80	"Kopinang surface"	-	"Main Plateau Surface"	"Fantofa Surface" Biochemical sediments
90	DEEP WEATHERING	+	DEEP WEATHERING	DEEP WEATHERING
100		-	KOIDU KIMBERLITES[8] & BASALTS	* EPIEROGENY *
	Detrital sediments			"Dongol Sigon Surface"
110		+	"Nimini surface"	
	*BASALTIC		DEEP WEATHERING	DEEP WEATHERING
120	VOLCANISM[6]*			
130	*DOLERITE		Liberian Coast Conglomerates[5] *EPIEROGENY*	* * EROSION * * * EPIEROGENY *
140	DYKE		TONGO KIMBERLITES[7]	Biochemical sediments
150	SWARMS[6]*			
160	"Kanuku surface"		"Loma Surface"	"Labe surface"
170	DEEP WEATHERING		DEEP WEATHERING	DEEP WEATHERING
180	DOLERITE DYKES*		DOLERITE DYKE SWARMS[7]	* * EROSION * *
190	OPENING OF CENTRAL ATLANTIC OCEAN			* * * * *
200	* * * * * *		FREETOWN IGNEOUS COMPLEX[7]	
250	EPIEROGENY AND BREAK-UP OF GONDWANALAND[567]*			
	Detrital Sediments[6]		"Palaeozoic Surface"	"Palaeozoic Surface"
300	TAKUTU RIFT VALLEY			
400	Marine Sediments (Amazon)[4]		Saionya Scarp Sediments[5]	Bove Basin Sediments[5]
500	* * EROSION * * * * * * * *		GLACIATION * EROSION * * * * * *	GLACIATION * EROSION * * * * * *
600				
	BRAZILIANA OROGENY[6]		ROKELIDE OROGENY[5]	MAURITANIDE OROGENY[5]
900				

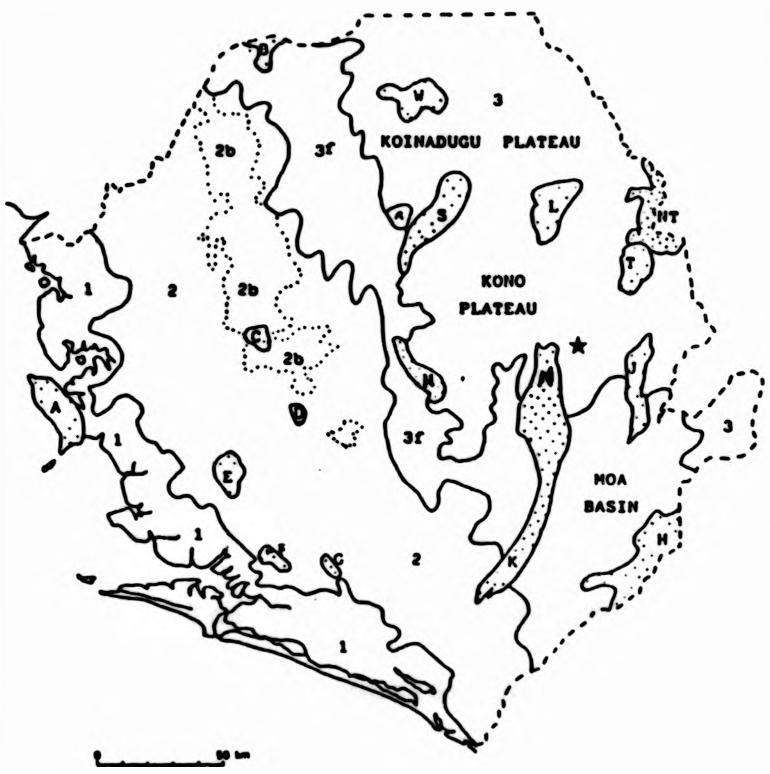
1. Refers to Guyana, Surinam, French Guyana, N.W. Brazil & E. Venezuela; based on Pollack, 1981, p.284, unless otherwise stated.
2. Estimate of marine transgressions (+) and regressions (-) for West Africa based on Douglas et.al.1973,p.525; and source No. 5.
3. Based on Michel 1973, p.24-25.
4. Blancaneaux, 1981, p.41.
5. Dillon & Sougy 1974.
6. McConnel 1975, p.322.
7. Beckinsale et.al., 1980.p.84-85.
8. Bardet & Vachette, 1966.
9. S.L. Geol.Surv.An. Rpt. 1955, p.3.
10. Gaskin (1975), cited in 11.
11. Thomas, 1980, 340-341.

Table 1.2 Comparative geological histories of Sierra Leone, Senegambia and the Guyanas.

Figure 1.4 Physiography and relief of Sierra Leone

Sierra Leone -

Physiographic regions



1 Coastal swamp and beach bar region

2 Interior lowland region 2a Bolilands (swampy grasslands)

3 Plateau and hill region 3f Foothill zone

Residual hills and mountains :-

A Freetown Peninsular : Basic igneous Complex

B Saionya Scarp : Sub-horizontal Silurian sandstones

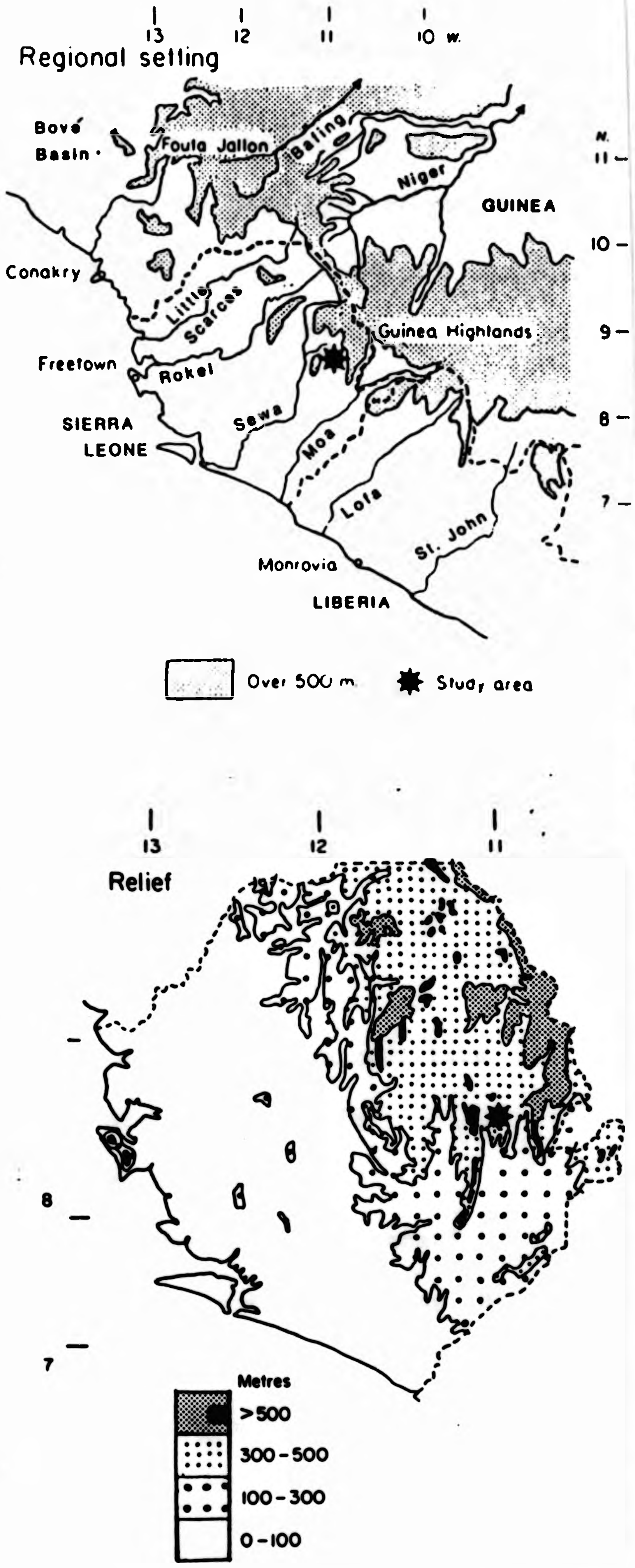
C Malal Hills } Rokel River metavolcanics
D Kasewe Hills }

E Moyamba Hills }
F Imperi Hills } Kasila gneisses
G Gbange Hills }

H Kangari Hills }
J Gori Hills }
k kambui hills } Schist Belts
N Nimini Hills }
S Sula mountains }

★ Study area

L Loma mountains }
NT Tingi-Niger Plateau }
T Tingi mountains } Intrusive granites
W Wara Wara mountains }



1.2 GEOMORPHOLOGY

From Figure 1.4 it can be seen that one of the main physiographic features of West Africa is the crustal dome of the Guinea Highlands. This highland belt stretches for almost 1000 km from the Ivory Coast and Liberia, reaching 1549m at Mount Nimba; through the Sierra Leone/Guinea highlands, where it peaks at 1945m in the Loma Mountains; to the Futa Djallon massif of Guinea and Mali, where it reaches 1537m.

Since the opening of the central Atlantic Ocean, about 180 million years ago, the Guinea Highlands have been a zone of crustal uplift. The uplift of the "Guinea Dome" or "Leo Uplift" has been complemented by subsidence along the coast of West Africa, producing the extensive coastal plains fronting the Ivory Coast, Sierra Leone and Sene-Gambia, and more recently the drowned estuaries and sand bars of Guinea Bissau, Sierra Leone and the Ivory Coast.

Drainage

Any analysis of the drainage patterns of West Africa must take into account the probable relief configuration of the Palaeozoic Gondwanaland super-continent. During late Palaeozoic times the "Proto-Atlantic Dome" would have formed along the West Africa/Guyanas suture of Gondwanaland, so that the landsurface of West Africa during the Palaeozoic would probably have sloped northwards and eastwards into the Niger Basin. This "Gondwana" drainage pattern must have been greatly distorted by the collapse of the "Proto-Atlantic Dome" and the rise of the Guinea Dome during Mesozoic times, but probable remnants of it are preserved on the Niger Basin and Atlantic sides of the Guinea Dome, such as the NE-SW trends of the Little Scarcies River in Northern Sierra Leone and the Niger River on the Guinea/Mali border (viz. Figure 1.4). Similar "ancient" river trends have been reported from trailing edge continental margins by Potter (1978).

Following the opening of the Atlantic,the "Gondwana" drainage pattern was modified in two main zones. The first zone of drainage modification occurred in the upper reaches of the rivers around the Guinea Dome. This produced radial drainage off the Futa Djallon and Sierra Leone/Guinea Highlands. Any "Gondwana" drainage lines which coincided with the new Guinea Dome drainage trends were enhanced. An example is the SSW-trending Moa Basin of Sierra Leone and the NE-trending entrenched tributary of the Niger at Kissidougou in Guinea (10°10'W, 9°10'N). A further modification was the production of peripheral drainage lines around the margins of the zones of uplift, such as the N-S trend of the Tinkasso River along the eastern flank of the Futa Djallon.

The second zone of modification occurred in the lower reaches of the rivers presently draining southwards and westwards into the Atlantic, due to both coastal subsidence and the effects of eustatic sea level changes. Two episodes of coastal subsidence appear to have affected the drainage of Sierra Leone. The first period of subsidence was apparently about a N-S axis, favouring the headward extension of westerly-draining rivers, which eventually captured much of the more northerly-trending "Gondwana" drainage system (viz. the middle sections of the Sewa and Rokel rivers in Figure 1.4). This period of river capture probably occurred after the collapse of the "Proto-Atlantic Dome". More recently, coastal subsidence has shifted to a NW-SE axis, probably in response to the loading of the local continental margin with the post-Mesozoic Bullom Series sediments. A distinct drainage system has developed within 50 Km of the coast in which most rivers drain perpendicular to the coast: within this belt there are 15 distinct drainage systems, whereas 100 Km from the coast there are only 8 distinct systems. Post-glacial rises in sea level, coupled with continued coastal subsidence, have produced the present dominantly drowned coastline.

Physiography

The relief and physiography of Sierra Leone are shown in Figure 1.4. Much of Sierra Leone, including the study area, consists of plateaux or near-planate surfaces, prompting Hall (1974, p.28-31) and MacFarlane et al (1981, p.6-8) to propose similar frameworks of "planation surfaces". summarised below:

1. The Bullom Surface, from 0 to 15m ASL
2. The Coastal Plain Surface, from 30 to 200m corresponding to the Interior Lowland Zone of Figure 1.4.
3. Intermediate surfaces between the Coastal Plain Surface and the Main Plateau Surface.
   (a) The Tongo Surface, at ca.230m
   (b) The 300m surface fringing the Main Plateau escarpment.
   (c) The Koidu surface at ca. 380m
4. The Main Plateau Surface, sloping gently southwestwards from the Koinadugu Plateau (500 to 450m) to the more dissected Kono Plateau (450 to 400m).

5. The Nimini Surface. between 650 and 720m.
6. The Sula Surface. between 500 and 600m.
7. The Loma Surface over 800m; at 1800m and 1200m in the Loma and Tingi Mountains respectively, due to local up-faulting.

Whilst there is little doubt that extensive near-planate surfaces do occur in Sierra Leone, the general framework proposed by MacFarlane et.al.(1981) after Hall (1974) has some major flaws. Although both sets of authors made comparisons between surfaces and offshore sediments described from other sections of the West African craton, the well-documented and relatively well-dated surfaces and offshore sediments of the Guyanan craton were not considered. A comparison is necessary, given the juxtaposition of the Guyanan and West African cratons prior to the opening of the Atlantic Ocean, Table 1.2 is an attempt to correlate available data on this topic.

With regard to the Guyanan craton, the premise that geomorphic surfaces of similar altitude have formed over similar lengths of time - and vice versa - has been disproved by Krook (1979) and Pollack (1981a, 1981b; 1985, pers.comm.). Pollack used coastal sediment data in conjunction with major element analyses of bauxites from three geomorphic surfaces in Surinam (at ca. 100m, 450-500m and 600-700m A.S.L.). He showed that these three "major surfaces" were actually only sections of a single early Tertiary surface, downwarped at the coast. A similar mechanism may explain the numerous "surfaces" below the Main Plateau of Sierra Leone. (Thomas et al., 1985b; viz. Appendix A). It appears that Sierra Leone has experienced polygenetic landform development, with planate surfaces being formed by both marine planation and sub-aerial erosion, but with deep chemical weathering followed by stripping of soil/regolith material - 'etchplanation' as outlined by Thomas (1974) - probably being the most dominant form of denudation. Regional comparisons of relief and lithology in Suriname by Kroonenberg and Melitz (1983) have indicated that etchplanation is also the dominant form of denudation in the Guyanas.

The marked contrast between the generally subdued relief of the Coastal/Interior Lowlands and the stronger relief of the Plateau and Mountain Zone probably reflects the continued uplift of the latter as a section of the Guinea Dome. Within this zone, positive and negative relief features are strongly related to variations in bedrock geology:

Positive relief - granitic plutons (Loma/Tingi Mts.)
- massive amphibolites (Nimini/Gori Hills)

Negative relief - mylonitic margins of plutons
- metasedimentary schists
- fracture zones and the Kimberlitic dyke swarms of Koidu and Tongo.

Although it appears that etchplanation has largely been responsible for the development of the Plateaux and Mountain zone (including the Koidu Basin) nearer the coast there is evidence that marine denudation may have formed extensive planate surfaces.The planation of granitic plutons near Kambia (13°00'W, 9°00'N) with marine deposits at 40m ASL in the same area (MacFarlane et.al 1981, p.7) supports this hypothesis; though far more fieldwork is needed on this topic before anything can be stated with certainty.

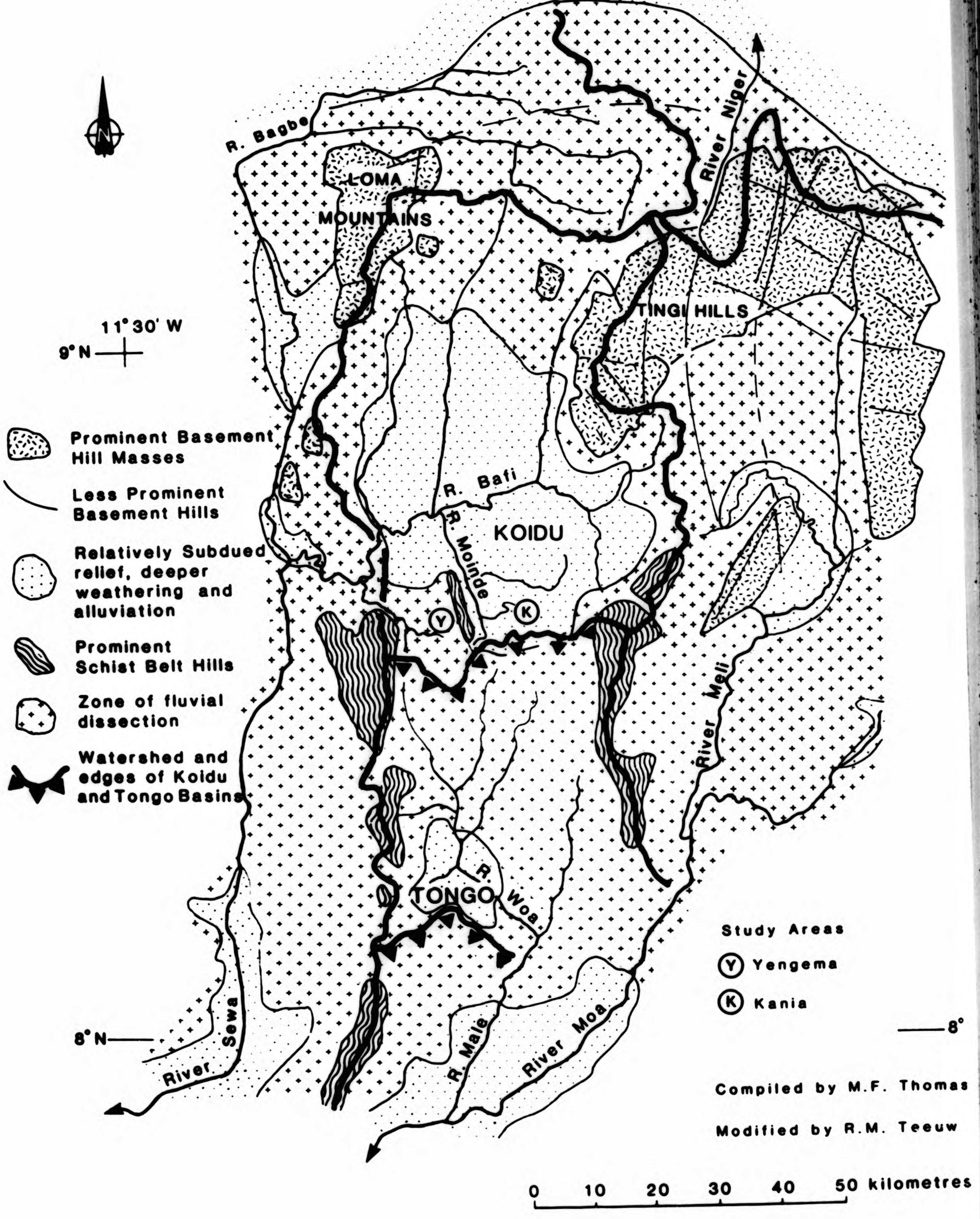


Figure 1.5 Eastern Sierra Leone : Geomorphology.

The Study Areas have markedly distinct landscapes, the Kania area having a low-relief saprolite-mantled landscape and the Yengema area having a higher-relief, dissected landscape (viz. Figure 1.5). Within these two types of landscape are three main terrain types, each controlled by the local lithology:

- granitic gneiss terrain dominates the Koidu Basin, particularly the Kania area, and is characterised by low-relief near-planate or gently domed interfluves, forming the "demi-orange" landscape of francophone workers, with occasional residual hills.
- granodioritic gneiss terrain only covers some 10% of the study areas, mainly around Yengema, and consists of either flat duricrusted hilltops with a footslope strewn with lateritic rubble and leading into a ramp-like glacis slope; or gently domed interfluves with ca. 1m thick topgravels of lateritic concretions.
- intrusive granite terrain covers some 20% of the study areas, mainly around Yengema. It consists of inselbergs, domes or kopjes fringed by glacis deposits, with frequent exposures of bedrock and corestones.

Diagrams showing the landscape types of the Yengema and Kania study areas are given in Figure 1.7, in connection with the soils of the Koidu Basin; more detailed descriptions of the terrain and landform types in these areas are given in Chapters 4 and 5. However, before moving on, the importance of valleyfloor landforms (swamps, floodplains and low terraces) in the geomorphic composition of the Koidu Basin should be emphasised. Valleyfloor landforms form 25-35% of the landsurface of the study areas (Table 4.1) with channelless swamps forming some 80% of the Koidu Basin drainage network (Hall, 1974, p.27).

Valleys are of the flat-bottomed 'Sohlenkerbtal' type (Louis, 1964) with steep sides and a convex slope leading up to near-planate or gently domed interfluves. Mining records show that valleyfloors are sites of deep chemical weathering, commonly down to 15m.

This indicates that solution and the subsurface lateral eluviation of suspended sediment are the dominant contemporary processes acting on the valleyfloors, with "high energy" fluvial transport and sorting playing a relatively minor (and seasonal) role. Observations that lateritic debris derived by colluviation from the interfluves is dissolved and dispersed in valley swamps (Sivarajasingham, 1969, p.9), and that valleyfloor saprolite is depleted in clay and silt (Thomas and Thorp, 1985, p.253), support the hypothesis that continuous 'low energy' removal of weathered material via the valleyfloors is a key process in etchplanation. 'High energy' fluvial/colluvial processes will apparently only be more effective at removing material from the Koidu Basin during periods of environmental instability associated with soil/saprolite stripping and enhanced fluvial activity - a topic that will be discussed more fully in Chapter 6.

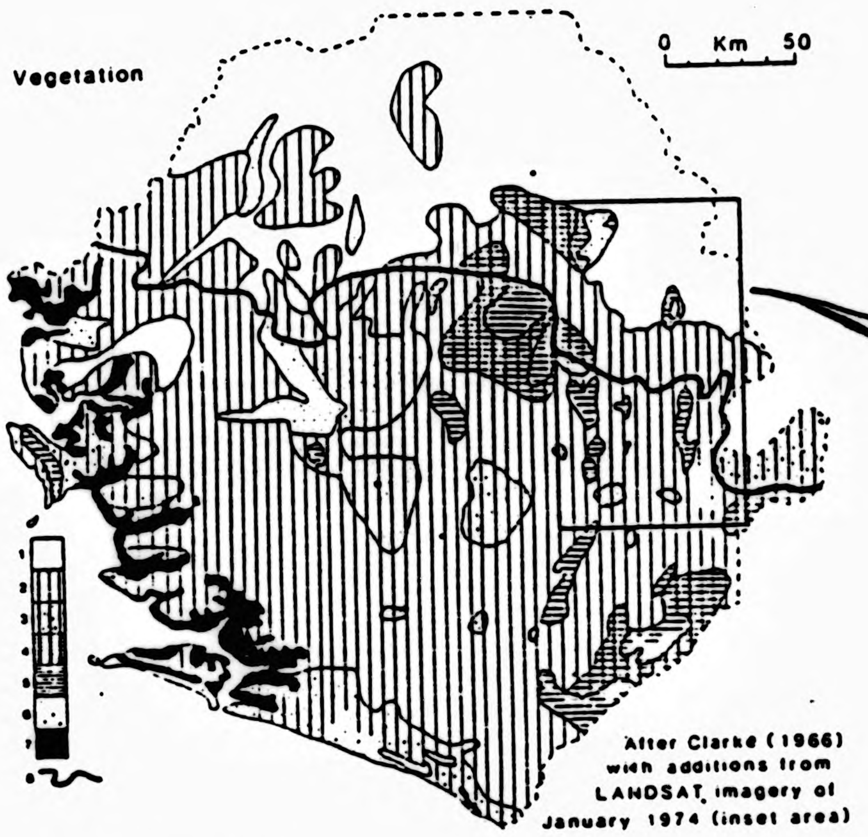
1.3 CLIMATE

The following summary of the three main climatic types affecting Sierra Leone is based on the work of Harrison-Church (1980, p.43-47).

The Coastal Monsoon climate is characterised by a hot dry season, with moist maritime winds producing a high relative humidity. The wet season is cooler and consists of line-squalls and easterly winds which peak in July. The mountains of the Freetown peninsular produce an orographic increase in rainfall, averaging 3510 mm/y, with 1000 mm falling in July alone. The Interior Lowland climate has a longer wet season, from July to September, with most rain falling during the early and late rains. Temperatures are high (max. 34.6°C in February) with relatively small diurnal variations. The Guinea Foothills climate of NE Sierra Leone is transitional between the Coastal Monsoon and Savanna climates; whilst the Guinea Highland climate of the Koidu region and SE Sierra Leone is a mountain modification of the southwest coastal monsoonal climate. Both the Guinea Foothill and the Guinea Highland climates have temperature minima occurring during the dry season (December/January) with maxima during the wet season (July/August).

The Yengema-Koidu area experiences a humid tropical weathering regime, with monthly temperatures ranging from a mean minimum of 14°C to a mean maximum of 35°C; with mean monthly rainfall varying from zero to 400 mm, and with 80% of the average annual rainfall (2355 mm) falling in six months (May to October).

There is virtually no published data on the intensity of rainfall in Sierra Leone. Data for Kortright in Freetown for 1961 shows that the average daily rainfall for the entire year was approximately 40 mm/day. Over 230 mm fell during one day in June 1961 (Gregory, 1964, Figure 13); this was probably concentrated into an afternoon downpour. Such events can trigger slope failures and cause severe rain-splash erosion, sheetwash rillwash, and gully erosion (Millington, 1985, pers. comm.). Two large landslides took place near the village of Charlotte on the Freetown peninsular on the night of August 10th 1945, killing at least 13 people. In the five days prior to the landslides 1121 mm of rain fell, with 401.8 mm falling on August 10th alone (Thomas, 1983, p.199). The high concentration of rainfall into a few months led Fournier (1962) to designate Sierra Leone as an area of high erosion intensity, exceeding 2000 tonnes/km^2/yr, for large formed catchments. Roose (1977) later confirmed this estimate of erosivity for the coastal areas and further confirmation has come from the work of Millington (1984), who found that the topsoils of both the coastal zone and the interior plateaux and hill zone (including the study region) were most susceptible to erosion.



After Clarke (1966) with additions from LANDSAT imagery of January 1974 (inset area)

1. Savanna

2. Farm Bush

3. Farm Bush grassland

4. Secondary forest

5. Primary forest

6. Grasslands

7. mangrove swamps

8. Forest-Savanna transition zone

A. Primary forest

B. Secondary forest

C. Farm Bush

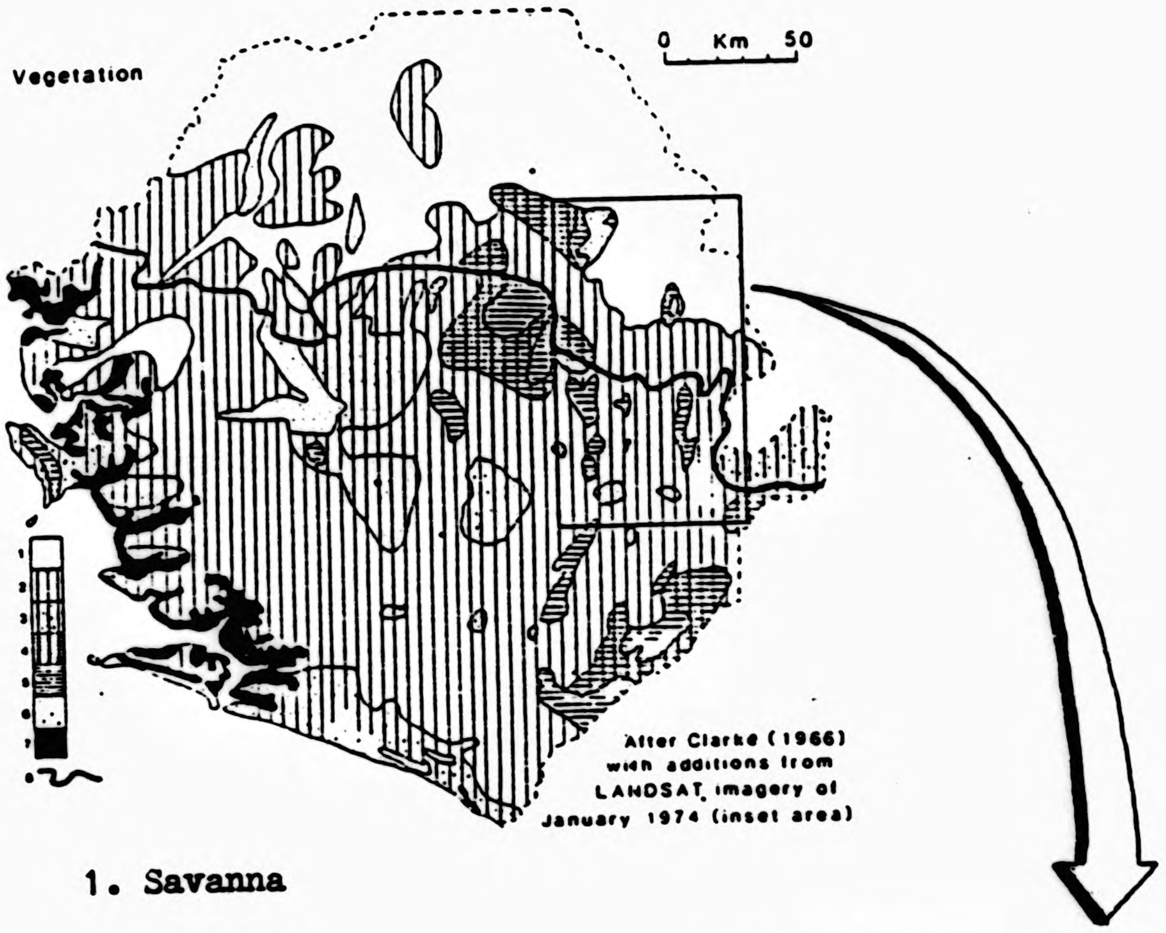
D. Derived savanna

E. Montane grasslands

Ⓚ Kania

Ⓨ Yengema

Figure 1.6 Sierra Leone and the study region : vegetation



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1. Savanna
2. Farm Bush
3. Farm Bush grassland
4. Secondary forest
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A. Primary forest

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E. Montane grasslands

◇K Kania

◇Y Yengema

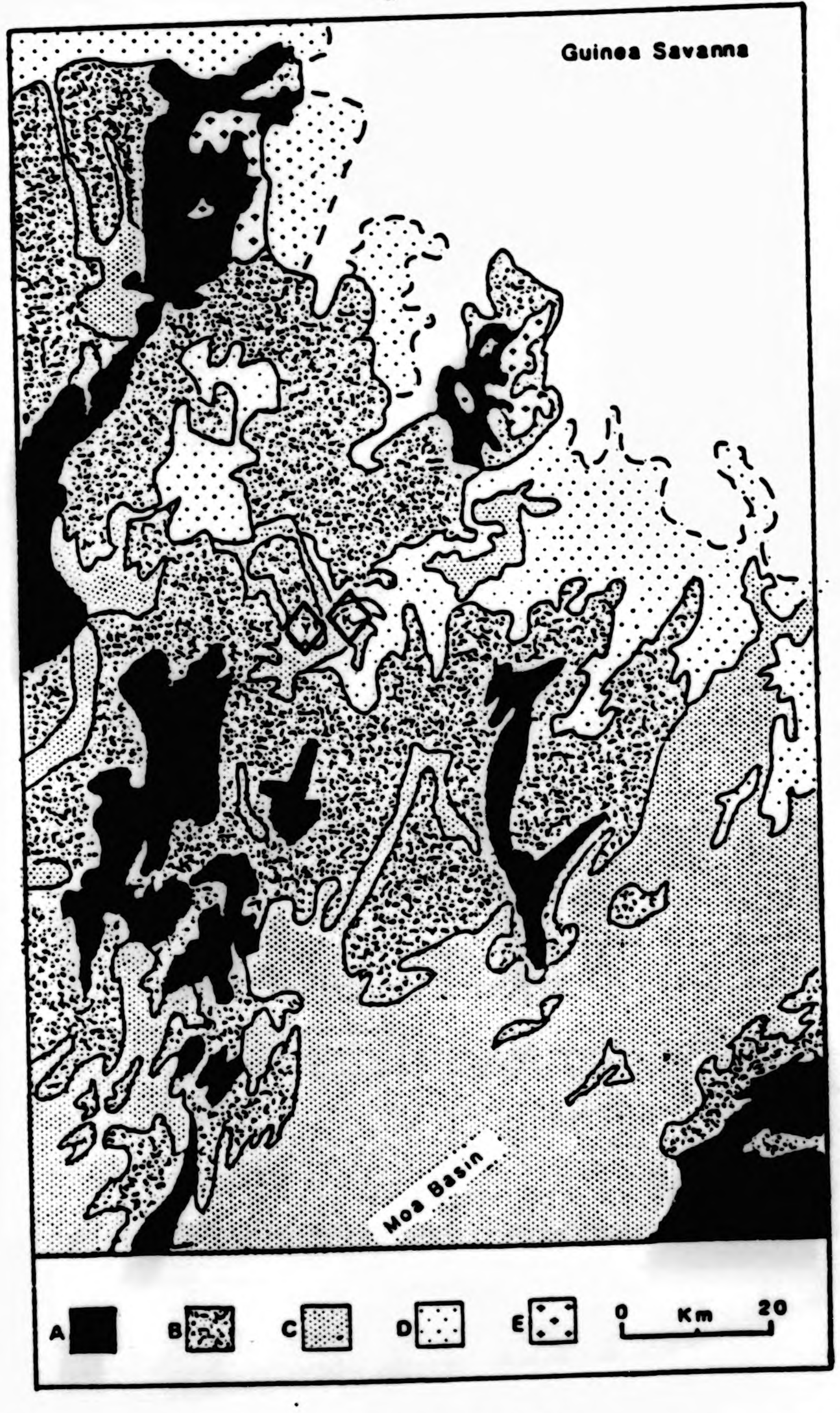

Figure 1.6 Sierra Leone and the study region : vegetation

1.4 VEGETATION

The major vegetation zones of Sierra Leone have been described by Clarke (1966, p.24) and Harrison-Church (1980, p.306). A LANDSAT-2 image of the study region has been used to produce a map of vegetation and land use (viz. Plate 1.1 and Figure 1.7), on which the following description of vegetation zones is based.

Moist Forest currently covers about 25% of the study region. Most of the forest is secondary, with primary forest being confined to the slopes and/or ridges of the main hill ranges. The secondary forest is being cleared for agriculture at a relatively rapid rate.

"Farm Bush" is a zone of periodic slash-and-burn farming with a fallow period usually of between 8 and 15 years, producing a mosaic of vegetation types ranging from "Elephant Grass" (Agropogon spp.) through to fire-resistant bushes and low trees, notably Oil Palm (Elaeis guineensis). The alluvial soils of the Moa Basin are relatively intensely farmed and form a distinct zone on the LANDSAT image.

Grassland occurs in three distinct forms: the short grasses (notably Mitragyna stipulosa) of the inland valley swamps, often converted to paddi swamps for rice farming; the aborescent sedges (Catagyna pologa) of the granite massifs; and the short grasses of iron pans on lateritic plateaux.

Savanna takes two forms in the study region, with Guinea Savanna occurring to the north and east of the Tingi-Niger Mountains and a zone intermediate between Guinea Savanna and moist forest occurring to the north and east of Koidu (viz. Figure 1.7). In the latter, tall forest is only found as strips along valleyfloors or as pockets protected from clearance by the local people as "sacred bush", thus "Derived savanna" is an appropriate term for this zone (cf. Harrison-Church 1980, p.61).

Young (1976, p.30-31) states that 'demi-orange' landscapes, which typify the Kania study area, are characteristic of rainforests; whilst inselberg and pediment landscapes, which typify the Yemgema study area, are characteristic of the savanna zone. Reference to Figure 1.7 shows that the Koidu Basin is anomalous in this respect, for the Kania area forms a westerly extension of the savanna zone, whilst the natural vegetation of the Yengema area appears to be rainforest, with the present forest/savanna vegetation apparently resulting from farming over the last 2000-3000 years. It may be that both the Yengema and the Kania areas were under rainforest until the onset of farming in this region. However, local factors are also involved and this topic will be more fully discussed in Chapter 6.

1.5 SOILS

The soil-types of Sierra Leone were outlined by Dijkerman (1969) whilst the characteristics of soils formed under the humid tropical climate of Sierra Leone were summarised by Odell et.al (1972, p.14). No detailed soil survey work has been published for the Koidu Basin, although both Stark (1968) and Sivarajasingham (1968) have produced F.A.O. reports on the soil and land use of the Moa Basin and adjacent hills, 60-100 km south of Koidu (viz. Figure 1.7). Both authors used landforms and surficial geology as the basis of their soil mapping, allowing a tentative classification of the soils of the Koidu Basin by comparison and analogy of similar landform/surficial geology assemblages. Figure 1.7(a) is an assemblage characteristic of the Kania study area, whilst Figure 1.7(b) is typical of the Yengema area. Each assemblage consists of inter-linking pedogeomorphic units.

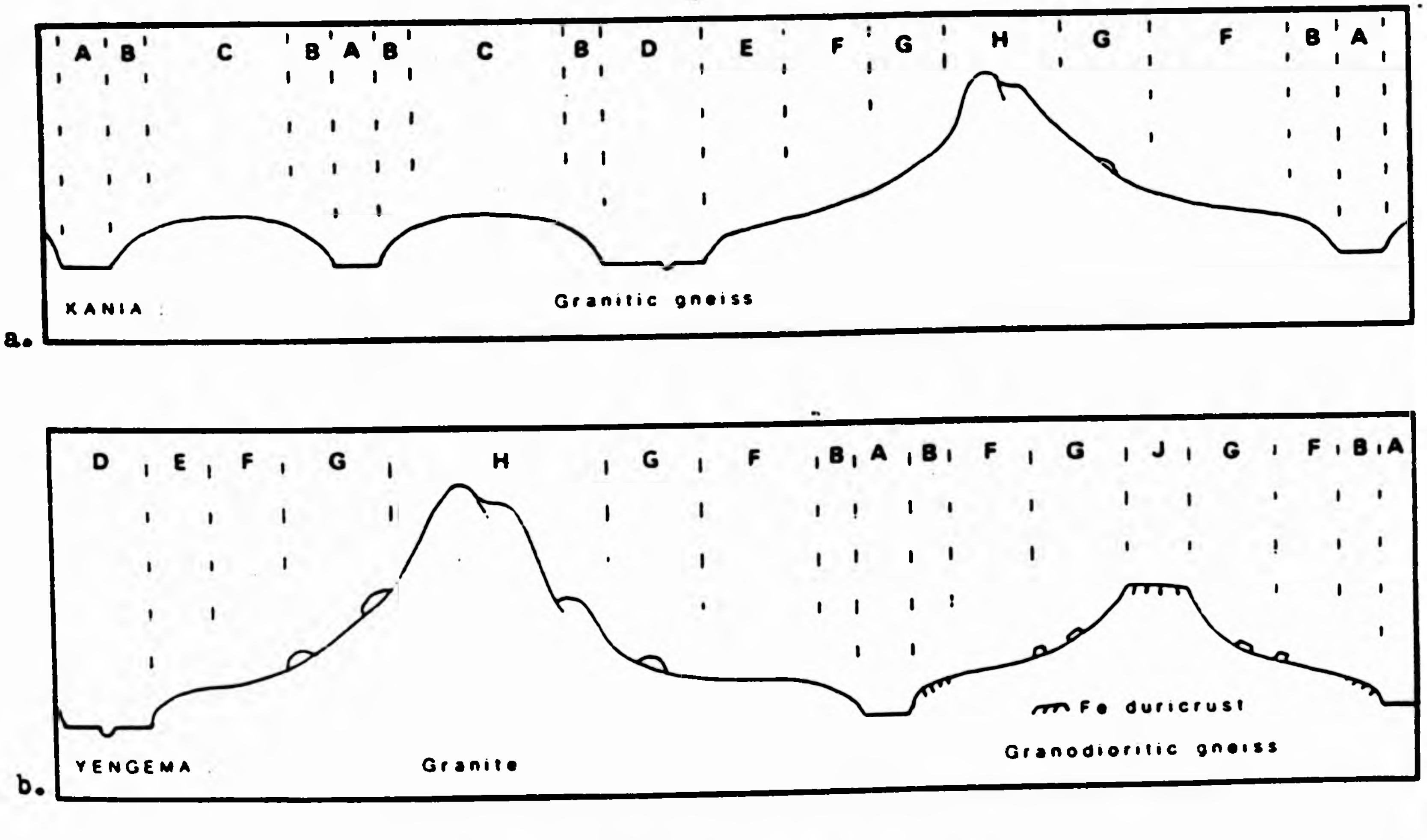

Figure 1.7 Soil-landform assemblages of the Koidu area.

Unit A consists of the inland valley swamps with 'Sohlenkerbtal' forms. They are very poorly drained and are flooded below 90cm for all of the year. Stark (1968, p.44-45) describes stratified alluvial/colluvial deposits with dominantly sandy loam textures and coarse basal quartz gravels. These are tentatively classified as Fluventic Tropaquents. It should be pointed out, however, that the channelless valley swamps which form up to 80% of the Koidu Basin drainage network lack fluvial stratification and appear to be essentially formed by eluvial "washing-out" of weathered material downvalley (Hall, 1974 p.28; Thomas, 1983, p.206). Tropaquetic Haplaquox or Hydric Tropaquents are more accurate classifications for these swamps, those with peaty topsoils having a Histic Haplaquox classification.

Unit B consists of valley edge colluvial wedges or distal glacis pedisediment deposits with surface slopes of 2-10°. These are well drained and slightly leached, with sandy clay loam to sandy clay textures. A topsoil 120 to 180cm thick overlies a sparse gravel consisting of at least 20% lateritic pisoliths that have been washed-down from the interfluve. These pisoliths are dissolving away under the hydromorphic conditions that affect this layer during the wet season. The C horizon is commonly gleyed and is overlain by a quartz gravel where former low terrace deposits have been truncated by the colluvial wedge. This unit is tentatively classified as Tropeptic Haplustax.

Unit C covers the near-planate or gently-domed interfluves. These are moderately drained, with surface slopes of 0-10°. Topsoils are commonly 30cm thick with sandy clay loam textures and a grey-brown colour. They overlie a gravel of at least 50% pisolithic laterite. Profiles over granitic gneiss tend to be 45-100cm thick, whilst those over granodioritic gneiss or mafic schist belt rocks tend to be deeper, 90-180cm, with a greater degree of termite activity and a more red-brown colour. These soils are tentatively classified as Clastoplinthic Haplustox.

Unit D, the riverine floodplain tends to have profiles 150-180cm deep, with stratified alluvium, often with sandy clay loam to sandy clay textures, overlying basal quartz gravels. Drainage is poor, with water always found below 120cm depth, and with seasonal flooding. Recently incised floodplains, which form extensive "river flats", tend to have moderate to imperfect drainage, a clayey B horizon with a fine to medium subangular blocky structure and a C horizon that is gleyed below 120cm. The tentative classifications for floodplain soils thus range from Fluventic Tropaquepts to Fluventic Oxic Dystropepts.

Unit E, the alluvial terraces, have slopes of 0-5°, with moderate to imperfect drainage. Profiles are 180-200cm deep, with a basal quartz gravel. Nodular laterite is apparently forming as in situ mottles within 90cm of the surface, above the layers that are modified by seasonal flooding. The soil matrix consists of yellow-brown clay loam or sandy clay loam with poorly developed structures and horizons. These soils are tentatively classified as Dystric, or Typic, Haplustox.

Unit F consists of the distal glacis deposits that merge into the valley edge deposits (Unit B), commonly with a downslope thickening of the topsoil. Drainage is moderate, though better near the valley edge where slight leaching occurs. Profiles are 140-200cm deep, often with topsoil 120-180cm thick. Topsoil is a brown to yellow-brown sandy clay loam to sandy clay, with a fine subangular, blocky structure but weak horizonation. A sparse gravel containing angular quartz fragments of duricrust, lateritic nodules and at least 20% pisolithic laterite, underlies the topsoil. This material has largely been derived by slopewash from the interfluve (Unit C), although Sivarajasingham (1968, p.20) noted that the lateritic nodules were apparently forming locally as <u>in situ</u> mottles that were only indurated after topsoil stripping. These soils are provisionally classified as <u>Plinthic</u>, or <u>Tropeptic, Haplustox.</u>

<u>Unit G.</u> the footslopes and proximal glacis, have surface slopes of 5-20° and good drainage. Profiles thicken downslope and are 130-180cm deep. These soils are red-yellow or yellow-red sandy clay loams to sandy clays and are moderately stoney. The gravel contains rock fragments, both fresh and Fe-indurated, with occasional lateritic nodules, indicating only localised transport of material. The development of both soil structures and horizons is poor. These soils are tentatively classified as <u>Typic Haplustox.</u>

<u>Unit H</u> covers residual granitoid hills and hillslopes with slopes over 20°, where soils are very shallow and stoney. Drainage is good, through sandy clay loam to gritty clay soils that are only 40-60cm deep. These soils are yellow-brown and have a strong fine structure. They have been provisionally classified as <u>Oxic Dystropepts.</u>

<u>Unit J</u> occurs over granodioritic or mafic schist belt rocks that form flat-topped hills or hillside benches. Topsoil stripping has led to the induration of a plinthite layer and the formation of a duricrust. Further erosion has led to the dissection of this duricrust.

At the close of this introductory chapter it is pertinent to emphasise that the rationale behind this research project is geomorphological, rather than pedological. The topsoil layer is only one of four main layer types (topsoil, gravel, alluvial/colluvial fill and saprolite) used to examine contemporary landform/material relationships in the Koidu Basin. The presence of relict materials and stratigraphic unconformities, coupled with the results of geomorphological surveys have then been used to provide insights into regional morphodynamics over the Quaternary era.

CHAPTER TWO

METHODS

2.1 LOGISTICS AND SAMPLING STRATEGY

The two major logistical problems were (a) the lack of transport, due to mechanical breakdowns and an overall shortage of vehicles at the mine; and (b) fieldsite suitability, due to widespread disturbance by diamond mining; and the need to work within 20 km of the National Diamond Mining Co. (N.D.M.C.) HQ, in case of fuel shortages.

Two major terrain types occur in the Koidu area: (i) extensive near-planate interfluves with few rock outcrops and (ii) areas of rock outcrop with inselbergs, kopjes and numerous glacis (pediment) slopes. The aim of the sampling strategy was to obtain detailed geomorphological and geological data for representative areas of these two major terrain types.

The Kania area (Figure 4.1) is an area of extensive near-planate interfluves. It was selected as one of the main study areas because there was a large amount of prospecting data on the area (including the trench of Thomas and Thorp, 1985, p. 254). Furthermore, the Kania area was being prepared for mining operations in early 1983, allowing vehicles for this project and the mining operations to be pooled, guaranteeing site access and keeping transport costs low. However, the original study site in the Kania area, selected from Air Photo Interpretation (API) maps and 1:5000 topographic base maps, had to be abandoned when reconnaissance fieldwork revealed extensive illicit mining from the previous wet season. The relatively undisturbed Pawpawyi stream was selected instead.

The Yengema area (Figure 4.1) is an area of extensive rock outcrops and glacis slopes. It was chosen as the second detailed study area (a) because there was virtually no disturbance from diamond mining; and (b) because working "on site" guaranteed site access, saved time, and required minimal supplies of fuel.

Plate 2.1 Pit sampling, Kania. This photo illustrates the problem of intervisibility (as well as the hazards of bush fires): the pits in the foreground fringe the 3m deep valleyhead of the Pawpawyi stream.

Plate 2.2 Headpan samples at the NDMC Prospecting Dept., prior to washing, gravel separation and the sorting into petrographic types.

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Plate 2.2 Headpan samples at the NDMC Prospecting Dept., prior to washing, gravel separation and the sorting into petrographic types.

A stratified system of sampling, based on the 'Ecological Traverse' method outlined by Avenard (1973) was found to be the most efficient method of both mapping and sampling. Of the other sampling systems that were considered, a random system would have been virtually impossible without elaborate arrangements to locate the sample pits in dense bush, as Plate 2.1 vividly illustrates. Furthermore, because some landforms are often less than 10m in width (e.g. swales and valley sides), a random scheme would have run the risk of not sampling some small - but important - landforms; and a systematic, grid-based system, sampling every 10m, would have involved too many samples and too much time to be feasible.

Provisional sample sites were selected from 1:20000 Air Photo Interpretation data transferred to available 1:5000 topographic Base Map prepared photogrammetrically by Hunting Surveys for N.D.M.C.. "Ground truth" was checked during reconnaissance fieldwork and new information was added to the 1:5000 Base Maps. Once selected, lines were cut through the bush from the interfluve crest to the valley floor at sites selected to contain as many different landform types as possible. Slope morphometry data was plotted onto 1:1250 mining site plans (along with any additional data from the 1:5000 A.P.I./Reconnaissance Maps) to produce Landform Maps. Samples were taken from pits dug along the transect lines at the mid-point of each unit landform. Pits were dug down to the bedrock or in situ saprolite.

This sampling scheme allowed the study, along each transect, of variations in both the form of the landsurface from interfluve crest to valleyfloor, and the nature of the materials from the landsurface down to the regolith/bedrock interface. The seriate distribution of the transects down the Pawpawyi and Boya/Nafayi valleys (Figures 4.5 and 4.9) allowed down-valley variations in materials and corresponding variations in the nature of the landsurface to be examined.

2.2 MAPPING

Remote Sensing

A false-colour LANDSAT -2 image taken on January 17 1979, using Bands 4, 5 and 7 was interpreted during the preliminary survey at Stirling University. A set of maps were plotted at a 1:250 000 scale, for eastern Sierra Leone and adjoining sections of Guinea and Liberia, showing geological structures and variations in lithology (Figures 1.2 and 1.3); major geomorphological features (Figure 1.5, largely after M.F. Thomas); and vegetation zones (Figure 1.6). At a late stage in this project Shuttle Imaging Radar (SIR-A) images of the Loma Mountains region became available and were interpreted, augmenting the structural geology map.

Air Photo Interpretation (API)

The interpretation and mapping of vertical air photos has occurred throughout most of this project, though at three distinct stages:

1. Preliminary office-based API mapping.
2. Further API mapping in conjunction with reconnaissance fieldwork.
3. Checking and augmenting API maps in the light of detailed (1:1250) morphometric and geomorphological mapping.

Two sets of vertical air photographs were used:

(a) 1:70 000 Infra-red transparencies, 20 x 20 cm; taken by the Institut Geographique National (France) during December/January 1975/76 (Nos. 279-283; 547-549 and 595-597).

(b) 1:15 000 Monochrome prints, 16 x 16 cm; taken by Hunting Surveys Ltd. during November/December 1966 (Job No. S337b).

Stereopairs from each set were examined under a 'Nikon' stereoscope and the stereoscopic images were mapped, using fine felt-tipped pens on an acetate sheet overlay, following the method of Allum (1966, p.27). Hand-held infra-red airphotography was carried out because it was hoped that surface depressions (e.g. interfluve swales) would appear more clearly because they should be moister than their surroundings. However, the results were poor, with only the marked differences in soil moisture regime between the valley floors and the interfluves showing up clearly.

<u>Geomorphological Mapping</u> was carried out at Reconnaissance-level, (1:20000 to 1:5000 scales) and Microrelief-level, (along transects at scales of between 1:5000 and 1:1000).

The compass-traverse method was used (with a prismatic compass, a ranging pole, a 30m measuring-tape, and strips of fluorescent tape to mark each station); either along pre-cut survey lines with one assistant to hold the pole; or through 'bush' with two additional assistants to cut the line. Offsets were made to distinctive landforms (e.g. gullies or core-stones) visible from the survey line. The geomorphological mapping symbols used were based on those of Cooke and Doornkamp (1974, p.363-376).

The 20 unit landforms that were recognised during fieldwork are given in Table 2.1; a copy of which is given in the Map Pocket for future reference. Each unit landform was coded to aid data storage and analysis. The rationale behind this coding gave hilltops and ridges the highest numerical ordering (500 and 510) and valleyfloor units the lowest (100-190), with terrain of intermediate elevation having codes of between 200 and 490. Gaps were left between groups of related unit landforms to allow for the insertion of any additional unit landform types. For instance valleyhead swamps (190), which were initially grouped together with valley swamps (180) on the basis of A.P.I. and field mapping, but were later shown to be a separate unit landform type after analyses of morphological and surficial geology data. A three-column code was used so that rocky terrain could be indicated, a '1' being placed in the right-hand column where rock outcrops larger than $1m^2$ occurred within 5m of the sample site (eg. 501, 291, 181, etc.).

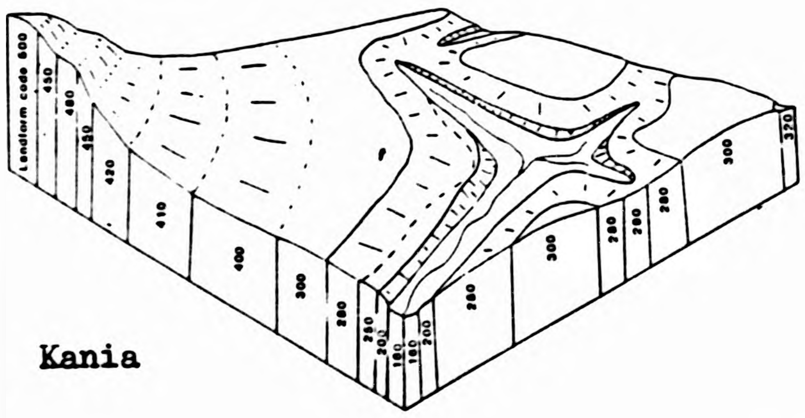
Morphometric Mapping was carried out in conjunction with the compass-traverse survey. A "Suunto" clinometer was used, along with the 30m tape-measure and the ranging pole, to measure the slope angle and distance between breaks of slope. Consecutive survey stations were never more than 30m apart. Distances between breaks of slope varied from over 100m along the long axes of some planate interfluves, to less than 1m down some valley heads and valley sides.

Code	Unit Landform
510	Ridge
500	Hilltop
490	Hillside bench
450	Hillside (+20°)
420	Hillfoot (10-20°)
410	Proximal glacis (4-10)
400	Distal glacis (1-4°)
320	Sloping interfluve(2-10°)
300	Planate interfluve (0-2°)
290	Swale (4-10°)
280	Interfluve rim (4-10°)
250(i)	Type I Low Terrace
250(ii)	Type II Low Terrace
220	Valleyhead (+10°)
200	Valleyside (+10°)
190	Valleyhead swamp
180	Valley swamp
160	Stream swamp
120	River Backswamp
100	River floodplain

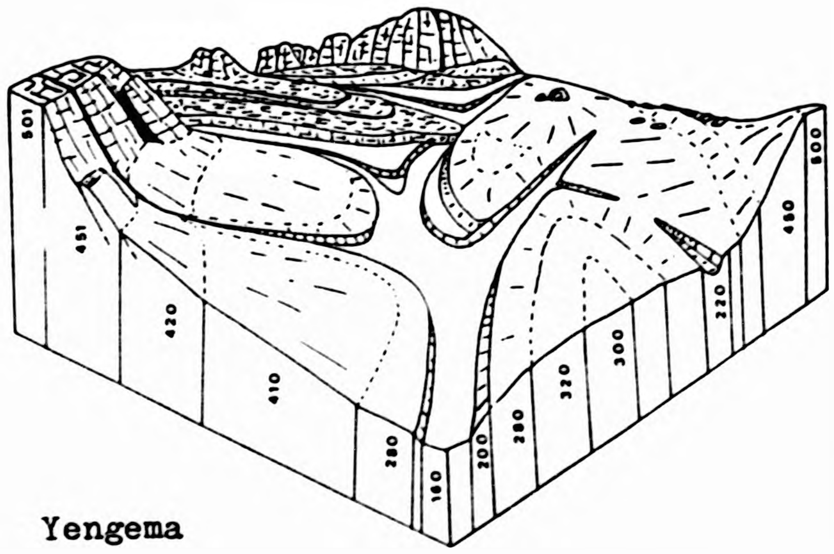
NB. 50l, 30l, 18l, etc. denote rock outcrops larger than $1m^2$ within 5m of site.

Table 2.1 Unit Landform codes and representative block diagrams.

Representative Block Diagrams



Kania



Yengema

Slope angles were checked by taking both fore-sightings and back-sightings on each station, the procedure being repeated if discrepancies of more than 1^{o} were found between fore-sightings and back-sightings. Measurements were made to the nearest 0.5^{o}. As a double check on both the compass-clinometer and slope morphometry surveys a survey team used tachiometric methods based from local bench marks, to plot the positions and altitudes of all the sample pits in the Yengema and Kania areas.

2.3. SURFICIAL GEOLOGY: SAMPLING

Most samples were collected from sample pits dug down to the bedrock and/or *in situ* saprolite. The main criterion for recognising *in situ* saprolite in the field was the presence of quartz/pegmatite veins. Where there was any uncertainty about whether or not weathered material was *in situ* or not, pits were dug down to at least 1.8m and then further sampled to 1m using a hand-held auger; a 2m-long, 1cm diameter pointed 'gravel bar' was then used to probe the underlying material to test for the presence of a buried gravel (and the pit was deepened accordingly to sample the gravel and saprolite).

In a few cases, where transects traversed inselberg summits, there was simply no surficial material to sample; whereas at sites associated with alluvial-colluvial cut-and-full events, the pits frequently were over 3m deep and the profile included two or three buried gravel layers. The average depth of the sample pits was 1.8m.

It should be emphasised here that the method of pit sampling used on this project was, given the large number of samples to be collected and treated, based partly on the system used by NDMC for mineral exploration (i.e., mainly to test for anomalous concentrations of heavy minerals), and partly on the geomorphological rationale that landform can be related to surficial material types, rather than on a sampling rationale with a pedological basis: it was not designed to identify soil horizons or map soil units.

Sample pits were of 1m diameter on the interfluves (Plate 2.1), but 2m diameter in the less-cohesive materials of the swamps and low terraces. A few samples were also taken from mine-cuts and prospecting trenches dug by a 'JCB' with a back-hoe. The pit sampling interval was every 30cm, down to the in situ saprolite or bedrock. Each 30cm sample layer was excavated, numbered and transferred to the NDMC Washsite in headpans for sieving and petrographic analyses (Plate 2.2). On the interfluves the dark brown sandy-clay topsoil was sampled as one layer, regardless of its thickness. This was done (a) because topsoil was invariably disturbed by farming and/or mining (ranging in thickness from ca. 100cm under undisturbed forest, to total absence at many sites; but averaging about 20cm thickness in the Koidu areas); and (b) because the textural and petrographic analyses of the underlying residual topgravel (or "stone line") were high-priority objectives of this study. In this sense the topsoil was considered, using mining terminology, as "overburden" .

The three types of sample (headpan samples, face samples, and *in situ* Kubiena box samples) were collected during the fieldwork.

Headpan samples each of $0.07m^3$ were collected from each 30cm layer of the pit; an extra headpan sample (making a total of $0.14m^3$) was taken for gravel layers. These headpan samples were wet-sieved at the NDMC washsite and the +8mm fraction was then sorted into petrographic types.

Face-samples for detailed particle size analysis and other laboratory analyses were collected in numbered heavy-duty plastic bags. Usually approximately 100g was collected if the layer was clay-rich, 300g if the sample was gravel-rich.

The Face-samples were collected from a $20cm^2$ area in the middle of each 30cm-thick layer, down a side of the pit which was parallel to the line of the transect. The relatively small size of these samples allowed sub-sampling of the main 30cm layers if features meriting detailed sub-sampling occurred, such as pockets of rounded gravel or infilled former tree-root zones.

In situ Kubiena box samples were collected from selected representative pits, following the method of Fitzpatrick (1980a).The Kubiena Boxes were made of 1mm alluminium sheeting, 100 x 50 x 35mm, with lids top and bottom. Both lids were removed from the box and the frame was gradually forced into the side of the sample pit, with the aid of a knife to cut through the material around the outside of the frame, until the box was full. One of the lids was then placed in position, then the frame (and usually about 1cm of projecting material) was removed from the pit side and trimmed with the knife. The second lid was then replaced and sealed with tape. Both lids were labelled with the sample's number, depth and orientation (i.e., whether the long axis of the box was vertical or horizontal). Thin sections were later prepared from these samples for micromorphological analysis.

All pits were photographed using a 35mm wide-angle lens and 400 ASA high-resolution monochrome film. Selected pits were photographed at 10 to 15cm intervals using a 100mm 'macro' lens, with a tripod for the camera to allow an adequate exposure time at the base of the pits.

A field datasheet (Figure 2.1) was completed for each pit, recording three sets of information:

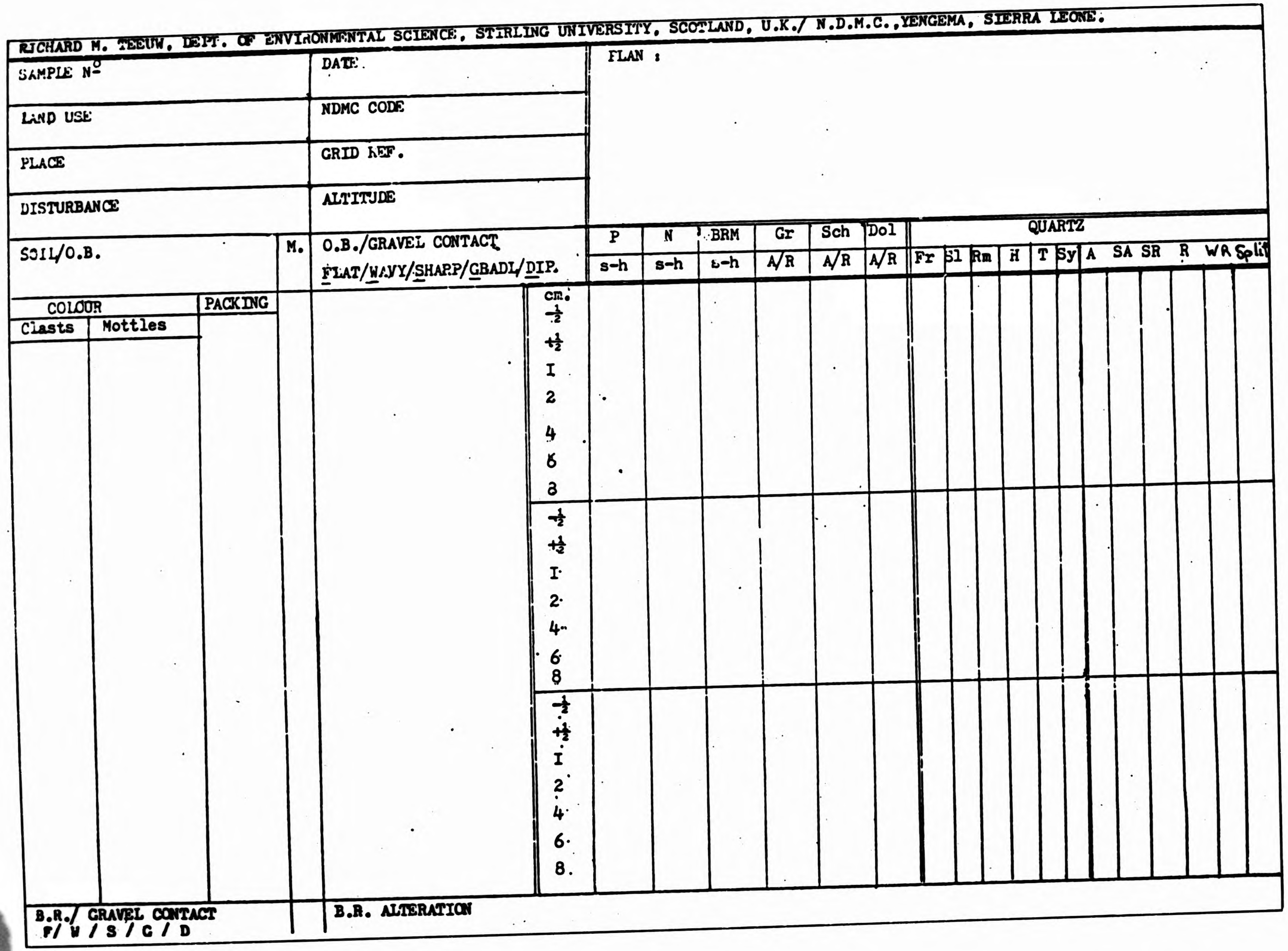
Location and geomorphological situation:

- Sample number; date; location.
- Grid reference and altitude above mean sea level (from NDMC 1:5000 Base Maps; and NDMC tachiometric follow-up survey).
- Land use and vegetation type (forest, dense bush; and various combinations of open bush, grassland and farmed land).
- Distance of pit from disturbed areas and type of disturbance, i.e., farming, mining, ant/termite mounds .
- Sketch map of geomorphological setting and nearest pits.

Pit profile description:

- Thicknesses, depths, textures and colours of non-gravel layers.
- Variations in the frequency of occurrence, size and colour of mottles.
- The nature of the boundary with the saprolite and between gravel and non-gravel layers: flat, wavy and/or dipping; sharp change (occurring under 10mm); gradual change (over 10-100mm).

Figure 2.1 Field data sheet.



RICHARD M. TEEUW, DEPT. OF ENVIRONMENTAL SCIENCE, STIRLING UNIVERSITY, SCOTLAND, U.K./ N.D.M.C.,YENGEMA, SIERRA LEONE.

SAMPLE N°
DATE
PLAN :
LAND USE
NDMC CODE
PLACE
GRID REF.
DISTURBANCE
ALTITUDE
SOIL/O.B.
M.
O.B./GRAVEL CONTACT
FLAT/WAVY/SHARP/GRADL/DIP.

cm.	P	N	BRM	Gr	Sch	Dol	QUARTZ											
	s-h	s-h	s-h	A/R	A/R	A/R	Fr	Sl	Rm	H	T	Sy	A	SA	SR	R	WR	Split
$-\frac{1}{2}$ $+\frac{1}{2}$ I 2 4 6 8																		
$-\frac{1}{2}$ $+\frac{1}{2}$ I 2 4 6 8																		
$-\frac{1}{2}$ $+\frac{1}{2}$ I 2 4 6 8																		

COLOUR
Clasts
Mottles
PACKING

B.R./ GRAVEL CONTACT
F/ W / S / C / D
B.R. ALTERATION

- Bedrock (B.R.) alteration (relatively fresh; red/brown gritty clay with/without mottles; or kaolinitic gritty clay).

Gravel layer description

- The thickness, depth and stoniness of each gravel layer (sparsely packed, packed, or well-packed gravel).

- The petrographic types and form of gravel clasts, using the "DAFOR" scheme: "Dominant", 75%; "Abundant", 50-75%; "Frequent", 25-50%; "Occasional", 5-25%; "Rare", 5% of total gravel.

Clast Petrography		Morphology
P, Pisoliths] N, Nodules]	(Lateritic concretions)	**Nodules and Mottles** soft (cemented) or hard (indurated)
BRM, Mottles	(Lateritic segregations)	**Quartz clasts**
		A/R, angular or rounded
Gr,Granite/Gneiss		SA/WR, sub-angular/well-rounded
Sch, Schist		Fr/Sl, fresh/slightly Iron-stained
Dol, Dolerite Q, Quartz		Rm/Sy, weathered rim/ sugary or saccharoidal texture
		H/T, heavily/totally Iron-stained.

Table 2.1 Gravel petrography abbreviations used in the field data sheet (Figure 2.1).

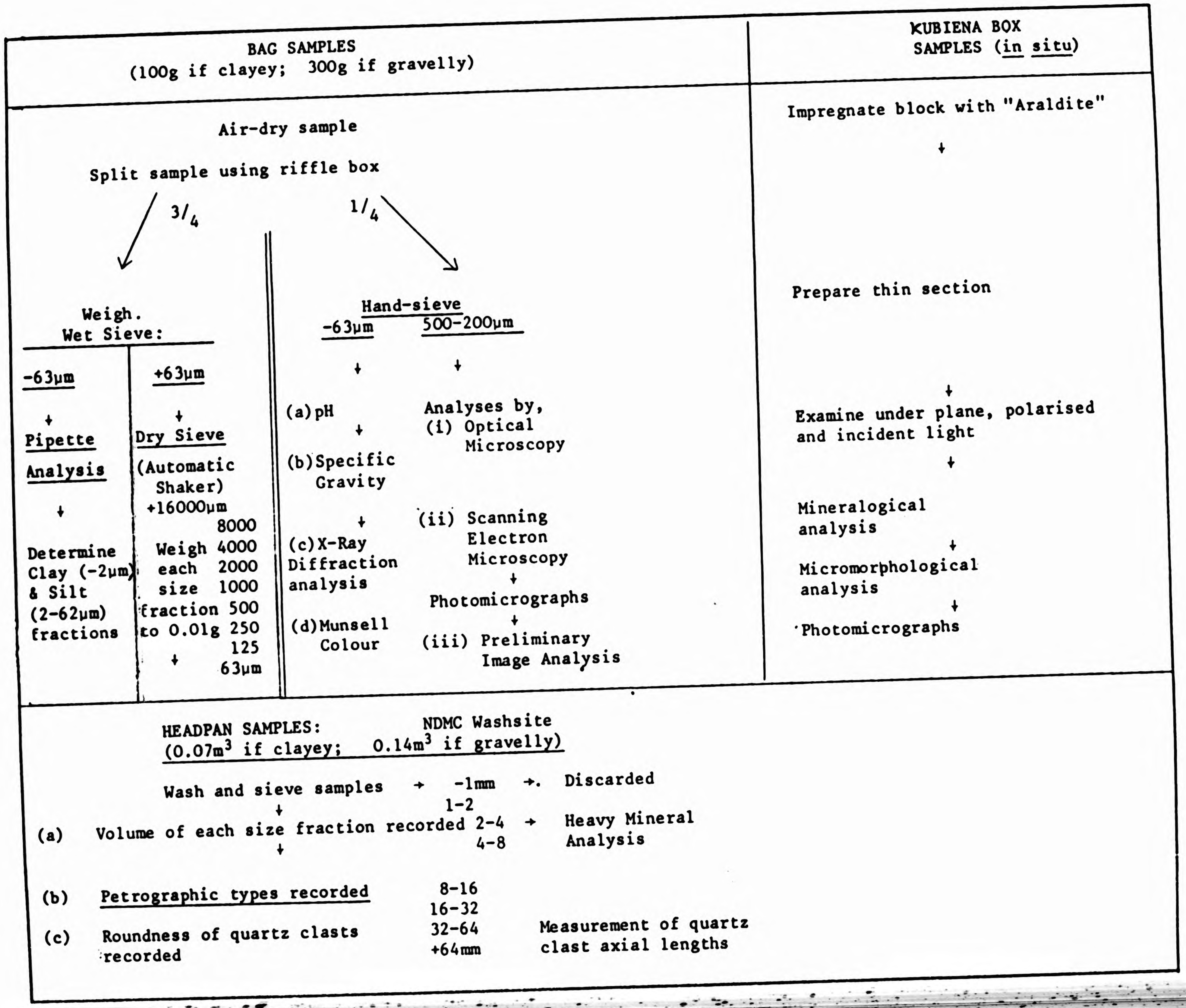
2.4 LABORATORY METHODS

The methods and sequences of laboratory analysis are summarised in Table 2.3. There is a clear distinction between those methods which could easily be carried out using the limited facilities for laboratory analysis at Koidu and those which could only be attempted using laboratory facilities in the U.K. Thus the foundations of the laboratory methods were the analyses of particle size distribution and of gravel petrographies both of which were relatively unsophisticated, low-cost techniques which could easily be carried out in Sierra Leone. Furthermore, both particle size distribution analysis (Muller, 1959; Pettijohn et.al., 1972, p. 68-88;Brown, 1985) and gravel petrography analyses (Cailleux and Tricart. 1959; Tricart, 1965 Frostick and Reid, 1980) are long-established indicators of formative environments. The micromorphological analyses could only be carried out effectively in U.K. laboratories, given the complicated sample pre-treatment procedures and sophisticated equipment needed for these analyses.

Particle Size Distribution

Two techniques were used to analyse the particle size distribution of the 100-300g face samples: sieving, based on BS1377 Test (7(A) (1975); and pipette analysis, based on BS1377 Test 7(C)(1975). After a preliminary wet sieve over a 63μm mesh the -63μm fraction was subjected to pipette analysis to determine the clay/silt proportions. The +63μm fraction was oven-dried and mechanically sieved through a nest of sieves graded at one phi unit each. The details of the two methods are given in Appendix B.

Table 2.2 Flow diagram of laboratory methods.



Gravel petrography and clast shape

Headpan samples (0.07-0.14m^3) from each pit were sent to the NDMC Washsite where they were washed and sieved into the following size fractions, the volumes of which were recorded in cc's:

-1mm, 1-2, 2-4, 4-8, 8-16, 16-32, 32-64, +64mm.

The -1mm "tailings" were discarded, but the 1-8mm fraction was further concentrated for an analysis of its heavy mineral content by the N.D.M.C. Prospecting Engineer. The +8mm fractions were retained and the 8-16, 16-32, 32-64 and +64mm clasts were sorted into their petrographic types, measured by volume (using a 1000cc or 200cc measuring cylinder) and recorded. Examples of each rock type were later photographed (Plate 5.1).

During the sorting of the +8mm fraction the degree of rounding of quartz clasts was recorded, using a Krumbein roundness chart (Gardiner and Dackcombe, 1983, p.111). The axial lengths of +32mm quartz clasts were measured using a 'shape-box' of the type described by Shakesby (1979, p.11-13). Indices of shape were calculated from the following formulae:

$$S = \sqrt[3]{bc/a^2}$$ (Krumbein, 1941a).

$$f = \frac{(a + b)}{2c} \cdot 100$$ (Cailleux, 1947).

where 'a' is the longest axis, 'b' is the intermediate axis and 'c' is the shortest axis.

Micromorphology

Micromorphological analysis is here taken to include not just the analysis of thin sections, but also the analysis of the form and surface features of sand grains examined by scanning electron microscopy (SEM).

Thin sections of in situ material were prepared from the Kubiena Box samples at the Soil Science Department of Aberdeen University, the samples were impregnated, sawn, mounted on glass slides and polished to produce 40x90mm thin sections, following the method of Fitzpatrick (1980a, p.6-22). A one-month course on 'Soil Micromorphology' was attended at Aberdeen University, after which the thin sections were interpreted in terms of their micromorphological and mineralogical contents. Photomicrographs of selected samples were made using plane, polar and incident light (Plates 5.2 to 5.7).

A preliminary scanning electron microscopy analysis of surface textures and particle outlines of sand grains from the 0.5 to 2.0mm size range was made using a 'Cambridge' Scanning Electron Microscope at Stirling University. The method of Krinsley and Doornkamp (1973) was followed in preparing 30 to 50 monocrystalline sand grains for SEM viewing. The surface features of each grain were ticked-off against a check-list of features compiled from the SEM studies of Krinsley and Doornkamp (1973), Bull (1981) and Le Ribault (1978), and following the procedure of Goudie and Bull (1984). The Image Analyser of the Department of Cell Biology, Strathclyde University, was used for a preliminary examination of quartz sand grains from swamps, low terraces, and interfluves. The results were encouraging, indicating that large numbers of grains (ca. 100/sample) could be rapidly analysed and a quantitative index of their formative environment obtained.

Unfortunately, this Image Analyser facility only became available towards the end of this research project, when lack of both time and funds prevented further more detailed follow-up work. The method certainly has potential as a means of indicating palaeoenvironmental conditions, with minimal sample preparation (hand-sieving and washing) and the ability to analyse 100 grains per minute.

Additional Laboratory Analyses

Representative samples of matrix material ($^{-}$63µm) were analysed to determine matrix pH, matrix density and matrix geochemistry. Matrix colour was recorded from air-dried samples using the 'Munsell' colour code system. Preliminary pH analyses proved to be so erratic, giving markedly different values for soils from similar sites, that no further pH analyses were attempted. The specific gravity of the matrix material was determined using the procedure of BS1377 Test 6(B) (1975).

X-Ray Diffraction (XRD) was used to examine aspects of the matrix geochemistry and clay mineralogy. Analyses were carried out at the Department of Soil Science, Aberdeen University. Samples were selected from the saprolite and colluvial and/or alluvial fill layers of four pits, each sited on different landforms. One set of mottles and one set of lateritic nodules were crushed and also analysed. The details of the sample preparation procedure for the XRD analyses are given in Appendix B.

2.5 STATISTICAL ANALYSES

The objectives of the statistical analyses were two-fold. Firstly, to standardise and describe the surficial geology data by means of percentages, ratios, descriptive statistics and indices of both particle sorting and petrographic composition. Secondly, to group and differentiate these data into (a) Layer Types and (b) Unit Landform Types, using group means and their coefficients of variation, as well as both bivariate and trivariate scattergraphs. In the event of this methodology failing to distinguish both Layer Types and Unit Landform Types, a follow-up programme of Cluster Analysis followed by Analysis of Variance was envisaged. The final results, summarised in Chapter 5 and Table 5.14 in particular, were clear enough for this follow-up programme to be waived.

Gravel petrographies were measured volumetrically in c.c.'s. as the differences between the relative densities of the variants (e.g., quartz 2.6g cm^{-3}; lateritic concretions 3-5g cm^{-3}) would have produced a distorted measure of the relative proportions of each variant had they been measured by weight. The MINITAB Statistical Package (Ryan et al., 1980) was used to calculate percentages and ratios of each variant for each Unit Landform Type. To provide both a summary of the petrographic composition of gravel samples and a means of mapping the areal variations in gravel layer composition, a Petrographic Index was produced, based on a trivariate scattergraph (viz. Figure 5.2).

Particle size distributions were measured at Phi Unit intervals ($= -\log^{2}d$; where 'd' is the particle diameter in millimeters) to normalise the data as an aid to the particle sorting studies (McManus, 1980). The weights of each size fraction were converted to percentages and cumulative percentages and then grouped into their respective Unit Landform Types using MINITAB. Data from representative transects were then selected for the plotting of particle size histograms and cumulative frequency graphs using "GINOGRAF" software (C.A.D.C., 1976). A simultaneous specification of both central tendency and sorting was then obtained by plotting the 99th percentile against the 50th percentile of each cumulative frequency curve to produce a C/M diagram (Pettijohn et al., 1972, p.73).

Laboratory error was estimated using the following method. A relatively large sample (ca. 1000g for gravelly material, ca. 500g for clayey material) was taken from three face samples with textures that encompassed the range of textural types encountered during the study. Each sample was quartered and one quarter set aside. The remaining quarters were then re-mixed and quartered again, giving four replicates. Both the first quarter and the four replicates were then randomised and their particle size distributions were measured by sieving and pipette analysis (re. Appendix B for detailed methods).

The results for each sample type, along with the formulae by which their standard deviations and standard errors were calculated, are given in Appendix B. Briefly, standard deviations were 0.38-1.07% for clay; 1.44-2.38% for fines (clay + silt); 3.63-3.74% for sand; and 2.65-3.59% for gravel.

CHAPTER THREE

LAND FORM. MATERIAL AND PROCESS

A review of studies in which the morphological variations variations of the soil/regolith body have been related to their formative processes is presented in this chapter. The "soil/regolith body" is defined as extending from the bedrock/regolith interface to the land surface; with areal variations from interfluve crest to valley floor due to eluvial/illuvial and colluvial processes, and down-valley variations due to fluvial processes (Conacher and Dalrymple, 1977). This review concentrates on examples from environments similar to that of the study region, that is, regions of dominantly felsic to intermediate crystalline rocks, which have experienced Quaternary bioclimatic oscillations,ranging from semi-arid through to perhumid conditions (Thomas and Thorp, 1985). As the fieldwork and results of this study are concerned with the morphological variations of surficial materials and the landsurface, this review concentrates on morphological properties, relating morphological variations to assumed variations in processes. The discussion moves from the formative processes and primary components of layers, to the morphologies of the layers themselves, and finally to the catenary variations of the soil/regolith body and the landsurface.

A summary of the processes acting on the soil/regolith body is given in Table 3.1. The intensity and duration of these processes was considered to be the key to soil genesis by Simonson (1959; 1978, p.18):

> "The balance of time among a host of individual processes is the key to the nature of every soil; that balance determines the characteristics of the soil profile and soil body....the ultimate character of a soil depends on the relative importance of all individual processes in each combination".

Physical Alterations

Interangular and surface stress sheeting and exfoliation
Pedoturbation
Particle size changes
Structure and bulk density changes

Translocations

Surface translocations (slopewash,rillwash, mass movement and fluvial processes)
Vertical subsurface translocations evapotranspiration, capillary rise, watertable fluctuations)
Lateral subsurface translocations (throughflow, piping, groundwater movement)

Chemical Alterations

Hydrolysis
Carbonation
Solution
Oxidation
Reduction Sf
Chelation
Hydration

Composite Processes

Pedoplasmation
Gleying and podzolization
Cheluviation
Ferruginization
Ferrallitization
Lateritisation

Table 3.1 Formative processes

The scope of this review does not allow for detailed descriptions of processes, these can be obtained from Ollier (1969), Carson and Kirkby (1972), Thomas (1974), Lal (1977a); Young (1976), Roose (1977), Statham (1977), Moormann (1981), Gerrard (1981), Selby (1982), Furley and Newey (1983) and Foss and Segovia (1984). The processes listed in Table 3.1 result from the operation of a few active agents, principally water and organisms. The intensity with which these agents operate is determined by variations in environmental factors (Dokuchaev, 1883; Jenny, 1941, 1946). Seven major factors are discussed in detail by Young (1976, p. 3-63): climate, geology, hydrology, relief, organisms, man, and time. Climate is clearly of paramount importance for determining the magnitude of water supply; whilst the other factors, particularly hydrology, contribute towards determining the intensity and duration of water supply for formative processes. The importance of water supply in soil formation was recognised by Milne (1936b, p.16-17), who noted that catenary differentiation was brought about by "drainage conditions, differential transport of eroded material, and leaching, translocation and redeposition of mobile chemical constituents".

3.1 PRIMARY LEVEL: PROCESSES AND COMPONENTS

At the most basic organisational level of processes and materials, two distinct morphological types of material form the end members of a continuum in terms of particle size and particle mobility, a distinction first made by Kubiena (1938; 1970, p.111):

> "The role of the fabric skeleton is that of a scaffold. It is the immobile part and characterised by a high stability....The fabric plasma represents the finely dispersed part of the fabric which may become easily transportable..."

At this basic level the dominant process types are those of chemical and/or physical alteration on, or close to the surfaces of skeletal grains. The material properties resulting from these processes include colour variations, clay mineral types, secondary mineral types, grain form variations, and the nature of the microfabric. These properties can only be adequately examined by micromorphological analyses of material (for instance: Brewer, 1964; Brewer et al., 1983, Fitzpatrick, 1980a, 1984; Murphy, 1985).

When process suites dominated by translocation processes become increasingly dominant, so the level of organisational of the material will increase, moving up to the secondary level of organisation with the formation of eluvial/illuvial horizons. The material properties of this secondary level of organisation can generally be examined in sample pits and include soil/saprolite structure, texture, and variations in stone line petrography. Over the next few pages the morphological components of primary through to secondary subsystems will be reviewed.

Mineralogy

The mineralogy of the soil/regolith body is dependent on either the mineralogy of the bedrock, or the mineralogy of translocated material, or both. Alteration of bedrock produces a bimodal framework of skeletal grains in a matrix of fine-grained alteration products or "plasma".

"Skeletal minerals" are those most resistant to chemical alteration, notably quartz and muscovite (Goldich, 1938; Brunsden, 1979b). Some minerals may be directly transformed into secondary minerals without significant disintegration of the original mineral grain, although their physical strength may be greatly reduced; an example is the alteration of feldspar crystals to kaoli nite or gibbsite pseudomorphs.

"Plasma minerals" result from chemical alteration processes on the surface of skeletal minerals or in the matrix material. Two types occur:

(i) Amorphous forms, consisting of colloids and chelates with various combinations of Ca, Na, K, Mg, Si, Fe and Al; and Fe/Mn sesquioxides (Carson and Kirby, 1972, p.233-4).

(ii) Clay minerals, mainly formed by the carbonation of feldspars, with secondary clay minerals mainly resulting from the desilicification of antecedent clay minerals. Both Bakker (1967) and Tardy et al. (1973) have shown that various types of secondary mineral assemblages can form from a common parent material, depending on the degree of leaching the parent material experiences.

Colour

Curi and Franzmeier (1984), working on Brazilian oxisols, found colour to be the most reliable indicator of soil type variations. Both Folster et al. (1971, p. 137) and Young (1976, p. 87) give similar tables of colour variations in the soil/regolith body due to corresponding variations in mineralogy. These are summarised in Table 3.2:

Mineral	Colour
Magnetite	Black
Manganese	Dark blue/black
Hematite and amorphous ferric oxides	Red
Goethite	Yellow/Yellow-brown
Lepidocrocite	Orange-brown
"Limonite"	Yellow/Yellow-brown
Hydrated amorphous oxides	Yellowish

Table 3.2: Mineral/colouration relationships

The red colour of most well-aerated tropical soils can be produced by relatively small amounts, 10-20%, of hematite or amorphous ferric oxides (Kubiena, 1970). The grey colour of leached or waterlogged soils results from the reduction and removal of these pigmenting minerals. Goethite apparently represents an intermediate stage between the well-aerated conditions and the waterlogged conditions, occurring in aerated but moist conditions, with excess water converting the goethite to "Limonite".

Microstructure

"Weathered rock and soil may be mineralogically identical, the difference between them lying in the arrangement of particles". This statement by Young (1976, p.91) reflects the basic premise of micromorphological analysis first emphasised by Brewer (1965). Within the soil/regolith body there is a continuum of structural arrangements ranging from microscopic features such as cutans, pores, tubules and microstructure types, through to the macroscopic features used to distinguish soil horizons, such as clay skins and ped types.

Flach et al. (1968) showed how "pedo-plasmation" by bioturbation and shrink/swell processes resulting from the alternate wetting and drying of clays, can lead to the progressive differentiation of the soil regolith body. The clay minerals most susceptible to shrink/swell processes are the 2:1 lattice clays, notably montmorillonite, however these clay mineral types are relatively uncommon with granitic parent materials and forest/savanna bioclimatic conditions of the study region, where Kaolinitic clays predominate. Avenard and Michel (1985, p.80) cite the relatively high plastic limits (20-35%) and shrinkage limits (15-20%) of Kaolonitic clays as the reasons for the negligible amount of cracks, slumps, landslips or flows in kaolinite-rich material. Young (1976, p.91) states that such material can be up to 80% clay and yet still be friable and permeable.

There appears to be a general consensus (Van Wambeke, 1962; Daniels et al., 1970, 1971; Young, 1976, p.90-91) that the soil/regolith body shows progressive stages of "structural maturity", and associated "textural maturity", over time. Recent research indicates that these assertions may be over-simplified. For instance,Young (1976, p.90) states that when "the B horizon is structureless or weakly structured, without clay skins, the soil is "dead": all weatherable minerals have gone and little further profile differentiation is taking place". However, micromorphological analyses of "mature" Ugandan clay-loams with Kaolinitic clay minerals and no weatherable minerals remaining, revealed contemporaneous soil formation with the production of incomplete blocky microstructures, proving that such soils were far from "dead" (Pidgeon, 1972). Furthermore, the friable and permeable nature of these forest/savanna kaolinitic soils appears to be largely due to the micro-aggregation of kaolinitic clay minerals and Fe/Mn sesquioxide secondary minerals (Ahn, 1970). Millot (1982, p.585) has pointed out that the collapse of these micro-aggregates due to environmental change or "aging" can lead to the collapse of the soil/regolith body, a theory partly supported by the observations of Furley (1975a, p.278), who found that the "oldest", interfluval, soils of a forest/savanna catena in Belize were not necessarily the most stable.

Texture

The textural variations of the soil/regolith body can be examined in terms of individual horizons or layers and also in terms of the entire soil/regolith profile. The texture of the entire profile depends firstly on the grain size and mineralogy of the parent material; and secondly, on the duration and intensity of chemical weathering, sites of intense weathering generally corresponding to sites of maximum clay formation. Ruxton (1958) noted that progressively more weathered granite had a progressively lower silt content relative to clay, and Van Wambeke (1962) cited a silt/clay ratio of less than 0.15 as indicative of highly weathered soil/regolith material.

The texture of horizons or layers depends more on the vertical and lateral translocations of clays and fine material. Detailed definitions of "eluvial" and "illuvial" layers are given in the U.S.D.A. Soil Taxonomy handbook (1975 p.19-27). Brewer (1968) showed that argillic horizons can result from either clay illuviation, or from <u>in situ</u> weathering and/or inheritance from parent material; whilst Webster (1965) pointed out that layers can show an apparent enrichment in clay after the absolute loss of fine material from overlying layers due to surface wash and lateral eluviation.

Three textural profile types are recognised in the classification scheme of Northcote (1971); summarised in Table 3.3.

Textural Profile Morphology

(i) Uniform: similar at all depths.
(ii) Gradational: gradual increase of clay with depth.
(iii) Duplex: relatively abrupt clay increase with depth.

Environmental/Soil type	Textural Profile Type
Rainforest	Gradational, with a well developed and deep B horizon.
Forest/savanna	Uniform, high clay content
Farm Bush (after forest) Central Sierra Leone	Gradational, with rare weak argillic horizons.
Savanna	Duplex, sandy topsoil over a textural B horizon.
"Actively weathering soils"	Gradational
"Highly weathered soils"	Duplex

Table 3.3. Textural Profile Types and Environment/Soil Relationships

(data from Young, 1976, p. 89; Central Sierra Leone data from Van Vuure and Miedema, 1973, p. 48).

Clast Form

There has been considerable research into the relationship of clast form to formative processes, notably by Zingg (1935), Keunen (1956) Sneed and Folk (1958), Krumbein (1941), Cailleux & Tricart (1959) and Bradley (1970) for pebbles; and by Moss (1966), Crook (1968), Avenard (1973) and Barret (1980) for sand; with Krinsley and Doornkamp (1973) and Bull (1981b) outlining the use of grain surface morphological variations as environmental indicators. There is general agreement that rounded pebbles are the result of the attrition and rolling associated with fluvial transport. Fieldwork by Boyé, (1960) indicates that under perhumid tropical conditions extreme chemical weathering may lead to the rounding of quartz pebbles, although this appears to be a unique case and the in situ, non-alluvial nature of the material Boye cited is open to question (Thorp, verbal comm., 1985). Mabasoone (1968, p.439) related the occurrence of distinct layers of sub-rounded pebbles in the rana deposits of Brazil to Quaternary bioclimatic oscillations and associated enhanced fluvial/colluvial activity; whilst Leveque (1979, p.127) concluded that the occasionally occurring, highly weathered rounded pebbles on interfluves in Togo were relicts of pre-Quaternary fluvial activity.

Analysis of sand grains has shown that well-rounded grains are almost certainly of aeolian origin, although the assertions that sub-rounded/rounded grains have experienced fluvial or shoreline environmental conditions, and that sub-angular grains are the result of in situ weathering, are less certain. Crook (1968, p.171) showed that sand samples from progressively more weathered soil material had higher frequencies of both rounded grains and angular grains. A partial explanation for this seemingly anomalous occurrence has been given by Magaldi (1978. p.969), who found that quartz grains in the A/B horizons of a Spanish soil were angular, apparently due to rapid etching by humic acids, whilst grains in the saprolite were sub-angular to sub-rounded, reflecting the lower pH of the groundwater and relatively slower etching of grains.

The use of sand grain surface morphology, examined by means of scanning electron microscopy, as a means of obtaining an indication of the formative environments a grain experienced has advanced considerably from the qualitative studies of Krinsley and Doornkamp (1971), to a more quantitative approach, exemplified by the work of Goudie and Bull (1984) who have used this technique to identify distinct phases of colluviation in Southern Africa . Considerable success has been reported by Avenard (1973) in relating the "exoscopy" of sand grains, such as their degree of surface staining and pitting, and their degree of rounding, to their position on summit areas, glacis slopes and valley floors in the forest/savanna regions of West Africa.

Gravel petrography

Two major groupings of clasts occur in the residual gravel layers: those derived from bedrock fragmentation, and those derived from Fe, Mn or Al sesquioxide accumulation.

(i) Rock fragments. Given the occurrence of gravel deposits in all the major bioclimatic zones of the world, and the importance of gravel clast form as an environmental indicator (Cailleux and Tricart, 1959; Briggs, 1977), there have been surprisingly few enquiries into the petrographic variations of gravel deposits. Notable exceptions are in the fields of glacial till provenance (for instance, Dreimanis and Vagners, 1972) and river gravel provenance (Sternberg, 1875; Plumley, 1948; Frostick and Reid, 1980). There is virtually no published work on the petrographic variations of tropical stone lines, apart from the studies of pedisediments by Ruxton (1958), and studies of gravel variations along interfluve/valley floor toposequences in Togo by Leveque (1979). Studies of petrographic variations in fluvial gravels under different climates are summarised in Table 3.4.

	Percentage loss/Km	
	Crystalline + Metamorphic	Quartz + Quartzite
Humid Tropics		
Tricart (1974,p.63)	100 to 33%	10 to 6.7%
Douglas (1980)	10 to 5.6%	less than 4.8%
Humid Temperate		
Pitman & Ovenshine (1968)	2.30%	-
Semi-Arid		
Plumley (1948)	1.40%	0.44%
Sneed & Folk (1958)	0.09%	-
Bradley (1970):		
Field study	0.30%	0.18%
Lab: Fresh rock	0.06%	less than 0.06%
Lab: weathered rock	0.30%	-

Table 3.4 Rates of pebble destruction per kilometre of fluvial transport.

There is clearly a correlation between the resistance of a gravel clast to chemical alteration, plus the amount of alteration the clast has undergone, and the rate at which that clast will be destroyed during fluvial transport. Dal Cin (1968, p.1094) formulated an index of pebble weathering:

$$\frac{\text{Quartz pebbles}}{\text{Quartz pebbles + Pebbles of other rock types}} .100\ \%$$

Humid tropical conglomerates gave values of 90 to 100%, whereas semi-arid conglomerates averaged only 14% on Dal Cin's index.

Although the studies of Table 3.4 and the index of Dal Cin may provide indications of the formative environments a gravel has experienced, studies of African stone lines (notably by Bruckner, 1956; Folster 1969, 1971; and Leveque, 1979), have shown these gravels to be polygenetic, having undergone a long-term and often complex development. The 'raña' stone lines of NE Brazil were found by Mabasoone (1966, p.439) to "consist almost entirely of the most resistant rock types, chiefly quartz", some quartz pebbles being sub-rounded. Given the bioclimatic oscillations experienced by NE Brazil during the Quaternary (Tricart, 1985), the 'raña' gravels have either formed (i) with the aid of intense chemical pre-weathering of material with later concentration of resistant clasts, or (ii) with slight pre-weathering but with intensive disintegration of weathered pebbles during short-distance fluvial transport or (iii) after the deposition of virtually unweathered polymict gravel formed by short-distance fluvial transport, and subjected to a later period of intense <u>in situ</u> chemical alteration. All three models of genesis may have played some part in the development of these gravels.

Boyé (1960, p.16) cites the occurrence under perhumid conditions of rounded to well-rounded pebbles in an apparently autochthonous gravel, the pebble rounding being due to intense chemical weathering with iron oxides filling cracks and possibly contributing towards their propagation, producing a sugary surface texture. A similar feature has been described from the micromorphological studies of Eswaran and Stoops (1979), for the infusion of soil plasma into sub-microscopic cracks in quartz grains, Fe/Mn sesquioxide-rich plasma producing "runiform" quartz clasts. The granularity of parent material has been shown by Rahn (1966, p.214) to account for the markedly different particle size distributions of pedisediments derived from andesite or from granite. Under semi-arid conditions of the fine-grained andesite produced pedisediments with a Gausian distribution; whereas the coarser granite, with more varied mineral grain sizes, produced bimodal pedisediments. Similar findings were made by Milhous (1982, p.168) for fluvial gravel.

(ii) Sesquioxide accumulations. Although there is considerable literature on the morphology of lateritic clasts, for instance Maignien (1971), Pullan (1967), Westerveld (1969), Leveque (1979), Fitzpatrick (1980), and MacFarlane (1983), there is no uniform system of classifying clasts. Table 3.5 is a summary of lateritic clast morphologies and genetic interpretations presented in the studies cited above.

Type	Form	Hardness	Size	Probable Genesis
CONCRETIONS 1A	Pseudo-pisoliths; no banding.	Very hard	-5cm	Erosion, rolling and rounding of lateritic fragments.
Transported				
In situ				
1B	Pisoliths with Fe "shells".	Moderate.	-1cm	Direct precipitation of Fe in Fe-rich clay.
1C	Pisoliths with banding or alteration rims of Fe and Al.	Moderate. to soft.	Various sizes	Bauxitization: Fe/Al diffusion process.
1D	Packed pisoliths with geothite or soil filling voids.	Moderate.	+0.5cm	Pedogenetic accumulations.
1E	Loosely spaced pisoliths, partially coated with Fe/Mn sesquioxides.	Moderate to soft.	-1cm	
1F	Basal pisoliths, well-packed and/or platy Fe/Mn sesquioxide accumulations, with horizontal voids.	Moderate to hard.	+0.5cm	Subsurface translocation and accumulation of Fe/Mn sesquioxides.
VERMIFORM 2A	Aggregates of pisoliths with vermiform cavities.	Moderate.	+0.5cm	Similar to 1D, but with eluviation of fines and goethite.
2B	Faunal passages-labyrinthine -vermicular	Moderate to soft.	Aggregates +0.2cm	Faunal activity - termites - worms.
2C	Root pseudomorphs	Moderate to soft.	Aggregates +0.1cm	Oxidation of roots/hyphae and chelated Fe compounds.
2D	Reticulate patterns of vermiform structures.	Moderate.	+0.5cm	Direct precipitation of limonitic iron.
2E	Pipe-like structures: near surface, vertical; mid-zone, anastomasing; basal-zone, horizontal	Moderate to hard.	+0.5cm	Form related to the predominant direction of subsurface translocation and later precipitation.
SEGREGATIONS 3A	Unbanded, clearly defines, irregular, nodular	Soft.	-2cm	Pseudogley segregations.
3B	Unbanded, coarse/massive, poorly defined, irregular,	Soft.	-200cm	Segregations formed under vadose conditions.

Sources: Pullan (1967), Westerveld (1969) MacFarlane (1976, 1984) Leveque (1979) Fitzpatrick (1980).

Table 3.5 Lateritic clast morphologies.

The study most comparable to the Koidu area is that of Van Vuure and Miedema (1973), working on granitoid terrain in central Sierra Leone, who found both vertical and lateral variations in sesquioxide clast morphology similar to those observed by Westerveld (1969) over metavolcanic rocks. These workers found that the irregular, relatively soft and porous lateritic segregations or "mottles" that formed in the zone of water table fluctuation, became smoother, harder and denser nearer the landsurface, culminating in concretions that were very hard, black, and often magnetic. Westerveld (1969), Van Vuure and Miedema (1973), and MacFarlane (1983) attributed such vertical variations in lateritic clasts to landsurface lowering and/or falling water tables, with both absolute and relative sesquioxide enrichment. The relationship between variations in the water table level and the morphology and distribution of sesquioxide clasts has recently been re-emphasised by detailed work in NE Australia (Coventry et al, 1983; Coventry and Williams, 1984).

Both Westerveld (1969) and Van Vuure and Miedema (1973) concluded that smooth, relatively hard and rounded lateritic concretions were rounded during slopewash; a view supported by mineralogical analyses which indicated only localised transport. Furthermore, R.P. Bourman (verbal comm., B.G.R.G. 'Laterites Workshop', Manchester University, 1985) has pointed out that lateritic concretions in the topsoil can suffer irreversible dehydration, with alteration to Maghemite, at temperatures as low as 300°C, as may occur during bush fires.

3.2 SECONDARY LEVEL: LAYERS AND PROFILES

At the secondary level of material organisation, subsurface vertical translocations lead to profile horizonisation (Greene, 1947); whilst subsurface lateral translocations produce pedon differentiation and influence the form of the landsurface, which is directly modified by surface translocations, such as slopewash, seepage zones, mass movements, and rilling. The down-slope and down-valley interlinking of these secondary level process-response features leads to the tertiary level of organisation, the "landsurface catena" of Conacher and Dalrymple (1977), termed the "geocatena" for the purposes of this thesis.

The main morphological features at the secondary level of material organisation are the horizons or layers of the soil/regolith body. Studies of the four main layer types recognised during fieldwork for this thesis will be briefly discussed below.

Regolith/Saprolite Layers

For the purpose of this thesis, "regolith" and "saprolite" are defined as being the end-members of a continuum of weathered bedrock types. This topic has been discussed by Haantjens and Bleeker (1970), who recognised three major stages of weathering: "skeletal", where the physical disintegration of the rock is more evident than chemical alteration; "immature", where significant quantities of clay are mixed with slightly altered and broken rock; and "mature", where the rock has been toally decomposed to clay minerals plus secondary and resistant minerals. "Regolith" corresponds to the "skeletal" stage of Haantjens and Bleeker, and the "Lithosol" Soil unit of the FAO soil map of the world (FAO-UNESCO, 1974). "Saprolite" corresponds to the "mature" weathering stage of Haantjens and Bleeker (1970); it can be sub-divided into an undisturbed type maintaining the original bedrock structure, the result of isovolumetric weathering (Ollier, 1967), and a disturbed type, which has been modified from the original bedrock structure by creep, collapse, or shrink/swell action (Aleva, 1983) and/or by pedoturbation (Millot, 1982). Situations in which exposed saprolite can be modified by eluviation, with the 'washing-out' of fine material by concentrated overland flow to produce a relative enrichment in coarse material, have been outlined by Webster (1965) and Goudie and Bull (1984).

Gravel layers

Three main petrographic types of gravel occur, lateritic gravels, rock gravels, and mixed lateritic/rock gravels.

Lateritic gravels have been reviewed by MacFarlane (1976, 1983), and for Sierra Leone, by Van Vuure and Miedema (1973). These authors report two main genetic types of lateritic gravel: in situ gravel, and transported gravel, as summarised in Table 3.5.

Rock gravels or "stone lines" can also be subdivided into in situ and transported types, with the classification of Marchesseau (1966) being most applicable:

-eluvial type, found by removal of fine material and residual accumulation by eluviation or biogenetic sorting (Webster, 1965, Hall, 1974, p.28; Nye, 1954)

-colluvial type, formed by mass movements, slope-wash transport, rilling and micro-pedimentation (Ruhe, 1959;

Rohdenberg, 1970; Furley, 1976; Debaveye and De Dapper, 1986); generally thicker topsoil downslope, with an irregular A/B soil horizon boundary;

- alluvial type, dominantly quartzitic, and including a relatively large proportion of rounded clasts, usually directly overlying bedrock or saprolite (Hall, 1974, p.32-38; Leveque, 1979, p.127).

Mixed gravels are most commonly found in forest/savanna regions. Their heterogeneity apparently reflects their polygenetic origins (Bruckner, 1956; Folster, 1964, 1969 .; Leveque, 1979). Detailed reviews of "stone lines" have been produced by Ricquier (1969) and Fairbridge and Finkl (1984); further discussion of gravel layers follows in Chapters 5 and 6.

Fill Layers

"Fill" is defined by the American Geological Institute (1976) as, "Any sediment deposited by any agent so as to fill or partly fill a valley, sink, or other depression". For the purposes of this thesis, alluvial and colluvial gravel layers are treated separately to "fill"; thus fill layers are here regarded as consisting of particles with diameters of less than 2mm. Three main types of fill occur in the study region, colluvial, alluvial, and alluvial/colluvial.

Colluvial fill layers tend to be sandy, though with significant amounts of clay, Watson et al. (1984, p. 225) give ranges of 45-65% sand, 15-25% silt, and 10-35% clay for southern African colluvia derived from various lithological types. The downslope sorting of material, giving coarse sandy deposits upslope and progressively finer deposits downslope, culminating in distal clayey deposits, commonly occur (Milne, 1935); although Webster (1965) has shown that localised zones of concentrated overland flow on the lower slopes can "wash-out" finer material, producing pockets relatively enriched in sand and coarse material.

Alluvial fill layers are characterised by stratification and highly sorted material, in terms of texture and petrography, mainly consisting of quartz and other resistant minerals of sand size, with clay contents generally being at a minimum in channel deposits and at a maximum in backswamp deposits. The structural and micro-morphological variations in alluvial fill types have been studied by Walker and Coventry (1976) and Collins and Larney (1981).

Alluvial/colluvial fill layers, as described by Avenard (1973a, 1975) from the Ivory Coast, occur in the valley swamps, particularly in the valleyhead zones where there is no permanent stream channel; this type of fill is characterised by stratified layers of quartz sand, some of which include lateritic concretions that are being dissolved by the swamp water (Sivarajasingham, 1968, p.9).

Topsoil Layer

For the purposes of this study "topsoil" is defined as the O/A (organic-mineral) horizon of the profile. The topsoil on interfluves in the Koidu area is rarely more than 0.3m, probably resulting from the intensive farming in the region and associated soil erosion: soils under undisturbed forest and are usually over 1m thick (Thorp, verbal comm., 1985). Working on similar terrain in central Sierra Leone, Van Vuure and Miedema (1973, p.10) cite the presence of thick colluvial/alluvial fill deposits along valley edges, which "wedge-out" towards the interfluves, as evidence of the stripping of interfluve soils. Similar deposits occur throughout West Africa (cf. Burke and Durotoye, 1971). In the Koidu area, they are usually capped by a thin (10cm) topsoil with sparsely-packed pisoliths and modules, indicating that these colluvial wedge deposits are much younger than the interfluval topsoils underlain by relatively thick lateritic gravels. The thin worm layer and thicker termite layer described by Nye (1954) from Nigeria and Ghana occur in the Koidu region, with Miedema & Van Vuure (1974) having studied in detail the effects of termite activity on topsoil in central Sierra Leone.

Variations in profile type

A key concept in landscape evolution studies is that of "Double surfaces of planation" devised by Budel (1957, 1965, 1968), which accepts that the landscape is not solely the result of weathering and erosion on the land surface, but can also be controlled by the subsurface lowering of the saprolite - bedrock interface, the weathering front, or "basal surface of weathering". The weathering front shows varying degrees of gradation between saprolite, regolith and bedrock and can occur at depths ranging from a few millimetres to, on rare occasions, over a hundred metres (Thomas, 1974, p.195). Weathering fronts have been extensively studied, notably by Falconer (1911), Harrison (1933), Budel (1957), Ruxton and Berry (1959, 1961a) and Ollier (1969). Studies of the spatial variations in the depth of the weathering front have been carried out by Thomas (1965a, 1966a), Feininger (1971) Faniran (1974) and Omorinbola (1983).

Recently, Aleva (1983) and Millot (1982) have emphasised the importance of other discontinuities which may occur in soil/bedrock profiles. Aleva (1983, p.383), working mainly in NE South America and SE Asia, recognised two weathering fronts; the first at the bedrock-saprolite interface, the second at the interface of the saprolite and overlying layers. "Stone lines" are considered by Aleva to be the result of surface denudation processes. The formative processes of Aleva's model are the collapse of bedrock structures inherited by the saprolite, creep and slow flowage of the saprolite, with the fill layers and topsoil above the stone line forming a layer of maximum mass flow, and with overland flow at the landsurface.

The model of Millot (1982, p.383), based on West African fieldwork, places more emphasis on the effects of pedogenetic processes. Millot recognises three "geometric discordances", firstly, the weathering front; secondly, the "leaching front", the base of pedogenetic activity; and thirdly, the landsurface, modified by surface wash in a similar manner to that proposed by Budel (1957).

3.3 TERTIARY LEVEL: CATENARY DIFFERENTIATION

A cornerstone of this hierarchy approach to material/land form relationships is Milne's concept of catenary differentiation, where soil differences are brought about by, "drainage conditions, differential transport of eroded material, and leaching, translocation and redeposition of mobile chemical constituents". Milne (1936b, p.16-17).

The analogy made by Greene (1947), relating the "washing-out" of fine material from upslope sites and its redeposition downslope to the vertical eluviation and illuviation processes operating in soil profiles, was adapted by Morison et al. (1948) to map extensive low interfluves ("eluvial complexes"), alluvial plans ("illuvial complexes") and transitional slopes ("colluvial complexes") in SW Sudan; and by Glazovskaya (1968, p. 303) studying variations in soil geochemistry. Implicit in these schemes is the concept that the landsurface can be divided into exporting ("eluvial"), accumulating ("illuvial"), and transporting ("colluvial") domains. This echoes the 'Aufbereitung' concept of Penck (1924) and is supported by the research of Furley (1968, p.39). Milne's concept of catenary differentiation (1935, 1936a) presented pedologists with a far more dynamic model of soil development than the profile/horizon - based studies it superseded. The very limited information that can be obtained from isolated profile studies was emphasised by Nye (1954, p.7):

> "A study of only vertical development in a profile omits half the picture. The lateral relationships and variations between corresponding horizons .....equally deserve study".

A review of catenary types

A total of 82 different catenary studies made on granite/gneiss parent material, from semi-arid through to perhumid forest environments, were examined for this review. The types of catenas occurring in the four main vegetation zones from which the examples were drawn, are given in Table 3.6.

	% of total occurring within each vegetation zone			
Vegetation zone	Rock outcrop	Laterite outcrop	No outcrop	% of vegetation zones
Forest	4.8	4.8	15.9	25.5
Forest/Savanna	3.7	12.2	13.4	29.3
Savanna	6.1	17.1	11.0	33.2
Semi-arid/Sahel	4.9	6.1	0.0	11.0
% of each catena type	19.5	40.2	40.3	100 n = 82

Table 3.6: Catenary types and Vegetation zones.

Although the findings of this review of catenary types will inevitably reflect the relative amounts of field work done in each vegetation zone, the results are in general agreement with the reviews of Moss (1968), Ollier (1979) and Gerrard (1981, p.72). Three main types of catena were found in this review: those with rock outcrops, those with laterite outcrops and those with no outcrops at all. Other findings were that, (i) forest zones have the highest frequency of no-outcrop catenas; (ii) the savanna zone has the highest frequency of both laterite-outcrop catenas and rock-outcrop catenas; and (iii) catenas with no rock or laterite outcrops are rare in the semi-arid/sahel zone.

The "traditional" catenary approach to soil distribution studies is effectively limited to the two-dimensional plane of downslope material transport:

> "The essential feature which gives genetic unity to a catena is that water and soil material can move laterally downslope. It is incorrect to apply the term, as has occasionally been done, to altitudinal sequences of erosion surfaces or river terraces, which lack this feature".
>
> Young (1976, p.272).

Whether or not "erosion surfaces" or river terraces lack the downslope lateral transfer of materials, if the catena is to be seen as the interfluve/hillslope/valley floor subsystem of the drainage basin, the definition of a catena must include a down-valley fluvial component on and through the lower slopes, river terraces, and the valley floor, moving material out of that drainage basin (Huggett (1975). This requirement is met by the "Landsurface catena" concept of Conacher and Dalrymple (1977, p.11):

> "Landsurface catena is defined as a three-dimensional pedogeomorphic body extending from the centre of the interfluve thus permitting extension by lateral additions to cover total landsurfaces - and from the base of the soil to the soil/air interface. Its minimum across-slope dimension is that of its constituent landsurface pedons ....".

Although relict layers or palaeosoils are excluded from the landsurface catena framework (they have to be considered separately as they were not formed solely by contemporary processes) this three-dimensional approach to material/landform relations appears to be partly based on the soil stratigraphy studies of Butler (1959; 1967, p.231):

> "The usual basis of soil study has been the profile, a vertical column of small though undefined cross-sectional area. Many profiles .. may comprise a soil mantle, each merging laterally into and being continuous with another. Soil mantles though extensive, are discontinuous, and it is the nature of their discontinuities and contacts which are significant."

Butler's soil mantle concept and stratigraphic approach to soil studies culminated in his "K-cycle" model of recurring periods of environmental stability with significant soil development, alternating with periods of instability, resulting in truncated mid-slope profiles, with colluvial/alluvial deposits on lower slopes eventually producing a sequence of buried ground surfaces. This is an application of Erhart's (1955) concept of environmental stability, or "Biostasie", alternating with environmental instability, or "Rhexistasie". Following Butler's 1959 paper there was a flush of pedo-geomorphic studies, notably Walker (1962a) and Mabbutt and Scott (1966). A detailed review of recent soil stratigraphic work has been given by Finkl (1980). McCallien et al. (1964) examined complex soil/saprolite profiles on a morphological basis, and considered both vertical variations and also areal variations in soil/saprolite structures. A summary of the types of patterns produced by areal variations in soil mantles has been given by Fridland (1976).

Finally, research by Arnett and Conacher (1973) indicates that high levels of association exist between pedogeomorphic features and drainage basin parameters. In turn, the studies of both Baker (1977) and Da Cunha et al. (1975) have shown that drainage basin parameters in both arid and humid tropical climates are strongly influenced by local bedrock geology. These findings are of particular relevance to the two Koidu Basin study areas, as they each lie in different drainage basins with different lithological compositions and with markedly different geomorphologies, as outlined in the following chapter.

CHAPTER FOUR

RESULTS: GEOMORPHOLOGY

4.1. The Koidu area is characterised by relatively subdued relief and extensive near-planate interfluves at ca. 390 + 20m A.S.L., termed the "Koidu surface" by Hall (1974, p.29), surrounded by Schist Belt hills which reach 810 m A.S.L. in the Nimini Hills; hence the term "Koidu Basin" (Thomas, 1980, p.347) is more appropriate. Comparison of Figures 4.1 and 4.2 shows the strong control that bedrock lineations and lithological variations have over local relief and drainage patterns.

The Schist Belt rocks of the Dowadu Hills form an interbasinal watershed between the Koidu-Kania area, drained by the Meya-Moinde river system, and the Yengema area, drained by the Gbobora-Nafayi river system. The long profiles of these rivers, and that of the Bafi River, are given in Figure 4.3. The westward-flowing Bafi River crosses three major knick points: an upper set of rapids (gradient 3.5m/Km) due to a regional fault zone; followed by a stretch of very gentle gradient (0.1 to 0.6m/Km); then a stretch of rapids (2.0m/Km) due to the relatively resistant rocks of the northern Nimini Hills (viz. the NW corner of Figure 4.1); before dropping some 10m at the Gambiadu Falls, caused by a major regional fault zone, to join the upper Sewa River (gradient 3.8m/Km). The relatively gently gradient of the Meya River (0.8 to 1.1m/Km) is due to that river flowing along a regional fault zone; conversely, the steep gradients of the Gbobora River (3.4 to 4.0m/Km) are largely due to that river cutting across the resistant rocks and major lineaments of the Nimini Hills Schist Belt. The very steep gradient of the middle and upper reaches of the Boya stream near Yengema (13.6m/Km) reflects the highly resistant local bedrock of intrusive granite.

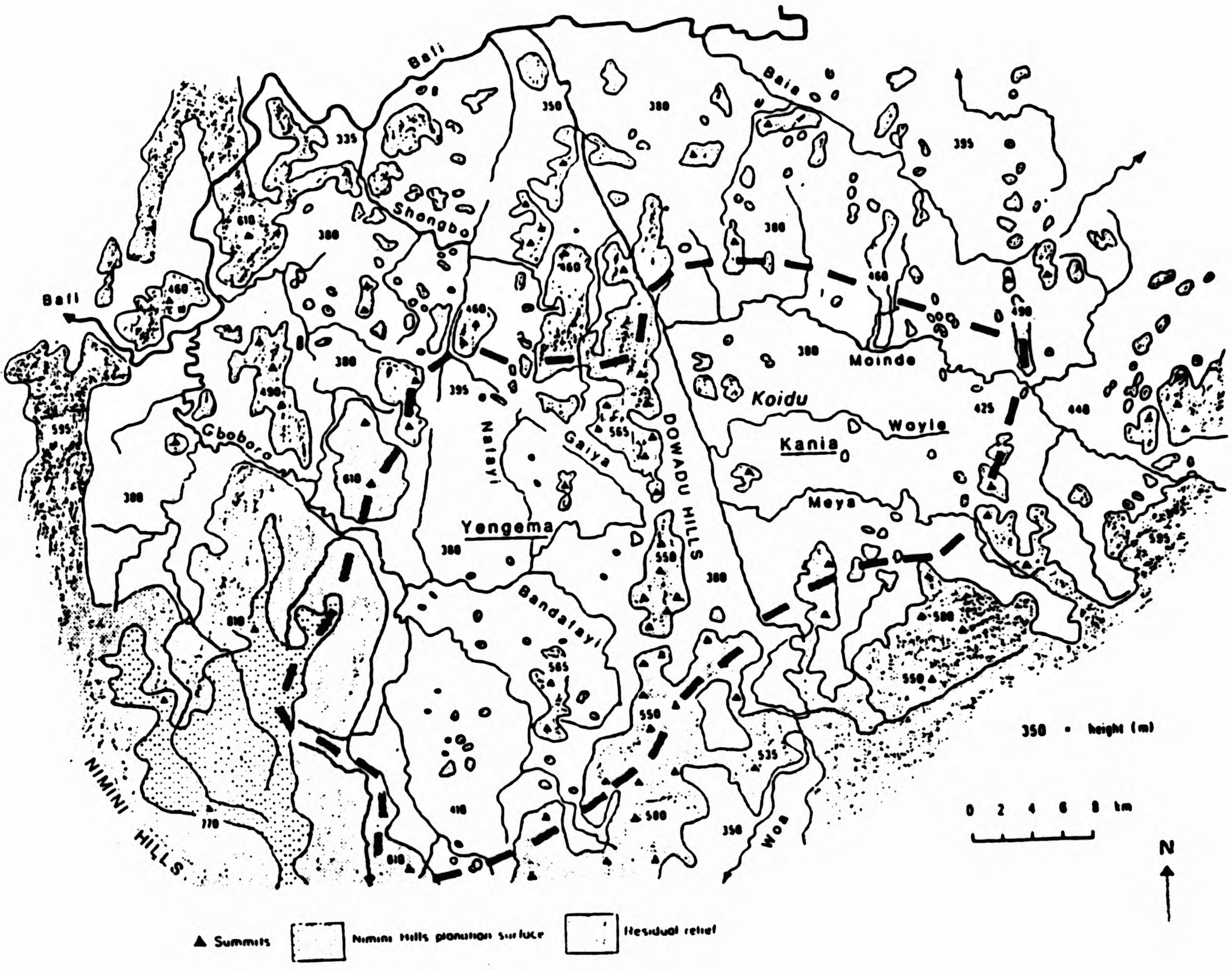


Figure 4.1 Koidu Basin, relief.

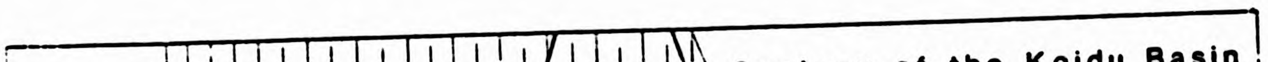


Figure 4.2

Geology of the Koidu Basin

(from Thomas & Thorp, 1980)

Insets: areas of Figures 4.6 & 4.10

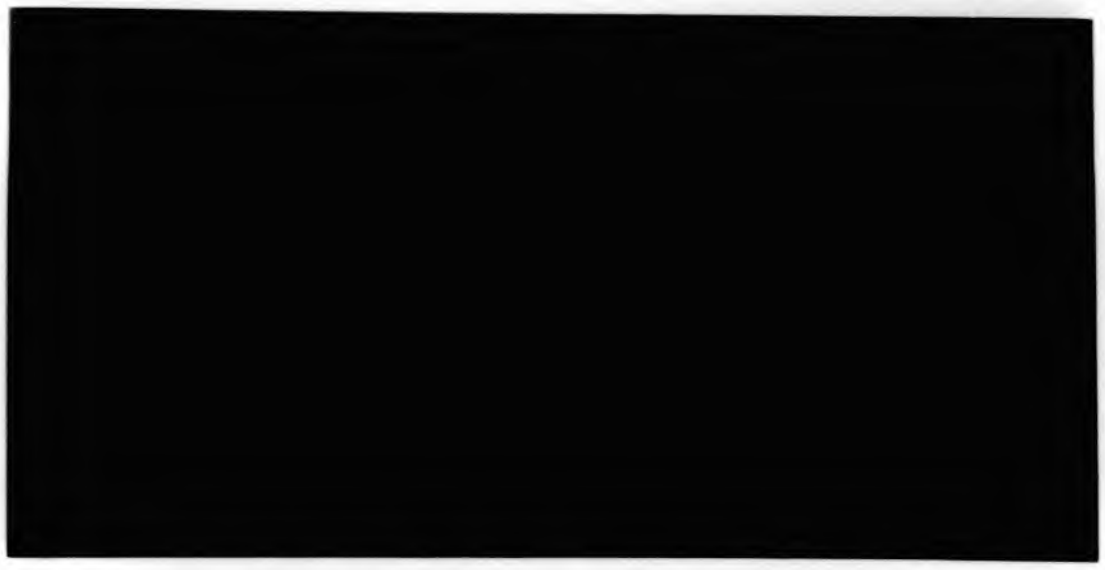


Plate 4.1 The Yengema area seen from the Dowadu Hills : foreground, the Gaiya valley; middle (L) Motema inselberg, (R) Holy Mountain inselberg; distance, Nimini Hills massif.

Plate 4.2 (R) View northwards along the Dowadu Hills, Schist Belt terrain with extensive glacis slopes; (L) Leopard Hill granitic inselberg.

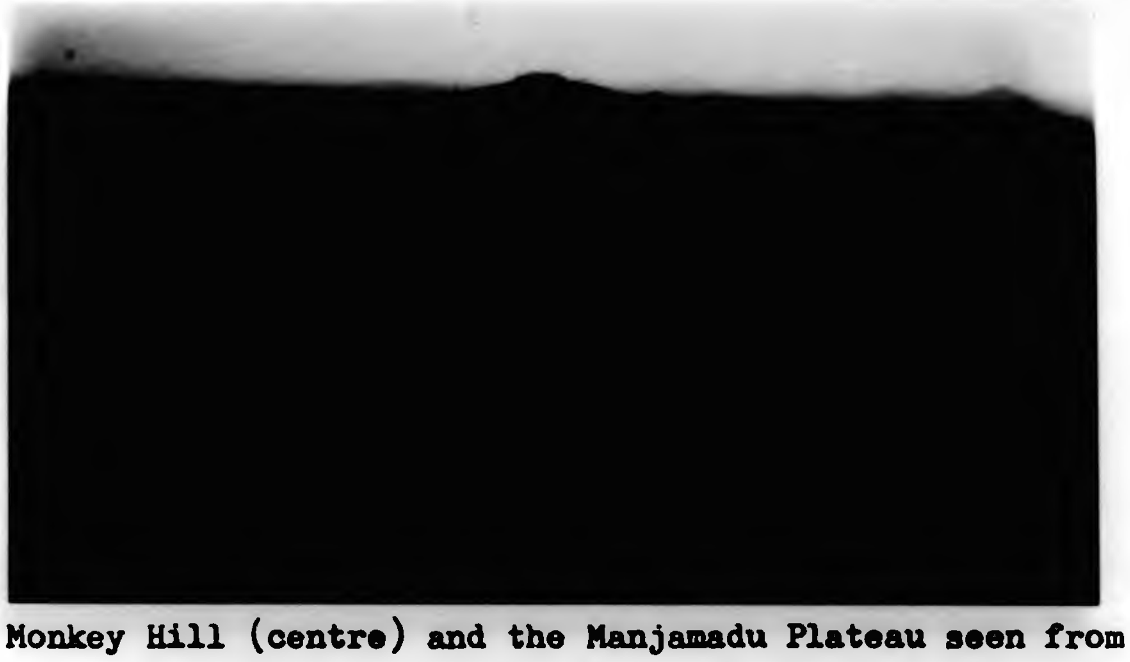


Plate 4.3 Monkey Hill (centre) and the Manjamadu Plateau seen from from the Dowadu Hills; foreground, the Meya-Moinde valley.

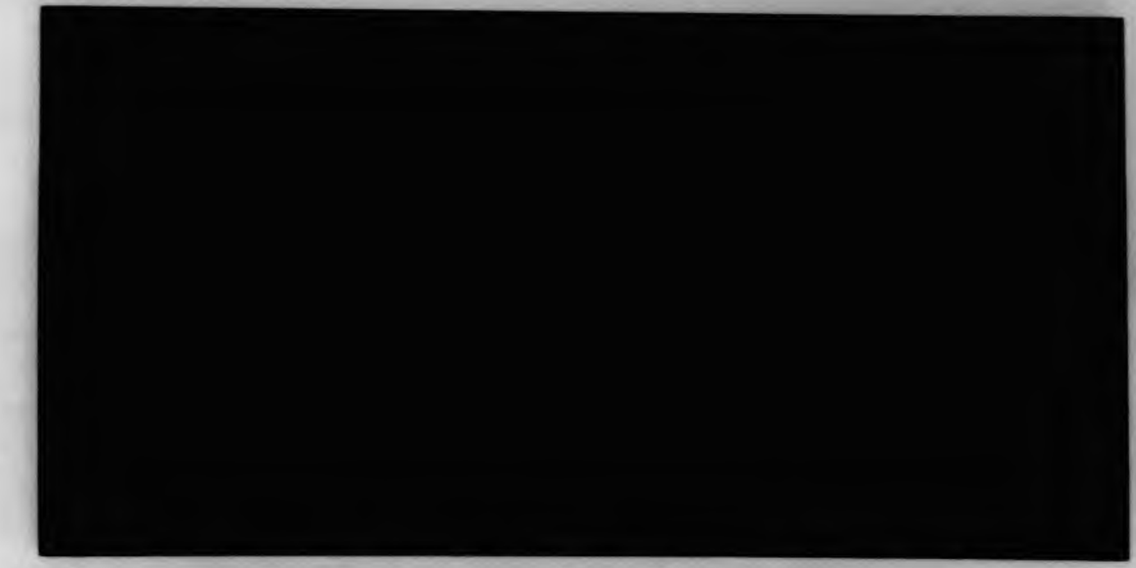


Plate 4.1 The Yengema area seen from the Dowadu Hills : foreground, the Gaiya valley; middle (L) Motema inselberg, (R) Holy Mountain inselberg; distance, Nimini Hills massif.

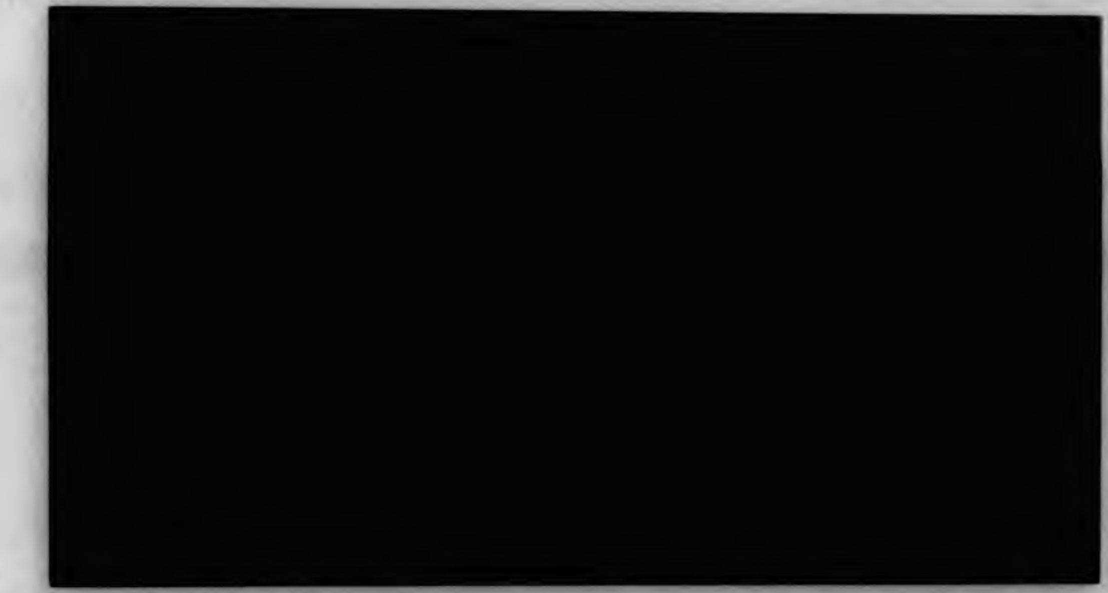


Plate 4.2 (R) View northwards along the Dowadu Hills, Schist Belt terrain with extensive glacis slopes; (L) Leopard Hill granitic inselberg.

Plate 4.3 Monkey Hill (centre) and the Manjamadu Plateau seen from from the Dowadu Hills; foreground, the Meya-Moinde valley.

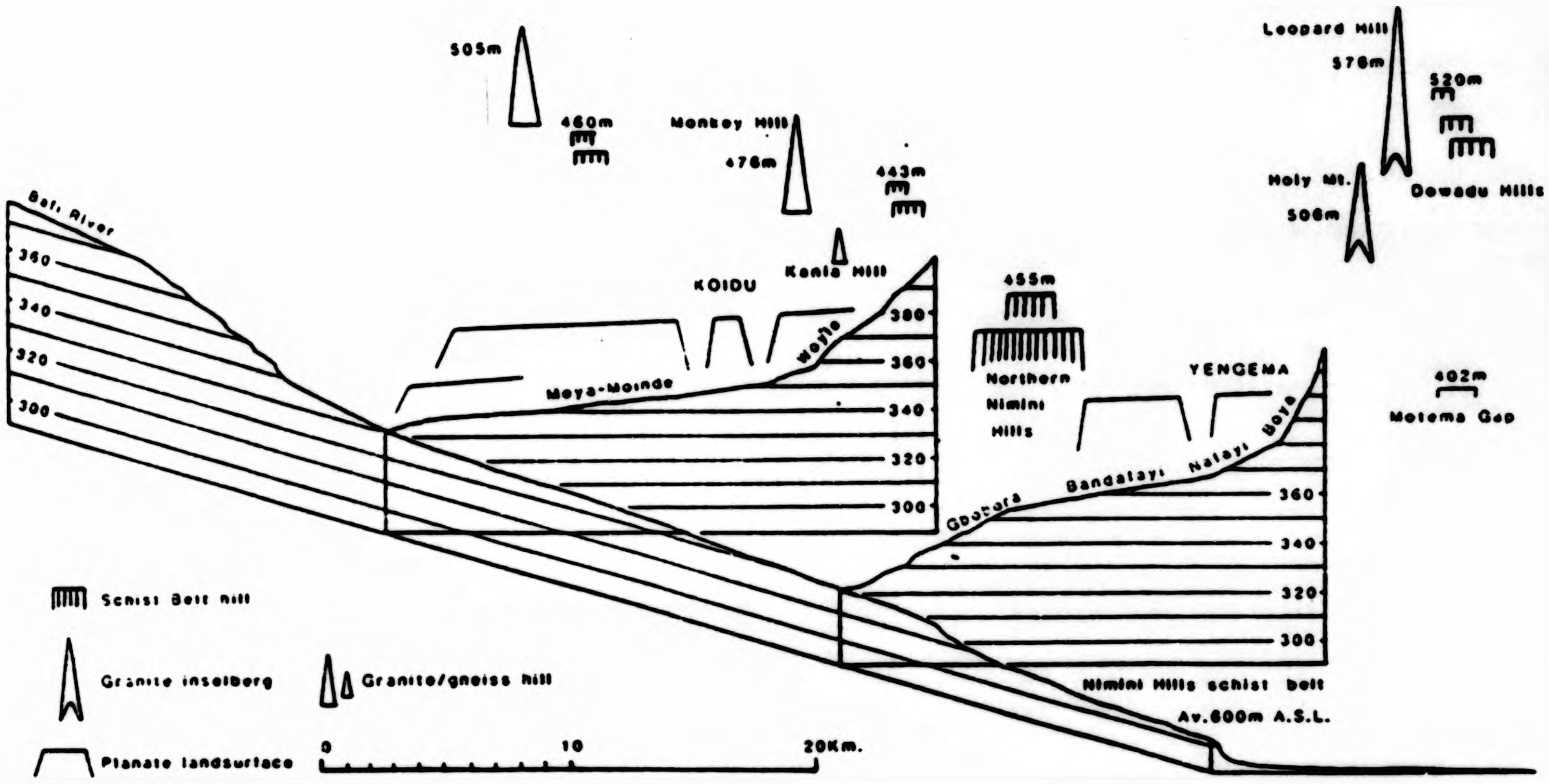


Figure 4.3 Long-profiles of rivers draining the Koidu Basin.

4.2 <u>The Kania area</u> lies in the headwater zone of tributaries draining into both the Meya and the Woyie rivers, near the centre of the Manjamadu Plateau, an area of extensive planate interfluves (mean elevation 386m A.S.L.; viz. Figures 4.4 and 4.5). The only large residual hills on this Plateau are Monkey Hill (476m) and Kania Hill (404m), formed from the Archaean granitic gneiss which underlies some 90% of the Plateau (Figure 4.6); the residual hills that form the eastern margin of the Plateau have formed from Proterozoic Schist Belt strata. The soil/saprolite cover is relatively extensive in the Kania area: only 14% of the 60 sample pits in this area encountered hard bedrock within 3m of the surface, compared with 55% of the pits in the Yengema area. Rock outcrops are rare on the Manjamadu Plateau, forming only 2.1% of the landsurface; they usually take the form of granitic gneiss corestones or kopjes, although two small inselbergs of intrusive granite occur near Koidu town (Figure 4.4).

YENGEMA	Altitude m A.S.L.	KANIA
**	457	*
	450	
	444	
	438	
*	432	
****	426	
***	420	
********	414	*
**	408	
*	402	*
**************	396	****
**	390	************
*******	384	***************
****	378	******
***	372	**
**	366	*
n=53		n=43
400.2m	Mean	387.7m
20.5m	S.D.	13.8m
	Landform frequency (%)	
17.0	Bare rock	2.1
10.6	Residual hills	10.4
37.6	Glacis slopes	13.3
10.5	Near-planate interfluves	40.9
12.2	Low terraces	8.3
12.1	Valley swamps	25.0
	Drainage density	
3.8	(Km/Km^2)	2.7
	% of pits with hard bedrock within 3m of surface	
55		14

Table 4.1 Comparative morphological data for the Yengema and Kania study areas.

Overleaf : Page 85, Figure 4.4

Geomorphology, Kania and the Manjamadu Plateau

Facing page :

Figure 4.4 **Geomorphology, Kania and the Manjamadu Plateau**

Lower map : **Relief and weathering features**

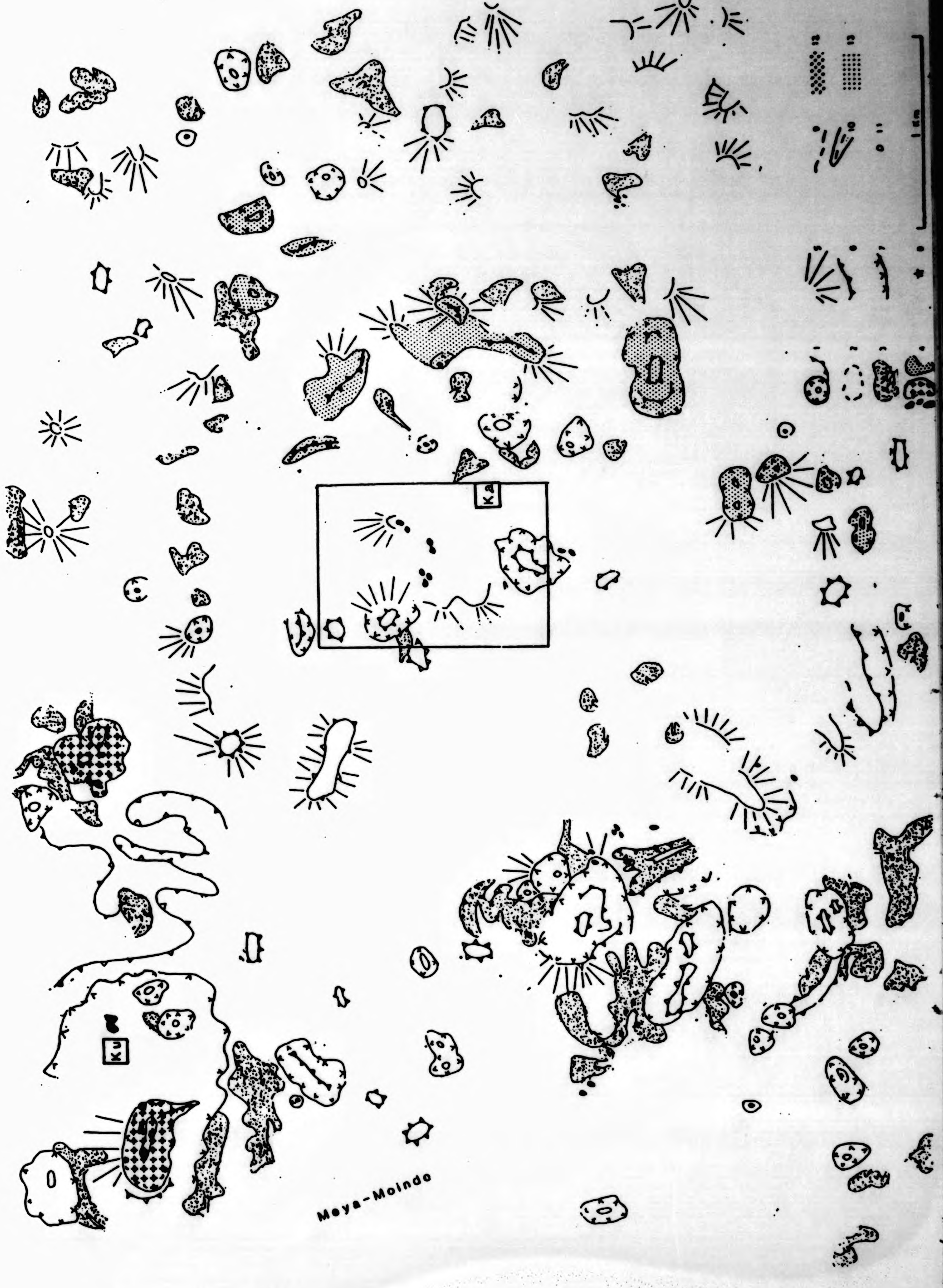
1. Residual hill and ridge
2. Low hill
3. Deep weathering zone
4. Corestones and granitic terrain/schist belt terrain
5. Glacis slope
6. Major convexity
7. Major concavity

Overlay map: **Fluvial features**

8. Windgap
9. Channelless valley swamp
10. Stream
11. Ground disturbed by mining
12. Flat interfluve ("High Terrace")
13. Low Terrace

Ka Kania village

Ku Koidu town centre


Ka
Kj
Meya-Moindo

Facing page :

Figure 4.4 **Geomorphology, Kania and the Manjamadu Plateau**

Lower map : **Relief and weathering features**

1. Residual hill and ridge
2. Low hill
3. Deep weathering zone
4. Corestones and granitic terrain/schist belt terrain
5. Glacis slope
6. Major convexity
7. Major concavity

Overlay map: **Fluvial features**

8. Windgap
9. Channelless valley swamp
10. Stream
11. Ground disturbed by mining
12. Flat interfluve ("High Terrace")
13. Low Terrace

Ka Kania village

Ku Koidu town centre

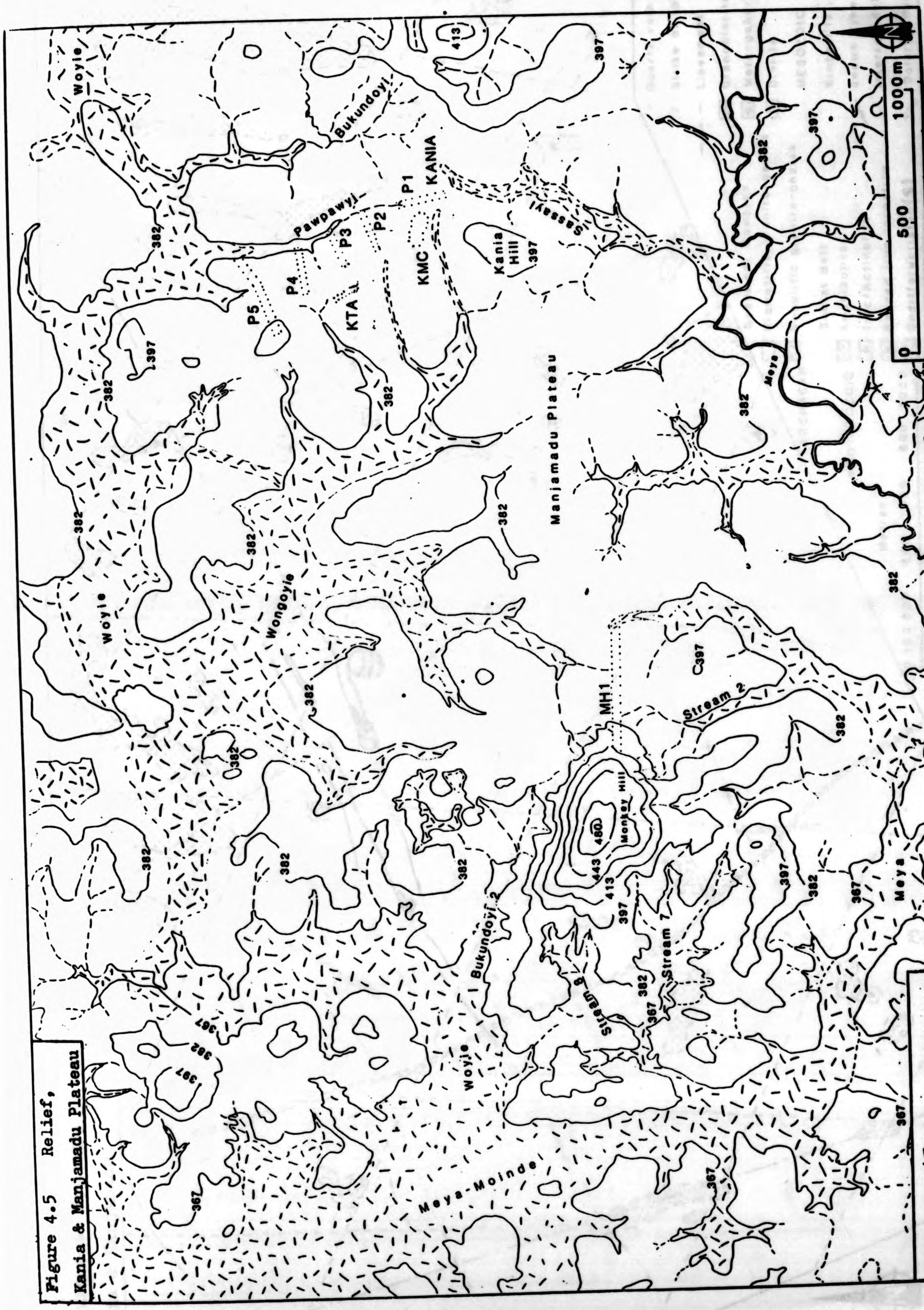


Figure 4.5 Relief, Kania & Manjamadu Plateau

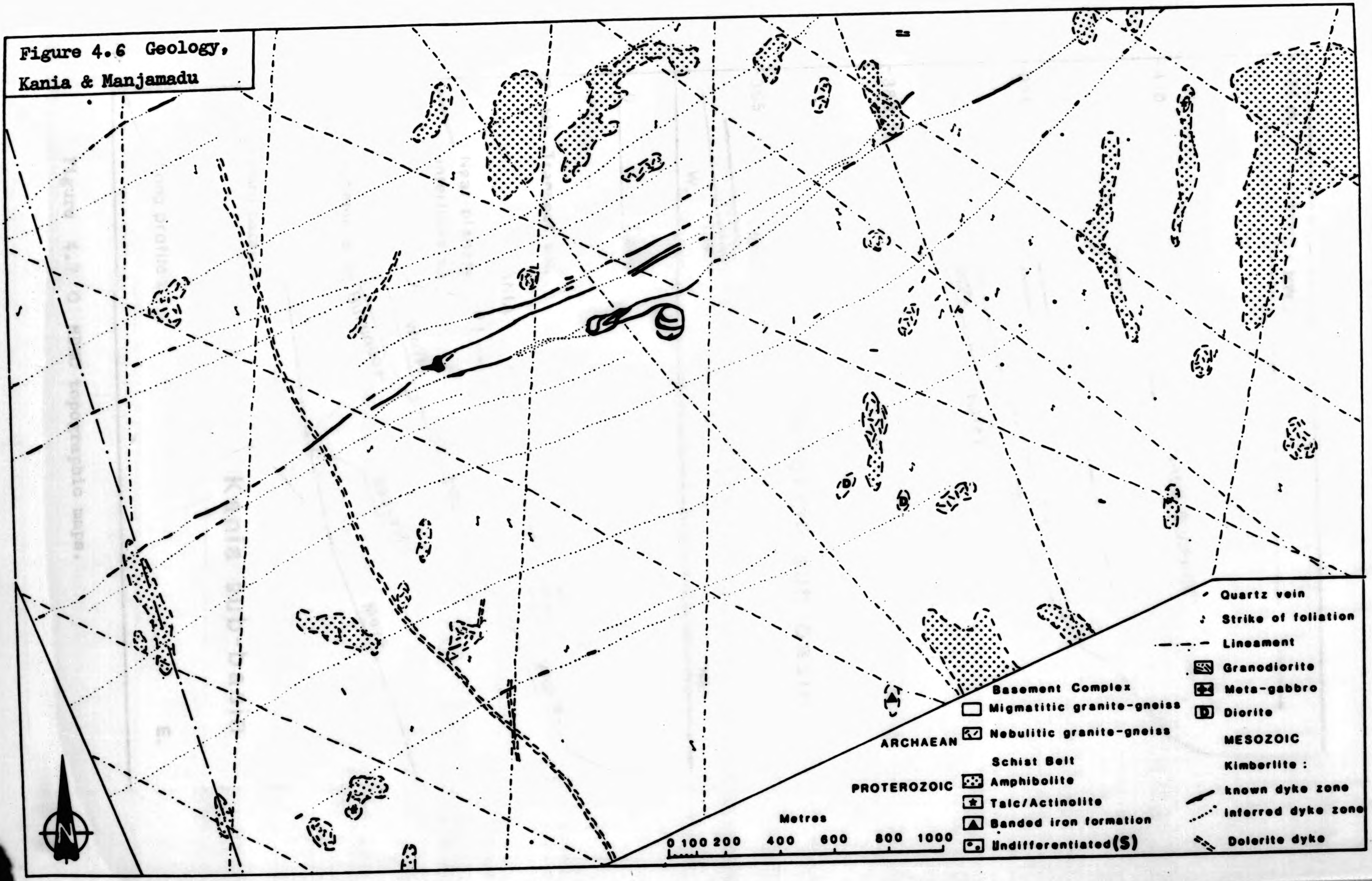


Figure 4.6 Geology, Kania & Manjamadu

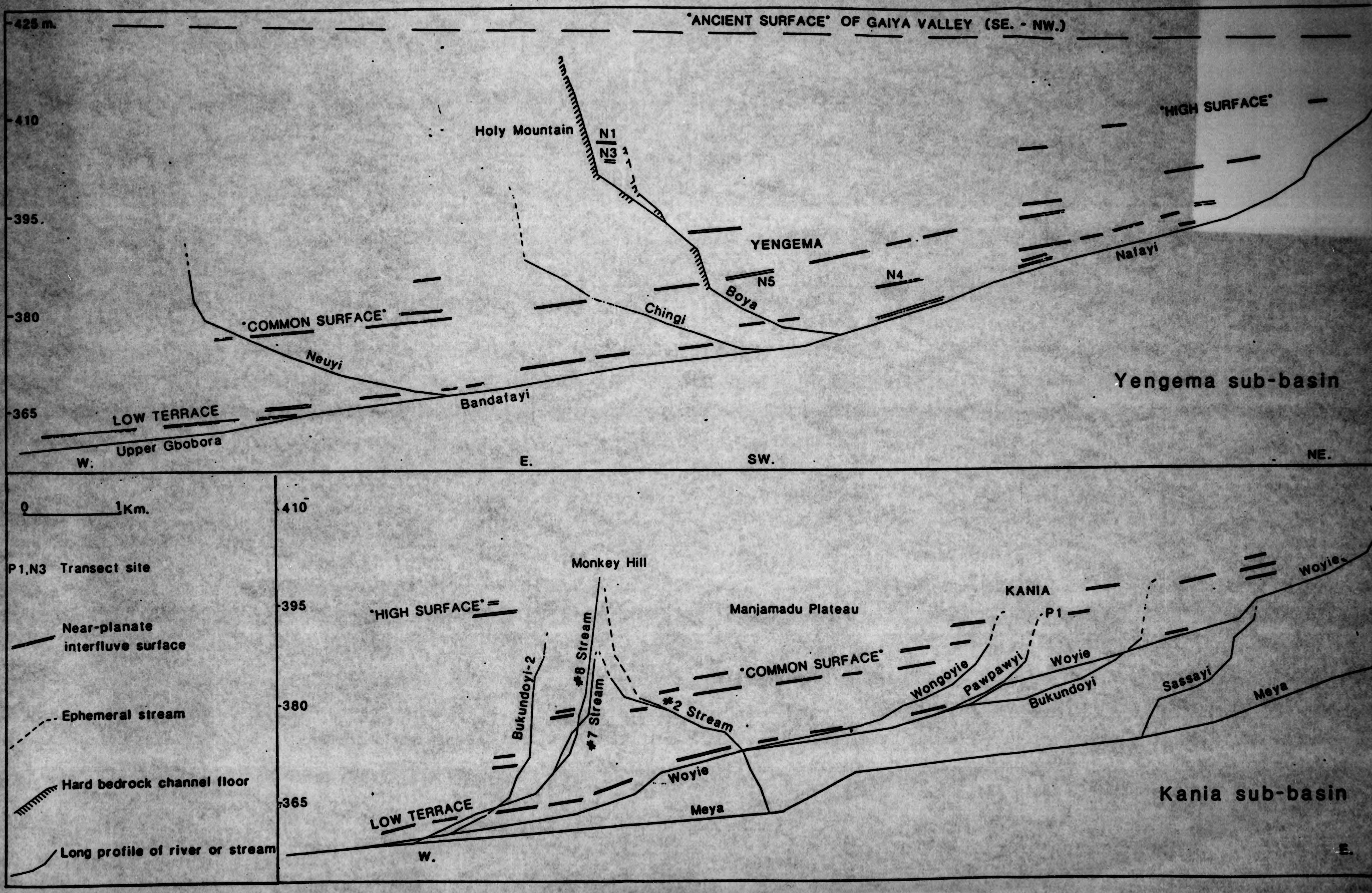


Figure 4.7 Detailed long-sections, Yengema and Kania sub-basins. Compiled from 1 : 5000 NDMC topographic maps.

On the basis of 1:20 000-scale airphoto interpretation, the planate landsurfaces of the Kania area were subdivided into "Low Terraces" of clear alluvial origin, and "Planate Interfluves" or "Hillside Benches" of uncertain origin. The detailed long sections of Figure 4.7, compiled from N.D.M.C. 1:5,000 scale maps contoured every 3m, support this subdivision, with distinct Low Terraces commonly occurring at altitudes of less than 6m above the main drainage channels; whilst the "Planate Interfluves" in fact consist of two major subgroups: a common "Common Surface" 5 to 10m above the headwaters of the Woyie river and 10 to 15m above the lower Woyie and Meya rivers; with a "High Surface" 30 to 35m above the Meya River.

A number of knick points stand out along the courses of the Woyie and Meya rivers. A comparison of the geological maps and 1:5,000 scale topographic maps indicates that only one of these knick points is due to a belt of resistant bedrock: this occurs on the Woyie River at 383m A.S.L., 0.4Km upstream of the Bukundoyi stream confluence (NE corner of Figures 4.5 and 4.6). The other knick points appear to be largely the result of river rejuvenation. Both the middle Meya and the lower Woyie rivers each cross a major knick point at ca.370m A.S.L.; that these two rivers have a common knick point altitude may be coincidence, but the occurrence of a second common knick point altitude, this time along the tributaries of these rivers at approximately 380m A.S.L., indicates that the Meya-Moinde river system has experienced a relatively recent "pulse" of rejuvenation. This rejuvenation appears to have been most effective below 370m A.S.L., as the "hanging valley" form of No. 2 stream in Figure 4.7 illustrates. It has also apparently led to fluvial incision along tributaries up to 380m A.S.L., producing the knick points along the

Wongoyie, Bukundoyie and Sassayi streams. The long profiles of these tributaries upstream of this 380m knick point, have apparently not been affected by this rejuvenation and have smooth concave long profiles; this includes most of the Pawpawyi Stream at the centre of the Kania sample area (Figure 4.5).

4.3 The Yengema area has both a greater variety of bedrock lithologies (cf. Figures 4.6 and 4.10) and a greater variation in relief than the Kania area (cf. Figures 4.5 and 4.9). Although the Archaean granitic gneiss is the most common lithological type of the Yengema area it only accounts for 60 to 70% of the bedrock, compared to 90% for the Kania area. The flanks of the Yengema sub-basin are formed by Schist Belt hill ranges, the northern Nimini Hills to the west and the Dowadu Hills to the east. Intrusive granites form the inselbergs of Holy Mountain and Leopard Hill. Granodioritic gneiss forms hills with flat, highly lateritized summits; whilst smaller residual hills are formed by nebulitic gneiss and rare gabbroic intrusions (Figure 4.10).

The higher proportion of bare rock and residual hills in the Yengema area relative to the Kania area, 19.6% versus 12.5% of the landsurface, (Table 4.1), may be the reason why glacis slopes are the most frequently occurring landform in the Yengema area, covering 37.6% of the landsurface; whilst planate interfluves are the dominant landform type of the Kania area, accounting for 40.9% of the landsurface (cf. Figures 4.4 and 4.8).

Overleaf : Page 91, Figure 4.8

Yengema, Geomorphology

Facing page :

Figure 4.8 Yengema, Geomorphology

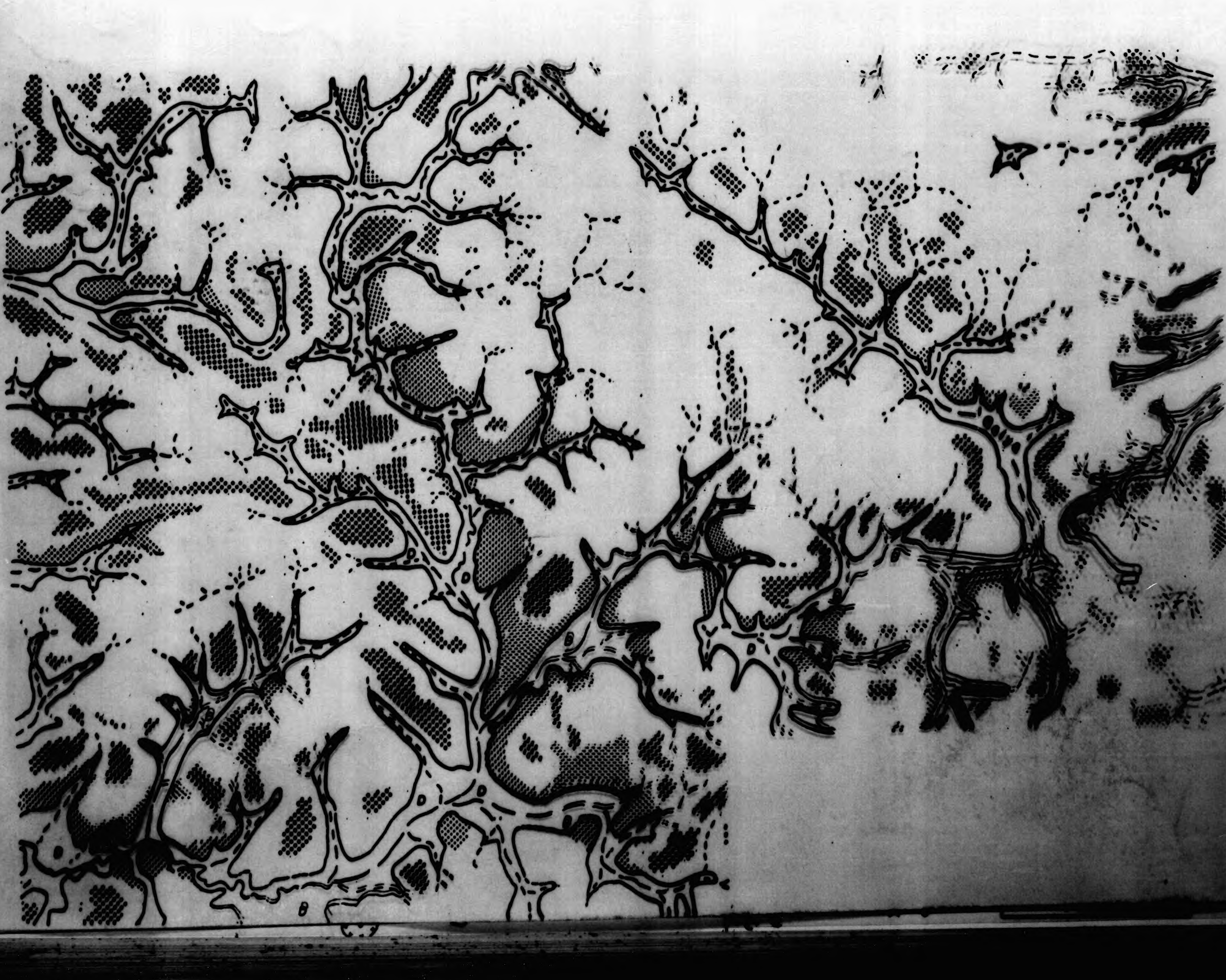
Lower map : **Relief and weathering features**

1. Residual hill and ridge
2. Low hill
3. Deep weathering zone
4. Corestones and granitic terrain/schist belt terrain
5. Glacis slope
6. Major convexity
7. Major concavity

Overlay map: **Fluvial features**

8. Windgap
9. Channelless valley swamp
10. Stream
11. Ground disturbed by mining
12. Flat interfluve ("High Terrace")
13. Low Terrace

Y N.D.M.C. HQ, Yengema



Overleaf : Page 91, Figure 4.8

Yengema, Geomorphology

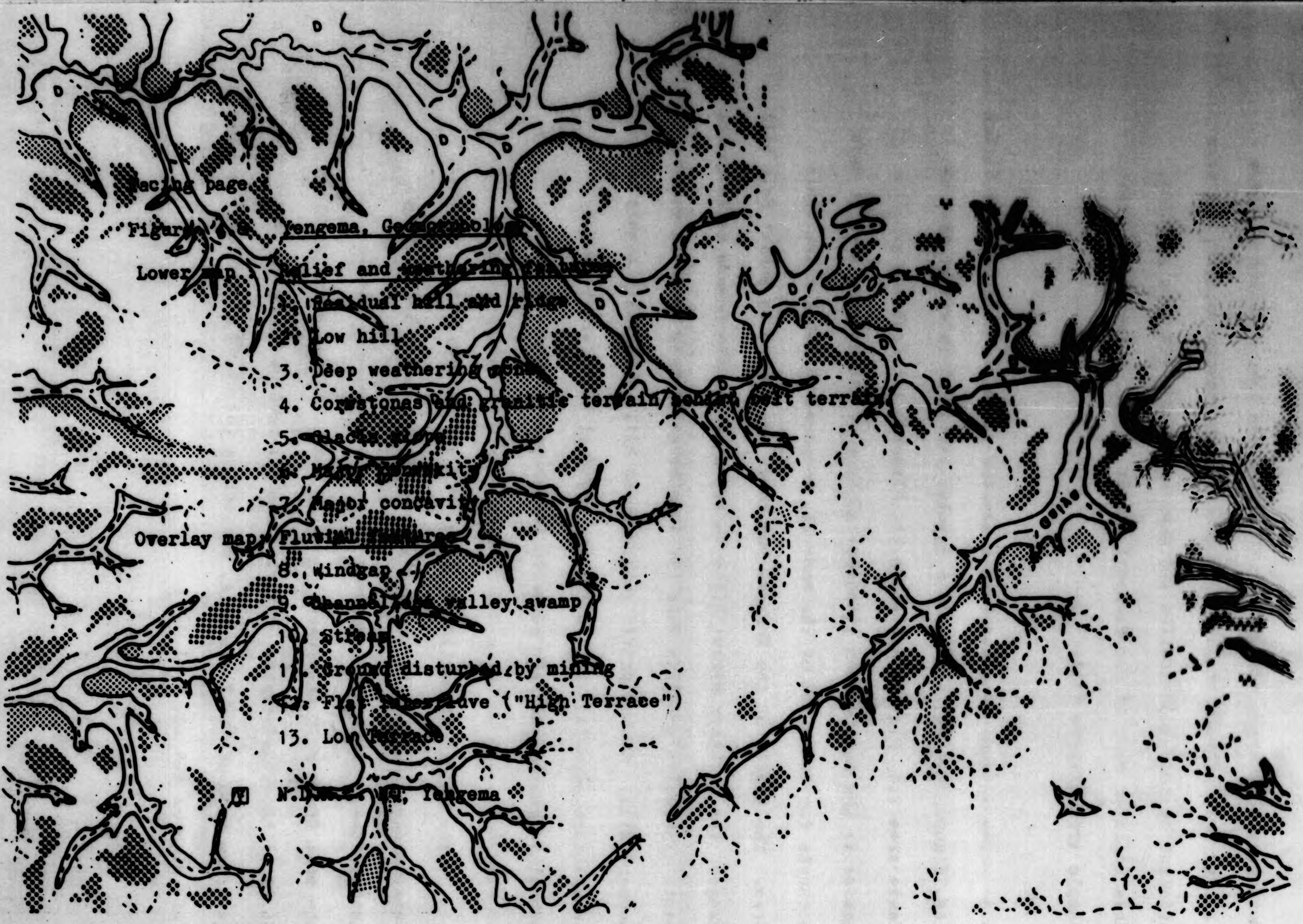


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Figure 4.8 Yengema, Geomorphology

Lower map: Relief and weathering features

1. Residual hill and ridge
2. Low hill
3. Deep weathering zone
4. Corestones and granitic terrain/pediment terrace
5. Glacis slope
6. Major convexity
7. Major concavity

Overlay map: Fluvial features

8. Windgap
9. Channelless valley swamp
10. Stream
11. Ground disturbed by mining
12. Flat interfluve ("High Terrace")
13. Low Terrace

Y N.D.M.C. HQ, Yengema

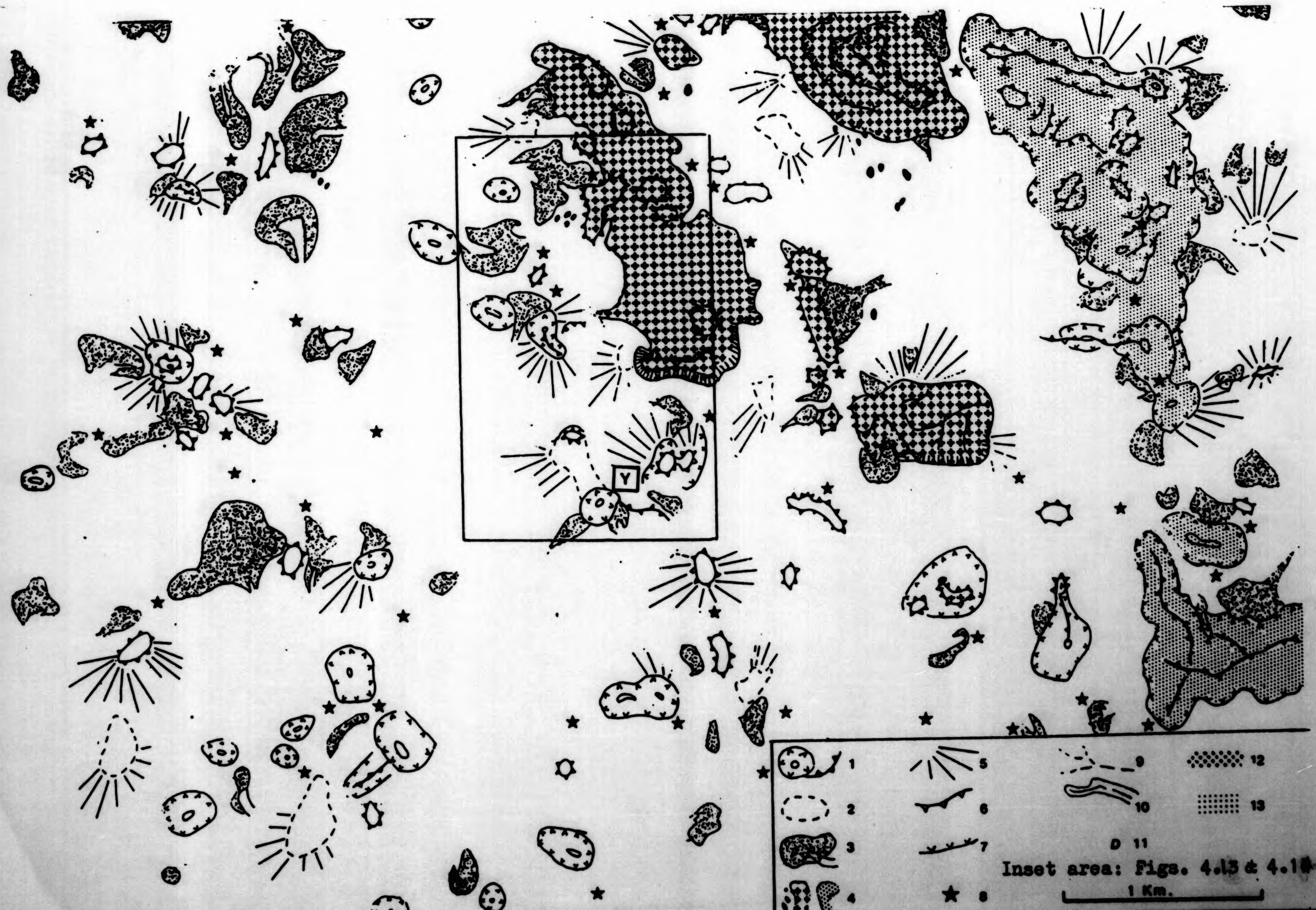

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Figure 4.8 **Yengema, Geomorphology**

Lower map : **Relief and weathering features**

1. Residual hill and ridge
2. Low hill
3. Deep weathering zone
4. Corestones and granitic terrain/schist belt terrain
5. Glacis slope
6. Major convexity
7. Major concavity

Overlay map: **Fluvial features**

8. Windgap
9. Channelless valley swamp
10. Stream
11. Ground disturbed by mining
12. Flat interfluve ("High Terrace")
13. Low Terrace

Y N.D.M.C. HQ, Yengema

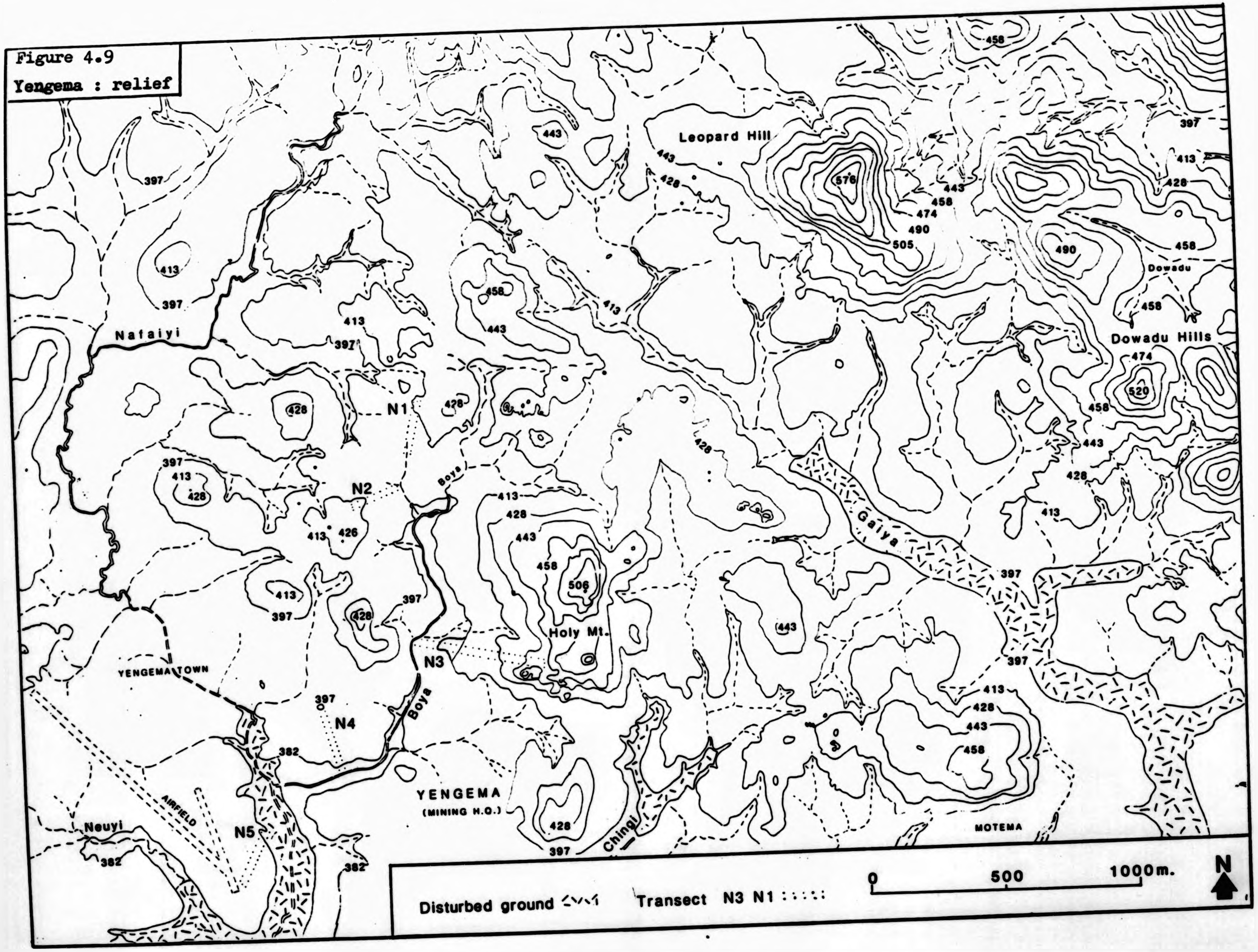
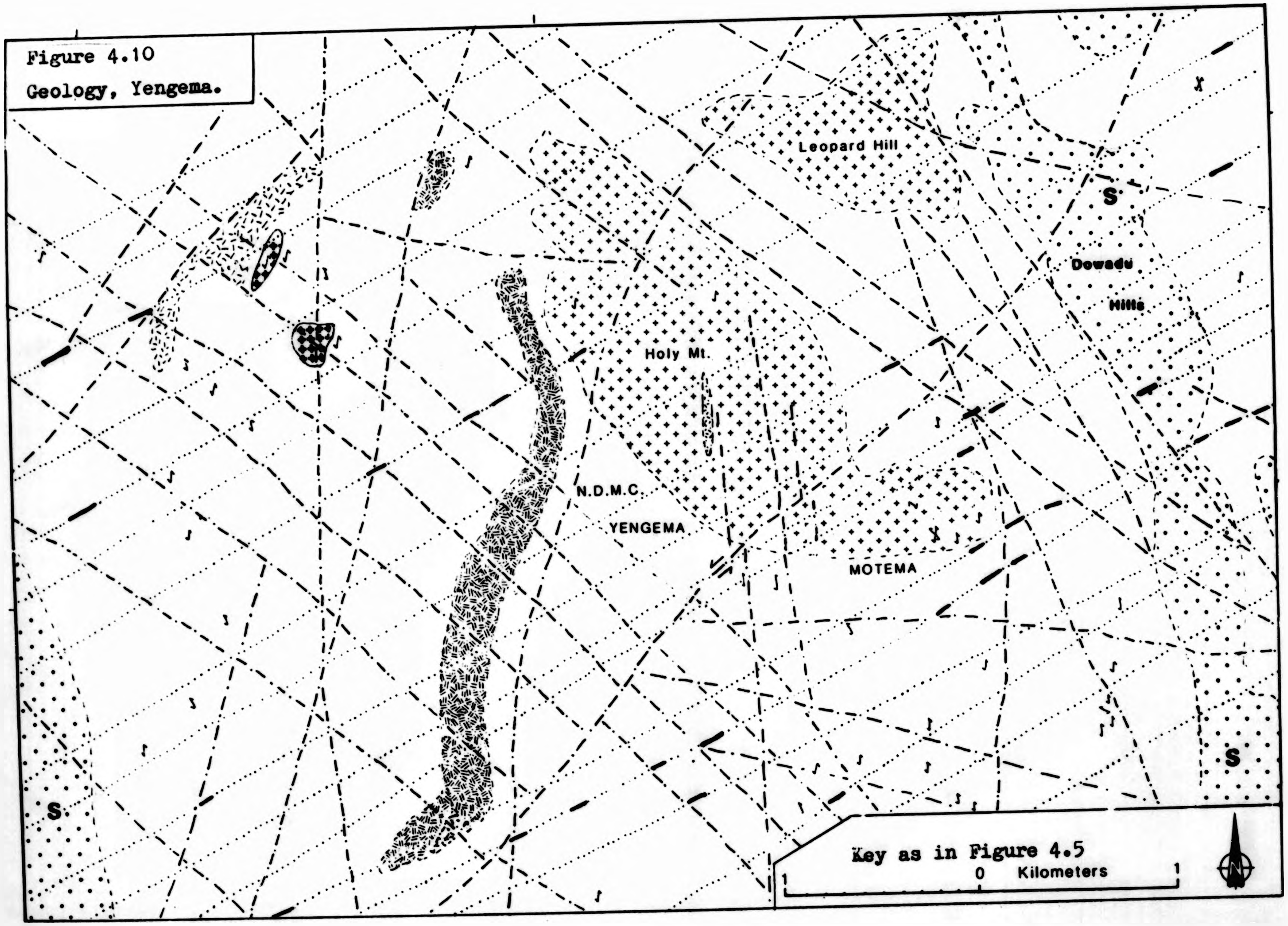


Figure 4.9

Yengema : relief

Figure 4.10

Geology, Yengema.



Key as in Figure 4.5

Although the variations in relief within the Yengema appear to be strongly correlated with variations in lithology, the analysis of landsurface altitudinal variations presented in Table 4.1 shows that three distinct "surfaces" occur in the Yengema area at ca. 414, 396 and 384m A.S.L., rather than the more scattered frequency distribution that might be expected from a landsurface totally derived from at least four different lithological types of considerable areal extent (viz. Figure 4.10. The implications of these three "surfaces" on the landscape development of the Koidu basin will be discussed more fully in Chapter 6.

Reference to Figure 4.7 shows that the long profiles of the rivers, tributaries, terraces and planate interfluves of both the Yengema and Kania areas have the same sequence of Low Terraces, "Common Surfaces" and "High Surfaces"; however, there are nevertheless some major differences between these two areas. Firstly, rock bars are virtually absent along the courses of streams and rivers in the Kania area, whilst they are common features in the Yengema area. Furthermore, channelless valley swamps are twice as common in the Kania area as in the Yengema area, with 25% versus 12% of the landsurface; and buried valley heads, whilst common in the Kania area,are virtually absent in the Yengema area. These differences are only partly due to lithological variations between these two areas. Regardless of bedrock differences, it is still evident that the Yengema area has experienced a greater degree of soil/saprolite stripping than the Kania area.

Secondly, none of the tributaries in the Yengema area were found to be "hanging" 6 to 10m above the confluence with their trunk river, as is the case with the tributaries of the Meya River in Figure 4.7 ; this may reflect a greater degree of fluvial incision. The Yengema area is apparently at a stage of landform development where much of the soil/saprolite mantle has been eroded away, producing valley floors with "pockets" of saprolite protected by rock bars that prevent "pulses" of river rejuvenation from rapidly progressing upstream. Conversely, the Kania area still has an extensive soil/saprolite cover. It seems that the saprolite of the Meya Valley is exceptionally deep, allowing the last "pulse" of river rejuvenation in this area to rapidly excavate a relatively deep channel, to which the gradients of tributary streams have not yet adjusted.

Finally, low terraces are more extensive in the Yengema area than in the Kania area: 12.2% versus 8.3% of the landsurface. The Yengema area low terraces can be subdivided into "older" low terraces with altitudes between 3 and 6m above the main channel, and "younger" low terraces with altitudes less than 3m above the main channel. Reference to Figure 4.7 shows that two sets of low terrace occur extensively in the Yengema area; whilst only one set occurs extensively in the Kania area

The rivers of the Yengema area appear to have experienced at least two relatively recent phases of rejuvenation and associated Low Terrace formation, probably during the late Quaternary and Holocene. The lack of a second, "older", low terrace group along the middle reaches of the Woyie river indicates that the Kania area has only experienced one recent phase of river rejuvenation. The data concerning drainage density, percentage of bare rock exposure and relative cover of saprolite presented in Table 4.1 support the hypothesis that the Yengema area has experienced a greater degree of fluvial incision and saprolite stripping than the Kania area. Further evidence comes from the relative numbers of windgaps recognised for each area from Figures 4.4 and 4.8: 25 for Kania, compared with 45 for Yengema.

Using the nomenclature of Thomas (1974, p.237), much of the Kania area corresponds to a "partially dissected etchplain", where simultaneous lowering of the landsurface and weathering front dominates over progressive stripping. However, given the minimal degree of dissection in the Kania area the term, "saprolite-mantled etchplain" is preferred here. Conversely, the Yengema area appears to be a "partially stripped etchplain", where fluvial incision and the stripping away of saprolite has in many places occurred at a faster rate than the renewal of saprolitic cover by weathering. It may be that the main reason for the greater degree of fluvial incision in the Yengema area was a major change in the drainage regime, possibly the breaching of the Nimini Hills rock bars by the Gbobora River to capture the Bandafayi/Nafayi/Gaiya drainage system, during a period of extreme environmental instability at the onset of the Quaternary. Prior to this postulated period of river capture, the drainage from the Yengema area was probably in a northerly direction towards the present Shongbo River. Evidence for this comes from the "Ancient Surface" indicated by the hillside benches, cols and summit levels of the Dowadu Hills along the valley of the Gaiya stream (Figure 4.7). This "Ancient Surface" slopes northwestwards with an average gradient of 0.5m/Km: this is the reverse of the present course of the Gaiya River, which flows southwards into the Gbobora system.

In contrast, the rivers of the Kania area do not appear to have been affected by any major reversals of drainage; although the relatively recent breaching of a rock barrier midway along the Meya-Moinde River appears to have sent a "pulse" of rejuvenation upriver.

4.4 Detailed geomorphology

The results of the detailed field mapping, initially drafted onto maps of 1:1250 scale, are presented in Figures 4.11 to 4.16, the location of each study area being given in Figures 4.5 and 4.8; the transects indicated on these maps are presented and discussed in the next chapter.

The Kania study area lies in the drainage basin of the Pawpawyi Stream, a tributary of the Woyie River, draining the Manjamadu Plateau (Figures 4.5 and 4.11). The Pawpawyi drainage system commences on the interfluves of the Kania area as gentle surface depressions, or "swales", which have mean slope angles of 5.2° and feed into the valley head or valleyside gullies from the planate interfluves (mean slope 0.8°, mean altitude 386m).

At the valley head there is a pronounced break in slope to angles of between 7° and 19° with a drop of 3-4m from the swale to the channelless valleyhead swamp. At approximately 100m downstream a large number of granitic gneiss corestones outcrop along the valley floor and a permanent channel occurs. Only one tributary valley joins the Pawpawyi valley downstream, although surface slope measurements indicate that another channel, now abandoned and infilled, may have joined the Pawpawyi on its lower right bank (Figure 4.12). The Pawpawyi valley has a sohlenkerbtal form (Louis, 1964), with a flat floor and steep sides. Small gullies occasionally occur along the valley sides, accompanied by outcrops of granitic gneiss corestones. Low terraces are of relatively small areal extent along the Pawpawyi valley; burial under colluvium has made their surface morphology indistinct from the interfluve rims.

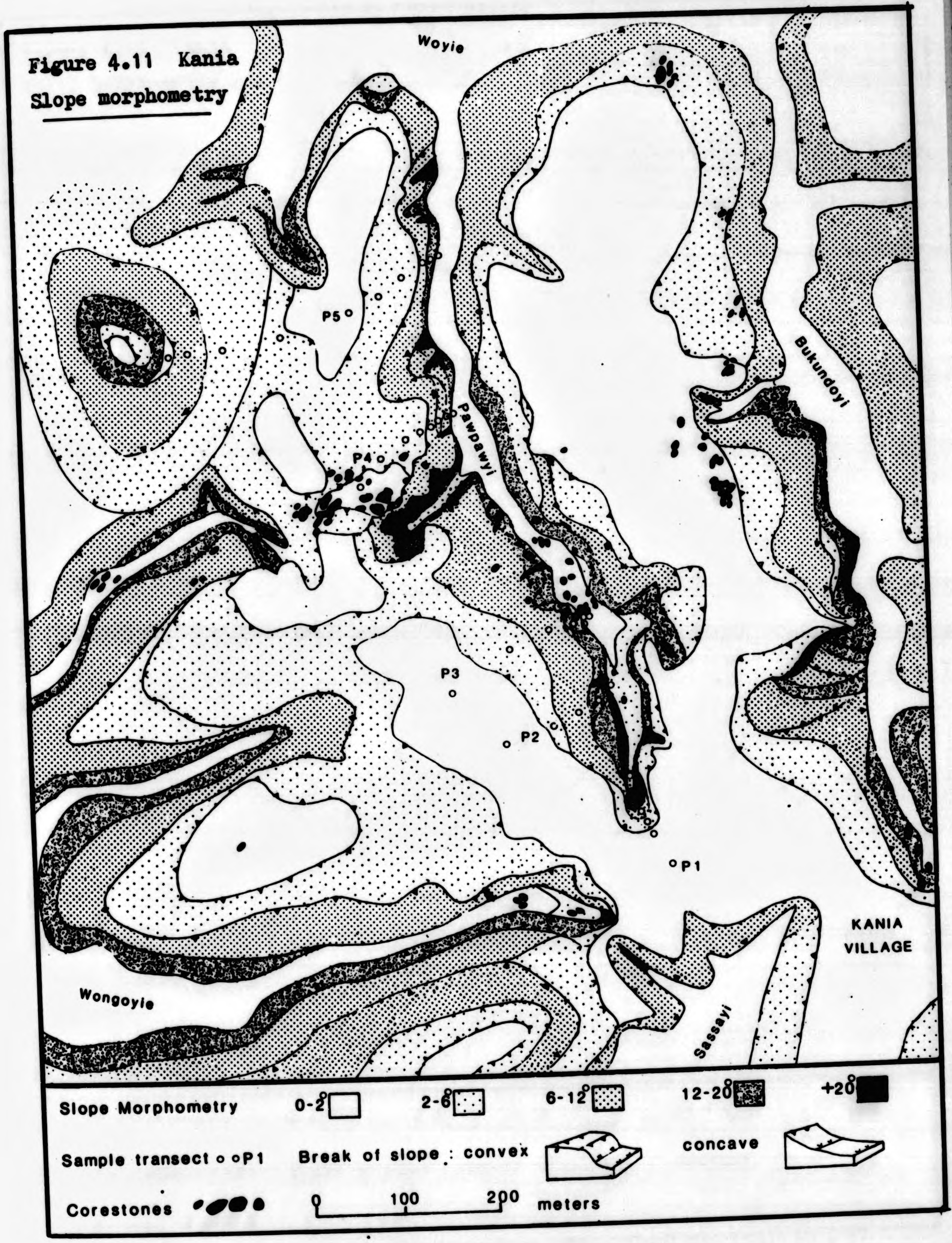


Figure 4.11 Kania Slope morphometry

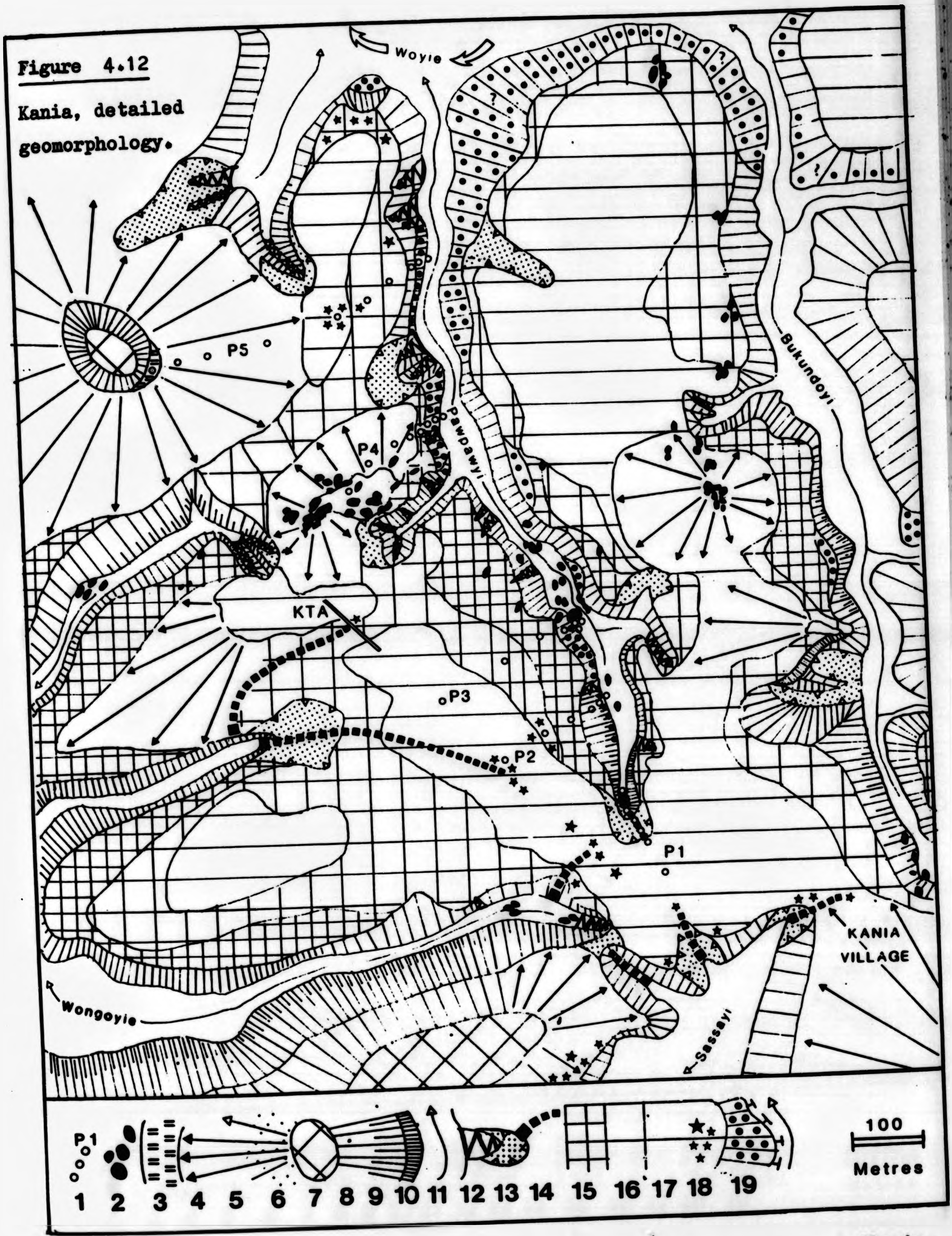


Figure 4.12

Kania, detailed geomorphology.

1 Transect No. 2 Corestones 3 Hillside bench 4 Glacis, depositional 5 Glacis,
erosive 6 Granitic terrain 7 Hill summit Hill/valleyside slope 8: 6°-12°
9: 12°-20° 10: +20° 11 Stream 12 Gully 13 Swale 14 Buried valleyhead
15 Interfluve rim 16 Sloping interfluve 17 Planate interfluve
18 'Ancient' alluvial deposits 19 Quaternary/Holocene low terraces.

Figure 4.13, Yengema : slope morphology

Figure 4.13, Yengema : slope morphology

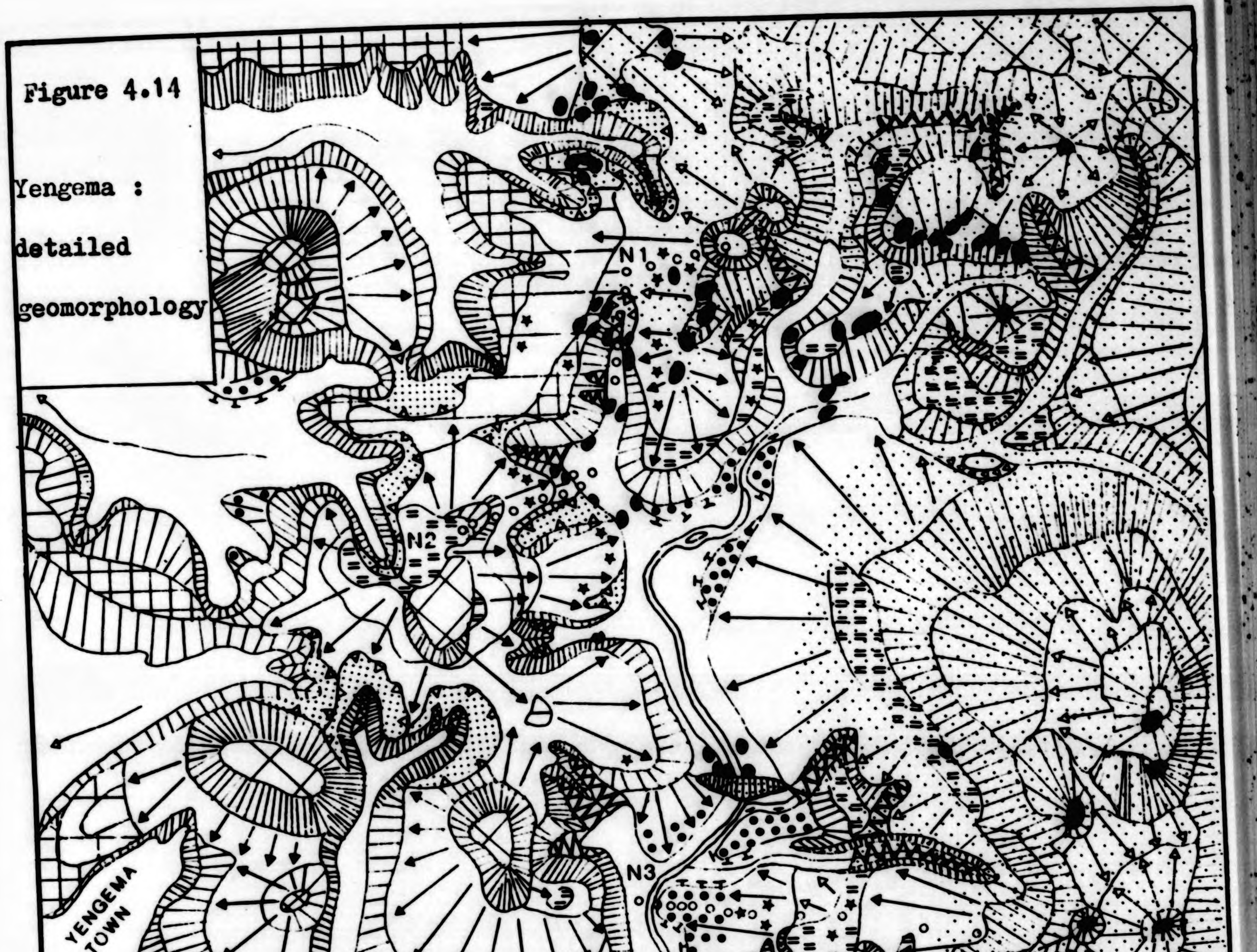


Figure 4.14

Yengema : detailed geomorphology

(Key as in Figure 4.12).

70-80% of the Kania study area consists of planate or near-planate interfluves. These are featureless, apart from two zones of nebulitic granite-gneiss corestones each fringing gullies that feed into the centre of the Wongoyie-Pawpawyi and Pawpawyi-Bukundoyi interfluves. However, the geomorphological map, (Figure 4.12), shows that the featureless surface of these interfluves is deceptive: extensive infilled valley heads and infilled depressions occur beneath them. This indicates that the local drainage system was once far more extensive and the ability of the Kania area streams to remove material from their valleys has since declined considerably.

Two granitic gneiss residual hills occur in the Kania area. These have hillside benches and relatively flat summits at ca.400m A.S.L. Both are fringed by glacis slopes, the most extensive being around the northern hill traversed by Transect P5 (viz. Figure 4.12).

<u>The Yengema study area</u> is centred on the Boya tributary of the Nafayi River (Figures 4.8 and 4.13). Reference to Table 4.1 and comparison of the slope steepness and surficial geology maps of the Yengema study area with those of the Kania study area (Figures 4.13 and 4.14 versus Figures 4.11 and 4.12), shows that the two study areas are geomorphologically quite distinct, although they are only 20km apart.

The Yengema study area is characterised by a relatively high proportion of rock outcrops and steep slopes. Glacis slopes are common, 37.6% of the landsurface, whilst planate interfluves account for only 10 to 15% of the landsurface. The Boya stream has its origins in the joint planes and fault zones of the rocky terrain of the northern extension of the Holy Mountain granitic intrusion; or, in the case of Transect M1, in the swales that commence in the glacis slopes which fringe these granitic inselbergs and extend down to the valley heads. Granitic corestones are frequent occurrences, particularly fringing valley heads and in the valley head swamps.

Four distinct types of terrain occur in the Yengema area: "Schist Belt", "gneissic", "granitic" and "granodioritic"; along with occasional "hybrid" types. Schist Belt terrain forms the margins of the Yengema sub-basin; elongate steep hills with boulder-choked streams pass into extensive glacis slopes that are often lateritized (viz. Plate 4.2). The gneissic terrain is similar to that of the Kania area, with extensive planate interfluves and occasional residual hills, though, unlike Kania, buried valley heads are virtually absent from the Yengema area. The granitic terrain is characterised by rock exposures, forming domes, kopjes and inselbergs, with Holy Mountain reaching 506m A.S.L. (viz. Plate 4.1), fringed by extensive glacis slopes, and with numerous corestones or even rock bars along the valley floors. Granodioritic terrain tends to be characterised by steep-sided, flat-topped residual hills, often with extensive hillside benches, which have largely formed as a result of the formation of lateritic duricrusts that have effectively "capped" these summits and benches. Blocks of ferricrete rubble occur in the footslopes of the granodioritic hills, which merge downslope into extensive glacis deposits consisting of red-brown colluvial sandy clay, as opposed to the generally grey-brown clayey sand of the colluvium from gneissic or granitic terrains. The interfluves from which Transects N4 and N5 were made, both fringing the Nafayi River (Figure 4.14), appear to be intermediate between the gneissic and the granodioritic terrain types. They both have planate or near-planate forms, but they also both have indurated granodioritic bedrock and a high proportion of duricrust fragments in their lateritic top gravels.

Unlike the Kania area, the river and stream terraces of the Yengema area have surface morphologies that are easily distinguished during field mapping, as along Transects M2, M3 ands M5, with only the terraces of Transect M4 being concealed by colluvial deposits. A further feature of the microrelief of the Yengema study area that distinguishes it from the Kania area is the common occurrence of two sets of lateritic pavements, with one set at ca. 10m and the other at 3-5m above the present valley floor. In contrast, only one lateritic pavement was found in the Kania area, capping the low terrace of Transect P3, 3m above the valley floor. These apparently formed by groundwater seepage and the "fixing" of iron sesquioxides, followed by a phase of fluvial incision, that left these former "groundwater laterites" high and dry above the valley floor.

The results of these detailed geomorphological surveys thus indicate that the Yengema study area has experienced a greater degree of fluvial incision and associated soil/saprolite stripping than the Kania study area. The geomorphological evolution of these two study sites will be discussed in detail in Chapter 6, following the presentation of the results of the surficial geology sampling programme in the next chapter.

CHAPTER FIVE

RESULTS: MATERIALS

The previous chapter presented the geomorphology and solid geology of the Koidu Basin, and introduced the concept that the landscape can be subdivided into terrain types and component landsurface units (Table 4.1). These were recognised by airphoto interpretation (A.P.I.) and confirmed by field mapping. A detailed examination of these landscape components - their morphology and, in particular, their surficial geology - is now given.

This chapter commences with a summary of the components of layers, notably rock fragments, clay minerals, other secondary minerals and sesquioxide accumulations, and their organisation within each layer type. Subsequent sections will further define the characteristics of each layer type, drawing largely from particle size distribution data. In turn, the characteristics will be defined for each profile type or morphofacies type, whose surface expressions have been taken to be the unit landforms identified by A.P.I. and field mapping. The textural and petrographic compositions of the main gravel layer from each sample pit will be used to test whether the morphometrically distinct unit landforms have equally distinct morphofacies types. Finally, the textual and petrographic data for all pits will be examined within a catenary framework in an attempt to infer the nature of the contemporary processes acting on the materials of the Koidu Basin and, as a consequence, identify relict features wihin these materials.

Overleaf : Page 106, Plate 5.1

Variations in gravel petrography

Facing page, Plate 5.1 : Variations in gravel petrography

1. Hard pisolithic concretions of laterite

2. Nodular lateritic concretions

3. Soft nodular lateritic concretions

4. Lateritic segregations

5-10 Vermiform laterite fragments and compound concretions

11-12 Fe-indurated granodioritic gneiss

13-17 Lateritic segregations, rich in kaolinite

18. Surface crust of lateritic pavement

19. Fe sesquioxide patena, surface of truncated saprolite, Kania

20. ?Bauxitic concretion

21. Ferruginised rounded quartz, Kania interfluve

22-24 Stages in the progressive ferruginisation of quartz clasts in interfluve gravels

25-27 Rounded quartz from the low terraces of the Gbobora and Nafayi rivers, Yengema, showing rims 'leached' of Fe sesquioxides

28-30 Fine, medium and coarse-grained granite, Yengema

31-33 Schist Belt rocks, Dowadu Hills :banded iron formation, mudstone, amphibolite

34. Palaeolithic handscraper, fashioned from a rounded quartz cobble, upper Boya stream, Yengema

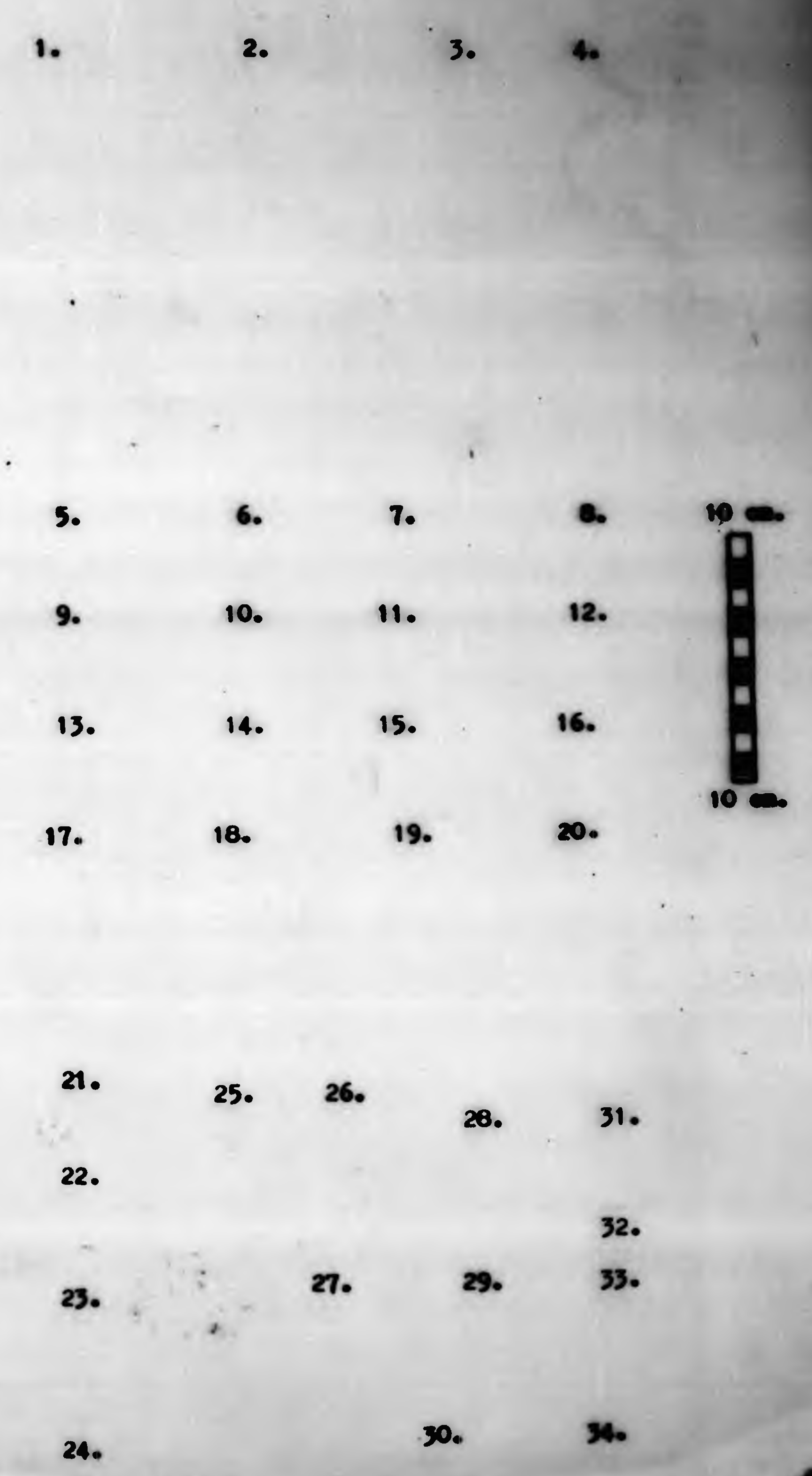


Plate 5.1 : Variations in gravel petrography

1. Hard pisolithic concretions of laterite

2. Nodular lateritic concretions

3. Soft nodular lateritic concretions

4. Lateritic segregations

5-10 Vermiform laterite fragments and compound concretions

11-12 Fe-indurated granodioritic gneiss

13-17 Lateritic segregations, rich in kaolinite

18. Surface crust of lateritic pavement

19. Fe sesquioxide patena, surface of truncated saprolite, Kania

20. ?Bauxitic concretion

21. Ferruginised rounded quartz, Kania interfluve

22-24 Stages in the progressive ferruginisation of quartz clasts in interfluve gravels

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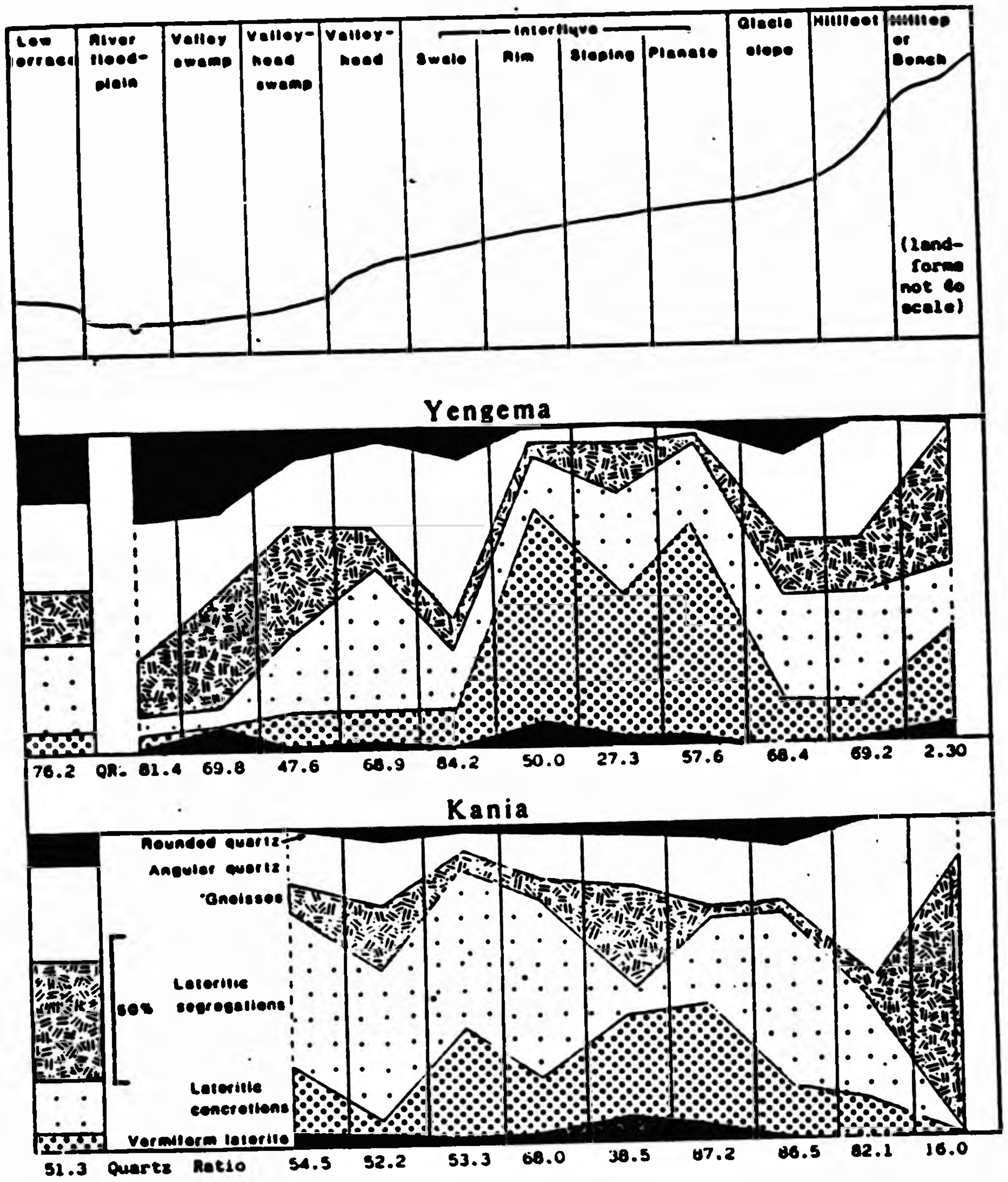
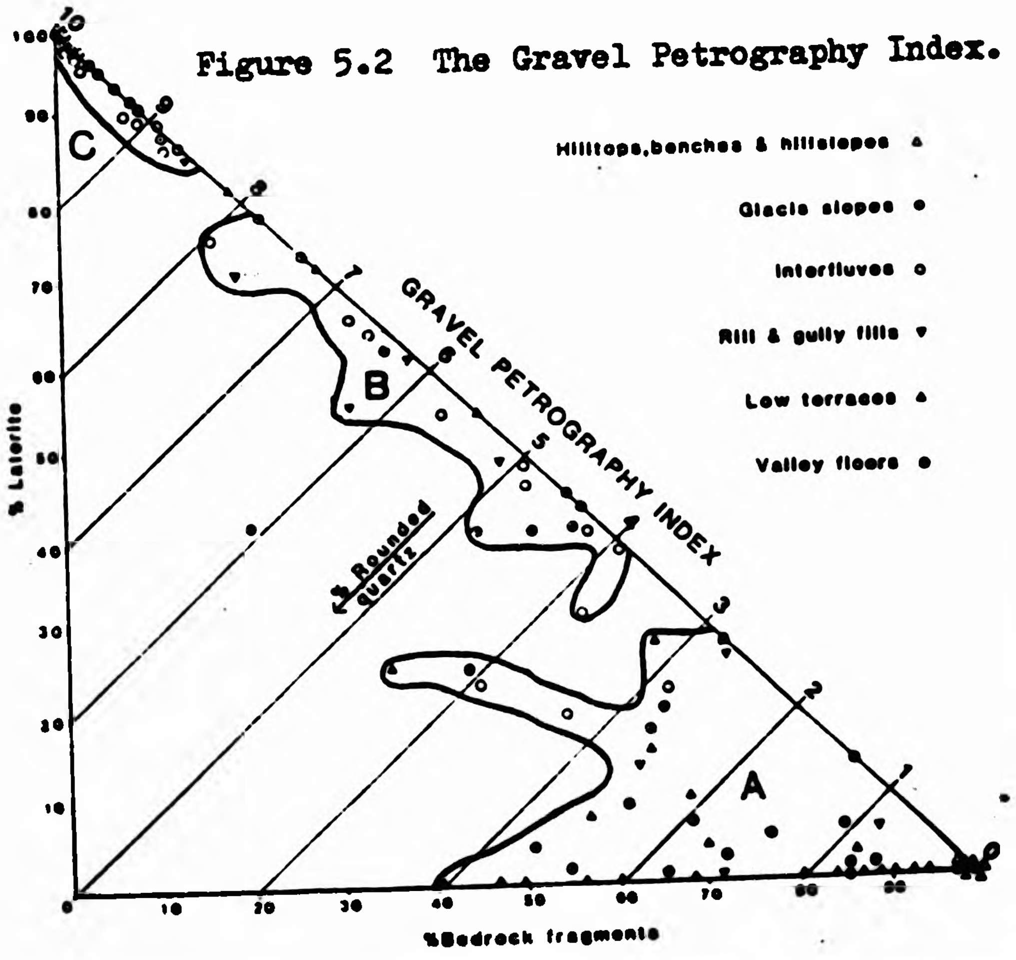


Figure 5.1 Variations in gravel petrography by landform.

Figure 5.2 The Gravel Petrography Index.



5.1 COMPONENTS OF LAYERS

The petrography of the gravels from the Yengema and Kania study areas is summarised in Figure 5.1, with photographs of each petrographic type in Plate 5.1. All of the iron sesquioxide accumulation types that are summarised in Table 2.5 occur in the Koidu Basin, with both in situ and transported lateritic concretions predominating in the Yengema area, but with lateritic segregations and nodular concretions intermediate between segregations and pisolithic concretions predominating in the Kania area.

Of the rock fragments, the "Gneisses" of Figure 5.1 can be subdivided into granitic-gneiss, the most common rock within the Koidu Basin, and granodioritic gneisses (cf.Plate 5.1), which were not found in the Kania area but formed the bedrock of 16 of the 50 Yengema sample pits. This difference in bedrock lithology partly explains the differences in gravel composition between the Yengema and Kania areas shown in Figure 5.1. The granodioritic gneiss, being more enriched in mafic minerals, weathers to give greater amounts of iron sesquioxide accumulations than the granitic gneiss, which tends to produce large amounts of vein quartz and granitic gneiss fragments.

The variations in gravel composition shown in Figure 5.1 also appear to partly reflect the different geomorphological histories of the Yengema and Kania areas that were outlined in Chapter 4, notably the greater degree of soil/saprolite stripping in the Yengema area. This is indicated most clearly by the marked increase in the proportion of angular quartz fragments, mainly at the expense of lateritic segregations, in the stripped swales of the Yengema area, relative to the unstripped swales of the Kania area. The presence, albeit rare, of rounded quartz cobbles in the gravels of Yengema hillside benches is a further indication that the Yengema area has experienced extensive drainage system modifications.

One assumption that is central to the following discussion is that rounded quartz clasts are the result of fluvial wear, rather than chemical weathering. If the proportion of rounded quartz was solely related to the amount of angular quartz fragments available for in situ chemical weathering, then the proportions of both rounded and angular quartz in Figure 5.1 should always show increases or decreases "in tandem" from one unit landform to the next . This does not happen from the hillfoot to glacis zones of both Yengema and Kania, nor from the valley-head slopes to the valley-head swamp of Yengema. This indicates that the proportions of rounded quartz are primarily due to the varying amounts of relict fluvially-rounded quartz in each unit landform.

From Plate 5.1, it is clear that quartz clasts in the predominantly lateritic gravels away from the valley floors are progressively stained by iron sesquioxides until they are entirely iron-stained, and often so structurally weakened that they develop a saccharoidal surface texture soft enough to crumble by hand. Thin section analyses indicate that this process is the same as the "pedoplasmation" described by Eswaran and Stoops (1979) that produces "runiform" quartz clasts (Plate 5.2). The thin section study showed that runiform quartz disintegrated relatively rapidly on being transported to hydromorphic sites, considerably increasing the proportions of sand and silt-sized quartz in the valley swamps.

The weathering index of Dal Cin (1968), referred to in Section 2.2, was applied to the results in Figure 5.1 to give the Quartz Ratio:

$$\frac{\text{\% quartz}}{\text{\% quartz} + \text{\% gneissic fragments}} \,.100$$

This index shows a progressive increase in the proportion of quartz from the valley heads, at 47%, through to the river floodplain, at 81%; however, it does not reflect the variations in the proportions of iron sesquioxide accumulations, which are useful indications of the <u>type</u> of weathering occurring. For instance, both the stripped swale zones of Yengema <u>and</u> the less disturbed planate interfluves of Kania give Quartz Ratios of 80 to 90%, indicating a high degree of weathering. Only on examining the proportions of iron sesquioxide segregations in the gravels from these two sites can the nature of this weathering be found: these values are 70% for the Kania interfluves, indicating that chemical weathering predominates; but only 30% for the Yengema swales, indicating that erosion and mechanical wear predominate.

In an attempt to circumvent this problem a Petrographic Index has been devised based on the ternary plots of the proportions of (i) Angular quartz and gneissic fragments, (ii) Rounded quartz, and (iii) Lateritic concretions and Vermiform laterite (Figure 5.2). Lateritic segregations and iron sesquioxide-cemented mixed gravels have been excluded from this Index because they are the most transient gravel components. As Figure 5.2 shows, the resulting distributions of each gravel sample show distinct groupings along a continuum between those rich in "Bedrock

Fragments" (set 'A': mainly from low terrace and valley floor sites) and the residual lateritic gravels of the interfluves (set 'C'). The proportions of rounded quartz are highest in the low terrace/valley floor gravels of set 'A'. The inclusion of some glacis/interfluve samples within set 'A' is clearly of relevance to exploration for palaeoplacer deposits; indeed, with a more intensive sampling scheme this Petrographic Index could be used to map areal variations in gravel petrography.

The mineralogy of the Yengema and Kania areas is summarised in Tables 5.1 and 5.2. The dominant clay mineral in both cases is kaolinite derived from the weathering of feldspars and biotite, the latter often giving a brown stain to the kaolinite due to the release of iron sesquioxides during its weathering. This is confirmed by both thin section studies (viz.Plate 5.2) and X-ray diffraction analyses. Gibbsite was also observed in minor amounts, most frequently within black pisolithic laterite concretions, but occasionally as a direct alteration product of feldspar (Plates 5.3A and 5.2C respectively). Gibbsite was particularly common along Transect B4, the low terrace/interfluve complex near the Boya - Nafayi confluence zone (Figure 4.14), where gibbsite occurs throughout the profiles. Conversely, in the Kania area gibbsite appears to be confined to the infilled valley-head zone, being largely absent from the other unit landforms. This indicates that two factors are responsible for the marked differences in gibbsite distribution: changes in local water table levels to produce very well-drained sites; and variations in local lithology, the granodioritic gneisses favouring gibbsite formation more than the granitic gneisses. This latter factor is well illustrated in the Yengema area, where the sites over granitic gneiss (N1A, N2A, N3A, and N3C in Table 5.1) have only occasional occurrences of gibbsite confined to the saprolite layer; whereas the nearby sites over granodioritic gneiss (N4A, N4E, and N4H) contain greater amounts of gibbsite.

Clay coatings and ferricutans (Plate 5.3) were not a common feature of thin sections from either Yengema or Kania. Coatings occurred most frequently as aureoles around biotite grains and lateritic concretions. Beaded cutans - indicative of pronounced clay deposition - were confined to the peripheral cracks and fissures of lateritic concretions. Thus it appears that these clay coatings and beaded cutans are not primarily the result of pronounced illuviation, as advocated by Brewer (1968), but more the result of weathering in and around lateritic concretions and biotite grains. The general absence of clay coatings and ferricutans in the valley floor deposits and recent low terraces, plus evidence from thin sections of the disintegration of clay coatings, the dissolution of lateritic concretions and the dissolution of iron sesquioxides from runiform quartz clasts, (producing their disintegration into sand and silt-sized particles), indicate clearly that valley floors are zones of overall clay/sesquioxide removal.

The most common iron sesquioxide minerals are goethite and hydrated amorphous iron oxides which were found in the layer matrices of the interfluve/low terrace zone, particularly as ferricutans along root passages and other soil pores (Plate 5.4). However, in the valley-floor and recent low terrace deposits, iron sesquioxide occurrence was limited to aureoles around allocthonous lateritic material. Haematite and amorphous ferric oxides were not found in the layer matrices, but occasionally occurred in lateritic concretions or in runiform quartz grains. Manganese sesquioxide accumulations were a rare occurrence, confined to gritty nodular concretions.

Table 5.1

1. Fe Sesquioxide Accumulations

Top soil & gravel	Nodules	Not sampled	Not sampled	± Concretions	Pisoliths + Nodules
Upper fill & Buried gravel	± Concretions			Nodules + gritty Nodules	Segregations ± Concretions
Lower fill	Absent	Absent	Absent	Soil relicts	
Basal gravel	Gritty Nodules	Soil relicts+ Broken Nodules	Gritty Nodules	Nodules	
Saprolite	Absent	Absent	Absent	± Pisoliths	Fe indurated saprolite

2. Matrix Mineralogy. Kao=Kaolinite; Gib=Gibbsite Fe=Fe sesquioxides.

Top soil & gravel	Kao ± Gib	Not sampled	Kao	Not sampled	Kao ± Gib
Upper fill & Buried gravel	Not sampled	Kao	Kao	Kao ± Fe ± Gib	Kao + Fe ± Gib
Lower fill	Kao + Fe			Kao ± Fe ± Gib	
Basal gravel	Kao + Fe	Kao ± Gib	Kao	Kao + Fe ± Gib	Gib
Saprolite	Kao + Fe	Kao ± Gib	Kao + Fe ± Gib	Kao + Fe ± Gib	

3. Clay Coatings & Ferricutans

Top soil & gravel	Absent	Not sampled	Not sampled	Not sampled	Not sampled
Upper fill & Buried gravel	Not sampled	Absent	Absent	Flecks of Goethite	Absent
Lower fill	Absent			Beaded cutans + Anisotropic flecks	
Basal gravel	In concretion cracks	Around concretions	Absent	Beaded cutans + Anisotropic flecks	
Saprolite	Absent	Absent	Around Biotite	Around Biotite	Fe indurated saprolite

4. Microstructure

Top soil & gravel	Alveolar to single grain	Not sampled	Granular to single grain	Not sampled	Lateritic gravel
Upper fill & Buried gravel	Not sampled	Stratified single grain	Single grain	Granular to massive	Labyrinthine to crumb
Lower fill	Single grain			Alveolar to Massive	
Basal gravel	Alveolar	Alveolar	Single grain Bridge to Alveolar	Alveolar to Massive with pores	
Saprolite	Massive saprolitic	Subangular blocky-Massive, saprolitic	Massive saprolitic	Subangular blocky to Massive	Indurated saprolite
Landform	Swamp	Valleyswamp	TerraceII	Terrace I	Interfluve

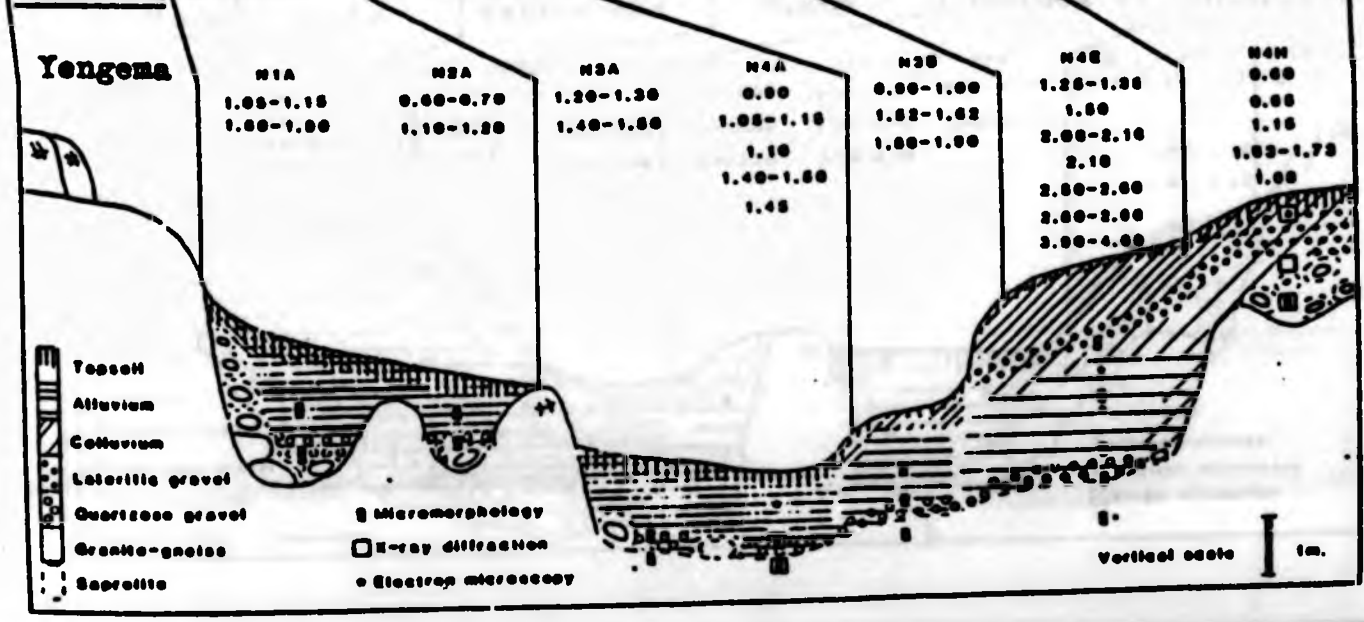
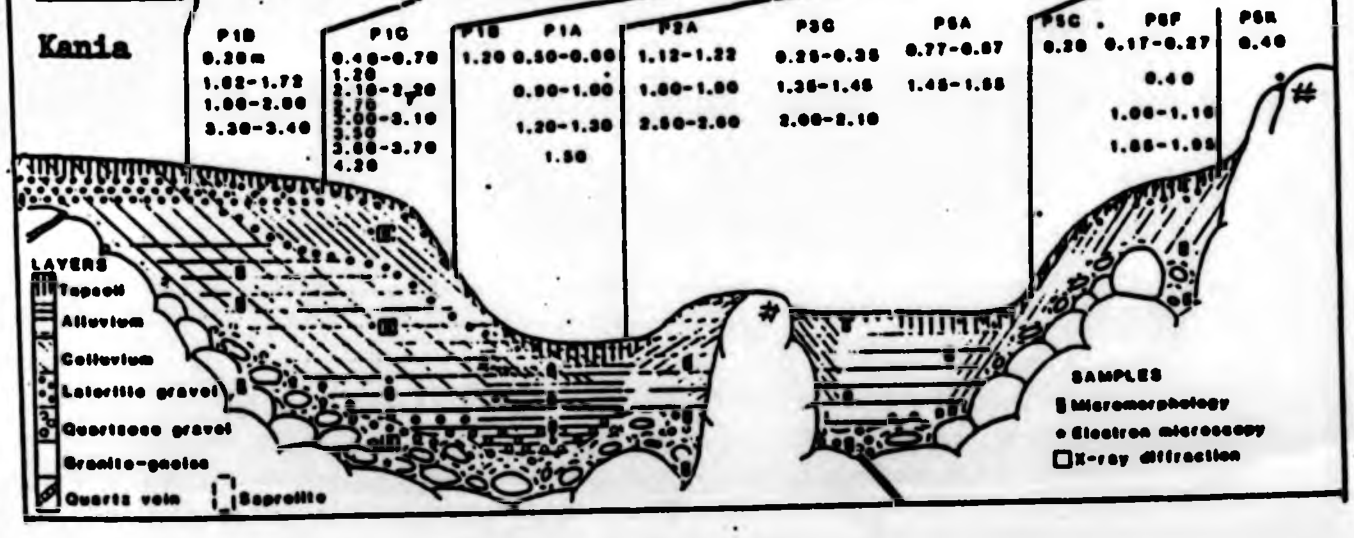


Table 5.2

1. Fe Sesquioxide Accumulations					
Top soil & gravel	Pisoliths, Nodules + Segregations	Pisoliths Nodules + Segrugations	± Concretions	± Concretions	Pisoliths + Nodules
Upper fill Buried gravel	Not Sampled	Pisoliths Nodules + Segregations	± Pisoliths	± Concretions	± Concretions
Lower fill	Segregations	Gritty Nodules + Segrugations	± Concretions	± Concretions	
Basal gravel		Sugregations + Pisoliths + Gritty Nodules	Pisoliths + Nodules + Gritty Nodules	± Pisoliths ± Nodules	± Pisoliths
Saprolite	Segregations	Segregations ± Pisoliths	Not Sampled	Segregations	
2. Matrix Mineralogy. Kao=Kaolinite, Gib=Gibbsite Fe=sesquioxides					
Top soil & gravel	Not Sampled	Kao + Fe ± Gib	Not Sampled	Kao + Fe	Kao + Fe
Upper fill & Buried gravel	Not Sampled	Kao + Fe ± Gib	Kao	Kao + Fe	Kao + Fe
Lower fill	Kao	Kao ± Gib	Kao ± Fe	Kao ± Gib	
Basal gravel		Kao ± Gib	Kao	Kao	Kao + Fe
Saprolite	Kao + Fe ± Gib	Kao ± Fe ± Gib	Not Sampled	Kao ± Fe	
3. Clay Coatings & Ferricutans					
Top soil & gravel	Not Sampled	Not Sampled	Not Sampled	Not Sampled	Coating pores and passages around Biotite
Upper fill & Buried gravel	Not Sampled	Around concretions	Absent or around Biotite in concretion cracks	Beaded cutans; Broken cutans; Anisotropic domains	
Lower fill	Coating pores and passages	Coating pores; broken cutans; also Mn coatings	Absent	Absent; or ± coating pores	Around concretions
Basal gravel		Around concretions	Beaded cutans in concretion cracks	Absent; or ± around concretions	Isotropic domains; ± around Pisoliths
Saprolite	Coating pores, around Biotite	Broken cutans; also, around Biotite	Not Sampled	Around biotite or absent	
4. Microstructure					
Top soil & gravel	Lateritic gravel	Lateritic gravel	Not Sampled	Granular to Irregular blocky	Labyrinthine to Irregular blocky
Upper fill Buried gravel	Not Sampled	Granular to Angular blocky	Crumb to Irregular blocky	Alveolar to Subangular blocky	Granular
Lower fill	Alveolar to subangular blocky	Subangular blocky	Granular to Alveolar		
Basal gravel		Incomplete subangular blocky	Bridge	Alveolar to Massive	
Saprolite	Granular to Massive	Subangular blocky-Massive saprolitic	Not Sampled	Massive saprolitic	Granular to subangular blocky
Landform	Swale	Valleyhead	Swamp	Terrace II	Interfluve



Overleaf : Page 115, Plate 5.2

Photmicrographs of thin sections

PLATES 5.2, 5.3 and 5.4 : PHOTOMICROGRAPHS OF THIN SECTIONS

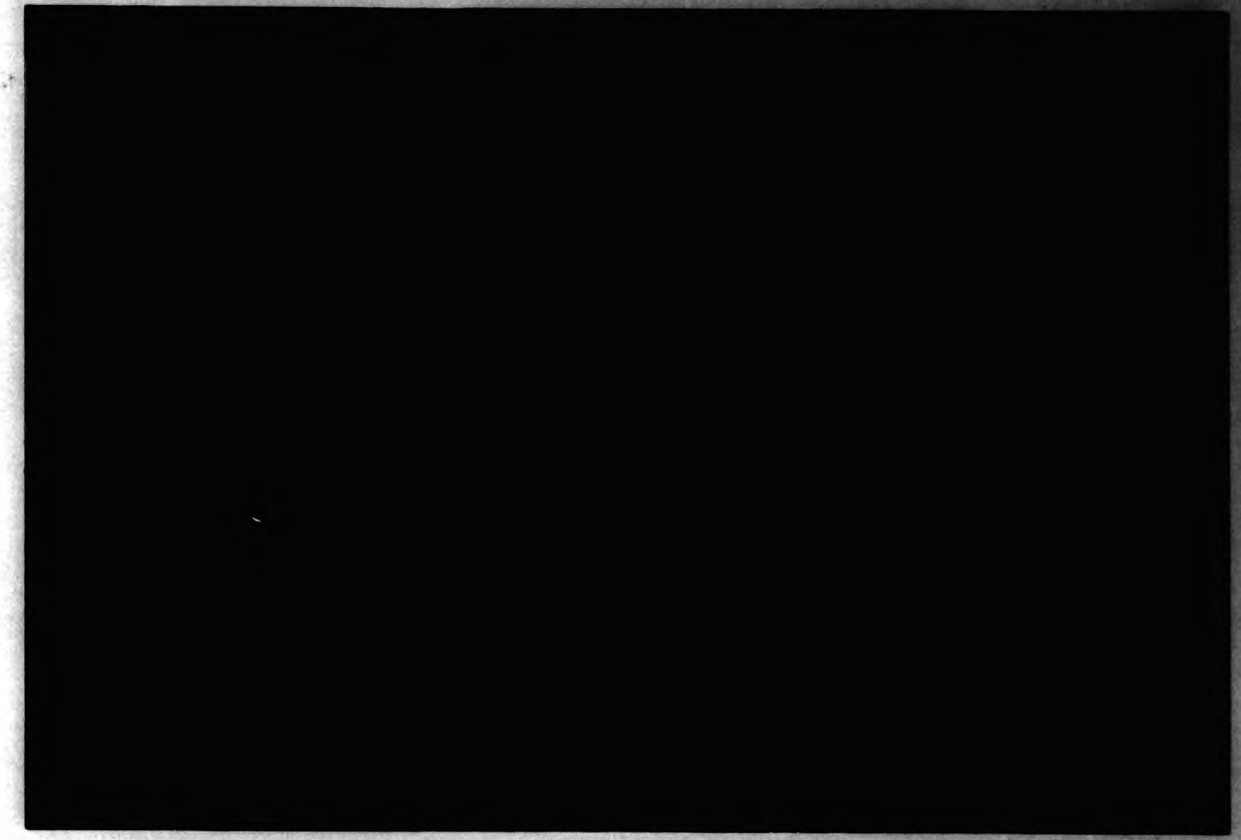
Facing page :

Plate 5.2A Dissolution of gritty nodular lateritic concretions; colluvial material washed into the valleyhead swamp of the Pawpawyi stream, Kania (Pit P1A).

Plate 5.2B Alteration of biotite to kaolinite, an intermediate stage, the alteration commencing from the ends of each biotite lathe.

Plate 5.2C Alteration of feldspar to give kaolinite pseudomorphs, Boya valley swamp gravel, Yengema (Pit N3A).

Overleaf : Page 116, Plate 5.3



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Overleaf : Page 116, Plate 5.3

Photomicrographs of thin sections

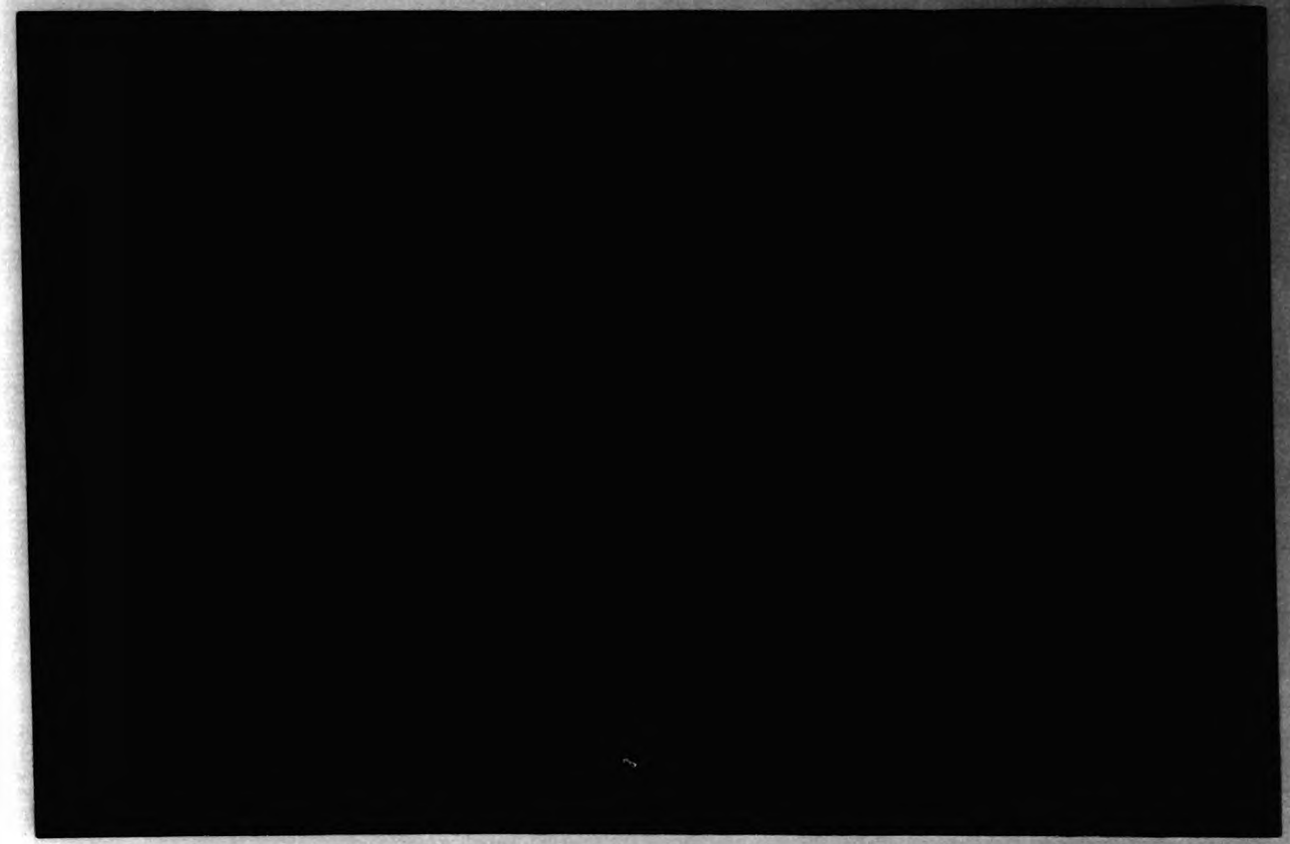
Facing page :

Plate 5.3A Pseudo-pisolithic lateritic concretion containing gibbsite (white dots); topsoil, Pawpawyi valleyhead swamp, Kania (Pit P1A).

Plate 5.3B Clay coatings and ferricutans (probably goethite). Three phases of iron sesquioxide-clay deposition are evident; fragmentation indicates a recent period of transport. (Pit P1A, topsoil).

Plate 5.3C Beaded cutans in the micofissures of a lateritic concretion; indicative of the neoformation and/or translocation of clay and sesquioxides. Topsoil, valleyhead of the Pawpawyi stream, Kania (Pit P1C).

Overleaf : Page 117, Plate 5.4



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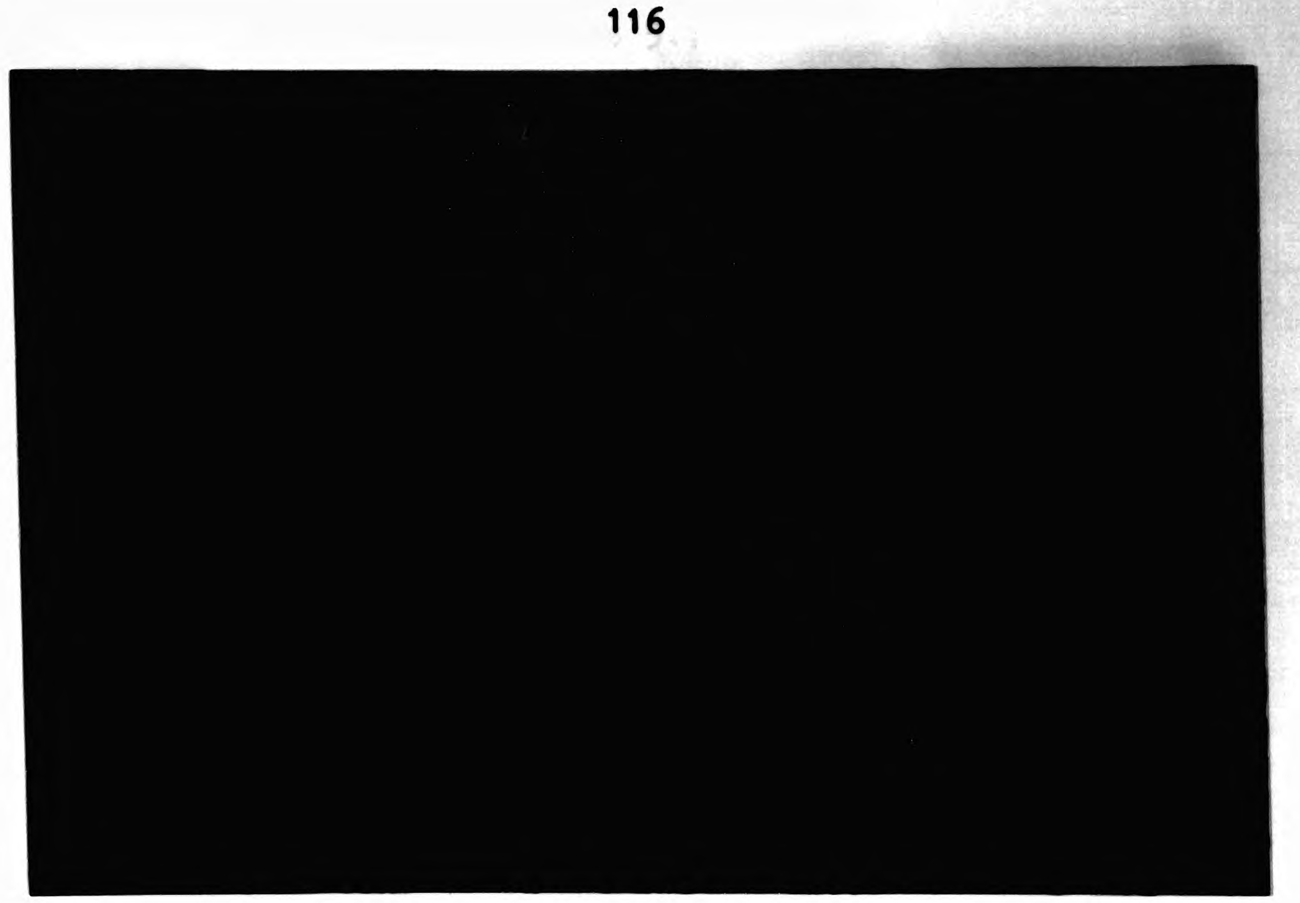

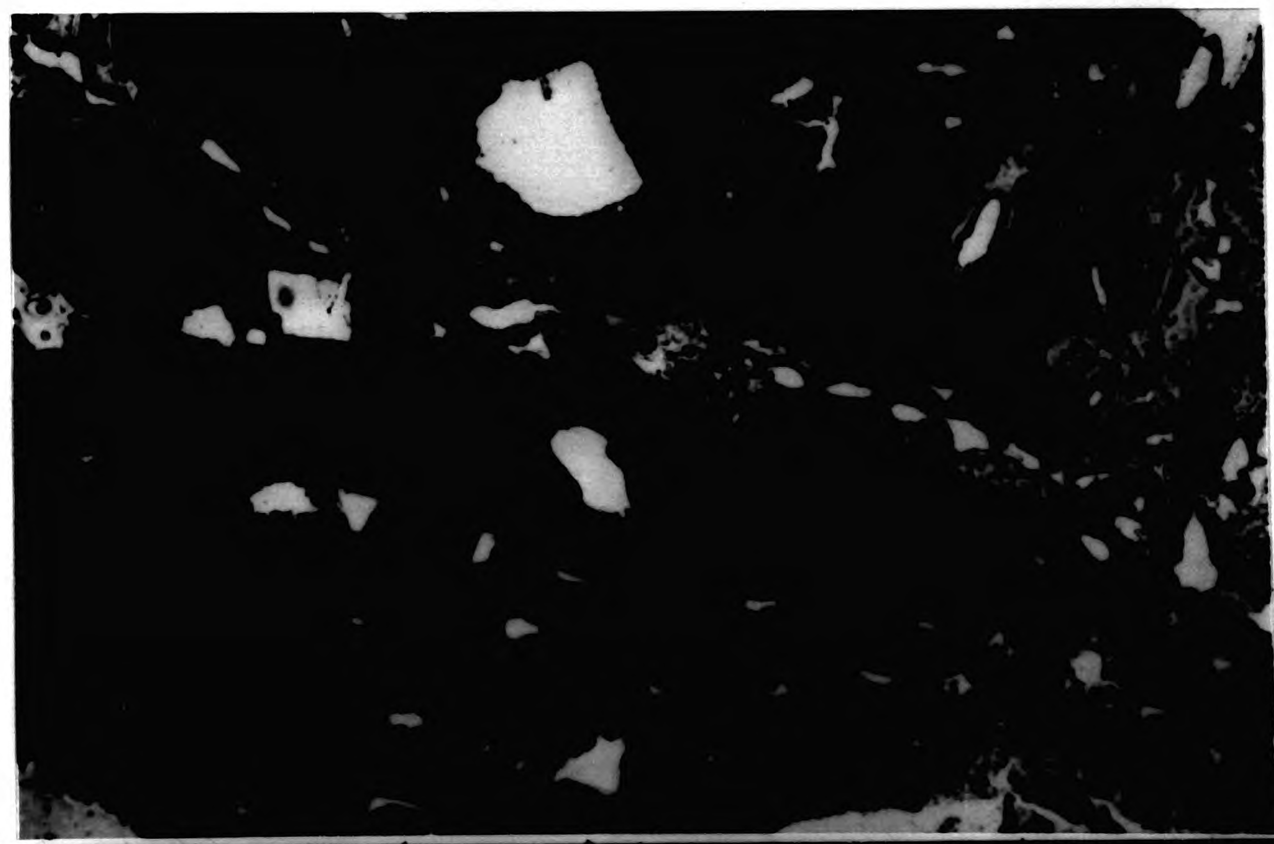

Overleaf : Page 117, Plate 5.4

Photomicrographs of thin sections

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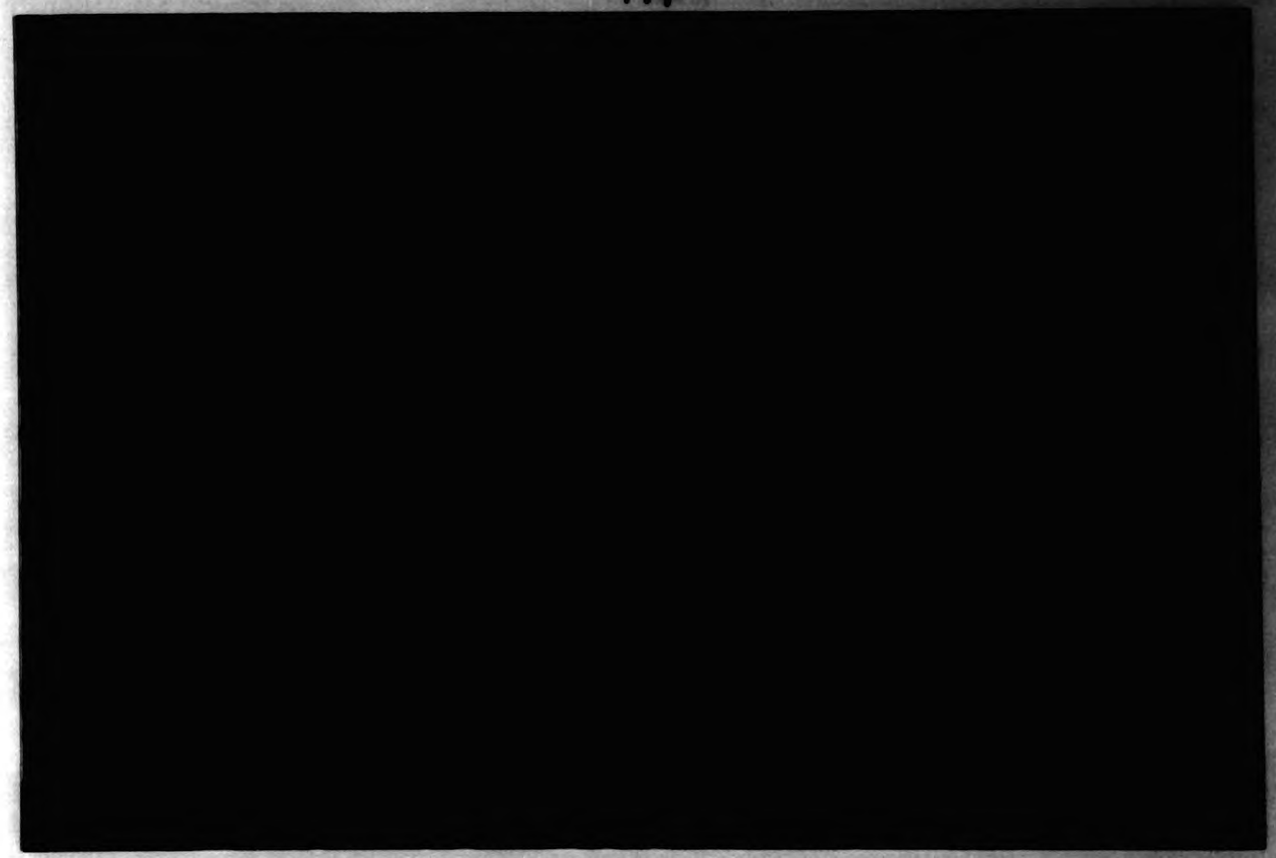
Plate 5.4A **Accumulation of iron sesquioxides around root passages and soil pores, Kania interfluve topsoil (Pit P5F).**

Plate 5.4B **Labyrinthine microstructure indicative of termite activity, with ensuing accumulation and oxidisation of iron sesquioxides. Topsoil, Boya-Nafayi interfluve, Yengema (Pit N4H).**

Plate 5.4C **Cross-section of an earthworm in a sandy loam topsoil, Kania interfluve (Pit P5F).**



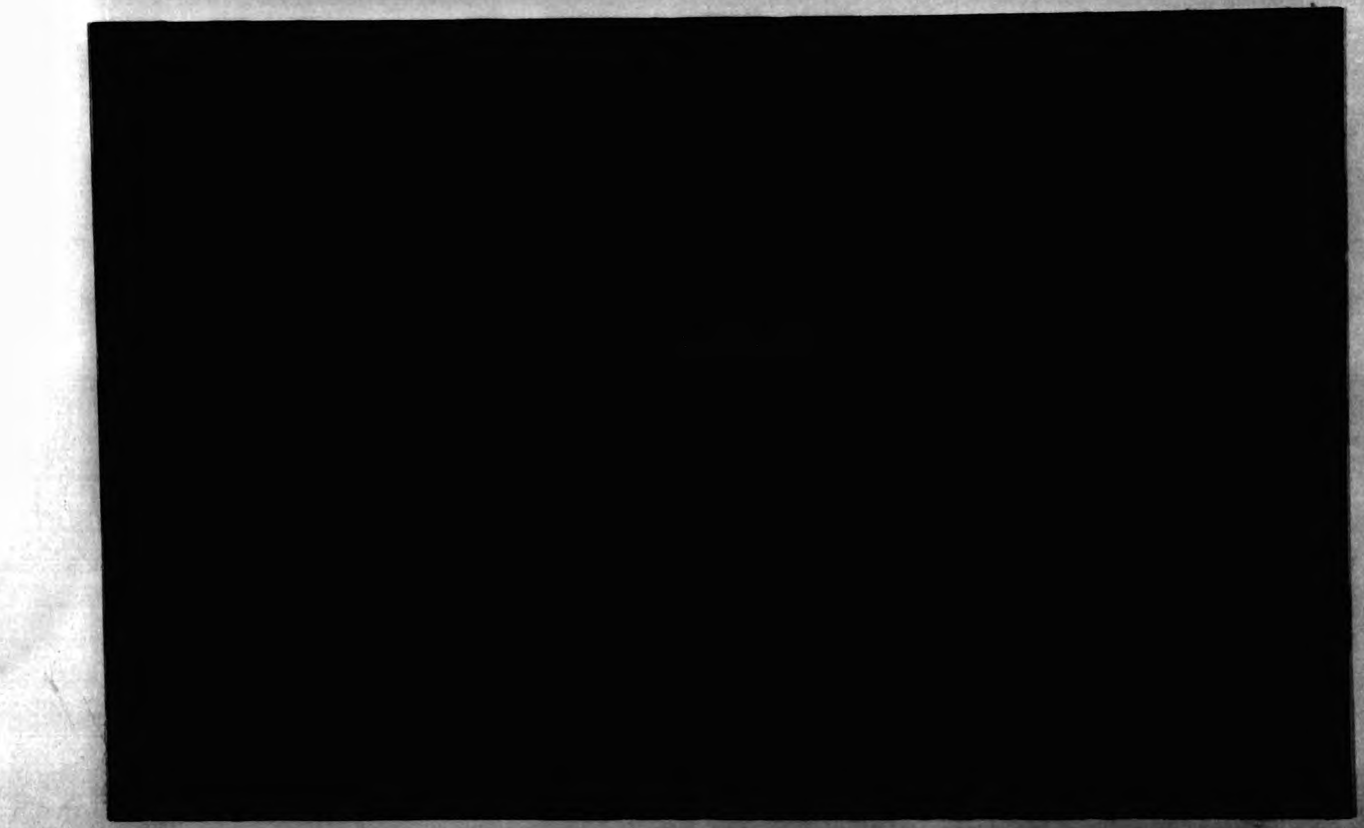


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Plate 5.4A Accumulation of iron sesquioxides around root passages and soil pores, Kania interfluve topsoil (Pit P5F).

Plate 5.4B Labyrinthine microstructure indicative of termite activity, with ensuing accumulation and oxidisation of iron sesquioxides. Topsoil, Boya-Nafayi interfluve, Yengema (Pit N4H).

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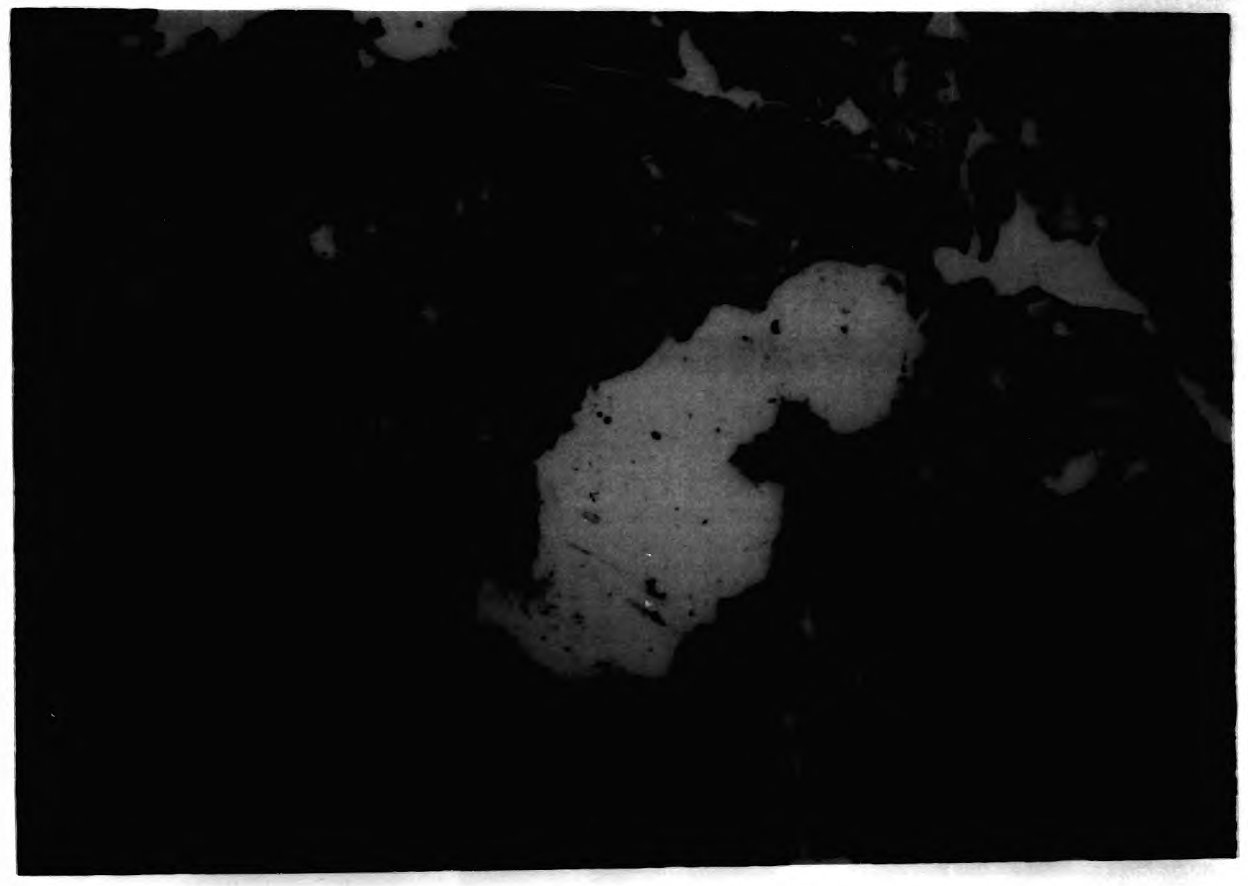


The analyses of thin sections indicate that contemporaneous accumulations of iron sesquioxides in the form of lateritic segregations, occur in the lower fill and saprolite layers of interfluval sites and occasionally in the low terrace saprolite. The absence of lateritic segregations from the valley floor sites provides further support for the hypothesis that these are zones of overall iron sesquioxide dissolution and removal.

The variations in the morphologies and distributions of iron sesquioxide accumulations noted from the thin section studies indicate that the Kania area has experienced a phase of soil/saprolite stripping. This was presumably prior to the phase of valleyhead infilling and saprolite regeneration. This stripping led to the erosion of in situ lateritic segregations from the saprolite, their induration under near-surface/sub-aerial conditions, and their incorporation into residual lateritic gravels as nodular concretions. The predominance of vermiform laterite fragments and various types of lateritic concretions in the Yengema interfluval gravels indicates that this area has experienced more than one phase of soil/saprolite stripping, as concluded from geomorphological data in Chapter 4.

The microstructures of the thin section samples are summarised in Table 5.3, using the terminology of Fitzpatrick (1980a, 1984). The distribution of these microstructure types within the sampled morphofacies types is shown in Tables 5.1 and 5.2. The microstructure variations of the basal gravel layers provide a further indication of valley-floor/low terrace morphodynamics. The valleyhead swamp basal gravel at Kania has a Bridge microstructure, indicating the translocation and partial retention of clay. Conversely, the valleyhead swamp, valley

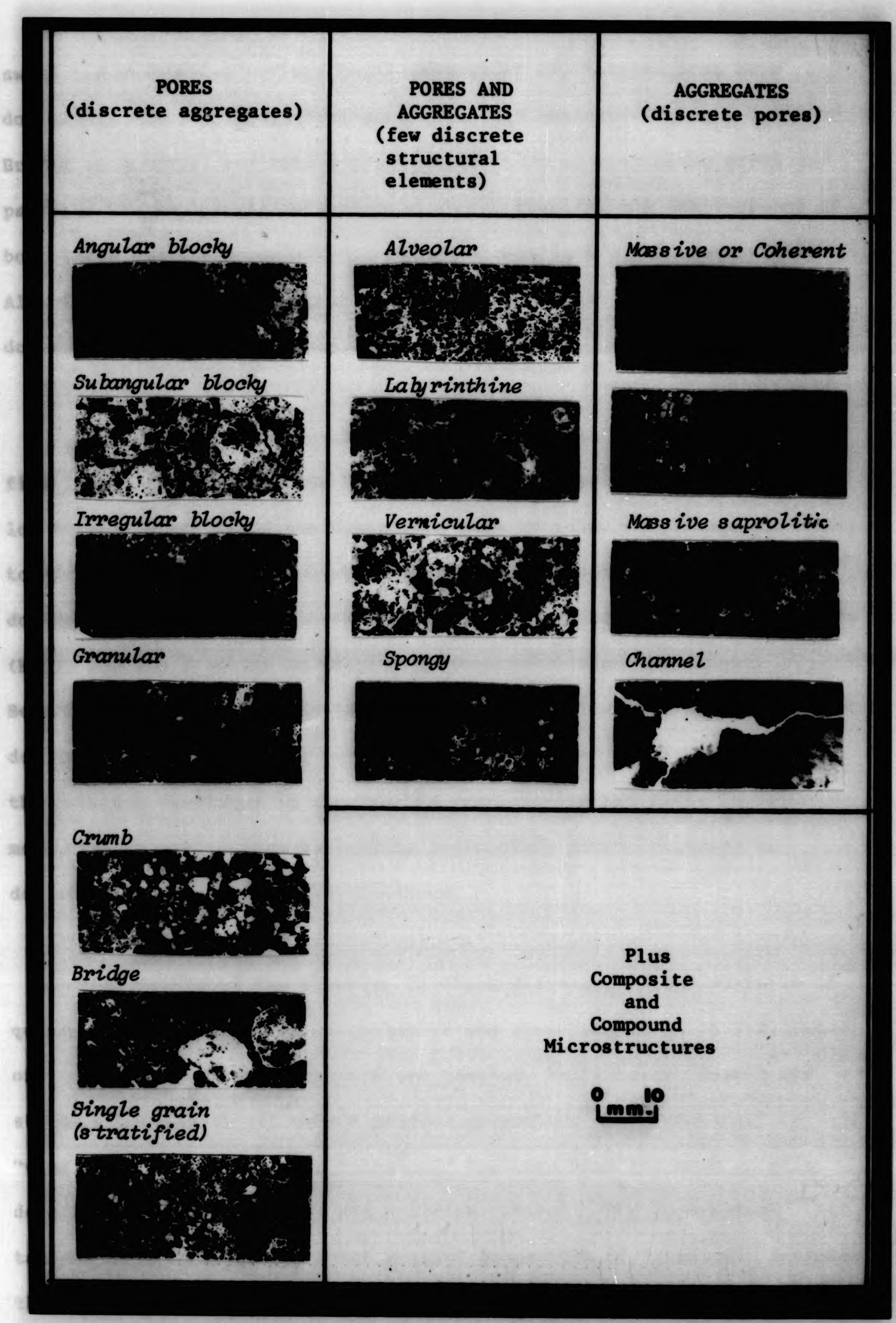


Figure 5.3 Types of microstucture observed in thin section samples.

Figure 5.3 Types of microstucture observed in thin section samples.

swamp and recent low terrace basal gravels of the Yengema area have dominantly Alveolar microstructures with only occasional Single Grain or Bridge components, indicating the translocation of clay along pores and passages but an overall retention of clay. Finally, the low terraces of both Kania and the Boya/Nafayi confluence zone have basal gravels with Alveolar to Massive microstructures, indicating that clay retention dominates over clay translocation at these sites.

Slightly different conclusions can be deduced from the alluvial fill layers of the Kania and Yengema areas. The valley head swamp and low terrace deposits of the Kania area have Granular or Subangular Blocky to Alveolar microstructures which appear to be intermediate between the dominantly Single Grain microstructures of the recent Yengema low terrace (N3C), and the Alveolar to Massive Microstructures of the (older) Boya/Nafayi terraces. This indicates that the valleyhead and low terrace deposits of the Kania area have been less disturbed by fluvial activity than similar landforms in the Yengema area, giving the Kania deposits more time to evolve from dominantly sedimentary microstructures to dominantly pedogenetic microstructures.

The results of the Scanning Electron Microscopy (SEM) analysis of quartz sand grain surface morphologies are presented in Table 5.3. Zones of pronounced material translocation (swales, valleyheads, swamps and stream floodplains) all show a greater proportion of "mechanical" or "wear" features relative to "chemical" features than the more <u>in situ</u> deposits of the interfluves and hillside benches. The Boya/Nafayi terrace deposit (N4E) has a far greater proportion of "chemical" features than the "recent" Yengema low terrace (N3C), supporting the deduction made from the thin section analyses that the Boya/Nafayi terrace has

	Mechanical features																	Morphology							Chemical features												
Sample pit & depth (m.)	1 Grain breakage	2.Edge abrasion	3.Breakages <10um	4.Breakages >10um	5.Conchoidals <10um	6.Conchoidals >10um	7.Straight steps	8.Arcuate steps	9.Parallel striations	10.Imbricate grinding	11.Adhering particles	12.Fracture plates	13.Meandering ridges	14.Straight scratches	15.Curved scratches	16.Mechanical V- pits	17.Dish concavities	18.Rounded	19.Sub-rounded	20.Sub-angular	21.Angular	22.Low relief	23.Medium relief	24.High relief	25.Orientated etch pits	26.Anastomosis	27.Dulled surface	28.Solution pits	29.Solution crevasses	30. Scaling	31.Carapace	32.Amorphous ppt. silica	33.Euhedral silica	34.Chattermarks	35.Silica "flowers"		
P5K 0.4	■	■	■	█	□	■	■	■	□		□	■	■	□		□	■		■	■	□	□	■	□		■	■	■	■	■	□	□	□			HILL BENCH	
P5F 0.4	□	□	█	█	█	■	█	█			█	█	■							█		□	□	■	□	█	█	█		█	█	█	□			INTERFLUVE	
P5C 0.2		□	█	■	■	■	■	█	□		■	□	■				□		■	■	□	□	■	□			□	□		█	■	■			□	VALLEY EDGE	
P2E 0.4	□	□	█	■	█	■	█	█				■	█		□	□	□		■	■		□	■	□	■	□	■	█		█	■	█	■			INTERFLUVE	
P1D 0.2		■	■	■	□	□	■	■	□		■	■	■	□	□	■	□		□	█	□	□	█	□		■	■	█	■	█						SWALE	
P1C 0.4		█	█	█	■	■	█	■			█	■	■			■	■		□	■	□	□	█		□		□	■	□	█		□				GRAVEL 3	BURIED VALLEY HEAD
1.2		□	■	█	█	■	█	█			■	■	█				□		■	■		□	█		■		□	■		■		█	□		□	FILL/GVL 2	
2.1		■	█	■	█	■	█	█			■	■	■	□		□	■		□	■	□	■	■	■	□			□		■		□				FILL 1	
2.7	□	□	█	█	■	■	█	█	□		■	█	■				□		■	■			█		█	□		█		█		□			□	FILL/GVL 1	
3.5	■		█	█	█	█	█	█			█	■	■				■	□	■	■			█		■	□	□	█	□	█	█	█	█			GRAVEL 1	
4.2			█	■	█	■	█	█			■	■	■				■		■	■		□	■	■	□	■	■	█	□	█	□	█	■			SAPROLITE	
P1B 1.2	□	■	■	■	□	□	█	█				■	■	□	□	■	■	□	■	■		■	■	□		□	□	■	□	█		□			□	VALLEY HEAD	
P1A 1.5		□	█	■	■	■	█	█	□		■	■	■	□		□	■		■	■	□	□	■	□	■	□		█	□	█	□	□				SWAMP	
P2A 2.1		■	█	■	■	■	█	█	□		■	■	█			■	■		■	■	□	□	█		□			■	□	■						LOW TERRACE	
N4A 0.9		□	█	■	█	■	█	█				■	■				□		□	■		□	■	□	□		■	□		■		█	■			STREAM	
N4E 1.5		□	█	■	█	█	■	█	□		█	■	■		■	□	■	□	■	■		□	■	□	■	■	█	█		█	█	█	■			TERRACE FIL	
2.1	□	■	█	■	█	■	█	█			■	■	■			□	■		□	■	□	■	■		■			█	□	█	■	█	■		□	TERRACE	
N4H 0.6			█	■	■	■	■	■			■	□	■			□	■		■	■		■	█		□	□	■	█		█	□	█				INTERFLUVE	

█ > 75% Abundant
■ 25-75% Common
□ 2-25% Present
0-2% Absent

TABLE 5.3 Results of the scanning electron microscopy study.

experienced a greater degree of post-depositional alteration. The SEM study also indicates that the gravels of the two Kania interfluve sites, (P5E and P2E), are largely derived from reworked ancient fluvial terraces. Both samples have markedly different surface morphologies than the other interfluve, swale or hillside bench samples. Preliminary Image Analyses of sand from the gravel layers of the nine Kania samples cited in Figure 5.3 produced three sets of Area/Parimeter values: 1.2 (Valleyhead swamp); 2.6 - 4.5 (Low terrace/Buried valleyhead); and 5.3-6.1 (Interfluve and Hillside bench sites).

5.2 LAYER TYPES

Three major groups of layer types were observed in the sample pits of the Koidu Basin: A, soil and fill layers; B, gravel layers; and C, saprolite or regolith layers. Examples of similar layer types from other tropical areas were cited in Section 3.2; the terminology used there is used in the following pages. Figure 5.4 presents the particle size distribution data from two sample transects, P1 at Kania (Figure 4.6) and N4 at Yengema (Figure 4.9), in the form of cumulative frequency curves. Plotting the D99 percentiles against the D50 percentiles of each curve summarises the size distributions of each layer type in the form of a C/M diagram (Figure 5.5).

A1, Topsoil, shows marked differences between interfluval, low terrace and valley swamp sites. Interfluval topsoils from both Yengema and Kania have mean silt + clay ("fines") values of 30 to 43%; gravel clasts over 4mm in size are largely absent from the Kania topsoils, whilst Yengema topsoils are notably coarser-tailed with clasts of up to

Figure 5.4 Cummulative frequency curve envelopes for particle size.

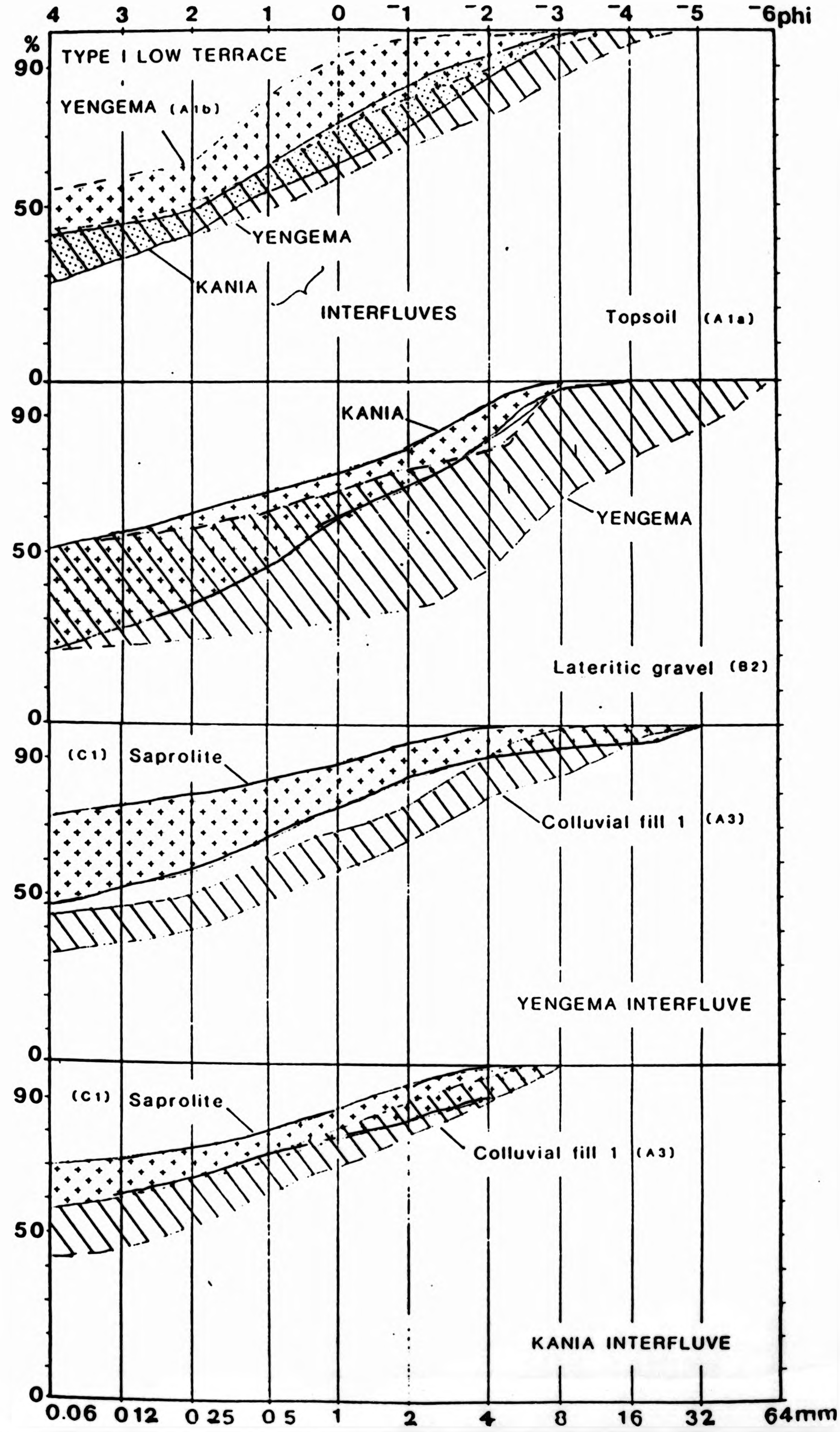
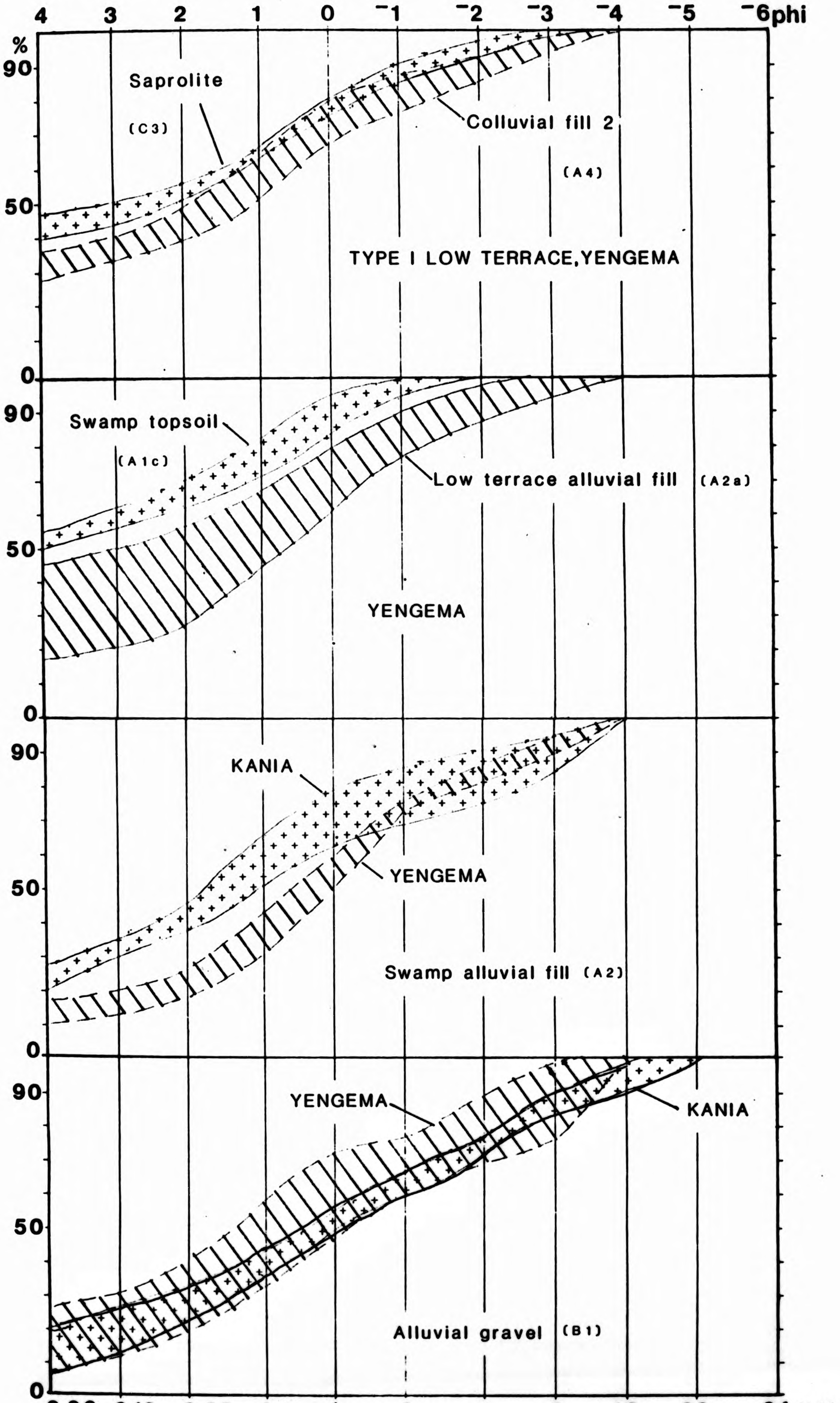
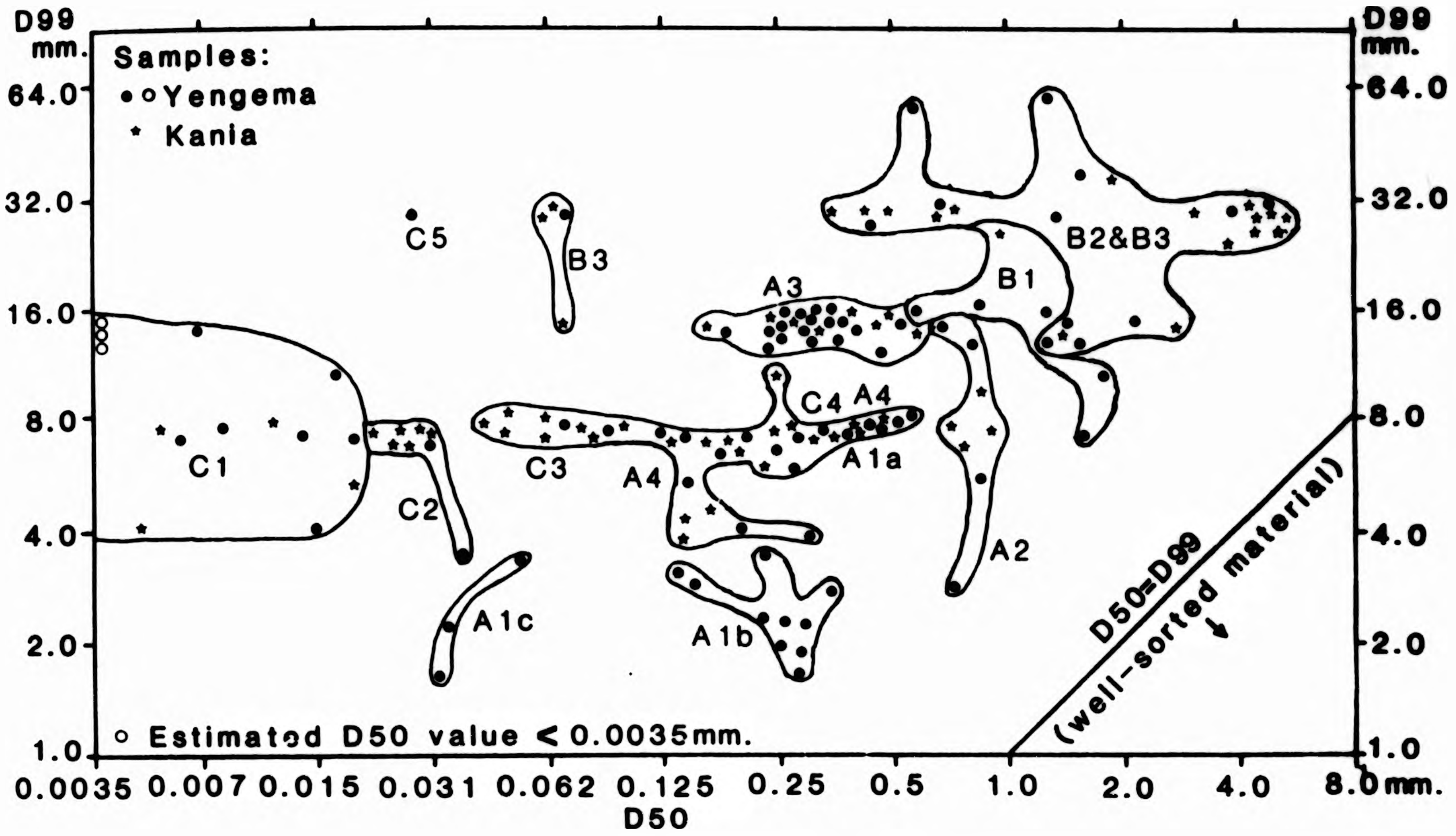


Figure 5.4 (contd.) Samples are listed in Appendix C.





A1a, interfluve topsoil A1b, low terrace I topsoil

A2 alluvial fill A3, colluvium I A4, colluvium II

B1, alluvial gravel B2, lateritic gravel B3, mixed gravel

C1, interfluve saprolite C2, riverbed saprolite

C3, low terrace I saprolite C4, truncated interfluve saprolite C5, indurated interfluve saprolite.

Figure 5.5 CM diagram for samples given in Figure 5.4

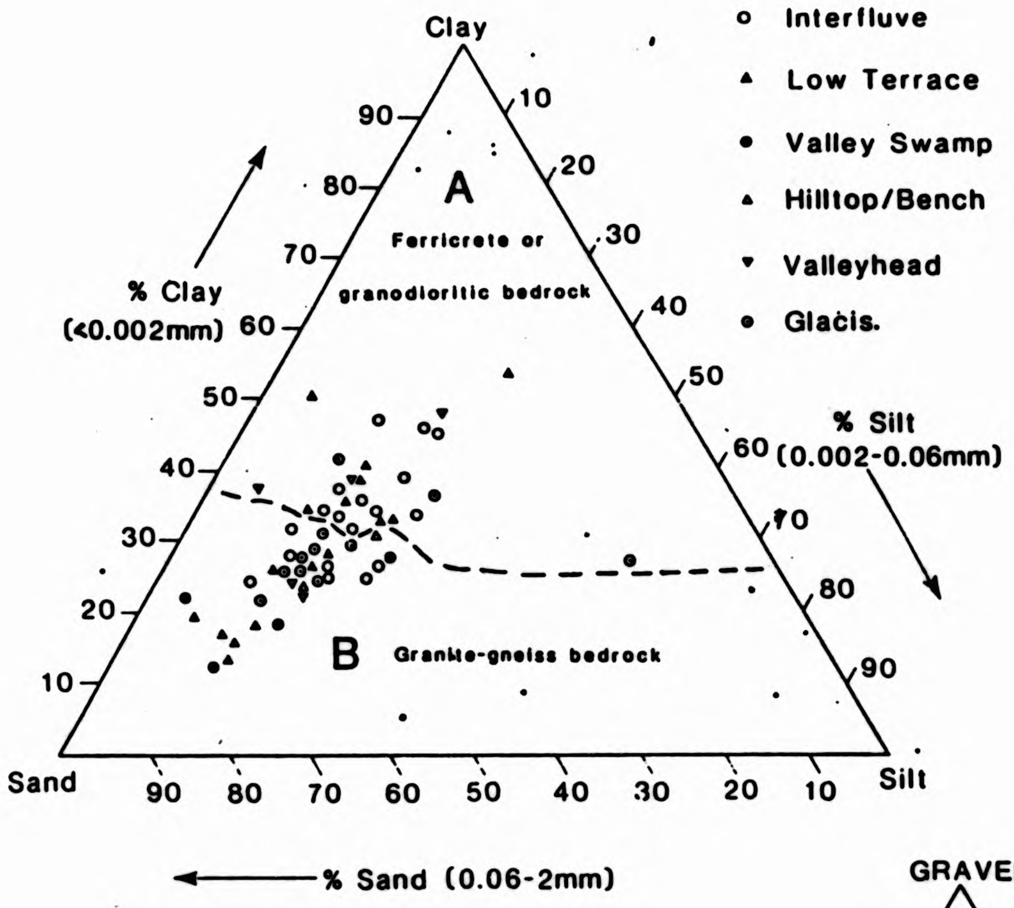
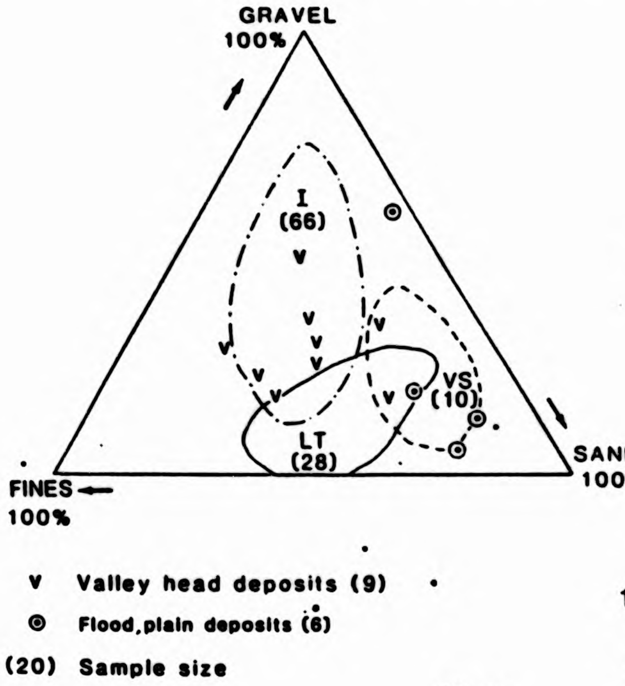
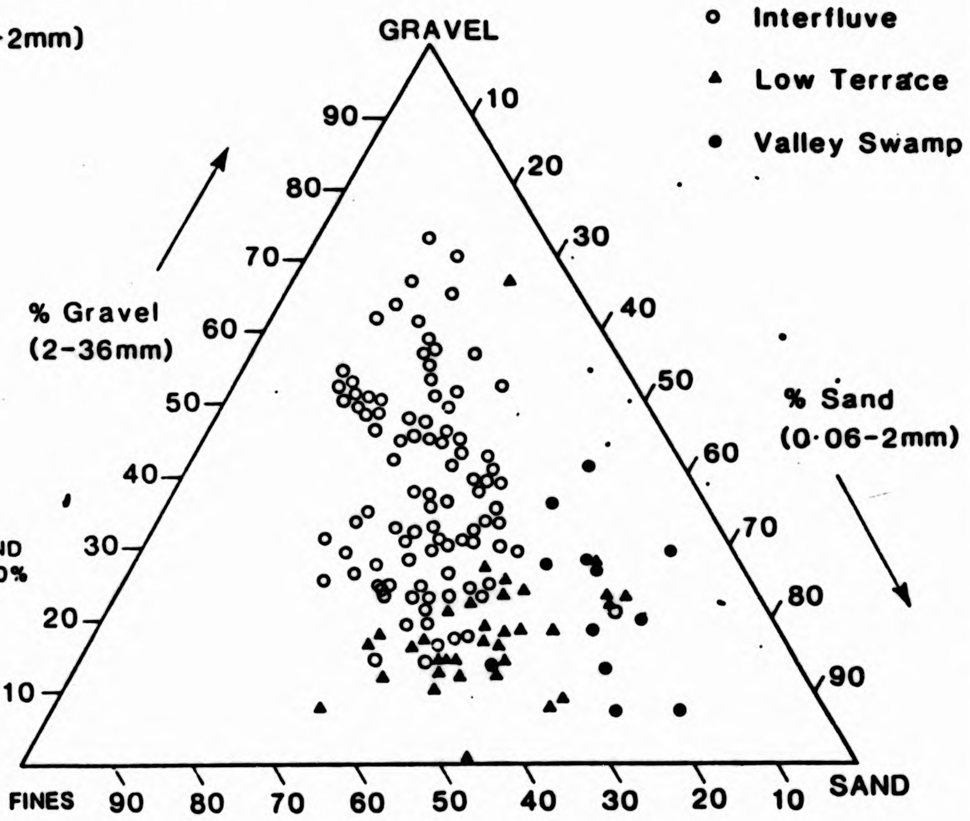


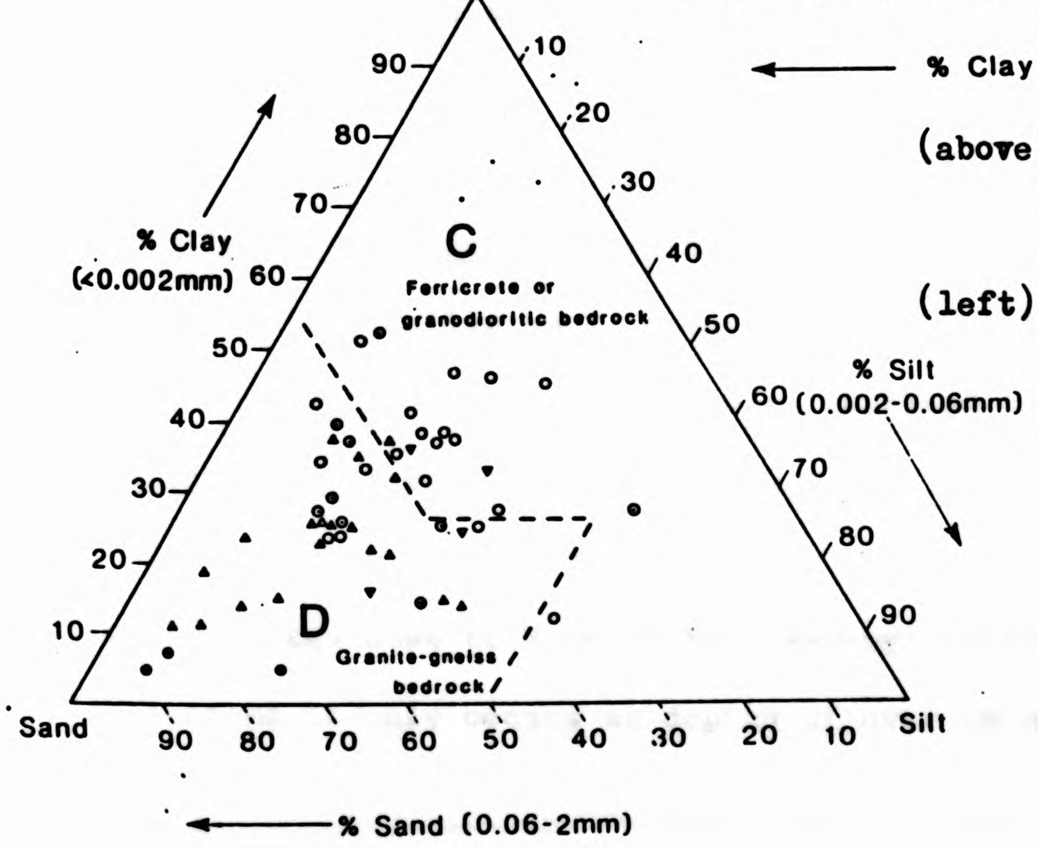
Figure 5.6a

Topsoil texture





(above) Figure 5.6b
Gravel texture.



(left) Figure 5.6c
Saprolite texture.

16mm. The Low Terrace topsoils can be subdivided into the low-lying, seasonally-waterlogged soils of the recent low terraces, henceforth termed "Type II" low terraces; and the higher-level, well-drained terrace soils such as the Boya/Nafayi terrace discussed in the previous section, here termed "Type I" low terraces. Both types of terrace topsoil have a higher proportion of fines than the interfluve topsoils, with values ranging from 33 to 55%. Figure 5.5, the C/M diagram, shows that the Type I topsoils are better sorted than the Type II topsoils: this may be due to the greater degree of colluvial reworking experienced by the Type I terraces. The valley swamp topsoils are highly organic and have a high fines content, ranging from 50 to 56%, with no clasts larger than 4mm. The variations in topsoil texture relative to landform type are summarised in Figure 5.6(a): the type of local bedrock is clearly a stronger control over topsoil's texture than its geomorphic position.

A2, Alluvial fill layers have relatively low fines contents, from 10 to 18%, and consist primarily of sand-sized clasts, although some particles are up to 16mm in size; these are the best-sorted samples from the Koidu Basin (cf. Figure 5.5). The alluvial fill layers of recently formed low terraces show a marked increase in the proportion of fines, to 20-27%.

A3, Colluvial fill layers form two distinct subgroups, of which only the lowest fill, Colluvium I, occurs in both the Yengema and the Kania sites, the upper colluvial fill being confined to the Yengema sites. Colluvium I is poorly sorted, with a high proportion of fines (45 to 73%). It occurs at varying depths in the Kania area, from 0.15m at the interfluve sites down to 3.0m in the Pawpawyi buried valleyhead, whilst at Yengema it only occurs at depths of over 1m at both interfluve

and Type I low terrace sites. This layer often overlies the saprolite layer and appears to be largely derived from it, as indicated by the similar cumulative frequency curves of these two layer types. Colluvium II only occurs in Type I low terrace deposits at depths of less than 1m; the cumulative frequency curve for this layer is similar to that of the Type I low terrace saprolite layer but is relatively depleted in fines, with only 27 to 40%.

The Gravel Layers consist of three main types: alluvial, lateritic and mixed. The variations in gravel texture relative to landform type are summarised in Figure 5.6(b). Only a brief summary of each gravel type is given here as a detailed study of gravel layers follows in section 5.3.

B1, Alluvial gravels consist almost entirely of quartz or bedrock pebbles, in a grey clayey sand matrix with only 9 to 19% fines and a coarse "tail" of particles up to 64mm in size in the stream deposits.

B2, Lateritic gravels occur most commonly on the planate interfluves. They contain nodular to pisolithic iron sesquioxide accumulations from 2 to 20mm in size, with occasional aggregates of concretions or fragments of vermiform laterite up to 200mm in size (Plate 5.1). The matrix is a red-brown sandy clay or loam with a high proportion of fines, from 20 to 50%. The coarsest gravels come from the granodioritic gneiss interfluves of the Yengema area.

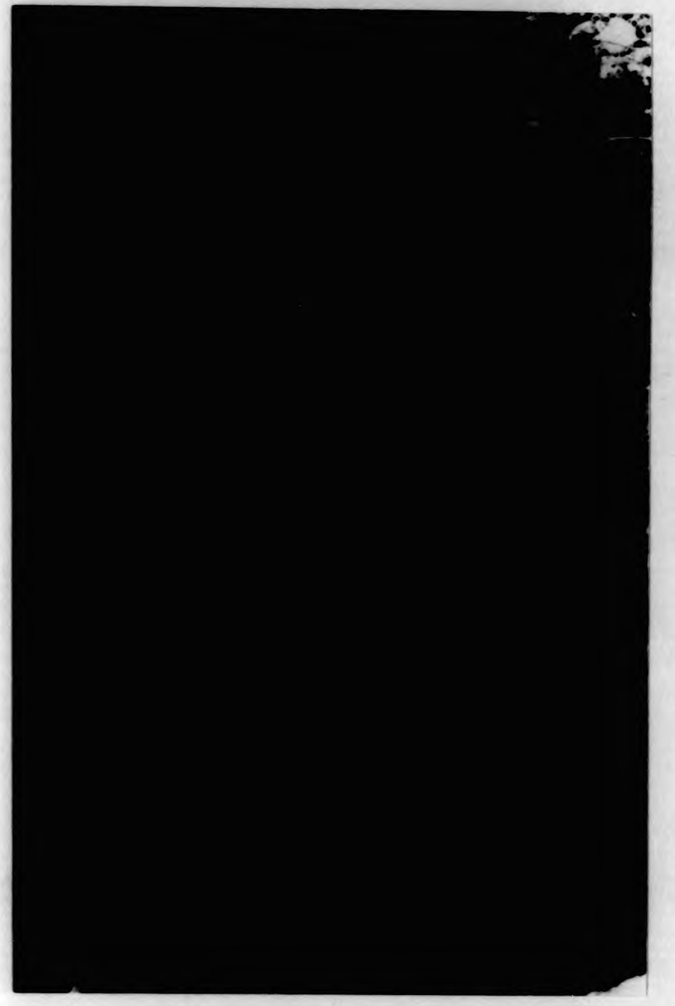
B3, Mixed gravels occur most commonly in buried valleyheads or infilled rills. They contain both iron sesquioxide accumulations, bedrock fragments and quartz clasts, often in an iron sesquioxide cement (viz. Plate 5.1). They have a high proportion of fines, from 19 to 49%, and a coarse "tail" up to 100mm in size.

C, Regolith and Saprolite occur in markedly different geomorphic positions, regolith being largely confined to hilltop and hillside/glacis slope positions where colluvial processes tend to dominate over chemical weathering; whilst saprolite occurs primarily in interfluve and valleyfloor domains where chemical weathering predominates. Regolith layers have gently sloping cumulative frequency curves with relatively small amounts of fines, but with a very coarse 'tail' no finer than 16mm. Conversely, the proportion of fines in the Saprolite layer is very high, 57 to 70% at Kania and 45 to 60% at Yengema, with most particles finer than 8mm in size. The relatively steep cumulative frequency curves of the Type I terrace Saprolite at Yengema, indicate that this saprolite has been "washed" and depleted of fines. Figure 5.6(c) shows that this is indeed the case, with riverbed saprolite showing an even greater depletion of clay. Figure 5.6 also illustrates the strong control bedrock lithology has over saprolite texture: granodioritic gneiss underlies only 6% of the saprolites with sandy clay or loam textures, but underlies 61% of the saprolites with clay loam or silt textures.

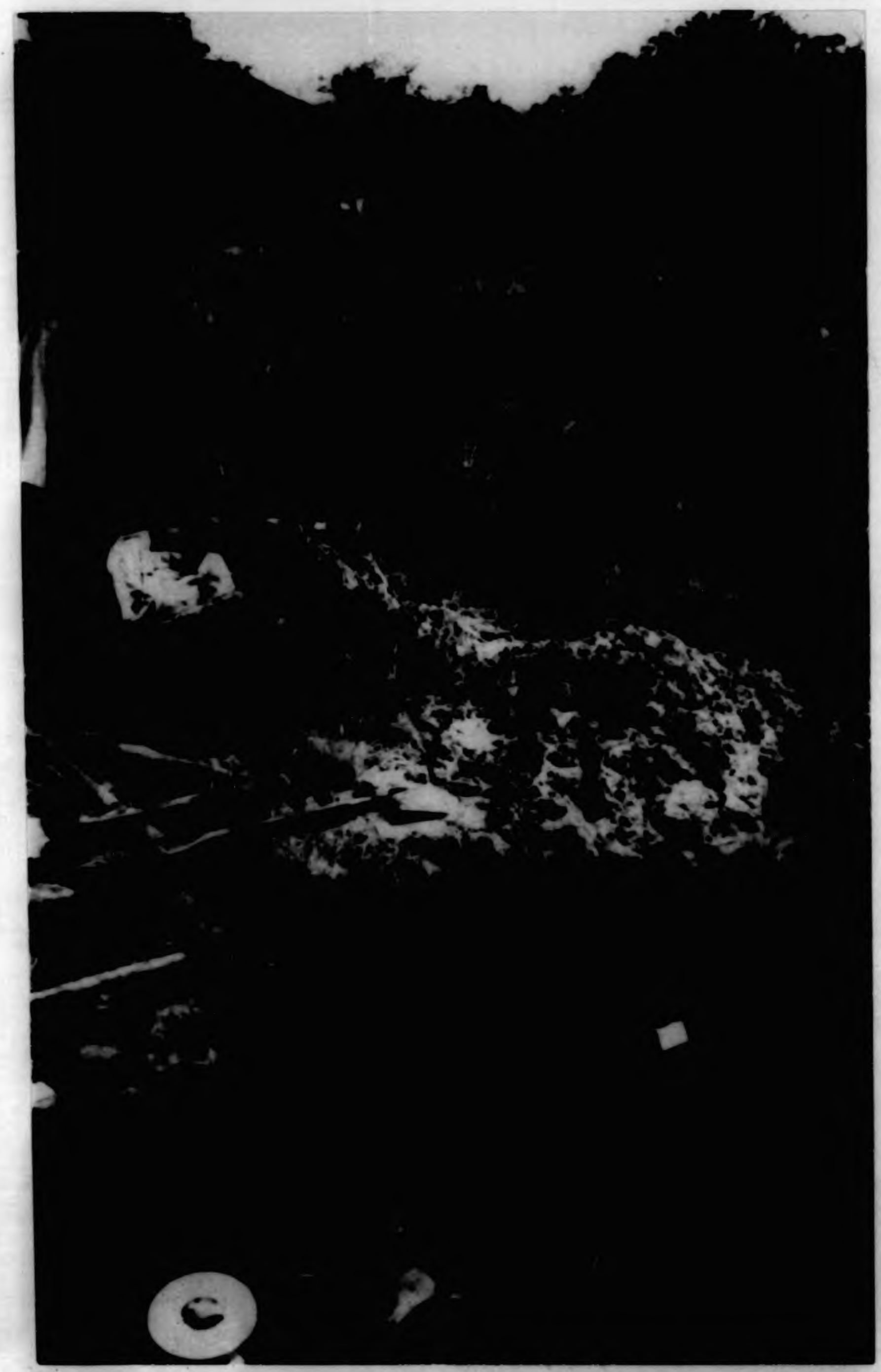
5.3 UNIT LANDFORMS AND MORPHOFACIES TYPES

This section will examine the premise that each unit landform has a characteristic morphofacies type, resulting from the geomorphic setting of that landform within the landscape and the varying intensities and durations of the pedo-geomorphic processes which affect that particular site. However, prior to that, some of the terminology used in this section must be explained.

Plate 5.5 A
Type II Low Terrace.



(below)
Plate 5.5 B
Boya valleyhead swamp.



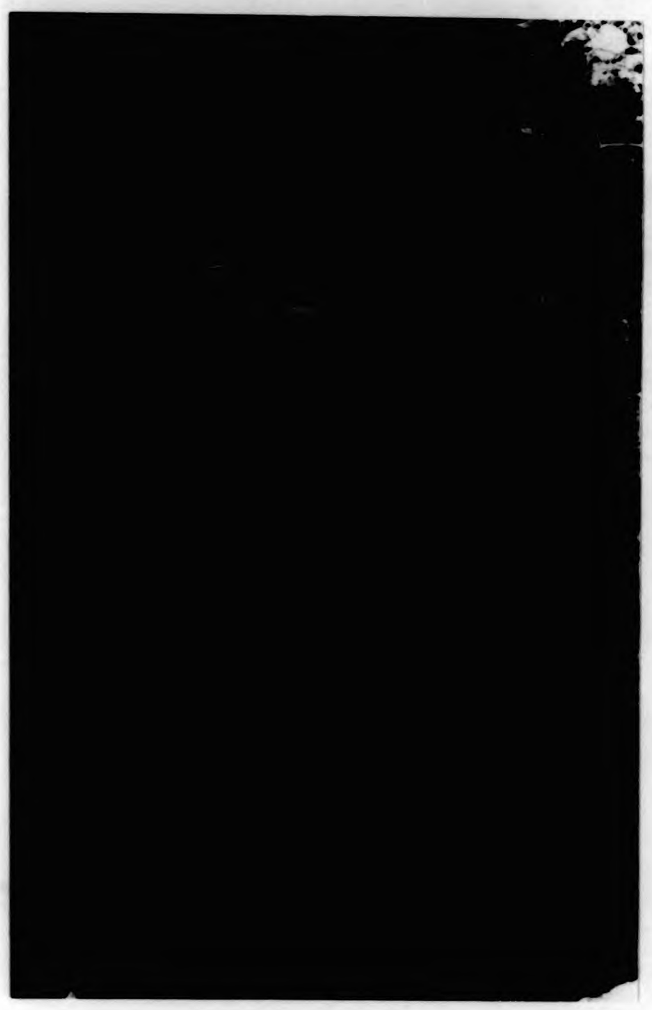


Plate 5.5 A
Type II Low Terrace.

(below)
Plate 5.5 B
Boya valleyhead swamp.

Plate 5.5 C Truncated saprolite, Kania.

Plate 5.5 D Glacis deposit, Yengema.

Plate 5.5 C Truncated saprolite, Kania.

Plate 5.5 D Glacis deposit, Yengema.

Overleaf : Page 132, Plate 5.6

<u>Detailed photographs of characteristic profile types</u>

Facing page :

Plate 5.6	Detailed photographs of characteristic profile types.
5.6A	Glacis deposit with rounded quartz pebbles, Pit N1H. 0.5m of red-brown clay loam colluvium overlies the gravel layer.
5.6B	Granitic gneiss interfluve profile, Pit P2E. c0.13m of grey-brown clay loam topsoil overlies a lateritic gravel with occasional angular quartz fragments.
5.6C	Granodioritic gneiss interfluve profile, Pit N4J. A thin loamy topsoil merges into athick lateritic gravel (c0.05-0.35m), which overlies saprolite showing "ghosts" of corestones. The saprolite merges with indurated bedrock at the profile base.

Facing page :

Plate 5.6	Detailed photographs of characteristic profile types.
5.6A	Glacis deposit with rounded quartz pebbles, Pit N1H. 0.5m of red-brown clay loam colluvium overlies the gravel layer.
5.6B	Granitic gneiss interfluve profile. Pit P2E. @0.13m of grey-brown clay loam topsoil overlies a lateritic gravel with occasional angular quartz fragments.
5.6C	Granodioritic gneiss interfluve profile, Pit N4J. A thin loamy topsoil merges into athick lateritic gravel (@0.05-0.35m), which overlies saprolite showing "ghosts" of corestones. The saprolite merges with indurated bedrock at the profile base.

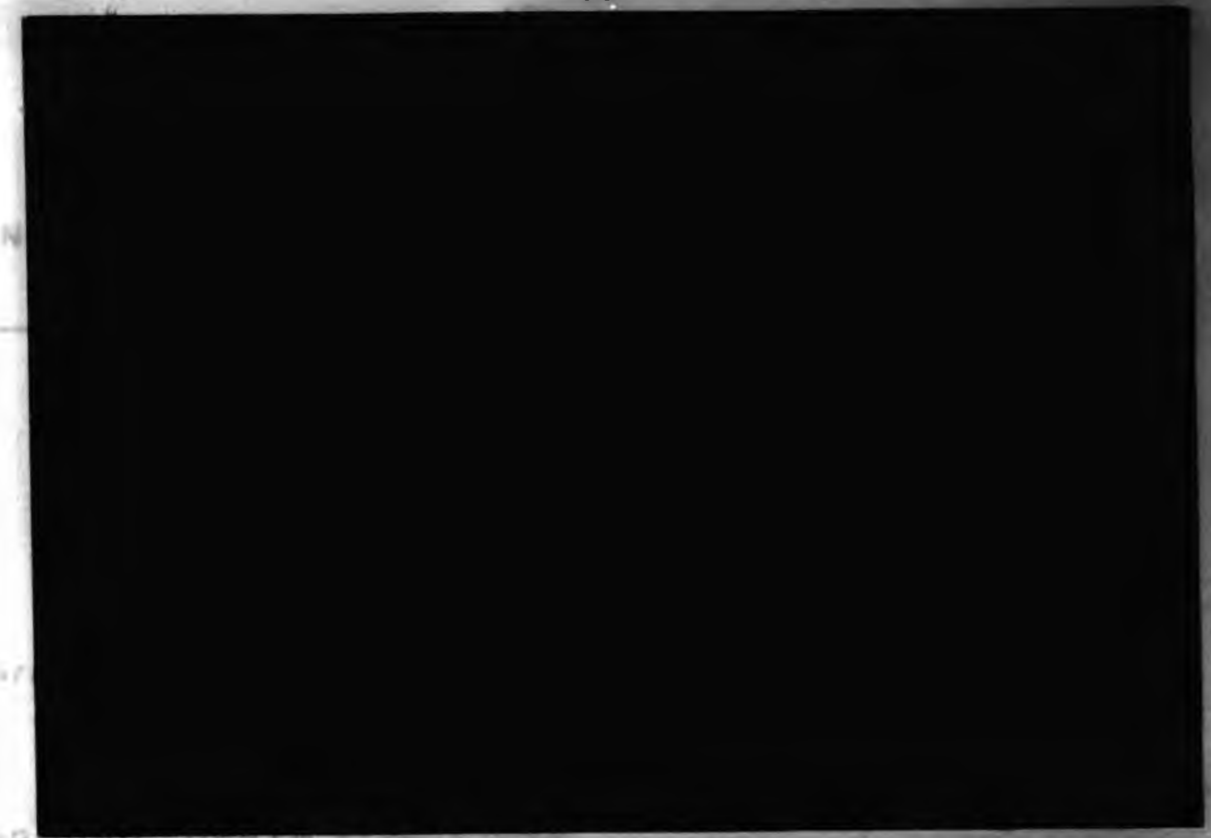
Overleaf : Page 133, Plates 5.7A & 5.7B

Facing page :

Plate 5.7A Patinated surface of a truncated saprolite , 2-3m from the buried valleyhead of the Wongoyie stream near Kania village (Figure 4.12). The broken pebbles of sub-rounded ferruginised quartz have white rims, apparently 'leached' of iron sesquioxides. Scale : red pen is 15cm long.

Plate 5.7B Palaeorill on Kania interfluve ('KTA' in Figure 4.12). The mixed lateritic/quartzitic gravel is in an iron sesquioxide cement. Cobbles extracted from this deposit are rounded and ferruginised, with 'leached' rims.

A



B

Facing page :

Plate 5.7A **Patinated surface of a truncated saprolite** , 2-3m from the buried valleyhead of the Wongoyie stream near Kania village (Figure 4.12). The broken pebbles of sub-rounded ferruginised quartz have white rims, apparently 'leached' of iron sesquioxides. Scale : red pen is 15cm long.

Plate 5.7B **Palaeorill on Kania interfluve** ('KTA' in Figure 4.12). The mixed lateritic/quartzitic gravel is in an iron sesquioxide cement. Cobbles extracted from this deposit are rounded and ferruginised, with 'leached' rims.

A

B

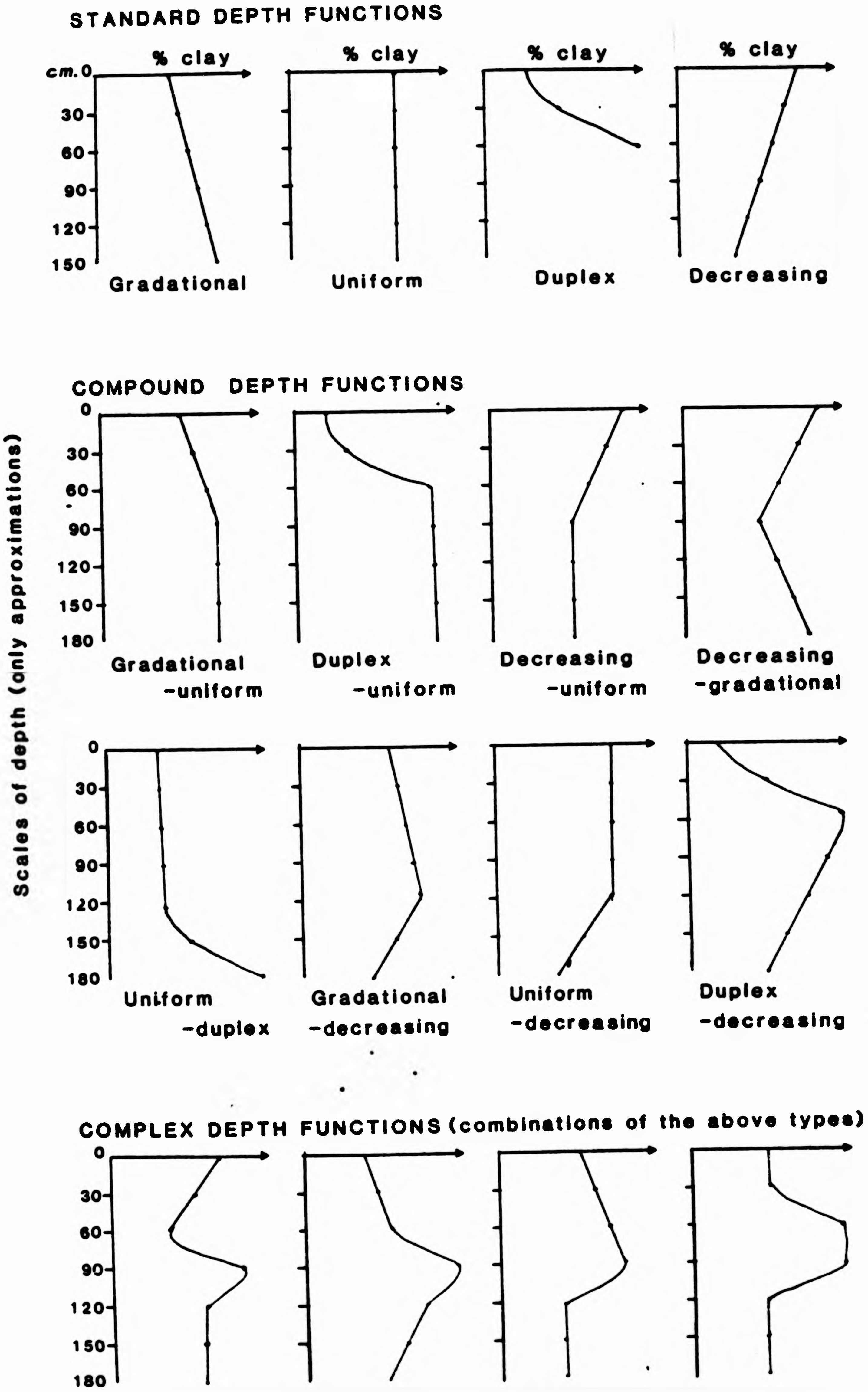
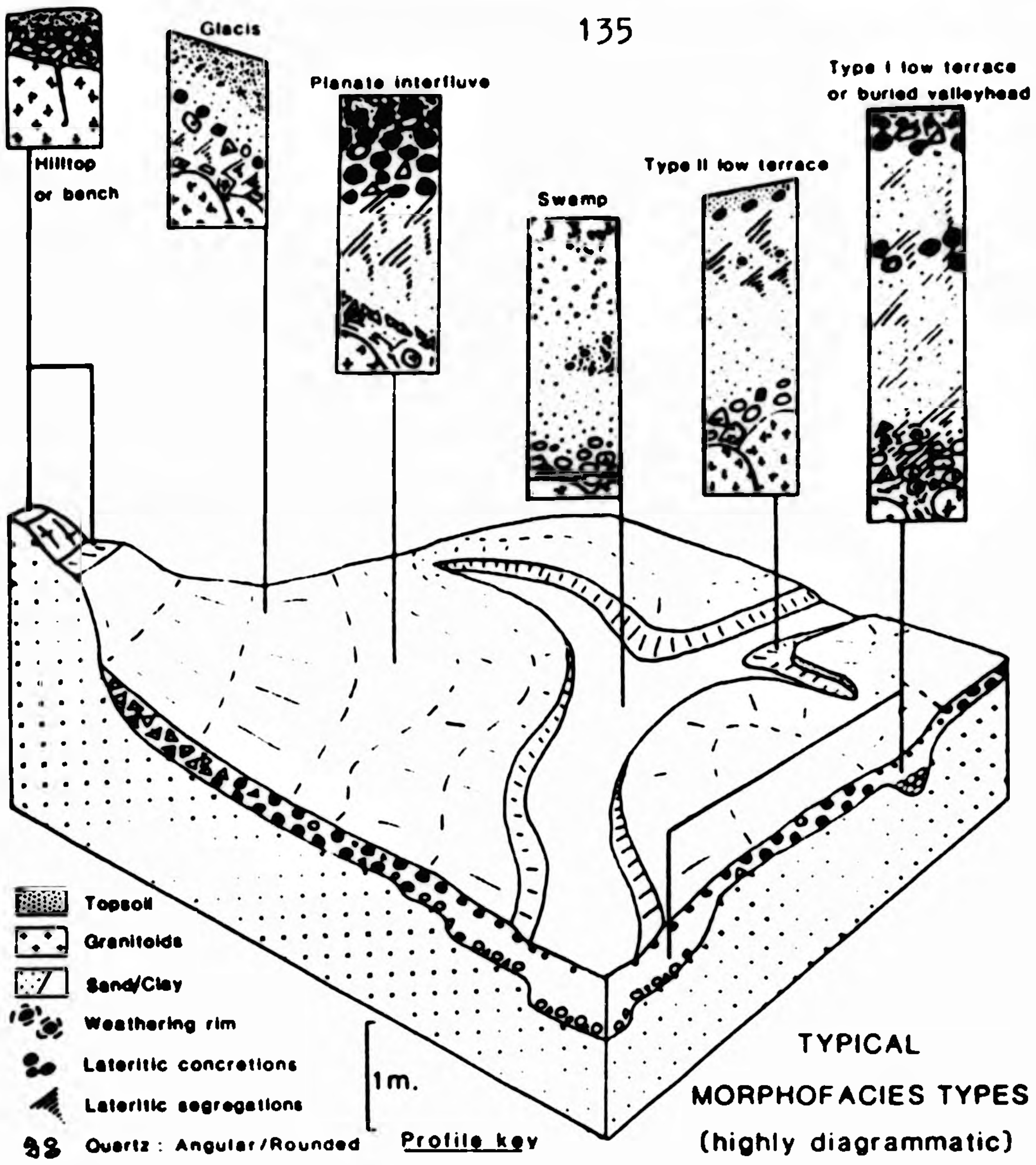


Figure 5.7 Types of percentage clay depth functions



TYPICAL MORPHOFACIES TYPES (highly diagrammatic)

(Number of samples in brackets)	Hillside benches (4)	Footslopes (4)	Proximal glacis slopes (7)	Distal glacis slopes (8)	Planate inter-fluves (10)	Sloping inter-fluves (9)	Swales (7)	Inter-fluve rims (8)	Low Terrace I (8)	Low Terrace II (14)	Valley swamps (7)	River floodplain (4)
Slope angle °	2.0	10.00**	4.7**	2.9*	0.8**	3.2*	5.2**	5.9**	2.8**	4.5	1.0	0.7
Profile depth(M)	0.83*	0.68	1.15*	1.42**	1.50**	1.61**	1.84	1.57*	2.55**	1.62**	1.50**	2.90
Topsoil thickness(M)	0.14	0.23	0.24*	0.43*	0.22	0.21	0.16	0.14	0.30	0.30	0.43	0.52
Top gravel thickness(M)	0.61*	0.33	0.35	0.26	0.39	0.55	0.24**	0.46	0.17	0.01	0.03	0.00
Basal gravel thickness(M)	0.00	0.00	0.00	0.01	0.04	0.02	0.14	0.02	0.25**	0.23**	0.40*	0.30*
Gravel Layer composition (mean %):-												
Clay + silt	26.8*	27.8	28.0	31.7**	34.4**	29.2**	30.9**	35.6**	37.1**	34.5*	17.3*	19.3*
Sand	32.1	41.2*	40.1*	37.8**	30.2**	27.9**	36.2**	31.9*	38.9**	42.1**	55.6**	59.7*
Gravel	41.0**	31.0**	32.0*	30.5*	35.4*	42.9*	24.5**	32.4**	24.0	23.3*	27.0*	21.2
Angular quartz	5.1	27.4	33.8	22.5	25.2	13.0	18.4	10.8	22.7	35.3	24.5	49.1**
Granitic fragments	49.0	43.0	11.4	3.7	14.6	1.1	0.6	2.6	10.0	26.3	22.6	15.2
Rounded quartz	0.5	0.0	13.0	8.4	5.2	1.9	3.2	0.7	20.2	11.6*	20.7	13.1
Laterite segreg-ations	23.4	12.7	21.4	51.7	8.0	17.8	41.0	30.0	41.3	18.0	18.8	7.8
Vermiform laterite	4.1	1.6	0.0	0.0	2.8	5.3	0.1	2.3	0.0	0.0	0.0	0:0
Laterite concret-ions	25.2	16.9	18.5	11.8	44.3	60.2	18.5	28.9	4.9	2.8	7.5	14.7
Bedrock ratio	64.5	72.7	58.1*	56.8	43.3	23.3	52.2	44.1	55.3*	78.9**	67.4**	70.1**
Rounded quartz ratio	0.6	0.0	17.7	15.4	6.2	2.5	8.8	7.6	31.1	14.8	22.3	14.2
% of pits with heavy minerals	50.0	0.0	28.6	37.5	40.0	44.4	100	25.0	78.0	64.3	100	100

Coefficients of variation : ** 10-30% * 30-50% (otherwise >50%)

Table 5.4 Morphofacies Types: morphometric, textural and petrographic data.

Reference is made below to the "depth function", or variation with depth, of the percentage clay. The system of Northcote (1971), with "Uniform", "Gradational" and "Duplex" trends (re.Table 3.3 and Figure 5.7) has been modified to include "Decreasing" trends where the % clay decreases from one sample point to the underlying sample point."Compound" depth functions occur where there are two types of trend down a profile; whilst "Complex" depth functions occur where there are more than two types of trend. It should be emphasised that the size range of the silt used in this study to determine silt:clay ratios was 2-62 µm, markedly coarser than the range originally used by Van Wambeke (1962). Table 5.4 provides a summary of the morphometry of each morphofacies type, plus the textural and petrographic compositions of the main gravel layer in each morphofacies type. The discussion of these results concentrates on the four most widespread unit landforms - glacis slopes, interfluves, low terraces and valley floors, which account for 86% of the sample pits.

Glacis slopes (Plates 4.2, 5.5A, 5.6A) are found fringing residual hills, inselbergs or kopjes and can be subdivided into proximal glacis with a mean slope of 4.7° and distal glacis, with a mean slope of 2.9°. Both profile depth and topsoil thickness double from the footslopes to the distal glacis, which have a mean profile depth of 1.42m and a mean topsoil thickness of 0.43m. In contrast, the mean thickness of the top-gravel decreases from 0.35m in the proximal glacis to 0.26 in the distal glacis. Reference to Table 5.4 shows that this may be due to a shift in the petrographic composition of the gravel from a relatively coarse angular quartz/bedrock gravel to a finer gravel composed primarily of lateritic segregations; there is also a decrease in the mean % of gravel-sized clasts and an increase in the mean % of fines from the proximal to the distal glacis.

The percentage clay depth functions for glacis slopes form two groups controlled by bedrock lithology. Glacis profiles over granitic gneiss have Uniform/Decreasing trends or Gradational/Decreasing trends (cf.Figure 5.7), indicating a surface depletion of clay and/or a mid-profile enrichment in clay. Conversely, glacis profiles over granodioritic gneiss have Decreasing/Uniform trends, indicating surface enrichment in clay. Analysis of the Silt:Clay ratio values for glacis deposits shows that they are multi-layered, the nature of the layers varying with the local bedrock lithology and its degree of weathering.

Layer	Granitic gneiss		Granodioritic gneiss
	(Weathered)	(Highly weathered)	(Weathered)
Topsoil	0.55 to 0.70	0.40 to 0.51	0.60 to 0.85
Colluvial fill	0.60 to 0.90	0.30 to 0.40	0.55 to 0.70 0.40 to 0.60
Saprolite	0.20 to 0.60 0.70 to 0.85	0.59 to 0.61	0.60 to 0.80
Regolith	0.70 to 2.50	Not sampled, occurs deeper than 3m.	0.50 to 4.70

Table 5.5 Silt:Clay ratios for glacis deposits.

The incidence of rounded quartz in the glacis gravels (from 3.5 to 11.4%) is unusually high relative to the hillside benches and footslopes, where rounded quartz clasts were virtually absent, and relative to the interfluval zone, where rounded quartz formed no more than 5.2% of the gravel. However, the rounded quartz in the glacis gravels consisted of large rounded cobbles which, though few in number, formed a large proportion of the gravel sample (viz. Plate 5.6A). Heavy mineral analyses were carried out on the +1mm size fraction: 28.6% of the proximal glacis gravels and 37.5% of the distal glacis gravels produced heavy minerals; whilst the footslope gravels were devoid of +1mm heavy minerals.

In conclusion, the glacis slopes are zones of material transfer, mainly by slopewash and lateral eluviation. The retention of rounded quartz cobbles and a moderate amount of heavy minerals relative to other morphofacies types, indicates that there is a size or density threshold above which these clasts are not moved.

Interfluves extend from the distal glacis slopes to the valley sides or valley heads. This "interfluve zone" can be divided into planate and non-planate areas, with the latter subdivided into sloping interfluves, swales and interfluve rims (cf. Table 5.4). Planate interfluves (Plates 5.6B and C) have a mean slope of only 0.8°. They grade into distal glacis slopes where residual hills occur, but where residual hills are absent, as on much of the Manjamadu Plateau, extensive planate interfluves occur (viz. Plate 4.3 and Figure 4.5). Planate interfluves have a mean topsoil thickness of 0.22m, almost half that of the distal glacis deposits; however, the mean topgravel thickness of 0.39m and the mean profile depth of 1.5m are both greater than those of the distal glacis deposits. Finally, buried gravels, although rare, are found more frequently in the planate interfluve deposits than the glacis deposits.

Sloping interfluves occur between the planate interfluves and the swales or interfluve rims and have a mean slope of 3.2°. Topsoil thickness is similar to that of the planate interfluve zone, but the mean topgravel thickness of 0.55m and the mean profile depth of 1.61m are both greater than those of the planate interfluve zone.

Swales are the zones of steeper-sloping interfluve terrain fringing valley heads or valleyside gullies. Their mean slope is 5.2°. Both topsoils and topgravels are relatively thin, mean values being 0.16m and

0.24m respectively. The mean profile depth is 1.84m, but this is highly variable, the shallowest profiles being in the Yengema area and the deepest profiles occurring in the Kania area, often with basal gravels.

Interfluve rims are the distal slopes of the interfluve zone, fringing the valley sides or low terraces with a mean slope of 5.9°. This landform was termed the "Valley edge" by Thomas et al. (1985a). "Interfluve rim" is preferred here as it implies a genetic continuity with the interfluve zone and because the distal sections of the interfluve zone are often separated from the valley sides by terrace deposits and are therefore well away from the present valley edge. Interfluve rim topsoils are even thinner than those of the swale zone, with a mean of only 0.14m.

The interfluve subdivisions described above have morphofacies types that are most clearly distinguished by the textural variations of the gravel layer (Table 5.4). The coarsest gravels occur in the sloping interfluve deposits, with means of 42.9% gravel and 27.9% sand, whereas swales produce the finest gravels with means of 24.5% gravel and 36.2% sand. Planate interfluves and interfluve rims have relatively high proportions of fines in their gravel layers with means of 34-36%, whilst sloping interfluves and swales have means of 29-31%.

Silt:clay ratios (Appendix C) show that the high fines values of the planate interfluve gravels are due to a large proportion of clay, whilst the high fines values of the interfluve rims are due to a large proportion of silt. Silt:clay values rise from 0.4-0.7 in the sloping interfluve zone to 0.8-1.71 in the interfluve rim zone. This indicates the retention of clay on the planate interfluves and progressively greater eluviation away from them. The percentage clay depth functions support this hypothesis:

planate interfluves having simple trends, either Uniform or Gradational; non-planate zones having various Compound or Complex trends (viz. Figure 5.7). These trends indicate that the non-planate zones have had a polygenetic development.

Part of the variation in top gravel texture between the interfluve morphofacies types can be explained by variations in gravel petrography (Table 5.4). Planate and sloping interfluves, the morphofacies with the coarsest gravels, have the highest proportion of lateritic concretions and vermiform laterite fragments, with mean values of 47 to 66%, compared to only 18 to 30% for swales and interfluve rims. Conversely, the non-planate morphofacies zones have high proportions of lateritic segregations, with means of 17 to 41%, compared to only 8% for planate interfluves. The neo-formation of lateritic segregations in the top gravel of the non-planate morphofacies, noted from the thin section analyses (Table 5.2), has effectively "diluted" the original content of rounded quartz and bedrock fragments. In excluding the lateritic segregations from the gravel petrography calculations, to give the Rounded Quartz Ratio and the Bedrock Ratio of Table 5.4, the swales and interfluve rims were found to have the higher values of both bedrock fragments, with means of 44 to 52%, and of rounded quartz, with means of 7 to 9%, than either the planate or gently sloping interfluves.

The occurrence of 1mm heavy minerals in the gravels of the interfluve zone morphofacies types (Table 5.4) indicates that planate and sloping interfluves are zones of retention, that interfluve rims are zones of depletion, and that swales are zones of concentration. This is in agreement with the findings of Thomas et al., (1985a, p.800; viz. Appendix

A), which were based on a more extensive database of diamond mining results. In a detailed study of the Pawpawyi-Wongoyi planate interfluve, an 80m trench ("KTA" in Figure 4.5) was dug and bulk-samples of 1-2m^3 were treated at the NDMC Prospecting Department to extract all heavy minerals over 1mm in size. The results are shown in Figure 5.8 and show two zones where ilmenite grades are an order of magnitude higher than the surrounding saprolite. The first, at the southern end of the trench is probably due to the presence of an ilmenite-rich kimberlite dyke a few metres further south. The second anomaly is from what appears to be an infilled rill, containing iron-stained rounded quartz cobbles with grey/white iron-leached rims and cobbles of vermiform laterite, all held in a yellow-brown sandy clay and iron sesquioxide cement (Plate 5.7B). If this deposit is a "palaeorill" it indicates a relatively recent cut-and-fill episode, during which the greatest concentration of rills would have been in the swale and interfluve rim zones. This hypothesis is supported by the S.E.M. data of Table 5.3: the highest incidence of

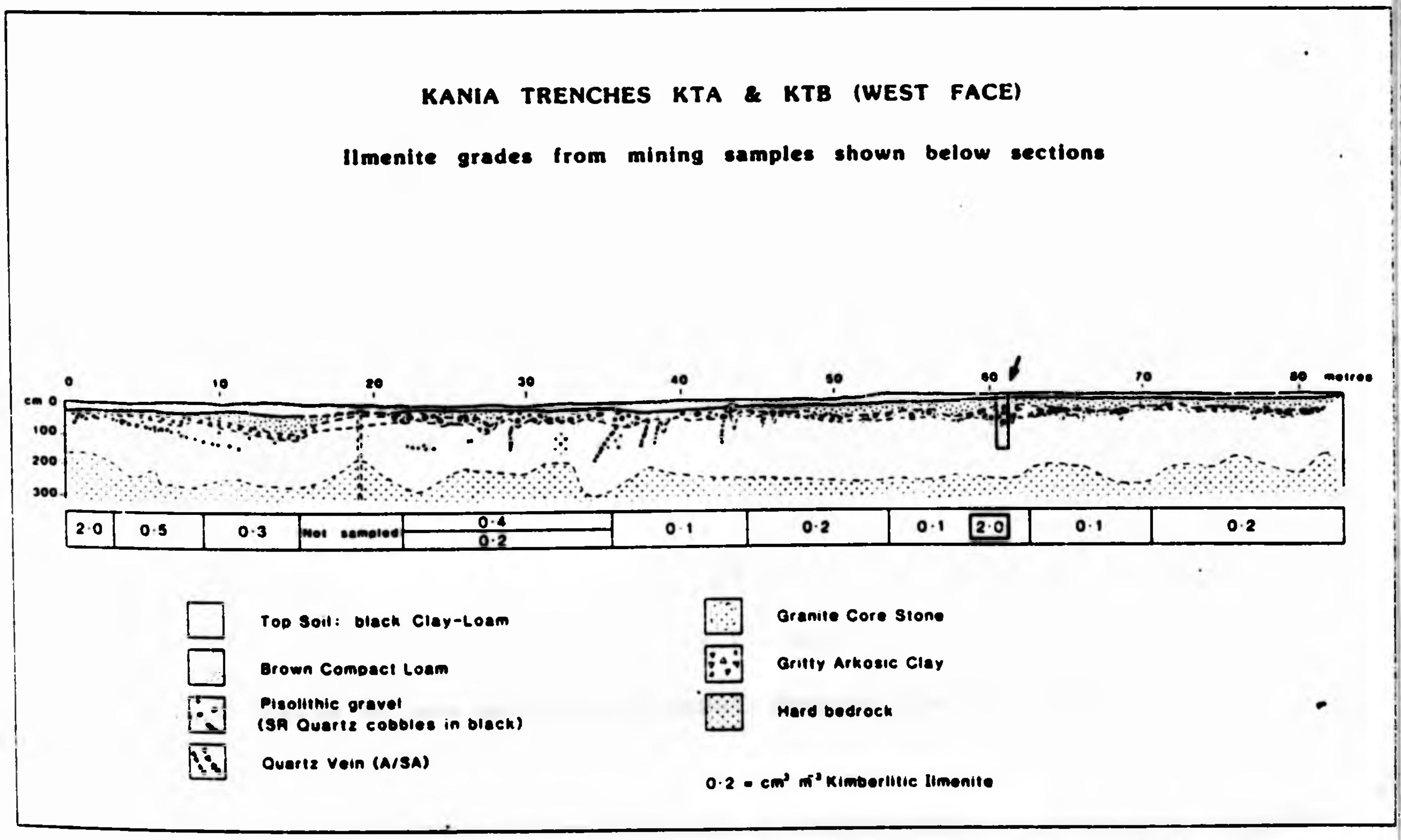


Figure 5.8 Kania palaeo-rill (arrowed) and associated ilmenite grades.

"mechanical" features in the interfluve zone occurring in the swale and interfluve rim gravels. The S.E.M. data also indicates that the gravel from pit P5E, the northern Kania interfluve site fringing the Woyie River (Figure 4.6 and Table 5.2), contains fluvially-derived sand grains. The distribution pattern of the sand grain surface morphology features from P5E bears a close resemblance to that of the alluvial/colluvial fill of the Type I terrace of the Boya/Nafayi confluence at Yengema, (pit N4D of Table 5.3).

The thin section analyses (Tables 5.1 and 5.2) highlight the dichotomy between the planate and non-planate morphofacies of the interfluval zone. The planate interfluve profiles are uniform, have solely kaolinitic clay matrices, but are severely modified by pedoturbation with Labyrinthine topsoil microstructures grading into saprolite with Granular to Subangular Blocky microstructures. The presence of very hard small black lateritic concretions of 1 to 5mm diameter in both the top gravel layer and the saprolite layer may indicate a period of soil/saprolite stripping under arid/semi-arid conditions with some pisoliths falling down desiccation cracks in the exposed saprolite (Thomas, pers.comm. 1986, has observed similar features in Ghana).

The non-planate interfluval morphofacies types are characterised by the presence of Gibbsite in the layer matrices (Tables 5.1 and 5.2). Furthermore, these morphofacies types show distinct layer discontinuities, hence the Compound and Complex percentage clay depth functions of this zone. The microstructural variations of the Kania buried valley head zone (pit P1C; Table 5.2), indicate that only the upper fill layer has experienced a degree of weathering and pedoturbation similar to the planate interfluve profile, with the lower fill layer and basal gravel layer apparently pre-dating the development of saprolite on the planate interfluve. The microstructural variations of the sloping interfluve zone appear to be controlled by bedrock lithology: the Kania sample, pit P1F, has Alveolar to Subangular Blocky microstructures over granitic gneiss saprolite, indicating a low level of pedoturbation. Conversely, the Yengema sample, pit B4H, has a Labyrinthine to Crumb microstructure over a granodioritic gneiss saprolite, indicating a high degree of pedoturbation, probably due to the relatively nutrient-rich bedrock.

In conclusion, the apparent uniformity of the Koidu Basin's gently sloping interfluves is deceptive. On the basis of both surface morphometry and profile morphology, four morphofacies types can be recognised in the interfluve zone: planate interfluves, sloping interfluves, interfluve rims and swales. These are summarised in Table 5.6.

	Planate Interfluve	Sloping Interfluve	Interfluve rim	Swale
Mean slope:	0.8°	3.2°	5.9°	5.2°
Topsoil:	Thick	Thick	Thin	Thin
Top gravel:	Thick	Thick	Thick	Thin
Basal gravel:	Rare	Rare	Rare	Occasional
RQ ratio:	High	Minimum	High	Maximum
Heavy minerals:	Retention	Retention	Depletion	Concentration
Lateritic clasts:	Maximum % lateritic concretions and vermiform laterite		Maximum % lateritic segregations	
SEM features:	"Chemical"	"Mechanical"	"Mechanical"	"Mixed"
Depth functions:	Uniform	-complex or compound-		
Clay types:	Kaolinite	-Kaolinite and gibbsite -		
Thin section analyses:	Pedoturbation - includes saprolite	Pedoturbation limited to topsoil and upper colluvial layer.		

Table 5.6 Morphological characteristics of the interfluve zone morphofacies types.

Low Terraces are found fringing the valley floors of the Koidu Basin. The textural and micromorphological data given in Figure 5.4 and Tables 5.1 & 5.2), indicate that two types of low terrace occur; this is supported by the morphometric and petrographic data of Table 5.4. Type I Low Terraces often merge into the interfluve margins. They have a mean slope of 2.8° and a mean profile depth 2.55m; with moderately well developed lateritic topgravels having a mean thickness of 0.17m.

Type II Low Terraces (Plate 5.6C) are confined to valley swamps and small streams. They have a steeper mean slope, at 4.5°, a shallower mean profile depth of 1.62m, and a sparse or absent lateritic topgravel that gives a mean thickness of only 0.04m.

The texture of Low Terrace topsoils is related to the texture of the saprolite of adjacent interfluves, indicating a colluvial source for this material (cf. Figure 5.6a). Low Terrace topsoils in granitic gneiss terrain have sandy to sandy loam textures, whilst those in granodioritic gneiss terrain have clay to sandy clay loam textures. However, the texture of the Type II Low Terrace upper saprolite layer is sand to sandy loam in all cases, regardless of bedrock type. This indicates that the lateral eluviation or "washing" of clay and silt from the upper saprolite is a major process in the valley floor/low terrace zone, as already indicated by the cumulative frequency curves of Figure 5.4 and the CM Diagram of Figure 5.5.

Type I Low Terraces, exemplified by those of the Boya-Nafayi confluence zone at Yengema, have a lower fill layer with a similar particle size distribution to that of the saprolite and lower fill of the interfluve zone. The upper fill is better sorted and richer in sand, and the topsoil is moderately well sorted with more fines and less gravel than the upper fill. Type II Low Terraces have soil and fill that bear a closer textural resemblance to the valley swamp deposits; their basal gravels have a greater proportion of sand and a lower proportion of fines than the Type I Low Terraces. This indicates that the latter either formed during a period of greater clay production than at present and/or that the Type I terraces have had a greater amount of time for the illuviation and neoformation of clay to occur. The Silt:Clay ratios give some clues about the nature of Low Terrace morphogenesis. These data are summarised in Table 5.8.

Layer	Type I Low Terrace		Type II Low Terrace
Topsoil.	0.4 - 0.6		0.4 - 0.5
Upper fill.	0.6 - 0.8	Only one fill layer	0.6 - 0.8 (with lenses of 0.2 - 0.3; 0.5-0.6 and 1.12)
Lower fill- Basal gravel.	0.5 - 0.6		
Basal gravel- Upper saprolite.	0.2 - 0.4		0.7 - 0.9
Lower saprolite.	0.3 - 0.8		1.5 - 1.7 (over corestones)

Table 5.7 Silt:Clay ratios from Low Terrace deposits

From these Silt:Clay ratio values it appears that the Type I terraces have undergone eluviation with the illuviation of this clay in the saprolite layer, particularly at the basal gravel/saprolite interface. This does not appear to have happened in the Type II Low Terraces, where clay has apparently been removed from the basal gravel and upper saprolite by lateral eluviation. The percentage clay depth functions for Low Terraces show surface enrichment and basal depletion of clay in the most recent Type II terraces with gradually Decreasing trends. However, Type II terraces further back from the valley swamp have Compound or Complex trends that indicate surface depletion, with midprofile enrichment and/or basal depletion of clay. Type I terraces have Complex trends that indicate varied and complex morphogeneses, although all samples show a clay-rich basal layer over the saprolite layer.

Further differences between the Type I and Type II Low Terraces were revealed by the thin section analyses. Kaolinite is the main component of the matrices in both types of terrace, but gibbsite - although present in <u>all</u> of the Type I terrace layers - only occurs in the saprolite of the Type II terraces. Yengema Type II terraces are dominated by Single Grain microstructures similar to those of the valley swamps, whilst Kania Type II terraces are dominated by Alveolar or Blocky microstructures, indicating illuviation or neoformation of clay. The Type I Low Terrace sample shows a greater degree of pedogenetic development, having Granular or Alveolar to Massive fill layers separated by a palaeosol with gritty nodular lateritic concretions and a Subangular Blocky to Massive saprolite (unlike the Massive Saprolitic microstructure of the Type II saprolite layer).

Lateritic concretions are largely absent from the Yengema Type II terrace deposits, only occurring as lenses of slopewash deposits or in the basal gravel, where they are brown, nodular, gritty and apparently dissolving away, for they have "leached" yellow-brown rims. The dissolution of lateritic concretions appears to be less intense in the Kania type II Terraces, where concretions were found in all layers above the saprolite; indeed, the presence of lateritic segregations in the saprolite indicates that the neoformation, rather than the dissolution, of iron sesquioxides occurs here. In contrast to the Yengema Type II terraces, the Yengema Type I terraces have lateritic concretions in all layers, even the saprolite layer, where rare 1 to 5mm diameter black pisoliths were found.

Clay coatings and ferricutans are absent from the Yengema Type II terrace deposits and appear to be concentrated in the lower fill and basal gravel layers of the Type I terrace, indicating illuviation and/or neoformation of clay and iron sesquioxides in these layers. Unlike the Type II terraces of the Yengema, the Type II terraces of the Kania area have an upper (colluvial) fill layer with frequent clay coatings,though they are often broken. Clay coatings become rarer down the profile and are limited to aureoles of iron sesquioxide compounds around weathering lateritic concretions or biotite in the basal gravel and saprolite. It thus appears that the degree of pedogenetic neoformation of clay and iron sesquioxides, and the effectiveness of their illuviation down through the profile, increases from the Yengema Type II terraces, where lateral eluviation removes all clay or sesquioxides accumulations; to the Kania Type II terraces, where the effect of lateral eluviation is much reduced, through to the Type I terraces, where neoformation and illuviation dominate.

The petrographic composition of the Low Terrace basal gravels (Table 5.4) provides further evidence that the Type I terraces are distinct from the Type II terraces. Type II terraces have greater proportions of angular quartz and bedrock fragments than the Type I terraces, which in turn have the highest proportions of rounded quartz, lateritic concretions and lateritic segregations. If the lateritic segregations are excluded from the gravel petrography calculations (viz. the 'Rounded Quartz Ratio' of Table 5.4), the Type I Terrace gravels have the highest mean values for rounded quartz of all of the samples from the Koidu Basin, with values even higher than contemporary floodplain deposits. This indicates that Type I terraces formed under environmental conditions are more favourable to the formation of alluvial gravels than contemporary conditions. This hypothesis gets qualified support from the S.E.M. analysis of sand grain surface morphologies, with the Type I Terrace sample (N4E in Table 5.3) having a greater proportion of rounded grains than the present valley swamp gravel of pit N4A. However, the qualifications are that, (a) the Type I terrace basal gravel may not be derived from the Boya Stream but from the nearby Nayafi River (Figure 4.9), which might account for the greater degree of sand grain rounding; and (b) it may be that these rounded sand grains are the result of diagenesis, with the Type I terraces experiencing a longer period of chemical weathering than the Type II terraces.

To conclude, the morphometric and morphological data clearly show that two main types of Low Terrace occur in the Koidu Basin: (i) the relatively simple Type II terraces with a single, dominantly fluvial, fill layer and a very sandy basal gravel, bearing a close resemblance to the valley swamp deposits; and (ii) the older and more complex Type I terraces with an upper colluvial fill layer overlying a buried lateritic gravel and a lower fluvially-derived fill layer overlying basal gravel. The sequence of landforms from the valley floor up to the Type I Low Terraces represents a <u>chronosequence</u>. This is most clearly illustrated by the percentage clay depth functions, which are at their minimum in the fluvial fill, basal gravel and upper saprolite of the valley swamp, where fine material is apparently removed by lateral eluviation. Once a (Type II) terrace forms, the dominant process apparently becomes the vertical eluviation of fines from the topsoil and fill layers, with illuviation and neoformation producing clay maxima at progressively greater depths over time, until the maximum percentage clay eventually occurs at the basal gravel/upper saprolite interface of the Type I terraces. The thin section analyses support this chronosequence hypothesis, showing that the sedimentary structures of the valley-floor deposits are progressively replaced by "pedogenetic" microstructures (i.e. Single-grain → Bridge → → Alveolar → Irregular blocky → Granular → Labyrinthine → Crumb microstructures) resulting from illuviation, clay/sesquioxide neoformation and pedoturbation, as one moves from the youngest to the oldest Low Terraces.

The Type II terraces of the Kania area, with clay coatings in the topsoil and fill layers, appear to be at an intermediate stage of development between the Yengema Type II terraces, where clay coatings are absent, and the Yengema Type I terraces, where clay coatings occur in the lower fill and basal gravel layers. This indicates a greater degree of pedogenesis on the Kania Type II terraces relative to the Yengema Type II terraces and supports the hypothesis that the Kania study area has suffered less disturbance from recent fluvial incision than the Yengema study area.

<u>Valley-floor</u> deposits in the Koidu Basin can be subdivided into two main types: <u>valley swamps</u> with channelless valley heads and drained by streams of up to Strahler Order 4; and <u>riverine floodplain</u> deposits, as along the Nafayi, Bandafayi, Woyie, Meya and Moinde rivers. Morphometric details are given in Table 5.4. Mean surface slopes range from 0.7° to 1.0°, the valley swamps being slightly steeper as they include valley head swamps which slope at 3 to 5°. The floodplain deposits have the deepest profiles of all the morphofacies types, with a mean depth of 2.9m; whilst valley swamps have a mean depth of 1.5m, similar to that of the Type II Low Terraces. Topgravel only occurs in the valley swamps, mostly in the valley head zone, due to slopewash from the interfluves. Basal gravels are thickest under the valley swamps with a mean of 0.4m compared to 0.3m for the floodplain deposits. Both values are greater than those for the Low Terrace basal gravels (0.23-0.25m), indicating that contemporary environmental conditions favour the build-up of thick basal gravels with higher contents of bedrock fragments and lower proportions of rounded quartz than occurred with the "ancient" Type I Low Terraces.

From the textural diagrams of Figure 5.6 it is clear that the valley floors have the sandiest basal gravel and saprolite layers, indicating pronounced lateral eluviation at the base of the profile. This is further indicated by the percentage clay depth functions, which all show a Decreasing trend at the base of valley floor profiles. The silt:clay values for the valley swamps (Table. 5.8) also show a relatively uniform decrease in clay with depth and a corresponding increase in the proportion of silt, whilst the floodplain deposits show more complex variations with depth .

<u>Layer Type</u>	<u>Valley Swamp</u>	<u>River floodplain</u>
Topsoil	0.95 to 1.30	0.45 to 0.50
Alluvial/colluvial fill	All values 0.70 to 1.82	0.60 to 0.70
Lower alluvial fill		Most values 0.45 to 0.80 (with lenses of 1.10 or 0.35 to 0.40).
Basal gravel		
Saprolite	1.66 to 4.03	1.00 to 1.10

Table 5.8 <u>Silt:clay ratios for valleyfloor deposits.</u>

On the basis of thin section data the valley swamps can be further subdivided into channelless valleyhead swamps and stream swamps (Tables 5.1 and 5.2). The <u>stream swamps</u> consist of peaty topsoils overlying an alluvial fill layer with a Single Grain/Stratified microstructure. This layer merges into the basal gravel layer with an Alveolar microstructure, and grey kaolinitic clay in the clayey sand matrix; the saprolite has a Subangular Blocky to Massive Saprolitic microstructure.

The Yengema valleyhead swamps also have topsoil and upper fill layers with Alveolar to Single Grain microstructures and a kaolinitic clay matrix, although gibbsite pseudomorphs of feldspar were occasionally found. The lower fill has a Single Grain microstructure. In contrast, the basal gravel has an Alveolar microstructure that merges into the Massive microstructure of the saprolite. Clay coatings were virtually absent from both valley and valleyhead swamp deposits, only occurring in the cracks and fissures of lateritic debris. Gritty brown lateritic nodules occur rarely in the valleyhead swamp basal gravel, where they are similar to those found in the buried palaeosol and lateritic gravel of the Type I Low Terrace. The Yengema valleyhead swamp deposits are apparently younger than the stream swamp deposits, where the basal gravel appears to be partly derived from the lower fill of the Type I terrace.

The Kania valleyhead swamp deposit has a basal gravel with a formerly Single Grain microstructure now partially infilled with kaolinitic clay, producing Bridge structures. This layer merges upwards into a lower fill with a Granular to Alveolar microstructure, a buried colluvial gravel with a Granular microstructure, and an upper fill with a Subangular blocky to Crumb microstructure. This indicates intense pedoturbation with the gradual replacement of originally sedimentary fabrics.

Lateritic concretions occur throughout the Kania valleyhead swamp deposit. Reference to Table 5.2 shows that their nature and distribution can be related to that of the lateritic concretions in the Kania

buried valleyhead. The preceding data, coupled with the greater degree of structural development in the Kania fill layers relative to the Yengema valleyhead swamp deposits, indicate that the Kania valleyhead swamp deposits have (a) had greater time to develop pedogenetic microstructures and/or (b) the Kania fills have been formed by the slumping of interfluve rim material from the valleyhead and interfluve margins. Either way, the Yengema valleyhead swamp deposits are dominated by fluvial/eluvial processes, rather than the colluvial /pedogenetic processes that dominate the Kania valleyhead swamps, supporting the deductions about the relative environmental stabilities of the two study areas made from geomorphological data in Chapter 4.

5.4 Catenary variations in gravel petrography

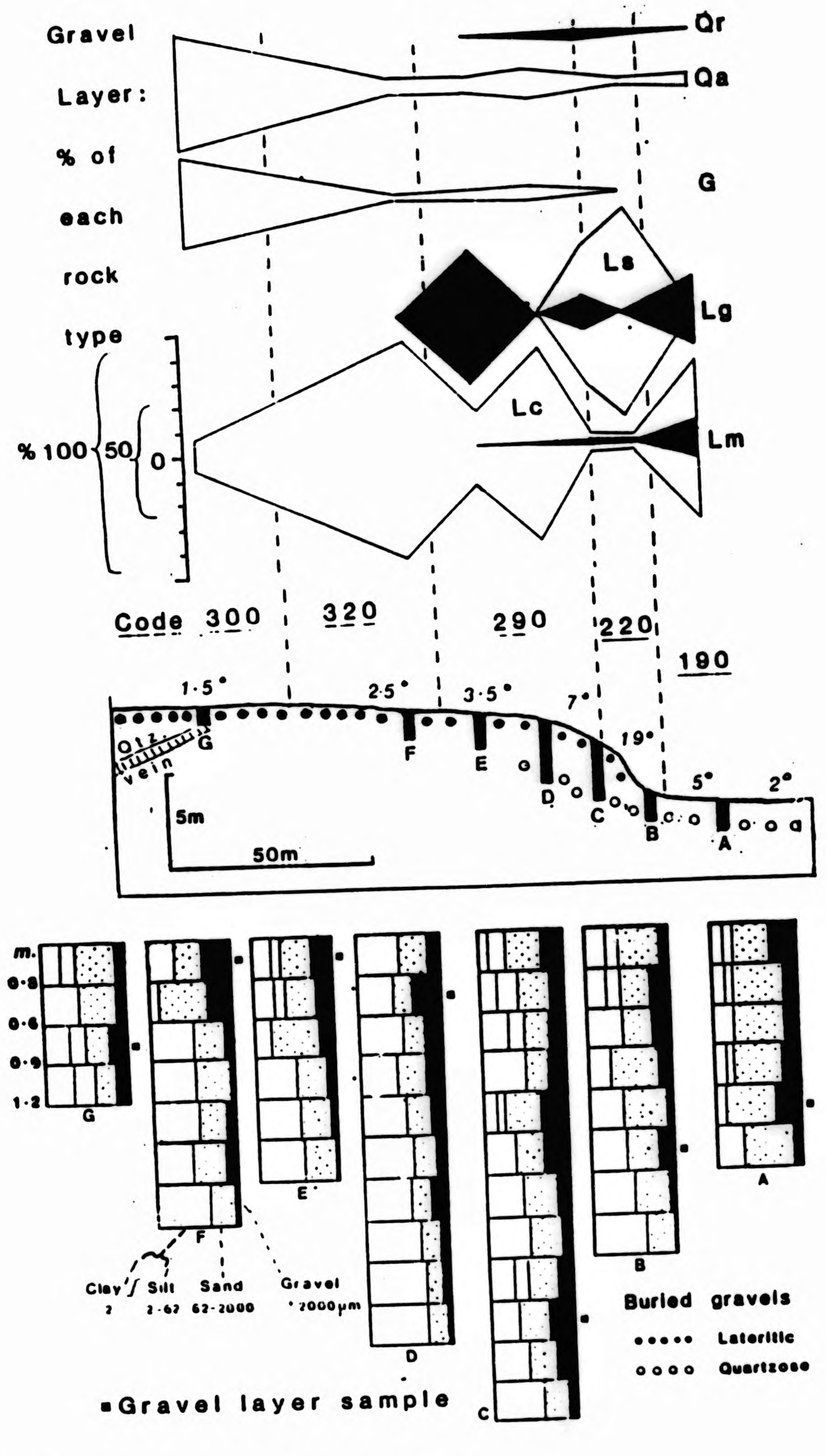
The gravel components described in Section 5.1 are now assessed in a catenary context using the interfluve crest/valley-floor sample transects. A key to the Unit Landform codes abbreviations and symbols used in the following transects is given in the Map Pocket.

The Kania study area is shown in detail in Figures 4.5 and 4.8. Extensive planate or gently sloping interfluves dominate the area, with only occasional residual hills and few rock outcrops (cf. Table 4.1).

Transect P1 extends from a planate interfluve near Kania village to the valleyhead and valleyhead swamp of the Pawpawyi Stream (Figure 5.9). The interfluval gravel is dominated by bedrock fragments, forming 85% of the gravel, the remainder being lateritic concretions. In the sloping interfluve gravel the proportion of lateritic concretions increases to 85% at the expense of the bedrock fragments.

Figure 5.9

Transect P1



Qr (black)	Rounded quartz
Qa	Angular quartz
G	Granitic gneiss
S	Schist Belt rocks
D } (black)	Dolerite
A	Amphibolite
Ls	Lateritic segregations
Lg (black)	Fe sesquioxide-cemented mixed gravel
Lc	Lateritic concretions
Lm (black)	Massive or vermiform laterite fragments

Fragments of iron sesquioxide-cemented mixed gravel form 50% of the gravel in the swale zone, with vermiform laterite fragments and rounded quartz each forming less than 10% of the gravel. In the valleyhead there is a marked increase in lateritic segregations to form 80% of the gravel. Conversely, in the basal gravel of the valleyhead swamp, lateritic segregations were not found, nor were bedrock fragments or any rounded quartz pebbles.

Three main conclusions can be drawn from Transect P1.

(i) The frequent occurrence of bedrock fragments in the planate interfluve gravel coupled with the relatively shallow profiles (Plate 5.5B) indicate that the saprolite of this area has been truncated. This is not surprising, given that the valleyheads and associated swale zones of three streams converge on this area. Furthermore, a residual hill is only a few hundred metres away (Figure 4.5); its proximity probably enhanced the degree of slopewash over this area. A buried valleyhead extension was sampled during this study, extending back from the Pawpawyi stream. Thomas and Thorp (1985) have described another buried valleyhead extending back from the Wangoyie stream (viz. Figure 4.12). Thus slopewash, rillwash and gullying are the likely mechanisms by which the interfluve soil/saprolite was stripped. Further evidence for saprolite truncation comes from iron sesquioxide patinas over indurated saprolite near the Wongoyie buried valleyhead (Plate 5.7A).

(ii) A seasonal seepage zone occurs in the present swale zone gravel, with soluble Fe^{++} sesquioxide probably reverting to insoluble Fe^{+++} sesquioxide segregations in the dry season (Alexandre and Streel-Potelle,1979). The fragments of iron sesquioxide-cemented mixed gravel that dominate the sloping interfluve gravel may be the remnants of a former higher-level seepage zone.

(iii) The presence of ferruginised rounded quartz pebbles in the valleyhead and swale zones, and their absence from the valleyhead swamp, indicates that these "ancient" clasts may survive local colluvial transport but they cannot survive under prolonged hydromorphic conditions. The same appears to be true of the lateritic segregations.

__Transect P2__ (Figure 5.10) has an unusually high proportion of rounded quartz (12%) in the gravel of the planate interfluve zone, as well as the rare occurrence of a schist cobble.

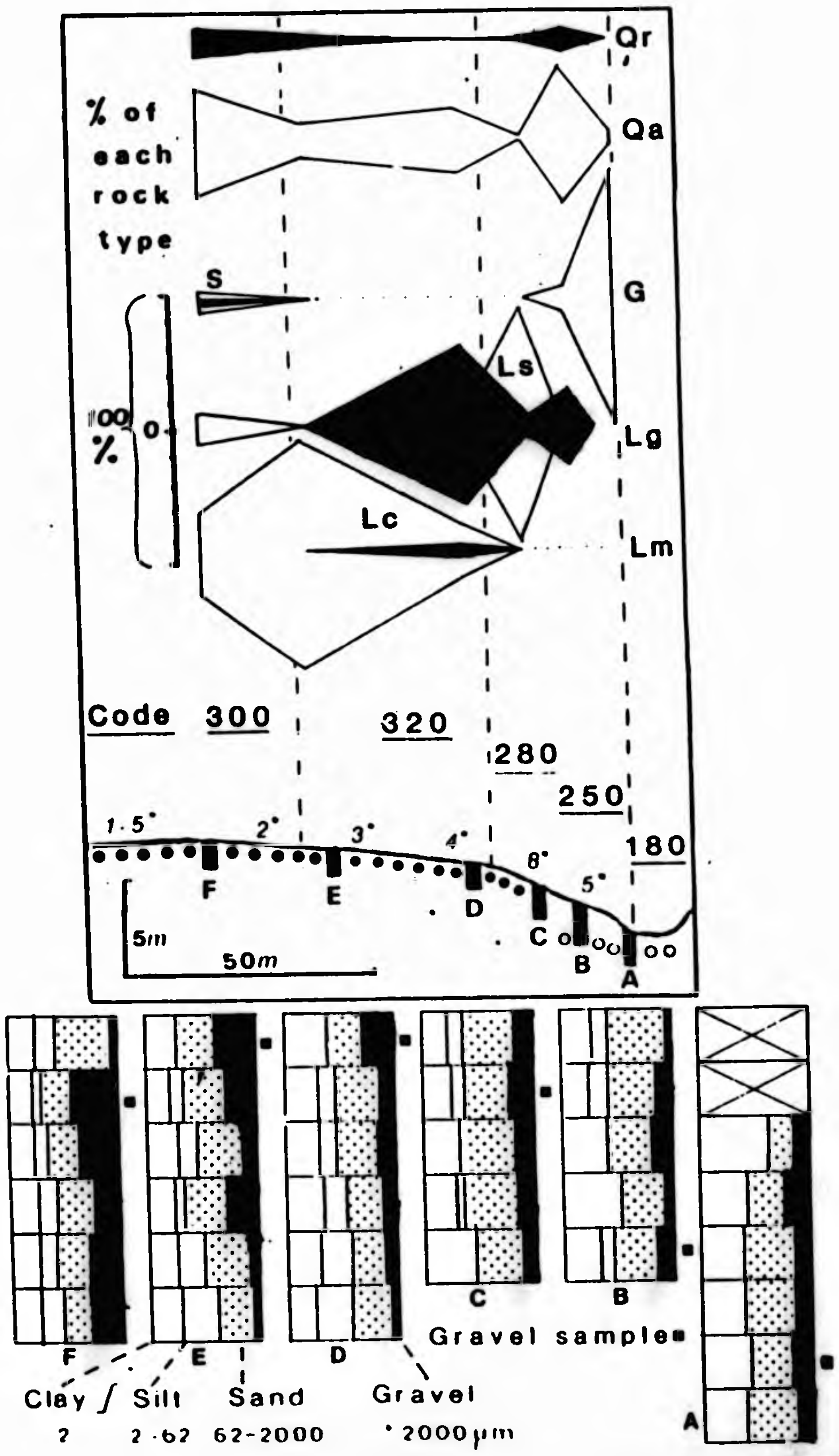


Figure 5.10 __Transect P2.__ Key as in Figure 5.9

From the planate to the sloping interfluve there is a marked increase in the proportion of lateritic concretions to form 75% of the gravel, but this decreases sharply in the sloping interfluve gravel and concretions are absent from the low terrace basal gravel. Both lateritic segregations and iron sesquioxide-cemented gravel fragments are most abundant in the interfluve rim gravel, forming 85% of the gravel, but this proportion decreases sharply in the low terrace basal gravel with the proportion of granitic gneiss clasts rising to form 94% of the basal gravel.

Two main conclusions can be made from Transect P2.

(i) The large amount of rounded quartz and the presence of a schist cobble point to an ancient fluvial source for some gravel components.

(ii) Two falls of the local water table appear to have affected this area. The most recent formed the interfluve rim seepage zone, where lateritic segregations account for 85% of the gravel; whilst an earlier fall apparently formed a seepage zone in the present sloping interfluve zone, now marked by fragments of iron sesquioxide-cemented gravel.

<u>Transect P3</u> (Figure 5.11), extends from the planate interfluve down to a distinct Low Terrace. Numerous corestones of porphyroblastic granitic gneiss outcrop in the Low Terrace and across the valleyfloor of the Pawpawyi stream. The gravel of the planate interfluve is dominated by lateritic concretions and lateritic segregations, each contributing about 40%. There is a progressive increase in the proportion of lateritic segregations at the expense of lateritic concretions at the interfluve rim, where the proportions of fragments of vermiform laterite and ferruginised mixed gravel also increase markedly.

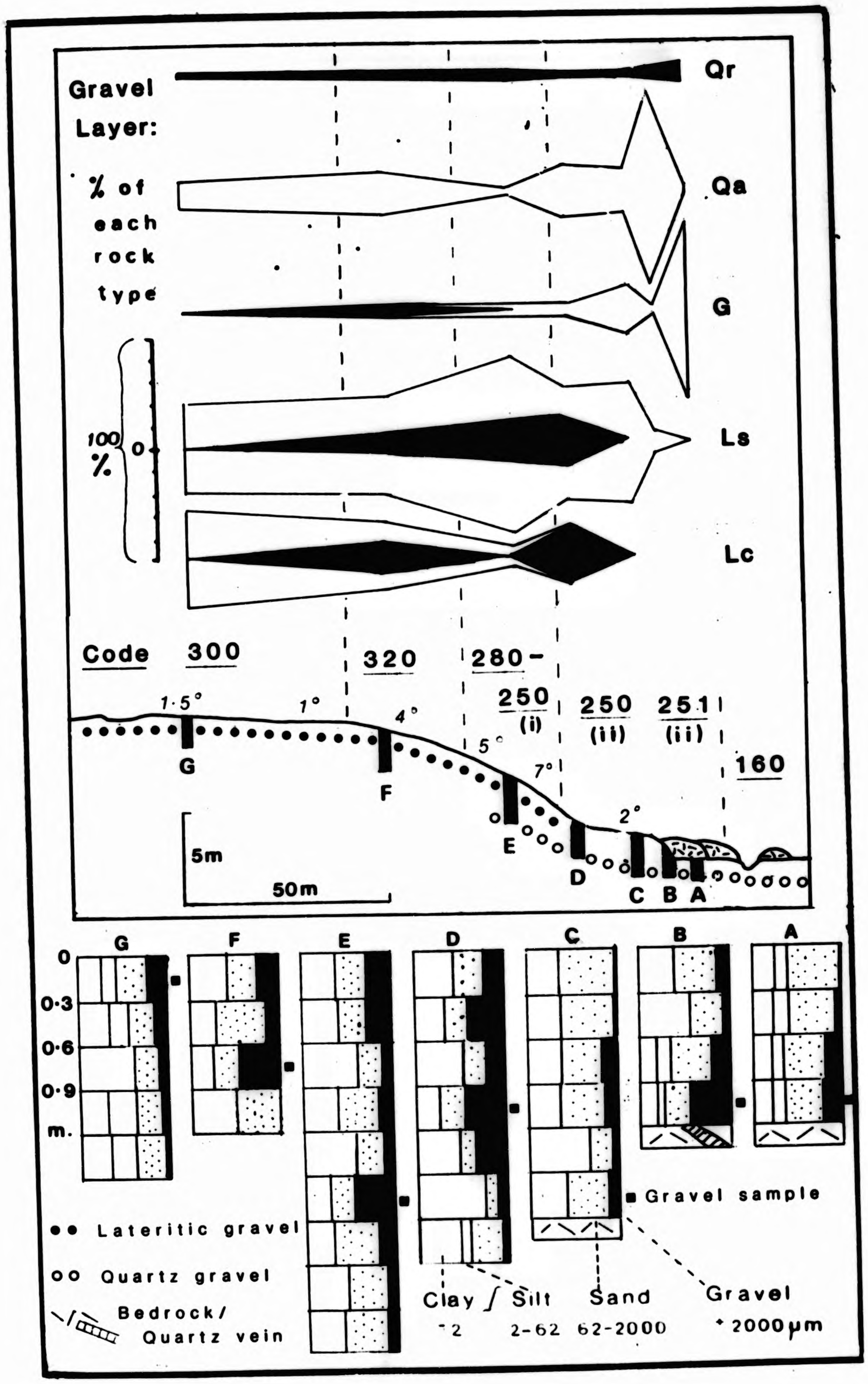


Figure 5.11 Transect P3

Key as in Figure 5.9

Two forms of Low Terrace deposit occur along this transect. The set proximal to the interfluve has a basal gravel similar to the topgravel of the interfluve rim, dominated by lateritic segregations and with rounded quartz accounting for no more than 10% of the gravel. The second set lacks lateritic concretions, has markedly fewer segregations and is dominated by fragments of bedrock or angular quartz, with rounded quartz forming 10 to 15% of the gravel.

In conclusion, Transect P3 can be divided into three morphonegetic domains.

(i) The Interfluve domain, dominated by lateritic components, though with the presence of both rounded quartz and schist pebbles indicating an ancient fluvial source for some material.

(ii) A Transitional domain, between the Interfluve and the Low Terrace, with the marked increase in the proportion of lateritic segregations indicating the presence of a seasonal seepage zone. This was most pronounced at the surface of pit P3D where farming has exposed a "lateritic pavement". The basal gravels of this domain have a petrographic composition that is closer to that of the Interfluve domain than the Low terrace/Valley swamp domain. This indicates that they are mainly the result of colluvial, rather than fluvial, processes. However, both diagenetic "aging" and pedogenesis could have modified what was originally a Low Terrace deposit.

(iii) The Valley Swamp/Low Terrace domain is dominated by bedrock fragments, with lateritic components and less-resistant bedrock being dissolved and removed downstream by lateral eluviation, leading to the active downwasting of valleyfloor saprolite.

__Transect P4__ (Figure 5.12) extends from an Interfluve corestone zone down a glacis slope to the low terrace and valley swamp of the middle Pawpawyi. The gravel from the corestone zone is dominated by fragments of hornblende-granite-gneiss and angular quartz. However, the proximal glacis sample, 30m from the corestone zone, is devoid of bedrock fragments. The gravel of the distal glacis, at its junction with the low terrace, shows a marked increase in the proportion of lateritic segregations, to 62%. The proportions of angular quartz, rounded quartz and bedrock fragments all show increases in the Low Terrace gravel, the exception being pit P4C which is dominated by lateritic components.

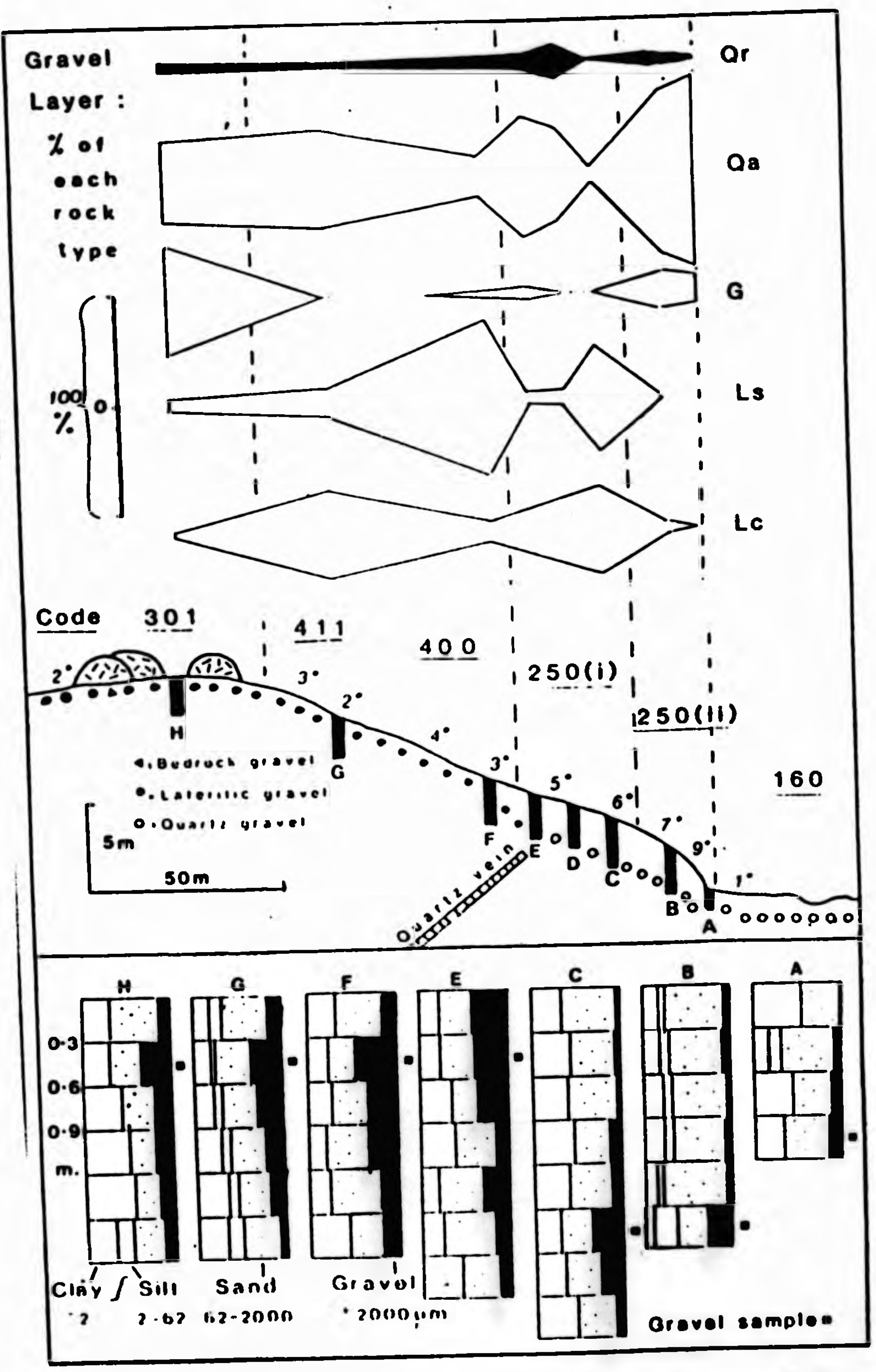


Figure 5.12 __Transect P4__.

Key as in Figure 5.9

In conclusion, two phases of terrace formation are indicated by the two peaks in the proportions of lateritic segregations. The maxima at the distal glacis/terrace junction appears to be the result of a seasonal seepage zone where the neoformation of segregations occurred. This seepage zone was apparently left "high and dry" by the fluvial incision that formed the lower Terrace. The consequent fall in the water table to the junction of the upper and the lower Terrace formed the lower seepage zone, producing a high proportion of lateritic segregations in the gravel. However, the high proportion of lateritic concretions in this zone indicates colluvial, as well as in situ, sesquioxide residual accumulation. This colluviation was then followed by fluvial incision, cutting the lower Terrace, plus alluviation to form the present valley swamp deposits.

Transect P5, shown in Figure 5.13, lies close to the Woyie River, extending from a hillside bench, down a glacis slope to the interfluve zone, valleyside and Low Terrace of the lower Pawpawyi stream (Figure 4.12).

The gravel of the residual hill summit and hillside bench consists entirely of granitic gneiss fragments. This proportion is reduced to only 25% at the proximal glacis, with that of lateritic segregations rising to 25% and that of angular quartz to 50%. In the distal glacis, bedrock fragments account for only 6% and lateritic segregations account for 80% of the gravel. On the planate interfluve there are marked increases in the proportions of both bedrock fragments and lateritic concretions, plus relatively high proportions of rounded quartz and vermiform laterite fragments. A sharp increase, from 40 to 80%, in the proportion of lateritic concretions occurs in the sloping interfluve gravel, but this drops to only 12% in the interfluve rim gravel, whilst

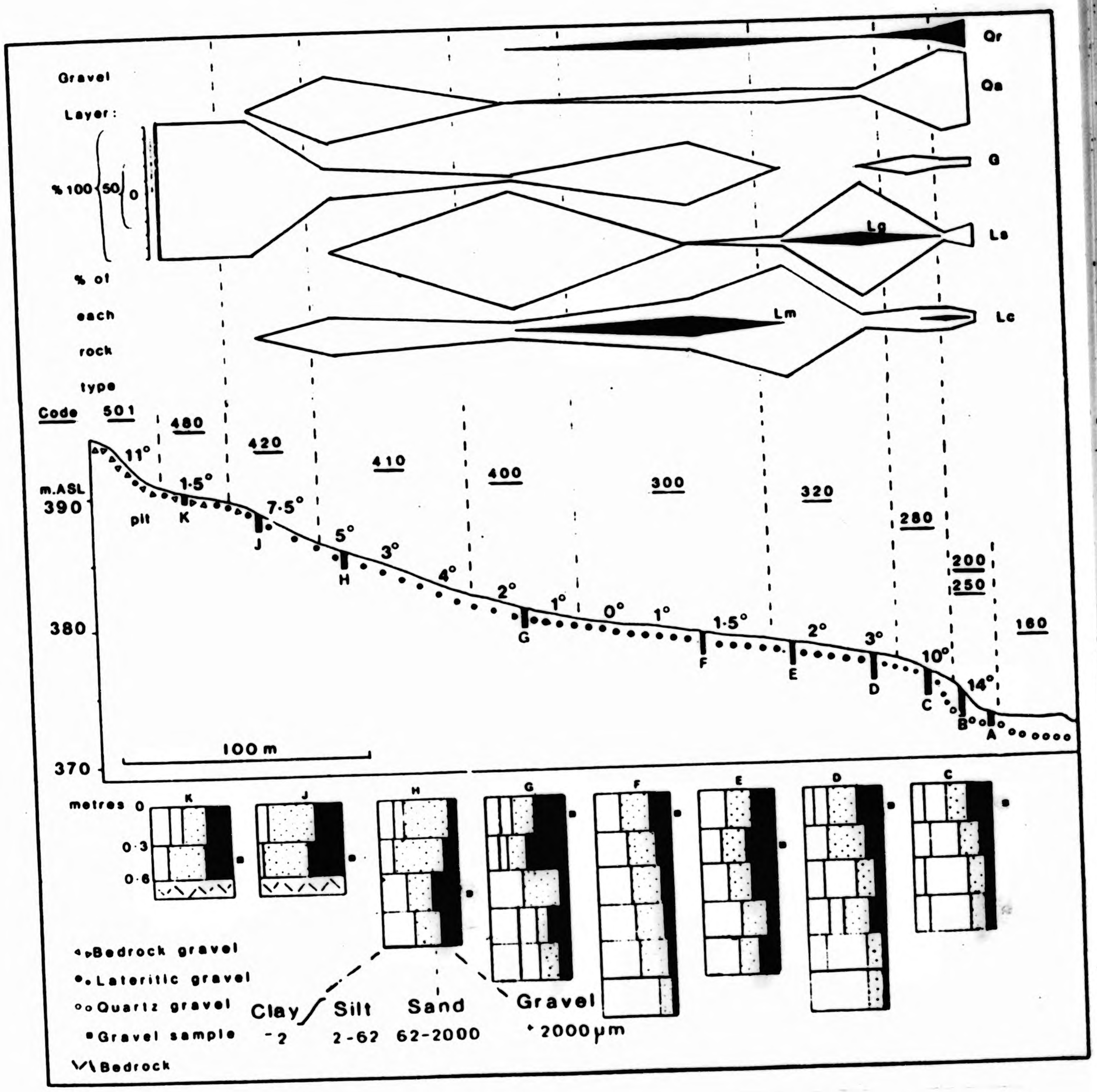


Figure 5.13 **Transect P5** Key as in Figure 5.9

lateritic segregations increase to 78%. The only components to show increases of more than 10% from the valley side to the Low Terrace were angular and rounded quartz.

Three main conclusions can be drawn from Transect P5.

(i) There appear to be two seasonal seepage zones, one at the glacis slope/planate interfluve junction, the other at the sloping interfluve/interfluve rim junction.

(ii) The fragments of vermiform and massive laterite on the planate interfluve indicate the former occurrence of a ferricrete layer, now dismantled.

(iii) The presence of rounded quartz in the gravels of the interfluve zone indicates an ancient alluvial origin for some of this material, as would be expected at sites fringing major rivers such as the Woyie. This supports the deductions made from micromorphological and textural data in section 5.3.

The Yengema study area is shown in detail in Figure 4.14, whilst Table 4.1 provides a summary of its geomorphology. Of the five Yengema transects, four are situated along the Boya stream and the fifth is situated on the right bank of the Nafayi River 0.5km downstream of the Boya/Nafayi confluence zone.

Transect N1 extends from the granitic inselbergs, domes and kopjes that form the headwater zone of the Boya stream, down hillfoot and glacis slopes to the swales and valleyhead of the Boya, finishing 50m along the valleyhead swamp (Figure 5.14). The hilltop and hillside gravels are dominated by fragments of angular quartz and granite, but between the hilltop and the hillfoot there is a 75% reduction in the proportion of these gravel clasts. Lateritic segregations show a progressive increase over the glacis slopes - at the expense of angular quartz clasts - until they form 94% of the distal glacis gravel. The most striking feature of these glacis gravels is the occurrence of rounded quartz cobbles, forming up to 12% of the gravel, plus the presence of both schist and dolerite cobbles (Plate 5.6A).

Hard granitic gneiss bedrock is exposed in the swale zone, flanked by corestones. The gravel here shows an increase in the proportion of angular quartz and bedrock fragments to 60-70%, at the expense of lateritic segregations. Although the proportion of lateritic segregations rises to 60% in the valleyhead gravel, it is reduced to only 28% in the basal gravel of the valleyhead swamp. The occurrence of lateritic concretions in this area is remarkably low compared to all other transects, the highest value (16%) significantly occurring in the basal gravel of the valleyhead swamp, indicating that the rocky headwaters of the Boya are inherently prone to environmental stress and exacerbated soil/saprolite stripping. Further conclusions for Transect N1 are given below.

(i) The occurrence of cobbles of rounded quartz, schist and dolerite in the glacis gravel indicates a former river course at the foot of the present inselberg, as was indicated by the geomorphological mapping (Figure 4.8).

(ii) Two active seepage zones appear to occur along this transect, one at the distal end of the glacis slope, apparently truncated by the commencement of the swale zone, the other at the swale/valleyhead junction, containing fragments of vermiform laterite presumably derived from a now dismantled ferricrete layer.

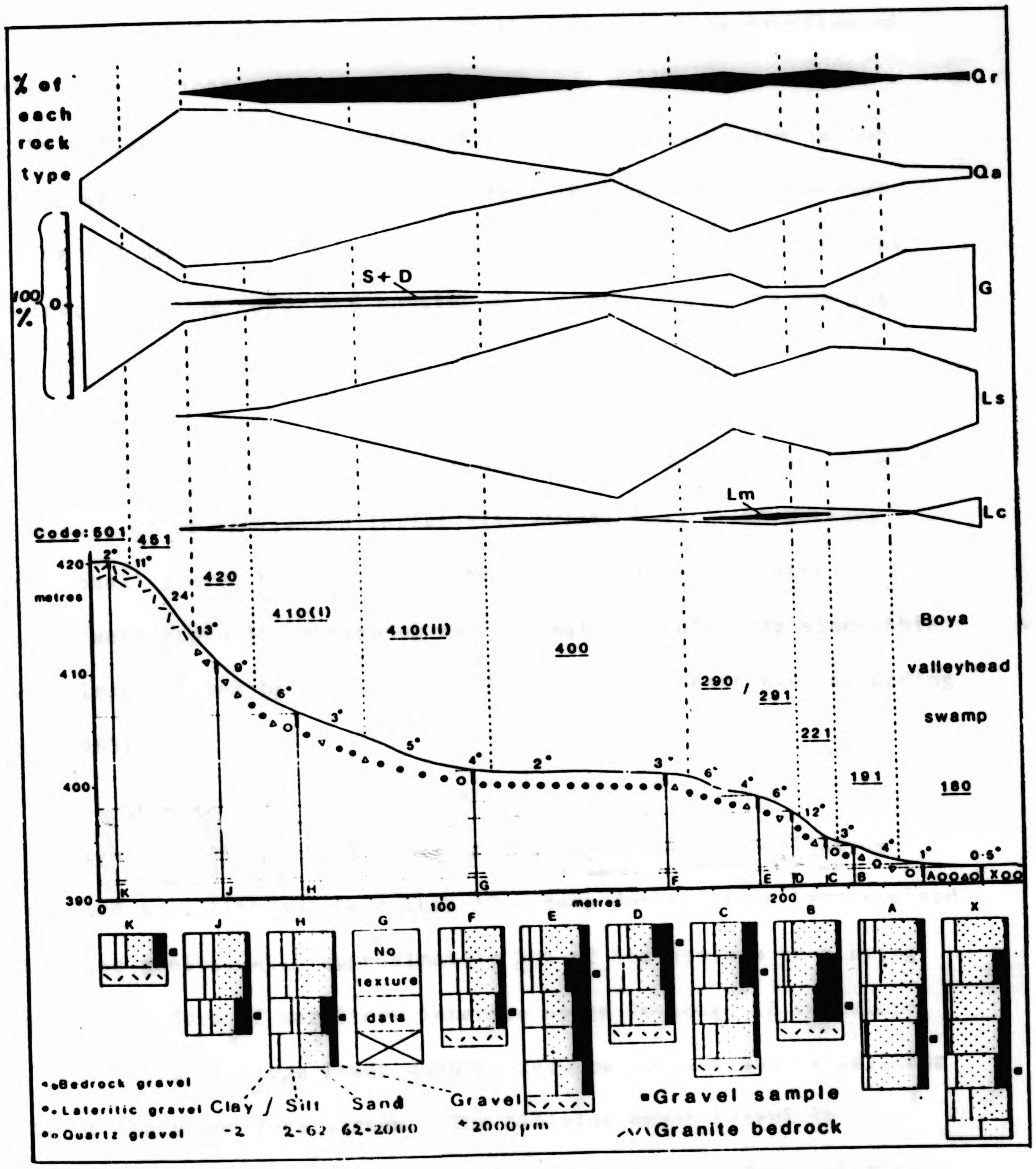


Figure 5.14 **Transect N1** Key as in Figure 5.9

(iii) The swale zone is a relatively high-energy colluvial/fluvial process domain where the soil/saprolite layer has largely been stripped away by concentrated overland flow, with the consequent destruction of lateritic segregations and concentration of more resistant clasts.

(iv) The increase in the proportion of granitic gneiss clasts in the valleyhead swamp basal gravel indicates that this is a zone of active weathering and downwasting with the export of fine material by lateral eluviation, producing cores and cobbles of granitic gneiss in the lag gravel.

The Boya valleyhead swamp also contains palm tree stumps buried under up to 1.0m of fluvial/colluvial fill (Plate 5.5D), and pottery shards in basal gravel buried under 1.5m of fill. This indicates pronounced soil/saprolite stripping and valleyfloor infilling since this area was first settled by man, between 2000 and 3000 years ago, according to Shaw (1983).

Transect N2 (Figure 5.15) commences from an extensive hillside bench mantled by a lithosol less than 10cm deep derived from ferruginised granodioritic gneiss, with approximately 30% of its surface area being outcrops or boulders of vermiform laterite up to 2m long. A footslope and extensive glacis slope leads down to the low terrace and valleyfloor deposits of the upper Boya stream. The hillside bench gravel is dominated by lateritic concretions and fragments of vermiform laterite. The occurrence of rounded quartz, albeit less than 5%, is notable at such a great distance - both horizontally and vertically - from the present valleyfloor deposits.

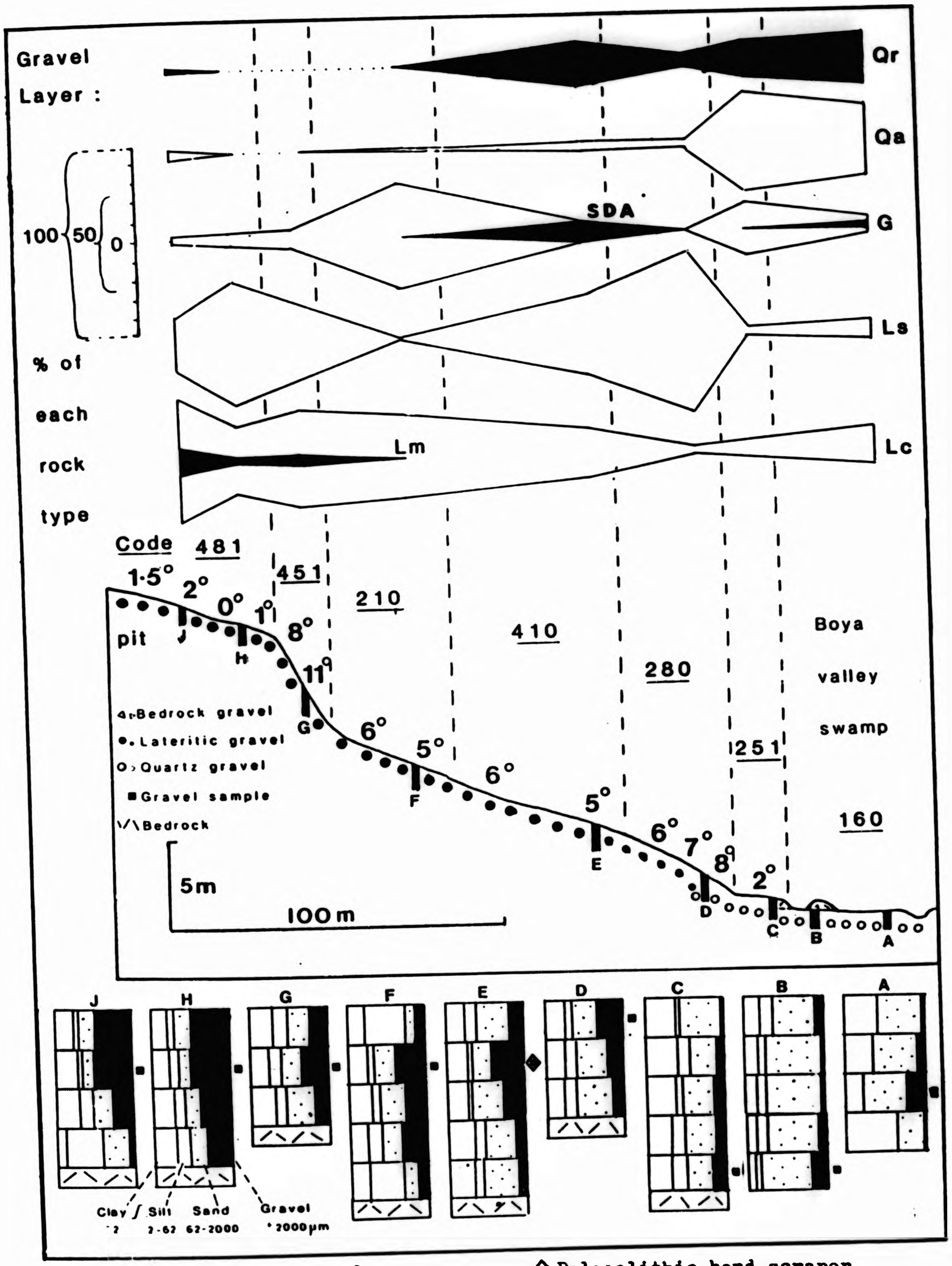


Figure 5.15 Transect N 2

◇ Palaeolithic hand-scraper.

Key as in Figure 5.9

At the margin of the hillside bench, there is a marked increase in the percentage of lateritic segregations, to 58%, but this decreases in the footslope and proximal glacis zones. Ferruginised bedrock fragments show a corresponding increase in these zones, with a decrease in the distal glacis gravel, where fragments of schist, amphibolite, dolerite and rounded quartz together form 33% of the gravel. An important find in the distal glacis gravel was a Palaeolithic stone scraper, shown in Plate 5.1 . The proportion of lateritic segregations reaches a maximum of 80% at the interfluve rim at the expense of all other gravel components. However, within 10m of the valleyside the proportion of segregations is reduced to less than 10%, the valley swamp basal gravel being dominated by bedrock fragments and rounded quartz.

Four main conclusions can be made from Transect N2.

(i) Seepage zones occur at the rims of both the hillside bench and the interfluve.

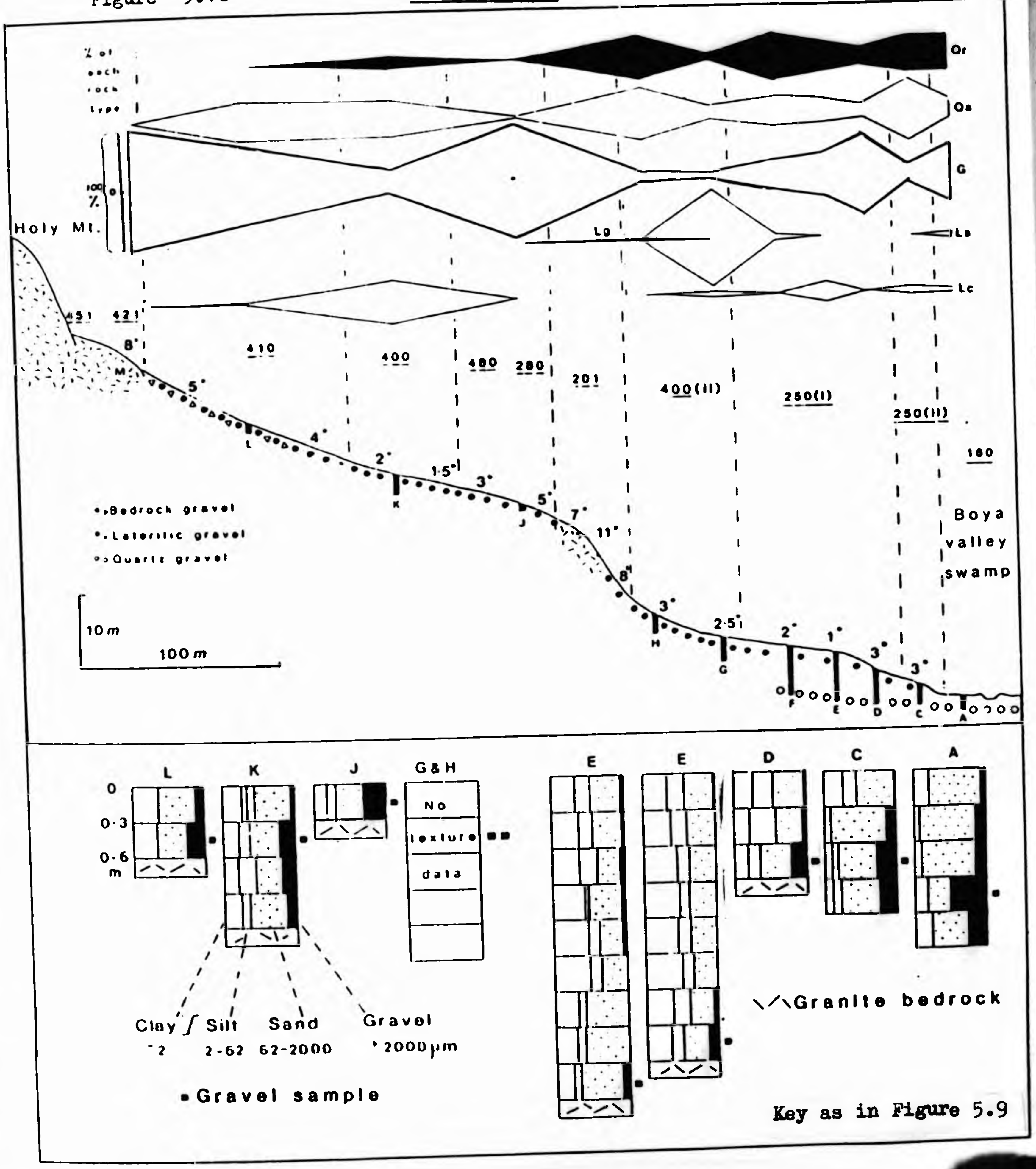
(ii) Large proportions of rounded quartz occur on both the lower slope deposits and the valleyfloor deposits, indicating an ancient input of fluvial material to the valley margins.

(iii) An even older set of fluvially-derived material occurs on the hillside bench, which then appears to have undergone pronounced laterization to produce a ferricrete deposit which is now being actively fragmented into blocks and rubble.

(iv) Dissolution and disintegration of lateritic segregations is occurring in the low terrace and valley swamp gravels.

Transect N3 (Figure 5.16) is dominated by the granitic inselberg of Holy Mountain, which is largely devoid of any soil or gravel, the footslope being a bare rock pediment. The proximal glacis gravel is dominated by bedrock fragments with only occasional

Figure 5.16 Transect N3



lateritic concretions - though these become more frequent downslope, forming 35% of the distal glacis gravel. This distal glacis deposit (pit N3K) merges into the hillside bench and has a markedly large proportion of rounded quartz, forming 12% of the gravel. The hillside bench has a shallow profile (0.3m) consisting of a clast-supported granitic gneiss gravel with a grey sandy loam topsoil. Below this hillside bench a second footslope/glacis slope sequence commences, henceforth termed footslope II or glacis II. The proximal glacis II gravel shows a 90% reduction in the proportion of granitic gneiss fragments relative to the hillside bench, with corresponding large increases in the proportions of both angular quartz and - unusually - rounded quartz, each increasing to 40%. The distal glacis II gravel is dominated by lateritic segregations, comprising 73% of the gravel.

The gravel petrographies of the Low Terrace and valley swamp zones of Transect N3 are broadly similar with proportions of granitic gneiss ranging from 20 to 55%, angular quartz from 15 to 40% and rounded quartz from 25 to 40%.

Three main conclusions can be drawn from Transect N3.

(i) Three sets of allocthonous gravels occur along this transect; the first on the Holy Mountain distal glacis, with both rounded quartz and lateritic concretions; the second, in the glacis II deposit below the hillside bench, dominated by both angular and rounded quartz; and the third set in the low terrace and valley swamp basal gravels.

(ii) Given that the Holy Mountain hillside bench appears to have been stripped of its soil/saprolite cover, it seems likely that the rounded quartz found in the glacis II deposit fringing the low terraces has been re-worked from the Holy Mountain distal glacis/hillside bench deposit. (iii) The main seepage zone for Holy Mountain is at the junction of the low terrace complex and distal glacis II and not, as might be expected, at the distal end of the higher-level Holy Mountain rock pediment. This indicates significant subterranean water transfer from the inselberg footslope to the low terrace, some 300m away.

Transect N4 (Figure 5.17), extends from a gently domed interfluve over an extensive low terrace complex to the lower Boya stream. The interfluve zone has a lateritic gravel 0.9 to 1.5m thick. The planate interfluve gravel is dominated by ferruginized granodioritic gneiss fragments (40%) and lateritic concretions (50%), with 5% angular quartz and 3% rounded quartz. The proportion of ferruginised bedrock fragments is greatly reduced in the sloping interfluve gravel, with lateritic concretions and vermiform laterite fragments forming 75% of the gravel. At the interfluve rim there is a pronounced increase in the proportion of lateritic segregations to 61%, at the expense of lateritic concretions.

Pit N4E appears to be transitional between the interfluve zone and the low terrace. A sparse quartzose basal gravel was found at 3m depth. However the main gravel layer occurs at 1m depth, buried under colluvial fill: lateritic segregations form 82% of this gravel. The basal gravel of the Type I low terrace has high proportions of both angular quartz and rounded quartz, though at Pit N4C this is masked by the occurrence of large volumes of lateritic segregations. The basal gravels of the Type II terrace and the valley swamp are very similar, both dominated by rounded quartz, with large amounts of granitic gneiss and angular quartz, but no lateritic segregations.

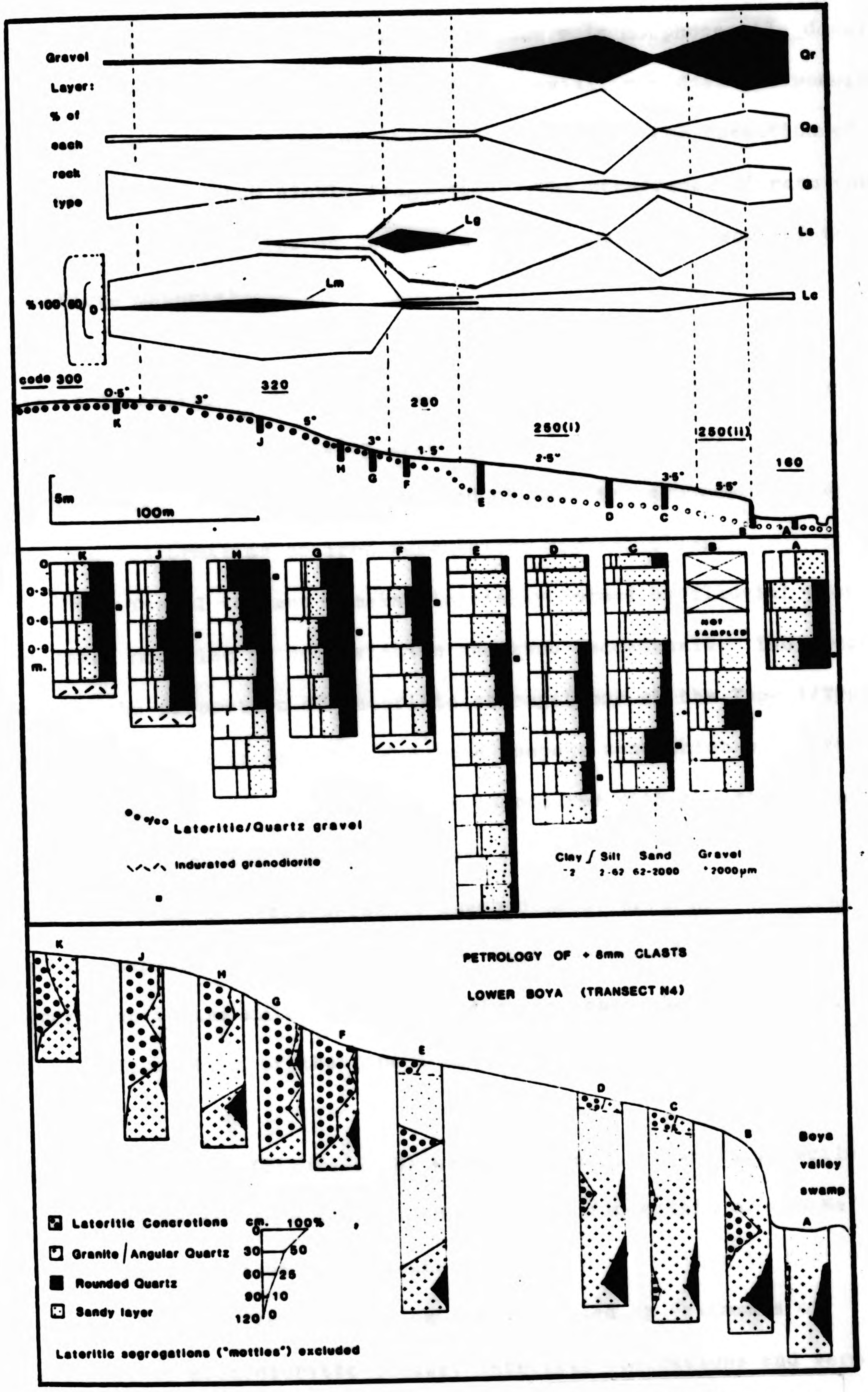


Figure 5.17 Transect N4 Key as in Figure 5.9

In conclusion, Transect N4 shows four main morphogenetic domains:

(i) An interfluve domain dominated by eluvial, residual and pedogenetic processes, with the ferruginisation of bedrock and the formation of a ferricrete layer, now highly fragmented. The occurrence of rare rounded quartz pebbles indicates an ancient alluvial source for some of this interfluve material.

(ii) A Transitional domain between the interfluve and the low terrace, with colluvial fill overlying mixed gravels dominated by lateritic segregations. This indicates a period of seasonal groundwater seepage with the neoformation of iron sesquioxide accumulations.

(iii) The Type I terrace domain, initially formed by alluvial processes but later modified by colluviation and then pedogenesis. The secondary peak in the proportion of lateritic segregations at the Type I/Type II terrace junction is probably due to a seepage zone which was left "high and dry" by the fall in water table associated with the stream incision and formation of the Type II Terrace.

(iv) The Type II Terrace/Valley Swamp domain. Although the Type II Terrace deposit is older, it appears that the prevalence of hydromorphic conditions is the main factor that distinguishes the composition of these gravels from those of the Type I Low terrace.

Transect N5 (Figure 5.18) extends from the planate interfluve on which Yengema Airfield is built down to the floodplain of the Nafayi River. The gravel of the planate interfluve is similar to that of Transect N4: 100 to 150cm thick and dominated by fragments of ferruginized granodioritic gneiss, lateritic concretions and vermiform laterite fragments. The gravel at the interfluve rim contains small amounts of rounded quartz, angular quartz, schist, amphibolite, and

ferruginized granodioritic gneiss, with larger amounts of both lateritic concretions and lateritic segregations at the interfluve rim. At the valley side there is a marked increase in the proportion of angular quartz at the expense of the lateritic components. The proportions of both rounded quartz and granitic gneiss show a steady increase from the valley side, each forming about a quarter of the Nafayi floodplain gravel.

Transect N5 shows three distinct morphogenetic domains:

(i) The Interfluve domain is dominated by lateritic concretions and fragments of both ferruginized bedrock and vermiform laterite, indicating that residual, eluvial and pedogenetic processes predominate here. It should, however, be noted that the presence of vermiform laterite fragments indicates the destruction of a former ferricrete sheet during a period of pronounced slopewash and gully action, and the presence of rare gravel components (rounded quartz, schist and amphibolite) indicates an ancient fluvial source for some interfluve material.

(ii) A Transitional domain at the valleyside, marked by a sharp increase in the proportion of lateritic segregations, indicating a seasonal seepage zone.

(ii) The Valleyfloor domain of the Nafayi River floodplain, where the lateritic components are dissolved and where there appears to be incorporation of bedrock fragments into the basal gravel. This is a domain dominated by chemical weathering, lateral eluviation and the active downwasting of the saprolite.

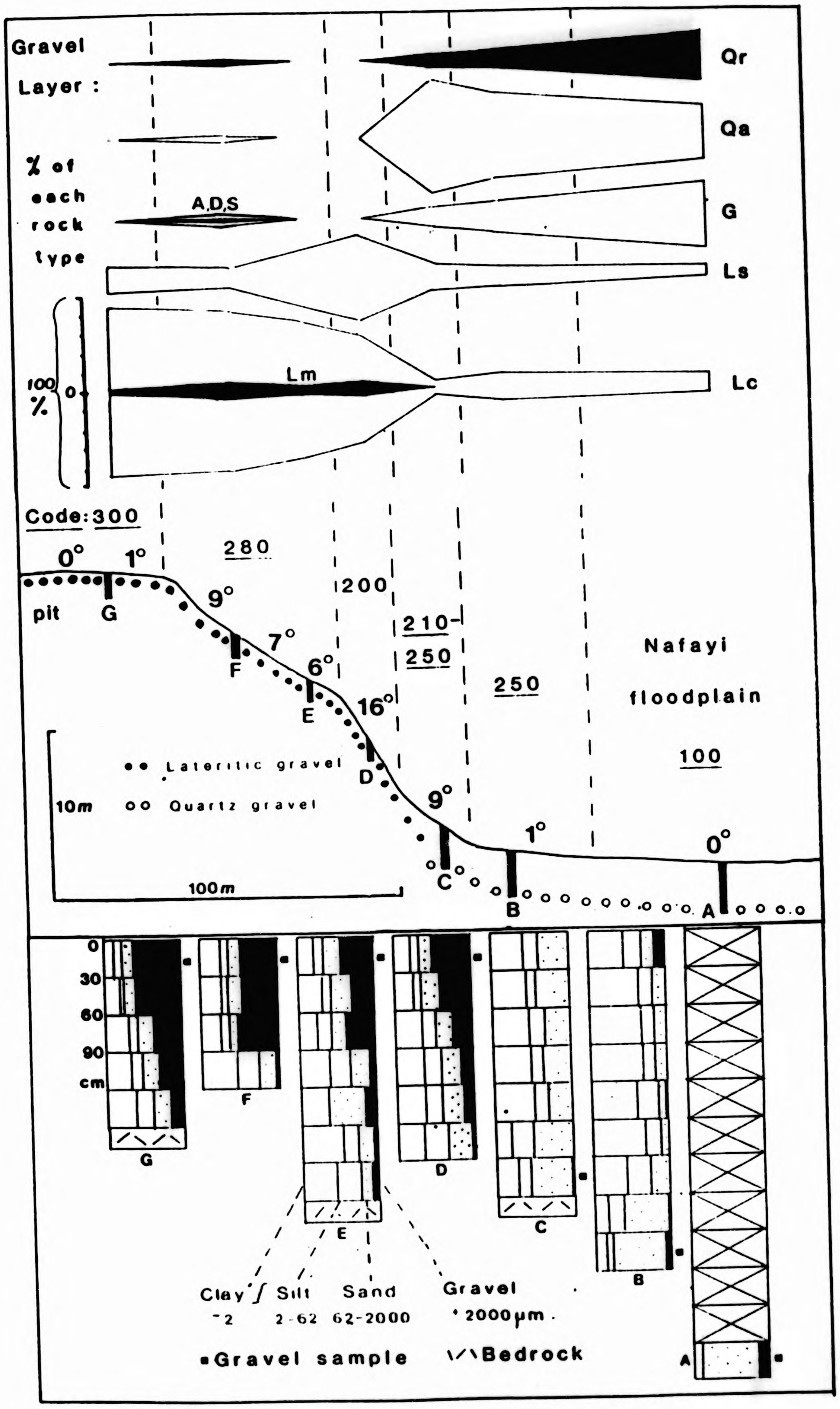


Figure 5.18 Transect N5 Key as in Figure 5.9

CHAPTER SIX

DISCUSSION

Given the impossibility of conducting meaningful empirical studies of morphogenetic processes in only two field sessions, the review of the interactions between landform, materials and processes presented in Chapter 3 was essential to the interpretation of the landform/material relationships observed during this study. The variations in material organisation within each unit landform type - as indicated by textural depth functions, gravel composition, layer micromorphology and profile morphology (Table 5.4) - led to the recognition and detailed description of a dozen morphofacies types. It appears that most of the variations between each morphofacies type can be attributed to the variable influences of three major process domains.

6.1 The Process Domains are given below, but first it should be emphasised that their operation in a given area can only be deduced from the presence of materials that are assumed to have resulted from a given set of processes.

The Residual Domain is dominated by pedogenesis and associated chemical weathering.

The Colluvial Domain is dominated by slopewash, soil/saprolite stripping, lateral eluviation and the precipitation of iron sesquioxides at seepage zones.

The Fluvial Domain is defined by the dominance of hydromorphic conditions over aerobic conditions. The main processes are channelled flow, the rolling and rounding of clasts, lateral eluviation and the

dissolution of iron sesquioxides. "Fluvial Domain" is a term of convenience, because three distinct process suites interact within it.

(i) Hydromorphic conditions and associated processes (such as, reduction, carbonation and hydrolysis) which permanently affect valleyfloors and seasonally affect low terraces or the lower layers of valleyside/interfluve rim deposits. Rills that extend into the otherwise residual domain of the planate interfluves, produce seasonally hydromorphic conditions along their channels.

(ii) The throughflow and lateral eluviation of clays and sesquioxides in vadose or valleyfloor water.

(iii) Sediment movement in concentrated flow along channels by saltation and traction.

It appears that at present the Fluvial Domain is dominated by process suites (i) and (ii), given that 80% of the Koidu Basin drainage network consists predominantly of channelless swamps (Hall, 1974; p.27), and that most river channels are rarely in contact with either their basal gravel or the valleyfloor bedrock. A similar morphodynamic environment has been reported from the humid tropical zone of Sri Lanka by Bremer (1981a) and Spath (1981).

Hilltop or bench	Hillside or Footslope	Proximal glacis	Distal glacis
COLLUVIAL -RESIDUAL	COLLUVIAL	COLLUVIAL	COLLUVIAL -RESIDUAL
Planate interfluve	Sloping interfluve	Interfluve rim	Swale or valleyhead
RESIDUAL	RESIDUAL -COLLUVIAL	COLLUVIAL -RESIDUAL	COLLUVIAL -FLUVIAL
Valleyhead swamp	Swamp or floodplain	Type II Low Terrace	Type I Low terrace
FLUVIAL -COLLUVIAL	FLUVIAL	FLUVIAL-COLLUVIAL	COLLUVIAL -RESIDUAL

Table 6.1 Morphofacies Types and their postulated contemporary Process Domains (in capital typeset).

From Table 6.1 it is clear that not all morphofacies types fall entirely within one process domain. In the majority of cases there is evidence of two contemporary process domains interacting to produce a morphofacies type. Where such compound domains occur the dominant process domain has been listed first. As an example, the recently-formed Type II low terraces clearly fall within the Fluvial domain as their steep valleyfloor sides are apparently maintained by seasonal flood erosion and as hydromorphic conditions at the base of the profile allow the downvalley lateral eluviation of clay and sesquioxides to occur. However, the Type II terraces also fall into the Colluvial domain, with evidence of slumping, slopewash and colluviation. In contrast, the older Type I terraces fall into the Colluvial/Residual domain as they have been extensively modified by colluviation and, more recently, by pedogenesis. There is no evidence of hydromorphic conditions and pronounced lateral eluviation at the base of the Type I terrace profiles to place them in the contemporary Fluvial domain.

The valleyfloor/low terrace sequence described above represents a chronosequence of alluvial sediments. There is a progressive shift from the fluvial process domain indicators of the swamp deposits, to the Fluvial/Colluvial indicators of the Type II terraces, to the Colluvial/Residual indicators of the Type I terraces (which often merge into the interfluve rim deposits). The rate of landscape modification in the Koidu Basin since the Mid-Quaternary has not been rapid enough to produce complete landscape inversion. The distribution of the fresh to slightly ferruginised rounded quartz pebbles found in the low terrace does not extend to the planate interfluves. This can be contrasted with the Gbangatok area of S.E. Sierra Leone, where late-Quaternary alluvial deposits now form planate interfluves as a consequence of rapid drainage system modification due to local tectonic tilting (verified by a study visit, May 1983). The highly ferruginised rounded quartz cobbles found in the planate interfluve gravels of the Koidu Basin are so markedly distinct from the relatively fresh cobbles of the low terraces (Plate 5.1) that they were probably initially deposited during an early Quaternary or even Tertiary phase of landscape modification. Leveque (1979, p.127), describes similar deposits from Togo. The 'ergodic principle', wherein certain spatial distributions can be related to temporal sequences (e.g., Savigear, 1952), is supported by these observations. Reference to Figure 4.7 shows that there is a small altitudinal distance separating contemporary valleyfloor deposits from Holocene/late Quaternary terrace deposits, but a relatively large distance between those low-lying deposits and the highly ferruginised "Common" "High" and "Ancient" interfluve surfaces of probable late Quaternary or Tertiary age.

The effects of climatic change are generally only felt after a relatively long time period in the order of 100-1000 years. Thus research into this topic is in an inherently weak position from the outset and has had to rely on the comparison of geomorphological systems from different climatic regimes, or the results of man-induced changes in geomorphic systems that simulate consequences of climatic change, such as the damming of rivers (Schumm, 1969, p.227). Fortunately, since Bruckner (1955) first proposed that the stonelines of West Africa were formed under a markedly different (arid) climate to the present, there has been considerable research into the effects of climatic change on, for instance, fluvial systems (Schumm, 1969, 1977; Fairbridge, 1976; Knox, 1977; Helgren, 1979; Alexandre and Streel-Potelle, 1979; Thomas and

Thorp, 1980); interfluve/valleyfloor systems (Mackel, 1974, 1979; De Dapper, 1978; Smith, 1982; Boulet et al., 1982); pediments and glacis (Burke and Durotye, 1971; Avenard, 1973; Barsch and Chester, 1972; Klammer 1981; Hogg, 1982; Watson et al., 1984); and pedogeomorphic systems (Ruhe, 1956; Butler, 1959; Stoops, 1968; Daniels et al., 1970; Morrison, 1978; MacFarlane, 1976, 1983). Most of these studies have had to rely on deductive reasoning, as few of the relevant processes lend themselves easily to empirical study. Exceptions are the fields of fluvial hydrology (eg., Schumm, 1956~~a~~), groundwater hydrology (e.g. Coventry et al., 1983), soil erosion (e.g. in Morgan, 1981; Millington, 1984; Valentin, 1984, 1985) and talluvial processes (Kesel, 1977; Frostick and Reid, 1982). However, the further development of absolute dating techniques, in particular C14 radiometric dating, has allowed many otherwise highly tentative deductions to be stated with greater confidence. Unfortunately this confidence is largely restricted to the 40,000-year range of C14 dating.

The presence of stratigraphic unconformities (such as truncated saprolites, colluvial wedges, palaeosols and buried gravels) in the majority of morphofacies types are taken as evidence of shifts in the areal extent of process domains in response to environmental changes. This hypothesis is supported by the C14 dating of valleyfloor and low terrace deposits in the Koidu Basin by Thomas and Thorp (1980). These C14 dates showed a remarkably close correlation with the widely-accepted Quaternary chronology of West Africa (Talbot, 1980; Street, 1981) based on the levels of Lake Chad and Lake Busumtwi (Ghana). The abundance of timber and vegetation samples from the time-periods accepted as being periods of humidity in West Africa, and vice versa, provide further evidence that the valleyfloor and terrace deposits are the result of bioclimatic changes, rather than random high magnitude flood events.

The diachronous, polygenetic nature of the Koidu Basin's lateritic topgravels is most clearly illustrated by two sets of indicator materials. Relative degrees of quartz clast ferruginisation can be used as an indicator of relative age, whilst the presence of exotic rock fragments, exotic minerals and rounded quartz clasts points to an ancient fluvial source of material. The stratigraphic indicators and indicator materials recognised during the surficial geology study are summarised in Table 6.2. The deductions regarding the process domains in which these indicator materials formed are, of course, tentative. The possible equifinality of some formative processes (Bertalanffy, 1950) has been considered and consequently all the known formative processes for a given material have been cited. However, it goes without saying that many aspects of material and landform morphogenesis in the tropics are still unknown.

The problem of establishing which of a given number of processes and/or what sequence of processes was responsible for the formation of a given indicator material can often be solved by an iterative study of all of the other indicator materials found in that particular deposit. For instance, the ferruginisation of quartz clasts may be due to either the relatively long-term process of pedoplasmation (Eswan and Stoops 1979), or the relatively rapid impregnation by Fe/Mn sesquioxides at both seasonal seepage zones and where "lateritic pavements" form. However, the latter process will probably also produce an iron sesquioxide-cemented gravel. Examination of the distribution of both

	Stratigraphic Indicator	Postulated Formative Processes	Process Domain
1.	Thickness of top gravel	Thickness increases over time due to surface wash of concretions and/or neoformation of segregations.	Colluvial-Residual
2.	Lateritic pavement	Induration of valleyside groundwater laterite following fluvial incision.	Residual-fluvial
3.	Wedge of colluvium	Erosion of interfluve soil/saprolite and washing into valley floor.	Colluvial
4.	Infilled rill	Concentrated overland flow from interfluve to gullies or valleyheads.	Fluvial
5.	Truncated saprolite	Soil/saprolite stripping.	Colluvial - fluvial
6.	Patinated saprolite surface	Stripping of saprolite; induration of Fe/Mn sesquioxides from seasonal surface flows.	Colluvial-residual
7.	Presence of a basal gravel	Erosion and formation of a lag gravel; burial under later fill deposits.	Fluvial or Colluvial
8.	Upper saprolite layer depleted in clay	Lateral eluviation ("washing-out") of fine material.	Fluvial or colluvial
9.	Hard black pisoliths in saprolite, & diamond 'Penetration Deposits'	(a) Infilling of desiccation cracks in stripped saprolite with lateritic rubble; only resistant clasts survive later chemical weathering. (b) Due to pedoturbation, transfer along root zones and faunal passages.	Colluvial Residual
10.	Textural depth functions: Simple (uniform/ gradational). Compound or Complex.	Site unaffected by soil/saprolite stripping. Polygenetic; alternating high and low energy events.	Residual Fluvial or Colluvial

Table 6.2a Postulated formative processes of stratigraphic indicators.

	Indicator Material	Postulated Formative Processes	Process Domain
1.	Rounded quartz clasts	Abrasion and rolling; concentrated overland flow.	Fluvial
2.	Schist belt rocks in gravel	Transport from schist belt hills flanking the study areas.	Fluvial
3.	Lateritic segregations	*In situ* sesquioxide accumulation, especially at seepage zones.	Residual
4.	Lateritic nodules	Induration of segregations following erosion and slopewash.	Colluvial
5.	Lateritic pisoliths	Long-term induration; well-rounded due to periodic colluvial transport.	Colluvial-residual
6.	Vermiform/massive laterite	Induration of saprolite, formation of duricrust.	Residual
7.	Ferruginized quartz & bedrock	"Pedoplasmation" of sesquioxides along microfissures.	Residual
8.	Pale rims on ferruginized clasts	Leaching of sesquioxides, hydromorphic conditions.	Fluvial
9.	Gibbsite	(a) Long-term alteration from kaolinite (b) Rapid formation, often direct from felspar, due to well-drained aerobic conditions.	Residual Colluvial
10.	Ilmenite anomaly in top gravel	(a) Local Kimberlitic source (b) Concentration by rills & gullying.	Residual Fluvial
11.	"Exotic" minerals in top gravel	Ancient alluvial source for corundum, tourmaline & staurolite.	Fluvial
12.	Quartz sand grain surface morphologies	Chemical weathering features. Features indicative of mechanical wear. Neither set of features dominant.	Residual Fluvial Colluvial
13.	Indurated soil relicts	Period of pedogenesis followed by instability and colluviation.	Residual-colluvial

Table 6.2b **Postulated formative processes of indicator materials.**

ferruginised rounded quartz and fragments of iron sesquioxide-cemented gravel shows that both types of material occur in the non-planate interfluve zone and the valley sides (Colluvial domain). Conversely, iron sesquioxide-cemented gravel is virtually absent from the Residual domain planate interfluves: only one example was found, the Kania buried rill deposit (Plate 5.7B). The absence of "ancient" highly ferruginised quartz pebbles from the valleyfloor deposits is partly due to their inherent (mechanical) weakness, but mainly due to the dissolution of impregnated iron sesquioxides, producing rapid disintegration in the hydromorphic environment.

Another example of the problem of deciding whether an indicator material was formed by a process suite that had either a low magnitude/long-term nature, or a high magnitude/short-term nature is provided by the presence of gibbsite. The micromorphological data show that it has two modes of formation. Firstly, gibbsite can result from the relatively long-term secondary mineral alteration of Kaolinite, as its presence in the saprolite layers of both valleyfloors and interfluves indicates. Secondly, gibbsite can form from Kaolinite or directly from feldspar (cf. Gaskin, 1975) at sites where drainage is particularly good. Thus gibbsite is found in all of the layers of both the Kania buried valleyhead deposit and the Yengema Type I terrace, regardless of the fact that the Kania deposit is apparently much younger than the Yengema Type I terrace. Hence drainage is apparently a more important factor in gibbsite formation than "aging", limiting the use of gibbsite for relative dating.

Name & Date[1]	Climatic Conditions[1]	Vegetation Cover[2]	Fluvial Activity[2]	Slope Activity[2]	Chronology of events and deposits	
					Previous work[2]	This study
Upper Quaternary 2.0-0.7 M.y.	Arid ↓	Savanna-Open scrub	Minimal Fluvial transport	Severe slopewash ↓	Formation of West African 'High Glacis'	?="Ancient surface" of Gaiya Valley and Yengema sub-basin.
700 000 - 120 000 y.	Probably wetter ↓	Forest Regenerating ↓	Increased erosion ↓	Gradual slope stabilization ↓		?Gbobora R. captures Yengema drainage:"Ancient surface" incised.
120-000.- 100 000	Semi-arid ↓	Savanna ↓	Minimal transport	Severe slopewash	Formation of West African 'Middle Glacis'	?="High surface" of Koidu Basin formed.
100 000 - 60 000	Humid ↓	Forest ↓	Increased erosion ↓	Gradual slope stabilization ↓		?Incision into Koidu Basin "High Surface".
60 000 - 41 000	Semi-arid ↓	Savanna ↓	Minimal transport ↓	Severe slopewash ↓	Formation of West African 'Low Glacis'	?="Common Surface" of Koidu Basin formed.
Ghazalian 41 000 - 20 000	Mainly humid, episodic dry phases ↓	Monsoon rain forest ↓	Seasonal floods ↓	Stable slopes and pedogenesis ↓	Coastal lignites; widespread inland swamps	Formation of relatively well-rounded gravels in Alluvial fill I; wide floodplains
Ogolian 20 000 - 13 000	Desiccation: hyper-arid, 18-14 000 y. ↓	Shift to savanna-open scrub ↓	Declining discharge ↓	Slopewash; formation of a lag gravel	Environmental instability	Soil/Saprolite stripping, truncated saprolite with Fe/Mn sesquioxide patina; fluvial/colluvial valley fill.
Holocene 'fluvial' 12 500 - 6 500	Progressive humidification with dry phases ↓	Gradual re-establishment of rain forest ↓	Erosion and incision. Accumulation. ?Declining activity.	Slopewash gradual stabilization pedogenesis ↓	Valleyfloor gravels formed Environmental stability	Incision to form Type I Low Terrace & valleyhead extensions; Kania rill; Lower colluvial fill; formation of Alluvial Fill II.
Intra-Holocene 6 500 - 3 500	Progressive desiccation ↓	Gradual deforestation. Clearance for agriculture	↓	Renewed slopewash		Formation of palaeosol capping lower colluvial fill of Type I terraces and Kania buried valley-heads.
Holocene 'Subpluvial' ca. 3 000	Short humid period ↓	↓	Renewed erosion ↓	↓ Accelerated slopewash ↓	Probable age of stone scraper from Yengema Upper colluvium[3]	Incision to form Type II Low Terrace &"lateritic pavements;" Alluvial Fill III in valleyhead swamps; Upper colluvial fill.
Holocene 'Normal' from 2 500	As today, minor fluctuations in humidity	↓ Intensive deforestation over last 50y.	Rapid accumulation ↓ Renewed erosion	↓ Accelerated slopewash		Boya valleyhead swamp: Burial of pottery shards under 1.5-2m of fluvial/ colluvial fill; recent burial of trees under 0.9-1m of fill.

Table 6.3 Postulated relationships between environmental changes and the deposits of the Koidu Basin

1. West African data from Rognon & Williams (1977), Servant & Servant-Vildary (1980), and Zinderen-Bakker (1979)
2. Koidu data from Thomas (1980) and Thomas & Thorp (1980)
3. Shaw (1983)

6.2 A model of landscape development

Table 6.3 is an attempt to correlate the postulated relative ages of the deposits and landforms examined in this study with the widely accepted chronology of Quaternary events in West Africa and the results of radiocarbon dating carried out on sediments from eastern Sierra Leone (Thomas and Thorp, 1980).

From Table 6.3 it is clear that periods of environmental stability have alternated with periods of instability. During the periods of stability there was a dense vegetation cover, stable slopes, and pronounced pedogenesis on the interfluves. Fluvial activity was limited to lateral accretion, the development of wide floodplains with extensive back-swamp deposits, and the production of a relatively well-rounded quartz-rich basal gravel.

The periods of environmental instability were apparently triggered by a shift from humid to semi-arid conditions, due to changes in the atmospheric circulation of West Africa resulting from fluctuations in the extent of the Quaternary ice sheets (Agwu and Beug, 1984; Stein and Sarntheim, 1984). The resulting decrease in annual rainfall apparently produced a degradation from tropical evergreen broad-leaf forest to deciduous open woodland/scrub, with the sparser vegetation cover allowing enhanced rainsplash erosion and slopewash at the onset of the rainy season. This led to soil/saprolite stripping, the deposition of wedges of colluvium on lower slopes and valleyfloor margins, and the extension of distal glacis slopes. Fluvial activity during these arid phases would have been minimal, with transport and erosion limited to rare flash-floods, leading to the infilling of both the valleyheads and the valleyfloor and producing a braided channel pattern, with alluvial deposits interdigitating with distal glacis pedisediments.

The return of more humid conditions near the end of these periods of instability probably produced even greater stripping and erosion, as the time taken for a denser vegetation cover to become re-established may have been too long to provide adequate protection against the increased rainsplash erosion and slopewash. An initial colluvial infilling of the valleyfloors would eventually be replaced by valleyfloor scour as vegetation stabilised the slopes and the discharge of the rivers grew. This fluvial incision would have formed new terraces (that were largely stripped of their alluvial fill layers by valleyside slopewash and gullying), as well as re-excavating the buried valleyheads with headward erosion, until the fluvial system achieved equilibrium.

There is archaeological evidence (Shaw, 1983) of human occupation in the Yengema area over the last 3,000 years, with farming probably beginning some 2,000 years ago. The resultant deforestation has produced a dominantly savanna vegetation type in the Yengema and Kania areas, despite the Koidu Basin having a seasonally humid, tropical climate. It appears that the present bioclimatic conditions pertaining in the Yengema and Kania areas are close to a threshold beyond which soil/saprolite stripping occurs. Indeed, in those parts of the Yengema area with extensive rock outcrops, stripping already exceeds soil/saprolite production.

Reference to Table 1.2, the geological and geomorphological events that have affected Sierra Leone, Senegambia and the Guyanas, shows that there is evidence of longer-term periods of alternating environmental stability and instability, respectively termed 'Biostasie' and 'Rhexistasie' by Erhardt (1955). The bauxites and nearshore sediments of the Guyanas are particularly well dated using a wide range of techniques, notably stratigraphy and profile morphology (Bleakley, 1964; Aleva, 1965, 1981); mineralogy (Krook, 1979); major element distributions (Pollack, 1981a, 1981b); and absolute dating, back into the Tertiary, by palynology (van der Hammen and Wijmstra, 1964). The results of these studies indicate that marine regressions produced aridity along the coastal margin of the Guyana craton (as well as a major lowering of base level) and thus led to a period of environmental instability. Conversely, marine transgressions produced enhanced humidity on land, associated with pedogenesis and deep chemical weathering. The analogy with the West African craton is clear: eustatic sea level changes would produce changes in regional base levels and, given the extensive coastal plain of the Sierra Leonean section of the craton, greatly alter the climatic regime of the interior. The application of this sea level/environmental change analogue to the West African craton is supported by the occurrence of submarine terraces and deltas off the Sierra Leonean coast, contrasting with palaeobeach deposits some 40m above present sea level (MacFarlane et al., 1981, p.7) and the evidence of terriginous environmental changes derived from the analysis of deep sea sediment cores (Bezrukov and Senin, 1970; McMaster et al., 1970). The presence of coarse arkosic sandstones, buried at depth in the Cainozoic Bullom Series sediments of Sierra Leone (MacFarlane et al., 1981), points to periods of low sea level, with arid climates producing minimal chemical weathering and severe erosion of the Basement Complex granitoids. The epierogenic uplift of the Guinea Dome during and after the opening of the Atlantic (Thomas et al., 1985b) can only have enhanced contemporaneous periods of environmental instability in the study region.

The eustatic sea level changes and tectonic deformations outlined above and recorded in Table 1.2 correspond to the "Boundary Conditions" described by Brunsden and Thornes (1979) in their discussion of landscape sensitivity and change. Theoretically, if the geomorphological evolution of the Yengema and Kania sub-basins was only the result of these boundary conditions, then two morphologically similar areas should result. The results of this study show that this is clearly not the case: two distinct sub-basins have developed within the Koidu Basin under the same set of boundary conditions. The reasons for this apparently lie in what Brunsden and Thornes (op.cit.) termed "External Variables", in this case variations in bedrock lithology, drainage system development and land use. All show marked differences between the Yengema and Kania sub-basins.

"Internal Variables" notably the effect of "aging" on the structure and fertility of soil (Furley, 1974, p.174; Millot, 1982, p.585), have apparently made a more limited contribution to the landscape evolution of the Koidu Basin, their effects being most effective in the Residual domain of the planate interfluves. This may explain why the Kania sub-basin, dominated by planate interfluves, has an open savanna vegetation when the present climate apparently allows for a secondary forest/savanna-bush vegetation. The adjacent, more dissected (and more intensively farmed), Yengema sub-basin has secondary forest/savanna bush vegetation, which may be largely due to the greater supply of minerals to the soil of this area from bedrock erosion..

A comparison of the altimetric frequency diagrams for the Kania and Yengema areas (Table 4.1) reveals a great deal about their relative morphogeneses. Whilst both areas have both "High" and "Common" surfaces at ca.396m and ca.385m A.S.L. respectively, the incision that led to the abandonment of the "High surface" by the rivers of the Kania sub-basin appears to have been gradual, with the "High surface" merging into the "Common surface" to form an extensive intermediate belt at ca.390m. In contrast, the fluvial incision that shifted rivers from the "High surface" to the "Common surface" in the Yengema sub-basin appears to have been relatively short, sharp, and profound, producing a clear break between the two surfaces. A similar pronounced incision appears to have affected the "Ancient surface" of the Yengema area which lies at ca.414m A.S.L. If the "Ancient surface" correlates with the High Glacis of West Africa it was probably incised some 700,000 years ago (Table 6.3).

Whilst the present Gaiya River flows south-westwards into the Gbobora river system, the gradient of the "Ancient surface" along the Gaiya valley is northwards towards the Shongbo river system (cf.Figure 4.1). This indicates that not only did a period of severe fluvial incision occur, but also that a profound drainage pattern modification affected the Yengema sub-basin, namely, the capture of the previously northerly-draining Yengema drainage by the Gbobora River. In contrast, there is no evidence of the Kania sub-basin experiencing such a profound modification of drainage pattern. This difference in drainage system development appears to be the only explanation for the Yengema area's greater sensitivity to periods of fluvial incision, during, and since, the Quaternary.

The Yengema sub-basin has been profoundly affected by river capture, given the evidence cited above. The ensuing changes in drainage direction and local falls in base level produced incision, valleyhead extensions and gullying, probably enhancing the effectiveness of soil/saprolite stripping in a similar way to that studied by Olofin (1980) in Northern Nigeria, where a drainage system was modified by reservoir construction. It is postulated that the degree of soil/saprolite stripping during this 'drainage modification period' was so intense that large areas of bedrock were exposed. The exposure of bedrock tends to produce a positive feedback loop, whereby the relative elevation of rock domes increases with each period of soil/saprolite stripping, as the relatively deep, easily-eroded foot-slope saprolite is removed, leading to the formation of inselbergs and bornhards (Willis, 1936; Ruxton, 1958; Thomas, 1966b, Huralt, 1967). Inselbergs are enhanced, rather than diminished and destroyed, by alternating periods of deep weathering and soil/saprolite stripping, becoming "acyclic" landforms. The granodioritic hills with duricrust cappings can be regarded as "partly acyclic", in that they have survived largely intact through the erosive periods of the Quaternary. However, during each erosive period there appears to have been fragmentation around the margins of these duricrust cappings, and they are gradually destroyed: their preservation depends largely on their original areal extent and degree of induration. Nevertheless, it appears that the inselbergs, rock bars and duricrust cappings of the Yengema area are "relict" features that were largely formed as a consequence of the profound changes in local drainage and local base level during the early Quaternary. They have not been significantly modified by the environmental instabilities of the late Quaternary.

The contemporary morphodynamics of the Yengema area appear to be poised between (i) pedogenesis with soil/saprolite formation and (ii) soil/saprolite stripping with fluvial incision and periodic "flushing-out" of valleyfloor sediments. The evidence for this includes the large areas of rock outcrop; the virtual absence of buried valleyhead deposits; the presence of recent Type II terraces; the absence of soil/saprolite cover in some swale zones; and the presence of 0.5-1.0m of recent colluvial/fluvial fill in valleyhead swamps. It may be that the Yengema sub-basin has been in this "threshold" situation since the postulated early Quaternary drainage system modification that apparently triggered so much incision and soil/saprolite stripping. If the local drainage system has still not achieved equilibrium this may explain the area's susceptibility to fluvial incision. The extensive rock outcrops only enhance overland flow and thus exacerbate soil/saprolite stripping.

<u>The Kania sub-basin</u> may, in fact, be an example of the type of landscape that existed in the Yengema area prior to the period of severe soil/saprolite stripping outlined above. The Kania area has maintained a relatively thick soil/saprolite mantle and consequently has few rock exposures, and a lower drainage density than the Yengema area (cf. Table 4.1). The main reason for this appears to be that the Kania area drainage system, has been undisturbed by the profound changes in drainage pattern that are thought to have affected the Yengema sub-basin. The Pawpawyi drainage basin is positioned in a headwater zone of the Meya-Moinde-Woyie drainage system (cf. Figures 4.1 and 4.5). Thus the deeply entrenched and long-established Meya-Moinde River appears to have acted as a "buffer" for the Kania area, placed well away from any river rejuvenation "pulses" that might have progressed up the Sewa and Bafi rivers. Thus the long-sections of rivers draining the Kania area (Figure 4.7) show that although a major river rejuvenation pulse has apparently progressed up the Meya and Woyie rivers to ca. 870m A.S.L., this has not yet affected the Pawpawyi stream, most of which lies above 880m.

From the preceding discussion it is clear that the Kania area has been less affected than the Yengema area by recent, probably Intra-Holocene, fluvial incision (cf. Table 6.3). However, the widespread occurrence of the "Common surface" in the Kania area as well as remnants of the "High surface", (Table 4.1 and Figure 4.7), indicate that the Kania area experienced at least two periods of major fluvial erosion to incise these surfaces. If the "Common" and "High" surfaces equate with the Low and Middle Glacis surfaces of West Africa, this would place the periods of incision at soon after 40,000 and 100,000 years B.P. respectively (cf. Table 6.3). This is in agreement with the model of landscape development outlined over the previous pages, in that extensive glacis deposits are thought to form under semi-arid conditions, with the return to more humid conditions being associated with severe fluvial erosion and enhanced soil/saprolite stripping. It thus appears that although the "boundary conditions" of regional base level and climate affecting the Koidu Basin dictate whether periods of glacis formation dominate over periods of fluvial incision, the local "external variables", particularly differences in lithology, drainage system development and degree of rock outcrop, dictate how effective periods of incision are in each sub-basin.

Other models that seek to explain tropical landscape development contain elements that explain some, though not all, of the material and landform associations observed in this study. Though it was not the aim of this study specifically to test for the operation of one or another model, it appears that the classical Davisian (1899) model of landscape evolution by the wearing-down of residual relief does not apply here; if anything, erosive events have tended to enhance the height of inselbergs over periods of 10^4-10^6 years. Nor can the pedimentation of hard rock surfaces proposed by King (1948) be a major contemporary process, given the extensive soil/saprolite mantles; furthermore, the wearing-back of residual relief only appears to occur in the relatively rare case of duricrust "breakaways".

A number of features recognised in this study have been described by previous authors who placed varying degrees of emphasis on the implications such features have on tropical landscape evolution. The relationship between (a) deep weathering and the formation of subsurface residual relief and (b) slope-wash and glacis formation was emphasised by Budel (1957). Soil/saprolite stripping was recognised by Bruckner (1955), Folster (1969), Rhodenberg (1970), Burke and Durotye (1971) and recently Debaveye and De Dapper (1986), as a key factor in the formation of interfluve stonelines. Mantled and stripped landscapes were correlated with periodic climatic events by Butler (1959), Mabbutt (1961a, 1966) and Avenard (1973a). The "steady-state" approach to tropical landsurface lowering has been supported by the studies of chemical weathering and lateral eluviation by Stheeman (1932, p.8), Ruxton (1958, p.375), Sivarajasingham (1968, p.9), Hall (1974, p.28), De Dapper (1979, p.99), and Spath (1981, p.226).

Long-term widespread fluvial erosion, or "panplanation" was proposed by Crickmay (1933; 1975) as a mechanism capable of producing extensive plains with rare residual hills. This theory is supported by the study of pediments and inselbergs in Arizona by Rahn (1966, p.214). The presence of rounded quartz cobbles in the lateritic gravels of interfluves in south-eastern Sierra Leone (Sivarajasingham, 1968, p.6), in the Ivory Coast (Leneuf, 1964) in central Togo (Leveque, 1979, p.127) and in South Australia (Milnes et al., 1985) also points to long-term fluvial reworking of the entire landscape. Leveque (op.cit.) proposed a pre-Quaternary age for the deposition and abandonment of the Togo fluvial deposits. The evidence from this study, both in terms of land form, with the "Common", "High" and "Ancient" surfaces; and in terms of materials, with the presence of rounded quartz cobbles in the interfluve-glacis gravels, partly supports Crickmay's panplanation hypothesis.

"Etchplanation", as outlined by Thomas (1974, p.228-257), allows all these threads of theory and observation to be tied together. This model has its foundations in the concepts of deep weathering followed by soil/saprolite stripping proposed by Falconer (1911, p.246), Wayland (1934) and Willis (1936); and on the "double surfaces of levelling" proposed by Budel (1957), with alternating periods of "biostasie" and "rhexistasie" (Erhardt, 1955) acting alongside "on-going" landscape lowering by the subsurface lateral eluviation of weathered material. The etchplanation model was largely derived from the results of African fieldwork, but recent supportive studies have come from central Australia (Fairbridge and Finkl, 1980); Arizona (Moss, 1977); Suriname (Kroonenberg and Melitz, 1983) and Malaysia (Debaveye and DeDapper, 1986), whilst Millot (1982) has proposed a similar model based on French pedogeomorphic research. Budel (1957) did not accept that tropical rivers had the ability to erode, incise and modify the landscape to any great degree. He proposed slopewash as the main agent of transport and erosion and paid relatively little attention to the effects of bioclimatic change. The results of this study show that slopewash and glacis formation are only one part of the sequence of events that produce tropical planation. It appears that over the long-term, during the Cainozoic, virtually the entire landscape has been affected by fluvial reworking, with the occurrence of at least three major periods of fluvial incision. The effectiveness of fluvial incision is greatly enhanced if the main material it acts on is deeply weathered saprolite, and it appears that periods of "biostasie" and pedogenesis preceded the postulated periods of major fluvial incision.

The presence of human artefacts incorporated in glacis stonelines or buried beneath 1-2m of colluvial/fluvial fill in the Boya valleyhead swamp indicates how serious and widespread the impact of man on the environment of the Koidu Basin has been over the last 3,000 years. The type of landuse by man, through the degree of forest clearance and the intensity of farming, has become an additional "external variable", having most effect on the degree of slopewash and glacis formation: in effect, a surrogate for semi-arid/open savanna bioclimatic conditions. The 1-2m of recent colluvial/fluvial fill in the Yengema valley swamps indicates that considerable amounts of topsoil have been eroded. In some swales and on some particularly narrow, elongate interfluves both topsoil and topgravel appear to have recently been eroded away as a consequence of forest clearance and over-farming (though these may have been sites of enhanced erosion and sparse topsoil/topgravel formation throughout the Quaternary).

More recently, the effects of mining disturbance over the last 50 years, although more localised than agricultural disturbance, may have an even greater long-term effect on the environment of the Koidu Basin (cf. Douglas, 1967a). The excavation of valleyfloor deposits and the construction of flood-relief channels has produced straighter channel flow. This may account for the recent Type II terraces in the Yengema area and the "pulse" of river rejuvenation apparently progressing up the drainage system of the Kania area. If the large-scale strip-mining of the glacis-interfluve stonelines goes ahead without measures to conserve and replace topsoil, hundreds of square kilometers of land would be virtually devoid of soil and vegetation cover for many years to come (see, for instance, Kreiger, 1984; Avenard and Michel, 1985). The effect on local environmental stability might then match the desertification phases of the Cainozoic. Add to this the effect of enhanced fluvial erosion, and the results could be catastrophic.

In conclusion, the differences between the Yengema and Kania study areas are apparently due to the effects that local variations in lithology, drainage system history, degree of rock outcrop, and landuse have on the balance between pedogenesis and fluvial incision, soil/saprolite stripping or glacis formation. The results of this study indicate that the etchplanation model can explain both the contemporary morphodynamics of tropical landscapes and also their long-term evolution, as well as providing a basis for predicting future environmental hazards.

6.3 Applications

The main application of this study has been in the field of mineral exploration, namely the distribution of secondary diamond deposits in the Koidu Basin. The evidence derived from the studies of both morphofacies types and interfluve crest/valleyfloor transects led to the recognition of over twenty stratigraphic and material indicators, (Table 6.2), each formed under one of three process domains: Residual, storing material; Colluvial, shedding material; and Fluvial, concentrating material. Within contemporary process domains relict indicator materials have been found, providing insights into the palaeoenvironments of such sites.

Of particular interest are those relict indicator materials formed by fluvial processes. Their occurrence in the deposits of hillside benches, glacis slopes and planate interfluves indicates that virtually every part of the Koidu Basin, has at some time during the Cainozoic been part of the fluvial domain. The distribution of diamonds in the extensive glacis/interfluve gravels is thus partly related to concentrations of diamond in ancient alluvial deposits, as well as being related to residual deposits derived from local kimberlitic bedrock.

The distribution of these secondary diamond deposits has been further complicated by both Quaternary and contemporary morphodynamics. During the Quaternary, gullying and rilling were severe enough to extend back into even the planate interfluves. The effectiveness of rills in concentrating material is illustrated by Walker's (1964) study of buried channels in a glacis deposit: the competence of the slopewash was 5mm, whereas that of the rillwash was 100mm. Similarly, the concentrations of heavy minerals from the palaeo-rill excavated at Kania were an order of magnitude higher than from adjacent lateritic gravels (viz. Figure 5.8). Rillwash on the interfluves of the Koidu Basin has produced "pay streaks" of re-worked and re-concentrated diamondiferous gravel in otherwise low-grade palaeoplacers. Further modification of these palaeoplacers has continued under contemporary process domains, with diamondiferous gravel being "diluted" by the neoformation of lateritic clasts, and concentrated by fluvial/colluvial abrasion and laterite dissolution under hydromorphic conditions.

The efficiency of mineral exploration has been improved by the use of a model that can explain the formation and distribution of diamondiferous deposits in terms of their initial long-term deposition and in terms of their more recent reworking and reconcentration. The use of a geomorphological model has allowed sites of long-term or recent material concentration to be targetted for mineral exploration, as well as allowing the use of a stratified sampling strategy based on the identification and selective examination of "high-potential" landforms, rather than the traditional, slower (and generally more expensive) systematic grid-sampling of virtually the entire landscape. Confidential reports on this topic have been prepared for both the National Diamond Mining Co. of Sierra Leone, B.P. Minerals International PLC and for Ghana Consolidated Diamond Mines Ltd./U.N.D.P. Birim Valley Project (Teeuw, 1983a, 1983b). The reader is referred to Thomas et al. (1985a), reproduced in Appendix A, for a full discussion of the mineral exploration applications of this study.

6.4 Assessment of methods used

Whilst it is acknowledged that a random system of field-sampling would have virtually eliminated any chance of sampling bias and allowed for a more rigorous statistical analysis of data concerning landform and material variations, the circumstances in which this project was carried out made such a sampling system virtually impossible to implement. One of the main problems with a system of random sampling would have been the accurate location of the sample sites, given the extensive planate interfluves, tall 'Elephant Grass', and consequent intervisibility problems. Furthermore, the field sampling had to be carried out within the constraints imposed by working in a district of active surface mining, where relatively few areas have been totally undisturbed by miners. On the other hand, one positive result of over 50 years of surface mining for this study was the large database of data on surficial geology for the Koidu Basin. In the end, the stratified system of pit transects outlined in Chapter 2 proved to be cost-effective, given the limited time, transport and funds available. One key point with this system is that the orientation of transects should not be solely orthogonal to the valleyfloor axis: at least one transect should cut the interfluve parallel to the valleyfloor. Were it not for this, the presence of palaeorills on Kania interfluve would have gone unnoticed.

A major flaw in the sampling strategy came during the laboratory analysis of particle size distributions. On hindsight, only two "representative" transects from each study area - some 200 to 250 samples - needed to be given the full particle size distribution analysis used for this study (re. Section 2.4). The other six transects, some 300 to 350 samples, need only have been sieved to find the percentages of fines (-62µm), sand (62-2000µm) and gravel (+ 2000µm) to provide adequate textural information. The time that would have been saved by reorganising the particle size analysis would have been better spent on the scanning electron microscopy and image analysis studies of sand grains, both of which showed potential as indicators of the formative environments the sand grains had encountered.

The micromorphological studies provided much useful information about the structural variations within and between morphofacies types. However, the near impossibility of taking <u>in situ</u> samples from the concretionary lateritic gravels and the easy access to the basal gravel/saprolite interface of the valley floors, led to an oversampling of the swamps and terraces in an attempt to test whether or not swamp saprolites were "washed" by lateral eluviation. This was at the expense of examining the micromorphological variations of the interfluve and glacis zone morphofacies types.

The limited amount of X-ray diffraction analyses that could be carried out for this study supported the clay mineralogy findings of thin section analyses, but could yield no information on the types of sesquioxide accumulations in the samples. Samples of lateritic segregations. nodules and pisoliths have since been sent to University College, Dublin, for electron microprobe analysis, in an attempt to fill this information gap.

The MINITAB statistical package was found to be an adequate and versatile means of analysing the large database amassed by this study. The c/m diagram (Figure 5.5) provided a useful, though time-consuming, means of distinguishing proposed layer types; whilst the ternary diagrams of Figure 5.6 provided a rapid means of testing whether or not proposed morphofacies types had characteristic textures for given layers. The silt:clay ratios and percentage clay depth functions were useful guides to the genesis of deposits. The index of gravel petrography not only showed marked variations between most morphofacies types but also provided a means of both summarising and mapping gravel compositions.

6.5 Summary of findings

1. Each type of Unit Landform, identified on the basis of detailed geomorphological mapping, was found to have a characteristic stratigraphy or "Morphofacies type" on the basis of profile morphology, gravel petrography and particle size distribution studies. Comparative analysis of the proportions of gravel (+2mm), sand (0.06 - 2.0mm) and fines (-0.06mm) was found to be the most effective way of distinguishing between both layer types and morphofacies types.

2. Three types of process domain have been recognised in the present landscape of the Koidu Basin: Residual, Colluvial and Fluvial. Each has been distinguished on the basis of a unique set of stratigraphic or material indicators. The presence of stratigraphic unconformities and exotic indicator materials in the majority of deposits points to shifts in the areal extents of process domains over time, largely in response to Cainozoic environmental changes.

3. Altimetric analyses reveal that both the Yengema and the Kania sub-basins have a stepped sequence of near-planate surfaces, from the valleyfloor and low terraces up to the "Common" and "High" surfaces of the interfluves. The hillside benches along the Gaiya Valley apparently are remnants of an "Ancient surface", the slope of which indicates that the Yengema sub-basin once drained northwards into the Shongbo River, rather than south westwards into the Gbobora River.

4. The relative ages of deposits (deduced from stratigraphic and material indicators) and the sequence of near-planate surfaces have been correlated with the widely accepted chronology of environmental changes in West Africa (Table 6.3). The climatic oscillations that have affected West Africa since the Tertiary have apparently greatly affected the Koidu Basin. Humid periods with intense pedogenesis and deep chemical weathering have alternated with arid periods characterised by soil/saprolite stripping. This scenario of geomorphic events fits the model of Etchplanation proposed by Thomas (1974) and refined by Thomas and Thorp (1985).

5. The markedly different landscapes of the Yengema and Kania sub-basins are apparently the result of local differences in lithology, degree of rock outcrop, drainage system development and land use. The degree of fluvial incision, in particular, appears to have been enhanced in the Yengema sub-basin, probably as a consequence of profound changes in drainage direction resulting from river capture by the Gbobora River in the early Quaternary. The greater degree of incision, soil/saprolite stripping and rock exposure in the Yengema area has produced a partially stripped etchplain. No equivalent period of severe fluvial incision has apparently affected the Kania sub-basin and it now forms a mantled etchplain.

APPENDIX A:

Paper on the applications of this study.

J. geol. Soc. London, Vol. 142, 1985, pp. 789–802, 8 figs, 3 tables. Printed in Northern Ireland

Palaeogeomorphology and the occurrence of diamondiferous placer deposits in Koidu, Sierra Leone

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SUMMARY: The geomorphology and diamond distribution within the Koidu alluvial diamond field in Sierra Leone are examined to provide a methodology for palaeoplacer appraisal within a humid tropical environment of diverse relief and headwater drainage containing local diamond sources. A morphogenetic terrain model is proposed for use in devising prospecting programmes, based on geomorphological mapping and sediment analysis of terrain units mapped at 1:1250. Valley floors including headwater swamps and stream floodplains provide a radiocarbon-dated late Quaternary stratigraphic framework for deductions concerning interfluvial domains containing remnant river terraces, and colluvial stoneline deposits interspersed with non-alluvial erosional slopes. Planar interfluves as well as piedmont 'glacis' contain alluvial indicators within gravels composed of bedrock quartz and iron concretions derived from former landsurfaces. A process history for the interfluvial domain indicates downwasting and diagenesis of ancient degraded alluvials, lateral shifts of drainage lines and continued supply of diamonds from erosion of local sources, the 'stonelines' functioning as feeders of coarse clasts from the interfluves towards the valley floors. The use of geomorphology to provide descriptive and genetic terrain models to guide prospecting for alluvial placers is advocated as a standard procedure for use by mining geologists.

The kimberlite sources in Sierra Leone occur as a deeply eroded system of dykes and small pipes intruded into the Archaean basement during the Cretaceous (92 Ma; Bardet & Vachette 1966). They occupy two fault-bounded basins in the east of the country, developed across migmatized gneiss, and granodiorite, intruded by late kinematic granites and enclosed by hill ranges of amphibolitic supracrustal rocks (Hall 1974; Rollinson 1978; H. R. Williams 1978; MacFarlane *et al.* 1981). Sedimentary xenoliths found in the pipes belong to a former Palaeozoic cover (Hubbard 1967, 1983), and possibly to the Ordovician Saionya Scarp Series which outcrops close to the Guinea border. Repeated uplift, tilting and faulting of the basement along the Niger–Atlantic watershed (Leo Uplift) to the north has led to periods of dissection by the Atlantic flowing drainage, interrupted by episodes of partial planation across the more susceptible rocks (Fig. 1).

Koidu is an area of low relief between 350 and 415 m a.s.l. comprised of shallow valleys and low, flat interfluves, interrupted by occasional granite inselbergs and schist-belt hills (Fig. 2). The area is part of a complex interior plateau (Dixey 1922; Hall 1974) and is drained, mainly to the north and west, by headwaters of the Bafi–Sewa River system, but encroaching headwaters of the Moa River sharply dissect the southern margins. Annual rainfall is 2300 mm, concentrated between March and October, and the natural vegetation cover was once tall rain forest, most of which has been cleared. However, the forest–savanna boundary is within 100 km and sharp rainfall gradients occur to the north, making this area particularly sensitive to climatic and vegetational change.

In the Koidu and adjacent areas, landscape evolution and placer formation during the later Cenozoic proceeded by the differential lowering of the basement rocks with respect to the duricrusted supracrustal formations, by deep chemical weathering and surface erosion of the saprolite mantles which were episodically accelerated by climatic fluctuations (Stein & Sarntheim 1984), and by pulses of epeiric uplift. Such lowering of deeply weathered basement landscapes while maintaining a generally planate form (and as relief increases on adjacent, more resistant formations) is termed *etchplanation* (Thomas 1974, 1980; Thomas & Thorp 1985). During the development of such etchplains, erosional energy on them remains generally weak so that while the landsurface is continuously lowered by the export of solutes, clays and fine sands, the weathering-resistant, larger and heavier clasts may be retained for long periods after the destruction of ancient landscape levels.

Since their extrusion during the Cretaceous, the diamondiferous kimberlites and the surrounding country rocks have probably been eroded by at least 1000 m. During this erosion, diamonds in excess of

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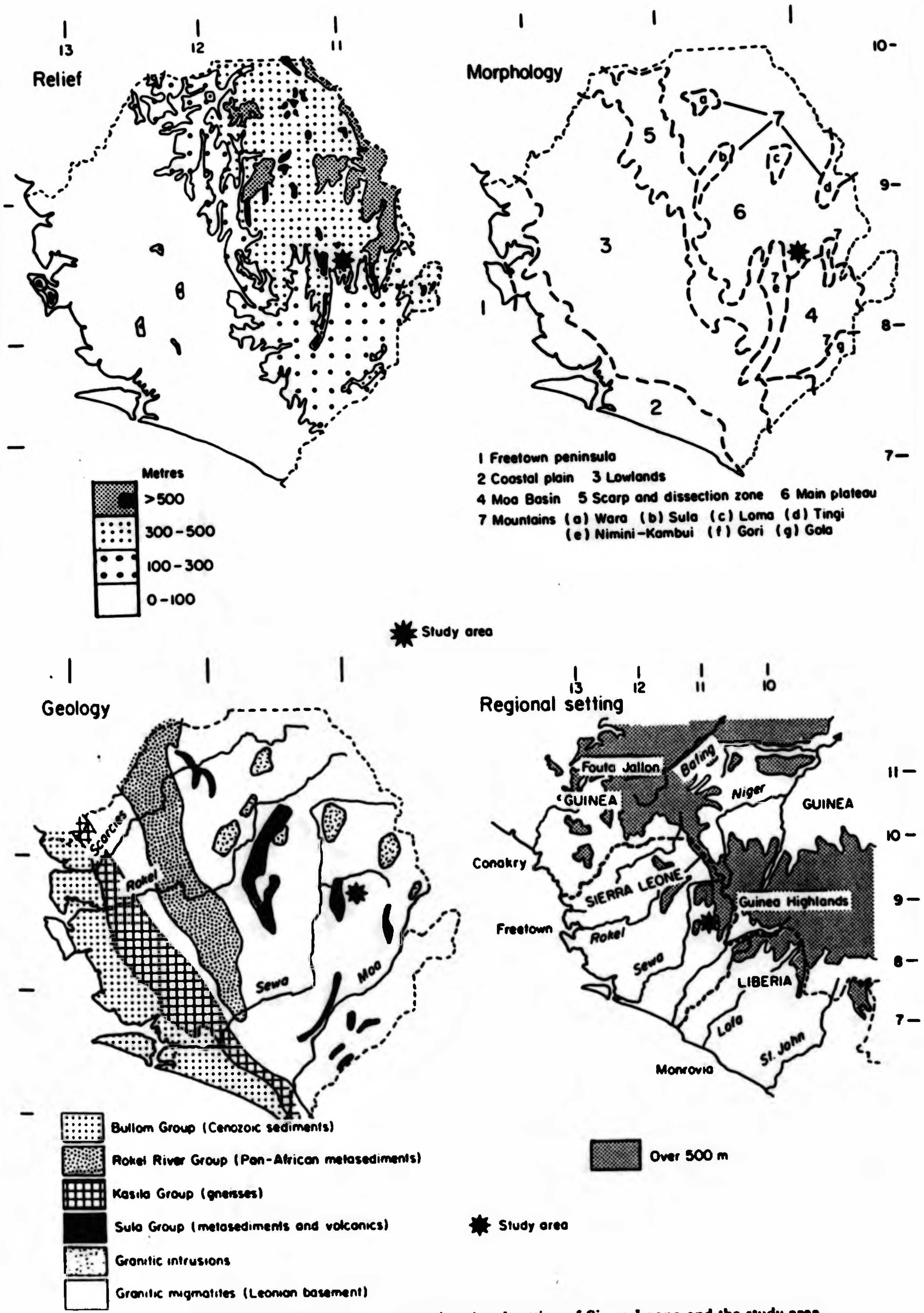

FIG. 1. Relief, morphology, geology and regional setting of Sierra Leone and the study area.

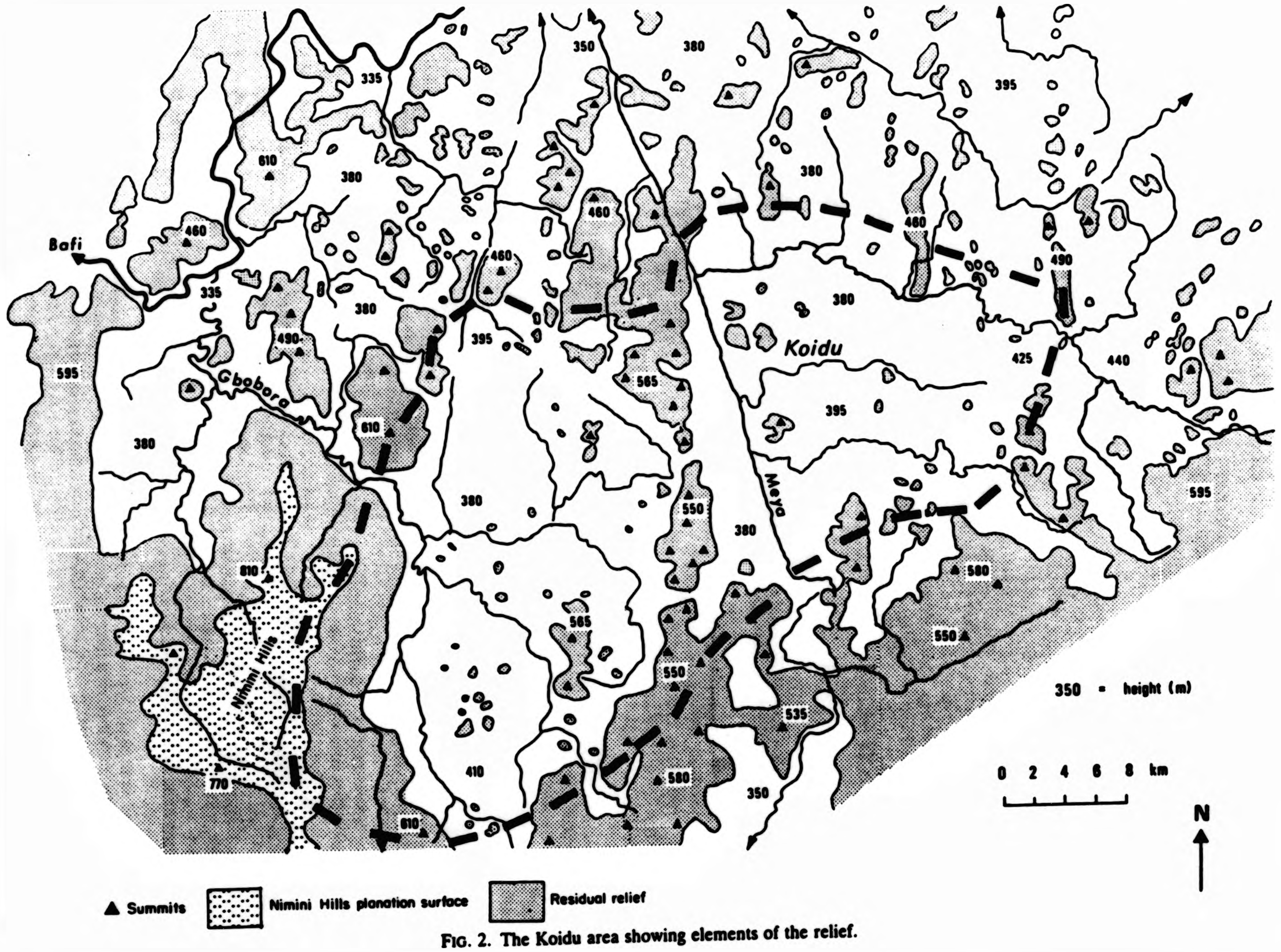

FIG. 2. The Koidu area showing elements of the relief.

50 Mcar. have been released from the two kimberlite outcrop areas at Koidu and Tongo and become widely dispersed down the Sewa and Moa river systems and over the coastal plains between these two rivers. An unknown quantity have also accumulated in the offshore sediments (Sutherland 1982).

Despite this long history of diamond release and long-distance transport, the bulk of the diamonds have been mined within 20 km of the two source areas, clearly implying long-term storage of diamond within the landscape. However, the floodplain alluvial sediments which contained the bulk of the mined diamonds show ages of less than 35,000 years (Thomas & Thorp 1980). These diamonds have clearly been derived mainly from earlier floodplain deposits by erosion. Remnants of these earlier deposits survive as fringing terraces and as enigmatic pockets of diamonds and alluvial pebbles in otherwise residual interfluvial gravels.

With decreasing volumes of 'pay' gravel, interest shifted towards these higher, degraded terraces and the interfluvial gravels. However, earlier prospecting experience had shown that in them diamond occurrence and grades usually could be accurately determined only by large bulk sampling. The reappraisal of these gravels therefore required different field procedures, based upon a detailed understanding of their geomorphology.

Aims and objectives

The main aim of this study is to provide a methodology for the appraisal of palaeoplacers that appear as higher level gravels in terms of their diamond-bearing potential. Three objectives were identified.

1. To develop a morphogenetic terrain model of the lease area which would embrace the fundamental landform units and their surface materials, and also offer an interpretation of their genesis. An important stage in this was the construction of a late Quaternary stratigraphy for the floodplain sediments. From this the process history of the redistribution of surface gravels on interfluves and slopes during the last 35,000 years has been inferred. Such a model should help to identify areas of persistent sediment departure, transfer and storage and areas of potential placer mineral concentration.
2. To develop appropriate field techniques of morphological mapping and description, and for the sampling and analysis of sediments, for use by prospectors who may have little formal training in geomorphology.
3. To develop a phased prospecting programme which would apply and refine the terrain model and subsequently locate and evaluate diamondiferous interfluvial gravels and define mining blocks.

The achievement of these objectives involved an iterative approach that started with interpretations of remote sensing products (Landsat 2, 1:70,000 IR and 1:20,000 panchromatic aerial photographs) and field reconnaissance to establish the main landform units. This was followed by reviews of existing prospecting data, field investigations and morphological and gravel mapping at a scale of 1:5000, to identify priority areas within which very detailed investigations at a scale of 1:1250 would be undertaken. This latter involved detailed morphological mapping, new pitting and mini-bulk sampling to specify the spatial, morphological, sedimentological, and petrographic characteristics of the interfluvial gravels and their diamond occurrence. The final stage was the large bulk sampling and trial mining of selected areas to define blocks for future mining.

The geomorphological parameters for this investigation included:

(i) surface morphology involving slope angle, form, position, microrelief and bounding breaks of slope;

(ii) spatial relationships amongst individual form units such as hillslope and valley catenary sequences, drainage and watershed networks and geological and structural alignments;

(iii) superficial materials associated with each landform unit and defined according to shape, particle size and petrography, and embracing assessment of the provenance of the clasts, the processes of their transfer in the landscape of their residual accumulation and later diagenesis; and

(iv) stratigraphy of deposits and the identification of sedimentary units not only in the conventional river channel deposits but especially amongst the degraded interfluvial formations.

The terrain model

Two major domains occur: the valley floors and the interfluves. They are schematically illustrated in Fig. 3.

The valley floor alluvial domain

This has been largely mined out, but remains the starting point for the reconstruction of late Quaternary history. The alluvial floodplains take two distinct forms: (i) the streamless headwater swamps (Strahler order 1 and 2) and (ii) larger valleys containing permanent stream channels.

The *headwater swamps* contain sediments usually less than 2 m thick comprising basal angular quartz gravels overlain by a sandy clay stratum that penetrates the gravel below as a matrix and is in turn overlain by finer grained alluvium and colluvium. The absence of any clear sedimentary structures makes it difficult to regard the basal gravels as channel sediments. However, the seasonal flooding of the entire valley floor can readily explain the development

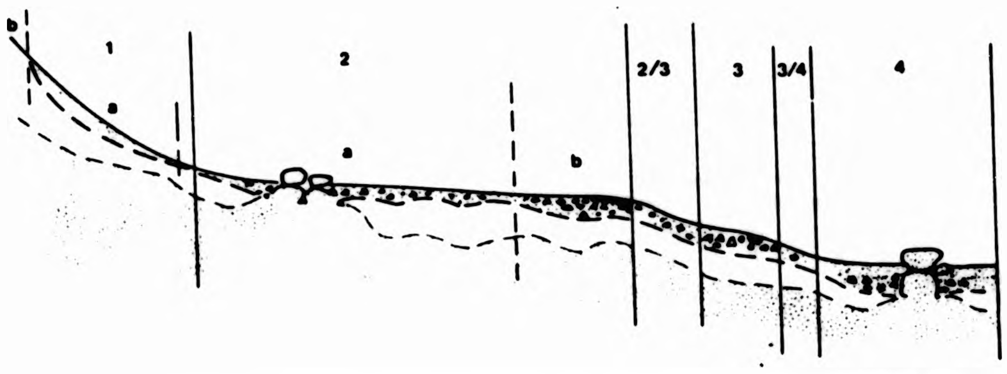

FIG. 3. Composite landform model for the Koidu area indicating domains with common process history. 1. **Hillslope** (a) gully fills and (b) erosional; 2. **Glacis** and planar interfluves (a) mainly non-alluvial, (b) former alluvial high terrace; 3. **Lower terrace**(s), partly degraded and/or colluviated; 4. **Valley floor** (swamp flat shown but also alluvial floodplain). Inter-terrace slopes exhibiting stone-lines shown as 2/3 and 3/4.

of the fine-grained upper layers that contain material from the adjacent valley slopes and episodes of channel flow in some of the valleys cannot be discounted. In agreement with Hall (1974) we consider the sub-swamp gravel to have accumulated by a combination of bedrock weathering and removal of finer sands and clays by surface and throughflow within the swamp environment, together with inheritance from terrace gravels and from valley-side stone lines.

Stream valleys of Strahler order 3 and above exhibit typical fluvial sedimentary structures. Study of field sections together with radiocarbon dating of contained organic debris have permitted the construction of a chronology for sedimentation in the area during the last 36000 years (Thomas & Thorp 1980). Within the present valley floors the oldest sediments rest on a bedrock floor 0.5–5 m above the deepest channels, but they do not everywhere form a distinct terrace above the more recent floodplain deposits. These older sediments were dated mainly from wood, leaf mould and fine detritus preserved in dark organic clay lenses that mark former backswamps, and all are older than 20550 years. Into these deposits deeper channels were scoured, exposing residual granite cores around which were deposited coarse gravels, often of cobble size, which contain wood that has become lodged beneath the granite cores and returns dates from 12500 to *c.* 8000 years BP, corresponding with periods of increased rainfall inferred by other writers (Street 1981; Street & Grove 1979; Talbot *et al.* 1984). From 8000 years BP onwards there have been further cut-and-fill episodes, particularly from *c.* 4500 years BP until the present, recorded by consistent local sedimentary sequences dated mainly by samples of wood which only very rarely appear to have been reworked from earlier deposits. The entire complex clearly records episodes of channel cutting and vertical aggradation, as well as normal lateral accretion of channel deposits from floodplain reworking.

A frequency plot of the ^{14}C determinations (Fig. 4) can be interpreted as indicating periods of greater and lesser fluvial activity. Specifically, periods with no dates may arise from a lack of floodplain reworking associated with reduced discharges and/or sparse riparian vegetation, whereas periods with clusters of dates suggest frequent floodplain erosion and reformation and increased occurrences of extreme discharges. The hiatuses and clusters of dates closely match the periods of lesser and greater humidity inferred from the sedimentary and pollen records elsewhere in W Africa (Street 1981; Talbot *et al.* 1984). This analysis provides a basis for understanding some of the effects of the bioclimatic changes that have occurred in the Koidu area, not only in the late Quaternary but over a longer period. At a more detailed scale, analysis of the gravel stratigraphies for sites with multiple ^{14}C determinations confirms that the floodplains of the larger rivers are comprised not only of spatially distinct sedimentary blocks but also, in places, of vertical aggradation and scour units which have dates falling into the same pattern of clusters and hiatuses.

Preliminary analyses of the data from the River Birim floodplain in Ghana also suggest that gravel calibre and diamond grades may differ systematically among the several chronosedimentary units, perhaps in response to the varying spectra of extrem discharges to which the units were subject. Traditional theories of alluvial placer formation have not yet taken full account of the late Quaternary changes in the magnitudes and frequencies of channel-forming and floodplain reworking events as determined by bioclimatic changes over timescales of 10^3–10^4 years. A general and highly speculative model can be proposed

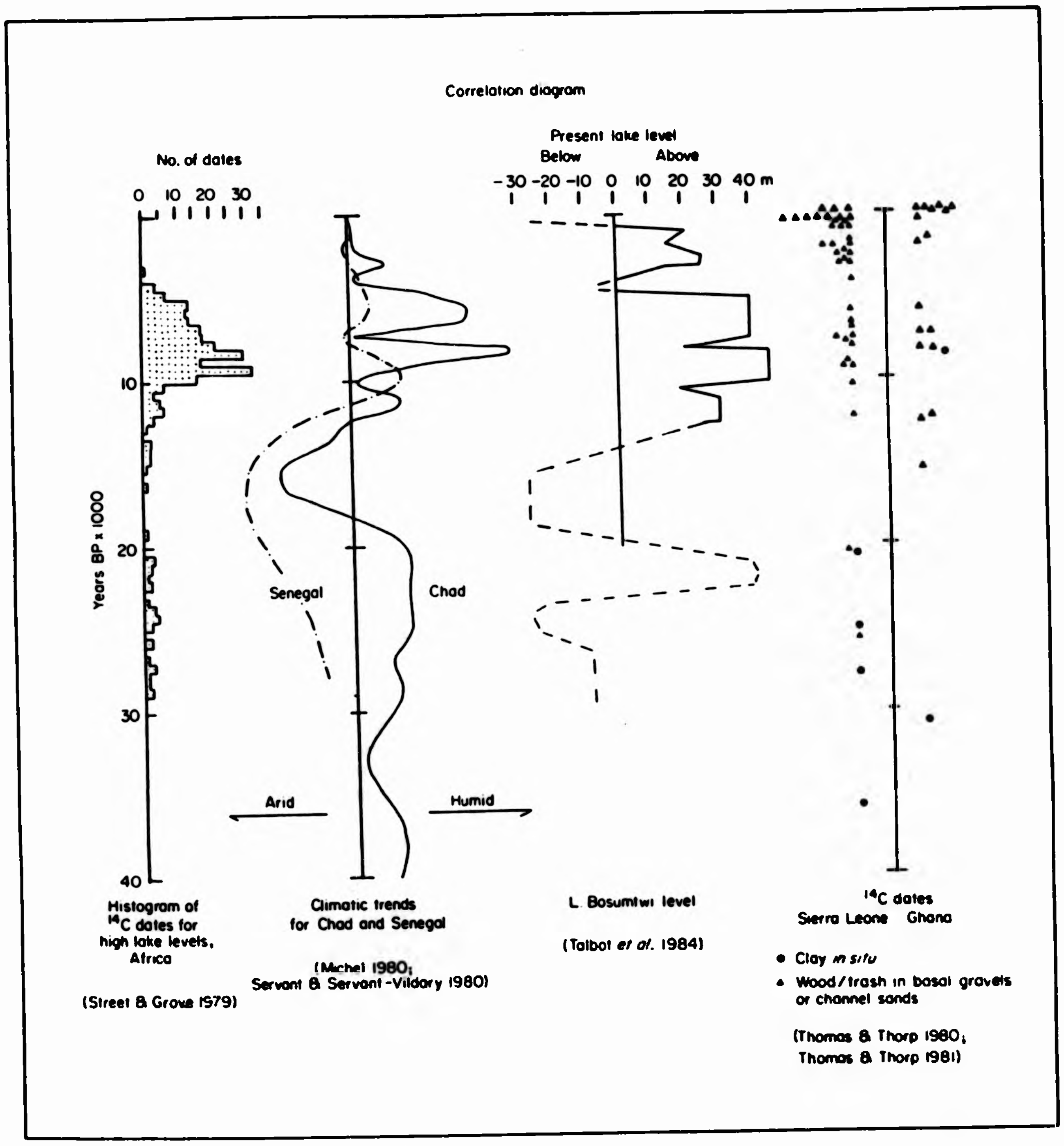

FIG. 4. Late Quaternary correlation diagram showing radiocarbon dates from Koidu, Sierra Leone and the Birim Valley, Ghana.

which links precipitation change with density of vegetation cover, and their effects on erosional energy and placer formation Fig. 5. It would seem important to examine other alluvial placers in the humid tropics for this kind of relationship.

The interfluvial domain

This includes the former alluvial domains of river terraces and non-alluvial, residual areas. The identification of river terraces in the tropics is not always

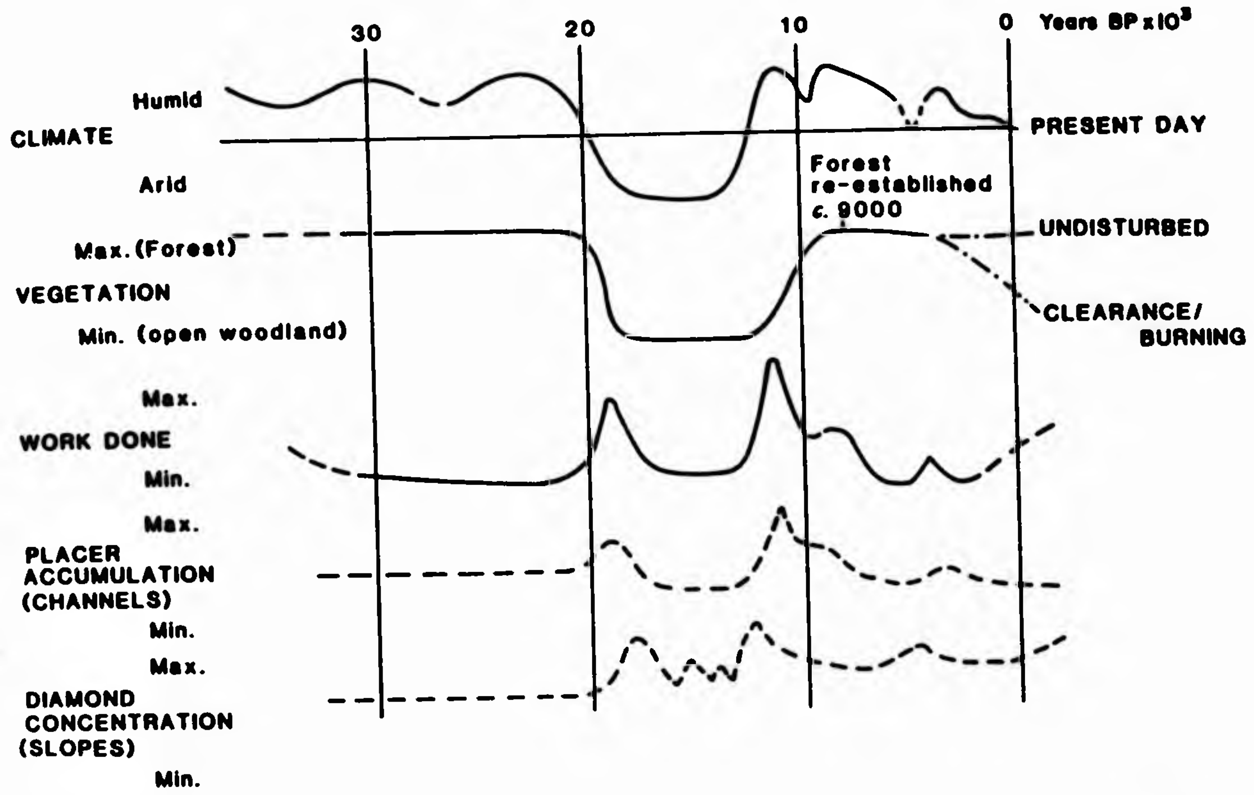

FIG. 5. Schematic diagram to show predicted response of river systems and hillslopes to late Quaternary environmental changes.

possible on the basis of morphology. Diagenetic changes, physical disturbance and burial beneath later colluvium make older features difficult to identify, and many terrace-like landforms are erosional rather than depositional in origin.

The interfluvial domain includes the following morphogenetic units.

A widespread *lower terrace* borders most streams and rests upon a bedrock bench less than 3 m above the present floodplain floors. Its gravels are relatively well preserved and indicate a system of wider floodplains and extended valley heads which have become buried by colluvial deposits. In the larger valleys, the terrace is a compound and dischronous deposit. Its more recent gravels have yielded ^{14}C dates of 35000–25000 years BP.

Reference to a *high terrace gravel* has always been part of the mining terminology for Koidu, but the recognition of undoubted alluvial deposits representing a true terrace alongside the present drainage has proved elusive; occurrences of older alluvial deposits are found between the lower terrace and the interfluvial areas as fringes and pockets within what would otherwise be described as non-alluvial domains.

Piedmonts and planar interfluves include 'glacis', a term used by French writers, for concave, ramp-like slopes extending from residual hillslopes as pediment-like forms with slopes of 2–6°. They form minor watersheds between headwater swamps, river confluences and among hilly residual relief. Elsewhere, interfluves are generally flat and planar along their crests and gradually steepen into the convex valley sides. Above the heads of the valleys, the interfluves are commonly dimpled by shallow depressions called swales.

Channelless stream heads start as imperceptible swales on the interfluves and then descend sharply towards the present swamp heads. They contain one to three superposed colluvial fills with more or less continuous quartz gravel layers overlain by structureless sandy clays and capped by an extension of the interfluvial gravels described below. Some of the fill material is partially duricrusted (Thomas & Thorp 1985; Fig. 6).

Residual hills and inselbergs rise abruptly from the glacis. Most have a regolith cover and are diversified by stream head ravines and frequent outcrops of corestones. Plugs of sediment that form gully-fill deposits are not uncommon.

Interfluves, stream heads and valley sides alike are underlain by a horizon of quartz and lateritic gravels. The quartz clasts are angular to well-rounded in shape but commonly sub-angular. Most are iron-stained but this varies, even in one section, from a dark brown

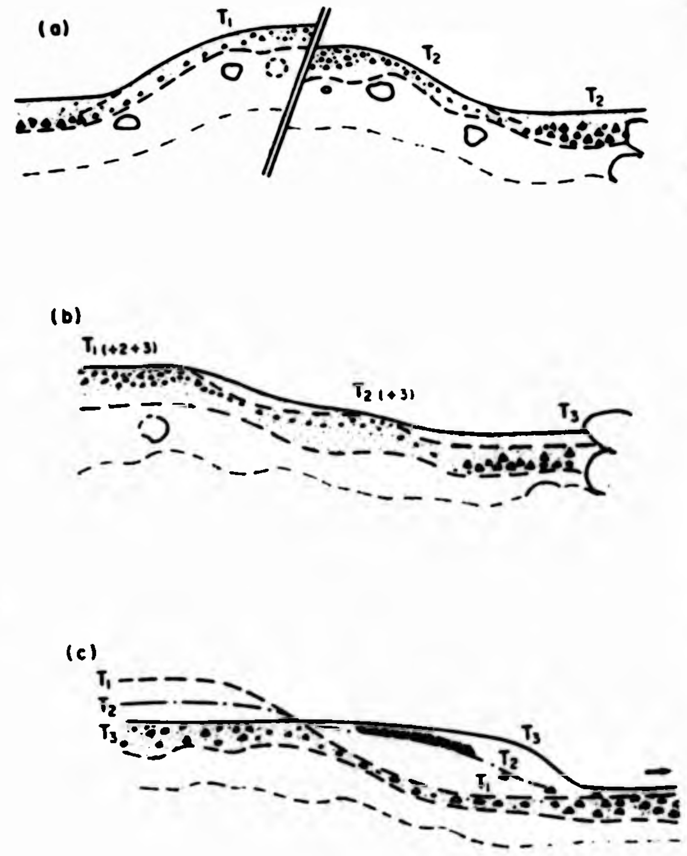

FIG. 6. Aspects of landform evolution in Koidu relevant to the distribution of palaeoplacer deposits. (a) Landscape lowering (downwasting) by surface erosion of fines and bedrock weathering, involving accumulation of lag gravels on interfluves and valley floors, and stone line formation across valleyside slopes (between time T_1 and T_2); (b) episodic lowering during three time units following a, but indicating incision of T_2 swamp floor to create a low terrace, and involving a period of channel flow; (c) valley head deposits associated with the three time units in (b) and resulting from episodes of colluviation. Lateritic clasts are shown in black; quartz clasts are unshaded; incipient duricrust is cross-hatched.

patina to interiors which are dark red, thoroughly penetrated by iron oxide and weakened to a crumbly texture. Thus, whereas some of the quartz pebbles have been recently derived from local unweathered veins, others have come from veins once higher up in a now truncated lateritic weathering profile, perhaps even from a duricrust, and yet others from lateritized alluvial deposits.

Similarly, the lateritic clasts comprise at least five types, distinguished by their shape, size, density, hardness and fabric. The main genetic distinction (Kaloga 1976; Muller *et al.* 1981) lies between the light, irregularly shaped, indurated mottles derived by recent erosion from local weathering profiles and the dense, hard, round, black cryptocrystalline pisoliths and pebbles of pisolithic duricrust, derived from an older, higher duricrusted weathering profile of which no intact trace now remains except on the summits of the neighbouring Nimini Hills. Other gravel components include weathered, lateritized bedrock pebbles and cobbles, and heavy minerals including ilmenite, worn corundum and, of course, diamonds. Gravel thickness varies from one-clast thick to 1 m but is usually 15–30 cm, and the degree of packing ranges from sparse and matrix-supported to dense and clast-supported. Virtually all the gravels have been modified in one way or another by farming, tree throws and bioturbation. Their original deeper soil covers have been eroded, and the gravel has penetrated into the subjacent weathered bedrock down root voids, by the upward translocation of fines by termites and ants and by gravitational sinking. Consequently, the lower boundary of the gravel horizon is uneven and diffuse. Some sections have shown shallow rills and others botryoidal iron precipitates on the gravel–bedrock interface, possibly indicating former surface water flows at this level.

These 'stoneline' gravels, therefore, can be regarded as a sheet with varying sedimentary properties that blankets virtually the entire landscape below the residual relief and merges into the sub-alluvial gravels of the valley floors. Indeed, the gravels of the valley floors, low alluvial terraces and stream-head sediments include clasts derived from the interfluvial domain stoneline gravels. In no sense, therefore, can these gravels be regarded as a fossil strata but they do integrate a long period of landsurface denudation and environmental change of which they may be the sole remnants.

From a placer perspective perhaps the most important characteristic is their high degree of spatial variability which occurs at two scales. In some locations, nearly all possible combinations of the properties described above can be seen within an exposure of 20 m×20 m. Despite this, over broader areas there are general similarities such that gravel types or facies can be identified, and their distribution mapped, related to bedrock lithology, and used to infer recent erosional history. Of particular importance is the occurrence of the 'older' clast types, the deeply stained, often worn quartz pebbles and the duricrust remnants, for their presence indicates the retention of clasts, some undoubtedly of alluvial origin, during considerable surface downwasting.

Fig. 7 depicts in a generalized form the distribution of some gravel properties over three contrasted types of interfluve. Although variations in bedrock lithology, depth of weathering, depth of profile truncation and late Pleistocene surface sediment transfer paths account for most of the differences in the proportions

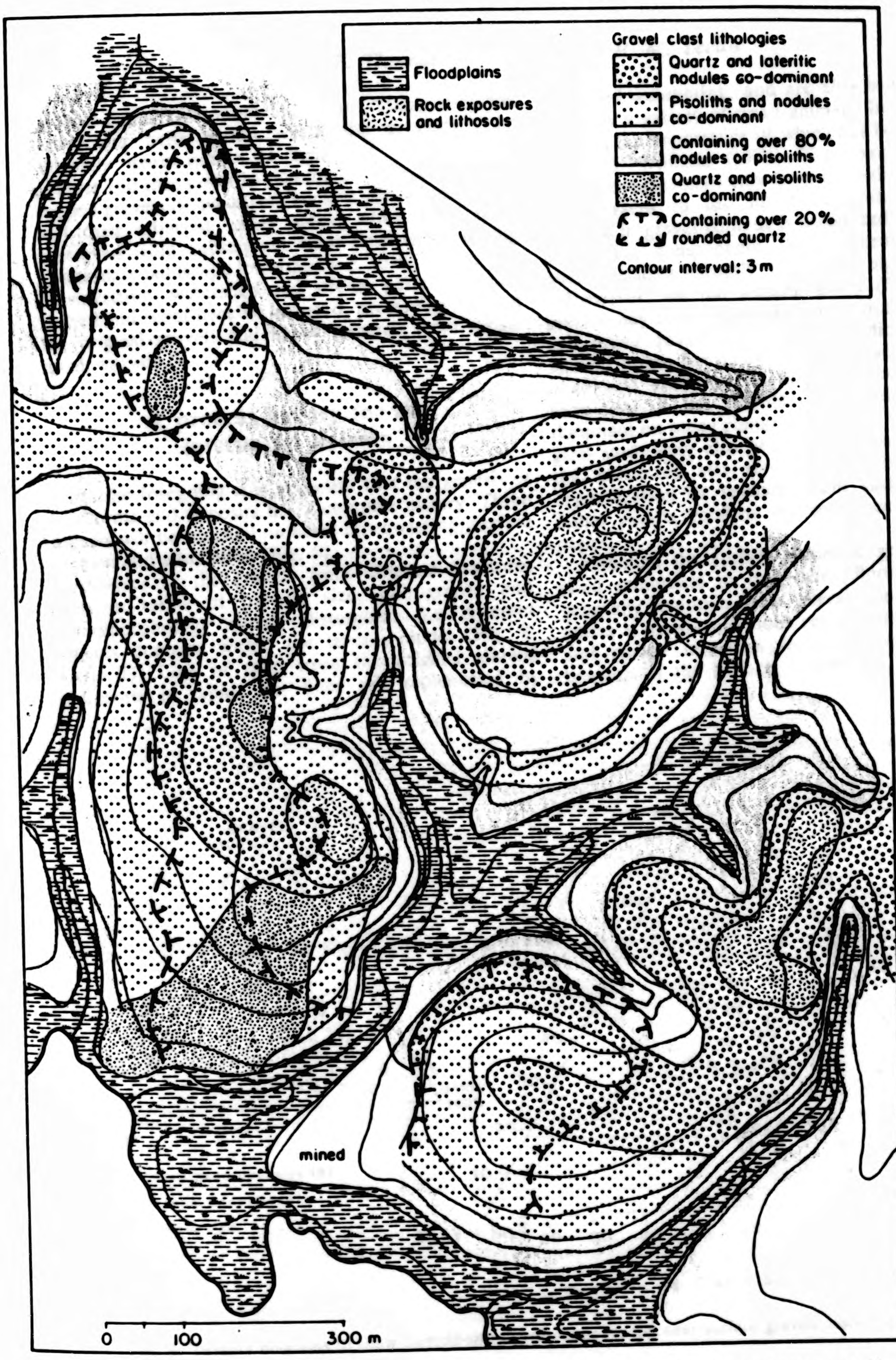

FIG. 7. Distribution of combinations of gravel clast types. The combinations are based on a ternary classification using data from 92 sampling pits.

of clast types, two anomalies occur. These comprise two linear belts within which the proportion of alluvially worn quartz is high and where quartz pebbles and iron pisoliths dominate. Collectively, they suggest gravels derived from ancient alluvial sediments and their adjacent valley sides, which have been preserved from subsequent total destruction during Quaternary landscape lowering by c. 30 m. During this downwasting, watershed and stream patterns locally shifted and relief became inverted, preserving some of the original gravels and heavy minerals from subsequent erosion.

A process history for the interfluvial domain

From the foregoing it is apparent that the genesis of landforms and deposits has a complex history. Three aspects will be touched on here: downwasting, surface erosion and alluviation (Fig. 6).

Analyses of the gravels from different landform units in terms of particle size, petrography and micromorphology clearly distinguish the different process domains within the terrain model (Fig. 8, Table 1). Loss of sand from the original alluvial sediments is rapid, but fines are replenished by continued weathering, and are also brought up from below by a variety of small animals, but especially by termites the importance of which has been stressed by M. A. J. Williams (1978). The composition of the gravels changes markedly from the valley swamps and low terraces to the interfluves, where the sharp increase in gravel content is accounted for by the rise in lateritic components. The percentage of rolled quartz declines abruptly, but is also highly variable.

However, on the sloping glacis (3–6°) bordering present-day floodplains, the concretionary iron is low and rolled quartz much higher, indicating a remote alluvial origin for many of these features and also a pedogenic environment that has not favoured the formation of the pisoliths and nodules which are dominant on many planar interfluves. Micromorphological study may also provide diagnostic evidence for the processes and sequence of iron segregation, crystallization or leaching from such deposits, and initial results confirm the inferences made in this paper.

Although the surface stoneline gravels have supplied sediments to the valley floor domains, they generally maintain their lateral continuity. This requires a quasi-continuous replenishment of both fine and coarse materials from the weathered profile beneath as the surface is lowered. This is achieved

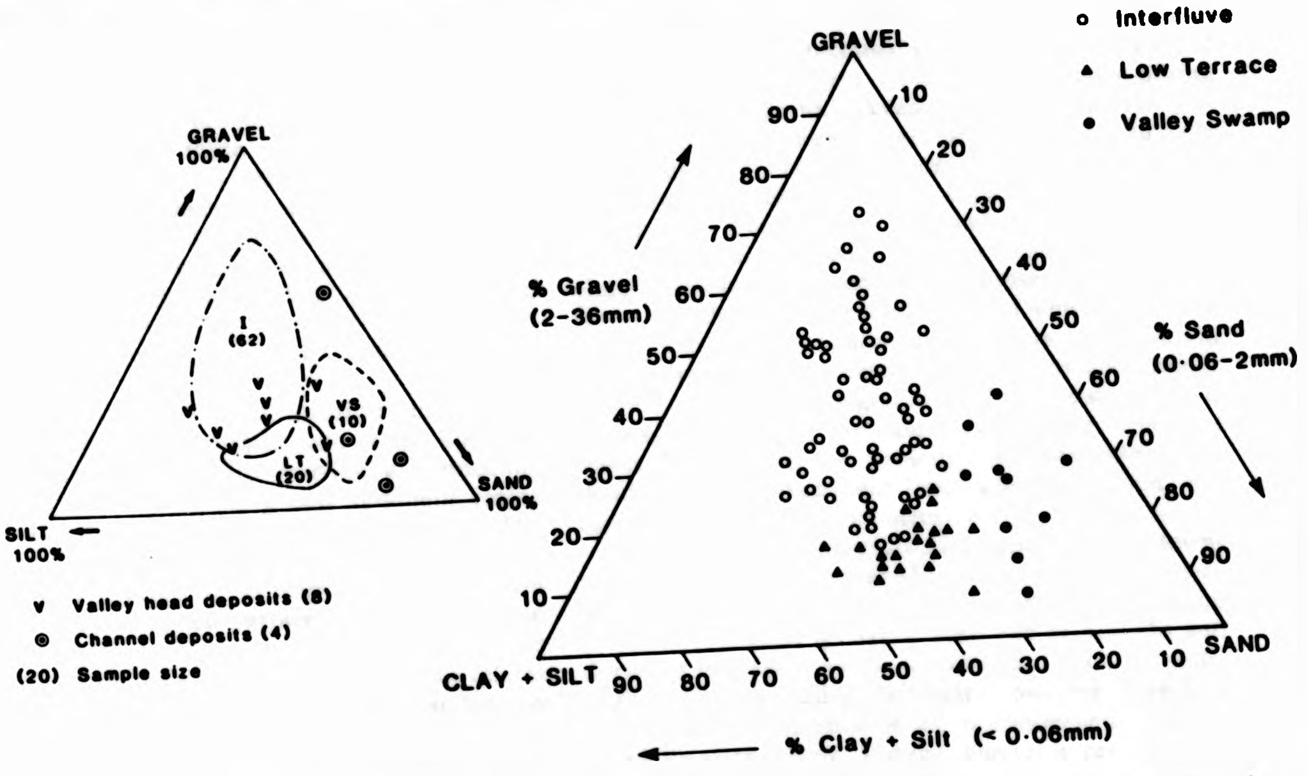

FIG. 8. Ternary diagrams to show particle-size distributions for the near-surface gravels associated with each major landform unit in the Koidu area.

TABLE 1. *Composition (particle size and petrography) of gravel layers from landform units in Koidu, Sierra Leone*

Landform unit		*Particle Size (wt%)*			*Gravel petrography (>8 mm %vol.)*				
					Quartz		*Bedrock pieces*	*Iron*[a]	
		Clay + silt	*Sand (>0.063)*	*Gravel (2–36 mm)*	*Rounded*	*Angular*		*Concretions*	*Segregations*
Swamps	$\bar{x}$	17.34	55.61	27.04	18.6	25.3	26.1	4.1	26.0
($n = 8$)	σ	6.32	8.01	10.46	$n = 8$				
	cv%	36.40	14.40	38.70					
Low terrace	$\bar{x}$	36.02	45.27	18.75	14.6	29.6	10.8	5.4	39.6
($n = 18$)	σ	6.88	8.61	8.76	$n = 28$				
		19.10	19.00	46.70					
Interfluves	$\bar{x}$	30.23	29.52	40.24	2.9	18.8	5.8	49.2	24.0
0–3°	σ	9.94	8.62	15.24	$n = 36$				
($n = 28$)	cv%	32.88	29.20	37.87					
Piedmonts	$\bar{x}$	35.19	33.47	31.34	12.7	18.2	24.4	18.2	26.3
3–6°	σ	9.15	10.71	13.71	$n = 12$				
($n = 16$)	cv%	26.00	32.00	43.74					

[a] Iron concretions include cryptocrystalline pisoliths and nodules; iron segregations include iron cemented sediments and 'pedo-relics', mostly indurated soil mottles.

mainly by the combined effects of soil fauna bringing fines to the surface from where they are gradually lost to the valley floors by surface erosion and creep; the heavier clasts and unweathered minerals gradually accumulate in the lower parts of the soil layer (M. A. J. Williams 1978). Once these gravels begin to accumulate they become a horizon of preferential soil water throughflow which accelerates the loss of fines. Elsewhere in W Africa these processes can produce such stonelines in less than 10 000 years (Roose 1980). *In situ* downwasting, especially of the flat interfluvial areas, is unequivocally demonstrated by clusters of vein quartz cobbles from vein thickenings and by the differential settling of the gravel sheet on either side of quartz veins and pegmatites. Such downwasting has characterized the humid, forested conditions of the Holocene.

The role of sheet and rill erosion and gravel compaction on the interfluves is seen in the colluvial stream head sediments which provide a connecting link between the downwasting and sediment losing interfluves and the sediment storing valley floors. The main colluvial fill probably formed sometime between 25,000 and 15,000 years BP in response to vegetation degradation and enhanced surface runoff during the 'Ogolian' dry period. Truncation of this fill and the emplacement of the thin, uppermost colluvium relates to the accumulation of the valley floor sediments which commenced during the early Holocene. On the interfluves during the arid phases, soils were eroded and the stoneline gravels became compacted, whereas in the swales they were partially stripped and shallow rills were eroded and functioned as feeders of surface flow into the stream heads. Erosion of the Holocene soils following cultivation, which exposed and further compacted the gravel horizons in this area, is a more recent phenomenon. Similar alternations of soil and gravel erosion and reconstitution by pedogenesis and downwasting must have occurred repeatedly during the Quaternary period (Avenard 1973; Peltre 1977).

Reference has already been made to the alluvially worn quartz pebbles commonly present within the interfluvial gravels on slopes adjacent to the larger present-day rivers. They are undoubtedly the remnants of former alluvial terraces which have been almost totally destroyed as morphosedimentary features, together with the landscapes of which they were a part. Occurrences of alluvial indicators at all levels in the landscape hint at even older deposits and greater degrees of landscape degradation. In some situations it is possible to infer the courses of former rivers at levels well above the present, and the shifting of divides during subsequent landscape denudation, but the evidence is often inconclusive.

Morphogenesis, therefore, has involved (a) downwasting of deeply weathered and lateritized interfluves and of valley floors alike to explain the accumulation of residual angular quartz in both and of pisoliths and duricrust fragments on the interfluves, (b) lateral shifts in river positions during landscape lowering to explain the sporadic occurrence on all morphogenetic units of alluvially worn quartz, and (c) changes in precipitation and vegetation conditions to explain the extensions and contractions of drainage networks in the stream-

TABLE 2: *Relationships between terrain units and presence of diamonds in prospecting pits for a test area*

	Percentage of pits			
Terrain unit	*All pits*	*With diamonds*	*Without diamonds*	*Terrain unit pits with diamonds*
Glacis	2	1	2	11
Interfluve crests	21	21	21	25
Swales	11	22	7	50
Stream heads	6	13	4	50
Valley edges	35	20	40	13
Valley sides	25	23	26	22
	100	100	100	

heads, the pediment forms truncating weathered profiles, and the episodes of soil stripping, gravel compaction and reformation (Fig. 3).

Diamond occurrence in the interfluvial gravels

The terrain model can be applied on two ways to understand and predict diamond occurrence in the interfluvial gravels: one using *morphology* to indicate landforms conducive to heavy mineral loss, retention, or concentration, and the other using *morphogenesis* to identify areas where gravel types and morphology together suggest longer term retention of both alluvial and residual clasts in the vicinity of primary sources.

To test the morphological parameters, 476 old prospecting pits in an area 2700 m × 1000 m were classified by their slope form, plan, inclination and terrain unit and their gravel properties and diamond grades analysed. Table 2 presents some of the results obtained for the terrain units.

The significance of the swales and the stream heads in storing or concentrating diamonds is apparent from the figures given in Table 2. The diamonds in these units can have come from two sources: subjacent kimberlites during the recent surface erosion which gave expression to these two landform units; and/or the adjacent interfluvial gravels by concentration during the episodes of accelerated surface erosion, the diamonds themselves being relict from the almost completely degraded ancient placers. For the purposes of prospecting it is important to know which of these two sources is yielding the diamonds. Table 3 separates the pits into sites underlain by or close to kimberlite and pits away from such sources. The figures suggest that the diamonds in the stream heads and on the glacis and valley sides are derived primarily by recent erosion into kimberlites, whereas diamonds on the planar interfluves and in their swales, which bear little spatial relationship to kimberlites, are primarily relics from degraded ancient placers. These inferences were broadly confirmed during the bulk sampling of several interflves.

The search for interfluvial areas with degraded ancient placers required a morphogenetic application of the terrain model which involved both morphology and an interpretation of process history. From the distribution of gravel parameters and facies in their local morphological context, it became possible to outline areas which, during overall landscape reduction by 5–30 m, may have lost, retained or gained gravel clasts and which may have been within or beyond alluvial influence. Bulk sampling tends to confirm that those facies characterized by a relatively greater abundance of one or both of the 'older' lateritic and alluvially worn clast types have higher diamond grades.

Sampling and mining within areas of such gravel facies, however, shows that diamonds are neither randomly nor evenly distributed. Local resorting of these gravels has undoubtedly proceeded subsequent to the formation of the original placer during later landform evolution, and the diamonds may be associated with the shallow rills at the base of the gravels

TABLE 3: *Influence of local kimberlite sources on diamond occurrence within prospecting pits from different terrain units*

	Percentage of pits with diamonds	
Terrain unit	*Over kimberlite*	*Away from kimberlite*
Glacis	6	0
Interfluves	27	20
Swales	47	56
Stream heads	83	21
Valley edges	5	5
Valley sides	58	14

and with the clusters of duricrust pebbles, pisoliths and very heavily stained quartz, some alluvially worn, which characterize these gravel types. Additionally, the sporadic diamond occurrences may be relics of an uneven distribution in the original placer. Such local enrichments are well known to placer geologists and were described as 'pay streaks' in a study of the Koidu floodplain gravels by Applin (1972).

Conclusions

The major diamond placers in Koidu were formed within the frequently re-worked basal channel gravels of alluvial floodplains, the diamonds being derived from local kimberlite sources, from the erosion of fringing low terraces, and from adjacent interfluves by gradual downslope transfer of clasts within stonelines (Fig. 6). Smaller placers were also formed in the headwater swamps by the gradual downwasting of the landscape, concentrating larger and heavier clasts with little downvalley movement. Such placers would be termed 'autochthonous' by Kartashov (1971), although in Sierra Leone some long-distance transport of diamonds has also occurred. Remnants of ancient placers survive on glacis and planar interfluves and are preserved in valley-head fills and other buried channels. The process of landscape lowering by continuous weathering and removal of fines (etchplanation) has led to further addition of 'late release' diamonds from local sources. These would remain close to their sites of liberation from the kimberlite but for the lateral transfer of surface materials across slopes. This process is episodic and has been dependent on the degradation of vegetation cover, mainly as a result of repeated dry phases during the Quaternary era (the most recent being the late Pleistocene Ogolian period), and with a possibly underestimated role being played by human disturbance of the former forest cover during at least 3 Ma.

Concentration of diamonds by these means depends on local landscape sensitivity to ecological change (Brunsden & Thornes 1979). Movement of clasts therefore is erratic in space and time and difficult to assess from surface morphology alone. However, with the development of an adequate terrain model and the application of detailed mapping techniques, prospecting can be guided into 'priority' areas of higher potential which may be sufficiently extensive to justify bulk sampling for low-grade lateritic gravel. Landform position with respect to source rocks, hillslopes and stream lines must be combined with the identification of landform units on scales up to 1:1250. Such units as planar interfluves, depressions or swales, valley edges and valley heads must then be individually tested for diamond occurrence. In some cases lateral slope transfer may have led to evacuation of heavy clasts from swales into adjacent valley heads, but elsewhere these swales may have retained gravel washed in from surrounding slopes which rise only imperceptibly to local topographic highs.

Finally, it is suggested that appropriate geomorphic models for long-term landform evolution, Quaternary environmental changes and their effects, and contemporary process domains should all contribute to the elaboration of placer distribution in areas of diverse relief. The use of such models must be subject to review and re-definition as prospecting proceeds and information is added, and this iterative use of a geomorphological understanding of landscape history and dynamics should become a standard part of the procedures used by mining geologists.

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APPENDIX B: Details of Laboratory Methods

B1 PARTICLE SIZE

Two methods were used to determine particle size distributions: nested sieivng and pipette analysis.

Sieving followed the procedure of the British Standards Test 7(A) of BS1377 (1975, p.30-31), apart from the sample pre-treatment procedure and the sieve-sizes that were used. Samples were treated in batches of 30. They were air-dried and then quartered, using a riffle box with 8mm slots. This left between 60g (if the sample was clayey) and 150g (if gravelly) for particle size analysis.

Each sample was ground with a rubber pestle for one minute, weighed to 0.01g, and then transferred to a 125cc numbered bottle. A sodium hexametaphosphate dispersant was added to the sample bottle, which was topped-up with distilled water, sealed and shaken for 10 hours. The sample was then poured over a 63 um sieve and the fines were collected in a 500cc measuring cylinder, topped-up with distilled water, for future pipette analysis. The +63 um fraction was oven-dried, then placed at the top of a nest of 9 sieves (from -4ϕ[16mm] down to 4ϕ[63 μm] at one-phi intervals), and sieved for 10 minutes using an 'Endecot' automatic shaker. Each size fraction was then weighed and noted, with percentages and descriptive statistics being calculated by a computer program.

Pipette analysis is based on Stoke's Law (1845), which states that spheres in a fluid fall at rates proportional to their size. Stoke's Law is discussed in detail by Muller (1967, p.77), who derived the following equations from Stoke's original formula:

$$= 17.48 \sqrt{\frac{z.h}{(D_1 - D_2)t}} \qquad (1)$$

$$(D1 - D2)t = \frac{z\,h}{\left(\frac{d}{17.48}\right)^2} \qquad (2)$$

where d = sphere diameter (in µm)

z = viscosity of the fluid (g/cm/s)

h = the falling height (cm)

D_1 = density of the falling sphere (g/cm^3)

D_2 = density of the fluid (g/cm^3)

t = the falling time (minutes)

Equation (1) allows the diameter of particles (assumed to be spheres), falling a known height in a known time, to be calculated. Equation (2) was used to calculate the time required for a particle of 2 um diameter to fall 10cm.

The average density of the -63 um fraction from six samples was found to be 2.60 g/cm^3. Sedimenation was in distilled water at 20°C, giving a density (D_2) of 0.9982 g/cm^3 and a viscosity (z) of 1.005.

Thus equation (2) becomes,

$$(2.60 - 0.9982)t = \frac{\underline{1.005 \times 10}}{\left(\frac{2\ \mu m}{17.48}\right)^2} \qquad (3)$$

$$1.60t = \frac{10.05}{0.013} = 767.18$$

$$t = \frac{767.18}{1.60} = 479.5 \text{ minutes(taken as } \underline{\text{8 hours)}}$$

The materials and procedure used for the pipette analyses were similar to those used in British Standards Test 7(c) of BS1377 (1975, p.33-58), apart from the sodium hexametaphosphate pre-treatment (given below).

Samples were placed in a constant-temperature room, at 20°C, for two hours, after which each sample was shaken and left to stand at one minute intervals. Exactly eight hours later the pipette was lowered to a depth of 100 + 1mm below the surface of the sample and the fluid was sucked up until the bulk of the pipette was full, then transferred to a numbered beaker, oven-dried, and weighed to 0.01g.

The weight of sediment in each beaker was obtained from the following calculations:

B = the weight of the beaker

Bs = the weight of the beaker, plus sediment

S = the weight of the sediment

S = Bs - B

Because the sediment weight includes the weight of the Sodium hexametaphosphate dispersant, a further calculation is needed to get the true weight of the sediment:

concentration of dispersant = 0.057g/ml

25 ml dispersant used/sample = 1.425g/sample

Sample diluted in 500 cc H_2O = 0.0028g/ml

Volume of sampling pipette = 24.17ml

weight of dispersant drawn-up by the sampling pipette (c)

=24.17 x 0.0028g

= 0.069g/sample

True weight of sediment (M3) = S-0.069g.

The percentages of clay (2µm) and silt (2-63 µm) are obtained from the following calculations:

Let M = the original weight of the sample

M1 = the weight of the +63 µm fraction

M2 = the weight of the -63 µm fraction.

From above, the true weight of the sediement (i.e., clay), M3 = S-0.069.

As each pipetting samples $\frac{24.17cc}{500cc}$ or $\frac{1}{0.048cc}$ of M2.

the total weight of the clay fraction, M3. is, $\frac{(S-0.069)}{0.048}$g

The weight of the silt fraction (M4) = M2-M3

Percent clay is, 100. $\frac{M}{M3}$

Percent silt is, 100. $\frac{M}{M4}$

Sample Pre-Treatment

1. The concentration of sodium hexametaphosphate + sodium carbonate recommended by BS1377 (1975, p.36) was not effective when red-brown (oxisol) clays were treated, so the more concentrated dispersant of the Soil Survey of England and Wales (Avery & Bascomb, 1974, p.19) was adopted.

2. Preliminary pre-treatment using Hydrogen Peroxide to remove organic matter showed that Fe/Mn mottles and concretions were partially destroyed, producing a 10% decrease in the weight of the gravel fraction and a corresponding increase in the weight of the fines fraction. This distortion of the true particle size distribution was due to the oxidation of manganese oxides by the H_2O_2 and resulting granular disintegration (Kunze, 1965 p.574). Fortunately, fewer than 10% of the samples were from organic-rich soils, so the hydrogen peroxide method of pre-treatment was not utilized.

B2 - X-RAY DIFFRACTION

Preparation and analyses were carried out at the Department of Soil Science, Aberdeen University. 10g of each sample was emptied into a 250cc beaker and mixed with 200cc of distilled water. One drop of ammonia was added and the solution was stirred.

Following the principle of sedimentation outlined above, each beaker was left for 4 hours and then a pipette sample was taken from the top 1cm of the beaker, ensuring that all the particles sampled were of clay size (2µm).

The pipetted sample was then released on to a numbered glass slide and left overnight to dry, before being examined under the XRD analyser. The computer analyses and print-outs were then interpreted by Dr. E.A. Fitzpatrick (Pers.comm.; 1984) of Aberdeen University Soil Science Department.

	Sandy Clay (Interfluve) P2E 1.05m	Sandy Gravel (Low Terrace) P4A 1.65m	Gravelly Sand (Swamp) N4A 0.75m
CLAY			
mean	26.25%	6.44%	6.42%
SD	1.07	0.38	0.66
SE	0.54	0.19	0.33
95% conf.	±1.71%	±0.60%	±1.05%
FINES			
Mean	47.74%	36.34%	14.66%
SD	1.82	2.38	1.44
SE	0.91	1.19	0.72
96% conf.	±2.89%	±3.79%	±2.30%
SAND			
mean	43.08%	49.54%	69.56%
SD	3.63	3.64	3.76
SE	1.81	1.82	1.88
95% conf.	±5.76%	±5.79%	±5.98%
GRAVEL			
mean	9.18%	14.52%	15.5%
SD	2.91	2.65	3.59
SE	1.45	1.32	1.80
95% conf.	±4.60%	±4.21%	±5.72%

SUMMARY

95% confidence intervals were:

Clay	±0.6 - 1.71%	Fines	±2.3 - 3.79%
Sand	±5.76- 5.98%	Gravel	±4.21- 5.72%

Table B1 **RELIABILITY OF PARTICLE SIZE DATA**

APPENDIX C: Samples used in Figures 5.4 and 5.5 (depths in metres)

Type I Low Terrace topsoil (A1b)

N4C 0.15; N4D 0.15; N4E 0.15; N4F 0.15.

Interfluve topsoil (A1a)

N4H 0.15; N4K 0.15; N4G 0.15 and 1.05 (buried palaeosol).

P1B 0.15; P1C 0.15; P1D 0.15; P5F 0.10; P5F 0.40; P5K 0.15.

Lateritic gravel (B2)

N4F 0.45 & 0.75; N4G 0.75; N4H 0.15, 0.75 & 1.35; N4K 0.45 & 0.75.

P1D 0.45, 0.75, 2.00 & 2.30; P;F 0.45 & 0.75; P5F 0.45.

Interfluve saprolite (C1)

N4F 1.65; N4G 1.95; N4M 1.05; N4J 1.25 & 1.55; N4K 1.05.

P1B 2.00; P1C 3.15 & 4.00; P1D 2.85; P1F 2.15; P5F 1.70.

Colluvial Fill I (A3)

N4E 1.35 & 1.65; N4F 1.05 & 1.35; N4G 1.35 & 1.65; N4H 1.65 & 1.95.

P1B 0.75, 1.05 & 1.65; P1C 0.85, 1.15, 2.05, 2.35, 2.65, 3.15 & 1.45;

P1D 0.15, 0.75, 1.05 & 1.35; P5F 0.70, 1.00, 1.30, 1.60 & 2.10.

Colluvial Fill II (A4)

N4C 0.15, 0.45, 0.75, 1.05 & 1.35.

N4D 0.15, 0.45 & 0.75; N4E 0.15, 0.45 & 0.75.

Low Terrace Saprolite (C3)

N4B 2.20; N4C 2.30; N4D 2.25; N4E 3.45.

Low Terrace Alluvial Fill (A2i)

N4B 1.85; N4C 1.65 & 1.95; N4D 1.05, 1.35, 1.65 & 1.95.

N4E 1.05, 1.35, 1.95, 2.25 & 2.55.

Swamp Topsoil (A1c)

N4A 0.15; N4B 1.00 & 1.45 (buried).

Valley Swamp Alluvial Fill (A2)

N4A 0.45 & 0.75; P1A 0.15, 0.45 & 0.75.

Alluvial Gravel (B1)

N4A 1.05; N4B 1.85

P1A 0.75 & 1.05; P1B 0.45; P1C 2.95 & 3.55; P1D 2.00 & 2.30.

APPENDIX C (contd.)

Particle size data

These data are given overpage: their format requires a brief explanation. '% Clay', '% Silt', etc, refer to the percentages of clay(-0.002mm), silt(0.002-0.062mm), fines(-0.062mm), sand(0.063-2.00mm) and gravel(+2.00mm) in each sample. Asterisks, * *, are used where no data are available. 'Slt:Clay' is the silt:clay ratio value.

'PIT/cm.' is the computer code used to identify each sample. The first three digits signify the sample-pit code as used in the text of this thesis (P1A, N1A, etc); the final three digits are the depth of the sample in centimetres (eg, ...015=15cm; ...105=105cm).

The Yengema area sample-pit codes are as follows: 11.0 to 11.9 = pits N4A to N4K; 12.0 to 12.5 = N3A to N3F, and 12.7 to 12.9 = N3J to N3L; 13.0 to 13.9 = N2A to N2J; 14.0 to 14.9 = N1X to N1J, and 14.9910 = N1K(depth, 10cm); 15.0 to 15.6 = N5A to N5G.

The Kania area sample-pit codes are: 21.0 to 21.9 = pits P5K to P5A; 22.0 to 22.6 = P4A to P4H; 23.1 to 23.6 = P3A to P3G, although 23.0 denotes pit P3C; 24.0 to 24.5 = P2A to P2F; 25.0 to 25.6 = P1A to P1G; and 26.6 = P1X, an additional swale zone pit.

	PIT/cm.	% Clay	% Silt	% Fines	% Sand	% Gravel	Slt:Clay
1	11.0015	28.12	26.94	55.06	44.74	0.20	0.96
2	11.0045	1.66	3.02	4.68	71.63	23.69	1.82
3	11.0075	5.93	10.25	16.22	59.01	24.78	1.73
4	11.0105	3.47	5.76	9.23	49.29	41.48	1.66
5	11.1120	32.59	22.99	55.58	44.32	0.10	0.71
6	11.1150	30.57	16.98	51.59	45.77	2.64	0.56
7	11.1180	14.05	12.08	26.16	37.21	36.63	0.86
8	11.1210	*	*	37.19	48.15	14.65	*
9	11.1240	*	*	56.67	38.82	4.52	*
10	11.2005	11.65	11.15	22.82	55.57	21.61	0.96
11	11.2025	14.80	14.20	29.00	71.00	0.00	0.96
12	11.2065	21.98	13.66	35.64	63.79	0.57	0.62
13	11.2085	21.12	11.51	32.53	67.23	0.24	0.55
14	11.2105	19.61	5.86	25.46	63.94	10.60	0.30
15	11.2135	19.06	17.73	36.79	50.18	13.03	0.93
16	11.2165	16.95	19.96	36.91	43.50	19.59	1.18
17	11.2195	16.83	13.42	30.25	31.53	38.22	0.80
18	11.2230	19.76	22.79	42.55	48.66	8.78	1.15
19	11.3015	17.20	11.80	29.00	70.70	0.29	0.69
20	11.3045	20.53	13.01	33.54	66.26	0.20	0.63
21	11.3075	21.51	13.93	35.45	64.25	0.30	0.65
22	11.3105	18.62	10.96	29.57	51.59	18.83	0.59
23	11.3135	22.21	6.40	28.62	46.61	24.77	0.29
24	11.3165	22.61	11.99	34.60	44.74	20.66	0.53
25	11.3195	21.84	20.06	41.90	46.19	11.91	0.92
26	11.3225	19.86	21.46	41.32	41.71	16.98	1.08
27	11.3260	19.80	27.33	47.13	47.86	5.01	1.38
28	11.4015	*	*	43.71	55.41	0.88	*
29	11.4045	*	*	44.36	54.68	0.96	*
30	11.4075	*	*	39.89	54.15	5.96	*
31	11.4105	*	*	26.41	49.60	23.99	*
32	11.4135	*	*	23.28	50.19	26.54	*
33	11.4165	32.30	16.02	48.06	38.11	13.82	0.50
34	11.4195	*	*	30.96	49.83	19.22	*
35	11.4225	*	*	39.57	47.03	13.41	*
36	11.4285	33.45	11.18	44.63	42.17	13.20	0.33
37	11.4315	*	*	49.22	40.66	10.12	*
38	11.4345	*	*	45.86	43.63	10.51	*
39	11.5016	*	*	54.48	26.30	19.22	*
40	11.5048	*	*	34.33	29.31	36.36	*
41	11.5080	*	*	38.72	29.40	31.88	*
42	11.5105	*	*	49.08	36.00	14.92	*
43	11.5135	*	*	56.48	32.76	10.77	*

44	11.5165	28.80	35.57	64.37	24.48	11.15	1.24
45	11.6045	27.09	12.14	39.22	35.20	25.57	0.45
46	11.6075	*	*	32.89	33.73	33.38	*
47	11.6105	23.04	27.00	50.03	23.92	26.05	1.17
48	11.6135	31.00	13.30	44.27	32.50	23.22	0.43
49	11.6165	38.31	22.35	60.67	32.78	6.55	0.58
50	11.6195	39.47	20.16	59.63	32.09	8.28	0.51
51	11.6225	36.94	17.33	54.28	33.97	11.75	0.47
52	11.7015	*	*	18.79	13.76	67.45	*
53	11.7045	16.13	10.66	26.79	25.98	47.23	0.66
54	11.7075	18.31	21.32	39.64	19.30	41.06	1.16
55	11.7105	26.72	13.72	40.42	36.17	23.42	0.51
56	11.7135	15.00	7.43	22.43	31.90	45.67	0.50
57	11.7165	43.56	24.77	68.33	24.53	7.14	0.57
58	11.7195	31.83	25.00	56.83	35.05	8.12	0.79
59	11.7225	37.15	27.04	64.12	32.68	3.21	0.73
60	11.8020	20.19	11.48	31.67	19.91	48.42	0.57
61	11.8050	26.80	10.18	37.00	23.50	39.51	0.38
62	11.8080	22.24	9.97	32.21	18.03	49.76	0.45
63	11.8110	26.52	7.46	33.98	20.08	45.94	0.28
64	11.8140	29.93	13.26	43.19	26.12	30.69	0.44
65	11.9015	24.21	12.61	36.82	30.66	32.52	0.52
66	11.9045	21.76	8.01	29.77	24.16	46.07	0.37
67	11.9075	24.42	13.34	37.76	25.90	36.34	0.55
68	11.9110	23.57	19.98	43.55	30.48	25.97	0.85
69	12.0020	*	*	19.61	72.32	8.07	*
70	12.0050	*	*	6.62	76.91	16.46	*
71	12.0125	*	*	15.98	30.61	53.41	*
72	12.0150	*	*	23.66	49.02	27.32	*
73	12.2020	27.25	20.53	47.78	50.49	1.73	0.75
74	12.2050	6.69	1.02	7.71	78.13	14.15	0.15
75	12.2080	10.38	8.57	18.95	52.19	28.86	0.83
76	12.2110	10.82	11.71	22.53	50.04	27.44	1.08
77	12.3015	37.88	18.19	56.07	41.12	2.81	0.48
78	12.3045	26.91	30.27	57.18	38.21	4.61	1.13
79	12.3075	19.77	15.97	35.74	41.50	22.76	0.81
80	12.4015	32.16	24.60	56.76	42.14	1.09	0.76
81	12.4045	38.10	23.23	61.33	38.16	0.51	0.61
82	12.4075	44.69	19.37	64.06	35.63	0.31	0.43
83	12.4105	47.43	14.97	62.41	37.28	0.32	0.32
84	12.4135	43.73	19.54	63.28	35.86	0.86	0.45
85	12.4165	51.72	14.75	66.47	32.66	0.87	0.29
86	12.4195	37.70	23.07	60.77	33.49	5.74	0.61
87	12.4220	32.81	17.50	50.30	37.15	12.55	0.53
88	12.5045	34.51	18.80	53.31	45.51	1.18	0.54
89	12.5075	34.31	26.03	60.34	34.64	5.03	0.76

90	12.5105	41.72	6.48	48.20	47.63	4.17	0.16
91	12.5135	44.25	19.44	63.70	33.23	3.07	0.44
92	12.5195	46.85	19.13	65.98	33.52	0.50	0.41
93	12.5255	28.99	14.62	43.61	55.73	0.66	0.50
94	12.5285	26.15	14.06	40.21	59.48	0.31	0.54
95	12.5300	22.94	8.29	31.23	59.89	8.88	0.36
96	12.5425	33.76	18.26	52.01	47.21	0.78	0.54
97	12.8030	18.35	12.49	30.85	36.90	32.25	0.68
98	12.9015	24.71	15.17	39.89	55.35	4.77	0.61
99	12.9045	22.00	13.41	35.41	42.30	22.29	0.61
100	12.9075	19.34	23.84	43.19	37.18	19.63	1.23
101	12.9105	24.38	14.85	39.23	45.74	15.02	0.61
102	13.0015	*	*	41.61	51.88	6.50	*
103	13.0045	*	*	35.82	51.11	13.07	*
104	13.0075	*	*	18.21	54.21	27.59	*
105	13.0105	*	*	62.99	33.38	3.63	*
106	13.2020	19.96	15.80	35.76	49.43	14.81	0.79
107	13.2075	13.38	9.02	22.40	74.77	2.83	0.67
108	13.2105	10.29	13.75	24.04	63.11	12.85	1.34
109	13.2135	8.03	8.02	16.05	62.46	21.49	1.00
110	13.3015	36.57	5.85	42.42	53.52	4.05	0.16
111	13.3045	37.49	16.20	53.69	35.61	10.70	0.43
112	13.3075	34.62	11.15	45.77	41.17	13.06	0.32
113	13.3105	31.91	16.49	48.40	38.87	12.74	0.52
114	13.3130	30.42	18.92	49.19	33.60	17.21	0.62
115	13.4015	21.84	13.49	35.33	28.77	35.90	0.62
116	13.4045	22.87	15.25	38.12	38.80	23.07	0.67
117	13.4075	22.86	14.91	37.77	49.75	12.49	0.65
118	13.5010	22.46	15.95	38.41	38.33	23.26	0.71
119	13.5035	20.42	11.40	31.83	24.02	44.15	0.56
120	13.5055	29.74	2.15	31.89	38.15	29.96	0.07
121	13.5075	31.52	15.32	46.84	35.23	17.93	0.49
122	13.5105	30.81	13.98	44.79	42.82	12.39	0.45
123	13.6015	22.82	50.31	73.13	14.36	12.51	2.20
124	13.6045	23.18	7.78	30.96	25.31	43.74	0.34
125	13.6075	27.64	13.69	38.99	30.79	30.22	0.50
126	13.6105	22.19	16.96	39.21	24.42	36.44	0.76
127	13.6135	22.39	46.16	68.55	16.26	15.19	2.06
128	13.7015	26.33	21.81	48.14	27.38	24.49	0.83
129	13.7045	24.20	14.75	38.96	24.84	36.20	0.61
130	13.7075	27.98	15.73	43.71	39.47	16.83	0.56
131	13.8015	22.91	11.39	34.30	15.79	49.91	0.50
132	13.8045	23.14	8.14	31.28	18.03	50.70	0.35
133	13.8075	28.33	12.08	40.40	18.17	41.42	0.43
134	13.8105	29.51	14.82	44.33	22.05	33.62	0.50
135	13.9015	22.85	7.89	30.75	18.25	51.00	0.35

136	13.9045	25.23	6.81	33.74	14.79	51.46	0.27
137	13.9075	35.99	12.78	48.77	24.06	27.16	0.36
138	13.9105	10.05	47.30	57.35	35.15	7.50	4.71
139	14.0015	20.25	5.72	25.71	69.08	5.21	0.28
140	14.0030	8.06	10.41	18.66	60.69	20.65	1.29
141	14.0075	2.14	6.05	8.18	80.17	11.65	2.83
142	14.0105	2.57	6.35	8.92	74.91	16.17	2.47
143	14.0135	*	*	16.21	63.72	20.06	*
144	14.0170	*	*	37.64	59.94	2.42	*
145	14.1030	11.71	14.01	25.72	68.32	5.96	1.20
146	14.1060	12.78	19.05	31.83	67.07	1.09	1.49
147	14.1090	10.35	13.15	23.49	70.92	5.58	1.27
148	14.1120	5.16	20.78	24.98	67.77	7.25	4.03
149	14.2020	13.23	12.51	25.75	69.92	4.33	0.95
150	14.2050	8.87	8.42	17.28	52.57	30.15	0.95
151	14.2080	9.09	9.32	19.46	45.69	34.85	1.03
152	14.3020	19.61	13.51	33.12	47.25	19.63	0.69
153	14.3035	19.07	17.06	36.12	38.31	25.57	0.89
154	14.3065	12.00	38.35	50.35	43.89	5.76	3.20
155	14.3100	13.97	27.18	41.15	52.08	6.77	1.95
156	14.4015	18.14	11.35	29.49	38.12	32.38	0.63
157	14.4045	24.26	17.57	41.83	42.52	15.65	0.72
158	14.4080	21.62	15.36	36.98	52.68	10.33	0.71
159	14.5050	16.26	10.84	27.11	39.72	33.18	0.67
160	14.5020	15.76	14.03	29.79	61.10	9.11	0.89
161	14.5075	20.92	11.92	32.83	42.04	25.13	0.57
162	14.5105	18.30	14.56	32.85	41.41	25.74	0.80
163	14.6020	19.72	14.69	34.41	63.34	2.25	0.74
164	14.5050	23.32	13.41	36.73	55.39	7.87	0.58
165	14.6080	26.22	20.10	46.29	42.58	11.13	0.77
166	14.6100	20.68	26.29	46.97	33.22	19.81	1.27
167	14.8010	22.52	19.13	41.65	56.34	2.01	0.85
168	14.8025	25.77	18.12	43.89	51.35	4.76	0.70
169	14.8055	31.35	9.81	41.16	41.15	17.68	0.31
170	14.8090	12.72	31.56	44.29	44.52	11.19	2.48
171	14.9015	25.54	17.04	42.58	52.20	5.23	0.67
172	14.9045	28.32	13.95	42.27	46.83	10.90	0.49
173	14.9075	19.26	14.42	33.68	41.48	24.85	0.75
174	14.9910	19.95	15.82	35.77	49.41	14.82	0.79
175	15.0285	*	*	11.58	73.30	15.11	*
176	15.1015	45.61	22.21	67.82	16.36	15.82	0.49
177	15.1050	59.98	21.02	81.00	18.92	0.08	0.35
178	15.1075	62.36	22.93	85.28	14.17	0.55	0.37
179	15.1105	64.47	22.70	87.16	12.38	0.46	0.35
180	15.1135	55.69	32.81	88.50	10.71	0.79	0.59
181	15.1165	61.65	28.15	89.80	10.01	0.18	0.46

182	15.1195	43.41	31.48	74.89	25.00	0.12	0.73
183	15.1225	17.12	18.91	36.03	62.99	0.98	1.10
184	15.1255	10.23	7.96	18.19	74.95	6.86	0.78
185	15.2015	39.26	18.85	58.11	41.32	0.57	0.48
186	15.2045	43.23	29.37	72.60	26.43	0.96	0.68
187	15.2105	48.03	17.72	65.75	33.81	0.44	0.37
188	15.2135	49.90	20.53	70.43	29.37	0.19	0.41
189	15.2165	24.01	37.94	61.95	37.63	0.42	1.58
190	15.2195	31.69	15.57	47.26	52.37	0.37	0.49
191	15.2225	15.85	7.90	23.75	75.13	1.11	0.50
192	15.3020	23.15	11.19	34.33	14.58	51.08	0.48
193	15.3045	27.11	10.21	37.32	17.71	44.96	0.38
194	15.3075	35.72	16.36	52.08	24.07	23.85	0.46
195	15.3105	37.82	19.41	57.23	28.97	13.81	0.51
196	15.3135	37.08	20.09	57.17	32.41	10.42	0.54
197	15.3165	31.19	33.61	64.80	32.40	2.80	1.08
198	15.4015	18.24	10.00	28.25	27.28	44.47	0.55
199	15.4045	31.72	10.97	42.69	24.25	33.07	0.35
200	15.4075	24.85	17.52	42.37	15.99	41.63	0.71
201	15.4105	37.98	26.44	64.42	29.25	6.33	0.70
202	15.4135	*	*	35.43	50.34	14.24	*
203	15.4165	52.98	20.55	73.53	22.95	3.52	0.39
204	15.4195	43.27	32.17	75.45	19.08	5.47	0.74
205	15.5020	23.11	11.06	34.16	15.50	50.34	0.48
206	15.5045	25.66	8.08	33.75	16.27	49.98	0.31
207	15.5075	26.28	8.70	34.99	10.59	54.43	0.33
208	15.5135	43.96	28.55	72.51	22.97	4.52	0.65
209	15.6020	12.65	9.61	22.26	14.18	63.56	0.76
210	15.6045	23.40	0.69	24.09	14.41	61.50	0.03
211	15.6075	31.84	10.47	42.32	20.30	37.38	0.33
212	15.6105	33.84	11.80	45.64	20.40	33.96	0.35
213	15.6135	39.14	19.30	58.44	24.94	16.62	0.49
214	21.0015	23.15	17.40	38.74	34.21	27.04	0.75
215	21.0035	*	*	20.98	51.24	27.78	*
216	21.1015	*	*	11.78	58.58	29.64	*
217	21.1040	*	*	7.85	51.02	41.13	*
218	21.2010	22.00	15.52	37.51	52.19	10.30	0.71
219	21.2040	*	*	21.36	59.67	18.98	*
220	21.2070	*	*	32.82	38.13	29.05	*
221	21.2110	*	*	42.42	32.70	24.88	*
222	21.3020	17.95	10.09	28.03	31.05	40.92	0.56
223	21.3045	17.45	12.42	29.87	22.70	47.43	0.71
224	21.3075	*	*	51.97	39.66	8.38	*
225	21.3105	30.72	8.55	39.27	37.68	23.06	0.28
226	21.3135	29.75	14.41	44.16	37.12	18.72	0.48
227	21.3165	29.95	13.62	43.58	40.27	16.15	0.45

228	21.4025	*	*	32.05	41.96	25.99	*
229	21.4045	*	*	41.53	35.08	23.39	*
230	21.4075	*	*	45.71	35.43	18.86	*
231	21.4105	*	*	48.76	36.31	14.94	*
232	21.4135	*	*	51.87	37.46	10.67	*
233	21.4170	50.81	17.50	68.36	22.70	8.94	0.35
234	21.5020	*	*	36.11	33.77	30.11	*
235	21.5050	*	*	28.63	32.63	38.74	*
236	21.5075	*	*	36.29	30.52	33.19	*
237	21.5105	*	*	54.70	34.59	10.71	*
238	21.5140	*	*	47.28	32.33	20.39	*
239	21.6020	15.45	17.80	33.25	33.57	33.18	1.15
240	21.6040	*	*	38.45	36.22	25.33	*
241	21.6070	23.83	40.85	64.67	23.54	11.78	1.71
242	21.6100	27.09	20.07	47.02	29.87	23.11	0.74
243	21.6130	*	*	76.63	16.39	6.99	*
244	21.6160	*	*	76.36	15.08	8.56	*
245	21.6200	*	*	74.61	23.36	2.03	*
246	21.7015	*	*	42.11	29.34	28.55	*
247	21.7045	*	*	58.73	32.47	8.80	*
248	21.7075	*	*	65.35	25.01	9.64	*
249	21.7105	*	*	66.32	22.85	10.84	*
250	21.9135	9.04	26.47	35.51	30.54	33.95	2.93
251	22.0020	*	*	52.88	44.20	2.92	*
252	22.0050	15.80	13.34	29.14	60.29	10.57	0.84
253	22.0080	*	*	43.37	40.48	16.15	*
254	22.0110	*	*	32.02	49.75	18.23	*
255	22.1015	17.33	6.97	24.31	65.79	9.91	0.40
256	22.1045	17.78	8.82	26.60	62.75	10.65	0.50
257	22.1075	22.32	7.76	30.08	64.31	5.62	0.35
258	22.1105	22.61	8.83	31.43	58.94	9.62	0.39
259	22.1135	13.12	7.59	20.71	70.85	8.45	0.58
260	22.1165	9.04	26.60	35.64	31.73	32.63	2.94
261	22.2010	*	*	34.31	60.63	5.06	*
262	22.2040	*	*	44.88	49.06	6.05	*
263	22.2075	*	*	41.28	53.31	5.40	*
264	22.2105	*	*	47.60	38.10	14.30	*
265	22.2135	*	*	42.07	45.25	12.68	*
266	22.2165	*	*	30.76	32.93	36.31	*
267	22.2195	*	*	33.84	36.23	29.93	*
268	22.2230	*	*	48.59	40.05	11.36	*
269	22.3025	*	*	23.16	34.27	42.57	*
270	22.3045	*	*	23.48	35.55	40.97	*
271	22.3055	*	*	35.49	25.93	38.57	*
272	22.3085	*	*	38.02	47.15	14.83	*
273	22.3115	*	*	19.36	47.15	33.49	*

274	22.3145	*	*	24.36	55.41	20.22	*
275	22.3175	*	*	43.75	42.45	13.81	*
276	22.4010	*	*	31.29	59.55	9.15	*
277	22.4025	*	*	23.60	34.08	42.33	*
278	22.4045	*	*	26.28	39.80	33.92	*
279	22.4075	*	*	20.65	45.54	33.81	*
280	22.4105	*	*	23.49	52.31	24.21	*
281	22.4140	*	*	43.03	37.94	19.04	*
282	22.5010	20.19	10.37	30.56	56.29	13.15	0.51
283	22.5025	17.28	5.82	23.11	38.17	38.72	0.34
284	22.5055	23.78	7.09	30.87	36.60	32.54	0.30
285	22.5085	29.54	9.67	39.21	40.28	20.51	0.33
286	22.5115	35.13	11.68	46.81	36.80	16.39	0.33
287	22.5145	32.57	19.13	51.70	39.44	8.86	0.59
288	22.6020	*	*	26.05	40.03	33.92	*
289	22.6075	*	*	50.70	28.89	20.41	*
290	22.6105	*	*	55.09	28.39	16.52	*
291	22.6165	33.11	20.09	53.19	33.14	13.67	0.61
292	23.0015	*	*	35.27	63.49	1.24	*
293	23.0045	*	*	36.25	59.93	3.82	*
294	23.0075	*	*	36.18	44.27	19.55	*
295	23.0105	*	*	35.25	50.35	14.40	*
296	23.0135	*	*	66.27	29.03	4.69	*
297	23.0175	*	*	40.35	51.84	7.81	*
298	23.1020	25.39	14.09	39.30	59.78	0.92	0.56
299	23.1050	23.44	17.33	40.78	53.13	6.09	0.74
300	23.1080	20.35	13.57	33.92	49.71	16.37	0.67
301	23.1110	20.28	15.23	35.52	45.95	18.53	0.75
302	23.2050	*	*	38.75	51.15	10.10	*
303	23.2075	*	*	56.20	38.93	4.87	*
304	23.2105	17.86	13.08	30.94	45.99	23.08	0.73
305	23.2135	18.38	7.21	25.60	27.77	46.63	0.39
306	23.3045	29.64	3.87	33.51	24.09	42.40	0.13
307	23.3075	*	*	52.35	25.20	22.46	*
308	23.3105	*	*	26.05	28.32	45.63	*
309	23.3130	*	*	49.17	16.52	34.31	*
310	23.3160	*	*	75.81	15.22	8.97	*
311	23.3190	47.05	9.07	56.12	37.11	6.64	0.19
312	23.4015	22.58	16.37	38.94	33.10	27.96	0.72
313	23.4045	*	*	40.65	31.16	28.19	*
314	23.4075	*	*	61.67	25.25	13.08	*
315	23.4105	*	*	39.57	43.14	17.30	*
316	23.4135	38.80	18.73	57.53	29.72	12.75	0.48
317	23.4165	18.29	7.30	25.60	27.77	46.63	0.40
318	23.4195	*	*	27.27	51.86	20.87	*
319	23.4225	*	*	46.29	43.66	10.05	*

320	23.4255	*	*	40.02	47.20	12.78	*
321	23.5045	*	*	28.30	55.60	16.10	*
322	23.5075	*	*	25.97	28.40	45.63	*
323	23.5110	*	*	50.30	49.70	0.00	*
324	23.6020	24.56	19.89	44.45	30.56	24.99	0.81
325	23.6055	32.65	25.07	57.72	27.83	14.44	0.77
326	23.6085	*	*	63.45	27.50	9.04	*
327	23.6115	30.84	33.17	64.01	28.97	7.01	1.08
328	23.6145	32.60	29.03	61.64	33.01	5.35	0.89
329	24.0110	*	*	59.76	28.45	11.80	*
330	24.0135	*	*	40.22	41.16	18.63	*
331	24.0200	*	*	37.30	51.46	11.24	*
332	24.0230	*	*	38.65	49.68	11.67	*
333	24.0260	*	*	41.02	46.48	12.50	*
334	24.0290	*	*	38.67	49.43	11.91	*
335	24.0310	*	*	32.50	56.34	11.16	*
336	24.1020	27.86	13.01	40.88	55.21	3.91	0.47
337	24.1050	26.66	14.31	40.97	45.19	13.84	0.54
338	24.1080	*	*	40.22	43.82	15.96	*
339	24.1110	*	*	52.39	40.70	6.92	*
340	24.1140	36.19	8.62	44.81	41.61	13.59	0.24
341	24.2020	22.90	13.22	36.12	45.44	18.45	0.58
342	24.2050	24.38	13.54	37.92	41.32	20.76	0.56
343	24.2120	25.92	5.51	31.43	50.01	18.56	0.21
344	24.3030	23.02	10.61	35.36	33.64	31.00	0.46
345	24.3060	31.38	16.10	47.49	39.77	12.74	0.51
346	24.3090	31.80	18.02	49.82	36.61	13.57	0.57
347	24.3120	30.49	21.86	52.35	37.46	10.19	0.72
348	24.3150	28.91	28.13	57.04	33.16	9.80	0.97
349	24.3180	23.80	33.81	57.60	35.91	6.49	1.42
350	24.4030	15.44	8.44	26.80	35.05	38.15	0.55
351	24.4060	24.34	9.64	33.98	35.91	30.10	0.40
352	24.4090	28.82	17.79	46.61	40.96	12.43	0.62
353	24.4120	24.72	8.15	32.87	35.75	31.38	0.33
354	24.4150	25.33	32.52	57.85	33.31	8.84	1.28
355	24.4180	26.40	35.51	61.91	31.79	6.30	1.34
356	25.0020	13.21	12.54	25.75	44.22	30.03	0.95
357	25.0050	15.14	11.07	26.20	59.10	14.70	0.73
358	25.0500	*	*	22.51	59.23	18.26	*
359	25.0110	*	*	19.38	57.92	22.70	*
360	25.0140	*	*	18.78	46.13	35.10	*
361	25.0170	*	*	28.35	61.03	10.62	*
362	25.1015	21.58	15.84	37.42	49.22	13.36	0.73
363	25.1045	21.39	16.95	38.33	36.31	25.36	0.79
364	25.1075	*	*	40.18	32.96	26.86	*
365	25.1105	*	*	25.94	56.43	17.63	*

366	25.1135	*	*	39.45	49.46	11.09	*
367	25.1165	*	*	42.88	51.34	5.78	*
368	25.2025	9.51	19.20	28.71	46.86	24.43	2.02
369	25.2055	19.81	30.91	50.72	35.22	14.06	1.56
370	25.2085	35.83	14.54	50.37	32.41	17.23	0.40
371	25.2145	15.66	5.71	21.37	45.97	32.66	0.36
372	25.2175	*	*	34.96	34.55	30.48	*
373	25.2205	*	*	41.49	40.33	18.18	*
374	25.2235	*	*	49.69	34.91	15.40	*
375	25.2265	32.25	17.74	50.00	29.78	20.22	0.55
376	25.2295	*	*	14.45	57.92	27.63	*
377	25.2315	*	*	52.22	33.54	14.24	*
378	25.2345	23.66	25.54	49.20	30.56	20.24	1.08
379	25.2375	21.90	32.31	54.21	37.48	8.31	1.48
380	25.3015	*	*	50.19	33.01	16.80	*
381	25.3045	*	*	41.41	28.40	30.20	*
382	25.3075	*	*	51.24	28.05	20.72	*
383	25.3105	*	*	45.56	33.89	20.56	*
384	25.3135	*	*	53.58	27.55	18.87	*
385	25.3165	*	*	59.61	26.81	13.58	*
386	25.3200	*	*	50.49	19.78	29.73	*
387	25.3230	*	*	63.12	21.05	15.83	*
388	25.3285	*	*	66.61	18.83	14.56	*
389	25.3315	*	*	63.68	24.81	11.51	*
390	25.4015	23.75	8.58	32.72	41.54	25.74	0.36
391	25.4045	29.53	12.71	42.24	36.00	21.76	0.43
392	25.4135	*	*	55.72	35.24	9.04	*
393	25.4165	*	*	57.90	39.26	2.84	*
394	25.5020	*	*	32.66	29.98	37.36	*
395	25.5050	*	*	7.87	60.22	31.91	*
396	25.5080	*	*	49.65	40.14	10.21	*
397	25.5110	*	*	54.79	35.28	9.93	*
398	25.5140	*	*	56.67	33.64	9.69	*
399	25.5170	*	*	51.25	37.74	11.01	*
400	25.5200	*	*	60.09	34.09	5.81	*
401	25.6025	23.39	20.91	44.25	40.66	15.10	0.89
402	25.6080	29.91	22.16	51.74	27.31	20.95	0.74
403	25.6110	*	*	64.60	20.77	14.63	*
404	24.7010	23.00	18.88	41.88	53.29	4.83	0.82
405	24.7035	20.11	8.06	28.17	27.23	44.60	0.40
406	24.7065	21.45	14.37	35.82	24.65	39.53	0.67
407	24.7095	27.97	15.72	43.69	32.05	24.26	0.56
408	24.7125	28.04	12.04	40.13	32.74	27.12	0.43
409	24.7155	26.31	18.85	45.16	27.53	27.31	0.72
410	26.6015	15.67	6.15	21.82	23.68	54.50	0.39
411	26.6045	20.36	14.42	34.79	21.99	43.23	0.71

412	26.6075	20.54	14.96	35.51	25.18	39.32	0.73
413	26.6105	*	*	39.87	22.65	37.48	*
414	26.6135	31.80	20.57	52.37	29.22	18.41	0.65
415	26.6165	*	*	48.04	34.25	17.71	*
416	26.6195	32.51	21.89	54.40	31.48	14.12	0.67

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Code	Unit Landform
510	Ridge
500	Hilltop
490	Hillside bench
450	Hillside (+20°)
420	Hillfoot (10-20°)
410	Proximal glacis (4-10)
400	Distal glacis (1-4°)
320	Sloping interfluve(2-10°)
300	Planate interfluve (0-2°)
290	Swale (4-10°)
280	Interfluve rim (4-10°)
250(i)	Type I Low Terrace
250(ii)	Type II Low Terrace
220	Valleyhead (+10°)
200	Valleyside (+10°)
190	Valleyhead swamp
180	Valley swamp
160	Stream swamp
120	River Backswamp
100	River floodplain

NB. 501, 301, 181, etc. denote rock outcrops larger than $1m^2$ within 5m of site.

Qr	(black)	Rounded quartz
Qa		Angular quartz
G		Granitic gneiss
S		Schist Belt rocks
D	(black)	Dolerite
A		Amphibolite
Ls		Lateritic segregations
Lg	(black)	Fe sesquioxide-cemented mixed gravel
Lc		Lateritic concretions
Lm	(black)	Massive or vermiform laterite fragments

Key to transect abbreviations

GLOSSARY

Note The microstructural terms used in the text of this thesis are those defined by FitzPatrick (1984); examples of the microstructural types observed in this study are shown in Figure 5.3, p119.

Alluvial fill Material finer than 2mm deposited by fluvial processes, commonly highly sorted deposits of quartz sand.

Alluvial gravel Material coarser than 2mm deposited by fluvial processes, commonly consists entirely of quartz clasts.

Basal gravel A buried gravel that directly overlies bedrock or saprolite.

Beaded cutan Clay-filled soil passages indicative of pronounced illuviation.

Biostasie A condition of biological equilibrium leading to minimal surface denudation and facilitating deep weathering; often used to describe the almost closed cycle of energy and matter within humid tropical rainforests (Erhart, 1955).

Breakaway Scarp zone of lateritic cap rock ('duricrust').

Cemented gravel Gravel cemented by iron sesquioxide-clay compounds.

Colluvial fill Material finer than 2mm deposited by colluvial processes.

Compound lateritic concretions Aggregates of lateritic clasts with an indurated iron sesquioxide matrix (viz. Plate 5.1).

Cutan A coating of clay around a soil pore or passage, indicative of illuviation.

Depositional glacis A glacis slope dominated by accretion, forming a wedge of colluvial fill that becomes thicker downslope and consists of progressively finer material (='bahada').

Distal glacis The glacis slope farthest from the hillside, mean slope 2.9 degrees.

Duricrust Bedrock, saprolite or detrital material enriched in iron sesquioxides that have since become indurated (='petroplinthite', ='ferricrete', ='massive laterite').

Erosive glacis A glacis slope dominated by erosion, commonly a bare rock surface (='pediment', ='glacis de denudation').

Etchplanation The deep weathering of a region under humid tropical bioclimatic conditions, followed by successive stages of soil-saprolite stripping that reveal progressively more of the basal surface of weathering during periods of environmental instability.

Exotic minerals Resistate minerals not occuring in local bedrock but nevertheless found in local surficial materials, indicating a fluvial source.

Fe-induration & Ferruginisation The input and induration of iron sesquioxides in a zone of alternate reducing(mobilising) and oxidising(fixing) conditions, producing a **Ferricrete**.

Ferricutan A coating of iron sesquioxides around a soil pore or passage.

Fill layers Transported material less than 2mm in size.
Fines The clay + silt size fraction (-0.062mm).
Footslope A unit landform positioned between the hillslope and the glacis slope, characterised by boulders derived from hillslope mass movements; morphometric data given in Table 5.4.
Glacis slope Gentle concave slope extending from the footslope zone; the proximal glacis (mean slope 4.7 degrees) is dominated by mass movements and slopewash and leads down to the distal glacis (mean slope 2.9 degrees) dominated by slopewash and pedogenesis.
High Terrace A mining term for planate or near-planate interfluves of possible ancient alluvial origin.
Hillside bench A near-horizontal bevel on a hillside (cf. Table 5.4).
Induration The hardening of iron sesquioxide-clay compounds.
Interfluves The section of the landsurface lying between the glacis slopes (where present) and valley sides; the various subtypes are summarised in Table 5.4.
Laterite Material resulting from the accumulation and induration of iron sesquioxides, or **laterisation** .
Lateritic clasts Commonly become less porous, harder and more regular in shape from the saprolite to the landsuface. Examples of the variations in clast form are given in Plate 5.1, morphologies and probable geneses are summmarised in Table 3.5.
Lateritic segregations or 'mottles' are in situ iron sesquioxide accumulations that are only slightly indurated, they are thus relatively soft, porous and tend to have an irregular shape.
Lateritic concretions are indurated iron sesquioxide accumulations. In situ concretions can occur, resulting from pedogenetic processes, but the majority of concretions appear to result from soil-saprolite stripping and subaerial exposure, induration and local transportation. Moderately hard nodular concretions eventually become harder, smoother, denser and rounder.
Lateritic pisoliths are the hardest type of lateritic clast, spherical, black and often magnetic. **Pisoliths** show concentric banding in thin section; **Pseudopisoliths** are amorphous.
Lateritic gravel consists almost entirely of lateritic clasts.
Lateritic pavement A ferricrete formed at the site of a former seasonal seapage zone and now left 'high and dry' by local stream incision; p104.
Low Terraces Fluvial terraces, subdivided into late Quaternary **Type I Terraces** and Holocene/Recent **Type II Terraces**; cf.Table 5.4.
Morphofacies Types Morphostratigraphic units whose surface expressions are Unit Landforms.
Patina A thin coating of indurated Fe/Mn sesquioxides on the surface of bedrock or truncated saprolite; viz. Plates 5.1 and 5.7A.
Pedoplasmation term used by Flach et al.(1968) for the alteration of parent material by shrink/swell action, wet/dry periods, roots and faunal activity.

Penetration deposits Mining term for diamonds found in non-kimberlitic saprolite.

Planate interfluves Interfluves with a mean slope of 0.8 degrees, dominated by residual and pedogenetic processes.

Proximal glacis Section of the glacis slope that follows on from the footslope, mean slope 4.7 degrees.

Regolith Equivalent to the 'skeletal' weathering stage of Haatjens & Bleeker (1970): the physical disintegration of bedrock is more evident than chemical alteration (='lithosol').

Residual hill Promanent hill with a thin soil/saprolite mantle, rather than the bare rock slopes that characterise inselbergs.

Rhexistasie The loss of biological equilibrium, resulting in soil-saprolite stripping; the opposite of biostasie (Erhart, 1955).

Rock gravel Gravel consiting of bedrock clasts, as opposed to lateritic clasts (='stone line').

Runiform quartz Where microfissures are impregnated with iron sesquioxides; viz. Plate 5.2.

Saprolite Bedrock decomposed to clay minerals plus secondary and resistant minerals; equivalent to the 'mature' weathering stage of Haatjens & Bleeker (1970).

Sloping interfluves Interfluve zone with a mean slope of 3.2 degrees.

Soil relict Lateritic segregation with a recognisable soil fabric.

Stream swamps Steep-sided, flat-bottomed swamps containing a stream channel.

Swales Surface depressions on interfluves that lead into valleyheads.

Topgravel Morphostratigraphic term for a gravel layer within 40cm of the landsurface.

Topsoil The O/A (organic-mineral) horizon of the profile, commonly a dark brown clay loam on the interfluves and peaty sandy loams on the valley floors.

Unit Landform A portion of the landscape with a characteristic surface form (slope angle, contour pattern, slope concavity/convexity, degree of rock outcrop, etc.), defined by detailed geomorphological mapping.

Valley swamps Flat-bottommed, channelless headwater swamps (='sohlenkerbtal' or 'dambos').

Valleyhead swamps The uppermost section of the valley system, typically a gently sloping valley swamp flanked by steep valleysides 2-3m high; considerable inputs of interfluve debris into the valley (via slumping and slopewash) in this zone.

Vermiform laterite anastamosing tubules of indurated iron sesquioxides of probable pedogenetic origin; viz. Plate 5.1.

Washed saprolite Saprolite depleted of fine material by lateral eluviation.

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ABSTRACT

The objectives of this study were to produce a landscape development model for a 400 km^2 granitoid basin in the West African forest/savanna zone, and to test whether variations in landsurface morphology can be related to surficial geology. Each Unit Landform identified by morphological mapping was found to have a characteristic Morphofacies Type on the basis of slope angle, depth to topgravel, presence of unconformities or palaeosols and depth to saprolite. Textural and micromorphological analyses confirmed the distinctiveness of each Morphofacies Type. Variations in 'stoneline' petrography provided insights into contemporary morphodynamics. Three Process Domains (Residual, Colluvial and Fluvial) apparently interact across the landscape to produce a unique set of stratigraphic and material indicators for each Morphofacies Type. The presence of relict indicators, such as fluvially-rounded pebbles in the residual interfluve gravels, points to extensive landscape modification.

Of the detailed study areas, Kania is classified as a 'Saprolite-mantled Etchplain' with extensive near-planate interfluves; whereas Yengema is a 'Partially-stripped Etchplain' with numerous rock outcrops and residual hills. This is partly explained by lithological differences, but the main cause appears to be drainage modification. Yengema's drainage was apparently captured by a regional trunk river during the early Quaternary, resulting in drainage reversal, fluvial incision and soil/saprolite stripping. Consequent extensive bedrock exhumation has made Yengema more sensitive to environmental instabilities than Kania (which escaped similar drainage disruption). Supportive evidence comes from the infilled Late-Quaternary valleyhead extensions and relatively deep profiles at Kania, versus the rocky valleyheads and shallow profiles characteristic of Yengema. 3000 years of farming and deforestation have caused soil/saprolite stripping, with 1-2m of colluvium filling valley swamps.