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THE ROLE OF GEOBOTANY, BIOGEOCHEMISTRY AND GEOCHEMISTRY IN MINERAL EXPLORATION IN SOUTH WEST AFRICA AND BOTSWANA — A CASE HISTORY

by

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ABSTRACT

Geobotanical, biogeochemical and geochemical investigations carried out on the western and northern fringes of the Kalahari Basin in South West Africa and Botswana, as part of a multi-disciplinary mineral exploration programme, were aimed at delineating a hitherto unknown but inferred mineralized province in Proterozoic sediments and associated extrusive rocks.

The investigations were based on a geological appreciation of the possible presence of Proterozoic sediments of comparable age and type to those of the Katanga System of Zambia that carries important stratiform copper deposits. Because the widespread cover of Tertiary and Quaternary Kalahari sediments and the scarcity of bedrock outcrops limited geological mapping, emphasis was placed on photogeological interpretation, geobotany, biogeochemistry, geochemistry and also geophysics in a research based exploration programme.

Initial air and ground reconnaissance revealed that distinctive vegetation associations distinguished areas of near surface bedrock from those with thick cover of sand and calcrete, and that their lineations reflected the geological structure and stratigraphy. The recognition of anomalous plant communities of *Helichrysum leptolepis* DC during ground reconnaissance near Witvlei led to the discovery, beneath cover of sand and calcrete, of copper mineralization in argillite bedrock that was subsequently exposed by trenching. This early success, coupled with equally promising geochemical results, prompted exploration over some 115 000 square kilometres of country.

The detailed investigations focused on four main areas, namely Witvlei and Dordabis (Gamma) in South West Africa and Ghanzi and Ngwaku in Botswana, each of which is characterized by specific environmental features posing particular exploration problems that required the development and application of appropriate techniques. The investigations which included basic geomorphological and soil studies necessary for the interpretation of geobotanical, biogeochemical and geochemical data, led to the location of copper deposits in all four areas.

In the Witvlei area where there are zones of near-surface subcropping steeply dipping strata planed by erosion and veneered by shallow sand, as well as areas of thick sand and calcrete cover, the investigations established relationships between the distribution of plant communities and bedrock geology, and determined the distributional aureole of plant species over and adjacent to mineralized bedrock. The strike continuities of mineralized zones could thus be traced, and the most suitable plant species be isolated for biogeochemical application. Furthermore, investigations of particle size distribution, and analyses of different mesh size fractions of surface and profile soil samples, revealed that copper mineralization in bedrock beneath sand cover could preferentially be detected by analysis of the −270 mesh fraction of surface soil samples as opposed to coarser fractions.

In the Gamma grant area, which is characterized by a succession of parallel sand dunes and intervening swales aligned at right angles to the inferred geological strike, by colluvial and alluvial cover and by abandoned water courses, the investigations concentrated on the interpretation of geobotanical, biogeochemical and geochemical data in the context of the geomorphology, on tracing the origin of transported geochemical anomalies and on assessing the role of biogeochemistry in detecting copper mineralization in bedrock beneath thick overburden. The investigations led to the location of copper mineralization in bedrock far from the sites of the transported geochemical anomalies.

In the Ghanzi area the investigations concentrated on establishing the relationships between vegetation associations and concealed bedrock geology, and in extrapolating the strike continuities of cupriferous strata. Spectacular fold patterns visible on aerial photographs faithfully reflect bedrock structures and lithology, that in turn control the distribution and nature of plant species.

In the Ngwaku area, an appreciation of the direct relationship between lithology and overlying vegetational types enabled the strike trends and structural complications of strata to be determined with ease. Furthermore, the recognition within the prevailing low savanna woodland of an anomalous shrub layer dominated by *Ecbolium lugardae* N.E. Brown enabled reliable predictions being made of the presence of cupriferous argillite and limestone bedrock beneath as much as 30 m of calcrete.

The investigations succeeded in locating sub-outcropping copper mineralization in seven different localities, and demonstrated the value of geobotany and biogeochemistry in exploration provided the relationships of vegetation distribution to environmental factors are understood.

* Incorporating data gathered and compiled by A. F. Boshoff, A. D. Buerger, M. M. Mason, L. Gadd, J. Hughes and R. C. Brown.

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I. INTRODUCTION

A study of Gemini satellite imagery, conventional black-and-white photography and the scanty geological information available suggested that an assemblage of late Proterozoic sediments that strike in a north-easterly direction across central South West Africa and north-eastern Botswana may be extensions to, and correlatives of, either the Katanga–Zambia Copperbelt or the Lomagundi System of Rhodesia, both of which carry copper deposits of economic significance. Furthermore, the known occurrence of stratiform copper mineralization in South West Africa, at the far south-western end of this belt, provided additional incentive towards the investigation of its mineral potential.

Because of its distribution, in both space and time, this sedimentary assemblage was considered to provide a favourable environment in which copper mineralization of stratiform type could well have been developed. Palaeontological dating of younger overlying sediments, and isotope dating of the effusive rocks that form the immediate basement, indicate that the age of the sediments is somewhere between 500 and 1 100 m.y., or broadly comparable with late Precambrian rocks that contain stratiform copper deposits in other parts of the world.

The exploration programme was thus premised upon an appreciation of a specific geological environment as being favourable to the presence of a hitherto unknown mineralized province, and not on the known presence of mineral

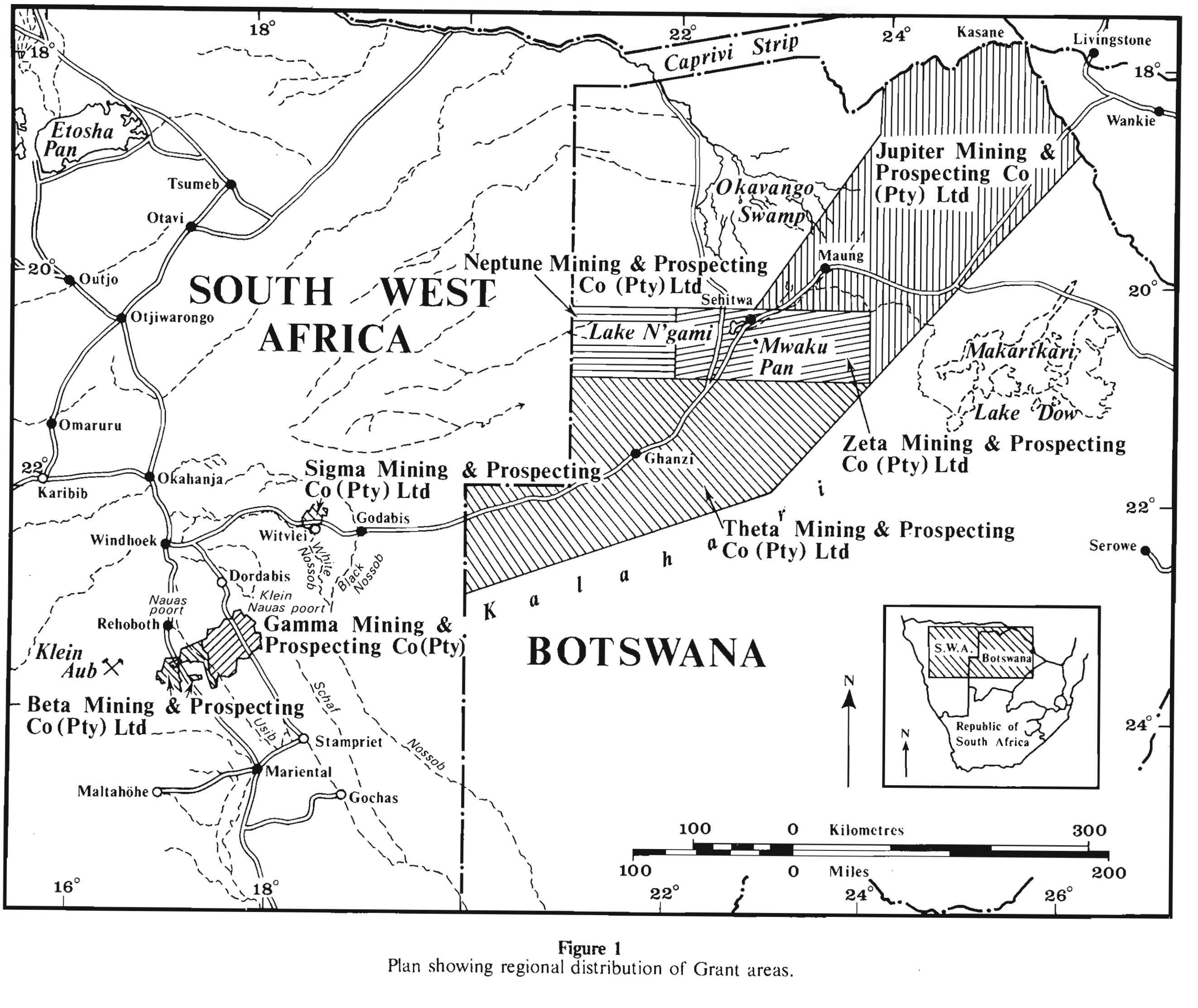


Figure 1
Plan showing regional distribution of Grant areas.

TABLE I

Suggested lithological correlation of the Dordabis Tsumis and Ghanzi systems with the Katanga system

SOUTH WEST AFRICA — REHOBOTH - DORDABIS AREA

SYSTEM	SERIES or FORMATION	ROCK TYPES
YOUNGER SYSTEMS DEVELOPED FARTHER SOUTH		
DORDABIS	DOORNPOORT	Thick basal conglomerate clay pellet conglomerate pink quartzites, calcareous quartzites, sandy limestones red slates **Stratiform copper beds**
DORDABIS	SKUMOK	Quartz-feldspar porphyry (effusive), rhyolites, ignimbrites, agglomerates, quartzites and sedimentary breccia
DORDABIS	OPDAM	Mafic epidotised lavas with basal conglomerate and interbeds of phyllites and quartzites
BASEMENT	MARIEN-HOF	Metasediments, metavolcanics, variegated schists, gneisses and granites

SOUTH WEST AFRICA — KLEIN AUB (largely after Handley 1965)

SYSTEM	SERIES or FORMATION	STAGE	ROCK TYPES	THICKNESS in feet
TERTIARY to RECENT			Kalahari sediments: windblown sand, calcrete and gravel	
NAMA	SCHWARZRAND		Shales and quartzites	
NAMA	SCHWARZKALK		Limestones; shales and quartzites	
TSUMIS	KLEIN AUB	UPPER QUARTZITE AND CONGLOM-ERATE (TSUMIS or KAMTSAS)	Pink to grey, granular, fine to coarse grained feldspathic quartzites containing randomly scattered pebbles in places; banded, ferruginous quartzites, conglomerates and possibly tillite	3000 - 8000
TSUMIS	KLEIN AUB	CALCAR-EOUS QUART-ZITE	Fine grained, pink to maroon or grey calcareous quartzites; no true limestones or shale bands present	3000 - 4500
TSUMIS	KLEIN AUB	CALCAR-EOUS SHALE	Alternations of fine shaly and calcareous strata with coarser quartzitic members that are in places pebbly **Cupriferous green argillites**	1900 - 3000
TSUMIS	KLEIN AUB	LOWER QUARTZITE AND CONGLOM-ERATE (DOORN-POORT)	Maroon quartzites, maroon shales, calcareous arenites and sandy limestones overlying ill-sorted basal conglomerate containing boulders of granite, porphyry and quartzite	2500 - 3500
TSUMIS	KLEIN AUB	INTRUS-IVES	Basic and acid dykes	
DORDABIS	SKUMOK		Quartz-feldspar porphyry (effusive), rhyolites, ignimbrites, agglomerates, quartzites and sedimentary breccia	
DORDABIS	OPDAM		not present	
BASEMENT	MARIEN-HOF		Metasediments, metavolcanics, variegated schists, gneisses and granites	

SOUTH WEST AFRICA — UHLENHORST - KHARUBEAM HILLS (after South West Africa Geological Survey and Anglovaal geologists)

SYSTEM	SERIES or FORMATION	STAGE	ROCK TYPES
TERTIARY to RECENT			Kalahari sediments: windblown sand, calcrete and gravel
KARROO	STORM-BERG		Basalt
	BUSCH-MANNS-KLIPPE		
TSUMIS	WITVLEI	KAMTSAS or TSUMIS C	Pink to grey, fine to coarse grained feldspathic quartzites with randomly scattered pebbles; banded, ferruginous quartzites and conglomerates
TSUMIS	WITVLEI	DOORN-POORT or TSUMIS A and B	Conglomerates, quartzites
DORDABIS	SKUMOK		Quartz feldspar porphyry (effusive), rhyolites and agglomerates
DORDABIS	OPDAM		Mafic epidotised lavas with interbedded conglomerates, phyllites, metavolcanics and metasediments

SOUTH WEST AFRICA — WITVLEI (modified by Cole and le Roex from Toens 1970 and Martin 1965)

SYSTEM	SERIES or FORMATION	STAGE	ROCK TYPES	THICKNESS in feet
TERTIARY to RECENT				
NAMA	BUSCH-MANNS-KLIPPE-			
TSUMIS		KAMTSAS or TSUMIS C	Brown feldspathic quartzites containing scattered pebbles some conglomerates; black sands plentiful; cross-bedding marked	
TSUMIS or DOORNPOORT	WITVLEI	TSUMIS B UPPER MIDDLE LOWER	Undifferentiated alternating sequence of maroon quartzites, calcareous arenites, green shales, cupriferous siltstones (argillites), thin bands of mud-pellet conglomerate and local limestones **Three cupriferous ore zones**, one of which is associated with pyritic carbonaceous shale overlying	± 20000
TSUMIS or DOORNPOORT	WITVLEI	TSUMIS A	Ill-sorted basal conglomerate	
DORDABIS	SKUMOK and OPDAM		Mafic to felsic lavas; basaltic andesites, rhyolite, quartz-feldspar porphyry pyroclasts, lavas; locally cupriferous	

BOTSWANA — GHANZI - LAKE NGAMI - NGWAKU PAN (after Botswana Geological Survey and Anglovaal geologists)

SYSTEM	SERIES or FORMATION	STAGE	ROCK TYPES
TERTIARY to RECENT			lake and pan sediments: fossil sand dunes; old pan calcrete: silcrete, calcrete
KARROO	STORM-BERG		Basalt, sandstone; conglomerate
TSUMIS	GHANZI	photo-geological studies indicate unconformities between major units but their precise position in the stratigraphical column remains to be determined	Fine grained sandstone, feldspathic sandstone: maroon colour, feldspathic, sericitic sandstone; argillite, phyllite and shale; limestone; thin bands, epidotic sandstone **Stratiform copper beds occurring in at two zones,** conglomerate
	KGWEBE		Effusive quartz-feldspar porphyry; coarse pyroclasts and epidotic tuffaceous sandstone; diabase. (Toteng) possibly effusive
BASEMENT			pink granitic gneisses with microcline dominant, hornblende and biotite xenoliths or dyke-like amphiboles

ZAMBIA (Mendelsohn et al 1961; correlation with S.W.A and Botswana formations tentative and based entirely on lithology and geographical distribution)

SYSTEM	SERIES or FORMATION	STAGE	ROCK TYPES	
	KUNDU-LUNGU	UPPER	Shale and quartzite	
	KUNDU-LUNGU	MIDDLE	Shale, tillite	
	KUNDU-LUNGU	LOWER	Dolomite, dolomite and shale tillite	KAKONTWE
KATANGA		MWASHIA	Carbonaceous Shale	
KATANGA		UPPER ROAN	Dolomitic argillite (quartzite, breccia) argillite and quartzite	
KATANGA	MINE	LOWER ROAN	Quartzite, argillite and feldspathic quartzite (dolomite)	HANGING WALL
KATANGA	MINE	LOWER ROAN	Argillite, impure dolomite, micaceous quartzite (greywacke, arkose)	ORE
KATANGA	MINE	LOWER ROAN	(Footwall conglomerate) argillaceous quartzite, feldspathic quartzite, aeolian quartzite, conglomerates	FOOT-WALL
LEFEBU AND MUVA			Granites, porphyry(muliashi) schists, gneisses, quartzites, metaquartzites and argillites	
LEFEBU AND MUVA				

MMC

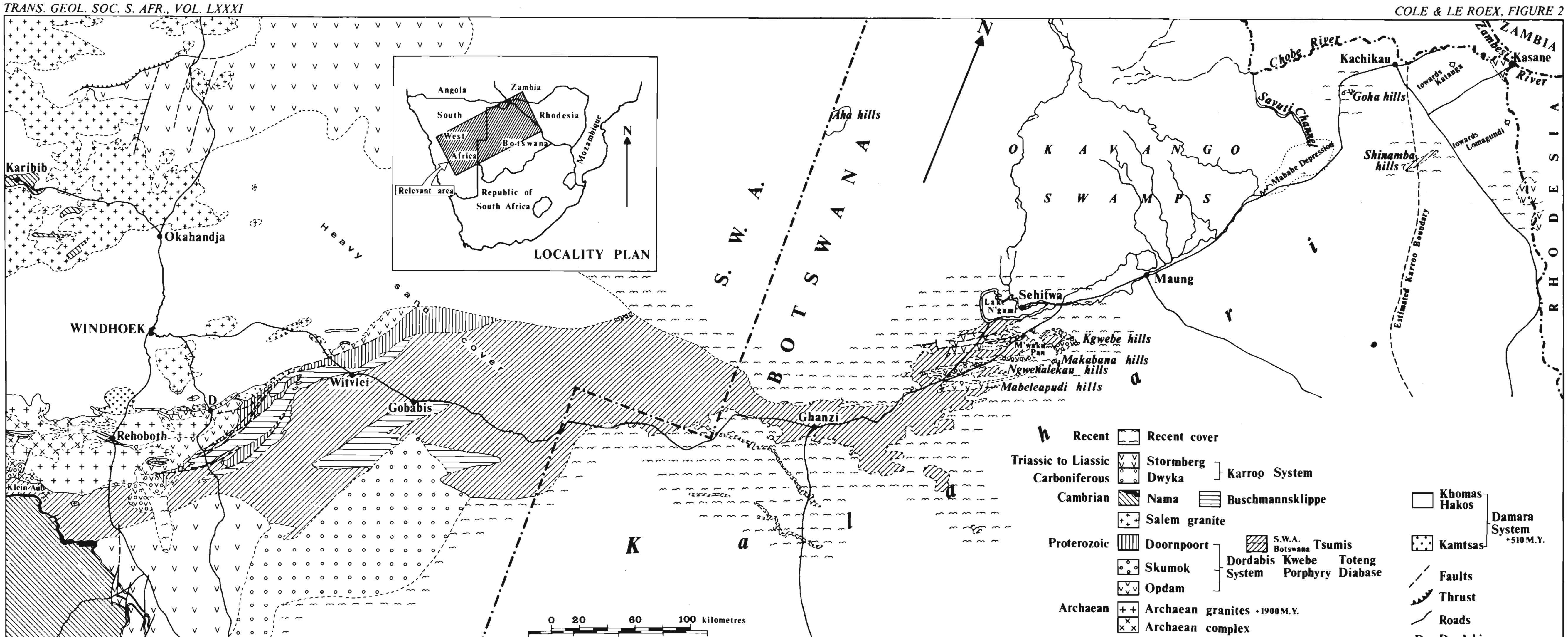


Figure 2

Trend of the Tsumis/Ghanzi sediments and other Precambrian formations across Central S.W.A. and North-western Botswana.

deposits. Consequently grants, conferring exclusive prospecting rights, were acquired over some 46 000 square miles of territory in the central and northern sectors of the Kalahari Basin in South West Africa and Botswana (Fig. 1).

During initial exploration reconnaissance the examination of vegetation along traverses orientated at right angles to the geological strike, as inferred from an aerial survey, led to the recognition of the plant species *Helichrysum leptolepis* as a possible indicator plant and to the discovery of zones of copper mineralization on the farm Okasewa, near Witvlei, where bedrock is concealed by soil and sand cover.

This early success was followed by geobotanical and biogeochemical investigations, by reconnaissance geochemical soil sampling on the Witvlei grant area and the adjoining farm Okasewa, and by geological and geobotanical reconnaissance over the tract of country extending from Witvlei past Gobabis to Maung.

These studies suggested four target areas for further investigation: Witvlei, the farm Sib in the Gamma grant, Ghanzi, and Ngwaku in Botswana. At this stage no mineralization was known of in Botswana.

II. PHYSICAL BACKGROUND

A. Geological Setting

Knowledge of the stratigraphical succession and the geological structure of the area was limited to information from a few localities only (Passarge, 1904; Gevers, 1934; De Kock, 1934; Wright, 1958; Boocock and Van Straten, 1962; Vermaak, 1962; Handley, 1965; Martin, 1965; Crockett and Jennings 1965). During this exploration programme contributions were made by company geologists and by the South West Africa and Botswana Geological Surveys, so that an overall appreciation of the geology of the area emerged. As a result it is now known that the areas investigated are underlain by a diversity of Precambrian rocks. Between the Naukluft Mountains south-west of Windhoek and the Botswana–Rhodesia border these formations have a strike length of over 1 000 km along which outcrops are rare (Fig. 2).

The Precambrian rocks referred to as the Marienhof, the Opdam, the Skumok and the Tsumis/Ghanzi formations conform in strike to the regional east-north-easterly structural grain characteristic of Southern Africa.

The sediments of the Tsumis/Ghanzi formations flank the southern border of the Damara geosyncline, and probably represent a shelf facies thereof. Their provenance undoubtedly comprised the older Opdam and Skumok lavas in which numerous small showings of both oxide and sulphide copper occur. The northern contact of these formations with the younger Damara rocks is probably of a faulted nature, whereas their southerly continuity is blanketed by younger Jurassic effusives and sediments of the Karoo System, by Cambrian Nama sediments and Kalahari surficial deposits.

The prevailing dip of the Tsumis beds is steeply to the south, but flattens around domal inliers of older Opdam and Skumok rocks.

Drag-folding, resultant upon interbed slippage that is in turn a function of regional folding, is prevalent and displays flat axial plunges that result in boat-shaped structures being formed that erroneously give the impression of great structural complexity. Distinct, almost vertical axial plane cleavage is impressed on all strata in the stratigraphical column. Transcurrent faults of small magnitude are present and strike faulting is suggested by the presence of local anomalies in the stratigraphical succession.

Early geological mapping within the areas now covered by the Grants had been undertaken only at widely spaced localities, with the result that a proliferation of local terms emerged that clouded correlation. Moreover, facies variations that characterise the Tsumis and associated formations further complicated the issue. On the basis of recent work an attempt is made to advance a broadly applicable regional correlation in Table I.

The oldest rocks in the area of interest are the metamorphosed ultrabasics, metavolcanics and metasediments of the Marienhof formation that outcrop on the farm of this name west of Rehoboth. Isotopic dating on galena yielded an age of 1 900 m.y. (Martin, 1965).

Farther eastward the Opdam and overlying Skumok formation comprise the immediate basement and show a large measure of geological uniformity across South West Africa and north-western Botswana. They consist of a suite of intermediate to acid lava flows interbedded with fluvial sediments, tuffs and pyroclasts. Perhaps the most dominant single unit here is a robustly developed flow of quartz-feldspar porphyry that weathers to physiographic highs that collectively form an excellent regional marker zone. Even where these rocks have been bevelled to featureless plains and covered by overburden it is possible to delineate the trace of the porphyry by way of aerial magnetics. Considerable use was made of this technique, for orientation purposes, in the endless flat sand/calcrete covered plains of Botswana. In Botswana these rocks are referred to as the Toteng Diabase suite, and are well exposed at the Mabeleapudi, Ngwenalekau, Kgwebe and Makabana hills. They are also well exposed east of Rehoboth in South West Africa.

Rocks of the Tsumis system, that unconformably overlie the older units described above, have been mapped by Handley (1965) in the area located south-west of Rehoboth. He divided them into four lithologically distinct stages that are listed in Table I. They consist in essence of poorly sorted basal polymictic conglomerates overlain by undifferentiated sequences of maroon quartzites/shales, feldspathic sandstones, green shales/argillites, marls, calcareous arenites/siltstones, carbonaceous pyritic shales and more than one zone in which beds of cupriferous argillite, that comprise the main ore bodies, are developed. Beds of limestone and dolomite are sparse in this formation in South West Africa but, together with the feldspathic sandstones, display a more robust development in Botswana. Copper mineralization is also present in quartzites, calcareous arenites and even conglomerates. Close analogies can be drawn between these stratiform ores and those of the Kupferschiefer marls, the Nonsuch shales of the White Pine deposits in Michigan, the Zambian Copperbelt and other comparable deposits of worldwide spread.

There is abundant evidence that this sedimentary sequence was deposited in a high-energy, well-aerated neritic/sub-littoral environment. However, the presence of carbon-rich pyritic shales does call for at least local stagnant basins in which euxenic conditions prevailed.

The still younger Bushmanklippe formation that is exposed between the villages of Dordabis and Gobabis is correlated with the probably Cambrian age Nama formation that is so widely developed in southern South West Africa. The lithology consists of shallow water dolomitic limestone, dolomite, shale, sandstone, oolitic limestone and heavily ripple marked white quartzite. Certain of the shales and quartzites comprise red beds. No significant mineralization has to date been found in these rocks.

A mineragraphic study of the ores at Witvlei was undertaken by Anhaeusser and Button (1973) who report as follows: "The main ore mineral was found to be chalcocite, occurring together with lesser amounts of digenite, bornite, chalcopyrite, covellite, pyrite, cuprite, native copper, malachite, azurite, chrysocolla, and iron ore. Although silver is consistently reflected in assays of the ore, no silver mineral could be detected using an ore-microscope. Electron microprobe tests showed that silver occurs as trace-amounts in solid solution in the sulphides." The ore minerals display evidence of progressive enrichment in copper through the range pyrite, chalcopyrite, bornite and chalcocite to native copper. The pyrite displays early diagenetic forms.

The mean grain size of the sulphide ore ranges between 4 and 8 microns and consequently requires extremely fine grinding (95 per cent −325 mesh) for the effective liberation of sulphides to produce a concentrate grading almost 50 per cent copper metal.

Zinc and lead mineralization, in addition to copper, was exposed north of Ghanzi, which suggests that Stanton's precepts regarding the elemental constitution of the sulphide components of stratiform sulphides of marine and marine-volcanic association may prevail here, viz. iron (as pyrite) alone in some deposits, in others iron + copper but never copper alone, iron + copper + zinc but never zinc alone, and finally iron + copper + zinc + lead but never lead alone. The stratigraphic levels above the main iron-copper ore zones should thus be carefully investigated in the hope of locating a fuller roster of metals in this mineralized province.

In summation it may be stated that we are here probably dealing with stratiform ore deposits of marine, and possibly marine-volcanic, association that show very positive relationships to specific sedimentary features.

B. Physiography and Geomorphology

The study area forms part of the great African Plateau rising to between 1 300 and 2 000 m on the west and sloping gradually eastwards to the Kalahari Basin. Drainage is towards the Kalahari but there are no perennial rivers. The largest water courses are those of the White Nossob and Black Nossob which, beyond the limits of the study area, unite before the junction with the Molopo, an intermittent tributary of the Orange. In the extreme north-east the Okavango River brings water from Angola and distributes it in a labyrinth of channels in the Okavango swamps from which some filters through to Lake Ngami (Fig. 1).

Near Windhoek the plateau exhibits evidence of several cyclic erosion surfaces cutting across steeply inclined strata comprising rocks of varying resistance. Here it is studded by numerous ranges of hills and by isolated inselbergs which rise sharply some 500 to 700 m above the general level. Eastwards as the sand cover increases towards the Kalahari, these become fewer and progressively lower until they finally disappear as a feature of the landscape.

The present drainage pattern is unrelated to present relief features and to the underlying geology. It apparently originated on a surface above that of the summit level of the ranges during a wetter climatic epoch. Stream courses are transverse to the alignment of the hills and to the geological strike.

Although dry for most of the year, in the west they are characterized by spectacular gorges like the Nauas and Klein Nauas poorts which the Usib and Schaf Rivers have cut through the resistant quartzites of the Tsumis System. Eastwards on the fringes of the Kalahari, notably south-east of Ghanzi and Dordabis, sand dunes, now fossilised, have dismembered former stream courses while in northern Botswana individual pans and chains of pans form the only relicts of former drainage systems.

Today pronounced ridges occur only where resistant rocks have survived planation in the later erosion cycles. South-east of Windhoek Kamtsas (Tsumis C) quartzites form prominent ranges (Fig. 2) whereas the Doornpoort arenites, argillites and dolomites (Tsumis B) produce subdued terrain. South-east of Dordabis, Opdam and Skumok Lavas form low rugged hills and in Botswana the Kgwebe quartz porphyries build the Mabeleapudi, Ngwenalekau and Kgwebe hills around which the Ghanzi sedimentary beds are probably present beneath windblown Kalahari sand.

From the viewpoint of mineral exploration three morphological features are of significance. Firstly, the less resistant potentially mineralized sedimentary rocks of the Tsumis System have been planed by erosion; secondly, these rocks have subsequently been mantled by residual soil and/or windblown Kalahari sand; thirdly, the present drainage is unrelated either to present topography or underlying geology.

Further important considerations arise from the nature of the geomorphological processes. Firstly, the infrequent characteristically torrential rainfall creates flash floods that deposit enormous quantities of sediments in the stream beds that reduce the effectiveness of stream sediment sampling as an exploration technique.

Secondly, the torrential rains falling on a landscape of steep-sided inselbergs and flat plains cause extensive sheet run-off, lateral corrasion and deposition that mantles the surface with a veneer of transported material. Purely residual soils are scarce and surface material rarely reflects the nature of the underlying bedrock.

Calcrete is widespread and in places is very thick, up to several metres. It follows that an understanding of both the geomorphological features and processes is important in the programming and interpretation of exploration techniques in the Windhoek–Maung area.

C. Overburden and Soils

The overburden is variable, both in nature and thickness, being related partly to bedrock geology and partly to geomorphology. Outcrops are rare and mostly confined to the ridges and isolated inselbergs. Over the level terrain the depth of overburden is known only from trench sections where it varies from a few centimetres to several metres. In some areas calcrete is known to exceed tens of metres in thickness and in others the mantle of Kalahari sand is known to exceed 30 m.

The characteristic soils are of the arid red earth type, generally immature and showing little or no profile differentiation. Only skeletal soils are present over Kalahari sand, over surface calcrete and over outcropping bedrock. On and around pans skeletal grey and brown soils of heavy texture occur, while dark grey or black clays surround Lake Ngami.

D. Climate

The climate over the areas explored is characteristically hot and semi-arid, with temperature extremes that increase towards the centre of the Kalahari basin. Rainfall that occurs as erratic downpours is concentrated in summer with the heaviest falls in January, February and March. The mean annual fall at Maung is 381 mm, at Ghanzi 431 mm, at Gobabis 381 mm and at Windhoek 356 mm. The summer day temperatures may rise well above 37 °C in the humid Maung area, with night temperatures seldom falling below 21 °C. The winter is characteristically dry, with day temperatures rising above 21 °C but with night occasionally falling below 0 °C. Frosts may occur in June, July and August.

E. Characteristic Vegetation and Dominant Species

The whole area is covered by savanna vegetation whose physiognomy and species composition varies with environment. Basically in the south-west it comprises low tree and shrub savanna of varying composition which alternates with and finally gives way eastwards to savanna parkland (Plate I) and still farther east to a low open savanna woodland in the warmer and slightly wetter areas near Lake Ngami (Plate II). Tables II and III illustrate in summarized form the relationship between plant species and geology.

Between Windhoek and Witvlei characteristic low tree and shrub savanna dominated by *Acacia mellifera* with as-

Plate I
Savanna parkland characterized by *Terminalia sericea* (left) and *Acacia giraffae* (right) trees over deep Kalahari sand between Witvlei and Gobabis.
(Ref. MMC/SWA 11/22A)

Plate II
Dense growth of the shrub *Echolium lugardae* occurring over zone of copper mineralization in calcareous argillite in the low tree savanna woodland characterized by *Acacia fleckii* and *Terminalia prunioides* north of the N'Gwenalekau hills and south of N'Gwaku pan.
(Ref. MMC/Bot. 13/32A)

sociated *A. hereroense, A. hebeclade, Tarchonanthus camphoratus, Grewia spp.* and *Phaeoptilum spinosum* shrubs and *Stipagrostis uniplumis* grass occupies level terrain where bedrock is relatively near surface.

Where deep sand mantles bedrock a more open parkland of vegetation develops that is characterized by taller *Acacia giraffae* trees.

North-east of Witvlei these associations alternate with an open parkland/low savanna woodland, dominated by *Terminalia sericea* and *Acacia giraffae*, which characterises areas of deeper and more extensive sand cover which becomes increasingly common in Botswana (Plate I). Around Ghanzi, low tree and shrub savanna occurs in areas with near-surface bedrock. Its composition, however, differs from that at Witvlei, notably in the additional presence of *Acacia reficiens* and *Combretum hereoense* trees and shrubs, the sporadic occurrence of *C.imberbe* trees and widespread occurrence of the suffruticose *Petalidium englerinaum*. North-eastwards low shrub savanna characterized by *Combretum apiculatum, Bauhinia maerantha* and *Croton gratissimus* (Plate III) alternates with savanna grassland dominated by *Aristida meridionalis* over the level sand-covered terrain of the Kalahari.

This in turn gives way to a low type of savanna woodland dominated by *Terminalia prunioides* and *Acacia erubescens* alternating with savanna parkland containing big *Acacia tortilis* and *A. erubescens* trees south of Ngwaku pan (Plate II). Throughout the whole area from Windhoek to Lake Ngami shrub communities characterized by *Catophractes alexandrii* occupy area of calcrete development (Plate IV).

TABLE II
Plant Species characteristic of particular superficial and bedrock geology in the Witvlei area, S.W.A./Namibia

Geological Formation	Type of rock	Outcropping and near surface bedrock	Calcrete cover	Kalahari sand cover	Copper mineralisation
Tertiary to Recent					
Nama	Limestones, quartzites		*Acacia mellifera* } trees *Boscia albitrunca* } *Catophractes alexandrii* shrubs *Leucas pechelli* *Hermannia damarana* } suffrutices *Pseudogaltonia clavata* } *Enneapogon cenchroides* grass	*Terminalia sericea* } trees *Acacia giraffae* } *Tarchonanthus camphoratus* } shrubs *Grewia flava* *Ozorea paniculata* *Stipagrostis uniplumis* } grasses *Schmidtia pappophoroides* }	
Tsumis C	Quartzites				
Tsumis B	Arenites, quartzites, argillites	*Acacia mellifera* } *Acacia hereroensis* } trees *Acacia hebeclada* } *Grewia flava* *Phaeoptilum spinosum* shrubs *Tarchonanthus camphoratus* *Stipagrostis uniplumis* grass	*Acacia giraffae* } trees *Acacia mellifera* } *Catophractes alexandrii* shrubs *Grewia flava* *Leucasphaera bainesii* } suffrutices *Aptosimum leucorrizum* } *Fingerhuthia africana* grass		*Helichrysum leptolepis* *Fimbristylis exilis* *Aristida congesta*
Tsumis A	Basal conglomerate	*Combretum apiculatum* } trees *Albizzia anthelmintica* } *Grewia flavescens* } *Commiphora pyracanthoides* } shrubs *Croton gratissimus* } *Mundulea sericea*			

TABLE III

Plant Species characteristic of particular superficial and bedrock geology in the Ngwaku Pan area, Botswana

Geological Formation	Type of rock	Outcropping and near surface bedrock	Calcrete cover	Kalahari sand cover	Copper mineralisation
Tertiary to Recent	Alluvium moderate to deep sand Very deep sand			*Acacia tortilis*, *A. erubescens* } trees *Eragrostis porosa* grass *Terminalia sericea* trees *Dichrostachys cinerea*, *Bauhinia macrantha*, *Croton gratissimus* } shrubs *Aristida meridionalis*, *Eragrostis horizontalis*, *Stipagrostis uniplumis* } grasses *Lonchocarpus nelsii*, *Croton gratissimus* } shrubs *Aristida meridionalis*, *A. kalahariensis*, *A. hordeacea* } grasses	
Nama					
Tsumis (Ghanzi)	Arenites, quartzites, argillites	*Combretum apiculatum* trees *Terminalia prunioides*, *Acacia erubescens*, *A. leudretzii* } trees	*Catophractes alexandrii* shrubs *Catophractes alexandrii* shrubs		*Echolium lugardae* shrub
Skumok Opdam (Kgwebe)		*Combretum apiculatum*, *Sclerocarya caffra*, *Markhamia acumimata* } trees			

III. EXPLORATION TECHNIQUES

Initial study of existing air photos, combined with reconnaissance flying, distinguished areas characterised by vegetational banding suggestive of near-surface bedrock, from others where irregular distributions of distinctive plant communities indicated the presence of superficial cover of differing thicknesses and contrasting nature.

The confirmation of these relationships by ground reconnaissance lead to the adoption of photogeology, accompanied by geobotany and geochemistry in areas of near-surface bedrock and by biogeochemistry in areas of deep overburden, as the primary exploration and research techniques. Geophysics was subsequently phased in in areas where mineralization was located.

The choice of geobotany as a possible exploration tool was further supported by knowledge of the success attained with this technique in the Dugald River area of Australia, where the environment resembles that at Witvlei (Nicholls *et al.*, 1964).

IV. REGIONAL EXPLORATION

Regional reconnaissance in both South West Africa and Botswana focused on the interpretation of air photos; the elucidation of major vegetational distribution patterns; the detection of geochemical copper anomalies; the establishment of the most suitable species for biogeochemical investigations; the determination of the nature and depth of overburden and the stratigraphical succession and strike of outcropping and sub-cropping bedrock. As a result parallel detailed studies were undertaken at Witvlei, at Sib, around Ghanzi and south of Ngwaku pan.

The specific exploration problems, being related to particular environmental conditions, necessarily differed in each target area. Consequently the applicability of individual techniques varied and the follow-up geochemical, geobotanical and biogeochemical programme assumed different patterns.

A. Witvlei

Areas of anticipated shallow overburden and near-surface bedrock, as suggested by vegetational lineation on air photographs, were selected for orientation studies on the farms located north and west of Witvlei.

Geochemical soil sampling in this area was undertaken across the inferred geological strike and anomalous zones indicated on Fig. 3.

During the initial reconnaissance geobotanical investigations were focused about two major bands of *Helichrysum leptolepis* located on Okasewa, each having a strike length of nearly 1 000 m over sand-covered terrain in which there is no indication of mineralization (Plate V). Random pitting on these bands revealed cupriferous bedrock, assaying up to 4 per cent copper, some 20 cm below surface. A series of transects followed to ascertain the precise relationships between plant species distribution, copper levels in the surface soil and bedrock conditions (Fig. 4). Furthermore a series of six pits was dug to clarify nature of the soil profile (Figs. 5 and 6).

It became very clear that a close relationship does indeed exist between plant distribution, copper levels in the soil and bedrock mineralization. However, trees and shrubs were absent from mineralized zones while *Stipagrostis uniplumis* and *Pogonarthria fleckii*, the typical grasses of the background vegetation, gave way to *Aristida congesta* and the labiate *Ocimum americanus* over the wider geochemical anomalies caused by secondary dispersion, and to *Helichrysum leptolepis* over the peak copper values associated with bedrock mineralization. Patches of *Helichrysum leptolepis* proved to be infallible guides to underlying mineralization in bedrock.

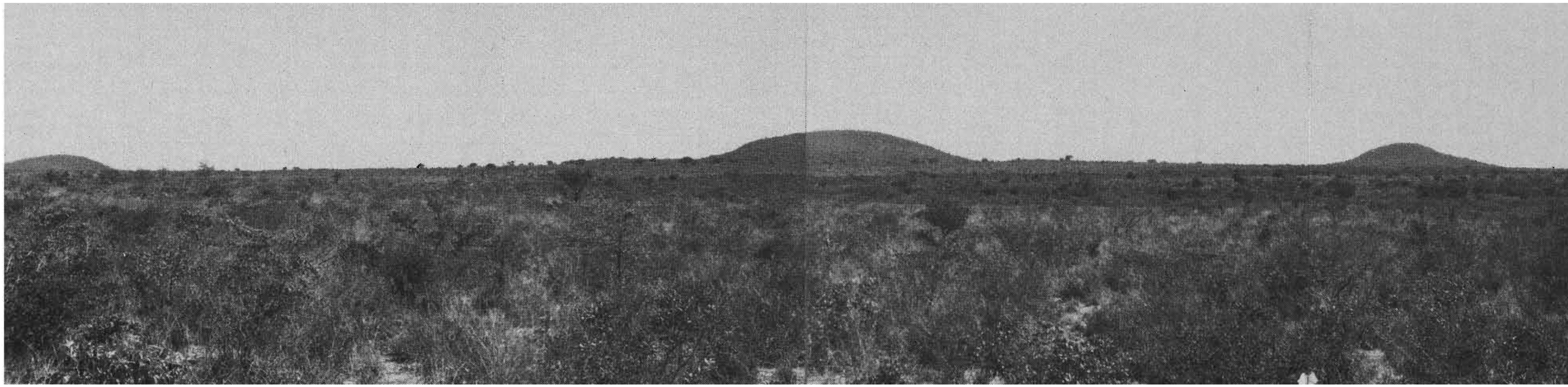


Plate III

View westwards to the Mabele-a-Pudi hills of outcropping K'Gwebe quartz porphyry from Potts road, N'Gamiland. In the foreground shrub vegetation characterized by *Grewia flava, Terminalia sericea, Croton gratissimus,* over deep Kalahari sand.
(Ref. MMC/Bot. 15/21-24)

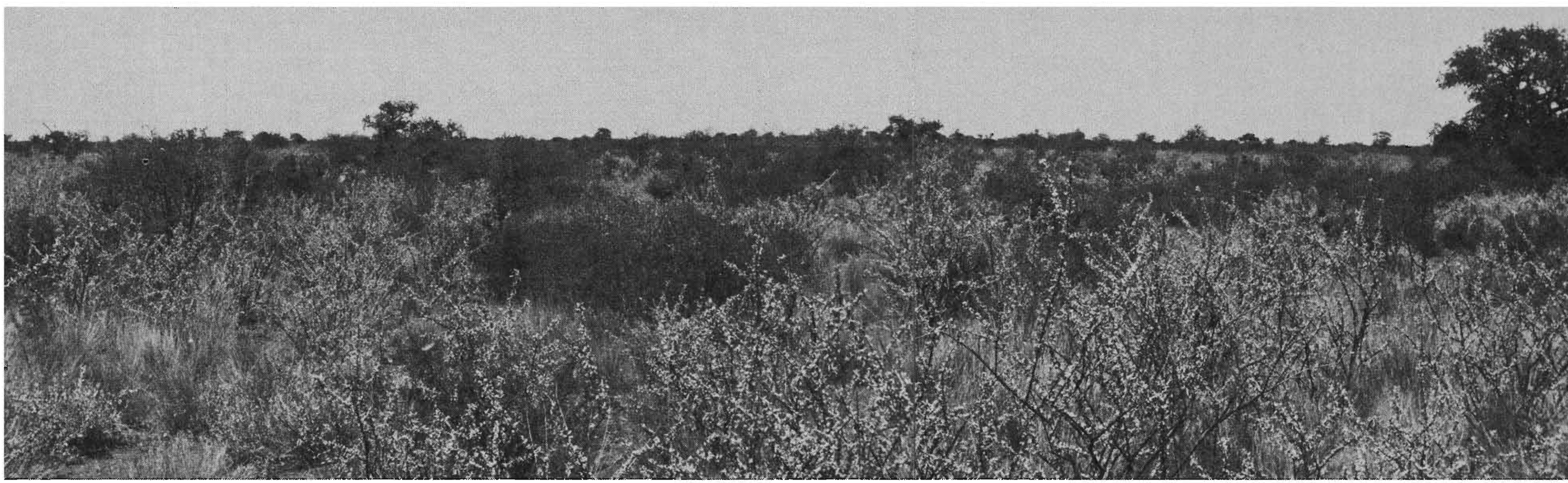


Plate IV

Vegetational banding reflecting lithology in folded strata north of Ghanzi. Belt of *Catophractes alexandrii* in foreground succeeded in turn by one characterized by *Grewia flava* (dark shrubs) behind, another characterized by small *Petalidium englerianum* (pale grey shrubs) and another of *Catophractes alexandrii.*
(Ref. MMC/Bot. 12/7–11)

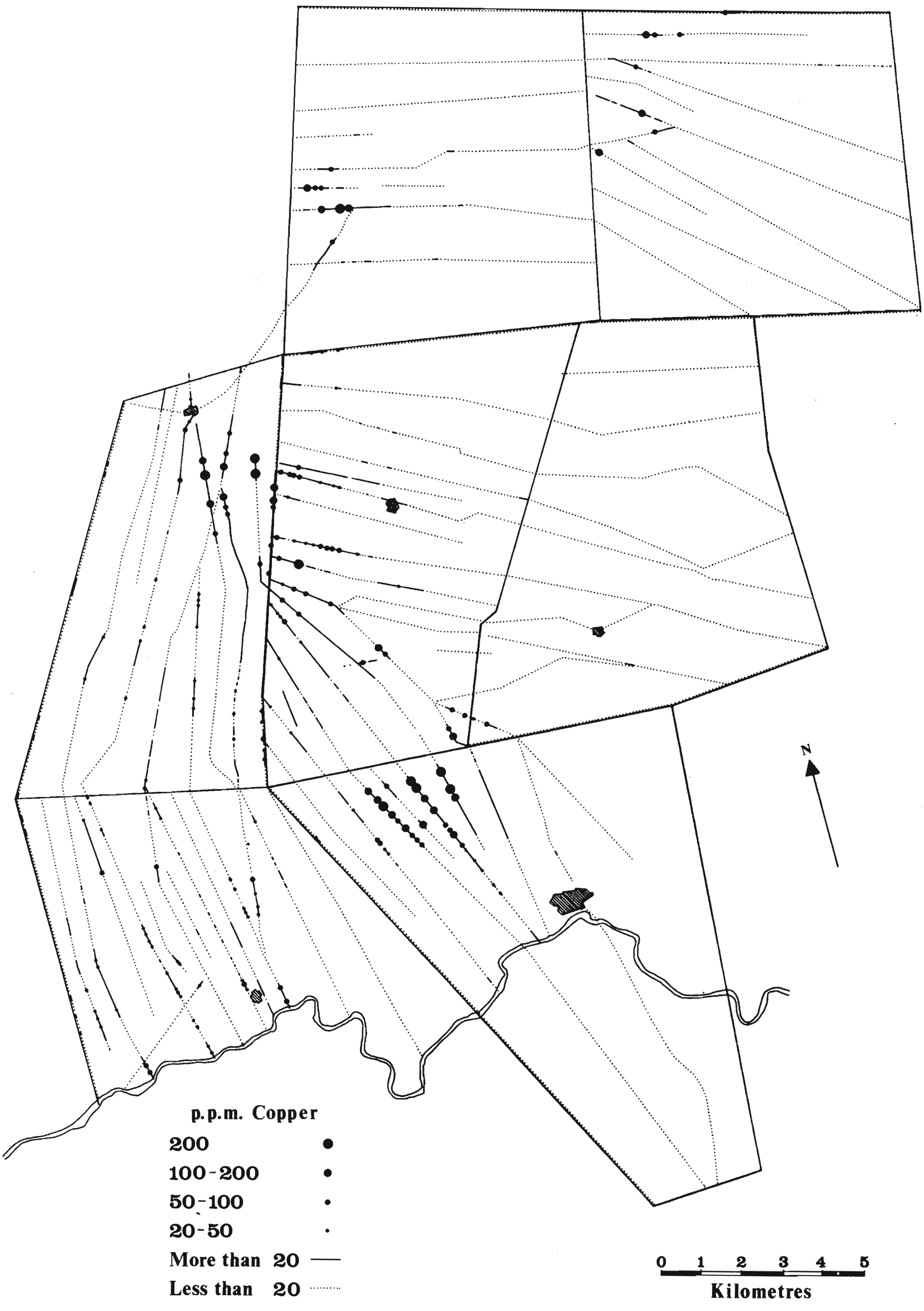


Figure 3
Results of geochemical soil sampling programme in the Witvlei area. (Sampling by E. W. R. Miller and Associates. Analyses by Anglovaal laboratory, Windhoek. Presentation of results by Bedford College.)

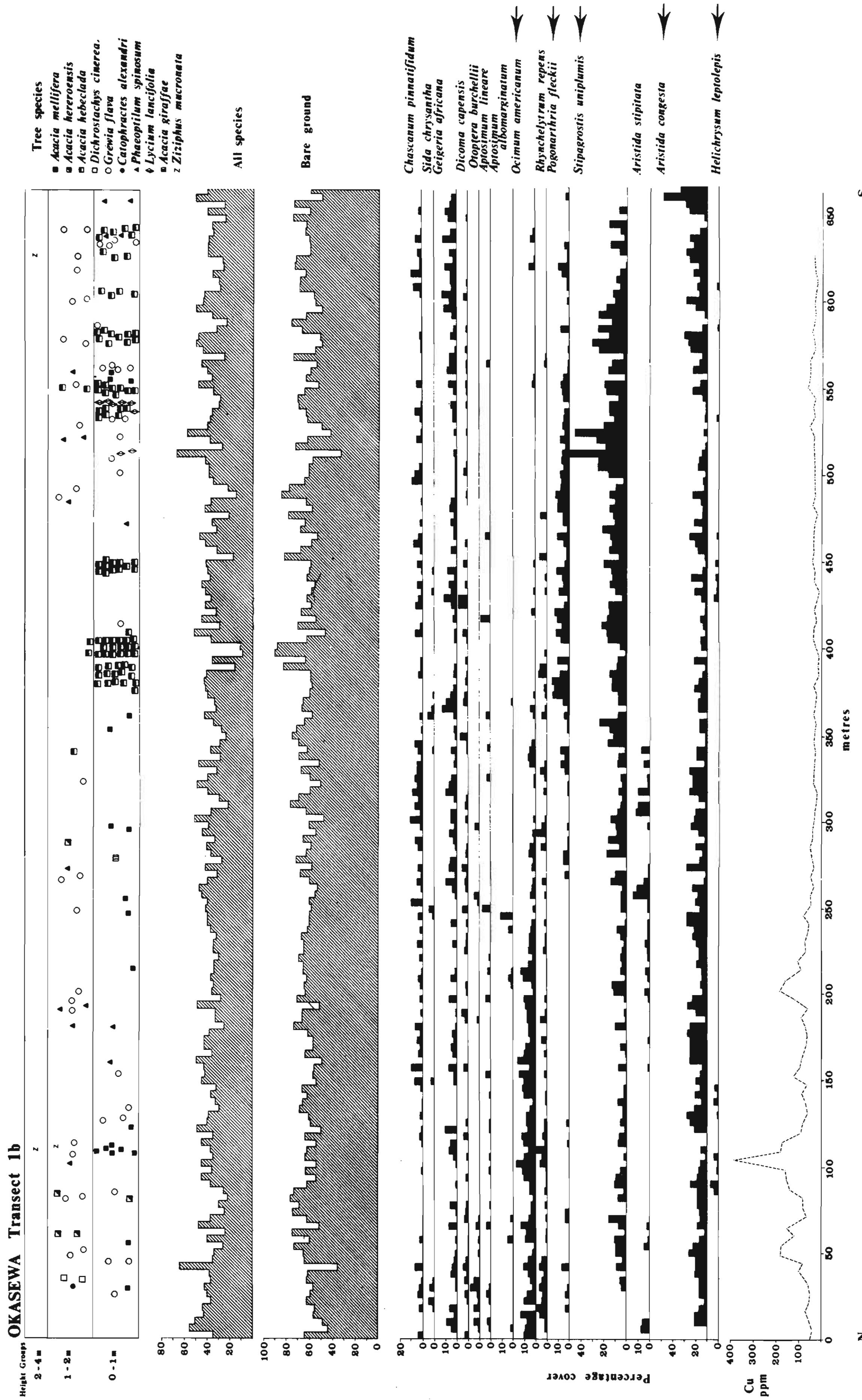


Figure 4

Transect 1b on farm Okasewa. Histogram showing the distribution of plant species and the copper levels in the −80 mesh fraction of the soil sampled at 10–15 cm depth. (Recording and sampling by L. Coupland and J. Cudmore, 1967. Analyses by Anglovaal laboratory, Windhoek.)

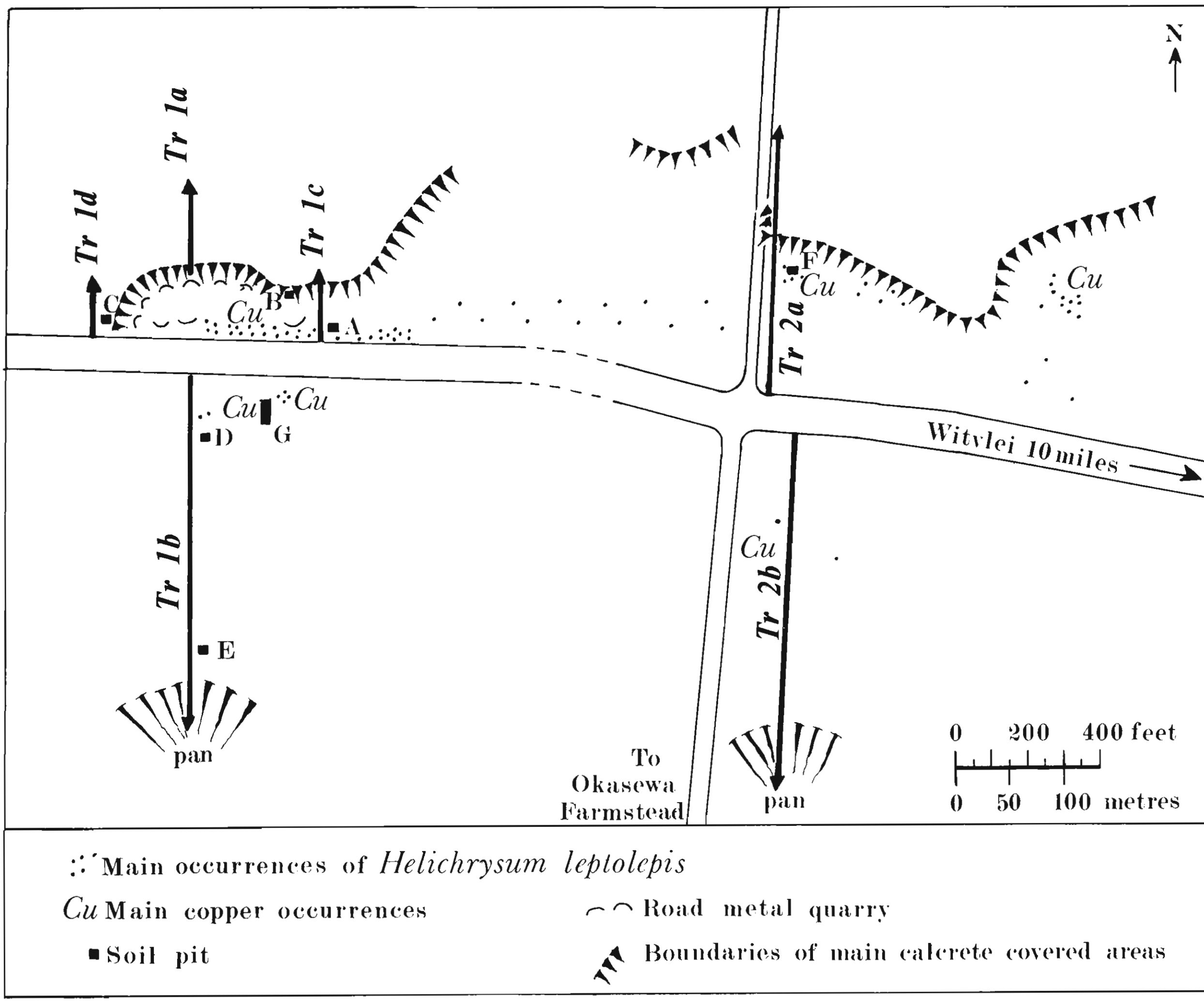


Figure 5

Plan showing the distribution of *Helichrysum leptolepis* copper occurrences and location of transects and pits on the farm Okasewa, west of Witvlei, South West Africa. (Fieldwork by L. Coupland and J. Cudmore, 1967.)

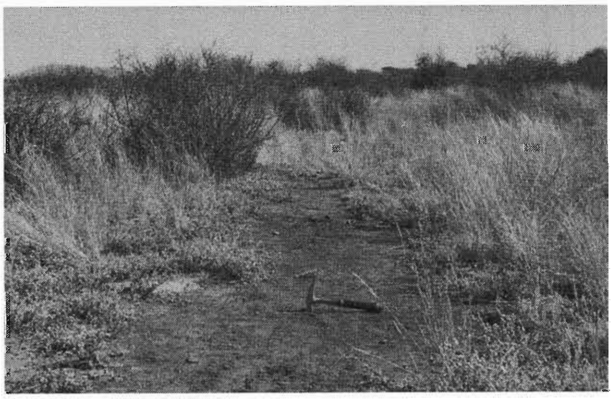


Plate V

Ground bare of vegetation bordered by belts of *Helichrysum leptolepis* south of the Windhoek–Witvlei road on the farm Okasewa, west of Witvlei. This revealed the first zone of copper mineralization in sub-outcropping argillite concealed by sand cover to be found by geobotany. Background vegetation of *Grewia flava* (left), *Acacia hereroensis* (background) shrubs and *Stipagrostis uniplumis* grass.
(Ref. MMC/SWA 2/24)

The pits revealed that while there is an average depth of about 15 to 20 cm of sandy soil overlying weathered bedrock, the cover is shallower over mineralized beds (Fig. 7). They also showed that near-surface calcrete boulders are associated with massive calcrete at 6 m depth.

Geochemical soil anomalies ranging as high as 450 ppm next focused attention upon the farm Okatjirute, on which the village of Witvlei is located (Fig. 8(a)). Here two broad bands of *Helichrysum leptolepis,* each over 1 000 m in length, were proved by pitting to overlie cupriferous argillites and arenites. Further reconnaissance across the adjoining farms Okatjirute West and Eskadron led to the discovery of still additional developments of *Helichrysum leptolepis* (Plate VI) over mineralized bedrock. These localities named and referred to later as the Copper Causeway and Malachite Pan areas, became important targets for detailed surface exploration that included subsequent drilling.

In the above areas, and even farther south on the farm Sib near Dordabis, the small and delicate plant *Fimbristylus exilis* occurs intimately associated with *Helichrysum leptolepis* and the peripherally developed pioneer grass *Aristida congesta.* They collectively comprise an anomalous assemblage of plants.

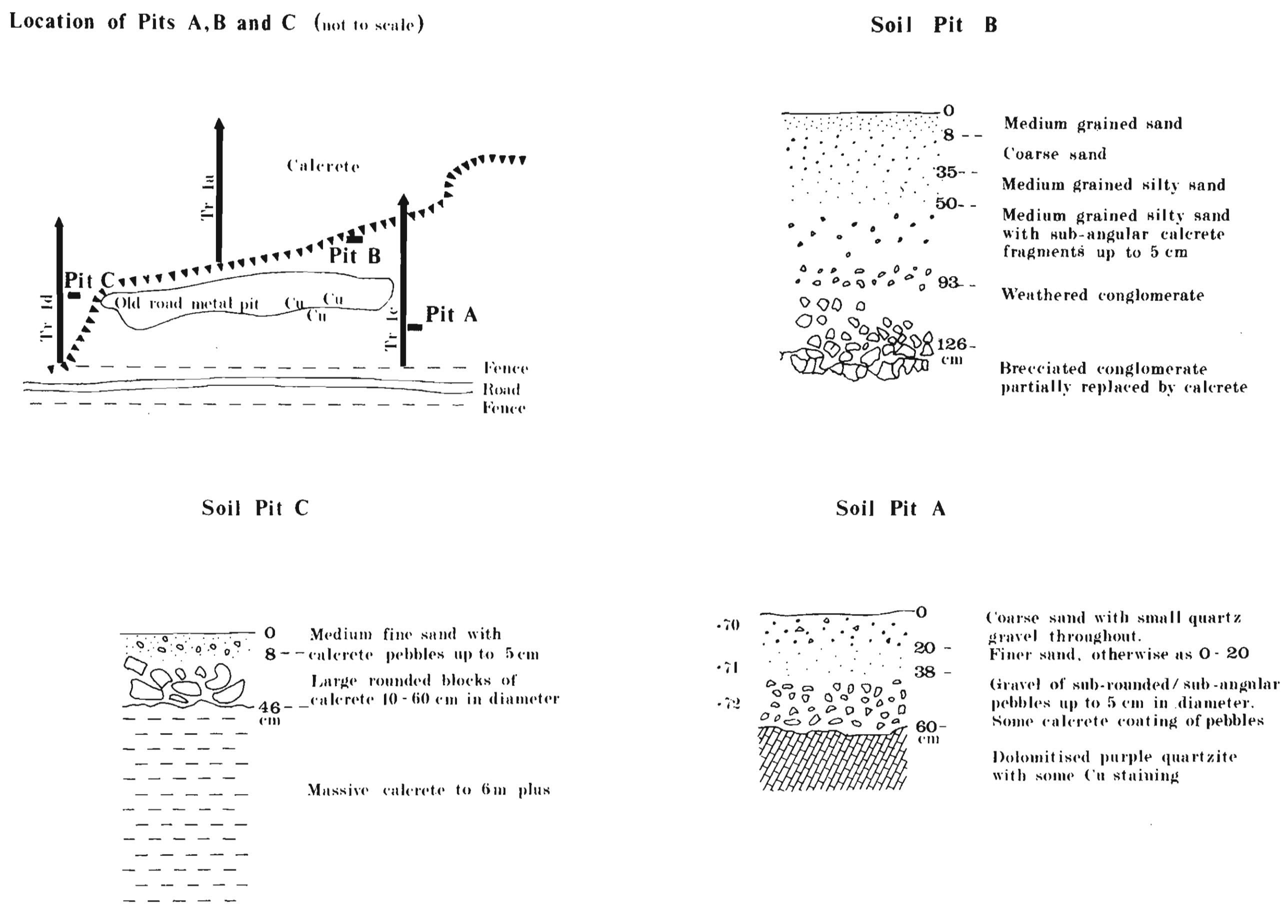


Figure 6
Soil profiles exposed in pits dug on the farm Okasewa. (Recording and sampling by L. Coupland and J. Cudmore, 1967.)

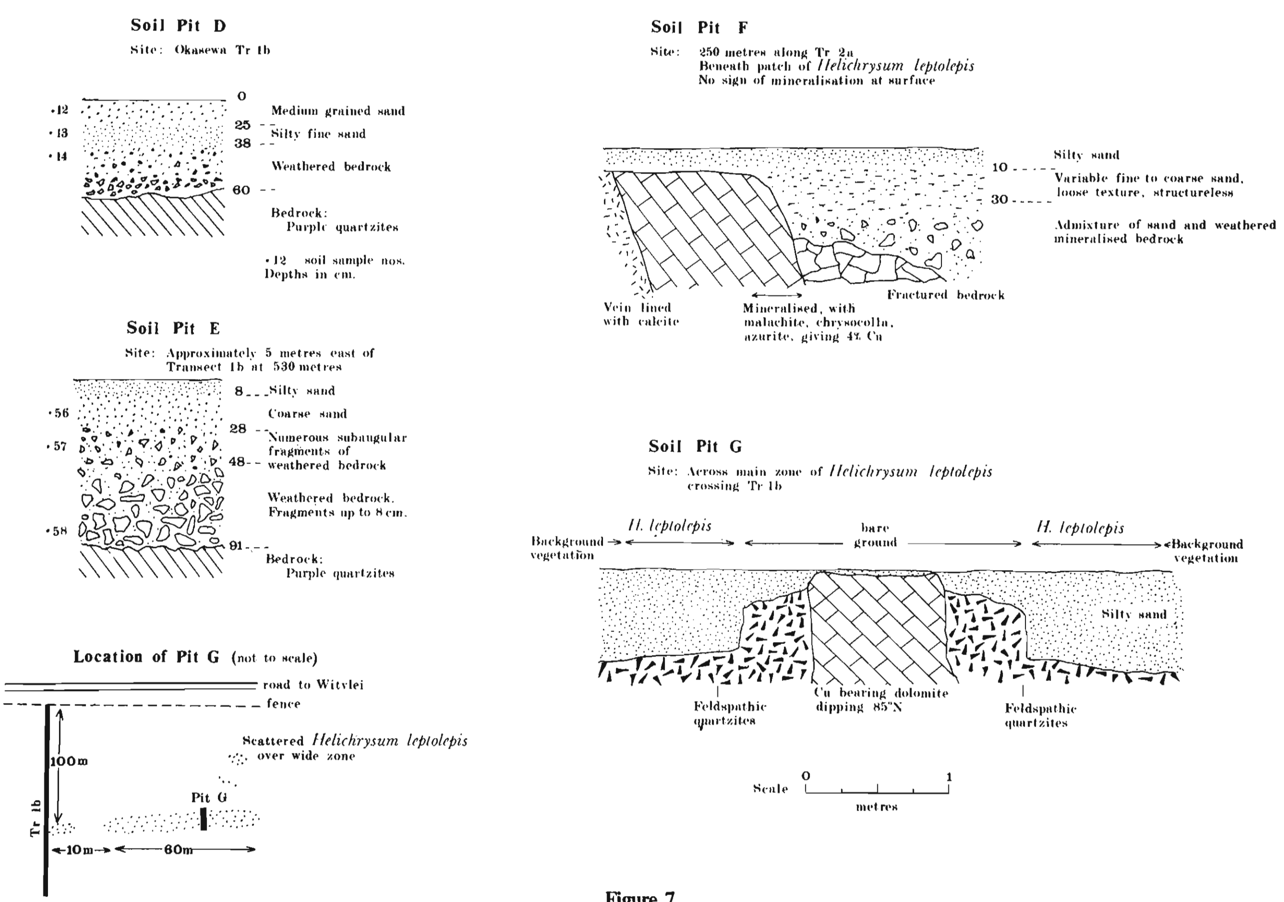


Figure 7
Soil profiles exposed in pits dug on farm Okasewa. (Recording by L. Coupland and J. Cudmore, 1967.)

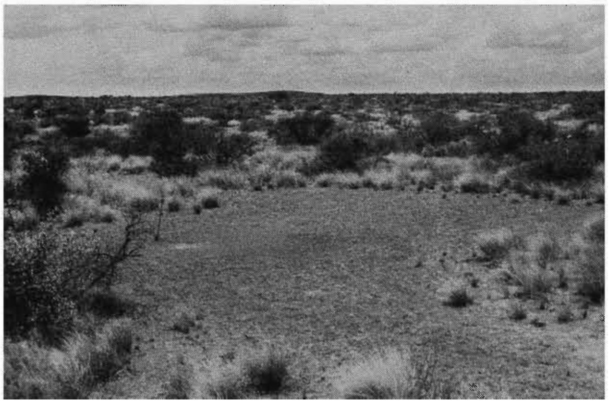


Plate VI
View west-north-westwards over geobotanical anomaly produced by *Helichrysum leptolepis* and *Fimbristylis exilis* ex *hispidula* replacing the background vegetation characterized by *Acacia mellifera* (right foreground) and *A. hereroensis* trees, *Grewia flava, Tarchonanthus camphoratus* shrubs and *Stipagrostis uniplumis* grass over sub-outcropping copper bearing argillite concealed by dark red sandy soil on Okatjirute West farm north of Witvlei. This area became known as the Copper Causeway.
(Ref. MMC/SWA 14/26)

A second orientation geobotanical/geochemical investigation was undertaken along two transects, one on Okatjirute and the other on Okatjirute West. The former, orientated at right angles to strike, was paralleled by a trench that was thereafter referred to as the Witvlei trench transect. The latter was orientated to cross the major geobotanical anomalies in the Copper Causeway areas where the strike could not be inferred. These investigations were undertaken in August 1966 when vegetation had been reduced by drought, but more detailed work was done here under optimum conditions after the rains in March 1967. The comparative results are shown in Figs. 8(a), 8(b), 9(a), 9(b).

Here again several important relationships between plant distributions and bedrock mineralization emerged, in that trees are absent and vegetation sparser and poorer in species composition over the succession of grey and reddish-brown arenites that interbedded with cupriferous argillite along the northern portion of the transect, than in the flanking non-mineralized arenites farther south.

Furthermore, striking variations are present in the development of herbs and forbs that show an antipathetic relationship to anomalous copper content in the soils. The dominant grass, *Stipagrostis uniplumis,* is absent over those zones where the copper content in the −80 mesh soil fraction, sampled at 10 to 15 cm depth, exceeds 300 ppm. *Helichrysum repens* and *Pogonarthria fleckii,* which occur less frequently, are absent from areas where the level is more than 200 ppm. The shrub *Barleria lanceolata* and the grass *Aristida congesta,* however, occur only in soils containing anomalous amounts of copper, with the latter becoming progressively more abundant as the copper level exceeds 200 ppm. *Helcihrysum leptolepis* and *Fimbristilus exilis* alone occupy those bands where copper values exceed 300 ppm.

At Witvlei the frequency of *Acacia hereroensis* and, compared with Okasewa, the greater abundance of *Catophractes alexandrii* is attributable to the more calcareous environment which, along strike, becomes increasingly marked towards a borehole in the Pos area on Okatjirute West. Here near-surface copper mineralization occurs in primary limestone.

On the farm Okatjirute West numerous patches of *Helichrysum leptolepis* which produced a complex distributional pattern were found to characterize the Copper Causeway area. Evidence of two orientations emerged; the stronger one, embracing two large circular occurrences linked by several smaller ones, trended north-north-east–south-south-west, slightly transgressing the geological strike which could be determined from isolated outcrops; the weaker one, consisting of several narrow corridor-like bands, trended west-north-west. The occurrences of *Helichrysum leptolepis* were mapped on a scale of 1 cm to 60 m while a date-recording and sampling transect was sited to bisect both the large circular patches and also a series of smaller areas where the plant occurred only sporadically (Fig. 10). The results (Figs. 10 and 11) revealed a major geochemical anomaly with copper values in the surface soil exceeding 100 ppm over a width of 200 m and with four major peaks, one exceeding 700 ppm. As at Okasewa and in the vicinity of the Witvlei trench, trees and shrubs were absent from sites where the −80 mesh fraction of the surface soil contained more than 300 ppm copper, and only small specimens of *Acacia hereroensis, A. hebeclada, Boscia albitrunca, Grewia flava* and *Phaeoptilum spinosum* occurred at the periphery of the highly anomalous zone. Within the broader soil-copper anomaly a greater variety of species and a prolific development of larger individuals in the background cover occurred. Here again striking changes in the ground layer were evident where only *Helichrysum leptolepis* and *Fimbristylis exilis* grow over the peak copper values with *Aristida congesta* occupying the peripheral zones of lower values.

With the abovementioned orientation data to hand, the different vegetation associations in the Witvlei area were mapped by air photo interpretation followed by field control investigations, whereas the depth of overburden was determined by seismic techniques. Close relationships between vegetation, overburden and bedrock geology were revealed (Figs. 12, 13 and 14).

The low tree and shrub savanna association characterized by *Terminalia sericea* and *Acacia giraffae* trees with the shrubs *Tarchonanthus camphoratus, Grewia flava, Orozoa paniculosa* and *Rhus ciliata* and the grasses *Stipagrostis uniplumus* and *Schmidtia pappophoroides* (3 on Fig. 12) is virtually coincident with areas of deep sand cover. Where thick accumulations occur at the foot of the Witvlei Berg and around quartzite hills along the northern boundary of Okatjirute, *Grewia retinervis* is also present. The sand cover everywhere exceeds 5 m and reaches 30 m in the southern part of Okatjirute where geological investigations established the presence of underlying Buschmannsklippe and Tsumis C formations that are unfavourable for copper mineralization.

Four distinct types of low tree and/or shrub savanna distinguish areas of disparate calcrete development. The first, composed of an association of *Acacia giraffae* and *Acacia mellifera* trees, *Catophractes alexandrii* and *Grewia flava* shrubs, *Leucasphaera bainesii* and *Aptosimum leucorrhizum* suffrutices and *Fingerhuthia africana* grass, characterises a series of calcrete ridges crossing the southern part of Eskadron and the central part of Okatjiruta West. A grassland dominated by *Stipagrostis uniplumis* covers the intervening sand-filled depressions which may be underlain by calcrete. The total overburden, mostly calcrete, is 5 to 23 m thick so outcrop is limited. However, on the farm Eskadron dense shrub vegetation along the curved crests of the calcrete ridges outlines the suboutcrop of a southerly plunging syncline. A second type consisting of an association of *Acacia mellifera* and *Boscia albitrunca* trees with *Catophractes alexandrii* shrubs, the suffrutices *Leucas pechelli, Hermania damarana* and *Pseudogaltonia clavata* and the grass *Enneapogon cenchroides* (4 on Fig. 12) occupies areas covered by extensive sheets of calcrete that range from 10 m to more than 36 m in thickness, and that probably overlie limestones and shales of the Buschmannsklippe formation. Where these beds are capped by thin

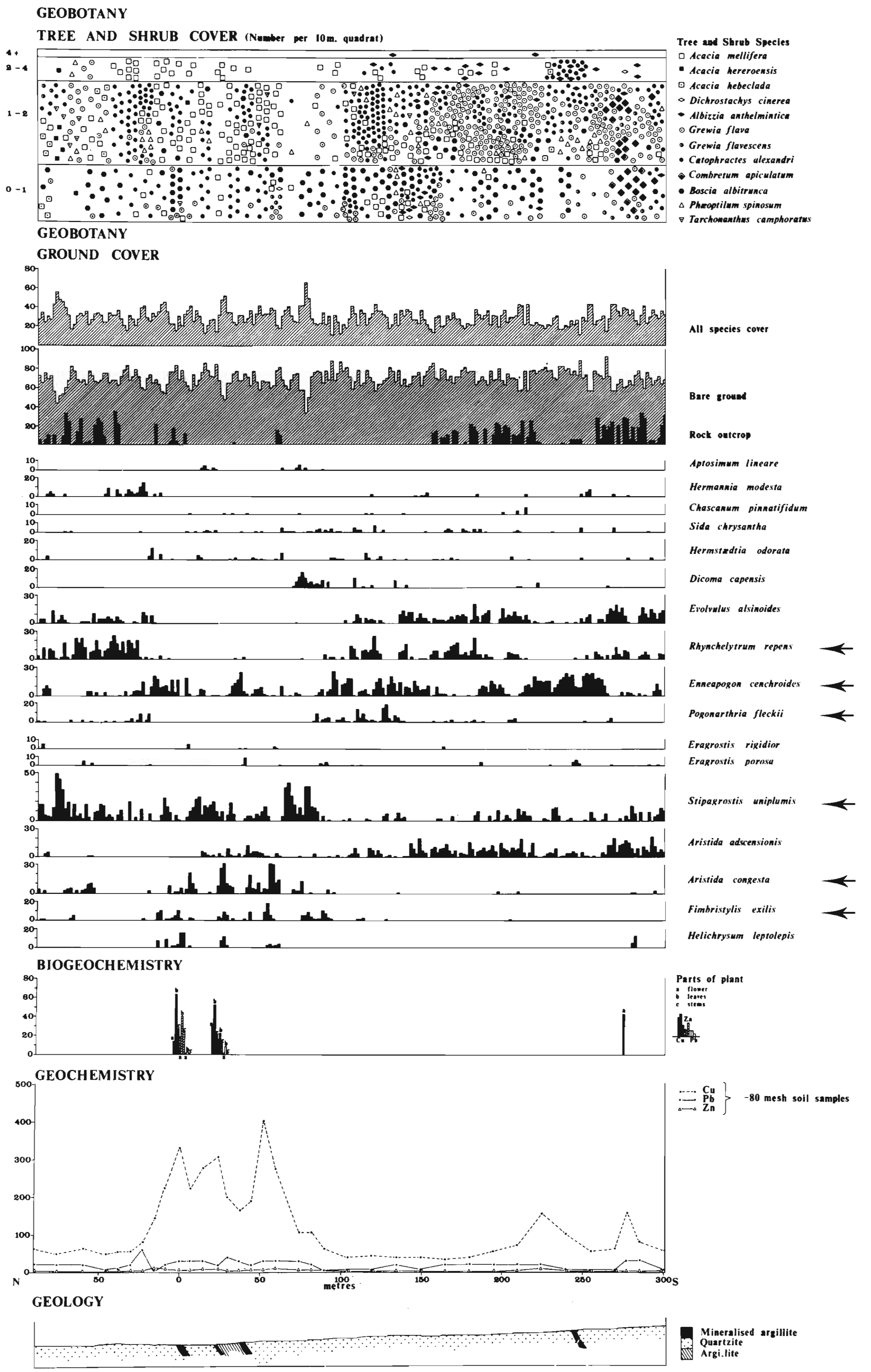


Figure 8 (a)

Reconnaissance transect undertaken in 1967 parallel to the main trench M6(3) on the farm Okatjirute, Witvlei, showing the distribution of plant species, copper, zinc and lead values in the −80 mesh fraction of the soils sampled at 10–15 cm, and in the samples of *Helichrysum leptolepis*, relief and geology. (Recording and sampling by L. Coupland and J. Cudmore. Soil analyses by Anglovaal laboratories, Windhoek. Presentation of results by Bedford College.)

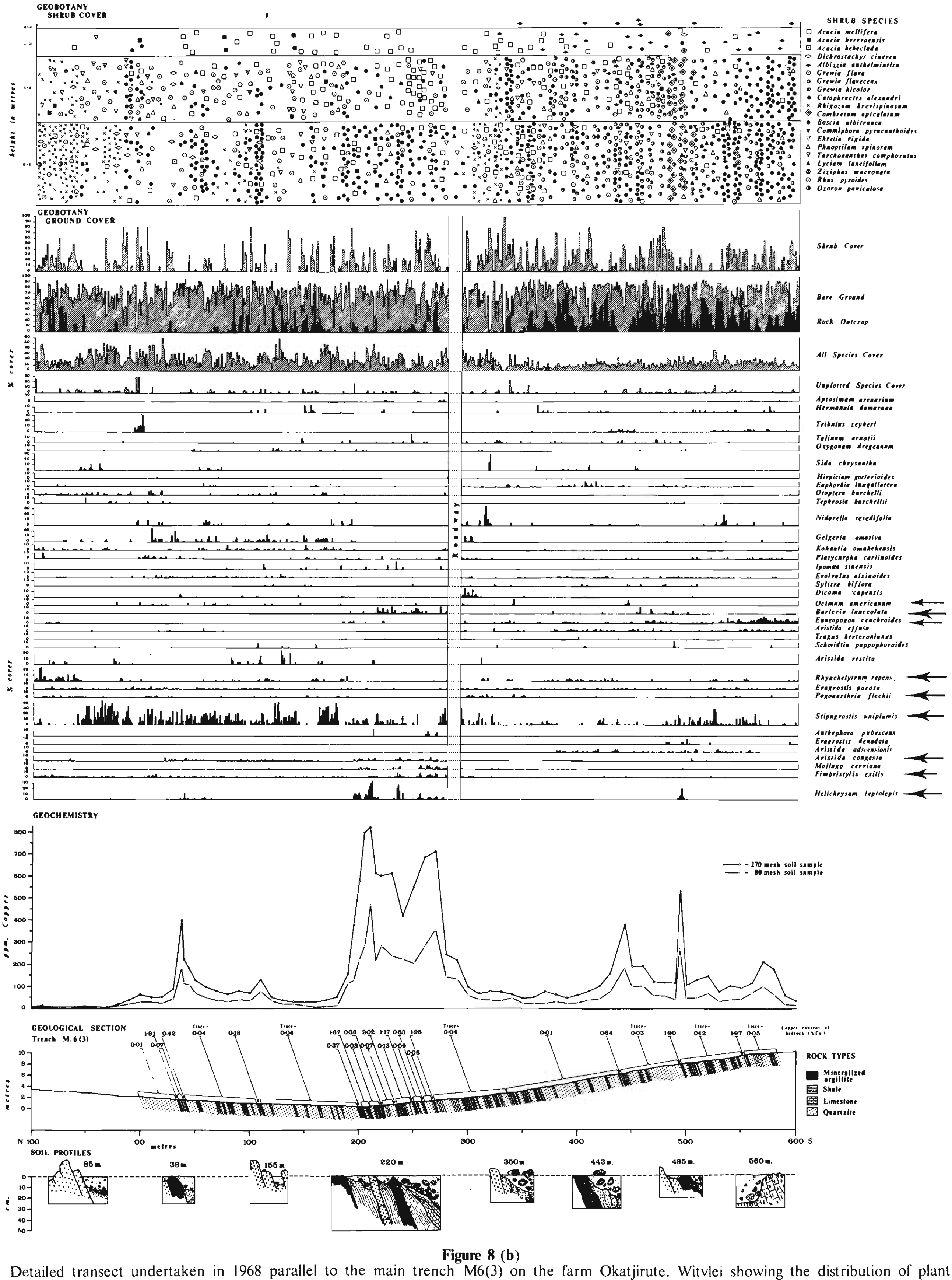


Figure 8 (b)
Detailed transect undertaken in 1968 parallel to the main trench M6(3) on the farm Okatjirute, Witvlei showing the distribution of plant species, copper levels in the −80 mesh and −270 mesh fractions of soils sampled at 10–15 cm depth, relief, geology and copper values in bedrock. (Recording and sampling by M. Mason, analyses by Bedford College laboratories.)

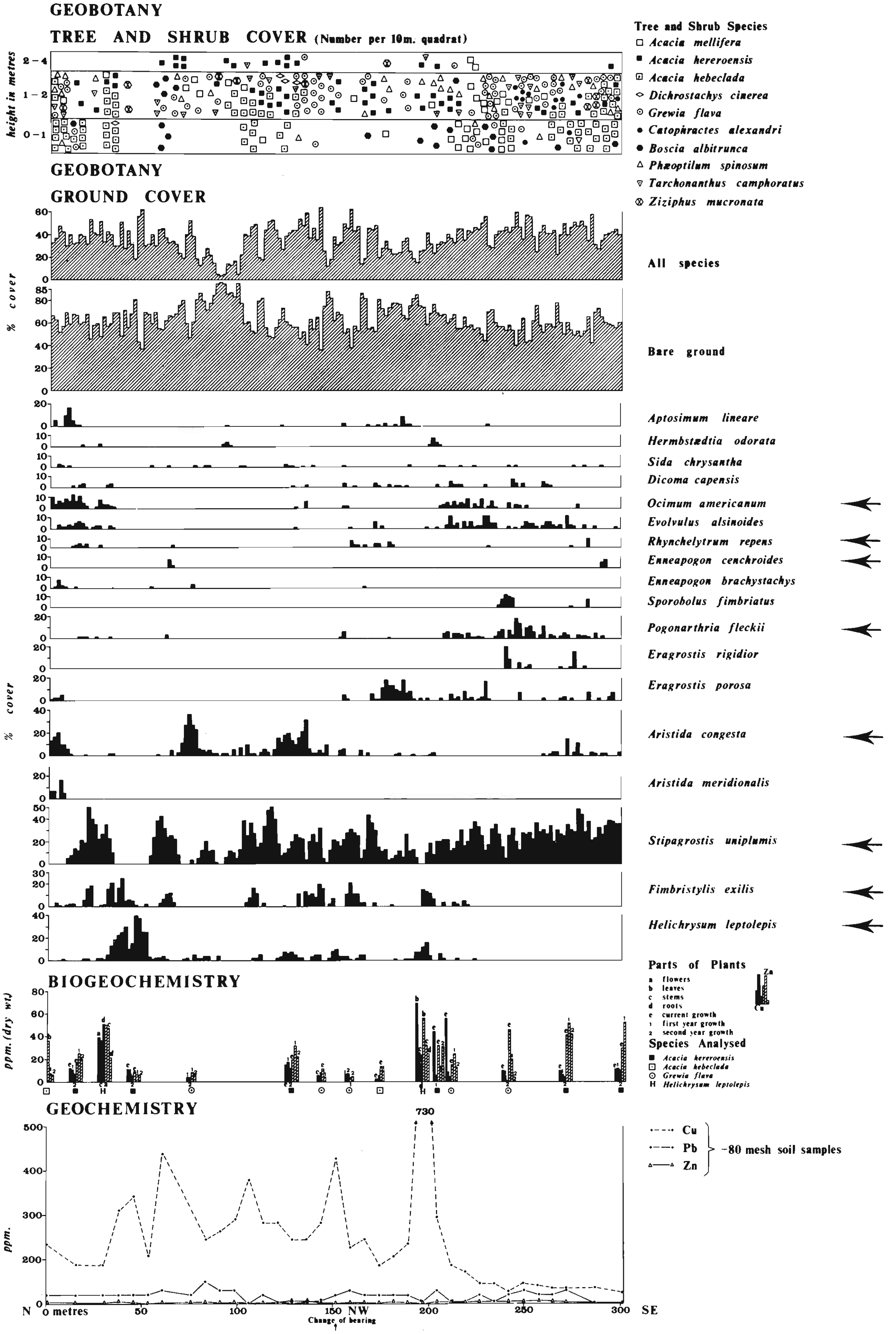


Figure 9 (a)

Reconnaissance transect undertaken in 1967 across the main geobotanical anomaly at the Copper Causeway, farm Okatjirute West, showing the distribution of plant species, copper, zinc and lead values in the –80 mesh fraction of soils sampled at 10–15 cm depth, and in samples of four plant species. (Recording and sampling by L. Coupland and J. Cudmore. Soil analyses by Anglovaal Laboratories, Windhoek. Plant analyses by Bedford College laboratories.)

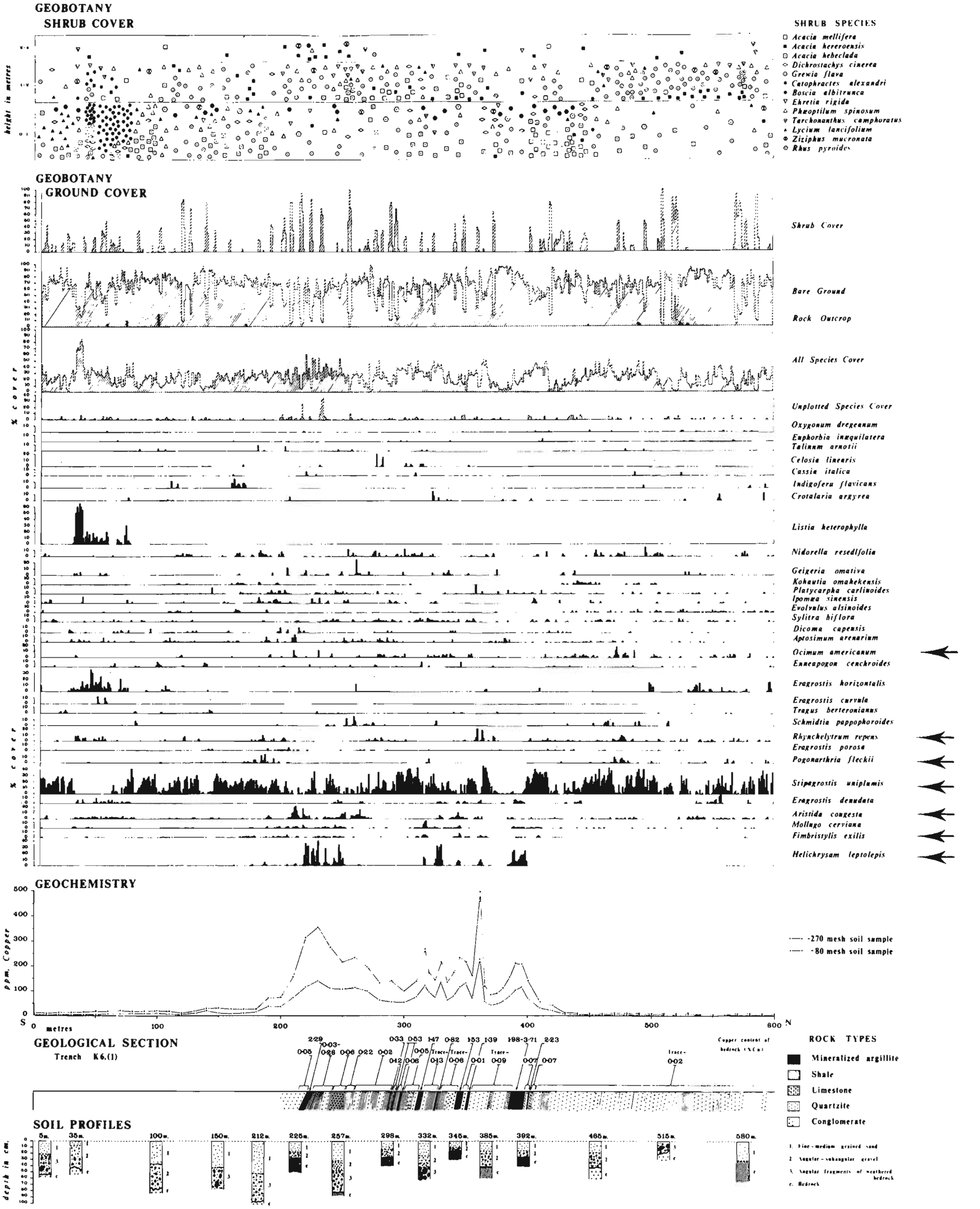


Figure 9 (b)

Detailed transect No. 55 undertaken in 1968 parallel to the trench K6(1) across the eastern periphery of the main geobotanical anomaly, Copper Causeway, farm Okatjirute West showing the distribution of plant species, copper levels in the −80 mesh and −270 mesh fractions of the soils sampled at 10–15 cm depth, relief, soil profiles, geology and copper values in bedrock. (Recording and sampling by M. Mason, analyses by Bedford College laboratories.)

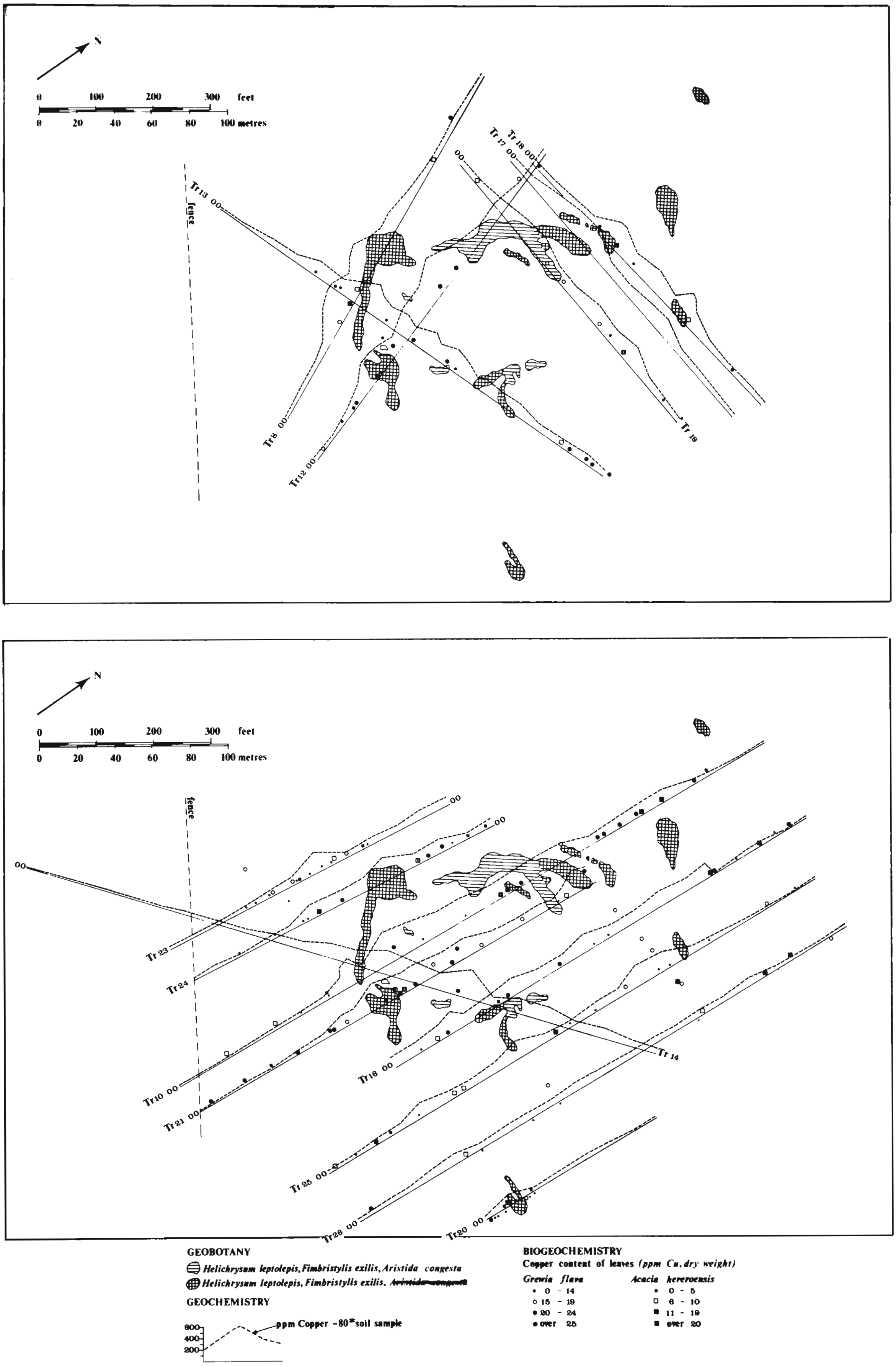


Figure 10

Copper values in the −80 mesh fraction of soils sampled at 10–15 cm depth and in plant species sampled along a series of transects in the Copper Causeway area, farm Okatjirute West, Witvlei. The main trench is parallel to and slightly east of Trench 24. (Geobotany by L. Coupland, J. Cudmore and M. M. Cole in 1967. Sampling by M. Mason and A. F. Boshoff as well. Analyses by Bedford College laboratories.)

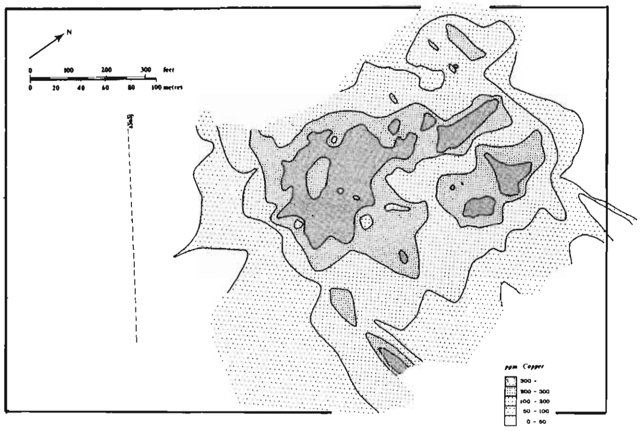


Figure 11
Isopleth map showing the distribution of copper values in the soils sampled at 10–15 cm depth in the Copper Causeway area, farm Okatjirute West, Witvlei area. (Based on sampling and analyses by Bedford College and Anglovaal Staff.)

calcrete or actually outcrop, as in the south of Grunental, a third type of shrub savanna consisting of *Catophractes alexandrii* and *Grewia flava* with suffrutices *Leucasphaera bainesii, Hermania damarana, Pseudogaltonia clavata, Pegolettia pinnatiloba* and the grass *Fingerhuthia africana* occurs. The same association also straddles the inferred unconformity between the Tsumis and Buschmannsklippe formations on the north of Grunental where the calcrete and sand overburden may be 5 to 15 m thick. A fourth type of tree/shrub savanna comprising *Acacia giraffae, A. karroo, A. hebeclada* and *Zizyphus mucronata* trees defines fossil drainage lines and pans which are floored by calcrete.

The differences in the vegetation cover over different thicknesses of calcrete are believed to be related to availability of additional water below the thicker accumulations. Here analyses of the leaves and twigs of deeply rooted shrubs and trees are considered more likely to detect bedrock mineralization than analyses of surface soils.

A study of the 1 : 28 000 aerial photographs covering the farm Eskadron established that two distinctive low tree and shrub savanna associations demarcate respectively areas of outcropping bedrock, and of shallow overburden less than 5 m thick. The one association comprised of *Combretum apiculatum* and *Albizia anthelmintica* trees and *Grewia flavescens, Commiphora pyracanthoides, Croton gratissimus* and *Mundelea sericea* shrubs outlines the conglomerate ridge of the Witvlei berg and the quartzite hills of Eskadron, Okatjirute and Grunental (1 on Fig. 12). The other comprising a disparate association of *Acacia hereroense, A. mellifera* and *A. hebeclada* trees with *Grewia flava, Phaeoptilum spinosum* and *Tarchonanthus camphoratus* shrubs and the grass *Stipagrostis uniplumis* (2 on Fig. 12) covers a broad belt of shallow overburden extending from the western border of Grunental through Eskadron and Okatjirute West into Okatjepuiko. Here plant distributions over different lithologies such as arenites and argillites closely reflect geological contacts, regional strike, faulting, fold structures and even the trend of specific mineralized beds. The areas marked 1 to 5 on Fig. 15 substantiate this.

To obtain a still fuller appreciation of the roles played by geobotany, biogeochemistry and geochemistry in mineral exploration, data recording and plant/soil sampling was undertaken along a series of transects in the Copper Causeway area where strong but complex geobotanical and geochemical anomalies had been disclosed during initial orientation studies. The transects crossed each known *Helichrysum leptolepis* anomaly and extended well into the background vegetation (Fig. 10). Trenches M 6(3) and K (6)1 were dug parallel to and east of Transect 24, and between transects 10 and 21 to provide still additional information.

The new geochemical sampling results revealed a marked copper anomaly in the surface soil with values exceeding 50 ppm over an area measuring approximately 230 m from north to south and 320 m from west to east that extends beyond the area sampled. The distribution of the plus 300 ppm soil values, considered together with the peak copper values in the plants, suggested that the mineralized beds had been folded.

A study of the trench sections clearly established a sympathetic relationship between the distribution of *Helichrysum leptolepis, Fimbristylis exilis, Aristida congesta* and the presence of copper values in surface soil and bedrock mineralization. Eight bands of mineralized argillite, the widest of which measured about 8 m, were shown to be present adjoining and below the large, circular patch of *Helichrysum leptolepis* and *Fimbristylus exilis* where the peak copper value of 750 ppm was obtained. The local geological succession and the distribution coupled to vegetation associations over a wider area suggests duplication of strata by folding.

Although the soil anomalies located during initial reconnaissance and orientation surveys in the Witvlei area were well defined, the copper levels obtained from analysing the −80 mesh fraction of soil taken at a depth of 10 to 15 cm below surface were low relative to what could have been expected above near-surface bedrock mineralization. To ascertain the reason for this and to determine optimum sampling and processing procedure for areas covered by surficial Kalahari sediments, investigations were undertaken of the particle size distribution, the copper content of different particle size soil fractions and also of the copper dispersion pattern through a calcrete/soil overburden profile.

As a first step in this direction mechanical analyses were done on bulk soil samples obtained from trench sections on Okatjirute West.* These revealed excessively low silt and clay contents, whereas sand and gravel fractions comprised from 90 per cent to over 95 per cent of the total. The particle size distributions for two of the samples are shown in Fig. 16. Sample 1818 was collected at a depth of 5 cm immediately above copper-bearing argillite exposed in trench K 6(4) on the Copper Causeway, and sample 1965 in sand at a depth of 30 cm immediately above copper-bearing limestone exposed in trench H7 north of Okatjirute West homestead. Sample 1818 consisted largely of fine- and medium-grained sand with smaller quantities of coarse sand and gravel. The combined silt and sand content was 2,16 per cent and the estimated clay content less than 0,1 per cent. Sample 1965 consisted almost entirely of fine- to medium-grained sand and contained only 0,8 per cent combined silt and clay, and a quantity of clay too small to be measured.

The studies showed that even above near-surface argillite the soils consist largely of windblown sand admixed with only minor amounts of clay. This high sand content is partially accounted for by composition of the argillites that consist essentially of relatively coarse silt particles falling in the size range 0,004 to 0,006 mm. Adjoining arenites that have suffered planation also contribute to the sand content. As trace element copper is normally absorbed by clay colloids present in organic matter it follows that under these conditions only low-order copper values can be expected even immediately above near-surface cupriferous argillite bedrock.

*The samples were dry sieved using a set of sieves ranging from 12700 to 53. The amount of soil retained on each sieve was recorded and an accumulative weight per cent curve drawn from the sample. The particle size distribution of the finest fraction, i.e. smaller than 53 was determined by means of a Coulter Counter.

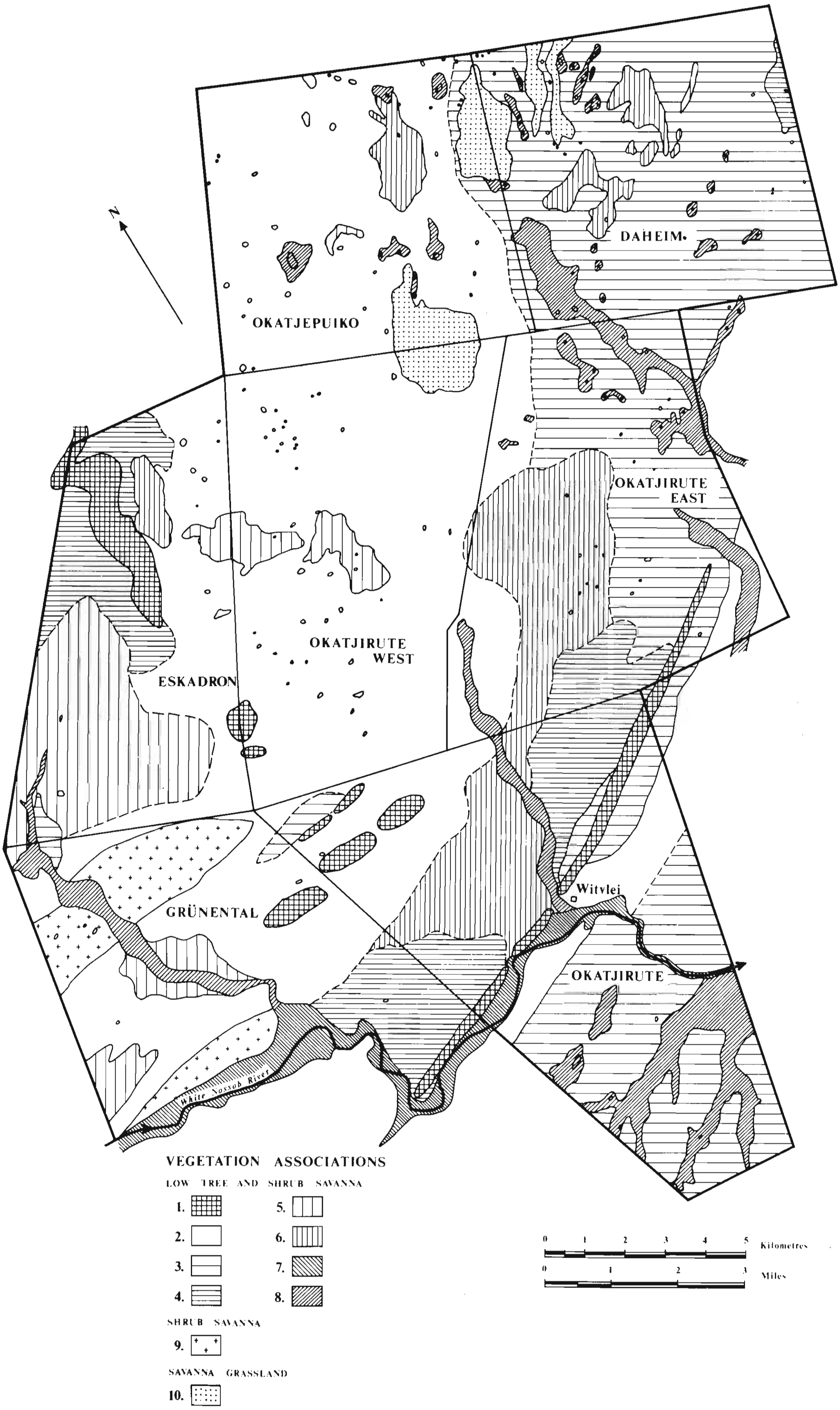


Figure 12

Distribution of vegetation associations in the Witvlei grant area, based on air photo interpretation and field investigation by M. Mason. Relationship to depth of overburden and bedrock geology emerges from comparison with Figures 11 and 13 respectively. For further details regarding numbering see Appendix III.

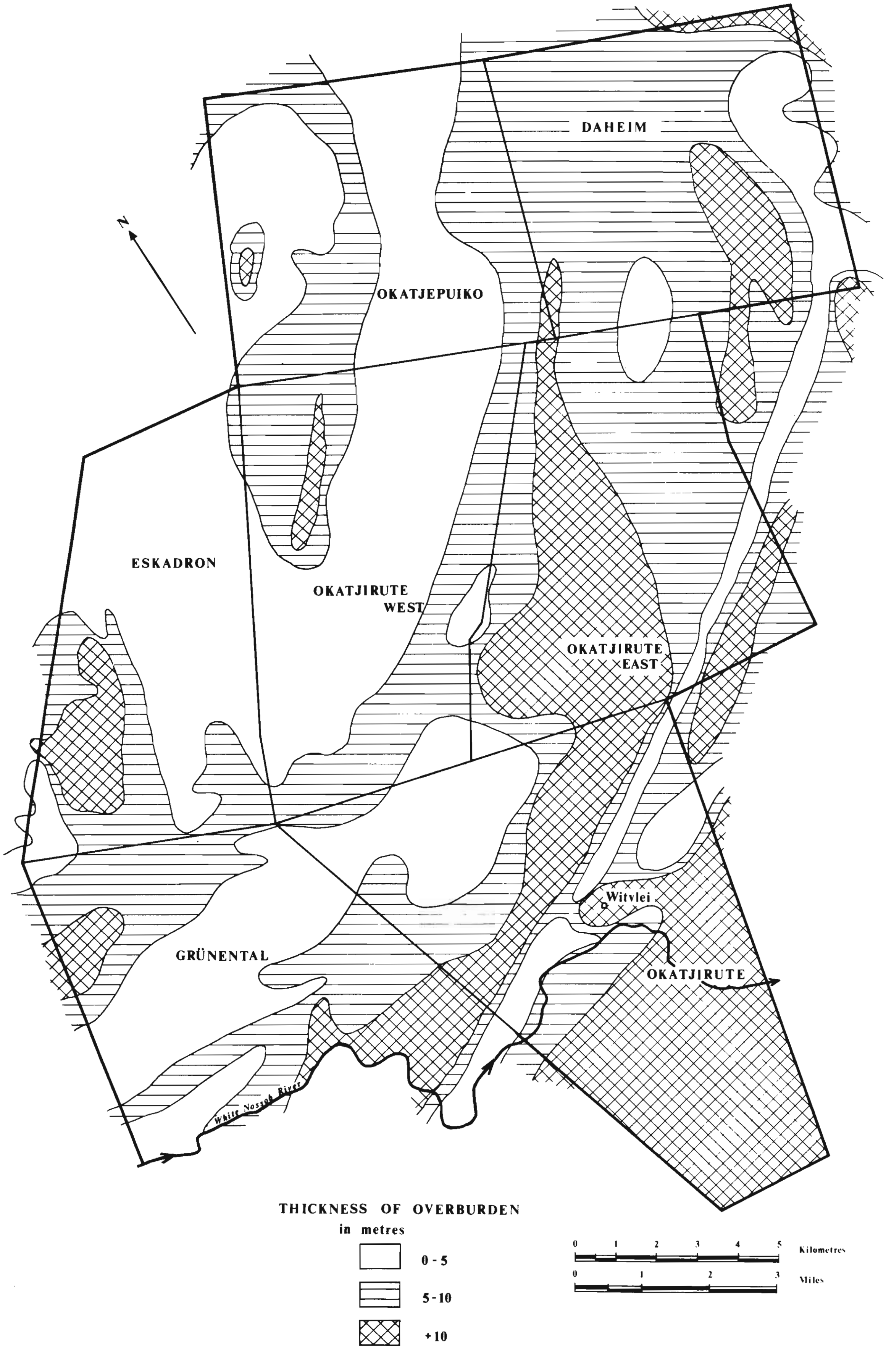


Figure 13

Thickness of overburden in the Witvlei grant area, based on seismic investigations by Anglovaal geologists. Relationship to vegetation associations and bedrock geology emerge from comparison with Figures 11 and 12 respectively.

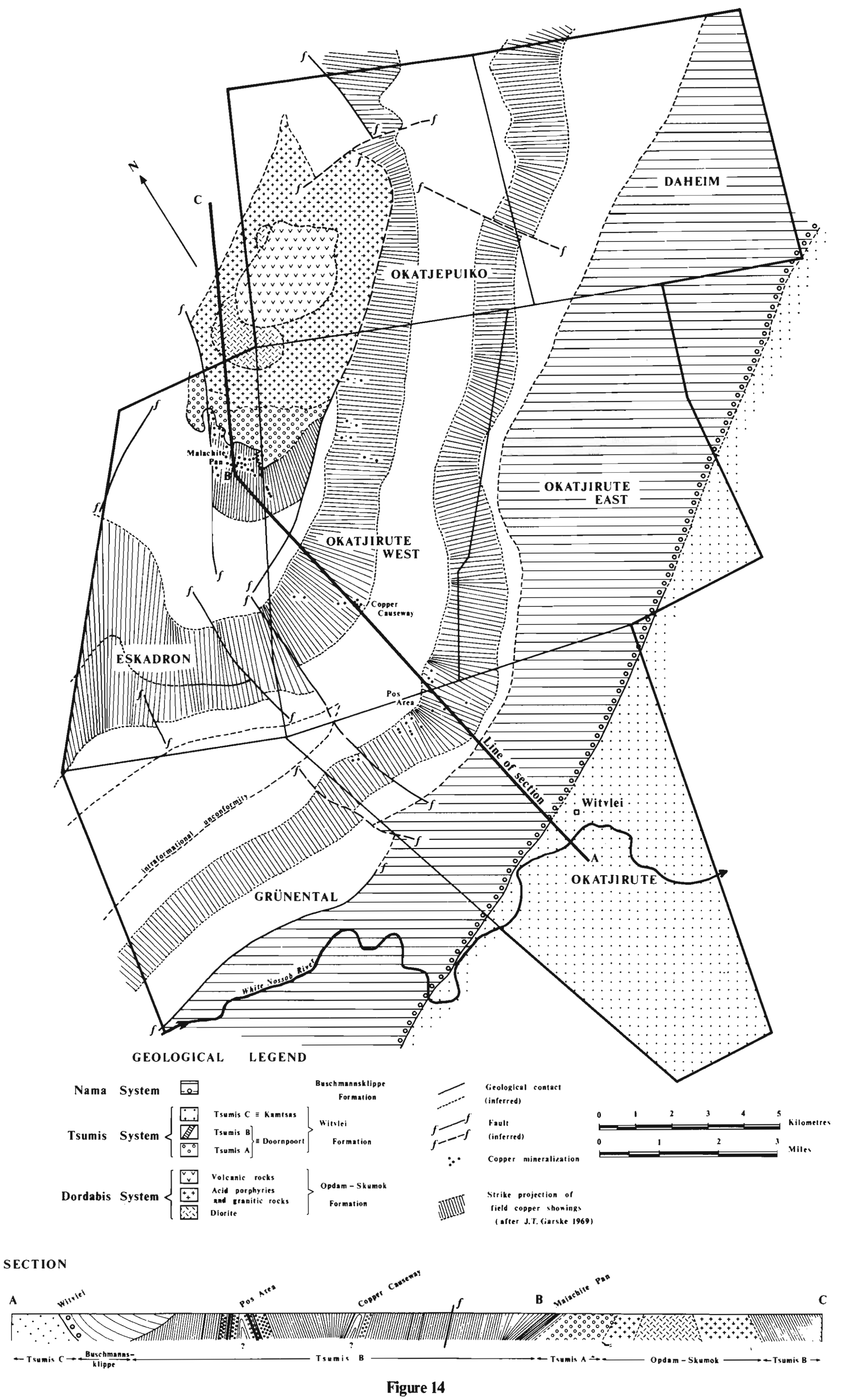


Figure 14

Geology of the Witvlei grant area based on air photo interpretation by J. Garske and field investigation by Anglovaal geologists. Relationship to vegetation associations and depth of overburden emerge from comparison with Figures 12 and 13 respectively.

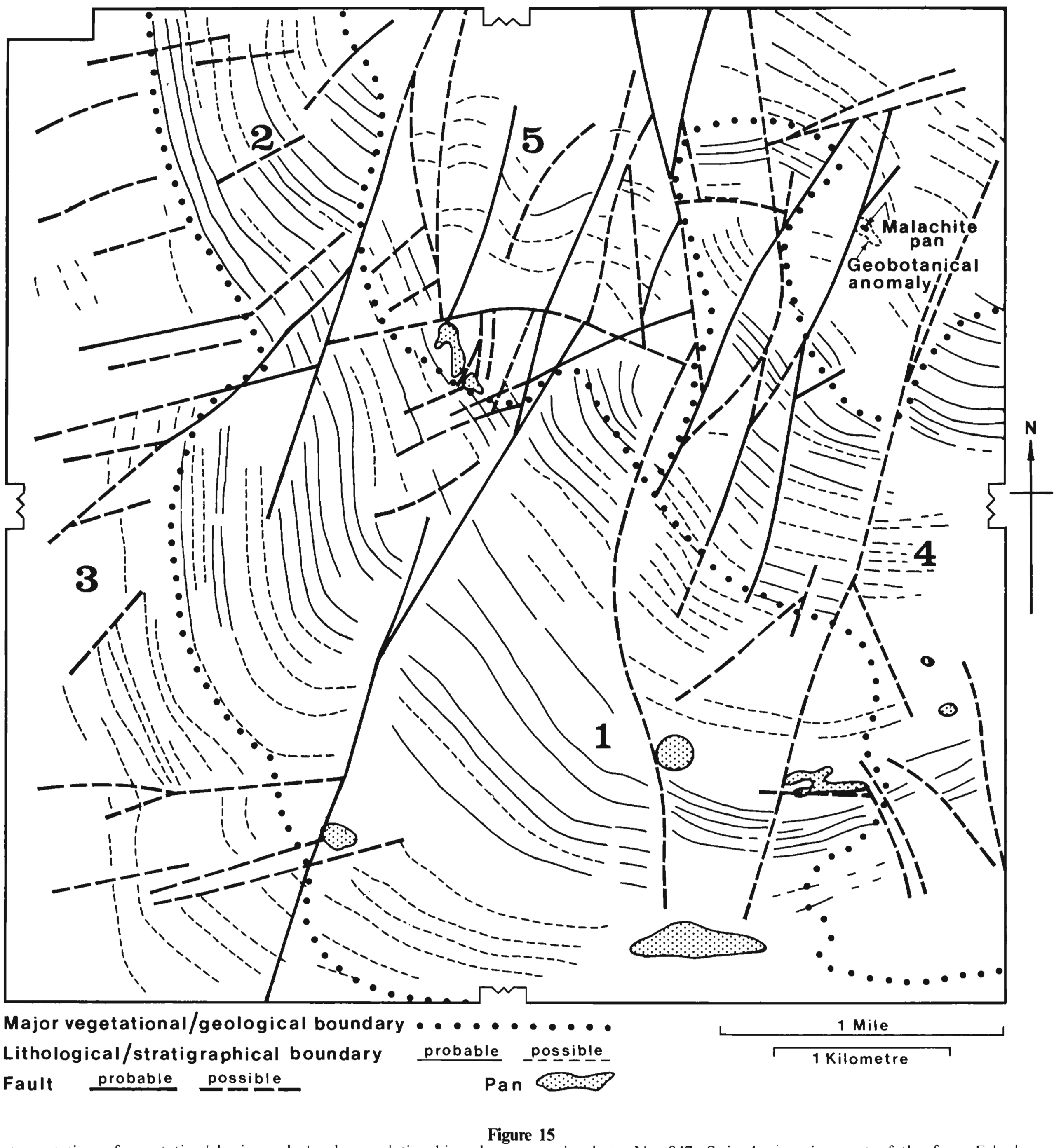


Figure 15
Interpretation of vegetation/physiography/geology relationships shown on air photo No. 047, Strip 4, covering part of the farm Eskadron, north of Witvlei. (Interpretations by M. M. Cole and M. Mason.) For further details regarding numbering see Appendix III.

However, two additional samples, numbered 1750 and 1769, collected over near-surface sub-outcropping cupriferous argillite, are anomalous in all size fractions with peak values ranging up to ten times background. Values of the −270 mesh fractions are twice as great as those of the −80 mesh fraction. In sample 1965 anomalous copper levels occur only in the −270 mesh fraction where the value of 67 ppm is over five times background; the −80 mesh fraction contains only 10 ppm copper and fails to disclose the copper-bearing limestone beneath the sand cover.

In this particular area, trench H 7 was chosen for investigating the secondary dispersion pattern of copper through the overburden/soil profile. The results (Fig. 18) established that it is subdued from the underlying mineralized limestone through the gravel layer and into the windblown sand; consequently the values in the −80 mesh fraction of the surface soil are only 15 ppm to 18 ppm, little above the background levels of 10 ppm to 12 ppm.

The geochemical investigations thus showed that −80 mesh soil sampling would disclose most mineralized strata sub-outcropping near surface, but not those concealed by sand cover. The −270 mesh fraction, however, is able to reflect mineralization below 60 cm of sand and 30 cm of sand and gravel cover, but screening to this mesh size is slow and arduous. Notwithstanding this it is clear that geochemical soil sampling is an effective exploration tool in areas of near-surface bedrock; but it must be recognised that its value decreases rapidly as the sand veneer thickens.

This conclusion focused attention on the possible use of biogeochemistry in areas having a calcrete and/or Kala-

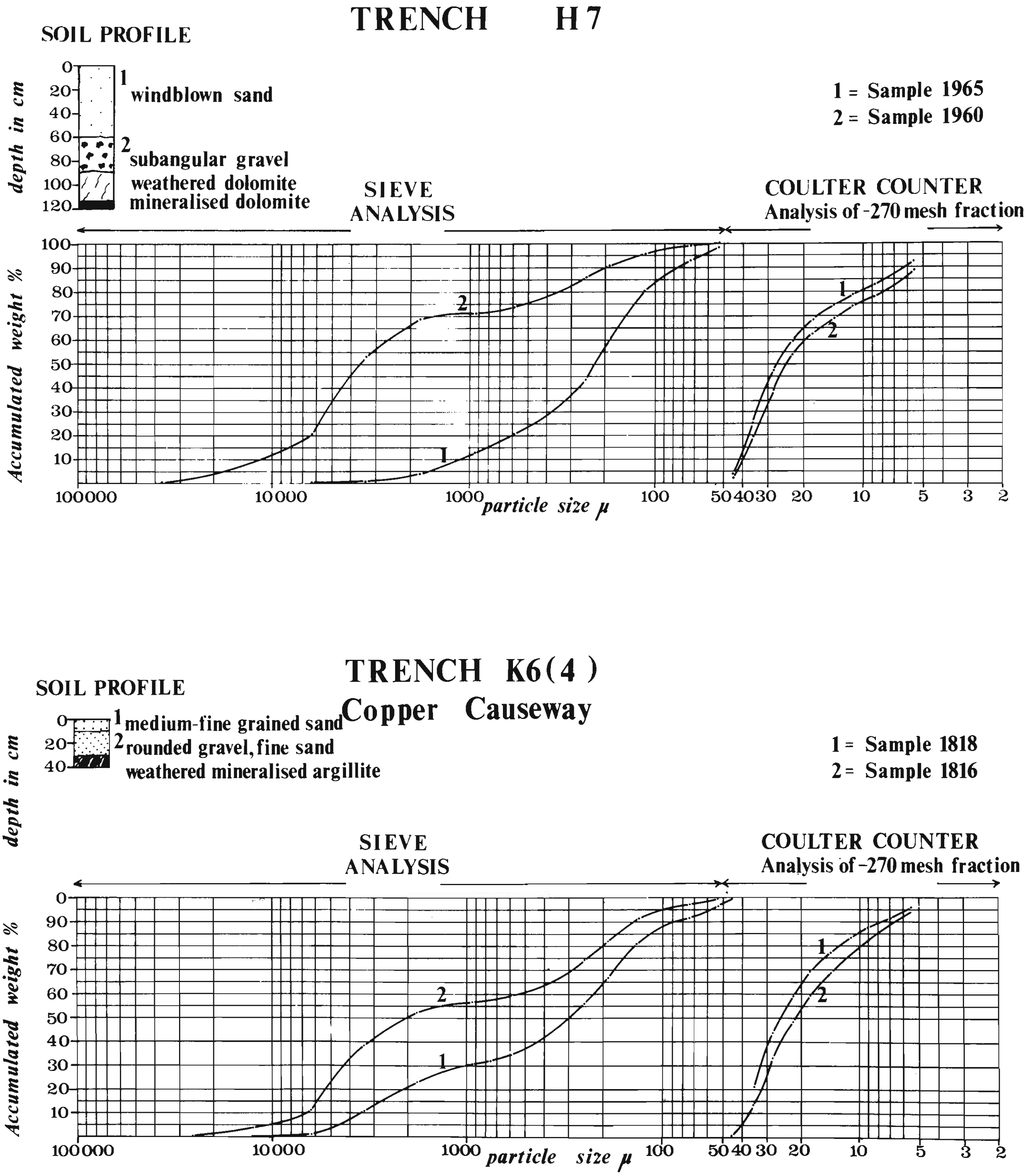


Figure 16

Particle size analyses on bulk soil samples collected from trench K6(4), Copper Causeway (samples 1818, 1816) and trench H7 (samples 1965, 1960) both of which are on the farm Okatjirute West, Witvlei. (Sampling by M. Mason. Analyses by Bedford College laboratories.)

hari sand cover. Such areas are readily recognised on aerial photos by their distinctive vegetation associations.

Plant samples collected in the Copper Causeway area in 1967 and 1968 were used to determine the most suitable species for biogeochemical investigations at Witvlei and other areas of similar environment.

Leaf and twig samples of *Phaeoptilum spinosum, Grewia flava, Acacia heroroensis, A. mellifera* and *A. hebeclada* were analysed. They showed wide variations in copper content, but whereas the first four all produced well defined biogeochemical anomalies *A. hebeclada* contained little copper even when growing over mineralized bedrock. Expressed in ppm dry weight the copper contents of *A. hereroensis* leaves taken from trees growing near mineralized bedrock varied from 14 ppm to 47 ppm compared with 4 ppm to 8 ppm in those from background areas. Twig samples contained lower but similarly contrasting amounts of copper. *Phaeoptilum spinosum* leaves contained from 9 ppm to 78 ppm copper, the highest values occurring in samples collected from sites on *Helichrysum leptolepis* occurrences and the probable strike continuity of copper-bearing horizons; twig samples contained less copper and displayed less contrast between mineralized and background sites. *Acacia mellifera* leaves contained from 6 ppm

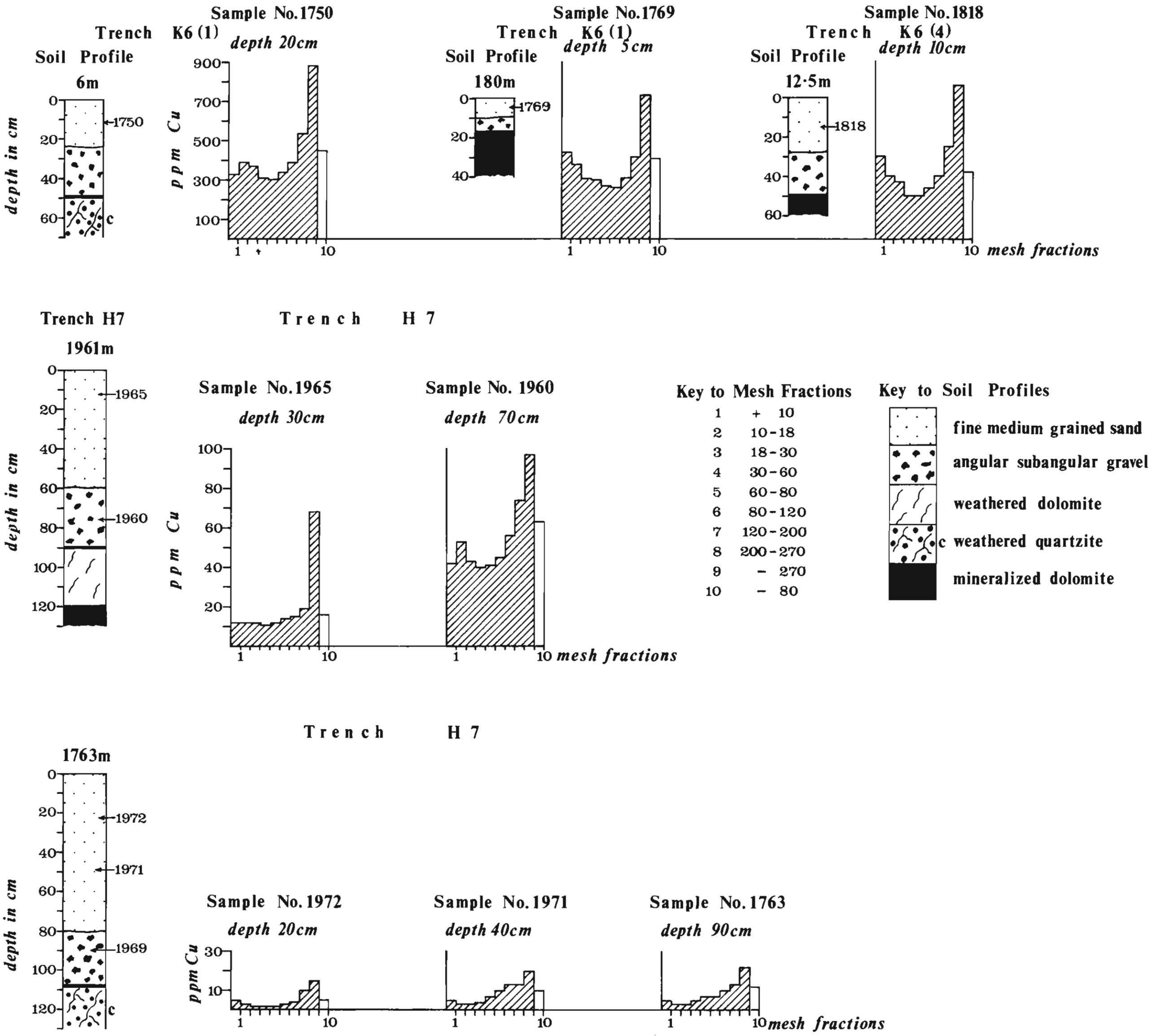


Figure 17

The copper content of various mesh size fractions of soil samples collected at several depths from several sites along the trenches K6 and K7, farm Okatjirute West, Witvlei. (Sampling by M. Mason. Analyses by Bedford College laboratories.)

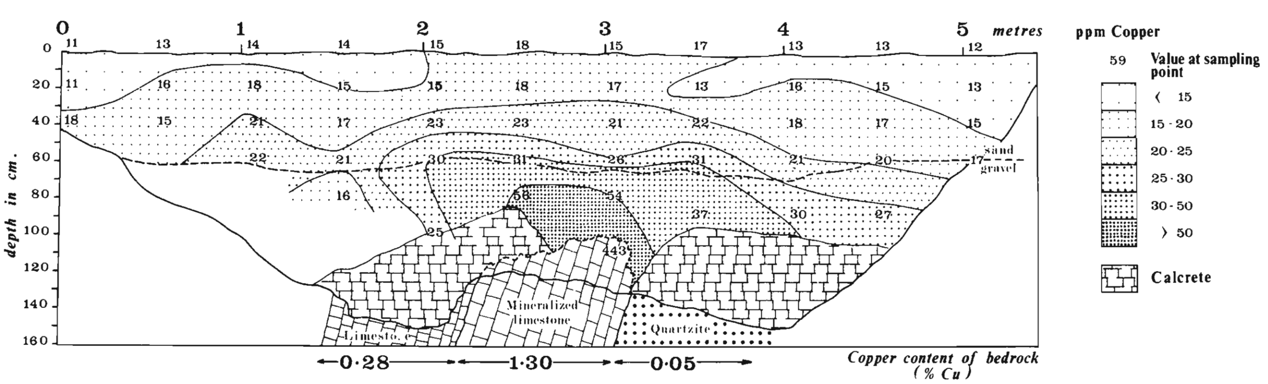


Figure 18

The secondary dispersion pattern of copper from a mineralized limestone into cover of windblown sand, trench H7, farm Okatjirute West, Witvlei. (Recording and sampling by M. Mason. Analyses by Bedford College laboratories.)

copper from background sites to 26 ppm over mineralized bedrock; twigs contained smaller but similarly contrasting amounts of copper. *Grewia flava* leaves contained from 10 ppm to 35 ppm copper and the twigs from 4 ppm to 35 ppm copper. The leaves and twigs of *Acacia hebeclada,* however, contained only 1 ppm to 4 ppm copper (Fig. 17).

It became clear that in the Witvlei area *Acacia hereroenses* and *Phaeoptilum spinosum,* which have deep tap roots, are the best species for biogeochemical sampling, that *Grewia flava* and *Acacia mellifera* which have extensive lateral roots may reflect near-surface copper mineralization and that *A. hebeclada,* which occupies overgrazed areas, is useless.

On the basis of these results geobotany, biogeochemistry and geochemistry were used extensively and successfully in the Witvlei area to establish the distributional aureole of plant species over and adjacent to mineralized bedrock, to trace the strike continuity of mineralized zones, to assist in the elucidation of structures and to locate further mineralized zones in areas covered by calcrete and Kalahari sand as well as those with near-surface bedrock. Several additional sub-outcropping copper deposits were located, notably around the Malachite pan on the farm Eskadron where, following drilling, an exploratory shaft was sunk.

B. Dordabis/Gamma

The investigation of the Gamma concession followed upon a reconnaissance discovery of a large geobotanical anomaly characterized by *Helichrysum leptolepis* associated with a small exposure of copper mineralization in argillitic bedrock along a dry drainage line on the farm Sib, south of the Kharubeam Hills. The environment of the area posed exploration problems which differed from those at Witvlei.

The Gamma concession straddled the Kharubeam hills, with flat plains to the south and mixed plain and hill country to the north (Figs. 19 and 20). It is drained by the ephemeral Schaf River that crosses the hills via a superimposed poort before dividing into numerous bifurcating channels that form a normally dry delta. In the south numerous large, parallel and closely-spaced sand dunes up to 25 m high, 100 m wide and several kilometres long trend north-north-west to south-south-east into the Kalahari (Plate VII).

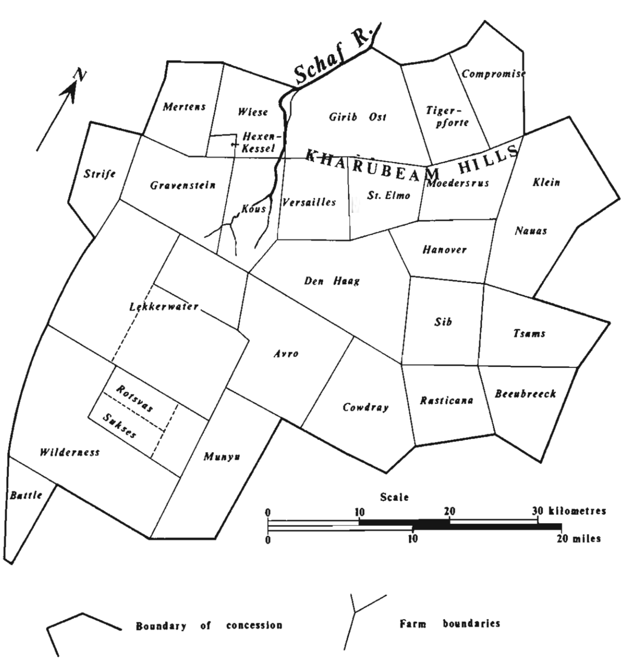


Figure 19
The Gamma grant area. Farm names and boundaries.

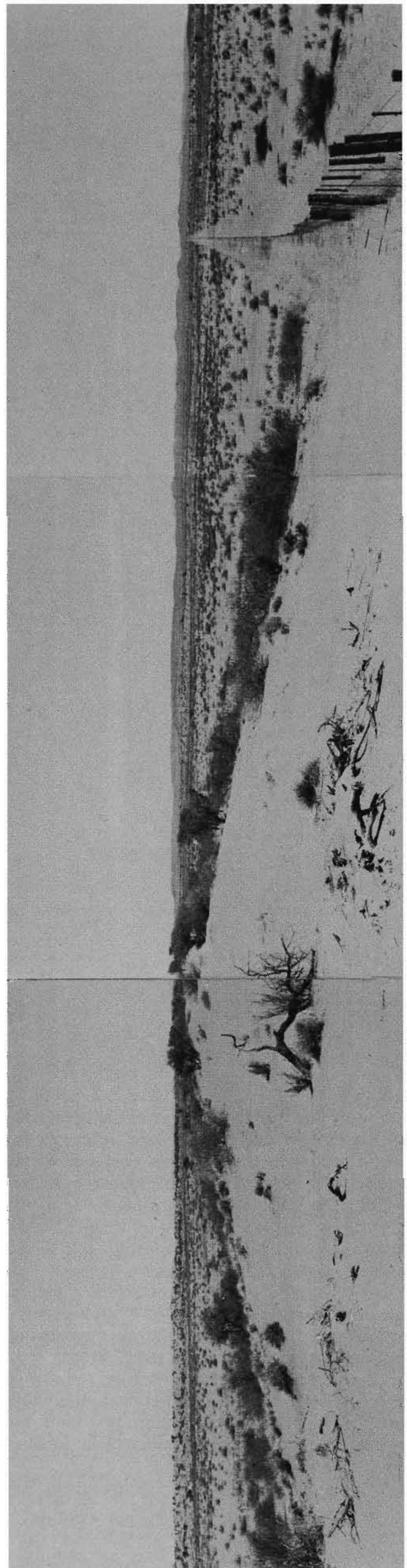


Plate VII
View north-westwards showing north-north-west–south-south-east-trending dunes, carrying *Boscia albitrunca* trees, alternating with swales or strate occupied by *Phaeoptilum spinosum, Rhigosum trichotomum* and other shrubs on the farm Strife, Gamma concession. Hills in the north are of quartzite of Doornpoort (Tsumis A) age. (Ref. MMC/SWA 49/30-32)

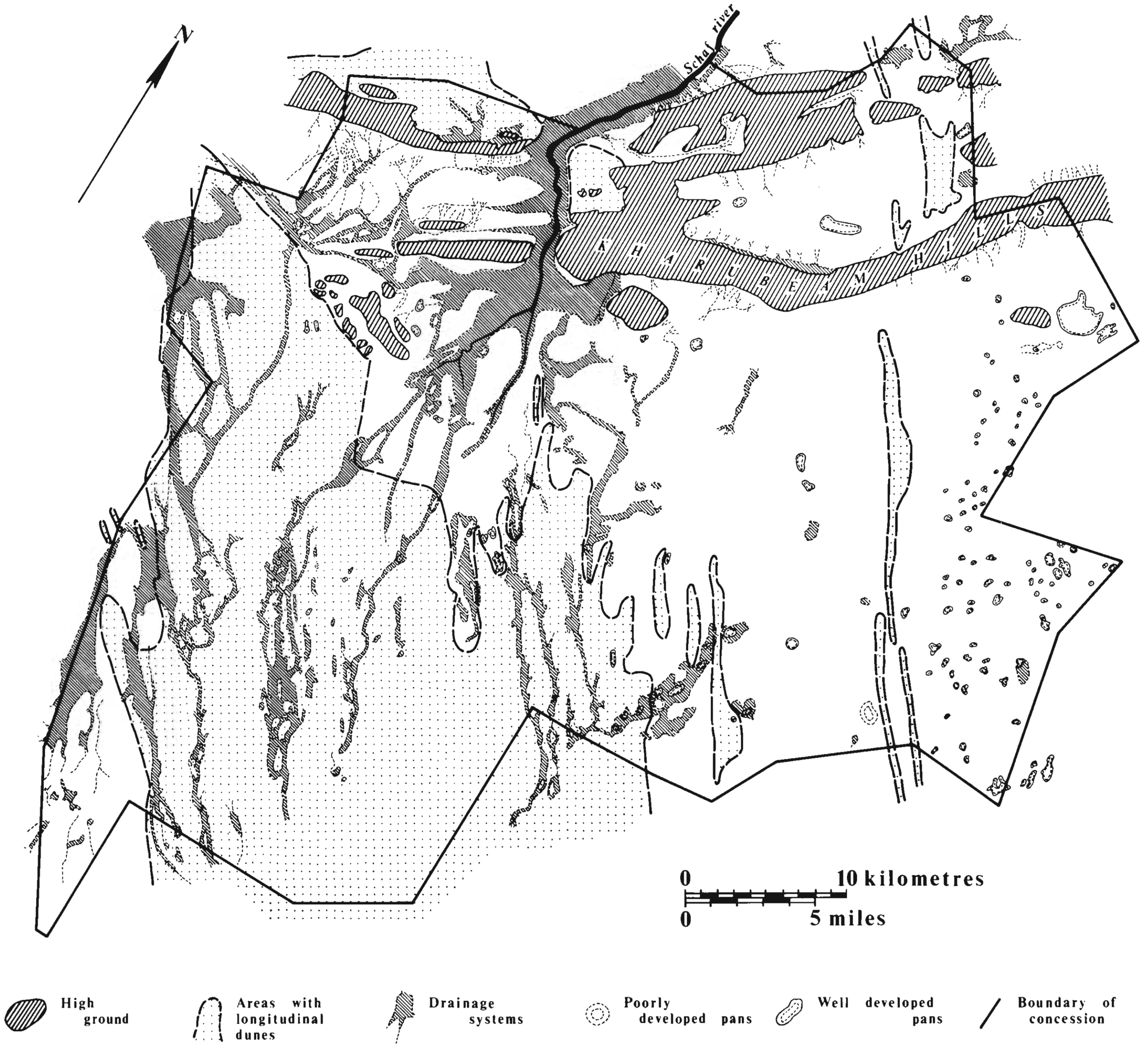


Figure 20
The Gamma grant area. Relief and drainage features. (Based on air photo interpretation and field investigation by A. F. Boshoff.)

Initially little was known of the geology of the area other than that the Kharubeam hills consisted of quartzites believed to be of Doornpoort age, whereas east–west-trending strata of the Tsumis formation were thought to underlie the colluvium, alluvium and aeolian sand cover of the plains (Fig. 21). The virtual absence of outcrop and the depth of overburden constituted major exploration problems.

Regional reconnaissance focused on establishing the relationships between vegetation associations and environmental factors around the Sib geobotanical anomaly, on elucidating regional geochemistry by using stream sediment and soil sampling techniques, on assessing the role of geomorphology in interpreting geochemical anomalies and the location of bedrock mineralization, and upon the role that could be played by biogeochemistry in areas of deep cover.

As the quality of the available aerial photographs was poor, reconnaissance flying and amateur photography was invoked during the initial studies of the vegetation and terrain features, and for selecting areas that merited more detailed investigation (Fig. 22).

The geobotanical anomaly on Sib, marked A, is clearly defined and is distinguished from the nearby pan (E) by its irregular shape and by the absence from its periphery of large trees like *Zizyphus mucronata* and *Diospyros lycioides*. Instead the small shrub *Petalidium parvifolium* characterizes the margins of the anomaly and also follows the drainage channels (F) to the pan. South of the anomaly an apparently treeless area of dark grey tone surrounded by a halo of light grey tone on the air photo (B) carries a distinctive vegetation comprising the tall shrubs *Catophractes alexandrii* and *Rhigozum trichotomum* associated with small *Parkinsonia africana* trees, the grasses *Stipagrostis ciliata* and *Enneapogon brachystachys* and the small shrubs *Aptosimum leucorrhizum, Corchorus asplenifolius* and *Nelsia quadrangula* where outcropping calcrete forms slightly elevated ground. To the north, east and west of the anomaly the even-textured area on the air photo is produced by low tree and shrub savanna composed of *Acacia mellifera* trees, *Catophractes alexandrii, Rhigozum trichotomum, Pheaoptilum spinosum* and *Acacia hebeclada* shrubs and *Stipagrostis uniplumis* grass which occupies plains mantled by gravel and windblown sand. The more open vegetation (D) with

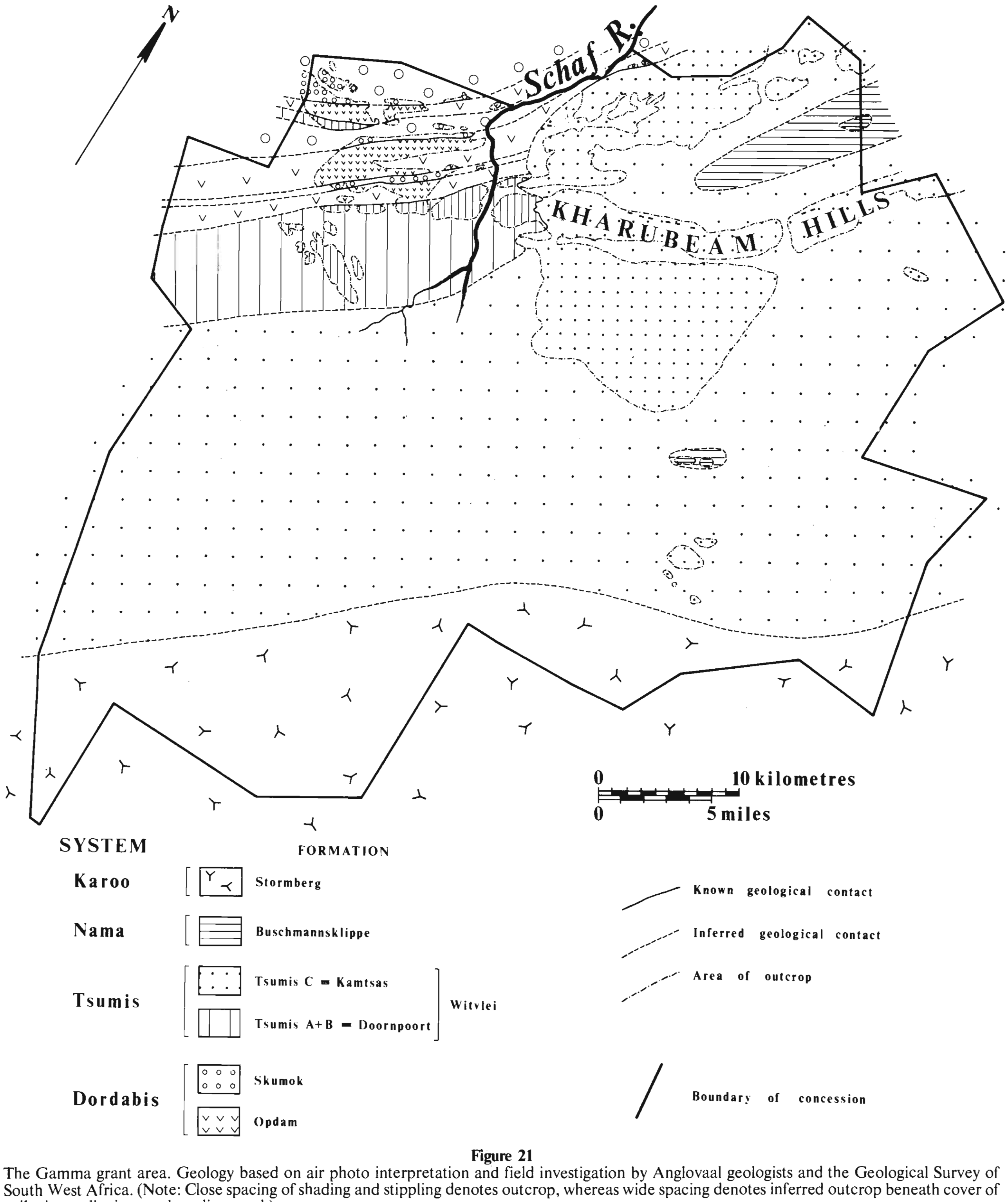


Figure 21

The Gamma grant area. Geology based on air photo interpretation and field investigation by Anglovaal geologists and the Geological Survey of South West Africa. (Note: Close spacing of shading and stippling denotes outcrop, whereas wide spacing denotes inferred outcrop beneath cover of colluvium, alluvium and aeolian sand.)

fewer shrubs, mostly *Acacia mellifera* and *Phaeoptilum spinosum* and denser grass cover of *Stipagrostis uniplumis* delineates rising ground with a deep cover of aeolian sand. The recognition of these communities and their associated terrain assisted in the location of transects for biogeochemical sampling in the Sib area.

Further air reconnaissance over a wider area indicated a complete absence of lineations and vegetational banding that at Witvlei reflects near-surface bedrock. regional strike and structure. It revealed, instead, irregular distinctive vegetation associations whose distribution is related to physiography and to nature and depth of overburden.

Regional geochemical investigations comprised stream sediment sampling along the channels of the Schaf River (Fig. 21) and surface soil sampling over a grid around the Sib geobotanical anomaly and along widely-spread fence lines. These revealed one major geochemical anomaly virtually coincident with the geobotanical anomaly, and several isolated weak anomalies. Field checking of the latter revealed a few specimens of *Helichrysum leptolepis* near the Uhlenhorst road, 13 km south of the old Klein Nauas fort (Fig. 20), but no indicator species were found near the anomalies along the channels of the Schaf River. Profile soil sampling showed that these anomalies were surface

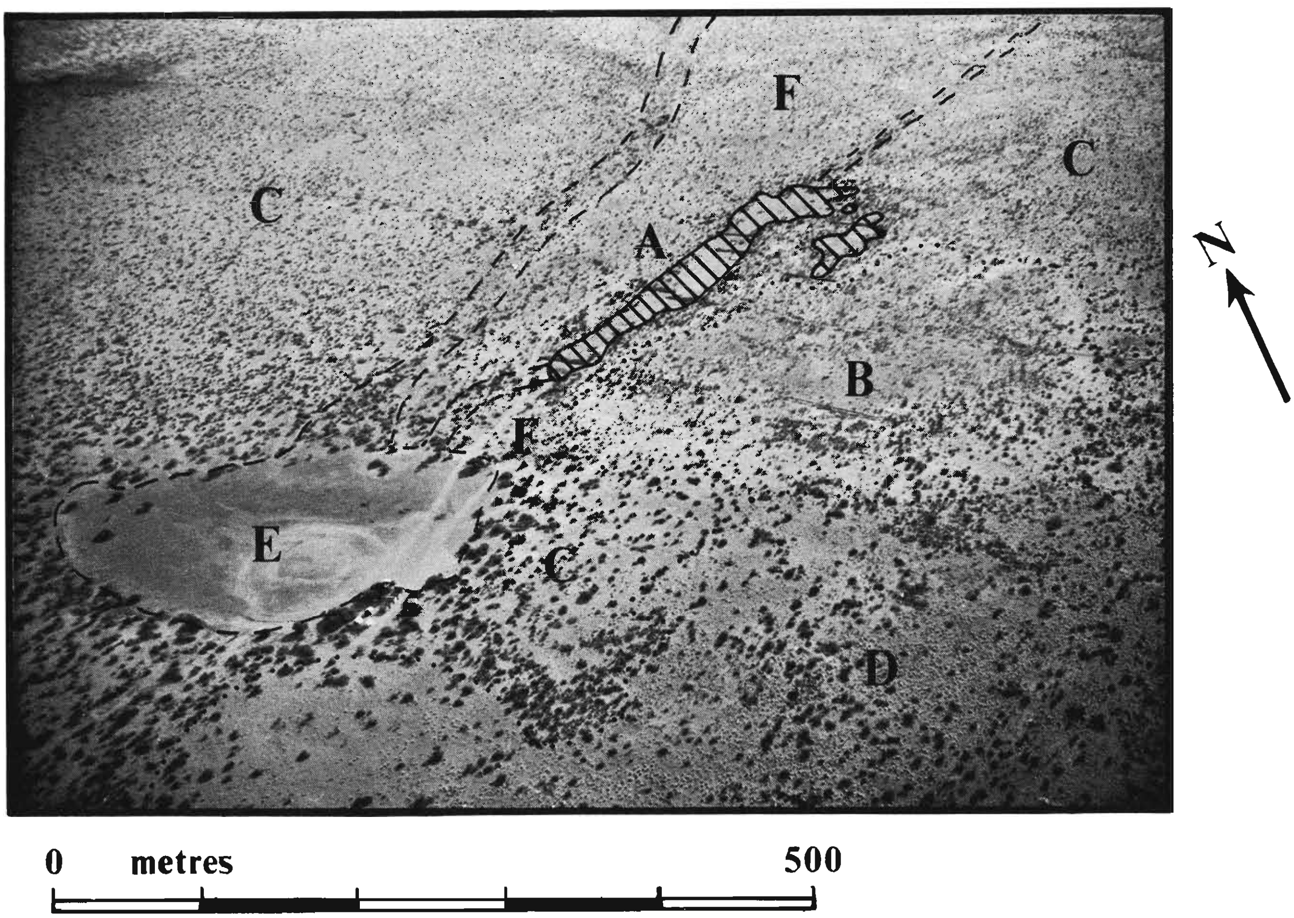


Figure 22
Interpretation of vegetation/physiography/geology relationships shown on an air photo No. MMC/SWA·20/17 covering the main geobotanical anomaly on the farm Sib, Gamma grant area. For further details regarding numbering see Appendix III.

phenomena associated with transported material. To trace their source studies of the geomorphology of the area, and particularly of the drainage history of the Schaf River, were undertaken.

The nature of the drainage patterns relative to relief and geology, the size and depth of the poort carrying the Schaf River through the Kharubeam Hills, the inland delta (of the river) and the extent of transported cover suggest that the Gamma concession is characterized by the remnants of superimposed drainage systems that originated in a wet epoch and that became dismembered by increasing aridity.

Studies of the superficial cover displayed in soil pits on Sib revealed large exogenetic pebbles of quartzite in a transported cover of sand and gravel. This suggested a source in, or north of, the Kharubeam Hills. Investigations north of the hills indicated that the level terrain was disparately mantled by alluvium and colluvium overlain in turn by wind-blown sand which had been piled into dunes against the hills. Discrete vegetation associations characterized disparate types and depths of overburden that permitted of their mapping. The emergent pattern suggested that the Schaf River had at some stage meandered over the area. Enquiry confirmed that this had occurred during a great flood in 1934 during which the river breached a sandhill blocking the poort in the Kharubeam Hills, to discharge its load over the present dry delta area farther south.

The further elucidation of the drainage history of the Schaf River suggested that the geochemical anomalies in the delta might be a legacy of exceptional floods and that the source of copper might be north of the Kharubeam Hills. This premise led to the discovery of copper mineralization in lavas on the farms Mertens and Hexen-Kessel some 7 km west of the main channel and poort of the Schaf River. Although bedrock exposures through the thick alluvial and colluvial cover are scarce here, the exposures of mineralization along the strike of the lava-metasediment assemblage do suggest linear continuity to specific cupriferous zones.

As geochemistry would have limited application in this area, biogeochemistry was chosen as the most promising exploration tool, and plant sampling was undertaken along a series of transects orientated at right angles to the inferred geological strike. This led to the discovery of further copper mineralization in trenches cutting the lavas and metasediments, and to follow-up induced polarization work being undertaken here.

West of Sib where parallel sand dunes that alternate with swales cross the inferred geological strike, the presence of the shrubs *Phaeoptilum spinosum* and *Rhigozum brevispinosum* in the swales suggested that the area was suitable for biogeochemical sampling. As the sampling of the deep-rooted *Phaeoptilum spinosum* at Witvlei was so successful, it was decided to concentrate on this species yet again. Anomalous copper values were found in one area of deep cover, but the discovery was not followed up by trenching or drilling.

From the above descriptions it is obvious that the exploration environment of the Gamma grant area differs from that at Witvlei, being characterized by extensive deep overburden of complex nature and distribution that necessitated emphasis being placed on biogeochemistry and the elucidation of the geomorphology.

Only the geobotanical anomaly present on the farm Sib was drilled on the Gamma grant following detailed biogeo-

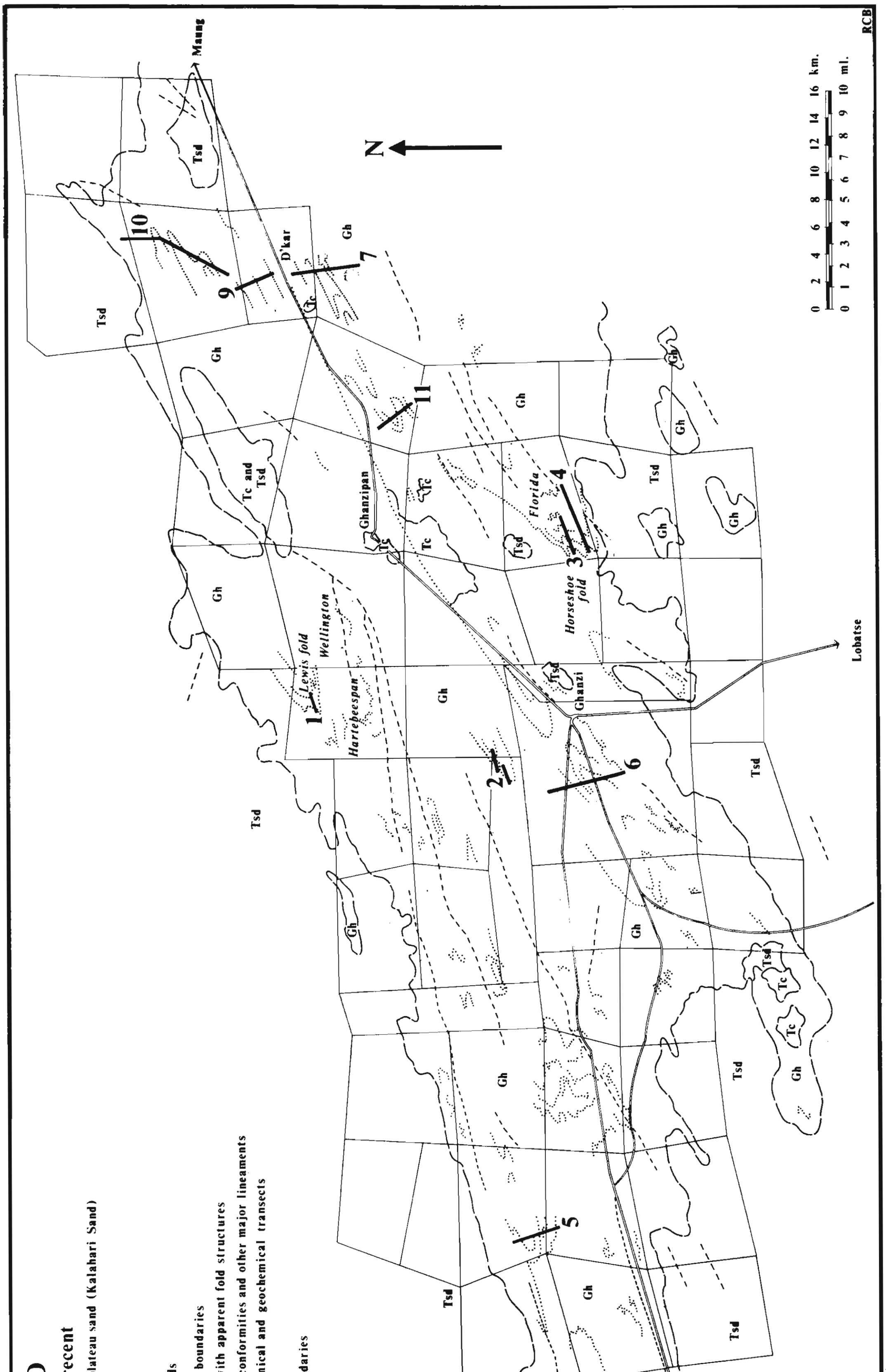


Figure 23
The Ghanzi area. Location of reconnaissance biogeochemical and geochemical sampling transects with photo geological interpretation after J. Garske.

chemical investigations. This disclosed the presence of a sub-outcropping low-grade stratiform copper deposit in an argillite/tilloid host rock.

C. Ghanzi

The reconnaissance of this area undertaken in 1967 established that the distinctive tonal and textural patterns on the air photos are produced by distinctive plant communities that are related to and reflect bedrock lithology (bedded sequence of sediments) and structure (drag folds) present beneath calcrete and Kalahari sand cover. In order to elucidate the relationships the vegetation was mapped over selected fold features along transects orientated along and at right angles to the axes of the folds. Geobotanical data recording and soil and plant sampling were carried out along these transects to delineate favourable sites on which to trench. At the same time relationships between the distribution of the vegetation associations and environmental factors over the region extending from the South West Africa border at Mamona to the Mabeleapudi hills at the Ngamiland border were investigated.

Around Ghanzi three fold features were examined in detail. One is situated south-east of Ghanzi on the farm Florida (Horseshoe fold), another immediately west of the town and the third on the farms Hartebeespan and Wellington (Lewis fold) (Figs. 23 and 24).

The investigation disclosed close relationship between the strength of the vegetation patterns and the thickness of the Kalahari sand cover, and between the distribution of individual plant communities and minor relief features and the presence of calcrete and/or superficial sand. These features were probably influenced by bedrock (Fig. 25).

The geochemical and biogeochemical investigations revealed copper anomalies over the Lewis fold. No indicator species were identified, regardless of the fact that trenching on the geochemical and biogeochemical anomalies disclosed low grade (0,1 per cent) copper mineralization in bedrock.

The soil geochemical anomalies produced by both the -80 and -270 mesh fractions contrasted strongly with background values. The anomalous values ranged from 80 to 200 ppm and 150 and 560 ppm respectively against a background value of 10 ppm copper.

Both the leaves and the stems of *Combretum hereroense, Grewia flava, Catophractes alexandrii* and *Acacia mellifera,* and in the case of the first mentioned, the fruits also, contained anomalous amounts of copper over the mineralized bedrock. In all cases the quantities of copper present were relatively low, but nevertheless at least two or three times the background values (Fig. 26). Regardless of the absence of indicator species geobotanical follow-up investigations showed that the mineralized beds could be traced along strike by virtue of distinctive vegetation cover.

The geochemical and biogeochemical investigations across the folds south-east, west and south-west of Ghanzi only produced values within the background ranges and failed to disclose any anomalies. The highest copper values in both soil and plant samples were obtained in the nose of the Horseshoe fold, where trenching indicated that they were associated with a green shale lacking visible mineralization (Figs. 27 and 28).

The Ghanzi area is characterized by dismembered drainage systems that are relics from earlier wetter climatic epochs, and numerous pans that act as foci for drainage accumulate the finer soil fractions. The drainage into the pans in places emerges from beneath considerable thicknesses of calcrete, and in those instances where mineralized beds were drained toxic solutes such as copper were introduced, resulting in distinctive vegetation features having been formed that include the presence of *Helichrysum leptolepis.* By studying the alignment of those pans displaying such features, inferences can be drawn regarding the proximity of sub-outcropping mineralized beds.

The discovery of low-grade copper mineralization around Ghanzi, under environmental conditions that differ from those prevailing at Witvlei and Gamma, clearly establishes the value of geobotanical, geochemical and biogeochemical exploration techniques for this area.

D. Ngwaku Pan

Initial ground reconnaissance and air photo interpretation indicated that the low tree and shrub savanna of the area between Ghanzi and Ngwaku pan varied in physiognomy and floristic composition according to the nature of the terrain but that near the Mabeleapudi, Ngwenalekau and Kgwebe hills it displayed strong banding parallel to the inferred geological strike, suggestive of a close relationship between vegetation and bedrock geology (Figs. 29 and 30. The banding was broken only by open grassland along drainage lines emanating from the hills and by uniform cover of shrubs and trees over fossil sand dunes.

Regional reconnaissance was directed towards elucidating the relationships between vegetations and superficial and bedrock geology in order to delineate favourable areas for geochemical investigations.

The studies showed that a vegetation of *Terminalia sericea* trees, *Dichrostachys cenerea, Bauhinia macrantha* and *Croton gratissimus* shrubs, *Aristida meridionalis, Eragrostis horizontalis* and *Stipagrostis uniplumis* grasses indicated thick Kalahari sand cover and that one of *Aristida meridionalis, A. kalahariensis* and *A. hordeacea* grasses with scattered *Lonchocarpus nelsoni* and *Croton gratissimus* shrubs indicated exceptionally deep sand, presenting particularly difficult exploration problems. Open parkland characterized by *Eragrostis porosa* grass with scattered *Acacia tortilis* and *A. erubescens* trees delineated vleis and pans floored with alluvium, necessitating caution in the interpretation of geochemical results. Low tree and shrub savanna dominated by small *Combretum apiculatum* trees associated with occasional *Sclerocarya caffra* and *Markhamia acuminata* trees occupied areas of outcropping quartz-porphyry rocks while an alternating series of low tree and shrub savanna, shrub savanna and low tree savanna woodland produced the vegetational banding suggestive of a near surface sedimentary sequence between Ngwaku pan and the Ngwenalekau hills. Within this assemblage woodland characterized by *Terminalia prunioides* and *Acacia erubescens* trees occurred preferentially on the heavier dark brown soils suggestive of argillaceous parent material while *Combretum apiculatum* commonly dominated on red sandy soils derived from arenites and *Catophractes alexandrii* on outcropping calcrete. Scattered patches of *Barleria senensis*, believed to be a possible copper indicator plant, occurred within the *Terminalia prunioides–Acacia erubescens* woodland south of Ngwaku pan.

Conclusions drawn from these geobotanical studies and various photogeological and geological considerations, that included the known presence of the quartz-feldspar porphyry marker zone, coupled to the favourable results yielded by a regional soil sampling programme all suggested that the area extending south from Ngwaku pan to the Ngwenalekau hills formed a favourable environment for the presence of yet further stratiform copper deposits that could be located by detailed geochemical investigation.

Follow-up geochemistry in due course revealed a major copper anomaly that was found to coincide with a well-defined geobotanical anomaly in which the distinctive blue flowered shrub of the Acenthaceae family, *Ecbolium lugardae*, replaced other shrubs, herbs and grasses in the ground cover of the open *Terminalia prunioides–Acacia eru-*

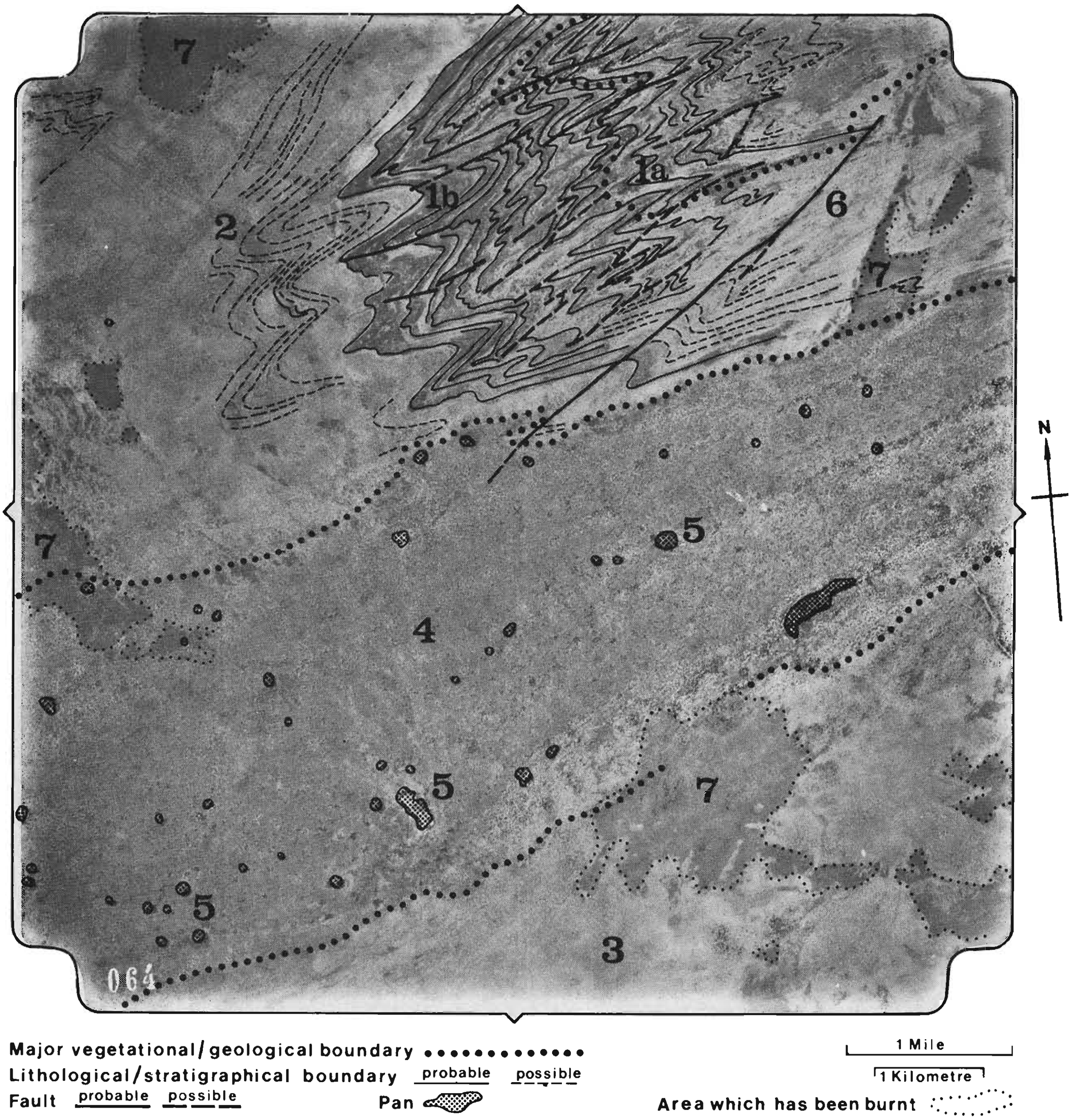


Figure 24
Interpretation of vegetation/physiography/geology relationships shown on air photo 28/BC/21 No. 064 covering the area south-east of Ghanzi. (Interpretation by M. H. Cole and R. C. Brown.) For further details see Appendix III.

bescens woodland which otherwise was unchanged. Trenching at several sites within the *Echolium lugardae** anomaly disclosed copper mineralization in both argillite and argillaceous limestone beneath 8 m of calcrete cover. Several minor geochemical anomalies were found by ground investigations to be related to minor drainage features emanating from the metasedimentary and metavolcanic assemblage comprising the Ngwenalekau hills in which minor showings of cupriferous mineralization are present.

As the work progressed it became clear that mineralized bedrock had to be located beneath thick calcrete cover, and that only weak geobotanical and biogeochemical anomalies could be expected. Consequently attention was focused also on the potential of biogeochemical and geophysical techniques.

In order to ascertain the most suitable species for the biogeochemical investigations the roots of the most common trees and shrubs present here were artificially exposed to ascertain rooting habit and depth. An extensive sampling programme of the leaves and twigs of the deep rooting species, notably *Boscia foetida* which retains its foliage throughout the year, *Acacia erubescens* and *Terminalia prunioides* was carried out in an attempt to locate zones of mineralization which do not have a geobotanical or geochemical expression.

These investigations yielded valuable results in that they differentiated geochemical anomalies emanating from bedrock mineralization from those of transported origin, and established the presence of copper anomalies in areas of overburden beyond the root penetration limits of *Ecbolium lugardae*.The geophysical investigations (phased into

*Recent investigations have revealed the presence of this species at the Palabora and Messina copper mines located respectively in the eastern and northern Transvaal.

Figure 25
Distribution of vegetation associations over the western part of the fold structure on the farm Florida of Horseshoe Ranch, south-east of Ghanzi. (Mapping by R. C. Brown.)

the exploration programme at a late stage) produced induced polarization anomalies that broadly coincided with the major geobotanical and geochemical anomalies north of the Ngwenalekau hills. Significantly, however, the geobotanical and geochemical anomalies delineated the extent of copper-bearing argillite and limestone, as confirmed by trenching and drilling, more accurately than the geophysical techniques which located also pyritic bedrock.

V. COMMENT AND CONCLUSIONS

The initial reconnaissance and orientation surveys established that vegetation is indicative of geological structure, lithology and nature and depth of overburden, and that the species *Helichrysum leptolepis* is an unfailing indication of copper mineralization in bedrock. This is particularly evident in areas of shallow overburden, but where Kalahari sand and calcrete mantle bedrock to appreciable depth interpretation becomes less definitive.

The vegetation conditions prevailing in the semi-arid areas studied favour geobotanical and biogeochemical sampling in that the cover is generally sparse and the species composition simple. Furthermore most species have extensive root systems comprising both major laterals and deep tap roots that respectively draw upon large near-surface areas and extend to great depths in search of water.

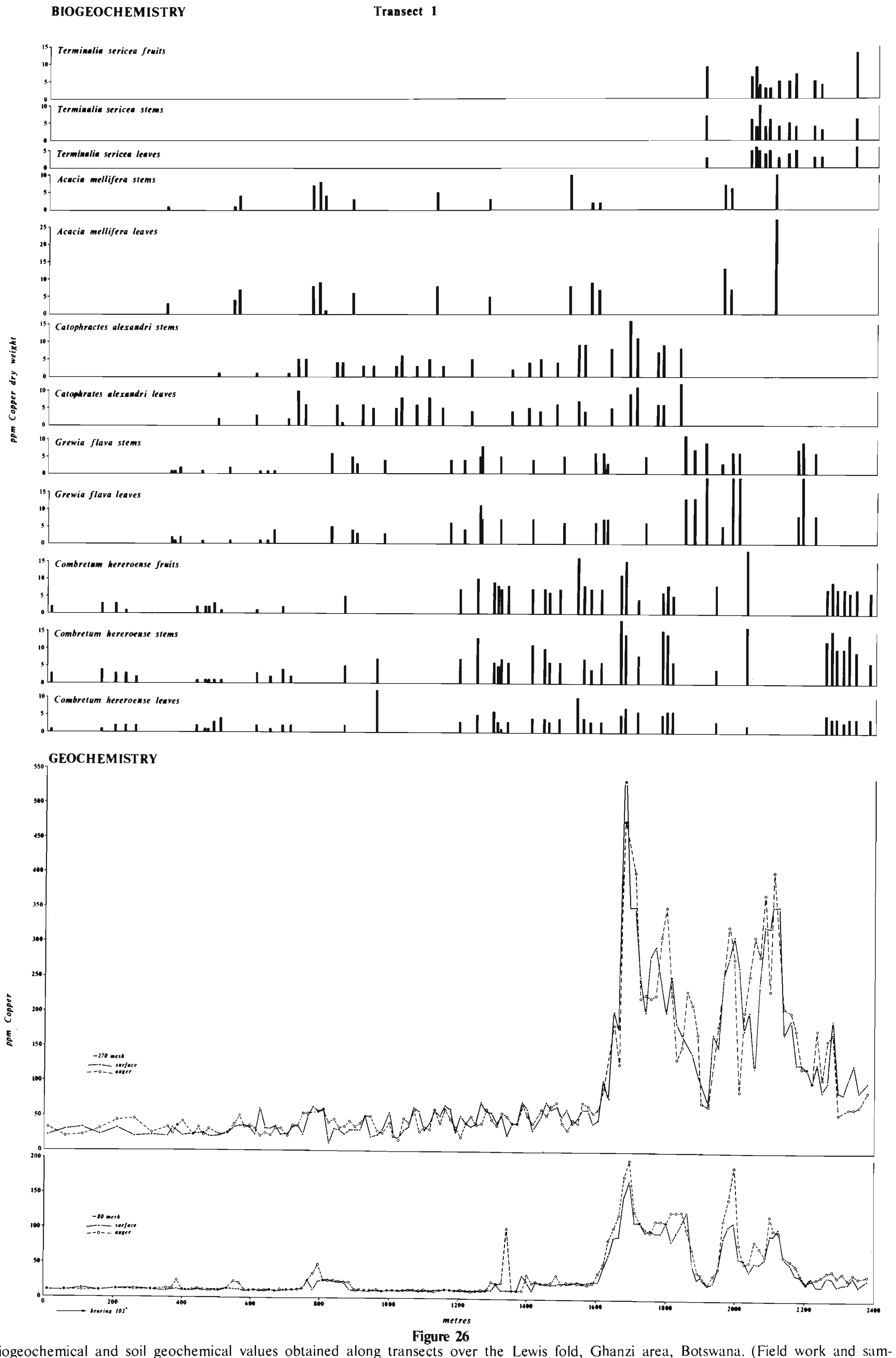


Figure 26

Biogeochemical and soil geochemical values obtained along transects over the Lewis fold, Ghanzi area, Botswana. (Field work and sampling by R. C. Brown. Analyses Bedford College laboratories.)

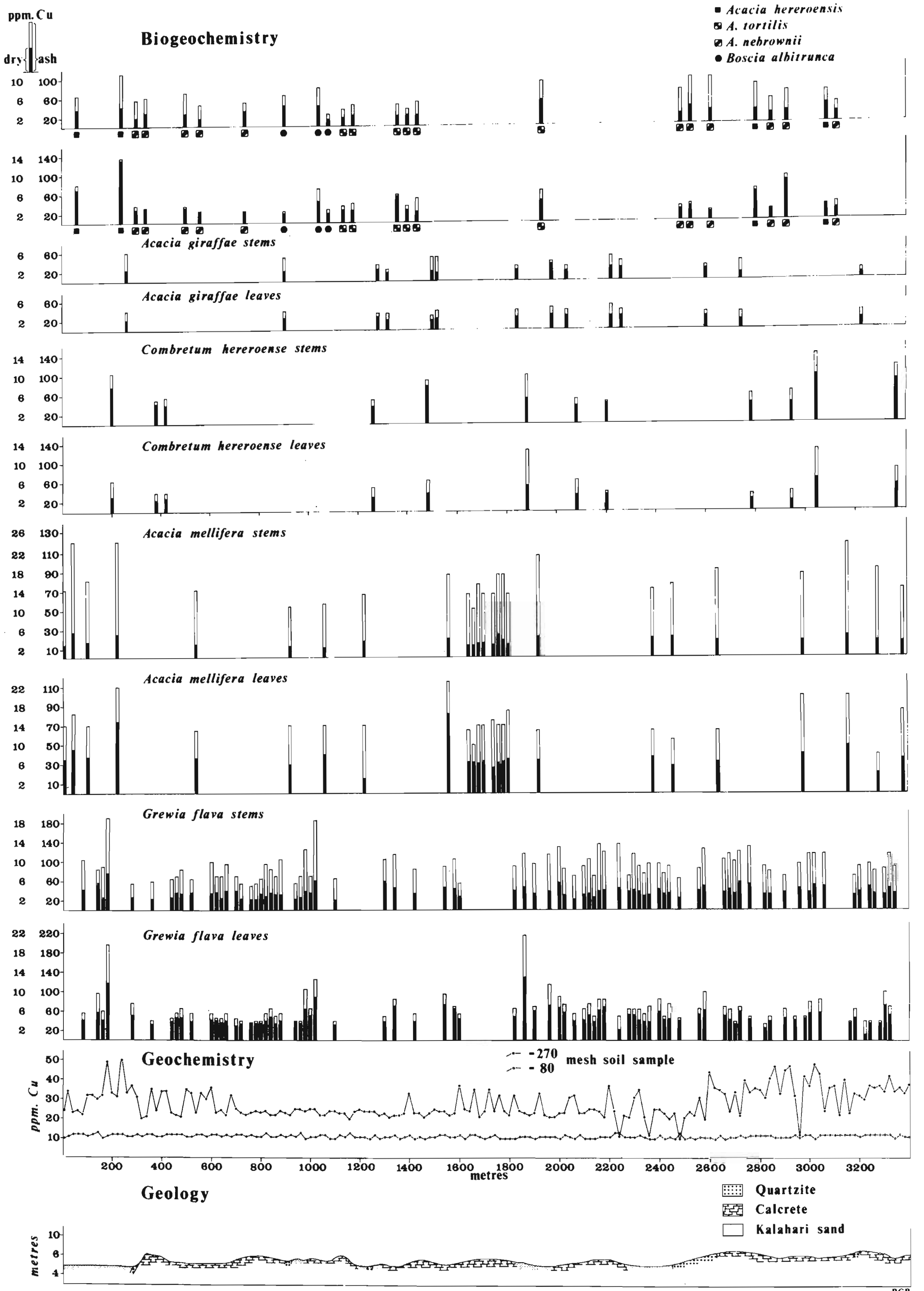


Figure 27

Reconnaissance Transect (Tr. 4) across the fold structure on the farm Florida of Horseshoe Ranch, south-east of Ghanzi, showing the copper values in the leaves and stems of four plant species and in the −80 and −270 mesh fractions of soils sampled at 10–15 cm depth. (Recording and sampling by R. C. Brown. Soil analyses by Anglovaal laboratories, Windhoek. Plant analyses by Bedford College laboratories.)

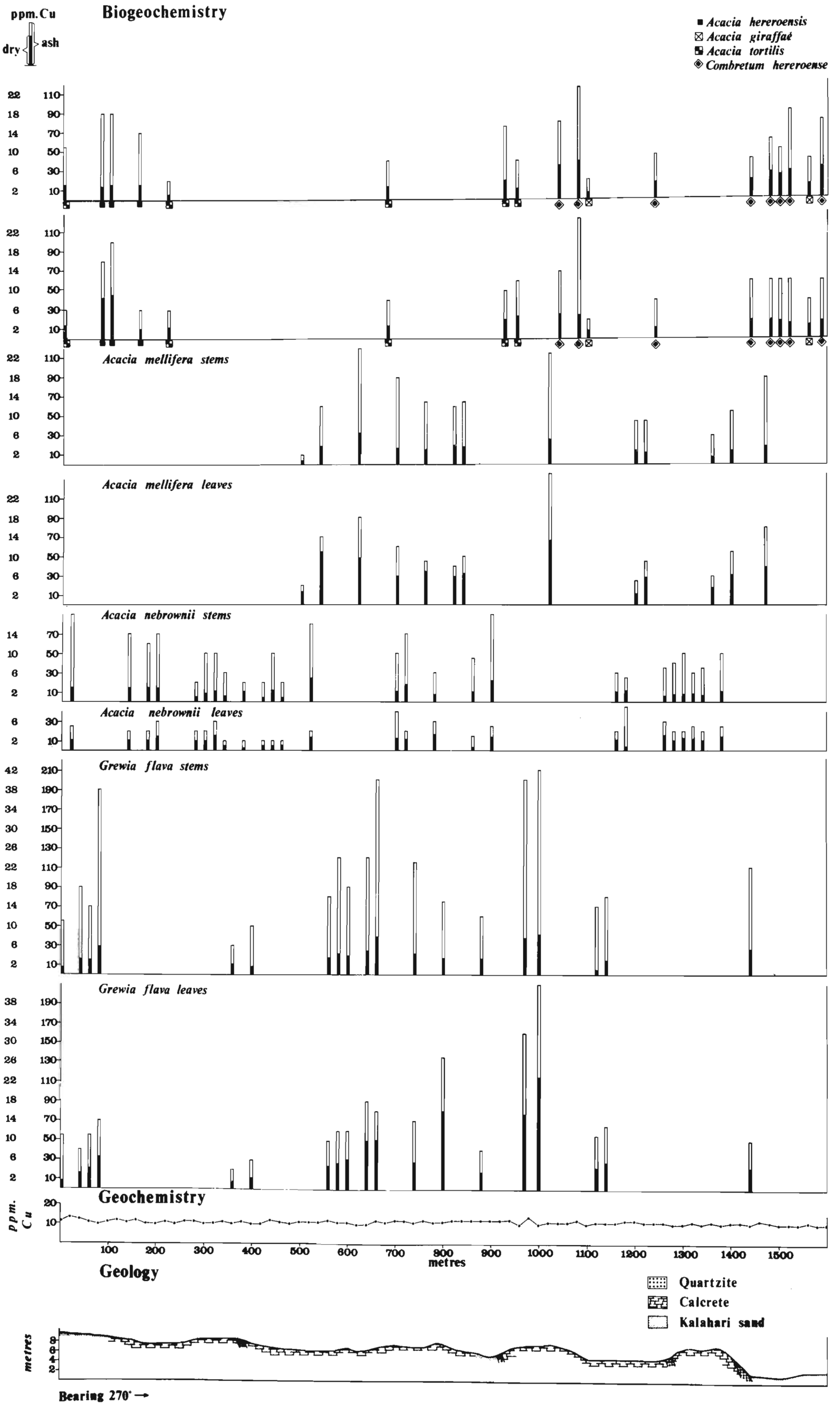


Figure 28
Reconnaissance transect (Tr. 3) across the fold structure on the farm Florida of Horseshoe Ranch, south-east of Ghanzi, showing the copper values in the leaves and stems of four plant species and in the −80 and −270 mesh fractions of soil sampled at 10–15 cm depth. (Recording and sampling by R. C. Brown. Soil analyses by Anglovaal laboratories, Windhoek. Plant analyses by Bedford College laboratories.)

Figure 29

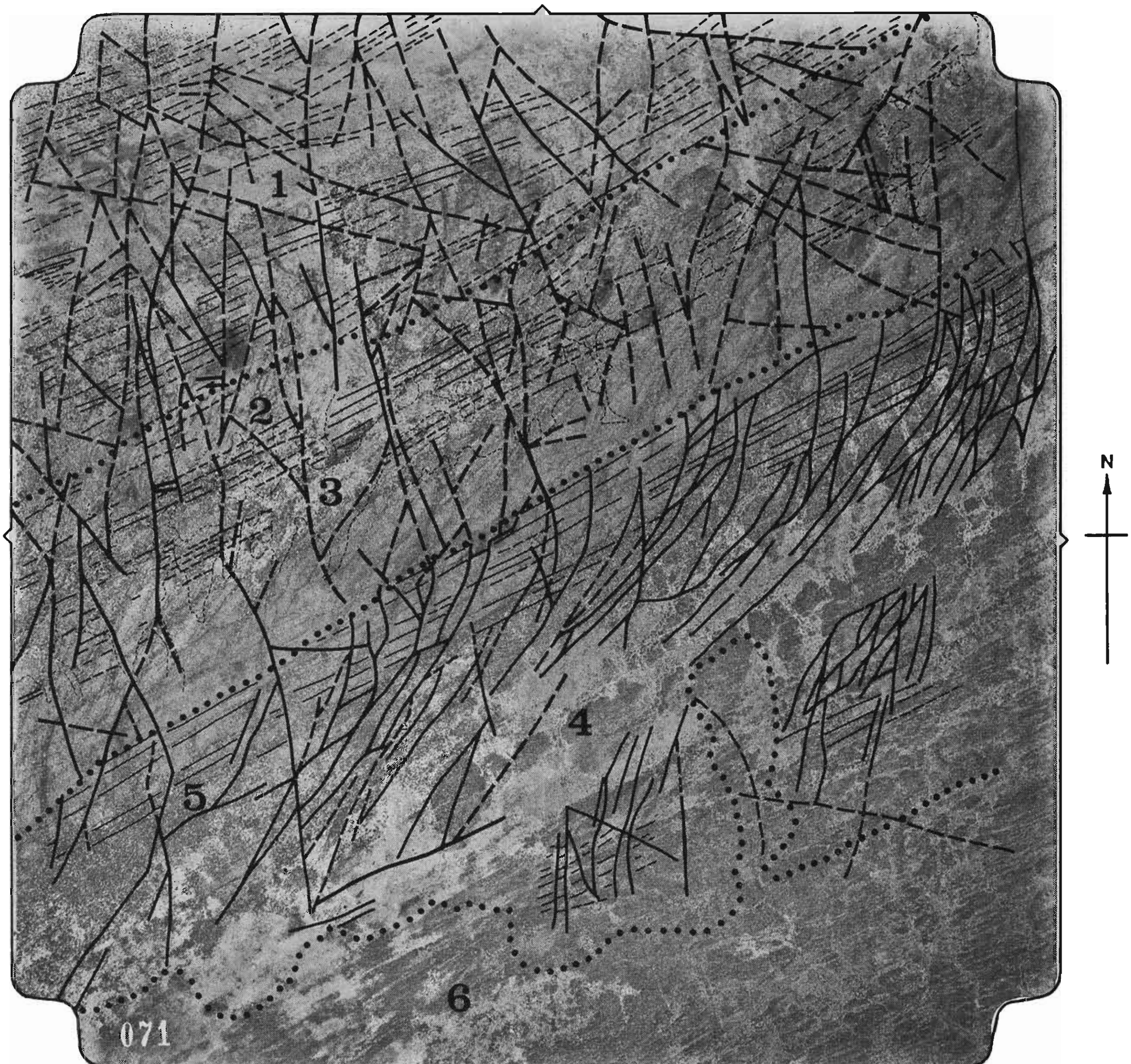
Interpretation of vegetation/physiography/geology relationships shown on the air photo 28/BC/7 No. 073 covering part of Ngwaku pan and the area to the south-east. (Interpretation by M. M. Cole and A. D. Buerger.) For further details regarding numbering see Appendix III.

Consequently the underlying lithology is reflected by the nature of the species present, and mineralization by the chemical content of plant material.

Certain species show a precise response to climatic variables such as the increase in atmospheric humidity during early summer. *Acacia* trees and shrubs, for example, respond to this by flowering shortly before the first rains in November. They carry their leaves into the dry season, shedding them after the early frosts of late June or early July, but the fruits may persist through the ensuing dry winter season. Identification of *Acacia* species was possible from observation of flowers, leaves, fruits and thorns at any time of the year, and this allowed of biogeochemical sampling. In the shrub layer most of the species produced leaves and flowers during the rainy season and, like *Acacia*, carry their leaves until the first frosts. The species of the ground vegetation layer, however, grow only during the rainy season with March as their normal flowering period. Some species like *Ocimum americanum* flower twice, after each of the January and March rains, but all species were found to shrivel and die during the dry season. *Helichrysum leptolepis*, however, constitutes a notable exception as it is most easily recognised during this period, a feature that facilitates mineral exploration.

In Botswana the *Terminalia* and *Combretum* exhibit a similar growth rhythm to the Acacias, while other trees and large shrubs shed their leaves during the dry period. Certain small shrub species, such as *Petalidium englerianum,* flower at this season. *Barleria senensis* was also found in leaf and flower during August.

Certain features of the soil profiles and of the sub-outcropping bedrock as exposed in pits and trenches appear, under conditions of deep overburden, to favour the application of geobotanical and biogeochemical sampling tech-



Major vegetational / geological boundary ●●●●●●●

Lithological / stratigraphical boundary probable possible } in Ghanzi beds of Tsumis formation in Areas 1, 2 and 3

Fault probable possible

Joints and fractures in the Skumok quartz porphyry in Area 4

Area with impeded drainage

1 Mile

1 Kilometre

Figure 30

Interpretation of vegetation/physiography/geology relationships shown on the air photo 28/BC/5 No. 071 covering part of the Ngwenalekau hills and adjacent areas. (Interpretation by A. D. Buerger and M. M. Cole.) For further details regarding numbering see Appendix III.

niques. The first such feature is the tendency for mineralized beds to form slight topographic highs on the sub-outcropping bedrock surface, and the second is the lesser developments of calcrete over mineralized beds than over adjoining country rock. Under such circumstances the preferred development of certain deep-rooted trees along the trace of a sub-outcropping mineralized bed may occur and, by their very presence as well as their metal content, provide definitive and useful anomalies.

While other exploration techniques, including geochemistry, play a very positive role in the multidisciplinary research programme practised in the Kalahari environment geobotany, biogeochemistry and photogeological interpretation are particularly effective.

The *Helichrysum leptolepis* and associated indicators proved most valuable in the areas of shallow overburden prevailing at the Witvlei and Gamma grant areas, whereas at Ngwaku Pan deeper rooting indicator shrubs, notably *Ecbolium lugardae*, contributed to the location of a copper-bearing zone obscured by a thick blanket of calcrete and wind-blown Kalahari sand.

Where environmental conditions were well understood the presence of distinctive plant communities provided valuable guidelines to thickness of overburden and the presence of appropriate host rock assemblages in which mineralization could hopefully be present.

Soil sampling as opposed to stream sediment sampling, in terrain characterized largely by superimposed and dismembered drainage patterns, clearly proved its value as a reconnaissance exploration tool, but is subject to the limitations imposed by depth and nature of overburden. Unconsolidated sand and gravel have a most inhibiting effect. It appears that the original premise that the Tsumis/Ghanzi assemblage of the strata comprised a favourable environment for the presence of stratabound base metal deposits has been substantiated by the discovery of cupriferous mineralization at different localities along 1 000 km of strike, viz:

1. On the farm Kojeka (Tsumis formation) and in the Gamma grant area (Opdam–Skumok formations).
2. At Witvlei (Tsumis and Opdam–Skumok formations).
3. On the banks of the Black Nossob River.
4. At Ghanzi (Ghanzi beds).
5. At Ngwaku Pan near Lake Ngami (Ghanzi beds).
6. At the Shinamba Hills, located 110 km south-west of Kasane (Ghanzi quarzites).

Furthermore, it is gratifying to reflect that this particular exploration venture has clearly demonstrated our ability to peer beneath the surficial sediments of the great Kalahari Basin that undoubtedly hosts many viable mineral deposits still awaiting discovery.

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The initial geobotanical and biogeochemical investigations undertaken in 1967 were, under the guidance of Professor Cole, implemented by Misses L. Coupland and J. Cudmore, research assistants under the programme "Investigations of Plant Indicators of Mineralization" sponsored by the British Natural Environment Research Council. Mr. A. D. Buerger replaced them in 1968 shortly after Messrs M. Mason and A. Boshoff had been appointed Research Students under three-year grants allocated to Bedford College by Beta Mining and Prospecting Company (Pty) Ltd, a wholly owned subsidiary of Anglo-Transvaal Consolidated Investment Co. Ltd. and Middle Witwatersrand (Western Areas) Ltd. In 1968 Messrs. Mason, Boshoff and Buerger worked together in the Witvlei and Ghanzi areas, but subsequently they worked in the Witvlei, Gamma and Ngwaku areas respectively. In 1969 Mr. R. C. Brown took over work in the Ghanzi area.

The photogeological investigation of all the prospecting areas was undertaken by Mr. J. T. Garske of Denver, Colorado, Mr. O. J. van Straten of Pretoria, Transvaal, established the Anglovaal geochemical laboratory in Windhoek and thereafter acted as consultant; Mr. J. B. Boniwell of Port Credit, Ontario, acted as geophysical consultant and Messrs. Geoterrex of Johannesburg as geophysical contractors. The regional geochemical sampling programme was effected by Messrs. E. W. B. Miller and Associates, Windhoek.

The maps and diagrams were drafted by the research assistants, by Mesdames Candy, Saunders and Dalton, by Misses Drury, Keeble and Wylder and Mr. Slough of Bedford College and by Mr. C. Bleach and Mrs. Heinrich of Anglovaal S.W.A. Ltd.

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REFERENCES

Anhaeusser, C. R., and Button, A. (1973). A petrographic and mineragraphic study of the copper-bearing formations in the Witvlei Area, South West Africa. *Trans. geol. Soc. S. Afr.*, **76**, 279–299.

Boocock, C., and Van Straten, O. J. (1962). Notes on the geology and hydrogeology of the central Kalahari region, Bechuanaland Protectorate. *Trans. geol. Soc. S. Afr.*, **65**, 125–171.

Cole, M. M. (1965a). The use of vegetation in mineral exploration in Australia. *Eighth Comm. Min. Metallurgical Congress, Australia and New Zealand, 1965.* Proc. Gen., **6**, 1429–1458.

———— (1965b). *Biogeography in the service of man.* Inaugural Lecture, Bedford College, University of London.

———— (1971a). The importance of environment in biogeographical/geobotanical and biogeochemical investigations. *In* C.I.M. Special Volume *Geochemical Exploration*, 414–425.

———— (1971b). Biogeographical/geobotanical and biogeochemical investigations connected with exploration for nickel-copper ores in the hot wet summer/dry winter savanna woodland environment. *J. S. Afr. Inst. Min. Metall.*, **71**, 199–214.

———— (1973). Geobotanical and biogeochemical investigations in the scherophyllous woodland and shrub communities of the Eastern Goldfields area of Western Australia, with particular reference to the role of *Hybanthus floribundus* (Lindl.) F. Muell. as a nickel indicator and accumulator plant. *J. Appl. Ecol.*, **10**, 269–320.

————, Owen-Jones, E. S., and Custance, N. Remote sensing in mineral exploration: *In:* Curtis, L. C. and Barratt, E. C., Eds. *Environmental Remote Sensing.* (In press)

————, Provan, D. M. J., and Tooms, J. S. (1968). Geobotany, biogeochemistry and geochemistry in the Bulman-Waimuna Springs area, Northern Territory, Australia. *Trans. Inst. Min. Metall.*, **77**, B81–B104.

Crocket, R. N., and Jennings, C. M. H. (1965). Geology of part of the Okwa valley, western Bechuanaland. *Rec. Geol. Surv. Bechuanaland,* 1961–62, 101–113.

De Kock, W. P. (1934). The geology of the Western Rehoboth, South West Africa. *Mem. No.* **1**, *Dept. Mines,* South West Africa.

Dunham, K. C. (1964). Neptunist concepts in ore genesis. *Econ. Geol.*, **59**, 1–21.

Ensign, C. O. White, W. S., Wright, J. C., Patrick, J. L. Leone, R. O., Hathaway, D. J., Trammell, J. W., Frits, J. J., and Wright, T. L. (1968). Copper deposits in the Nonesuch Shale, White Pine, Michigan. *In:* Ridge, J. D., Ed., *Ore Deposits of the United States 1933-1967,* **1**, 460–488. Am. Inst. Min. metall. Petrol. Engrs., Inc., New York.

Gevers, T. W. (1934). The geology of the Windhoek District in South West Africa. *Trans. geol. Soc. S. Afr.*, **37**, 221–251.

Handley, J. F. (1965). General geological succession on the farm Klein Aub 350 and environs, Rehoboth District, South West Africa. *Trans. geol. Soc. S. Afr.*, **68**, 211–224.

Martin, H. (1965). *The Precambrian Geology of South West Africa and Namaqualand.* Precambrian Res. Unit. Univ. of Cape Town, 159 pp., tables, maps.

Nicholls, O. W., Provan, D. M. J., Cole, M. M., and Tooms., J. S. (1964). Geobotany and geochemistry in mineral exploration in the Dugald river area, Cloncurry district, Australia. *Trans. Inst. Min. Metal.*, **74**, 695–799.

Passarge, S. (1904). Die Kalahari. Dietrich Reimer, Berlin. 822 pp., tables, photos, maps.

Pettijohn, F. J. (1957). *Sedimentary Rocks* (2nd ed.). Harper & Sons, New York.

Vermaak, C. F. (1962). *Batawana Reserve — Bechuanaland Protectorate Geological Report.* Rep. J. C. I. Co. Ltd. (unpublished).

Wright, E. P. (1958). Geology of the area south of Lake N'Gami. *Rec. Geol. Surv. Bechuanaland Prot.* for 1956, 29–35.

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APPENDIX I

Analytical Techniques

BEDFORD COLLEGE LABORATORIES

Preparation

1. *Soils:* −80 and −270 mesh size fractions were separated by sieving, using stainless steel sieves.
2. *Plants:* Plant material was ashed overnight in Pyrex beakers. The ashing was carried out in Wild Barfield M30 muffle furnaces, fitted with fused silica linings, at 410 °C ± 10 °C.

Analysis

0,1 g of plant ash or soil was digested in 10 ml $NHNO_3$ at 95 ° in a waterbath. Analysis was by Atomic Absorption (Southern Analytical A3000) using the 3247 Å Cu Line.

ANGLOVAAL LABORATORIES

Soil Preparation and Analysis

For the 1967 initial reconnaisance undertaken by E. W. B. Miller and Associates, soil samples were collected using fine mesh tea strainers. In 1968 these were replaced by stainless steel sieves which thereafter were used for separating the −80 and −270 mesh fractions. Initially analysis was by chemical method but subsequently procedures were the same as at Bedford College using an Atomic Absorption Spectrophotometer (Tetron).

Plant Preparation and Analysis

The dry plant samples were first ground in a coffee mill. 2 grammes of ground material were taken, 30 ml of 3N.HCl added and the mixture boiled for 10 minutes. This was cooled to room temperature, filtered, washed three times with 15–20 ml of 3N.HCl and analysed for copper by Atomic Absorption Spectrophotometer.

NOTE: Tests were carried out to determine the analytical accuracy and reproducibility of analyses of plant samples. For this purpose bulk samples of leaves and twigs of common species were used. The results showed that for leaves the analytical precision at the 95 per cent confidence level varied from ±4 per cent for *Grewia flava, Boscia albitrunca* and *Catophractes alexandrii* to ±9 per cent *Tarconanthus camphoratus*. For twigs the variation in analytical precision was greater.

APPENDIX II
List of Plant Species

ACANTHACEAE
- *Barleria lanceolata* (Schinz) Oberm.
- *Barleria senensis* Klotzsch
- *Ecbolium lugardae* N.E. Br.
- *Justicia gurkeana* Schinz
- *Petalidium englerianum* (Schinz) C.B.Cl.
- *Petalidium parvifolium* Schinz

AMARANTHACEAE
- *Leucosphaera bainesii* (Hook. F.) Gilg
- *Nelsia quadrangula* (Engl.) Schinz

ANACARDIACEAE
- *Ozoroa paniculosa* (Song.) R. A. Fernandes
- *Rhus ciliata* Licht.
- *Sclerocarya caffra* Sond.

BIGNONIACEAE
- *Catophractes alexandrii* D. Don
- *Markhamia acuminata* K. Schum.
- *Rhigozum brevispinosum* Kuntze
- *Rhigozum trichotomum* Burch.

BURSERACEAE
- *Commiphora pyracanthoides* Engl. ssp. *pyracanthoides*

CAPPARACEAE
- *Boscia albitrunca* (Burch.) Gilg & Bened.
- *Boscia foetida* Schinz

COMBRETACEAE
- *Combretum apiculatum* Sond.
- *Combretum engleri* Schinz
- *Combretum erythrophyllum* Sond.
- *Combretum hereroense* Schinz
- *Combretum imberbe* Wawra
- *Terminalia prunioides* Laws.
- *Terminalia sericea* Cambess.

COMPOSITAE
- *Helichrysum leptolepis* DC.
- *Pegolettia pinnotiloba* (Klatt). Hoffm. ex Dinter
- *Pteronia eenii* S. Moore
- *Tarchonanthus camphoratus* L.

CONVOLVULACEAE
- *Evolvulus alsinoides* L.

CYPERACEAE
- *Fimbristylis hispidula* (Vahl.) Kunth (*F. exilis* (Kunth)) Roem. & Schult.

EBENACEAE
- *Diospyres lycioides* Desf.

EUPHORBIACEAE
- *Croton gratissimus* Burch.

GRAMINAE
- *Anthephora pubescens* Nees
- *Aristida congesta* Roem. & Schult.
- *Aristida hordeacea* Kunth
- *Aristida meridionalis* Henr.
- *Aristida stipitata* Hack. ex Schinz
- *Cenchrus ciliaris* L.
- *Chloris virgata* Sw.
- *Enneapogon brachystachyus* (Jaub. & Spach) Stapf
- *Enneapogon conchroides* (Licht.) C. E. Hubbard
- *Eragrostis denudata* Hack.
- *Eragrostis horizontalis* Peter
- *Eragrostis pallens* Hack.
- *Eragrostis porosa* Nees
- *Eragrostis rigidior* Pilg.
- *Eragrostis superba* Peyr.
- *Fingerhuthia africana* Lehm.
- *Pogonarthria fleckii* (Fleck) Hack.
- *Rhychelytrum repens* (Willd.) C. E. Hubbard
- *Schmidtia bulbosa* Stapf
- *Schmidtia pappophoroides* Steud.
- *Stipagrostis uniplumis* (Licht.) de Wint
- *Tragus racemosus* Steud.

LABIATAE
- *Leucas pechuellii* (O. Kunze) Guerke
- *Ocimun americanum* L.

LEGUMINOSAE
- *Bauhinia macrantha* Oliver
- *Lonchocarpus nelsii* Schninz ex Heering & Grimme
- *Mundulea sericea* R. Viguier
- *Parkinsonia africana* Sond.
- *Tephrosia dregeana* E. Mey

LILIACEAE
- *Pseudogaltonia clavata* (Bak.) Phil.

MALVACEAE
- *Hermannia damarana* Bak. f.
- *Hermannia modesta* (Ehrenb.) Masters
- *Sida chrysantha* Ulbr.

MIMOSAE
- *Acacia erubescens* Welw. ex Oliv.
- *A. fleckii* Schinz
- *A. Giraffae* Willd.
- *A. hebeclada* DC.
- *A. hereroensis* Engl.
- *A. karroo* Hayne
- *A. leudretzii* Engl.
- *A. mallifera* Benth.
- *A. nebrownii* Burtt Davy
- *A. reficiens* Wawra
- *A. tortilis* (Forsk.) Hayne
- *Albizia anthelmintica* Brongw.
- *Dichrostachys cinerea* (L.) Wight & Arn.

NYCTAGINACEAE
- *Phaeoptilum spinosum* Radlk.

OLACACEAE
- *Ximenia americana* L.

RHAMNACEAE
- *Zizyphus mucronata* Willd.

RUBIACEAE
- *Mollugo cerviana* (L.) Ser.

SCHROPHULARIACEAE
- *Aptosimum albomarginatum* Marl. & Engl.
- *A. leucorrhizum* (E. Mey.) Phill.

TILIACEAE
- *Corchorus asplenifolius* Burch.
- *Grewia bicolor* Juss.
- *G. flava* DC.
- *G. flavescens* Juss.
- *G. retinervis* Burret

NOTE on *Fimbristylis hispidula* (Vahl.) Kunth (*F. oxilis* (Kunth)) Roem & Schult.

The specimens of *Fimbristylis hispidula* (Vahl) Kunth *(F. exilis* (Kunth) Roem & Schult were named as *F. exilis* in the Pretoria herbarium. In personal communications Miss S. S. Hooper of the Kew herbarium states that, 1956, the leading cyperologist of the day, J. H. Kern, came down in favour of using *F. hispidula* (Vahl) Kunth. *Scripus hispidulus* (Vahl) (1805) has priority over *Isolepis exilis* (Kunth). The contention that *F. hispidula* Kunth is based on *S. hispidulus* Vahl, however, relies on two pieces of inconclusive evidence. He cites Vahl's type locality as the first locality among his records and he drops his own epithet *exilis*.

The name *Fimbristylis exilis* (Kunth) Roem & Schult. has been used throughout this paper.

APPENDIX III

Further Details Relating to Captions of Certain Figures

Figure 12

Distribution of vegetation associations in the Witvlei grant area (based on air photo interpretation and field investigations by M. Mason).

LOW TREE AND SHRUB SAVANNA	HABITAT
1. Characterized by *Combretum apiculatum* and *Albizia anthelmintica* trees, *Grewia bicolor, G. Flavescens, Commiphora pyracanthoides, Croton gratissimus* and *Mundulea sericea* shrubs.	Conglomerate ridge of Witvlei berg and quartzite hills on Eskadron, Okajirute and Grunental.
2. Characterized by variable association of *Acacia hereroensis, A. mellifera* and *A. hebeclada* trees, *Grewia flava, Phaeoptilum spinosum* and *Tarchonanthus camphoratus* shrubs and *Stipagrostis uniplumis* grass.	Level terrain with near surface bedrock.
3. Characterized by *Terminalia sericea* and *Acacia giraffae* trees, *Tarchonanthus camphoratus, Grewia flava, Oroza paniculosa* and *Rhus ciliata* shrubs and *Stipagrostis uniplumis* and *Schmidtia pappophoroides* grasses.	Thick sand cover.
4. Characterized by *Acacia mellifera* trees, *Tarchonanthus camphoratus* shrubs and *Stipagrostis uniplumis* and *Aristida congesta* grasses.	Sand and gravel accumulation on the northern side of Witvlei berg and around the quartzite hills on Eskadron.
5. Characterized by *Acacia giraffae* and *A. mellifera* trees, *Catophractes alexandrii* and *Grewia flava* shrubs, the suffrutices *Leucasphaera bainesii* and *Aptosimum leucorrhizum* and the grass *Fingerhuthia africana.*	Calcrete capped ridges.
6. Characterized by tall *Acacia mellifera* and *Boscia albitrunca* trees, *Catophractes alexandrii* shrubs, the suffrutices *Leucas pechelli, Hermannia damarana* and *Pseudogaltonia clavata* and the grass *Enneapogon cenchroides.*	Thick calcrete sheets masking bedrock.
7. Characterized by *Acacia giraffae, A. karoo, A. hebeclada* and *Zizyphus mucronata* trees.	Fossil drainage lines and pans floored by calcrete.
8. Characterized by *Acacia giraffae* and *A. karoo, A. hebeclada* and *Zizyphus mucronata* trees.	Alluvium along current drainage lines.
SHRUB SAVANNA	
9. Characterized by *Catophractes alexandrii* and *Grewia flava* shrubs with the suffrutices *Leucasphaera bainesii, Hermannia damarana, Pseudogaltonia clavata* and *Pegolettia pinnatiloba* and the grass *Fingerhuthia africana.*	Shallow calcrete over shales and limestones of the Buschmannsklippe.
SAVANNA GRASSLAND	
10. Characterized by *Aristida stipitata* and *Eragrostis pallens* grasses.	Thick sand cover.

Figure 15

Interpretation of vegetation/physiography/geology relationships shown on the air photos strip 4, No. 047 covering part of the farm Eskadron, north of Witvlei. (Interpretations by M. M. Cole and M. Mason.)

1. Area of mixed low tree and shrub savanna displaying vegetational banding which reflects near-surface bedrock.
2. Area of *Combretum apiculatum* low tree and shrub savanna producing an even tone and displaying vegetational banding which reflects outcropping quartzite forming a prominent ridge.

   In both 1 and 2 low vegetational banding suggests a folded structure.
3. Area of mottled texture with discernible lineations produced by *Acacia mellifera* trees in deep sand and gravel cover.
4. Areas of alternating light and dark tone produced by successive belts of *Stipagrostis uniplumis* grassland on sandy tracts and heavy tree and shrub cover of *Acacia giraffae*, and *Tarchonanthus camphoratus* and *Grewia flava* over calcrete.
5. Area of darker tone covered by large *Boscia albitrunca* and *Acacia mellifera* trees over calcrete.

Figure 22

Interpretation of vegetation/physiography/geology relationships shown on air photo MMC/SWA 20/17 covering the main geobotanical anomaly on the farm Sib, Gamma Grant area. (Photograph by M. M. Cole: Interpretation by A. F. Boshoff and M. M. Cole.)

A. Geobotanical anomaly where a sparse growth of *Helichrysum leptolepis, Fimbristylis exilis* ex *hispidula* with *Aristida congesta* at the periphery replaces the background vegetation.
B. Shrub savanna characterized by *Catophractes alexandrii* and *Rhigozum trichotomum* occurring over elevated ground with outcropping calcrete.
C. Low tree and shrub savanna with mixture of small *Acacia mellifera* trees, *Catophractes alexandrii, Phaeoptilum spinosum, Rhigozum trichotomum* and *Acacia hebeclada* shrubs over plains mantled by gravel and wind-blown sand.
D. Open grassland of *Stipagrostis uniplumis* with scattered *Acacia mellifera* and *Phaeoptilum spinosum* shrubs over rising ground with deep sand cover.
E. Pan with *Zizyphus mucronata, Diospyros lycioides* and *Acacia hebeclada* trees around its margin.
F. Relatively closely spaced *Petalidium parvifolium* shrubs along drainage channels.

Figure 24

Interpretation of vegetation/physiography/geology relationships shown on the air photo 28/BC/21 No. 064 covering the area southeast of Ghanzi. The inset shows the area covered by Fig. 26. (Interpretation by M. M. Cole and R. C. Brown.)

1. Apparent fold structure outlined by belts of grassland dominated by *Stipagrostis uniplumis* in silt filled vales alternating with low tree and shrub savanna characterized by *Boscia albitrunca* on ridges.
   (a) Ridges with denser tree growth, possibly promoted by increased water supply at the contact of argillite and arenite bedrock at depth.
   (b) Ridges with more open tree growth, possibly over near surface arenites.
2. Discernible but less well-defined apparent fold structure weakly outlined beneath sand cover of up to 4 m depth by narrow bands of low *Acacia giraffae* trees and *Grewia flava* shrubs which probably delineate water-bearing horizons at the contact of quartzites and shales.
3. Uniformly speckled textured areas where a low tree and shrub savanna characterized by *Combretum imberbe, C. hereroensis* and *Terminalia sericea* trees and *Grewia* spp. and *Combretum* spp shrubs occupies thick sand cover of over 4 m depth.
4. Area of darker tone with evenly distributed large *Combretum imberbe* trees on calcrete cover obscuring bedrock geology.
5. Approximately circular pans, often calcareous, carrying a dense grass cover with a ring of trees of various species at their periphery.
6. Belt of dense *Combretum imberbe* and associated trees species defining a linear feature, possibly a fault, which may be associated with increased ground water.
7. Irregular areas of darker tone produced by the effects of fire.

Figure 25

Distribution of vegetation associations over the western part of the fold structure on the farm Florida of Horseshoe Ranch southeast of Ghanzi. (Mapping by R. C. Brown.)

LOW TREE AND SHRUB SAVANNA	HABITAT
1. Characterized by *Boscia albitrunca* trees with *Acacia nebrownii, A. mellifera, Grewia flava, Ximenia americana* and *Tarchonanthus camphoratus* shrubs and *Petalidium englerianum, Leucasphaera bainesii, Melhania rehmannii* suffrutices and *Enneapogon brachystachys* and *Cenchrus ciliaris* grasses.	Calcrete covered ridges.
2. Composed of *Zizyphus mucronata* and *Acacia tortilis* trees, *Grewia flava, A. hebeclada* and *A. nebrownii* shrubs, and *Cenchrus ciliaris* grass.	Pan
3. Characterized by mixed trees and shrubs — *Combretum hereroense,* and *Acacia fleckii* trees, *Grewia flava* shrubs, *Tylosema esculenta* tubers and *Stipagrostis uniplumis* grass.	Immature arid red earth soils over near surface bedrock.
4. Characterized by mixed trees and shrubs with species named above and in addition *Petalidium englerianum.*	Sand covered calcrete ridges.

SAVANNA GRASSLAND

5. Dominated by *Stipagrostis uniplumis* with scattered shrubs of *Grewia flava, Acacia nebrownii, Petalidium englerianum* and trees of *Acacia giraffae.*	Linear silt filled depressions.
6. Dominated by *Stipagrostis uniplumis* with scattered shrubs of *Ximenia americana.*	Sand filled shallow depressions.

Figure 29

Interpretation of vegetation/physiography/geology relationships shown on the air photo 28/BC/7 No. 073 covering part of Ngwaku Pan and the area to the south-east. (Interpretation by M. M. Cole and A. D. Buerger.)

1. Variable tree and shrub cover of *Terminalia sericea, Dichrostachys cinerea, Commiphora pyracanthoides* and other species over deep sand.
2. Grassland on Ngwaku Pan.
3. Grassland and open parkland dominated by *Eragrostis porosa* with scattered *Acacia erubescens* and other tree species over areas of impeded and internal drainage.
4. Low tree and shrub savanna displaying vegetational banding and delineating an inferred fold structure in the Ghanzi beds of the Tsumis Formation.
5. Belts of larger trees associated with postulated faults.
6. Uniform low tree and shrub savanna characterized by *Terminalia sericea* over more elevated ground of sand dunes.

Figure 30

Interpretation of vegetation/physiography/geology relationships shown on air photo 28/BC/5 No. 071 covering part of the Ngwenalekau hills and adjacent areas. (Interpretation by A. D. Buerger and M. M. Cole.)

1. Low tree and shrub savanna composed of alternating belts dominated by *Combretum apiculatum* and by *Terminalia prunioides* and *Acacia erubescens* over inferred arenites and other sedimentary rocks of the Ghanzi beds of the Tsumis formation.
2. Low tree savanna characterized by *Terminalia prunioides* over argillites and other sedimentary rocks of the Ghanzi beds of the Tsumis formation.
3. Grassland and open parkland dominated by *Eragrostis porosa* with scattered *Acacia erubescens* trees over areas of impeded and internal drainage.
4. Low tree and shrub savanna characterized by *Combretum apiculatum* over quartz porphyry bedrock of Skumok age forming the Ngwenalekau hills.
5. Belts of larger trees mainly *Combretum apiculatum* following joints, some of which form drainage lines, in the Skumok quartz porphyry.
6. Variable tree and shrub cover of *Terminalia sericea, Dichrostachys cinerea, Croton gratissimus* and other species over deep sand.