THE PANS OF THE SOUTHERN KALAHARI, BOTSWANA

by

Ian Nicholas Lancaster M.A.

Fitzwilliam College

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PREFACE

This dissertation is the result of investigations of the pans of the southern Kalahari conducted during two periods of field work in Botswana in May to September 1972 and April to August 1973, together with the subsequent analyses of the samples collected.

The southern Kalahari today is still a wild and comparatively inaccessible place. Travel in the area is only really possible along the few bush tracks that exist, and even then it is time consuming and heavy on fuel. Over much of the area potable water supplies are absent or unreliable. Considerations of safety and logistics thus dictate what it is possible to undertake. Regrettably, from the scientific point of view, many of the conclusions reached in this dissertation must be regarded as tentative, as it was not always possible to obtain conclusive evidence in support of them.

Except where stated, all the data presented in the following chapters is the product of the surveys and analyses conducted by the writer. No research in collaboration with others was undertaken.

Additional information was derived from the following sources:
The meteorological data presented in Chapter 2 was provided by Mr. R.J.F. Anderson of the Weather Bureau, Gaborone, Botswana.

Information on the internal composition of the dunes at Kongwe and Sekoma pans was derived from samples made available by T. Baillieul, then of the Geological Survey, Lobatse, Botswana, who conducted the drilling programme.

The analyses of water in the pans in April 1973 were undertaken by courtesy of the Director of Geological Survey, Lobatse, Botswana.

The mollusca from the inner dunes were identified by Dr. A.C. Van Bruggen, Rijksmuseum van Natuurlijke Historie, Leiden.

All figures in this dissertation were drawn by my wife Judith, who also typed the manuscript.

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In addition, I wish to thank my supervisor, Mr. A.T. Grove, for his continued assistance, encouragement and helpful comments and suggestions at critical times in the production of this work.

Lastly, but by no means least, I wish to thank my wife, Judith, for her invaluable help and support as field and laboratory assistant, typist and cartographer, without which this dissertation could never have been produced.

DECLARATION

I hereby declare that this dissertation is not substantially the same as any I have submitted for any degree, diploma or any other qualification at any other University. Furthermore, no part of this dissertation has been, or is concurrently being, submitted for any degree, diploma or any other qualification.

I.N. Lancaster, M.A.

SUMMARY

The main geomorphic features of the southern Kalahari in Botswana are the 1000 pans or small dry lakes which lie along the broad watershed between the Nossop - Molopo and Makgadikgadi drainages.

No previous detailed studies exist of the pans, which appear to have developed under climatic conditions unlike those of today, and appear to represent further evidence for Quaternary climatic change in the region.

The pans, which may have a grassed, partly grassed or bare clay surface, are contained in shallow sub circular to sub elliptical isolated depressions, on the southern side of which is an area of fringing dunes, indicative of a deflation origin for the pan depressions.

Analysis of the distribution of the pans shows that they are strongly clustered, but do not form aligned groupings.

Two dune ridges, both formed by northerly winds, are identified. The composition of the dunes shows that the outer dunes were formed by deflation from the site of the pan depressions and the inner dunes by deflation of sandy pan deposits.

The nature of the deposits which underlie the pans and the flanks of the inner dunes is described, and upper sandy and lower clayey phases identified. Their composition indicates that the pan depressions once held extensive permanent lakes, which gradually contracted as the climate became drier. The nature of the pan surfaces today is shown to represent a sequence as the pans are excavated by deflation.

The paleoclimatic significance of the three main periods in the origin and development of the southern Kalahari pans is discussed. The pan deposits provide further evidence for a major wet period in the Kalahari some 12000 to 20000 years ago. Deflation to form the outer dunes took place in the arid period that occured 20000 to 25000 years ago, and the inner dunes were formed during dessication of the climate some 10000 to 12000 years ago.

CHAPTER 1.

INTRODUCTION

THE PANS OF THE SOUTHERN KALAHARI

The southern Kalahari in Botswana is a great gently undulating sand plain at an altitude of 1100 to 1200 m above sea level, covered by shrub and bush savanna and receiving a very variable annual rainfall of 250 to 400 mm.

The principal geomorphic features of the area are the thousand or so pans which break the monotony of the otherwise almost featureless sand plain. Most of the pans, or small ephemeral or dry lakes, are contained in sub circular depressions some 1.5 to 4 km across and 10 to 30 m deep. On the southern side of the pans is an area of fixed arcuate sand dunes, which rise to a height of up to 40 m above the depression floor and extend for 1 to 2 km from the pan edge.

At the present time the pans, which may have a grassed, partly grassed or bare clay surface, contain shallow water bodies or "playa lakes" after heavy rains or wet seasons.

In southern Africa, any depression that holds water after a period of rain is called a pan. Consequently the assemblage of landforms described above is popularly called a pan. However, for the purposes of this dissertation the term pan will be used to refer to the flat central portion of the depression that may be covered by water after rain. The term pan as used here is thus synonymous with playa, defined by Neal (1965) as the flat central portion of a desert basin.

LOCATION OF STUDY AREA

The location of the study area is shown in Figs. 1.1 and 1.2, and covers an area of approximately 130000 km^2.

The southern Kalahari in Botswana forms a small part of the Kalahari basin, a vast sand covered plain that stretches north from the Orange river in South Africa to the watershed between the Zambesi and Zaire rivers and beyond to 1 ^{o}N latitude. The Kalahari basin is bordered to the west by the highlands of Namibia (South West Africa) and Angola, and on its eastern side by the hills and plateaux of eastern Botswana, Rhodesia and Zambia. According to Wellington (1955)

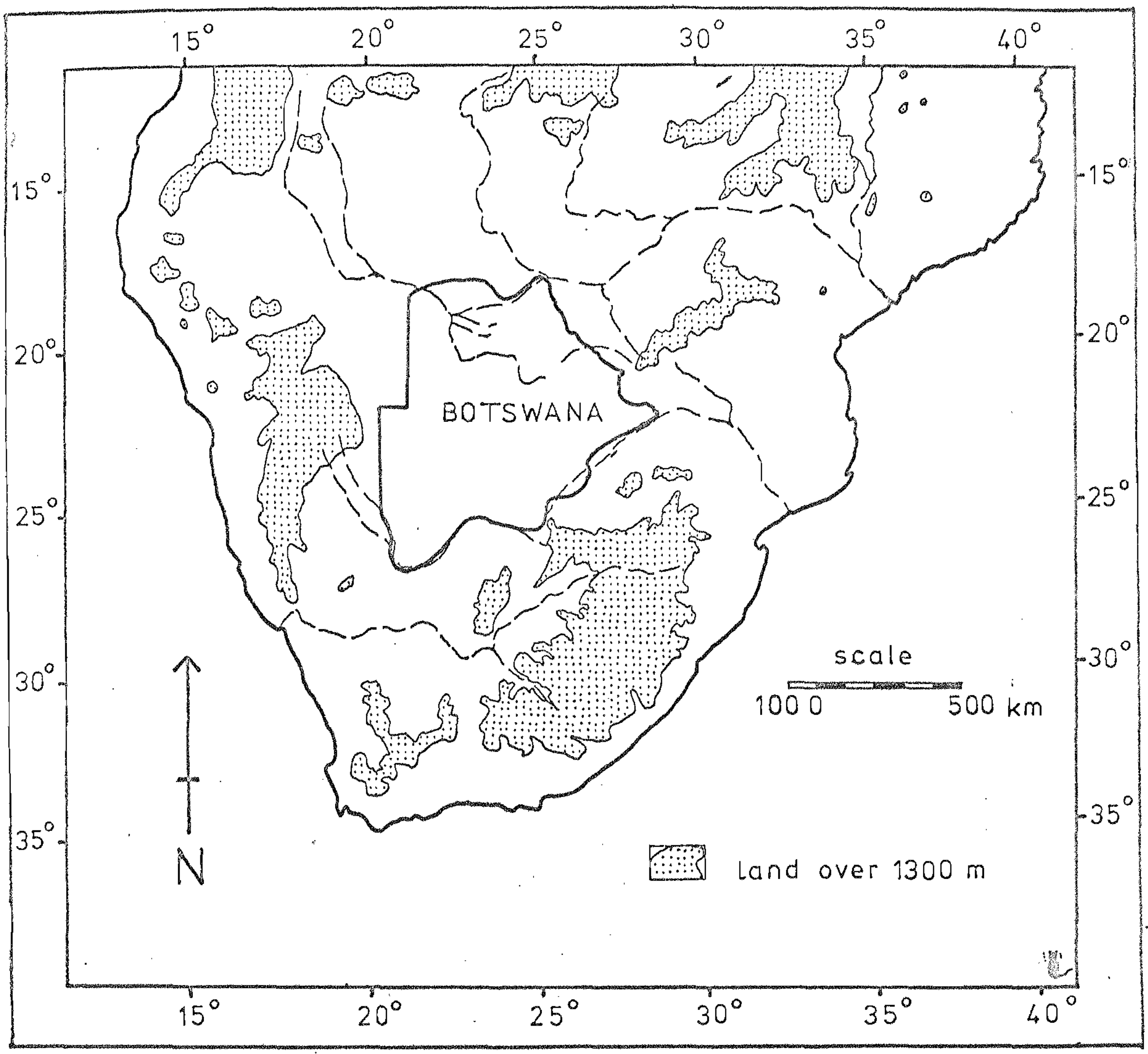


Fig. 1.1 Location of Botswana.

it is probably the largest sand covered area in the world, with an area of some 2.5 million km².

COMPARISONS WITH OTHER SEMI ARID AREAS

The southern Kalahari in Botswana, although often called a desert, is in fact almost everywhere covered by shrub and bush savanna. Only in the southwest of the country, in the vicinity of the Nossop-Molopo confluence, are areas of bare mobile sands encountered. The area may be more accurately described as a thirstland, with a semi arid to sub arid climate.

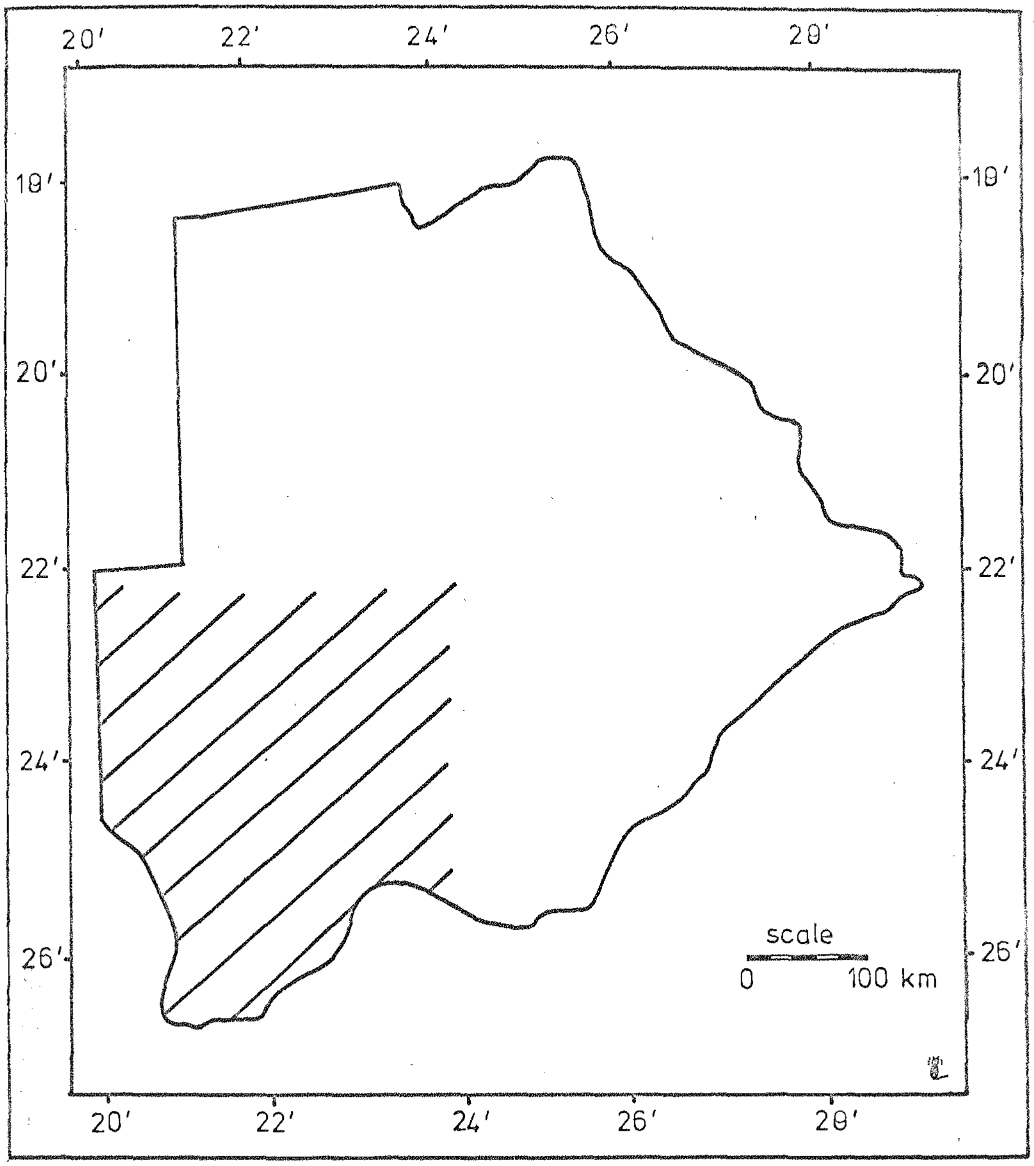


Fig. 1.2 Location of the study area in Botswana.

On the basis of Meigs' classification of semi arid and arid climates (Meigs 1953) the climate of the southern Kalahari may be compared with that of parts of the Sahelian zone of West and Central Africa; western Queensland, Australia; parts of northern Argentine and Uraguay; southern Texas, U.S.A. and northern Mexico. All these areas have a similar semi arid climate with an annual rainfall of 200 to 500 mm, falling in the summer, or hot season, when mean temperatures are in the range 20 to 30 °C. During the winter, or cold season, mean temperatures drop to 10 to 20 °C.

In terms of the physiography of the southern Kalahari with its low relief at a relatively high altitude, unconsolidated surface deposits and lack of surface drainage, comparisons are more difficult to make. Grove (1969) likened the physiography of the Kalahari to that of the Sahelian zone of West Africa. Both are semi arid areas of low relief, and their landforms appear to have developed under periods of alternating wet and dry climates in the Quaternary. However, the Sahel is at a lower altitude than the Kalahari and somewhat warmer.

In many respects the southern Kalahari may be more closely compared with the southern High Plains of Texas, U.S.A.. Both areas have a similar climate, with a high evaporation rate and a low summer rainfall. Geologically, the areas are similar with unconsolidated sandy surface deposits forming featureless plains at an altitude of 1000 to 1200 m. The existence of small lake basins and lack of surface drainage are again a point of comparison.

PREVIOUS GEOMORPHOLOGICAL RESEARCH IN THE KALAHARI

The Kalahari has attracted the attentions of geologists and geomorphologists for some time. Apart from the observations of travellers and hunters like Andersson, Oswell and Livingstone, the first descriptions of the geomorphology of the Kalahari are contained in Passarge's Die Kalahari (1904).

Since the 1920's there have been a series of descriptions of the geology and geomorphology of the Kalahari by Du Toit (1927), Rogers (1934, 1936), Wayland (1952, 1954), Wellington (1955) and Boocock and Van Straten (1962), mostly based upon reconnaissance studies of the area with a view to the development of its mineral and water resources. It was not until the availability of aerial photography of the whole of the Kalahari in the mid 1960's that the true nature and extent of the landforms of the region became known. Grove (1969) provided the first comprehensive description of the landforms of the Kalahari, based upon a detailed study of this aerial photography. Grove's work indicated the great variety of landforms in the region, many of them giving clear evidence of Quaternary climatic fluctuations.

Cooke and Warren (1973) have summarised the nature of geomorphic research in arid and semi arid regions, and suggest that it consists of a period of exploration, characterised by reconnaissance studies of the geomorphology, followed by a period in which more detailed studies of landform and processes takes place. This pattern has clearly applied in the case of the Kalahari, and Grove's 1969 study can be seen to mark the culmination of the reconnaissance phase of geomorphology in the Kalahari. The writer's study of the origins and development of the pans of the southern Kalahari can be seen to be directly inspired by the work of previous investigators, particularly Grove, who have pointed to the existence of an unusual, yet widely occuring, landform of uncertain origin. The present study can also be seen to mark the beginning of the second stage of geomorphological investigation in which detailed studies of landform and processes are undertaken.

PREVIOUS WORK ON PANS IN SOUTHERN AFRICA

There are considerable numbers of pans in southern Africa. Rogers (1940) estimated that there were 9000 pans 100 m or more across in the Kalahari between the Orange river and the Zambezi. Outside the Kalahari an equally large number of pans exist in parts of the northern Orange Free State and Transvaal.

The pans in the northern Cape Province were described and attributed to wind action by Rogers (1908) and Du Toit (1907, 1926). In the "Panneveld" of the western Transvaal and northern Orange Free State there are large numbers of pans, apparently the remnants of former river systems, which have been described by Wellington (1943) and Coetzee (1960). Recently, Butzer et al (1973) have studied the sequence of deposits preserved in Alexandersfontein pan, near Kimberley, and concluded that the pan held a large permanent water body some 16000 years ago. A further group of pans occurs in the Lake Chrissie area of the eastern Transvaal. Wellington (1945) concluded that they represented remnants of the head waters of the Vaal river, beheaded by the capture of tributaries by the eastward flowing Usutu river. Subsequent modification of sections of the river valleys by silting and wave action resulted in the present shape of the pans. There are considerable numbers of pans in Namibia (South West Africa), Werther (1935) described line and sand pans in the headwaters of the

Auob and Nossop rivers. Jaeger (1939) investigated a large number of pans, and described their form and deposits in some detail.

But despite their large numbers and distinctive nature the geomorphology of the southern Kalahari pans has received little attention. In the literature on the area only Boocock and Van Straten (1962) and Grove (1969) make more than a brief reference to the pans. In view of this it is not surprising that: "the origins and development of the pans remains a matter of hypothesis and conjecture" (Blair Rains and Yalala 1972), a situation not uncommon in the study of important desert landforms. There is thus a need for a comprehensive investigation of the origins and development of the pans of the southern Kalahari.

THE PANS OF THE SOUTHERN KALAHARI AS A FOSSIL LANDFORM

The existence of fixed dunes adjacent to lake basins which contain 3 to 4 m of lacustrine deposits, but are now dry or occupied by ephemeral lakes, is clear evidence of past climatic conditions in the Kalahari unlike those of the present day. Evidence of considerable climatic fluctuations in the region during the Quaternary was first recognised by Wayland (1954) who stated that the Pleistocene episodes in the Kalahari provided a sequence of contrasts, the impressive evidence of which could hardly be bettered, if indeed equalled, anywhere in Africa. Grove (1969) recognised two periods of Quaternary aridity and sand movement in the Kalahari, with an intervening humid period, during which the Makgadikgadi depression was occupied by a 34000 km^2 lake.

The pans of the southern Kalahari may thus be considered as relict or fossil landforms, preserved by the present inactivity of the processes that led to their formation. Such fossil or relict landforms are common in semi arid and arid areas and their study is an important part of desert geomorphology (Peel 1966).

Many landforms are not diagnostic of the climatic conditions under which they were formed and their existence cannot be reliably used to indicate the nature of past or present climates. However, when the evolution of a landform involves both erosion and deposition it may be possible to reconstruct the sequence of erosional and depositional environments by a study of the nature and stratigraphy of the deposits formed. The evidence from sediments and other deposits composing a landform is frequently a more reliable guide to past environments than its morphology.

However, some landforms may yield valuable paleoclimatic information. For example, the orientation of dunes has been widely used (Hack 1941, Melton 1940, Reeves 1965, Grove 1958) to indicate paleowind directions, and abandoned shorelines in lake basins are invariably indicative of a dessication of the climate. In addition comparisons with modern "active" examples may be made, enabling recognition of past environmental conditions. The work of Bowler (1970, 1973) on clay dunes has shown the value of such comparisons.

Consequently this study of the origins and development of the southern Kalahari pans will focuss upon two main aspects of their geomorphology: the dunes on the southern side of the pans and the deposits contained in the pan depressions. Studies of dunes adjacent to lake basins, notably Reeves (1965) and Bowler (1970), have demonstrated that their orientation, form and composition can yield valuable information of the environments in which they were formed, and thus on the origin and development of the adjacent lake basins. The deposits of the lake basins similarly preserve a record of past depositional environments, and examination of the stratigraphy of lake and dune deposits enables a relative chronology of the development of the lakes to be built up.

Since the pioneering work in the western U.S.A. (Russell 1885, Gilbert 1890) investigation of ancient lake basins have been carried out in many parts of the world. Most of the studies have been concerned with the record of Pleistocene climatic fluctuations contained in the deposits and shorelines of the lake basins, and indicate that many basins in present semi arid and arid areas contained sizeable permanent lakes during the Pleistocene. Illustrative of this approach is the work of Smith (1968) at Searles Lake, California, U.S.A.; Washbourn-Kamau (1971) in the Nakuru-Elmenteita basin, Kenya; and Grove, Street and Goudie (1975) in the Rift Valley of southern Ethiopia.

However, investigations of the origins and development of small lake basins in semi arid areas are much less common. In this context Reeves' study of the pluvial lake basins of west Texas, U.S.A. (Reeves 1966) and Bowler's work in southeastern Australia are noteworthy. Reeves' work shows clearly that study of the origins and development of lake basins can yield valuable information on past environments by pointing to the processes involved in their formation and development. Bowler's study of lakes in southeastern Australia shows clearly the great value of correlating lake and dune deposits to build up a picture of the evolution of the lake basin.

AIMS OF DISSERTATION

The aims of this dissertation are: to describe the main features of the geomorphology of the pans of the southern Kalahari, and to put forward hypotheses to explain their origin and development.

In the absence of any previous detailed investigations of the southern Kalahari pans it is inevitable that much of what follows is descriptive. Thus a comprehensive description of the topography of the pans studied is given in Chapter 3, as a preliminary to a more detailed discussion of the origins and development of their main geomorphic features in subsequent chapters.

Clearly, the pans are today relict or fossil landforms and an explanation of their origins and development must necessarily involve a consideration of past environmental changes in the Kalahari. It is hoped that this study of the origins and development of the pans of the southern Kalahari will provide further information on the nature of Quaternary climatic changes in the Kalahari.

The following chapters will, after a discussion of the present environment of the southern Kalahari, consider the topography and distribution of the pans; the morphology and composition of the dune complexes; and the morphology and deposits of the pan depressions.

CHAPTER 2.

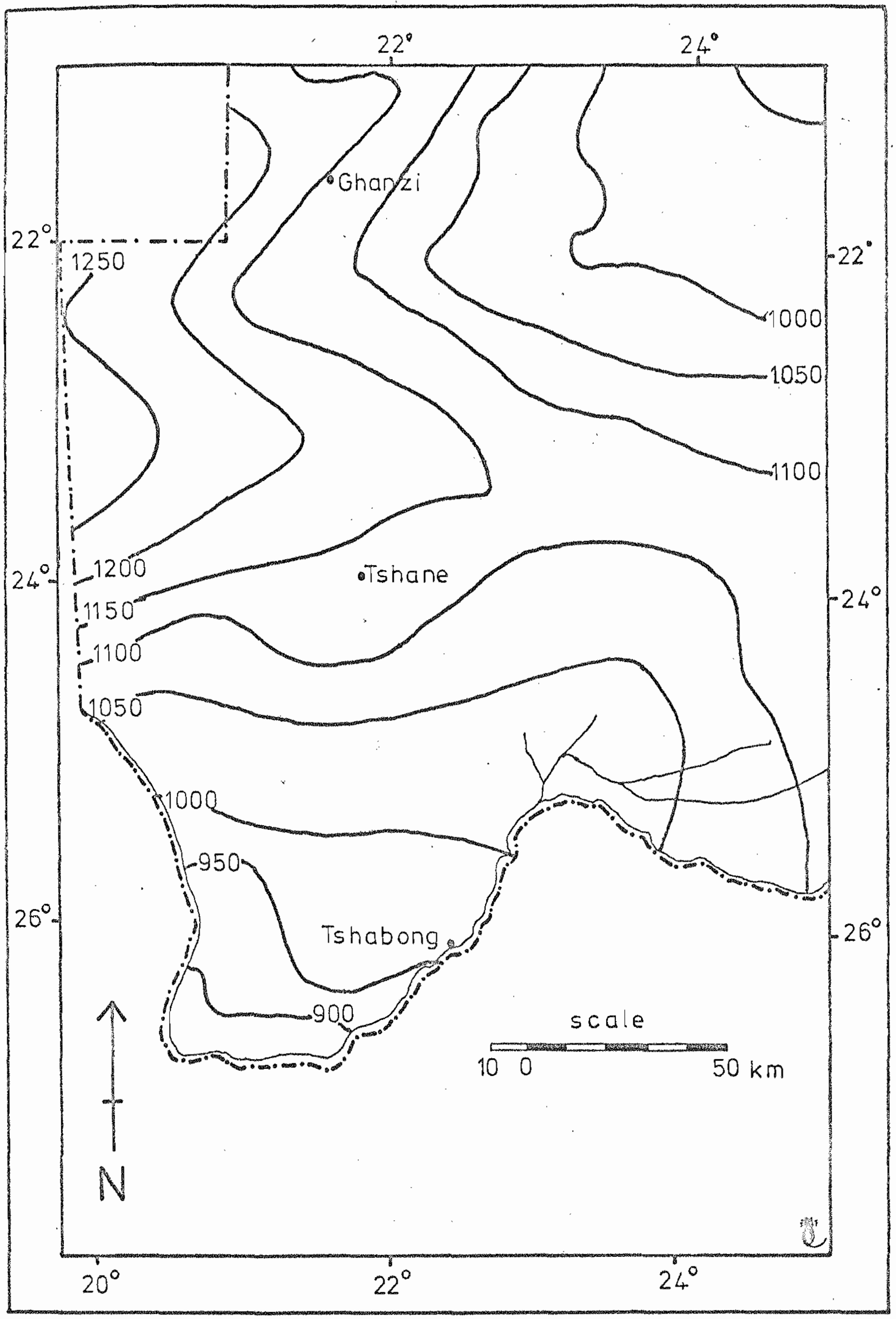


Fig. 2.1 Topography of the southern Kalahari.

Heights above sea level in metres. Contour interval 50 m. After M.S. map by C.V. Reeves 1975.

of 200 km near Tshane. West of Tshane the ridge narrows slightly and gradually rises to its maximum altitude of 1250 m above sea level in the Kule - Ncojane area. To the north, the land falls to the Okwa and Mmone valleys at an altitude of approximately 1000 m. On the southern side of the ridge there is a gentle fall to the confluence of the Nossop and Molopo rivers which lies at 900 m above sea level. The southern Kalahari thus forms a watershed between the Okwa river system draining towards the Makgadikgadi depression, and the Nossop - Molopo rivers which join the Orange river near Upington, Cape Province. This divide was called the Bakalahari Schwelle by Passarge (Wellington 1955), and is regarded by Wellington (1955) as a very ancient watershed between the northern and southern Kalahari basins.

There are few topographic features of note over much of the area, apart from the pans and their associated dunes. Locally relief is of the order of 3 - 4 m and consists of irregular low ridges separated by wide shallow depressions, giving rise to a gently undulating topography. In some areas, for example between Tshabong and Mabuasehube, the ridges are more marked and the depressions narrower giving rise to a confused, hummocky topography. Many of these undulations, which carry a denser cover of trees and shrubs, can be seen on air photographs to have a northeast - southwest to north - south trend. They appear to be equivalent to the "faint furrow patterns" described by Grove (1969) and the more extensive lineaments, visible on the ERTS imagery of the area, which curve round from east northeast - west southwest south of the Makgadikgadi depression to northeast - southwest and north - south over much of the southern Kalahari and to north northwest - south southeast in the south and southwest of the area, and appear to represent the degraded remnants of longitudinal dunes. In the southwest of the area, in a belt up to 100 km wide along the Nossop and Molopo valleys there are areas of well developed dune ridges which form an extension of the fixed dune systems of the adjacent areas of the northern Cape Province and Namibia (South West Africa). The dunes in the southwest of Botswana are sand ridges 5 - 10 m high and 100 - 500 m apart with a characteristic dendritic pattern similar to that described by Mabbutt (1968) in Australia. Lewis (1936) described similar dunes in adjacent areas of South Africa, and suggested that they were formed by northeasterly winds. Grove (1969) noted that many of the ridges

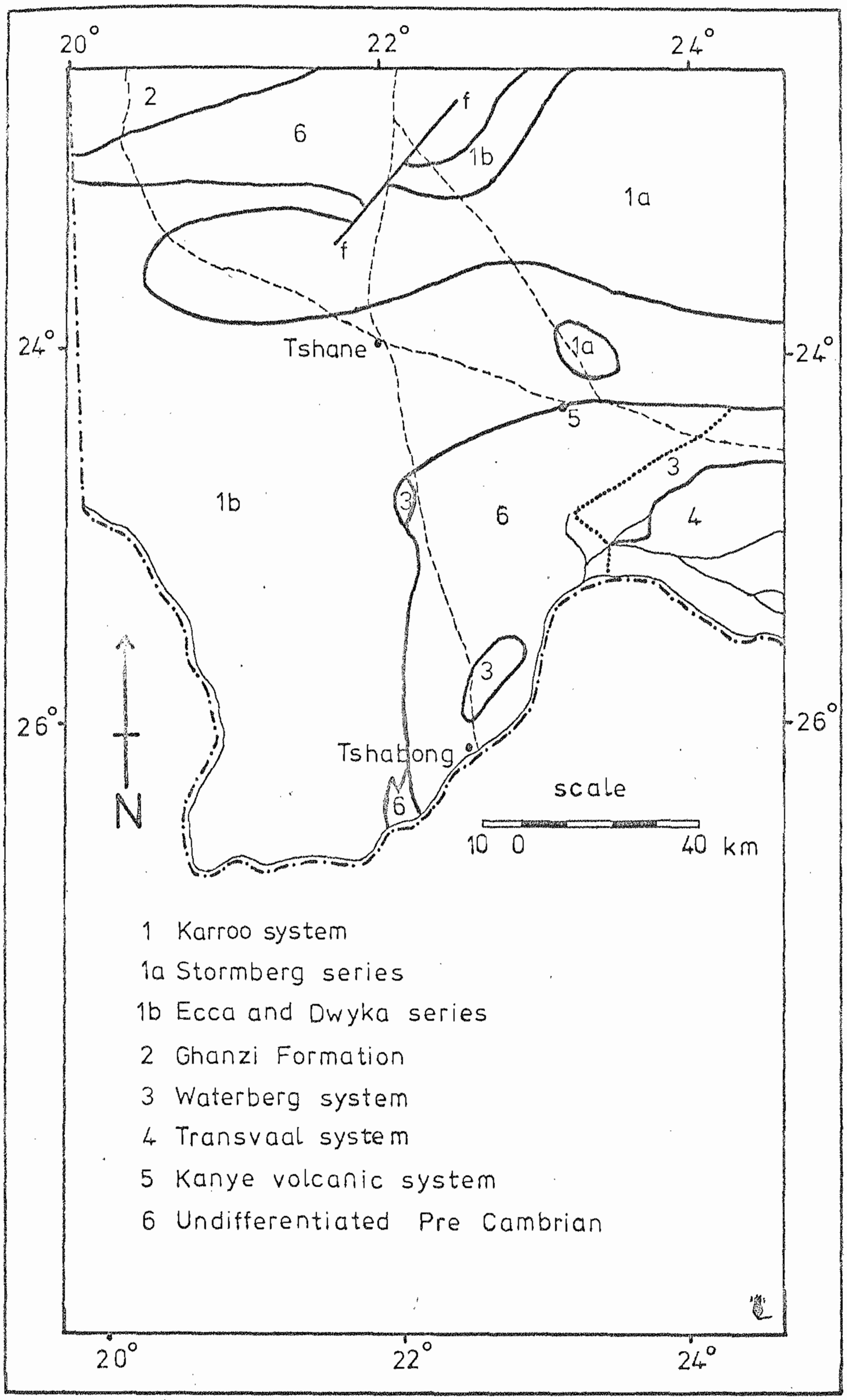


Fig. 2.2 Geology of the southern Kalahari.

All areas are mantled by variable thickness of Kalahari Beds. After Geological Map of Botswana. Lobatse 1973.

coalesced to form Y junctions with the stems pointing to the southeast, and concluded that they were longitudinal dunes formed by northwesterly winds. However, Goudie (1970) pointed to the problems of equating the existence of longitudinal dunes trending northwest - southeast in the area with the northeasterly winds of today and suggested that former wind regimes may have been different.

Forming the northern margins of the southern Kalahari are the extensive Okwa and Mmone dry river systems with valleys up to 50 m deep and 1 - 2 km across in places. These river systems formerly drained the highland areas of Namibia (South West Africa) and eastern Botswana and flowed to the Makgadikgadi depression. The Nossop and Molopo rivers, forming the southern boundary of the area, rarely carry water in their lower parts. Normally, the Molopo is dry below Mafeking, although occasional flows may reach Bray in very wet years (e.g. 1967, 1972, 1974-5). The form of the valleys of all these dry rivers suggests that they once carried much higher discharges, and all are locally deeply incised into calcretes. At Pitsane and Khuis the Molopo has cut gorges 30 m deep in schists and quartzites. The Nossop is incised to a depth of 10 - 20 m in calcareous sandstones assigned to the lower parts of the Kalahari Beds.

Set in the gently undulating topography of the watershed area are the pans, which are contained in small sub circular depressions 2 - 5 km across and 15 - 20 m deep. They, and the crescentic dunes on their southern margins, form the only topographic features of note over much of the southern Kalahari.

Locally the sand surface is broken by outcrops of pre Kalahari rocks, which give rise to low hills. In the Sekoma area, Waterberg System sandstones form a low northeast - southwest trending ridge between Khakhea and Sekoma. At Tshabong, outcrops of similar rocks give rise to low, rounded hills.

GEOLOGY

The geology of the southern Kalahari is depicted in Fig. 2.2. Much of the area is mantled by Kalahari Beds, and as a result, knowledge of the underlying geology has been obtained by examination of borehole samples.

The southern Kalahari forms part of the Kalahari basin, which has been infilled with sedimentary and volcanic deposits since Pre Cambrian times. The central parts of the area are underlain by rocks of the Karroo System which lie in a 150 - 200 km wide basin trending northeast - southwest, which links the Karroo of South Africa and Rhodesia. On the northwestern side of the basin are the sandstones and arkoses of the Ghanzi Formation, forming the Ghanzi ridge. Underlying the eastern parts of the southern Kalahari and forming the southeastern flanks of the Karroo basin are Pre Cambrian Waterberg System sandstones and quartzites and Transvaal System dolomites. The whole area is mantled with a variable thickness of Kalahari Beds of varying lithologies, culminating in the surface Kalahari sands.

The eastern parts of the southern Kalahari are underlain by Pre Cambrian rocks, which extend to Mabuasehube pan in the west, Kokong in the northwest and Tshabong in the south. It would appear that much of this area is underlain by sandstones, conglomerates and quartzites of the Waterberg System. The low hills northeast of Tshabong are composed of reddish grey quartzites which Du Toit (1954) correlated with the Matsap Beds of the northern Cape Province. Similar rocks are exposed north of Khakhea and form the low ridge between here and Sekoma. At Khakhea pan itself a sedimentary succession composed of purple and green shales, banded siltstones, ripple marked quartzites is exposed, and is regarded as being part of the Waterberg System. Other small outcrops of Waterberg sandstones occur northeast of Sekoma pan and at Mobutsane. Extensive outcrops of shales with a near vertical dip may be seen on the west side of Mabuasehube pan and mark the most westerly extent of the Waterberg System in the southern Kalahari.

The area to the southeast of Sekoma is underlain by shales, quartzites and banded ironstones of the Transvaal System. Acid tuffs and lavas at Kokong pan appear to represent an isolated outlier of the Kanye Volcanic System.

Much of the Kalahari in Botswana is underlain by rocks of the Karroo System. Outcrops in the southern Kalahari are rare and consequently much of the information about these rocks is derived from borehole samples. Dwyka Series tillites are exposed on the north side of Mpaathutlwa pan and at Khuis, along the Molopo river. The Ecca Series

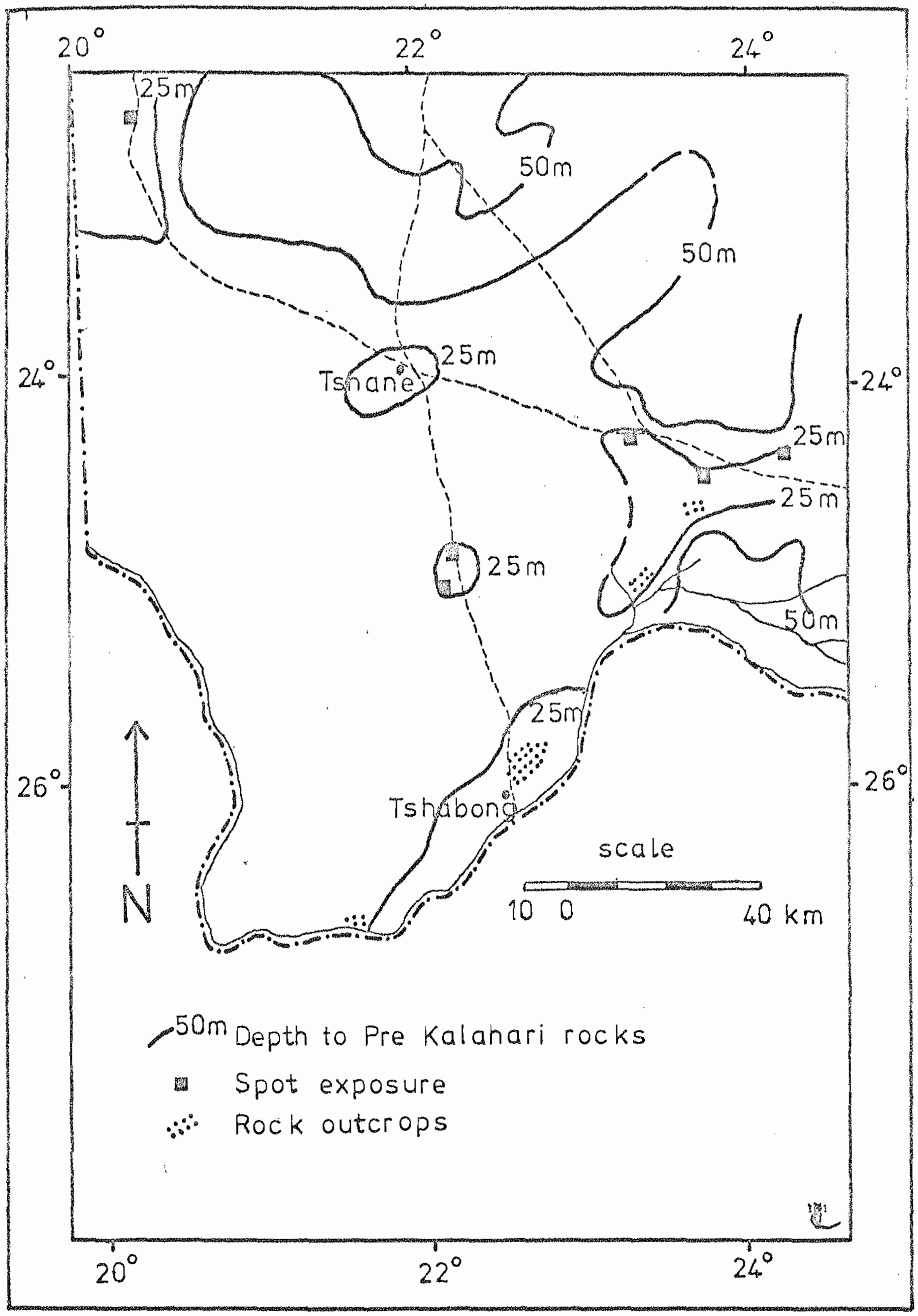


Fig. 2.3 Thickness of Kalahari Beds.

From borehole records, Geological Survey Department, Lobatse.

is represented in the southern Kalahari by a lower arenaceous phase, which occurs on the southeastern side of the Karroo basin as far west as Kokong; and an upper argillaceous phase consisting of shales, mudstones and siltstones, which underlies much of the western part of the area. Ecca sandstones and shales outcrop at Ukwi and Ncojane pans in the far west of the southern Kalahari. Stormberg Series sandstones underlie the northern parts of the area and extend into the central Kalahari. In part, the northern margins of the study area are underlain by the sandstones and arkoses of the Ghanzi Formation.

Kalahari Beds mantle the whole of the study area. Their thickness is highly variable, as Fig. 2.3, compiled from borehole records, shows. In general terms, the Kalahari Beds appear to increase in thickness away from the watershed area towards the central Kalahari, and in the Molopo farms area, south of Sekoma. However, Kalahari Beds are thin or absent altogether from much of the area between Tshabong and Khakhea. Locally, great variations in the cover of Kalahari Beds may exist. At Kokong the cover is thin and Kanye Volcanic System felsites outcrop, but 10 km to the west at Mashiaphotsana pan a borehole intersects 100 m of Kalahari Beds.

The lithology of the Kalahari Beds is varied and reflects their deposition in continental conditions. However, four main lithological types may be identified. The lowest member of the Kalahari Beds are the Kalahari marls, described by Du Toit (1954) from the northern Cape Province. In the southern Kalahari they appear to be associated with drainage lines and hollows in the pre Kalahari surface (Boocock and Van Straten 1962) and are intersected by boreholes on the upper Molopo valley and in the area northeast of Tshane.

Above the marls are calcareous sands and sandstones, often partly silicified, which are widespread in adjacent areas of Namibia (South West Africa) (Mabbutt 1957) and occur in the lower Nossop valley where they form bluffs 5 - 10 m high. Similar deposits appear to exist in the vicinity of Ukwi pan, where they form a 5 m high bluff on the north side of the pan, and at Tshane.

Table 2.1

Rock Units Occuring in the southern Kalahari

Sedimentary, metamorphic and effusive

Age	Stratigraphic Unit	Lithology
Tertiary to Recent	Kalahari Beds	Sands
		Pan sediments and calcretes
		Calcified and silicified sandstones and limestones
		Marls
Late Carboniferous to Jurassic	Karroo System	
	Stormberg Series	Sandstones, with subordinate shales and marls
	Ecca and Dwyka Series	Arkoses and shales
		Mudstones and shales
		Tillites and varved shales
Late Pre Cambrian	Ghanzi Formation	Sandstones, with subordinate shales and limestones
Mid Pre Cambrian	Waterberg System	Sandstones, grits, conglomerates and quartzites
	Transvaal System	
	Pretoria and Griquatown Series	Shales, quartzites and subordinate conglomerates, limestones, banded ironstones and andesites
	Dolomite and Black Reef Series	Dolomites, with subordinate banded ironstones, cherts, shales and quartzites
	Kanye Volcanic System	Felsites
Early Pre Cambrian	Basement Complex	Serpentinites
		Undifferentiated gneisses

Intrusive igneous rocks

	Karroo	Dolerite
	Post Waterberg pre Karroo	Diabase
Mid Pre Cambrian		Ultrabasic

Reddish brown quartz sands mantle much of the southern Kalahari and form the uppermost member of the Kalahari Beds. Sands of a similar type occur widely from the Zaire basin watershed to the Orange river, in the areas between the highlands of the Transvaal and Rhodesia and the plateaux of Namibia (South West Africa) and Angola. In the southern Kalahari their thickness is variable, but rarely more than 30 m. Their precise origin is unclear, but they do appear to have been laid down under continental conditions by a combination of fluvial and aeolian processes. Recent work in Zambia and Botswana (Baillieul 1972, Savory 1965) seems to indicate that the Kalahari sands are derived from upper Karroo sandstones, particularly of the Stormberg Series, although other sources such as the sandstones of the Ghanzi Formation may be locally important (Baillieul 1973). It also seems clear that the Kalahari sands have been redistributed a number of times in the late Quaternary. Wayland (1954), on basis of archaeological evidence, stated that there had been three periods of movement of Kalahari sands, in Magosian, Middle Stone Age and Pre Palaeolithic times. Baillieul (1973) recognised three types of Kalahari sands in Ngamiland, including fossil dune sand, which he correlated with Dixey's Kalahari Sand II at the Victoria Falls, and reworked dune sand.

Estimates of the age of the Kalahari Beds have varied from Cretaceous to Recent, and Rogers (1936) saw them as a result of long continued continental deposition similar to that of the Karroo System. It appears, on the basis of work in Zaire (Cahen and Lepersonne 1952) that the lower members are late Tertiary to early Pleistocene, and the upper sands have a probable Pleistocene age with much redistribution during successive periods of climatic change.

CLIMATE

Climatic data for Ghanzi, Tshane and Tshabong which are the three meteorological stations in, or adjacent to, the study area are presented in Fig. 2.4. Records exist from 1923 at Ghanzi and Tshabong, and from 1960 at Tshane. The data was provided by Mr. R.J.F. Anderson of the Weather Bureau, Gaborone.

The climate of the southern Kalahari is semi arid, with dry winters (April to October) characterised by warm days and cold nights; and hot summers, during which most of the annual rainfall of 250 - 350 mm falls.

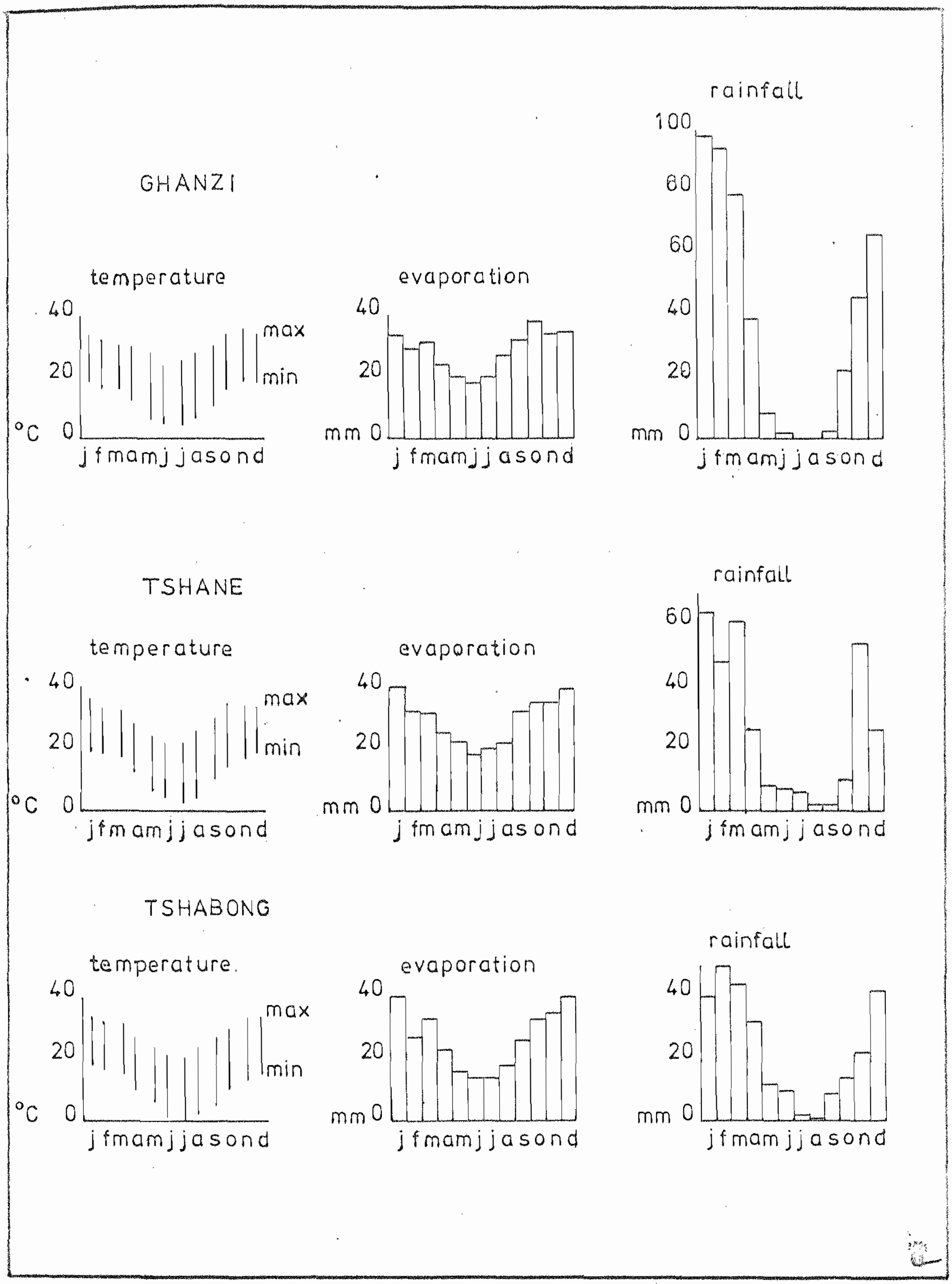


Fig. 2.4 Summary of climatic data.

The Kalahari lies within the southern hemisphere high pressure belt, which is made up of a series of anticyclonic cells, which are particularly marked over the oceans. The climate of the Kalahari is dominated by one of these cells which is situated over the southern Indian Ocean and southeastern South Africa. The position of the cell alters with the position of the sun, giving rise to a seasonal distribution of precipitation and winds in the area.

In winter, the anticyclone intensifies and moves north with the sun to a position over the eastern Transvaal. Slowly subsiding dry air with a strong temperature inversion and outblowing winds dominates the climate of the Kalahari at this time of year. As a result of the stable anticyclonic conditions there is negligable rainfall. Days are warm and sunny, whilst the nights are cold as heat is rapidly lost by radiation in the cloudless conditions. Occasionally, very deep depressions over the south Atlantic move through the northern Cape Province and penetrate the southern Kalahari to bring small amounts of winter rainfall.

In summer, the anticyclone weakens and moves southwards to a position over the Natal coast. At the same time heating of the land gives rise to a weak low pressure area over northern Botswana and southern Angola. From October to April these conditions allow maritime air to move over the land, bringing a moist, unstable airstream to the Kalahari from the east and northeast. In this situation of converging airstreams vertical transport of air takes place freely. According to Jackson and Tyson (1971) rainfall under these conditions is convectional as a result of slow vertical movement of air associated with convergence of airstreams and a layer of moist air deep enough to allow its latent instability to take effect. The rains are usually heavy and may be accompanied by hail. There is normally a clear diurnal pattern of rainfall, with storms occuring in the late afternoon and early evening.

In the Kalahari the amounts of rainfall are limited by the fact that the air reaching the area has lost most of its moisture during its long passage overland. Consequently, although the synoptic conditions may favour heavy rainfall, the low moisture content of the atmosphere limits the actual amount that falls. The mean annual rainfall over a period of 20 years at Ghanzi and Tshabong and 15 years at Tshane is

452, 278.5 and 310 mm respectively. Almost all the rainfall occurs between October and April, with a maximum between December and April.

Fig. 2.5 shows that mean annual rainfall amounts in the southern Kalahari decrease from northeast to southwest. Over most of the area mean annual rainfall is 300 - 400 mm, with the driest areas receiving some 250 mm. The rainfall occurs in convectional storms of great intensity and very localised extent. As a result annual rainfall totals may be highly variable. The percentage seasonal variability of rainfall totals, expressed as the coefficient of variation (standard deviation /mean) increases from 40 % in the north of the area to over 80 % in the south. Pike (1972) stated that variability of rainfall was inversely proportional to the amount of rainfall received. However, the map shows that this is an oversimplification of the case, as the 300 mm isohyet crosses the 40 to 80 % seasonal variability isolines. It appears that the pattern of rainfall totals and variability is a combination of two factors. Rainfall decreases to the southwest as a result of the decreasing moisture content of the air as it moves further from its source region. The variability of the rainfall increases towards the south away from the main convergence zone over northern Botswana. Consequently, the probability of favourable synoptic conditions for heavy rainfall decreases in this direction.

There is little variation in air temperature over the area. As can be seen from Fig. 2.4, temperatures in the southern Kalahari are highest at a maximum of 35 - 38 °C in September, October and November, just before the rains, when cloud amounts are small. The highest mean monthly minimum temperatures (18 - 20 °C) occur during the period December to February and this is the period of the minimum diurnal temperature range.

During the winter temperatures are much lower, with mean monthly maximum temperatures in the range 21 - 25 °C, and mean monthly minimum temperatures in the range -1 - 5 °C. There is a considerable diurnal temperature range which is greatest in July, when it is 20°C. Air frosts are quite common in June, July and early August.

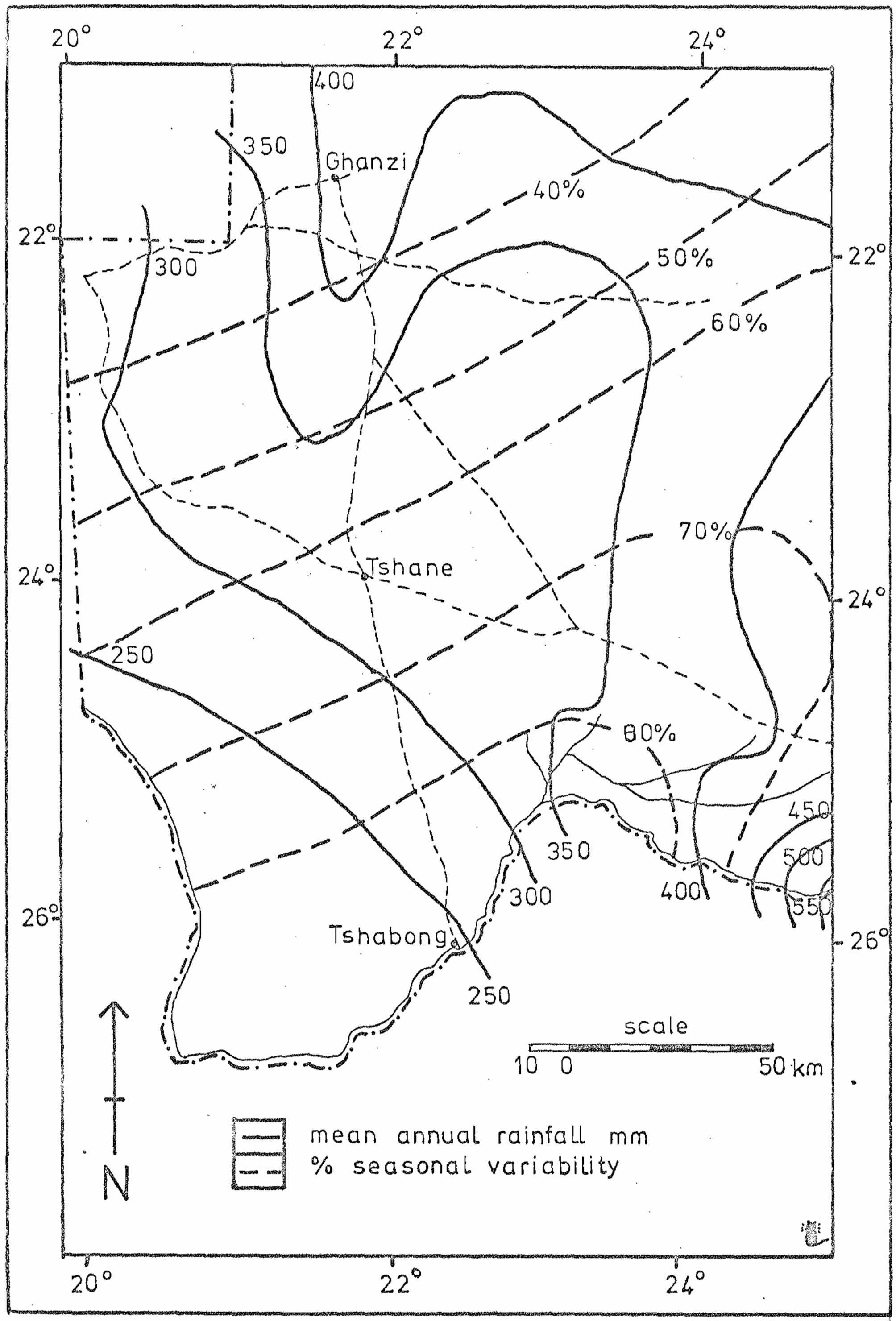


Fig. 2.5 Mean annual and seasonal variability of rainfall.

After UNDP/FAO Rainfall Map of Botswana.

Evaporation rates in the southern Kalahari are high and exceed rainfall during all months. The mean annual evaporation from a class A evaporation pan is 3293.4 mm at Ghanzi, 3680.7 mm at Tshane and 2926.6 mm at Tshabong. Evaporation is at a maximum (350 - 400 mm per month) during October, when insolation is highest and winds are strong. The minimum evaporation rates are recorded in the winter, when they are 180 - 210 mm per month. Relative humidity is generally low and rarely rises above 40 % in the middle of the day. Maximum relative humidity at 14.00 hours occurs during the summer, when it is 30 - 45 % and falls to 20 - 25 % during the winter.

Fig. 2.6 shows wind roses for Ghanzi, Tshane and Tshabong. At Ghanzi, winds are dominantly easterly, with 57 % of all winds blowing from between north and east. At Tshane, winds are dominantly northerly, with 65 % of all winds from between northeast and northwest. The winds at Tshabong are more evenly distributed in direction, but tend to be westerly, with 50 % of all winds blowing from the sector between southwest and north. The different patterns of wind directions recorded reflect the anticlockwise spiral of outblowing winds around the South African anticyclone. A seasonal change in winds is detectable, with winds being lighter and more variable in direction during the summer. In the winter, stable anticyclone conditions give rise to stronger and less variable winds.

HYDROLOGY

As a result of the low rainfall and high evaporation rates all water bodies in the southern Kalahari are ephemeral, and surface water is found only in the pans and parts of the dry river valleys immediately after heavy rain. Perrenial springs which used to occur at Khakhea and Tshane no longer flow, as the aquifers supplying them are now tapped by boreholes.

Runoff is all areas is very low, as a result of the low rainfall, high evaporation rates and highly permeable surface sands. The capilliary porosity of the surface Kalahari sands is high and all the infiltrating rainfall is retained by the sand, to be lost by evapotranspiration from the vegetation cover. No recharge to groundwater takes place at the present time, in areas covered by more than 10 m of sand, as the highly porous sands absorb all the rainfall. Boocock and Van Straten (1962)

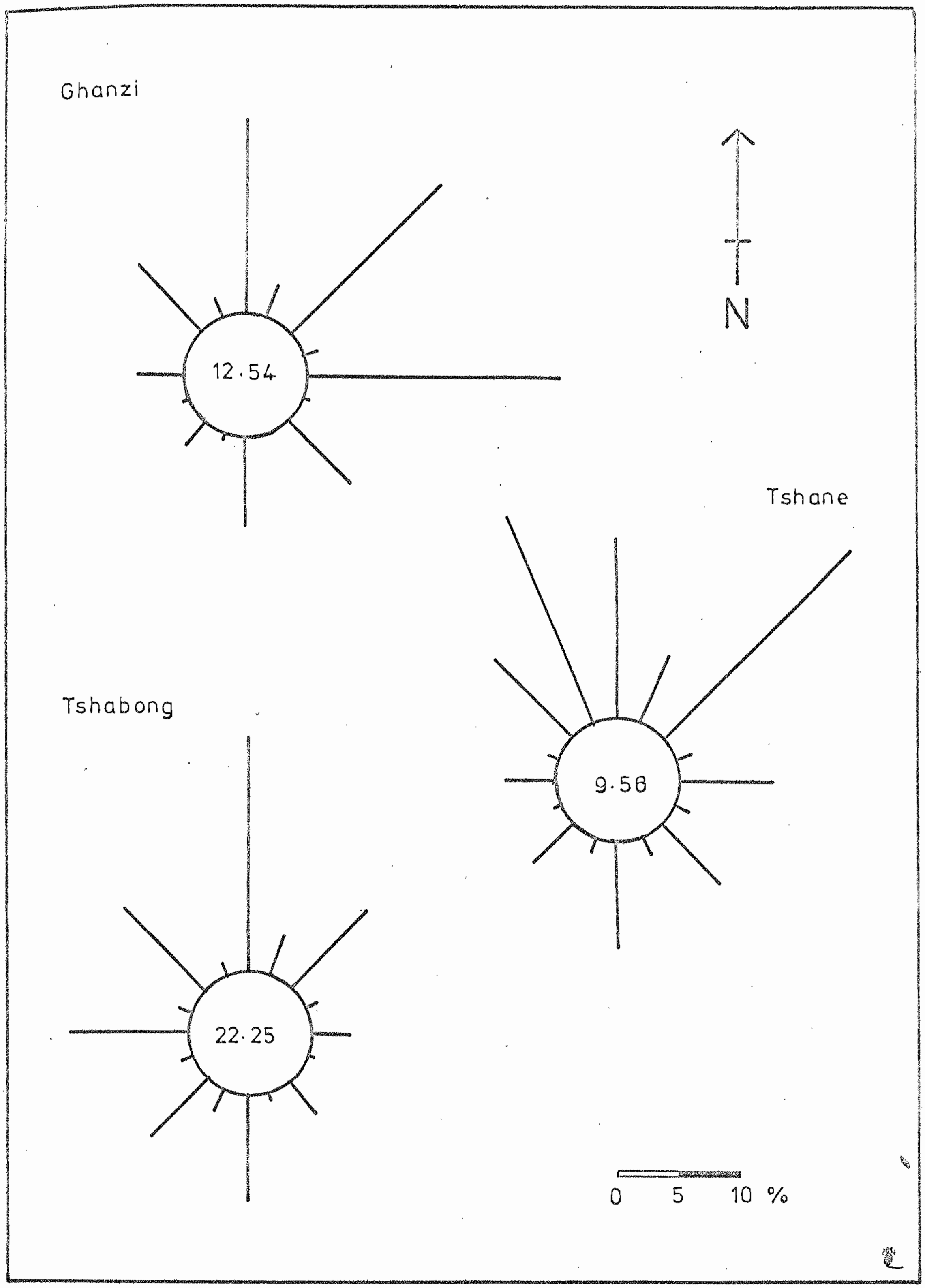


Fig. 2.6 Percentage frequency of all winds at 14.00 hrs.
Calms in circle.

suggest that present rainfall in the Kalahari is less than half that needed to allow direct recharge of groundwater. As a result the groundwater bodies in the Kalahari are essentially fossil or recharged from outside the area. Most of the aquifers lie in the pre Kalahari rocks as the Kalahari Beds are only locally a good aquifer, in the calcareous sandstones at Tshane and the basal marls of the upper Molopo valley. In most parts of the southern Kalahari the water table lies 30 m or more below the surface and can only be reached by deep boreholes. Locally, there may be perched water tables, tapped by shallow wells, in the pans.

VEGETATION

Five main vegetation types were recognised in the southern Kalahari by Blair Rains and Yalala (1972). Their distribution, which is shown by Fig. 2.7, reflects the increasing aridity of the area towards the southwest. Around the settled areas of Tshane and Sekoma, the vegetation is much affected by the activities of man and his cattle. Locally edaphic variations may be important and result in the vegetation taking on a mosiac pattern in which a small number of woody and herbaceous species combine in various ways to give different types of shrub and tree savanna and grassland.

Arid semi desert vegetation is found in the southwest of the area where the rainfall is less than 250 mm. The vegetation cover is sparse, and includes some species such as Acacia haematoxylon, Monechma hereronse, M. incanum and Stipagrostis amabilis which are not found elsewhere. Grasses, which include Eragrostis spp., Stipgrostis spp. and Schmidia kalahariensis, provide a discontinuous ground cover.

A large part of the southern Kalahari is covered by bush savanna, with Acacia giraffae, A. mellifera subsp. detinens and Boscia albitrunca as the main tree species. Common shrubs are Grewia flava, Rhus comiphorides and Zizyphus mucronata. The grass cover is more continuous and includes Aristida spp., Eragrostis spp., Panicum coloratum and Schmidtia bulbosa. These species are combined in a variety of ways to form mosiac patterns of shrub savanna, tree savanna or grassland with scattered shrubs. It appears that the denser areas of trees and shrubs are found on low rises, and more open grass dominated areas in depressions.

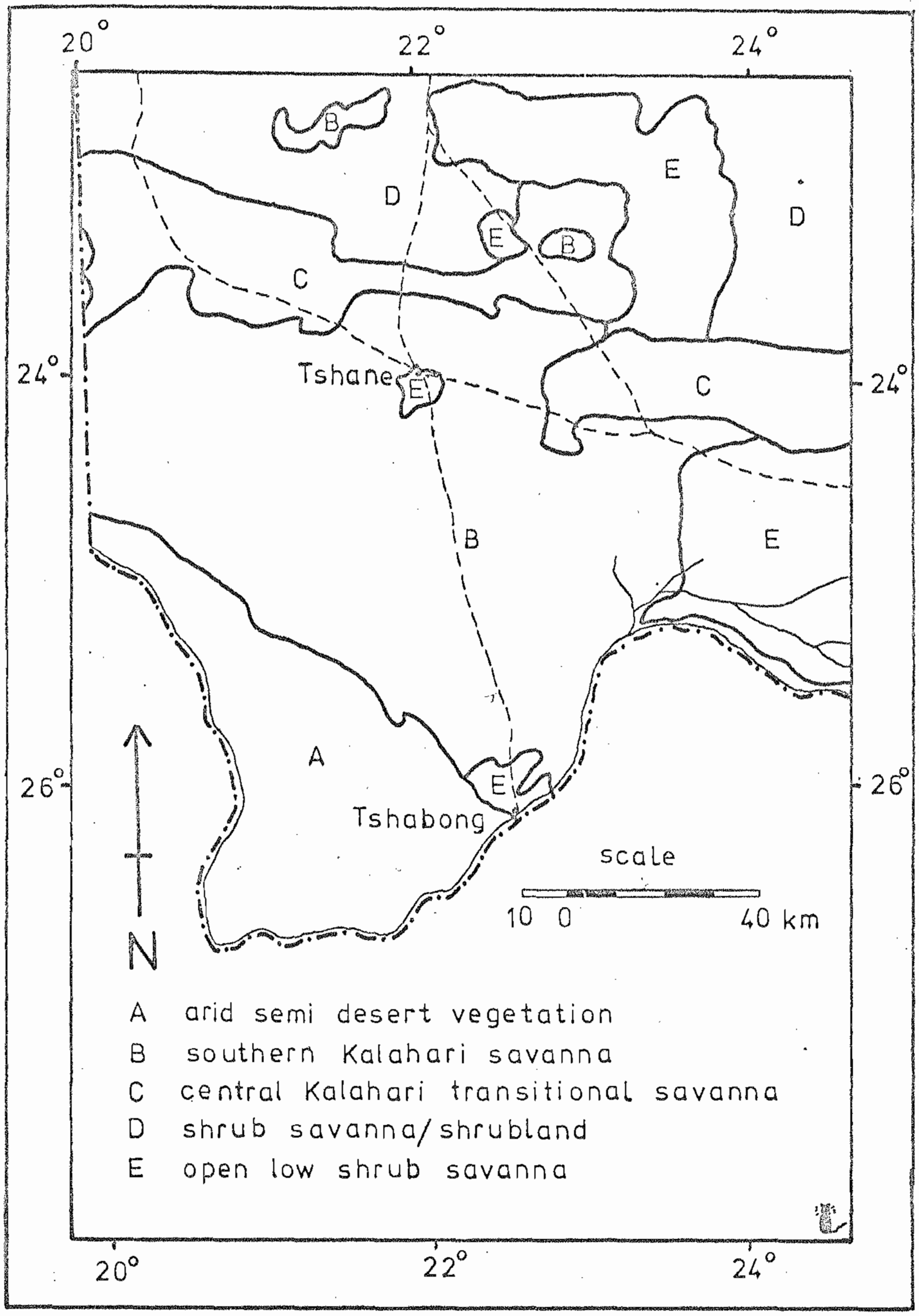


Fig. 2.7 Vegetation types.

After Blair Rains and Yalala (1972).

North of Tshane is a narrow zone of the Central Kalahari transitional savanna. The species are generally the same as are found in the southern Kalahari savanna, but with the addition of Lonchocarpus nelsii and more frequent Terminalia sericea.

Between this zone and the Okwa valley is a broad belt of shrub savanna or shrubland with a greater frequency of shrub and tree dominated areas. Once again, species are similar to the southern Kalahari savanna, with Lonchocarpus nelsii, Acacia uncinata and A. fleckii being common trees. The dense shrub layer is made up of Grewia retinervis, Zizyphus mucronata and Rhigozum brevispinosum.

Locally edaphic conditions or considerable human activity may result in the formation of areas of open low shrub savanna. At Tshabong thin soils on Matsap quartzites give rise to large areas of open grassland and shrub savanna. South of Tshane an area of shrub savanna dominated by Terminalia sericea with a sparse grass cover has developed as a result of overgrazing by cattle.

In the Sekoma and Tsetong areas there are extensive open savannas much affected by over grazing, in which, as distance from water increases, the number of woody plants such as Terminalia sericea and Acacia mellifera subsp. detinens declines and the grass cover of Eragrostis spp. and Aristida spp. increases. South of Khakhea there are large areas of open grassland with scattered trees of Acacia mellifera subsp. detinens.

Parris (1968) has shown that a number of species are associated with the areas around the pans. These include Acacia mellifera subsp. detinens, A. newbrownii, Dichrostachys cinerea and Catophractes alexandrii on the dunes to the south of the pans and A. newbrownii and Cenchrus ciliaris on the margins of the pan. Common grasses around the pans are Cynodon dactylon and Sporobolus spp..

FAUNA

The southern Kalahari contains a large population of plains game. Most species are physiologically and behaviourally adapted to the dry conditions and lack of surface water. Common species are the red harteboest (Alcelaphus busephalus), blue wildebeest (Connochaetes taurinus), springbok (Antidorcas marsupalis), steenbok (Raphicerus campestris) and gemsbok (Taurotragus oryx). Also common are the black backed jackal (Canis mesomelas) and the spotted hyena (Crocuta crocuta). The ostrich (Strutho camelus) is frequently seen.

All the species are highly mobile and Parris (1970) states that the pans play an important role in their movements, attracting animals in search of drinking water in the rains and salts during the rest of the year. Quite large pits, 1 m across and 30 cm deep, may be dug by animals in search of water or salts lying below the pan surface. In addition the hooves of the antelopes may trample and destroy vegetation on the pan surface.

CONCLUSIONS

This chapter has described the main features of the natural environment of the southern Kalahari in Botswana as a background to the subsequent discussion of the origins and development of the pans which occur in the area.

Topographically, the southern Kalahari forms a broad watershed between the drainage of the Makgadikgadi depression and the Molopo and Nossop rivers that join the Orange river. On each side of the watershed, which cuts across the Karroo basin, the Kalahari Beds increase in thickness towards the upper Molopo river and the central Kalahari basin, indicating that the divide is of some antiquity. Sands of Kalahari type mantle the whole of the region with a depth of up to 30 m. Successive periods of their redistribution by fluvial and aeolian processes have resulted in a gently undulating surface topography, in which the pans and their associated dunes form the most conspicuous feature.

The semi arid climate of the southern Kalahari may be viewed as a result of the position of the area in the centre of the southern African sub continent, between the cyclonic disturbances of the Cape Province winter rainfall zone and the sub tropical convergence zone to the north. Today, the climate of the area is dominated by the South African anticyclone, but shifts in the strength and position of any of these systems would result in considerable climatic and environmental changes throughout the area. The development of the pans shows that this has been the case in the recent past.

CHAPTER 3.

THE TOPOGRAPHY OF THE SOUTHERN KALAHARI PANS

INTRODUCTION

There are some 1000 pans of varying shape and size in the southern Kalahari. To date no comprehensive descriptions of their topography or geomorphic features have been made as previous writers on the area have given very brief and often incomplete descriptions of the pans.

Passarge (1904) noted the abundance of tufa (calcrete?) found around pans and the importance of pans as sources of water for game animals. Rogers (1934) identified three types of pan in the Kalahari, including the sand pan, which he stated was very widely distributed. He noted the existence of calcretes around the edges of pans of this type, and also the presence of clays and carbonates on the pan floor, making the pans impervious to water, which became saline as it evaporated, thus inhibiting plant growth. Wayland (1952) described the existence of sand dunes on the south and southeast sides of the pans, which he said were mainly circular in shape. He noted the existence of bedded calcretes and silcretes, diatomites and bleached sands within the pan depressions, which were floored with impervious deposits. Van Straten (1955) recognised three types of pan surface: grassed pans, with a sandy clay surface supporting a dominantly grassy cover; ungrassed pans, with a sparse cover of halophytic vegetation; and saline pans, with a saline or highly alkaline clay surface, often deeply etched into calcretes. Boocock and Van Straten (1962) noted the existence of a well developed sand ridge around the southern side of the pan depression, which could lie 15 m or more below the surrounding sand plain. Grove (1969) described the existence of a belt of pans 50 km or more wide along the Bakalahari Schwelle from Sekoma to Kule. He stated that the pans, with a spacing of 15 km, each had one or more lunette type dunes on their southern side, and were contained in round or slightly north - south elongated hollows.

In view of the lack of knowledge about the topography of the pans, it is clear that a detailed description of them is an essential preliminary to a consideration of their origins and development.

The aims of this chapter are: to describe the topography of the pans in the southern Kalahari; to point to the aspects of the geomorphology of the pans which need to be explained in order to account for the origin and development of the pans; and to describe hypotheses that have been put forward to account for similar features elsewhere in the world.

TOPOGRAPHIC DESCRIPTION OF THE SOUTHERN KALAHARI PANS

Five representative groups of pans in different parts of the southern Kalahari were selected for detailed study after a search of the aerial photography of the area, taken at scales of approximately 1:50000, 1:64000 and 1:40000 in 1961, 1964 and 1970 respectively. (see Appendix 1). The pans for study were chosen in groups to facilitate comparisons, and for logistic convenience. As a result there is a certain bias in favour of pans in the eastern and more accessible part of the southern Kalahari, as Fig. 3.1, which shows their location, demonstrates.

The groups of pans selected were as follows:

Area 1: Samane, Samosadi, Bee and Tatsewe pans, located northwest of Sekoma.

Area 2: Sekoma, Kongwe, Keng, Kgama, Khakhea and Khesekwe pans, located to the southwest of Sekoma.

Area 3: Motsobonye, Kokong, Mashiaphotsana, Mogatse and Dead Tree pans, in the area around Kokong.

Area 4: Bosobogolo, Mpaathutlwa and Mabuasehube pans in the Mabuasehube Game Reserve, some 120 km north of Tshabong.

Area 5: Nwatle, Masetleng, Pussy, Ukwi and Urwi pans in the area between Tshane and Kule.

The topographic descriptions that follow are based upon the writer's field observations, supplemented by a study of the relevant aerial photography.

In the absence of any detailed contour maps for the southern Kalahari, all heights referred to are the products of the writer's surveys, and are related to an arbitrary datum on the pan floor.

Area 1: Samane, Samosadi, Bee and Tatswe pans.

The first group of pans lies in the eastern part of the southern Kalahari, some 25 km northwest of Sekoma, in an area of gently undulating open bush savanna, incorporating extensive grasslands. The location of the pans studied is shown in Fig. 3.2.

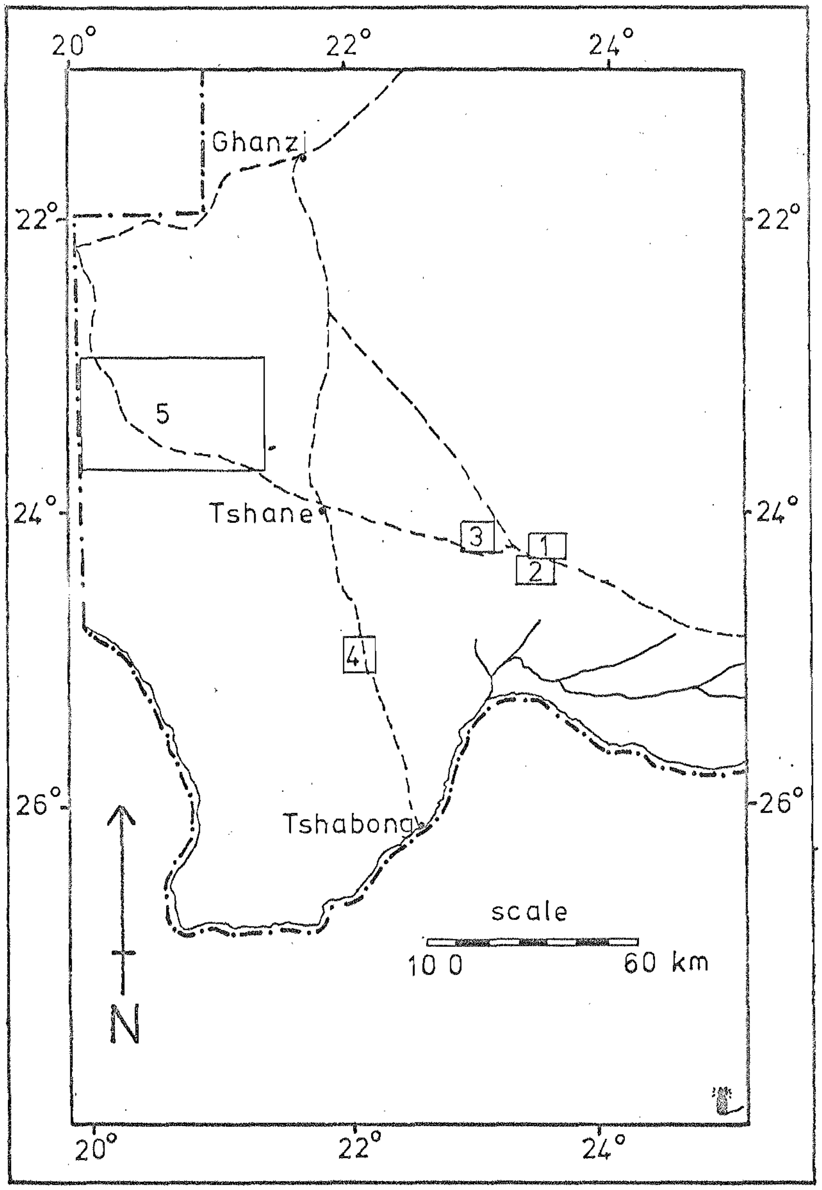


Fig. 3.1 Location of groups of pans studied.

Samane pan (Fig. 3.4 Plate 1) has an area of 0.33 km^2, is pear shaped and measures 0.75 km by 0.50 km. The grey sandy clay surface of the pan has a dense cover of short grasses and several waterholes or "pan pools" may be found towards its southeast side. These pools are flooded to a depth of 30 cms after the rains, but soon dry up to reveal greyish brown calcareous clays. The pan occupies the centre of a well defined sub circular depression 1.18 km^2 in area and 8 to 10 m deep. On the northerly and easterly sides of the pan, the gentle slopes of the depression are interrupted by a break of slope, some 300 m from the pan edge where the red brown surface sands, similar to those of the

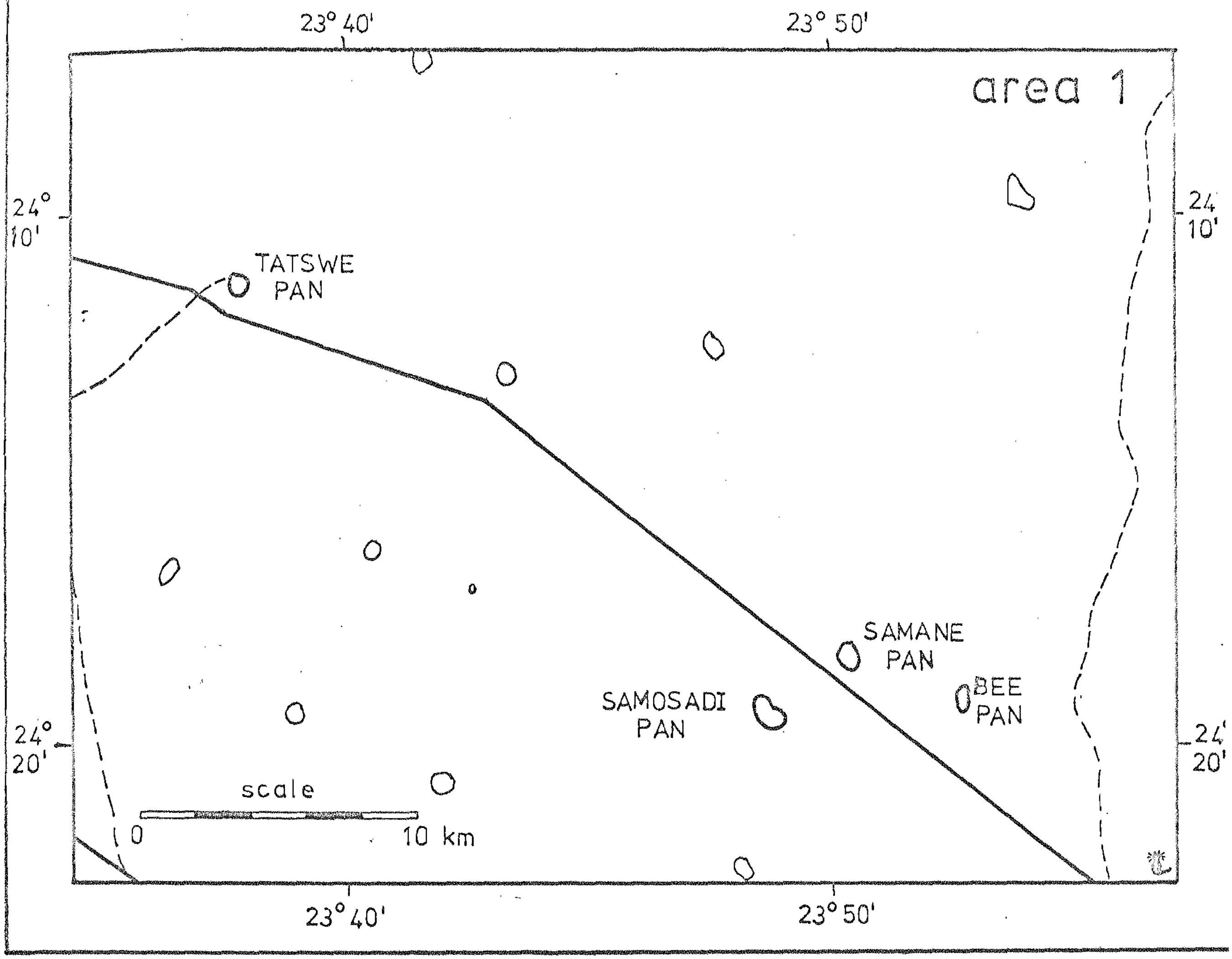


Fig. 3.2 Location of pans studied in area 1.

surrounding sand plain, give way to grey brown fine sand, often with calcrete nodules, which forms a belt encircling the pan.

On the southern side of Samane pan lie two arcuate dune ridges. A gentle slope leads up from the pan floor to the first of them, called the inner dune, which consists of fine grey brown sand covered with small trees and shrubs, mainly Acacia spp.. The crest of the inner dune lies 12 m above the pan datum and 350 m from the pan edge. It is separated from the much larger outer dune by a shallow depression 100 m wide. The grass covered crest of the outer dune, which is composed of red brown sand, is some 850 m from the pan edge and 23 m above the pan datum. The inner and outer dunes merge together on the southeast side of the pan.

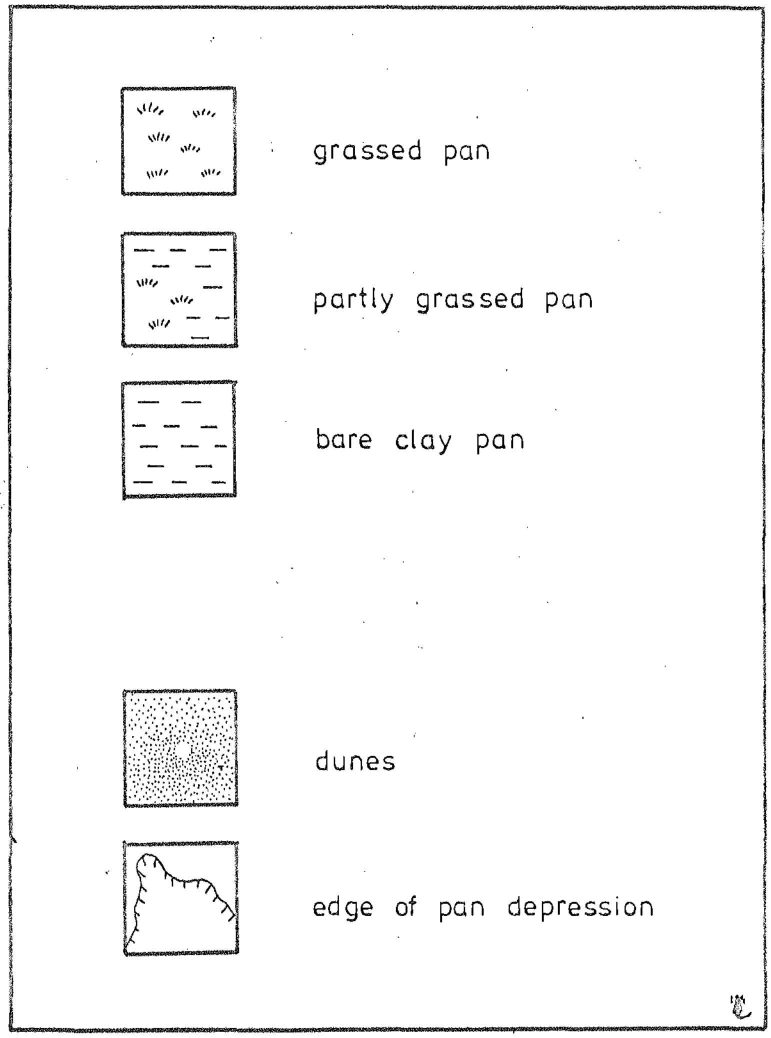


Fig. 3.3 Key for all pan maps.

Samosadi pan (Fig 3.4 Plate 2) lies 3 km southwest of Samane pan. It is somewhat larger than Samane pan being 0.57 km^2 in area, is elliptical in shape, and measures 1.2 km by 0.7 km. As at Samane, the surface of Samosadi pan is grass covered and has a number of waterholes. It lies in an elliptical depression 8 to 9 m deep, which is asymmetric in form, with much steeper slopes along its northeastern edge. Surrounding the pan itself is an extensive area of grey brown sand, with calcrete nodules occuring at the surface. In the southeast corner of the pan depression, flat lying calcretes and silcretes are exposed. Once again there is a similar arrangement of inner and outer dunes. The hummocky crest of the outer dune lies 23 m above the pan datum and 900 m from the pan edge. It is separated from the inner dune, which carries a dense cover of small trees of *Acacia mellifera subsp. detinens* and small scrubby bushes, by a shallow ill defined depression.

Plate 1. Samane pan: view south over grassed pan surface to dunes. Inner dune crest is marked by darker line of trees, bare outer dune crest beyond.

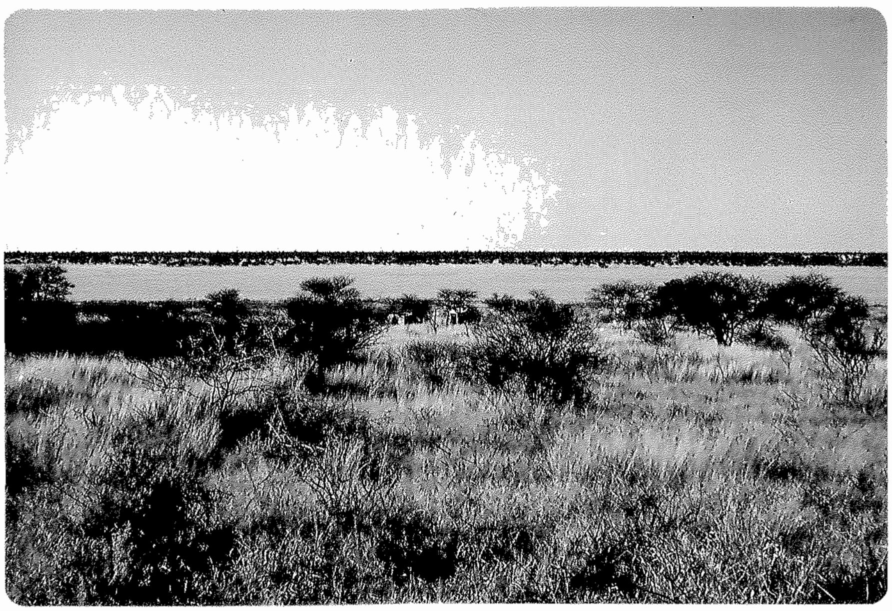


Plate 2. Samosadi pan: view north from crest of inner dune over grassed pan surface.

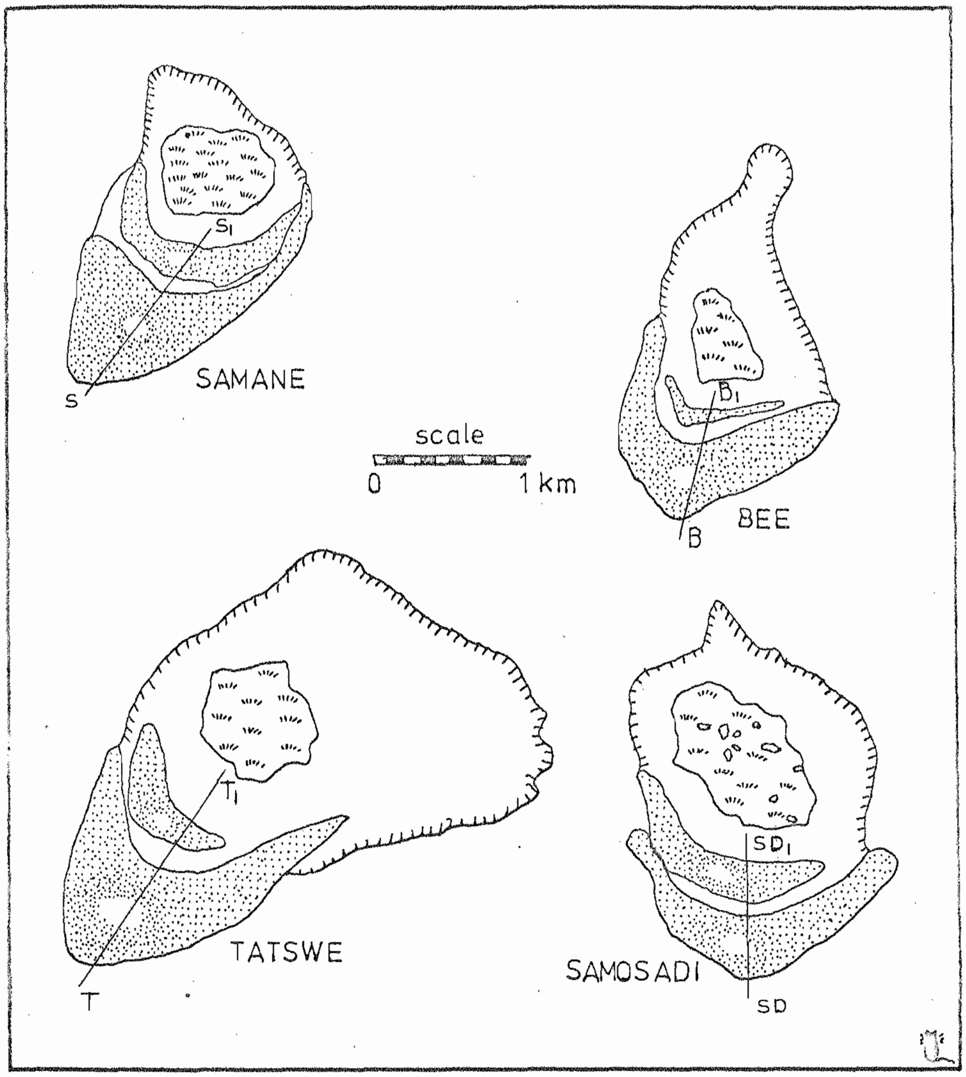


Fig. 3.4 Pans studied in area 1.

Bee pan (Fig. 3.4), otherwise unnamed on maps of the area, lies 3 km southeast of Samane and is the smallest pan in the group, being 0.18 km^2 in area. It is shaped like a triangle with the base towards the southeast, and measures 0.55 km long by 0.45 km across at its widest point. The pan is situated in the southern part of a lemniscate depression 1.15 km^2 in area and 6 m deep, which is very poorly defined on its northern side.

The pan surface is covered by short grass, with a single waterhole, surrounded by nodular calcretes, in which grey calcareous clays are exposed. Bee pan has a single low dune on its southern margin, rising to a height of 12.5 m above the pan datum. The panward slope of the dune is grey brown sand, whilst the far slope of the dune is composed of red brown sand.

Tatswe pan (Fig. 3.4) lies 25 km northwest of Samane pan along the Ghanzi cattle trek route. It is an almost circular pan 0.75 km across and covering an area of 0.43 km^2, situated in the centre of an 11 m deep depression 4.25 km^2 in area. The pan surface has extensive areas of bare grey clay, flooded after the rains, separated by areas of short grass. As at Samane, there is a break of slope 500 m from the pan edge on the northern side of the pan, where the red brown sand of the surrounding area gives way to grey brown sands, which thinly cover calcretes and calcreted clays.

The arcuate ridges of the inner and outer dunes are located on the southwest side of the pan. The panward slope of the inner dune is covered by small scrubby bushes, often growing out of mounds of sand, rather like nebkha. Between them are wind rippled areas of bare sand, indicative of present day sand movement. The outer dune is separated from the poorly defined crest of the inner dune by a shallow depression. The crest of the outer dune, once again composed of red brown sand, lies 1050 m from the pan edge and 27 m above the pan datum.

A borehole at the pan, now abandoned, yielded saline water supplies, and intersected the following sequence of deposits:

0 – 0.6 m	clay
0.6 – 4 m	sandstone
4 – 22 m	silcrete
below 22 m	Ecca sandstone

Of these deposits, probably only the clay can be regarded as a pan deposit.

<u>Area 2: Sekoma, Kongwe, Keng, Kgama, Khakhea and Khesekwe pans</u>

This group of pans, with the exception of Kgama pan, lies to the south of the low ridge of Waterberg sandstones, thinly covered by sand, that runs in a northeasterly direction from Khakhea to a point northeast of Sekoma. This ridge is the only topographic feature of note in the area, which is generally flat or gently undulating. The vegetation is open bush savanna, which is in many places heavily overgrazed.
The locations of the pans studied are shown in Fig. 3.5.

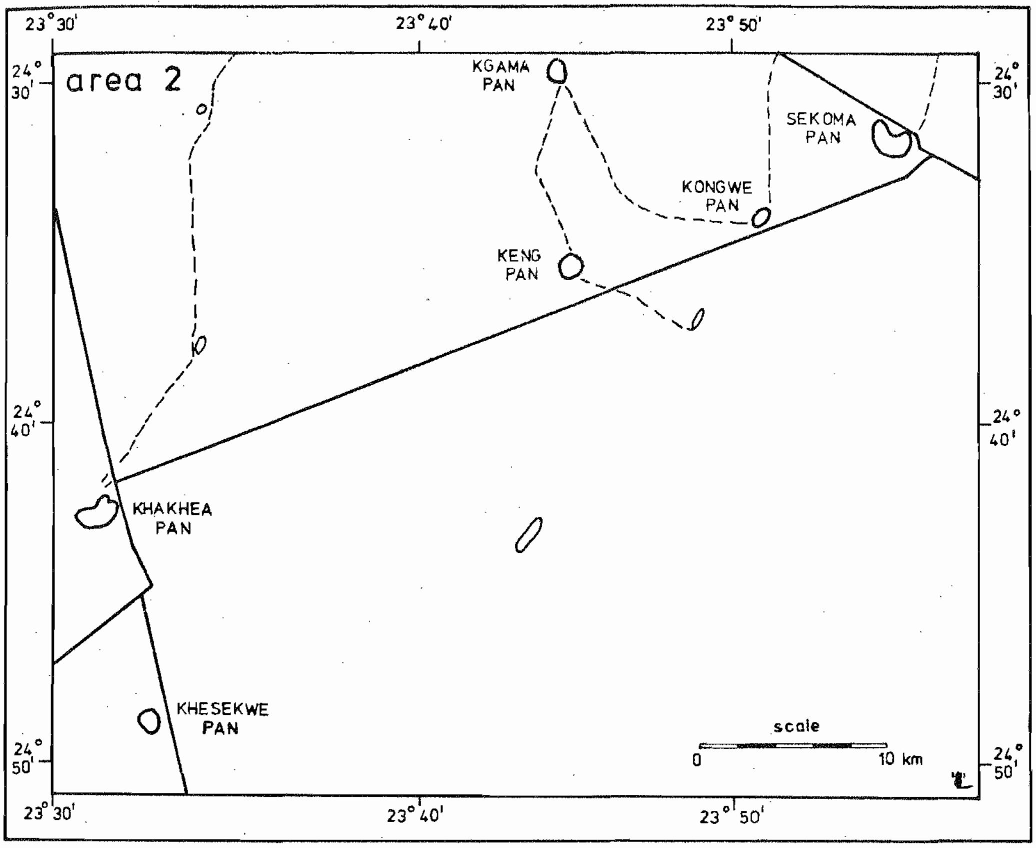


Fig. 3.5 Location of pans studied in area 2.

Sekoma pan (Fig. 3.6 Plate 3) is the largest pan in this group, and is in fact one of the largest pans in the southern Kalahari as a whole. It measures 2.1 km in length, 1.25 km across at its widest point, and covers an area of 1.87 km^2. The hourglass shaped pan has a granular clay surface and, after heavy rains, floods as a shallow sheet of alkaline water.

The pan occupies the southern part of an irregular oval depression 15.50 km^2 in area and some 15 m deep. Extensive spreads of calcretes, often incorporating subangular weathered fragments of Waterberg sandstones, can be found on the northern and eastern slopes of the pan depression. In places they may extend 700 to 800 m from the pan edge at the surface or under a thin sand cover. On the southwest side of the pan calcretes, often containing fragments of Waterberg sandstones, outcrop massively, forming a 2 to 3 m high bench that can be traced for some 500 m around the pan edge. A small quarry on the north side of the pan exposes a 2 m high face cut in calcrete.

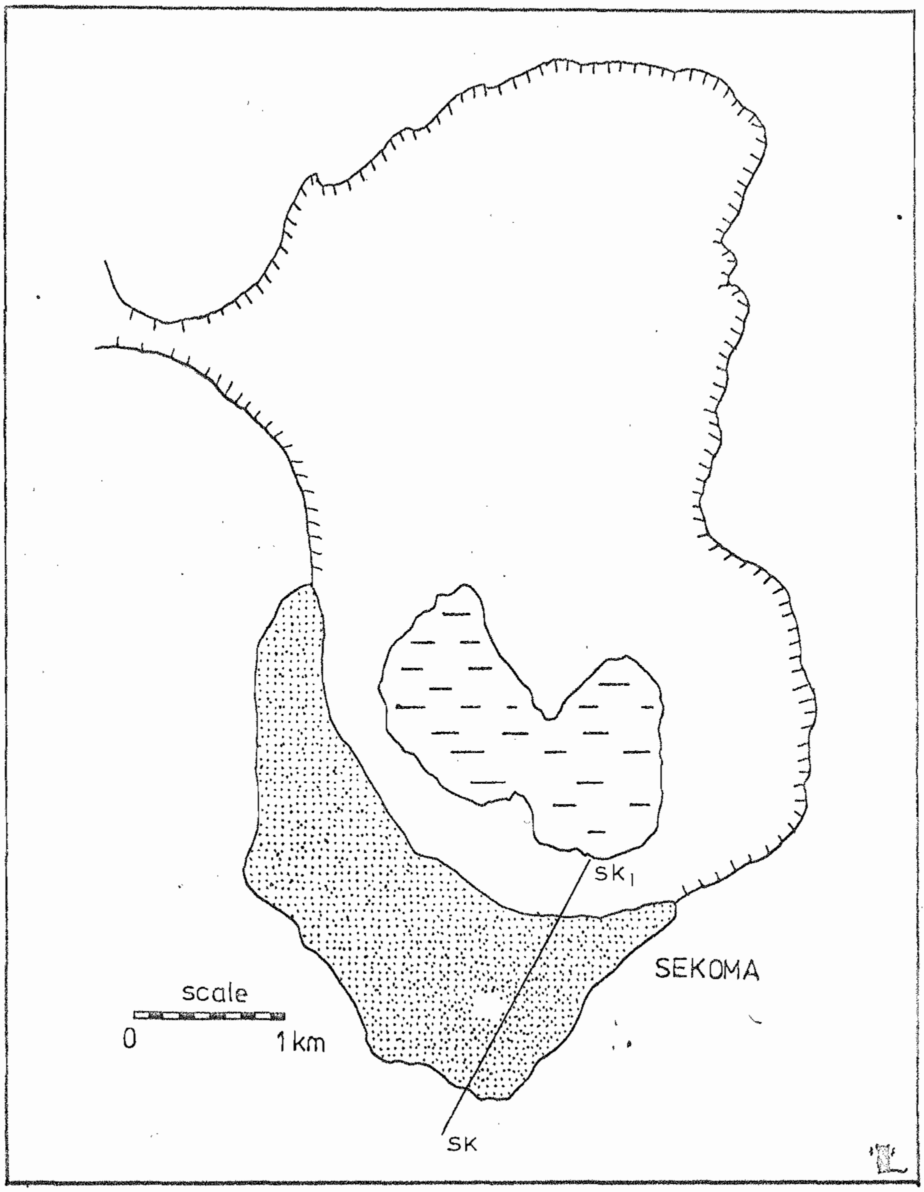


Fig. 3.6 Sekoma pan, area 2.

On the southern side of the pan there is a massive dune ridge with its crest line at a height of 37 m above the pan floor. The topography of the dune is very confused and hummocky in nature and has a dense cover of 3 m high or larger trees, mainly Acacia mellifera subsp. detinens. As a result it is difficult to identify separate inner and outer dune ridges, either on the aerial photographs or on the ground. The panward slopes of the dune are composed of fine grey brown sand similar to that found on inner dunes elsewhere. The far slope of the dune is composed of red brown sand, comparable with that of outer dunes elsewhere.

Shallow wells in the southeast corner of the pan expose green silcretes and white calcretes overlain by greyish clays at a depth of 2 to 3 m. A borehole located 500 m northwest of the pan intersects the following sequence:

0 – 6 m	sand and rubble
6 – 30 m	silcretes
below 30 m	Waterberg sandstone

Another borehole, near the pan edge, intersects:

0 – 1 m	calcrete
1 – 12 m	silcrete
12 – 35 m	red clay
below 35 m	Transvaal System dolomite

Clearly the bed rock geology is somewhat complex, but these records do show that the whole area of the pan and its surroundings are underlain by a considerable thickness of silcretes which thin out towards the pan floor. The origin of the red clay is uncertain, but it may represent the basal member of the Kalahari Beds, as similar deposits of red clays and marls are found in boreholes to the south of Sekoma, in the Molopo farms.

Kongwe pan (Fig. 3.7) lies 10 km southwest of Sekoma, along the road to Khakhea. It is a small, almost circular pan, measuring some 1.15 km across, and is situated in a well defined depression 12 m deep, which has well marked gullies running into it on the north and east sides. The surface of the pan, which covers an area of 0.58 km^2, is composed of a grey sandy clay, supporting a thin cover of herbs and grasses. After rain, the pan is covered by extensive shallow pools of water. There is a small exposure of Waterberg sandstones on the western side of the pan.

On the southwest side of the pan are the well wooded crests of the grey brown inner and red brown outer dunes, with their crest lines lying 13.5 m and 21 m respectively above the pan datum. The panward slope of the inner dune is furrowed by a number of small gullies. In 1972, before it was filled in, one of these was 2 m deep and 3 m wide, exposing the grey brown sand of the inner dune, containing abundant shells of the xerophytic land snail xerocerastus schultzei (Boettger).

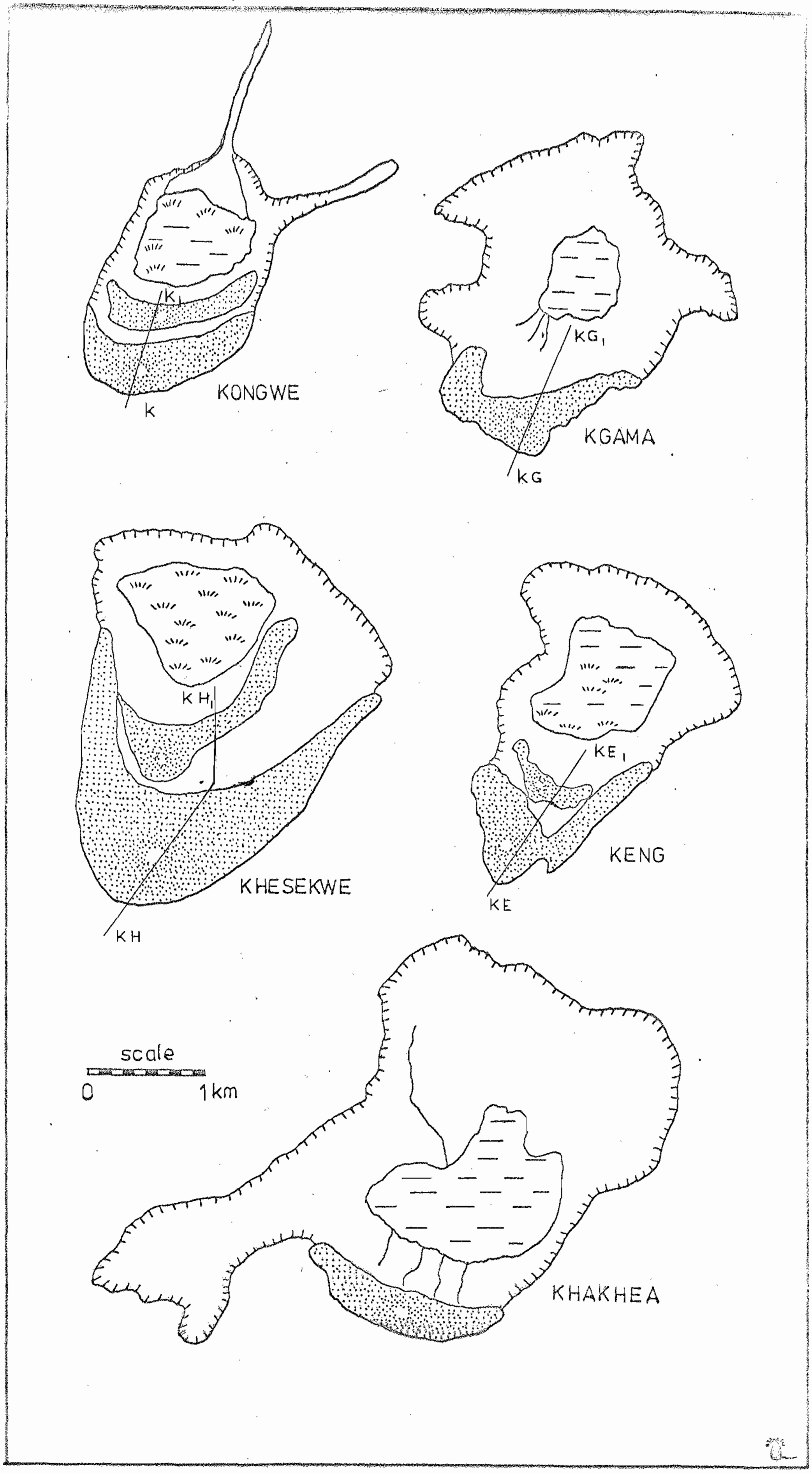
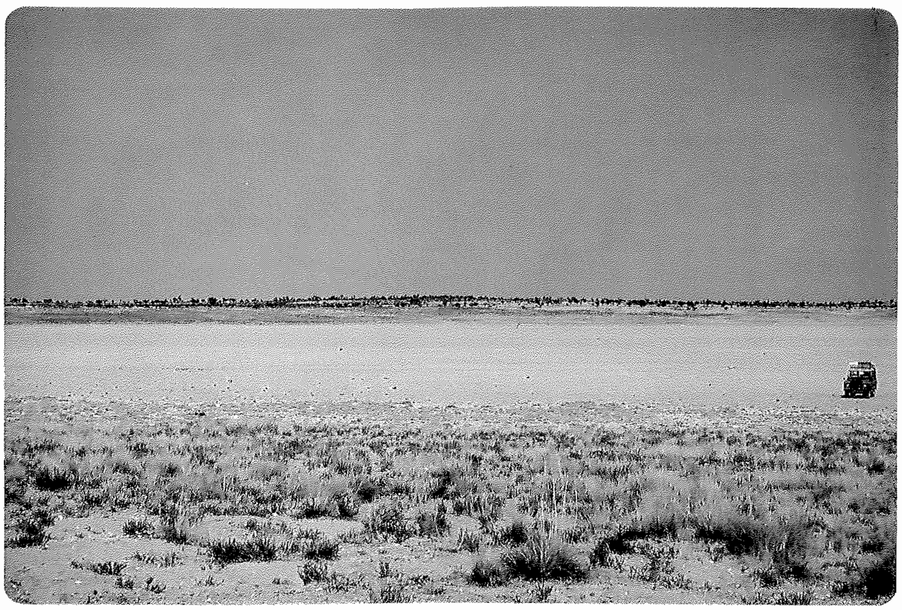


Fig. 3.7 Pans in area 2

<u>Plate 3.</u> Dekoma pan: view southwest to dune over bare pan surface. Calcretes in foreground are indurated pan deposits, marking former extent of pan.



<u>Plate 4.</u> Kgama pan: view south over bare clay pan surface to dune ridge. Note colonization of pan surface by grasses.

A borehole in the centre of the pan intersects 10 m of boulders (sic) overlying Waterberg sandstones.

When the pan was first visited in late August 1972 there was extensive evidence, in the form of recent sand accumulations, of recent deflation from the pan surface, probably caused by the large numbers of cattle at the borehole.

Keng pan (Fig. 3.7) lies some 10 km southwest of Kongwe pan, along the road to Khakhea. It is an almost square pan, with a sandy clay surface, measuring 1.15 km by 0.85 km, and covering an area of some 0.79 km^2. It lies in the centre of a depression 3.25 km^2 in area and 12 m deep. On the southwest side of the pan there is a 2 m high degraded notch cut into the grey brown sands of the inner dune which can be traced for some 500 m along the edge of the pan. It appears to have been formed when the pan contained water more frequently and in greater amounts than today. There are abundant nodular calcretes in the vicinity of this notch.

The inner and outer dunes, the crests of which lie 14 and 24 m respectively above the pan datum, are located on the southern side of the pan. In plan they have a marked parabolic shape. The topography of the dunes is hummocky and a little confused, and the inner dune is not easily defined. Both dunes carry a dense cover of Acacia mellifera subsp. detinens.

The cover of Kalahari Beds in the area is very thin, and the pan appears to occupy a small depression in the pre Kalahari surface. There is a small outcrop of an asbestos bearing ultrabasic intrusion in the western corner of the pan. The depth of pan deposits appears to be small, and the shallow wells in the pan cut through some 2 m of greenish grey silcretes before reaching the underlying ultrabasic rocks.

Kgama pan (Fig. 3.7 Plate 4) lies 12 km due north of Keng pan, on the northern flanks of the Khakhea - Sekoma ridge, in an area of open grassland with scattered trees. The pan is almost square in shape, with a bare clay surface. It measures some 0.80 km across covers an area of 3.9 km^2, and lies in the centre of a well defined

15 m deep circular depression. The sides of the pan depression are furrowed with numerous shallow gullies, and once again possess the characteristic break of slope and change from red brown to grey sand at about 100 m from the northern edge of the pan. Extensive areas of nodular calcretes and sheet silcretes are exposed around the edges of the pan.

The dunes at Kgama pan are not particularly extensive. There is no separate inner dune developed, and the outer dune consists of several more or less separate hummocks of red brown sand, with their crests at a height of some 24 m above the pan datum. The poorly developed nature of the outer dune is unusual, and contrasts sharply with the size and depth of the pan depression. The panward slopes of the dune have a cover of grey brown sand, which has abundant calcrete nodules present. More extensive sheet calcretes outcrop at the pan edge and at places up the slope of the dune for some 400 m from the pan edge. The lower parts of the panward slope of the dune are also furrowed by gullies up to 2 m deep, which are particularly well developed in the southwest corner of the pan.

At the time of the writer's visit to the pan, in late August 1972, extensive sand movements were taking place on the panward slopes of the dune, where much bare sand was visible. There is a small water hole in the southeast corner of the pan, in which some 1.5 m of green silcrete is exposed.

Khakhea pan (Fig. 3.7 Plate 5) is unusual in many respects and possesses features that are not found at pans elsewhere in the Kalahari. It lies immediately to the south of the Sekoma - Khakhea ridge and occupies the southern part of a + 20 m deep depression some 4.0 km^2 in area. The pan is oval in shape, measuring 1.65 km in length by 1.30 km across, with a small embayment on its northern side, and covers an area of some 1.29 km^2. It has a bare clay surface, which floods to a depth of some 25 cm or more after rain (Plate 18).

The northern side of the pan is overlooked by a bluff some 5 to 6 m high (Plate 6), topped by a cliff up to 2 m high of massive calcretes. In places they have been twisted and buckled, possibly as a result of

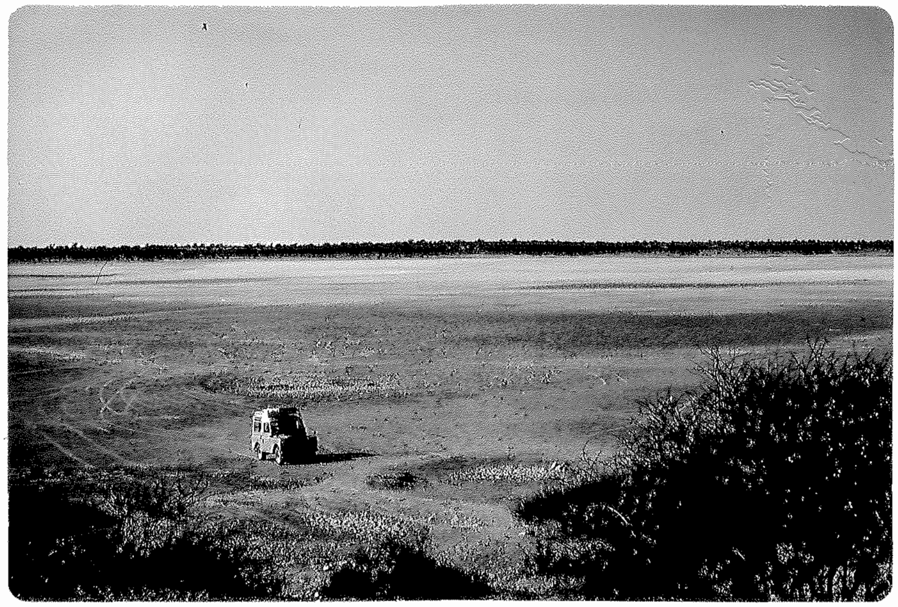


Plate 5. Khakhea pan: view south over bare clay pan from bluff on northwest side of pan.

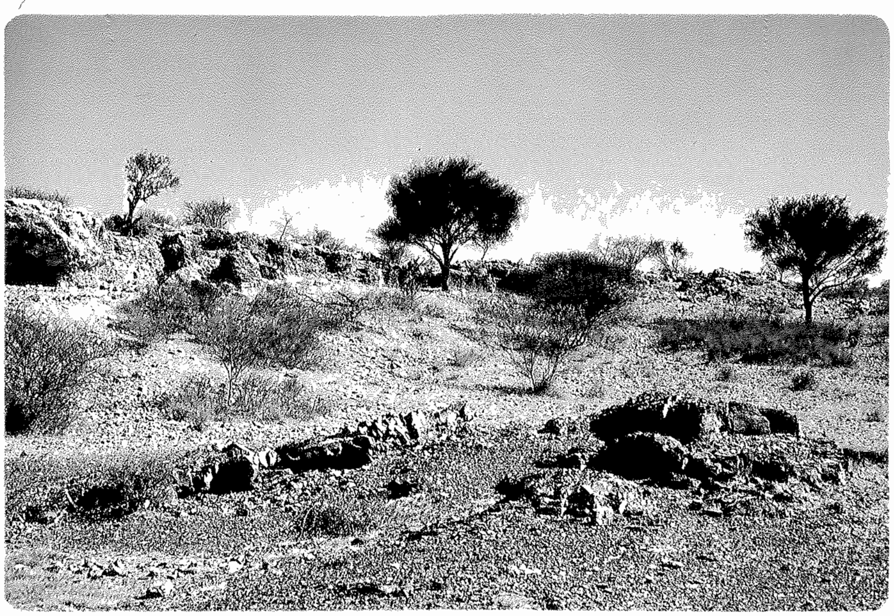


Plate 6. Khakhea pan: bluff topped by calcretes on north side of pan; notch at base of calcretes may represent level reached by paleolake in pan. Outcrop in foreground is of Matsap Beds shales.

slumping or calcrete replacement of original rock structures. In many places the calcretes appear to be a calcreted scree deposit as they contain abundant angular or sub angular fragments, up to 10 cm across, of Waterberg sandstones. Below the calcretes are an extensive series of purple and green shales, banded and calcareous siltstones, ripple marked quartzites and thin dolomite beds, which have been folded into a northeast - southwest striking anticline and extensively intruded by diabase sills. In addition, many parts of the succession, which Boocock and Van Straten (1962) correlate with the Matsap Beds of the Waterberg System, are extensively silcreted. In addition to the area described above, the are sporadic outcrops of similar rocks in many parts of the northern side of the pan depression.

Around the edge of the pan, particularly on its southern side, there are extensive areas of green and grey silcretes, occuring as flat sheets. Further from the pan edge these silcretes are replaced by sil-calcretes and then by calcretes. The southern side of the pan depression is furrowed by rills and small gullies up to 1 m deep and 3 to 4 m wide. They cut down through the surface grey brown sands to expose panward dipping calcretes, which can be correlated with those around the pan edge. At some distance from the pan edge, on the southern side of the depression, there are a number of small exposures of blue green silcretes and red brown sandstones. The origin of these deposits is unclear, but they may be part of the Matsap Beds succession.

At Khakhea, the red brown outer and grey inner dunes do not appear to exist. The inner dune is represented by a hummocky area of grey brown sand around the southern side of the pan, whilst the outer dune may be represented by an area of hummocky red sand on the edge of the pan depression at about 800 m from the pan edge.

Many of the features described above are poorly developed or not found elsewhere at pans in the southern Kalahari. They probably owe their particular form to the unusual geologic and hydrological conditions existing at Khakhea.

Khesekwe pan (Fig. 3.7 Plate 7) lies some 15 km south of Khakhea on the old road to Bray, in an area of gently rolling tree and bush savanna. The pan is heart shaped and measures 1 km across. It occupies the centre of a depression some 8 m deep and 3.69 km^2 in area. The slopes of the northern sides of the depression are noticeably steeper than elsewhere, possibly as a result of the calcretes which outcrop there. The surface of the pan is covered by long grass and there are several waterholes in which whitish calcareous clays are exposed. A well in the pan intersects 3 m of whitish clays and calcretes.

On the southern side of the pan there is a gentle rise to the crest of the inner dune of grey sand, 7 m above the pan datum. Separating the inner and outer dunes is a 300 to 400 m wide depression, underlain in part by calcretes at a depth of 1 m. The outer dune of red brown sand is almost treeless, in contrast to the well wooded inner dune. Its crest line lies 1.5 km from the pan edge and is 25 m above pan datum.

A borehole to the southwest of the pan shows that the area is underlain by 70 m of calcareous sandstones and calcretes resting unconformably on diabase.

Area 3: Motsobonyo, Kokong, Mashiaphotsana, Mogatse and Dead Tree pans. The third group of pans lies in the vicinity of Kokong in an area of gently rolling to flat bush savanna, which incorporates extensive tracts of well wooded country. Borehole records indicate that the Kalahari Beds in the eastern part of the area are less than 50 m thick, and there is a small outcrop of felsites of the Kanye Volcanic System at Kokong. The location of the pans studied is shown on Fig. 3.8.

Motsobonyo pan (Fig. 3.9 Plate 8) is almost circular, with an area of 0.65 km^2 and lies about 1 km west of the Kanye - Ghanzi road some 15 km north of Kokong. The pan, which measures 1 km across, has a bare clay surface and lies on the eastern side of a well defined sub circular depression some 14 m deep and 6.27 km^2 in area. When the pan was visited in early May 1973, the surface of the pan was covered with a thin layer of liquid mud, the penultimate stage of the drying

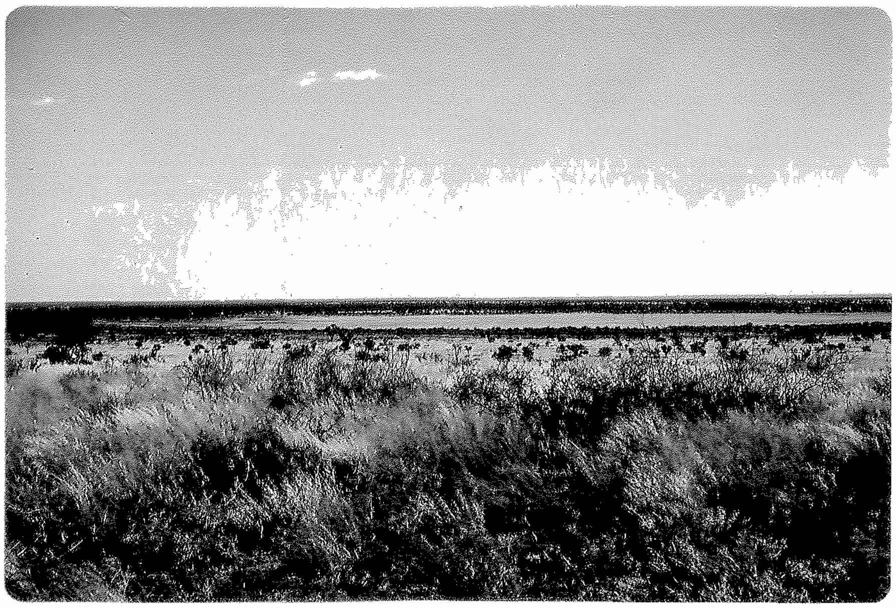


Plate 7. Khosolwe pan: view north from crest of outer dune. Note extent of interdunal depression. Tree covered ridge on pan edge is inner dune.

Plate 8. Motuobonye pan: view west from pan edge to inner dune. Sands on pan edge in foreground were exposed by wave action when pan held water 50 to 100 cm deep.

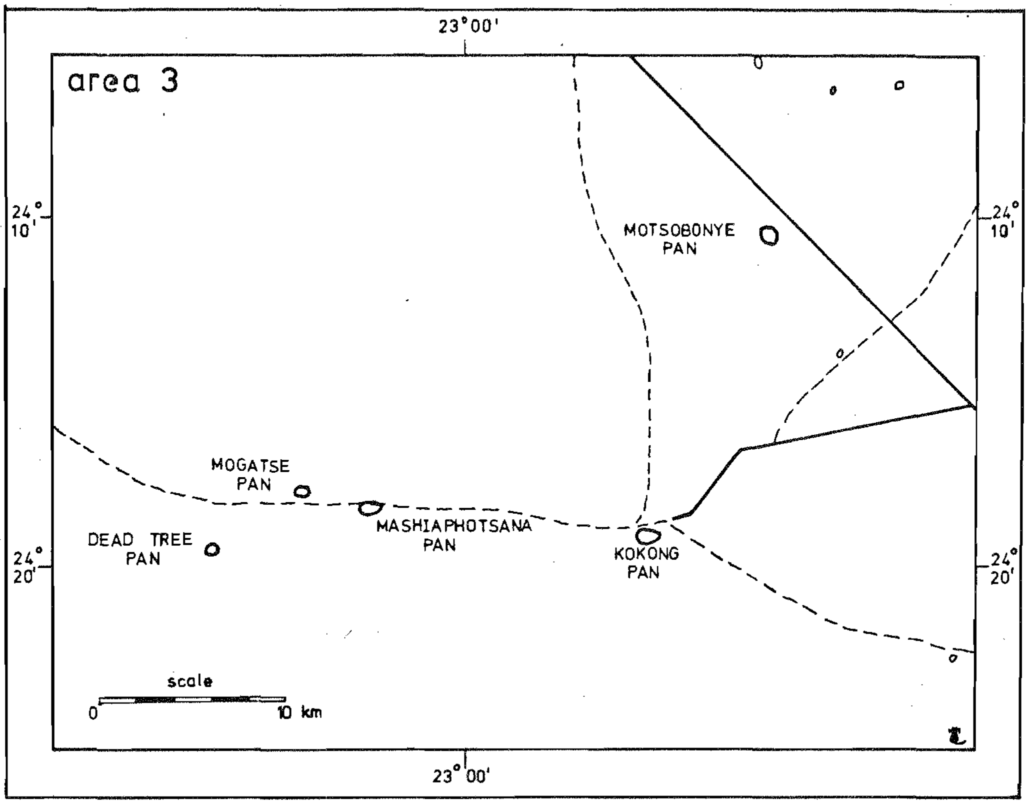


Fig. 3.8 Location of pans studied in area 3.

out of the pan after heavy rain in the area a month previously. The grass covered slopes of the depression are cut by numerous small rills and gullies, particularly on the northeastern side of the pan, where there are a number of small calcrete outcrops. The southern side of the pan is marked by a 0.5 m high notch cut into the grey brown sands forming the panward slopes of the inner dune. It was presumably formed when the pan held greater amounts of water.

There is a straight slope up from this notch to the crest of the inner dune 635 m from the pan edge and 21 m above the pan datum. The inner dune is covered by long grass and small woody shrubs and consists of three distinct summits, not unlike the dunes at Kgama pan. It is separated from the outer dune of red brown sand by a 30 m wide depression. The outer dune, with its crest line 22 m above the pan datum, is relatively small compared to the inner dune.

Kokong pan (Fig. 3.9) was not studied in any detail. It is an oval shaped pan, covering an area of 0.85 km^2 and measuring 1.15 km long and 0.95 km across, with a partly grassed floor. On the north side of the pan there are extensive outcrops of felsites of the Kanye Volcanic System as well as smaller outcrops of silcretes and calcretes, which are exposed in the numerous small gullies that furrow this area.

The dunes on the southern side of the pan are quite large. The hummocky crest of the inner dune lies at a height of 25 m above the pan floor. However, the outer dune is less well developed and is much smaller than the inner dune.

Mashiaphotsana pan (Fig. 3.10) is the most easterly member of a group of pans which lie 10 km west of Kokong on the track to Tshane, in an area of gently undulating bush savanna.

The pan surface is grass covered, with a number of small waterholes, and lies in the centre of a heart shaped depression 3.12 km^2 in area, and 9 m deep. The pan itself is poorly defined, and the slopes of the depression gradually merge into a number of small level areas, bare of grass, in the centre of the depression. In one of these there is a small well 2.8 m deep, in which calcareous sands, nodular and laminar calcretes and olive green sands are exposed. From the well section, it appears that the pan sediments are 1.5 m thick.

A gentle slope leads from the centre of the depression to the crest of the inner dune, 20 m above the pan datum. The inner dune, of grey brown sand, curves round the southern half of the pan depression. The outer dune is, in comparison, very small and proved difficult to locate in the gently undulating area round the pan.

Mashiaphotsana pan is linked by a shallow linear depression to a small unnamed pan 3 km to the southeast, where there are extensive calcrete outcrops. A borehole in the vicinity of Mashiaphotsana pan shows that the area is underlain by 100 m of Kalahari Beds, overlying Ecca Series sandstones and shales.

Mogatse pan (Fig. 3.10 Plate 9) lies 5 km west northwest of Mashiaphotsana pan, along the track to Tshane. It is an almost rectangular pan, covering an area of 0.73 km^2 and measuring 1.2 km by

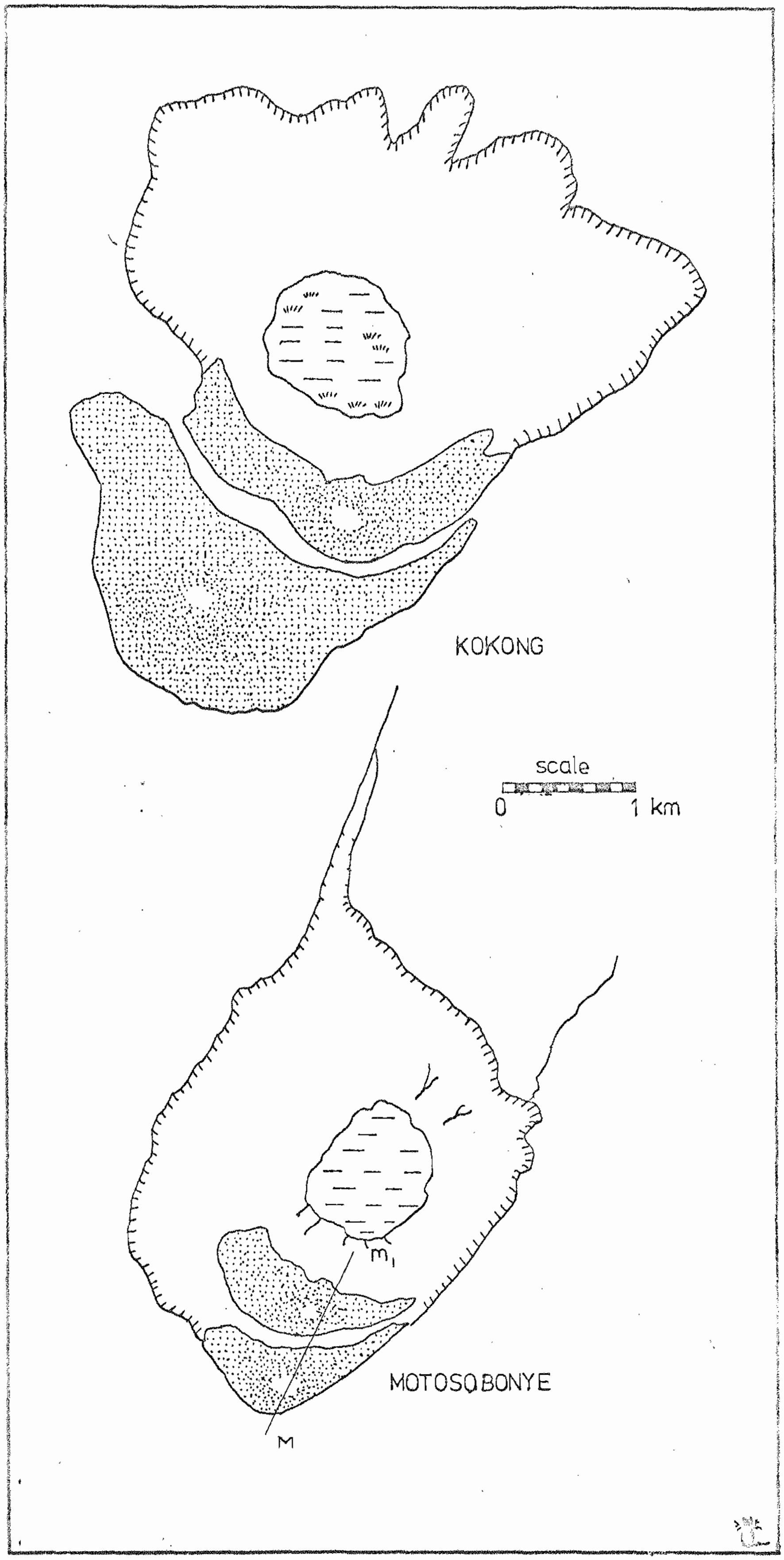


Fig. 3.9 Kokong and Motsobonye pans, area 3.

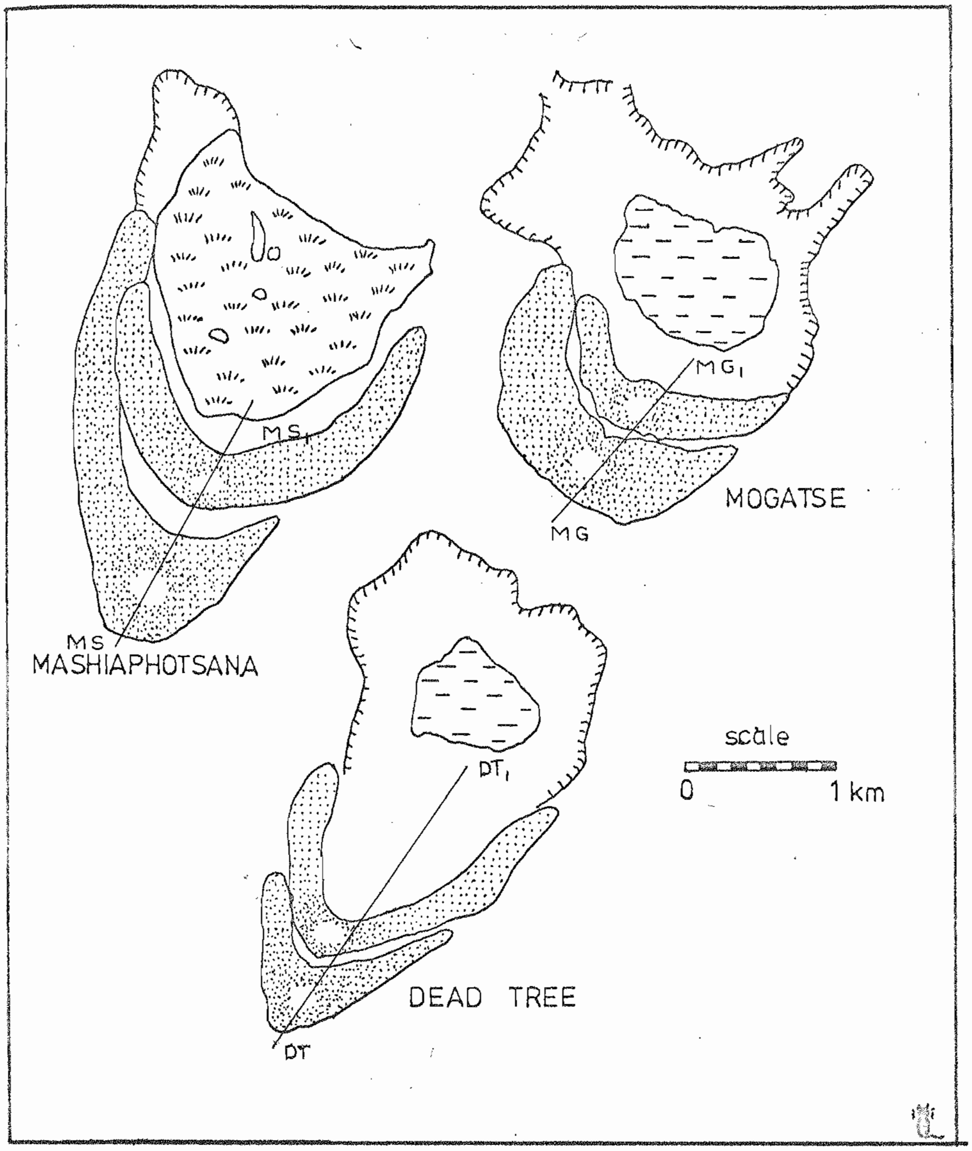


Fig. 3.10 Mashiaphotsana, Mogatse and Dead Tree pans, area 3.

0.9 km, with a bare clay surface. The pan is situated towards the eastern side of an oval depression 15 m deep and 3.25 km^2 in area, the slopes of which are quite steep, particularly on its northern side. The floor of the depression is not wholly occupied by the pan, as there is a wide area to the northwest of the pan covered with woody shrubs and with frequent calcrete outcrops, which appears to mark a former extension of the pan. Two small gullies lead into this area.

Plate 9. Mogatse pan: view northwest from inner dune to bare clay pan. Grassed area to west of pan marks former extension of pan.

Plate 10. Dead Tree pan: view north over pan (with wildebeest and hartebeest). Grassed area to north of pan represents former extension of pan.

On the southern side of the pan are the inner and outer dunes. Unlike those at the pans described so far, the dunes are not arranged concentrically, but are offset from one another. At Mogatse pan, the inner dune is found around the south and southeast sides of the pan, whilst the outer dune is located on the south and southwest sides of the pan, suggesting that they were formed by winds from different directions. There is a straight slope from the pan to the crest of the inner dune, of grey brown sand, 29 m above the pan datum. It is separated on its western side from the outer dune of red sand, with its crest 31 m above pan datum, by a shallow interdunal depression some 200 m wide.

Dead Tree pan (Fig. 3.10 Plate 10) otherwise unnamed so far as the writer is aware lies some 3 km due west of Mogatse pan. The pan itself is heart shaped, with a bare clay surface, and measures 0.80 km by 0.70 km, covering an area of 0.39 km^2. Like Mogatse pan, Dead Tree pan does not occupy the whole of the floor of the depression. Encircling the pan there is a 150 m wide area of flat ground, with abundant calcrete outcrops, especially on the northern side of the pan, which appears to represent a former extension of the pan.

On the southern side of the pan there is a straight rise from this area of calcrete to the crest of the inner dune, 18 m above the pan datum. The inner dune is not well defined, and merges with the red sand outer dune, the crest of which lies 23 m above the pan floor. Both dunes have a very marked parabolic shape in plan and are slightly offset in the manner of the dunes at Mogatse pan.

Area 4: Bosobogolo, Mpaathutlwa and Mabuasehube pans

Bosobogolo, Mpaathutlwa and Mabuasehube pans lie 120 km north of Tshabong in an area of undulating topography. They are the most accessible of the pans of the Mabuasehube Game Reserve, which was created around this group of pans. The pans in this group are situated on the southern edge of the area of the highest density of pans.

The vegetation of the area is shrub savanna of the southern Kalahari type, modified here by the relative aridity of the climate (rainfall here is about 250 mm per year, with an 80 % seasonal variability) and

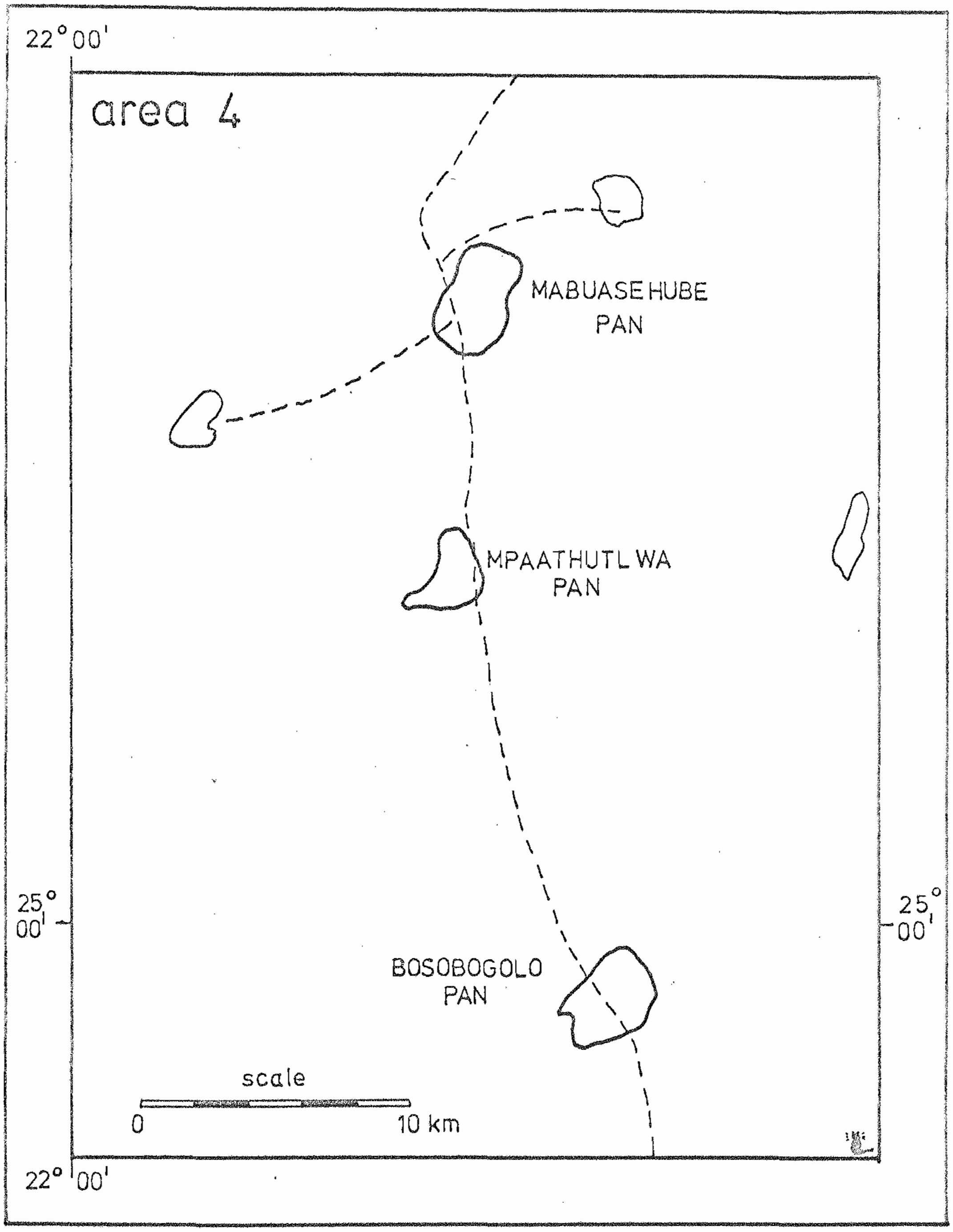


Fig. 3.11 Location of pans studied in area 4.

the fact that the area was overgrazed when it was settled in the 1930's and 1940's. The combined result of these two factors is a generally poor grass cover.

In the Mabuasehube area, the cover of the Kalahari Beds appears to be thin. Vertically dipping shales and sandstones of the Waterberg System outcrop on the northern and western sides of Mabuasehube pan. At Mpaathutlwa pan, 10 km to the south, there is an outcrop of Karroo System Dwyka tillites on the northern side of the pan. The area thus lies on the eastern boundary of the Karroo basin of the Kalahari. Massive calcretes are common around Mabuasehube pan and along the road between it and Mpaathutlwa pan. The location of the pans studied is shown on Fig 3.11.

Bosobogolo pan (Fig. 3.12) is the southermost of the Mabuasehube group of pans. It is an oval pan, measuring 2.24 km long by 1.28 km wide and covering an area of 2.0 km^2. The sandy clay surface of the pan is covered by short grass, with a few small waterholes surrounded by calcrete on its southern side. Bosobogolo pan lies in the centre of a sub circular depression 7.12 km^2 in area and some 10 m deep.

Around the edge of the pan there is a zone 80 to 100 m wide of grey sandy clay with abundant calcrete nodules, supporting a sparse cover of short grass and herbs. This zone, which appears to represent a former extension of the pan, increases to a width of 200 m in the southwest corner of the pan. On the northwestern side of the pan it forms a small embayment in the slopes of the pan depression, into which a small gully leads. In common with most of the pans described so far, there is a distinct break of slope between the outer and inner slopes of the pan depression, associated with a change from red brown to grey brown sand with sporadic calcrete nodules.

On the south and southeast sides of the pan there is a well developed set of dunes. The inner dune of grey brown sand is well wooded and extends around the southeast and south sides of the pan. Its crest line lies 26 m above the pan datum. To the south it merges with the massive outer dune of red sand, although elsewhere the dunes are separated by a small depression. The outer dune rises to a crest line 36 m above the pan datum, and has a much more open type of vegetation, with extensive areas of grass and bare sand.

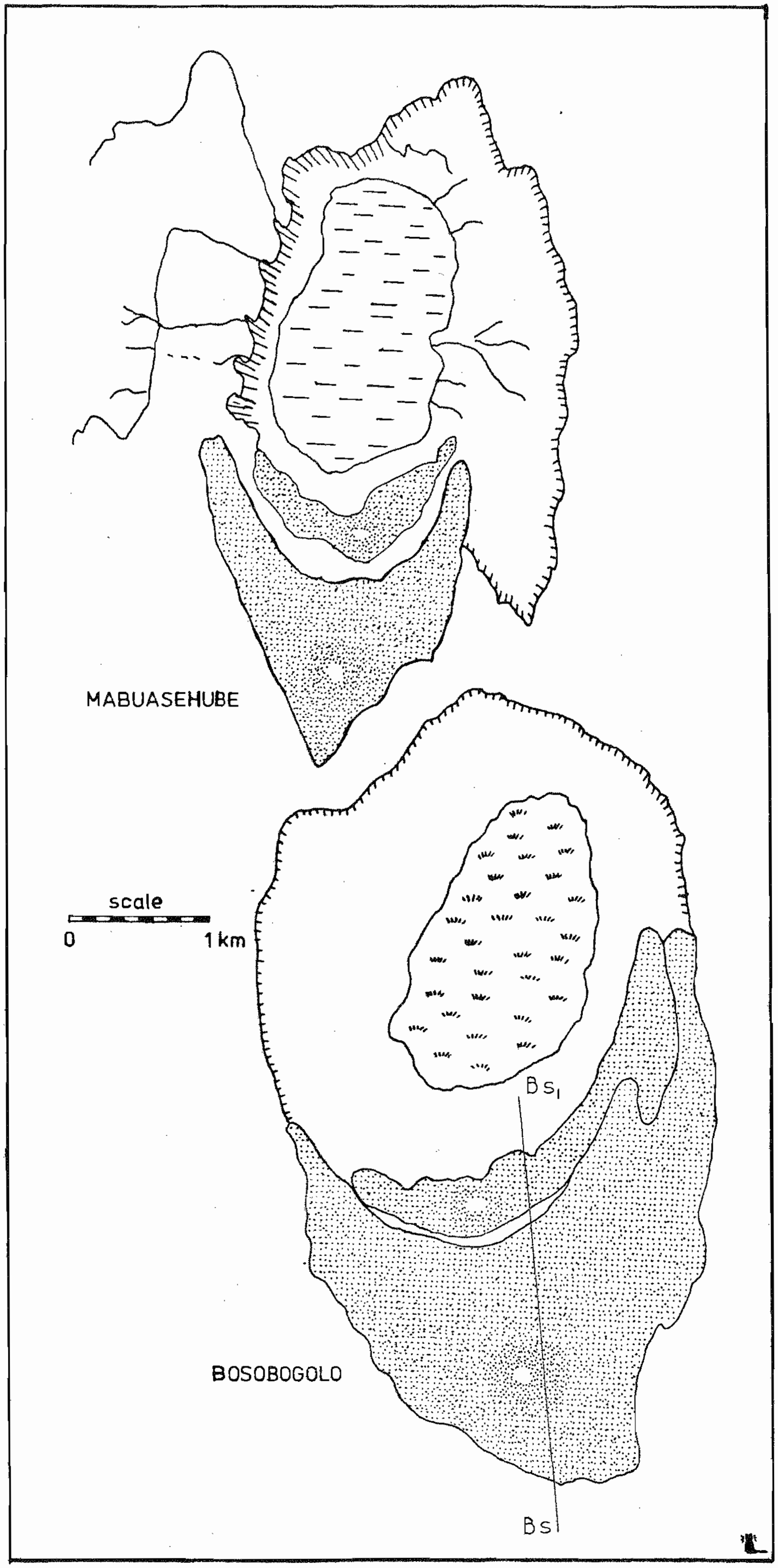


Fig. 3.12 Mabuasehube and Bosobogolo pans, area 4.

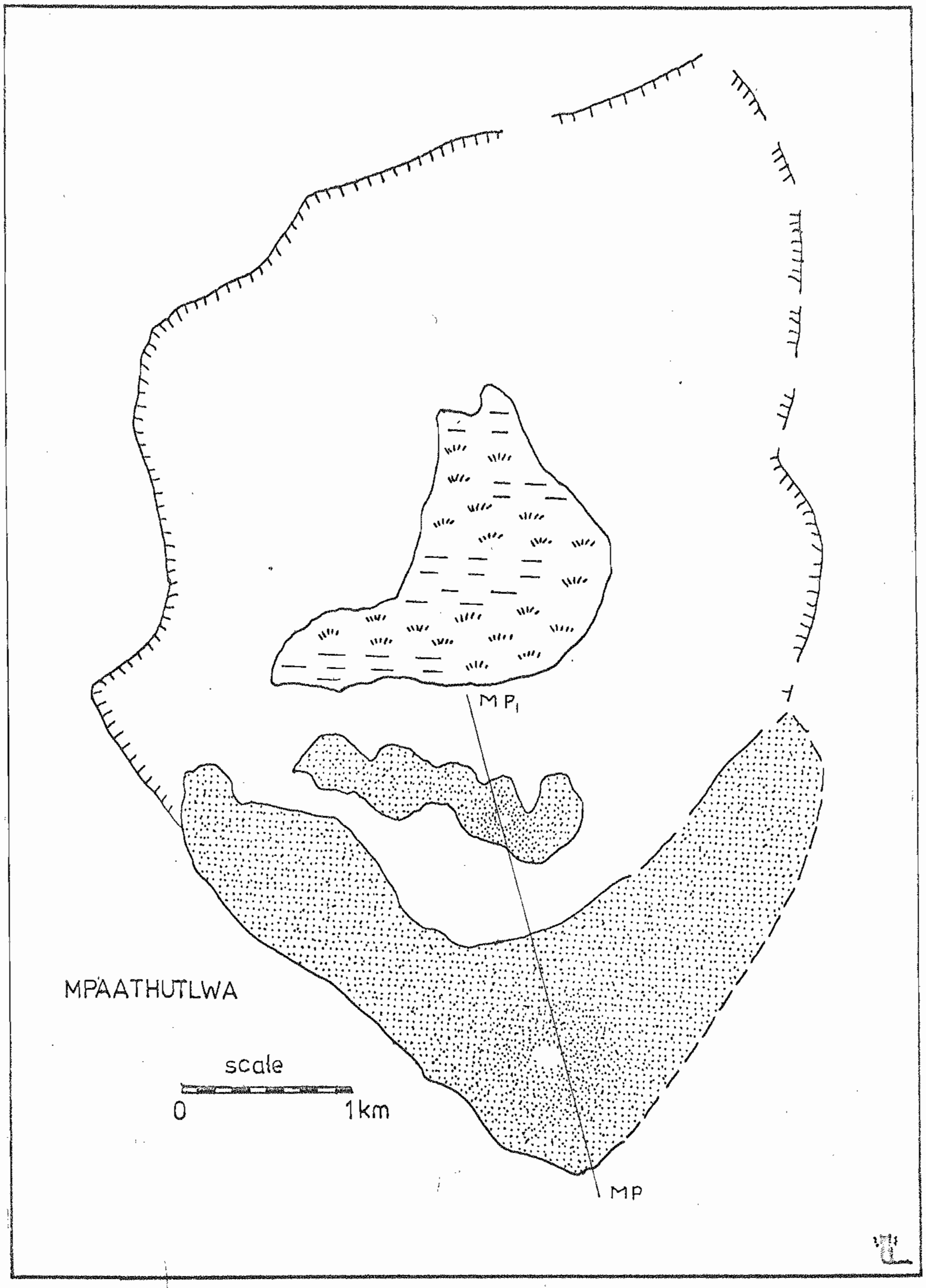


Fig. 3.13 Mpaathutlwa pan, area 4.

Mpaathutlwa pan (Fig. 3.13 Plate 11) whose name means Giraffe pan in Tswana, lies 15 km north of Bosobogolo pan, on the track to Tshane. It is a crescent shaped pan, measuring 2.08 km across by 1.61 km long, and covers an area of 1.72 km^2. The surface of the pan is bare granular clay, with occasional areas of short grass, much favoured by springbok for grazing. Mpaathutlwa pan lies on the southern side of an almost square depression 14.72 km^2

in area and 30 m deep. The outer slopes of the depression are very gentle, but become much steeper towards the pan, where calcretes outcrop. On the north side of the pan there is an extensive outcrop of calcified Dwyka tillite.

On the southern side of the pan is an area of dunes. The main dune ridge lies 1800 m from the pan edge and rises to a crest line 47 m above pan datum. It forms a massive crescent shaped accumulation of sand curving around the southern side of the pan. The main bulk of the dune is composed of red brown sand. No inner dune as described elsewhere seems to exist. There is a straight slope 600 m long of very sparsely vegetated grey brown sand from the pan edge to an area of massive calcretes and sil-calcretes thinly covered by grey sand and calcrete rubble some 300 to 400 m wide and rising 3 m above the surrounding area. This outcrop of calcretes extends around the southern edge of the pan in a position where one would expect to find an inner dune. The surface of the outcrop is gently undulating, with distinct rills and gullies leading from it to the pan. On the side away from the pan, the calcrete dips under red brown sand for 100 m until it can no longer be traced. From its position and topography, it would seem that this area of calcrete is the indurated core of the inner dune, from which the surface sands have been removed and deposited against the face of the outer dune. Deflation is certainly taking place today at Mpaathutlwa pan, for numerous "dust devils" were observed while the writer was at the pan, in July 1973. (Plate 17).

Mabuasehube pan (Fig. 3.12 Plate 12) lies 15 km north of Mpaathutlwa pan. It is an oval pan, measuring 2.0 km long by 1.6 km wide, and covers an area of 1.95 km^2. The pan, which has a bare clay surface, lies in the centre of an ill defined depression 5.44 km^2 in area, and 30 to 40 m deep. The sides of the depression are steep in the immediate vicinity of the pan, especially on the western side, where there is a 15 m high bluff, topped by 2 m thick massive calcretes, overlooking the pan. The lower parts of this bluff are developed in vertically dipping red shales of the Waterberg System, which strike in a north - south direction. Similar outcrops can be found on the northern and eastern sides of the pan, where they form similar but more subdued slopes. There are numerous small gullies and rills furrowing these rock cut slopes, some of which have built small fans into the pan.

Plate 11. Mpaathutlwa pan: view south over pan. Note break of slope on north side of pan which marks transition between red brown sands of outer slopes of depression (in foreground) and grey brown sands around pan edge.

Plate 12. Mabuaschube pan: view southeast to tree covered dunes from bluff on west side of pan.

On the southern side of the pan there is an extensive area of dunes, covering an area up to 2 km from the pan. Both the outer dune of red brown sand, and the inner dune of grey brown sand have marked parabolic shapes. Investigations by Professor Revill Mason, of the University of the Witwatersrand, (R. Mason pers. comm.) have shown that the area of the pan was occupied or visited by men in the Middle Stone Age, presumably when the water supply from the pan was more reliable than today.

Area 5: Nwatle, Masetleng, Pussy, Ukwi and Urwi pans.
This group of pans lies in the unsettled area between Tshane and Kule, along the infrequently used track between these two places. The topography of the area is gently undulating, with an almost undisturbed bush savanna vegetation. In many places the trees reach heights of 10 m and the vegetation takes on a parklike appearance. Game is abundant in all parts of this sector of the Kalahari. Rainfall averages some 300 mm per annum. Little is known about the underlying geology of the area as there are no boreholes between Tshane and Kule, but evidence from boreholes bordering the area suggests that the whole of this part of the Kalahari is underlain by Karroo System sandstones and shales of the Ecca Series, which outcrops at Ukwi pan. Apart from the surface Kalahari sands, the Kalahari Beds in this area may be represented by thick calcretes and calcareous sandstones, known to exist in neighbouring areas of Namibia (South West Africa). The location of the pans studied is shown in Fig. 3.14.

Nwatle pan (Fig. 3.15 Plate 13) is the most easterly of this group of pans and lies approximately 100 km west of Tshane. The pan is lemniscate in shape, measuring 1.16 km long by 0.56 km wide and covers an area of 0.34 km^2. It has a bare clay surface and lies on the eastern side of an oval depression 4.32 km^2 in area and 10 to 15 m deep, which is poorly defined on its northern edges, but has quite steep slopes and a well defined edge on its west and southwest sides. The pan is surrounded by a 200 to 400 m wide zone of grey brown sand, with abundant calcrete nodules, which appears to represent a former extension of the pan. On the north side of the pan this zone widens out and becomes quite extensive. Its northern extent is marked by a distinct break of slope and vegetation change from a sparse cover of

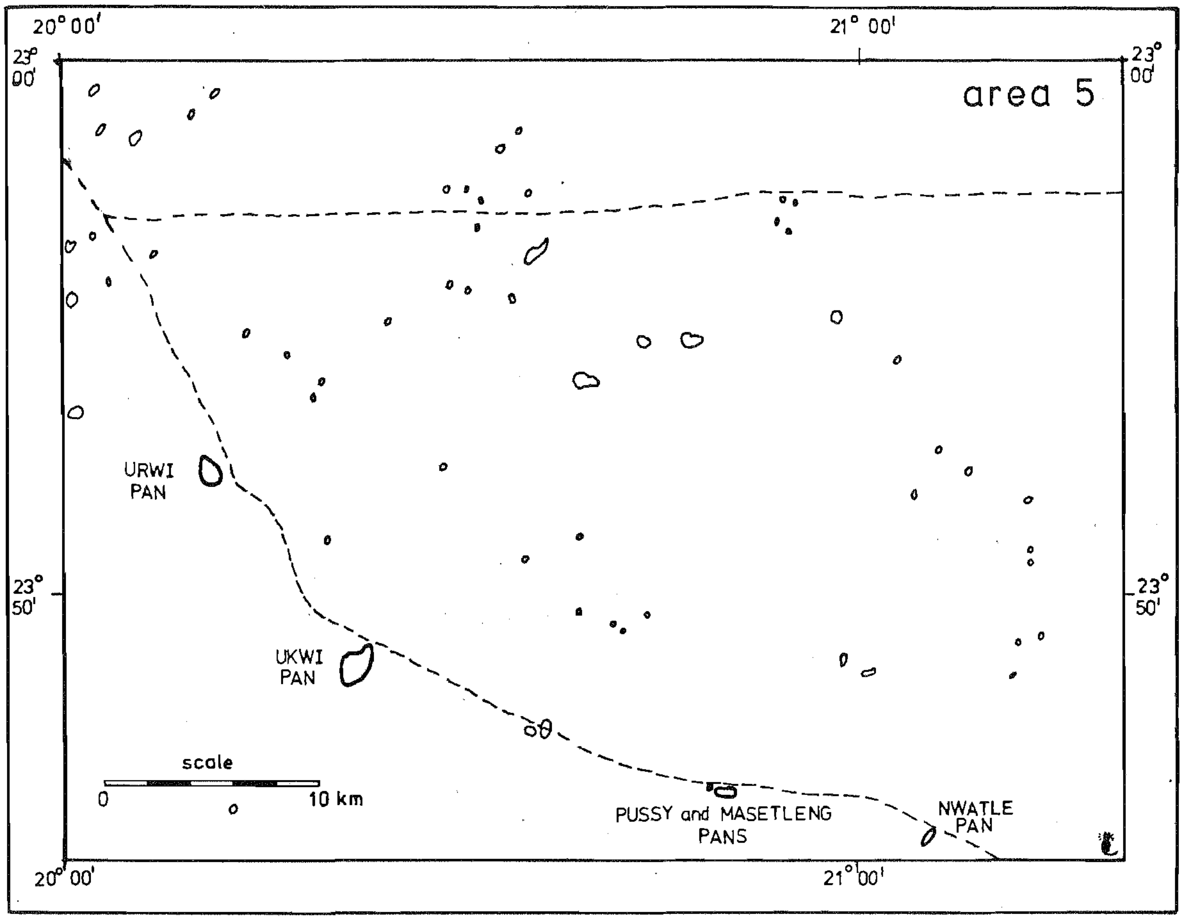
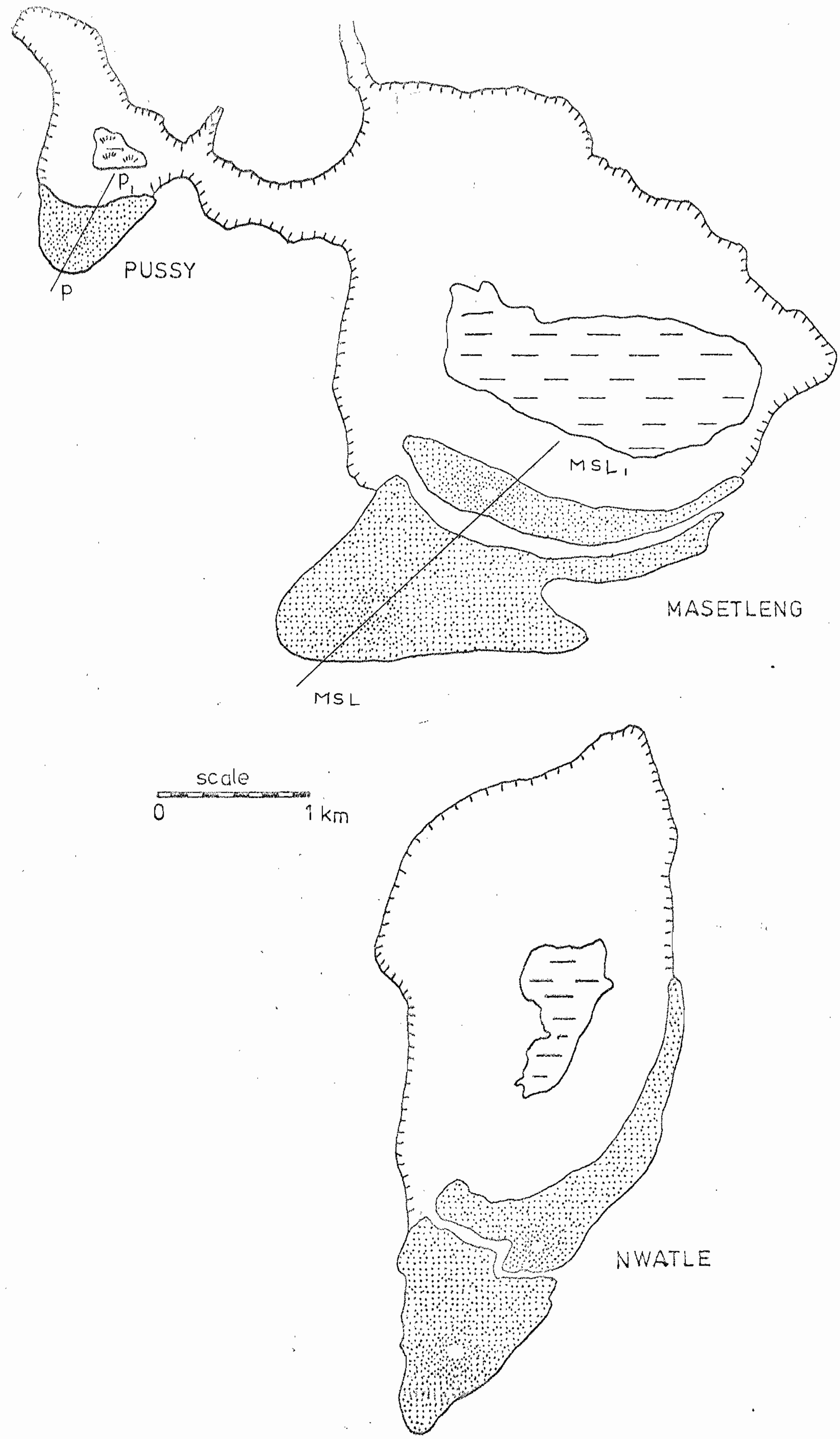


Fig. 3.14 Location of pans studied in area 5.

herbs to one of small shrubs and medium height grass. On the upper side of the break of slope the surface sands are red brown in colour.

Curving around the southern and southeastern sides of the pan is a massive dune ridge of grey brown sand, with its well wooded crest line some 25 m above the pan datum. In contrast, the outer dunes are poorly developed and consist of a roughly triangular accumulation of brown and red brown sand with a general level some 15 m above pan datum. The hummocky nature of the accumulation suggests that it represents a coalescence of small crescentic dunes. It appears that the period of sand movement that created the inner dune was considerably more effective than its predecessors.



P1
PUSSY
P
MSL1
MASETLENG
MSL
scale
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1 km
NWATLE

Like those at Mogatse and other pans some 200 km to the east, the dunes at Nwatle pan are offset, with the outer dunes on the southwest side of the pan and the inner dune on the south and southeast sides of the pan.

Deflation appears to be quite active at Nwatle pan today. In many parts of the pan, there are small residuals of grass covered sandy soil up to 3 m across rising 30 to 40 cms above the present pan surface. In addition, there was a continuous cloud of dust being blown off the pan during a period of windy weather when the writer was at the pan in late July 1973.

Masetleng pan (Fig. 3.15 Plate 14) lies some 18 km west of Nwatle pan along the track to Kule. It is an oval shaped pan, measuring 2.08 km long and 0.92 km across, with a bare clay surface and covers an area of 1.45 km^2. Masetleng pan is located on the southeastern side of an almost square depression 6.72 km^2 in area and 22 m deep. As at Nwatle, the depression is asymmetric in form with steeper slopes along its southeastern margins. Around the edge of the pan there is a zone where calcretes outcrop at or near the surface. This zone is particularly extensive on the north and northwest sides of the pan, where it is up to 800 m wide. Like similar areas at Mogatse, Bosobogolo and Nwatle pans, it appears to represent a former extension of the pan. There is a sharp boundary to this zone, marked by a vegetation change from very short grasses and herbs to longer grass and shrubs, and a slight break of slope. In the northwest corner of the pan depression there are two shallow linear depressions about 200 m wide, clearly traceable on the ground and easily visible on the aerial photography. One of the depressions leads west northwest to a small pan, Pussy pan, described below. The other leads north to two small pans about 2 km away.

On the southern side of Masetleng pan are large inner and outer dunes, both well wooded. The inner dune, of grey brown sand, rising to a crest line 22 m above the pan datum and 750 m from the pan edge, forms a crescent shaped ridge around the south and southeast sides of the pan. It is separated from the outer dune of red brown sand by a shallow depression some 100 m wide. In plan, the outer dune forms a triangular accumulation of sand on the south and southwestern sides

Plate 13. Nwatle pan: view north from inner dune. Areas in foreground and surrounding pan are underlain by sandy clays indicating former extension of pan.

Plate 14. Masetleng pan: view south over bare clay pan to dunes. Note "islands" in pan, which are residuals of sandy phase of pan deposits, otherwise removed by deflation.

of the pan, with its main bulk lying opposite the centre of the pan depression. The crest line of the outer dune lies 34 m above the pan datum and 1500 m from the pan edge.

Pussy pan (Fig. 3.15), otherwise unnamed to the writer's knowledge, lies about 1 km west northwest of Masetleng pan. It is linked to Masetleng pan by a shallow depression floored by grey brown sand, some 200 m or more wide. Pussy pan itself is sub circular in shape and measures some 0.3 km across. It has a partly grassed surface, with a small water hole surrounded by long grass in the centre of the pan. Pussy pan lies on the southern side of a depression some 0.90 km^2 in area and 5 to 6 m deep. Sporadic outcrops of calcrete can be found on the western side of the depression. A small and shallow gully some 500 m long enters the pan in its northwesterly corner.

From the pan floor there is a straight slope up to the crest of the single dune 600 m from the pan edge and 14 m above the pan datum. The panward slopes of the dune are composed of grey brown sand, whilst the far slope and crest are of red brown sand.

It appears that Masetleng and Pussy pans form part of a local drainage system that was interconnected at some time in the past.

Ukwi pan (Fig. 3.16 Plate 15) lies 50 km northwest of Masetleng pan, along the track to Kule. It is a heart shaped pan with a bare whitish clay surface measuring some 4.4 km across and covering an area of 7.45 km^2, making it, in terms of surface area, the largest pan in the southern Kalahari. Ukwi pan lies in the southern part of a depression 16.64 km^2 in area. The outer slopes of the depression slope almost imperceptibly to the pan, but, some 400 m from the pan edge, there is a sharp break of slope and a change from red brown sands to grey brown sands with abundant calcrete nodules. At the pan edge, there is a further break of slope, and a steep slope with some calcrete outcrops, leads down to the pan. On the northern side of the pan, a bluff, topped by massive calcretes 3 to 4 m thick, forms the pan edge. A meandering gully, some 200 to 300 m wide, leads from the northeast corner of the pan. There are sporadic outcrops of purple shales of the Ecca Series, and green silcretes can be found on the southern and eastern sides of the pan.

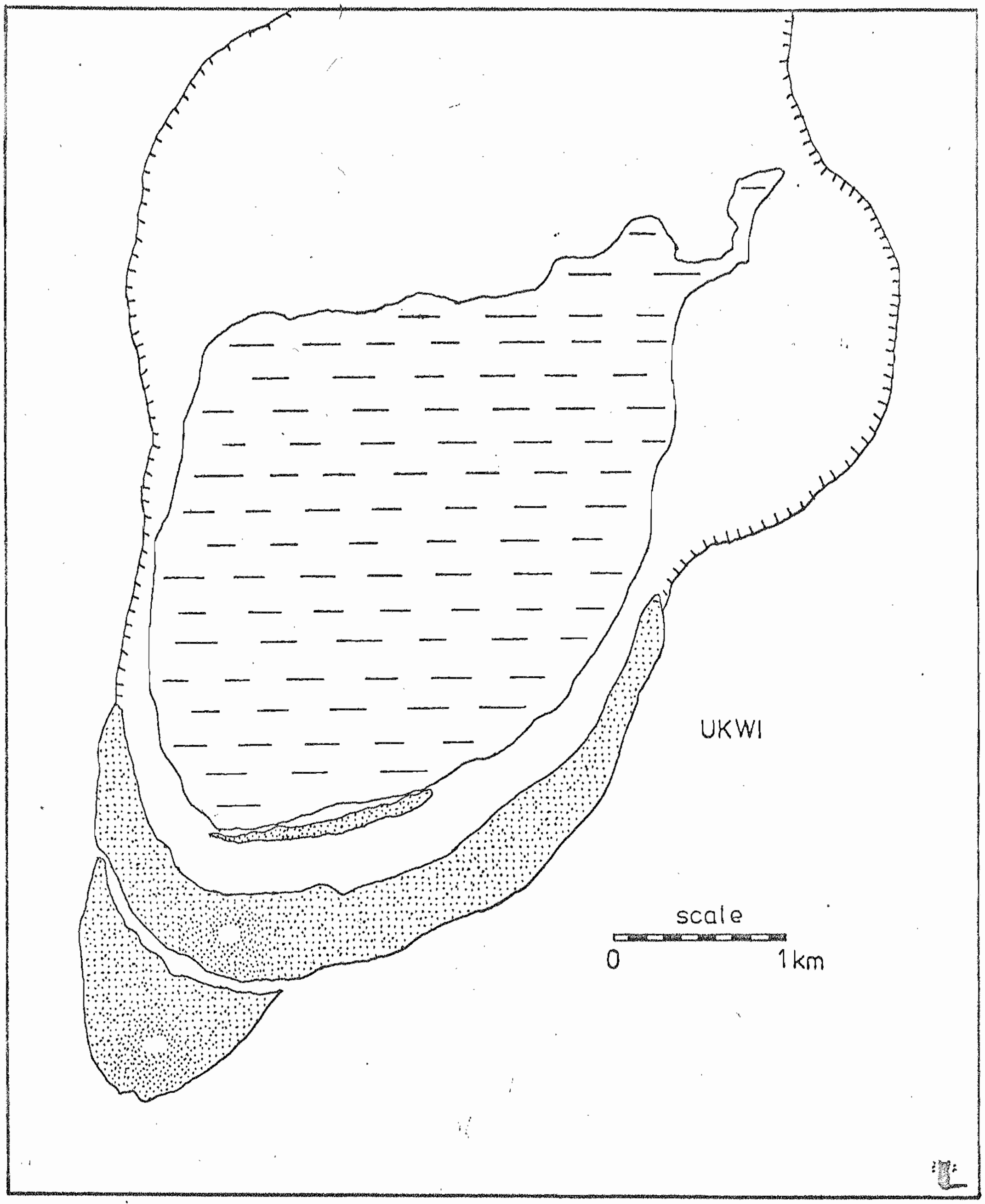


Fig. 3.16 Ukwi pan, area 5.

On the southern side of the pan there is an extensive area of dunes, which possesses some unusual features. There appear to be three distinct dunes that can be easily recognised, with the possibility of a fourth. Immediately on the pan edge is a small dune, covered with a few woody shrubs, with its crest line 2 to 3 m above the pan floor. It is composed of course sand, often quite angular and can be traced for 1 km around the southern edge of the pan. The panward slope of this dune is cut by a 50 cm high notch, which from its fresh appearance suggests a recent formation, with the pan flooding to a depth of up to 1 m. Beyond this dune, which appears to be receiving material today, there is a depression, at the same level as the present pan floor and with a similar surface. It appears to be flooded from time to time. On the southern side of the depression is an area of massive calcretes, thinly covered with grey brown sand. From this calcrete outcrop, there is a steep rise to the well wooded crest of a massive dune of grey brown sand, some 800 m from the pan edge and 40 m above the pan floor. From the crest of this dune, which curves around the south and southeast sides of the pan and appears to be the main dune ridge, there is a steep fall to a small depression and a rise to a smaller dune of brown sand. Beyond this there is a hummocky area of red brown sand. It would appear that the general form of the main dunes at Ukwi resembles that of those at Nwatle.

Urwi pan, (Fig. 3.17 Plate 16), which was the last pan studied in the field work period, lies 25 km northwest of Ukwi pan. It is a semicircular pan, covering an area of 2.10 km^2 and measuring 1.4 km long by 1.48 km across, with a bare powdery clay surface. Urwi pan lies on the southern side of a depression some 30 m deep and 15.52 km^2 in area, which is very poorly defined on its north and northwest sides. As at Ukwi pan, there is a distinct break of slope between the outer and inner slopes of the depression, accompanied by a change from red brown sand and bush savanna vegetation with long grass to grey brown sand with calcrete nodules and a thin grass cover. There is a further break of slope at the pan edge, marked on the northern side of the pan by a small bluff topped by a calcrete outcrop similar to that at Ukwi pan.

On the southern side of the pan there is an extensive area of dunes, stretching for 3.5 km from the pan edge. Three distinct dune ridges can be identified. Five hundred metres from the pan edge is the crest line of the first dune, composed of grey sand, 22 m above the pan datum. It is separated from the second dune, composed of grey brown sand with its crest line 800 m from the pan edge and 28 m above the pan datum, by a narrow depression. A 100 m wide depression separates the second or middle dune from the outer dune of red brown sand, which is a massive accumulation of sand with its crest line 2.5 km from the pan edge and 40 to 50 m above the pan datum. It appears that the outer

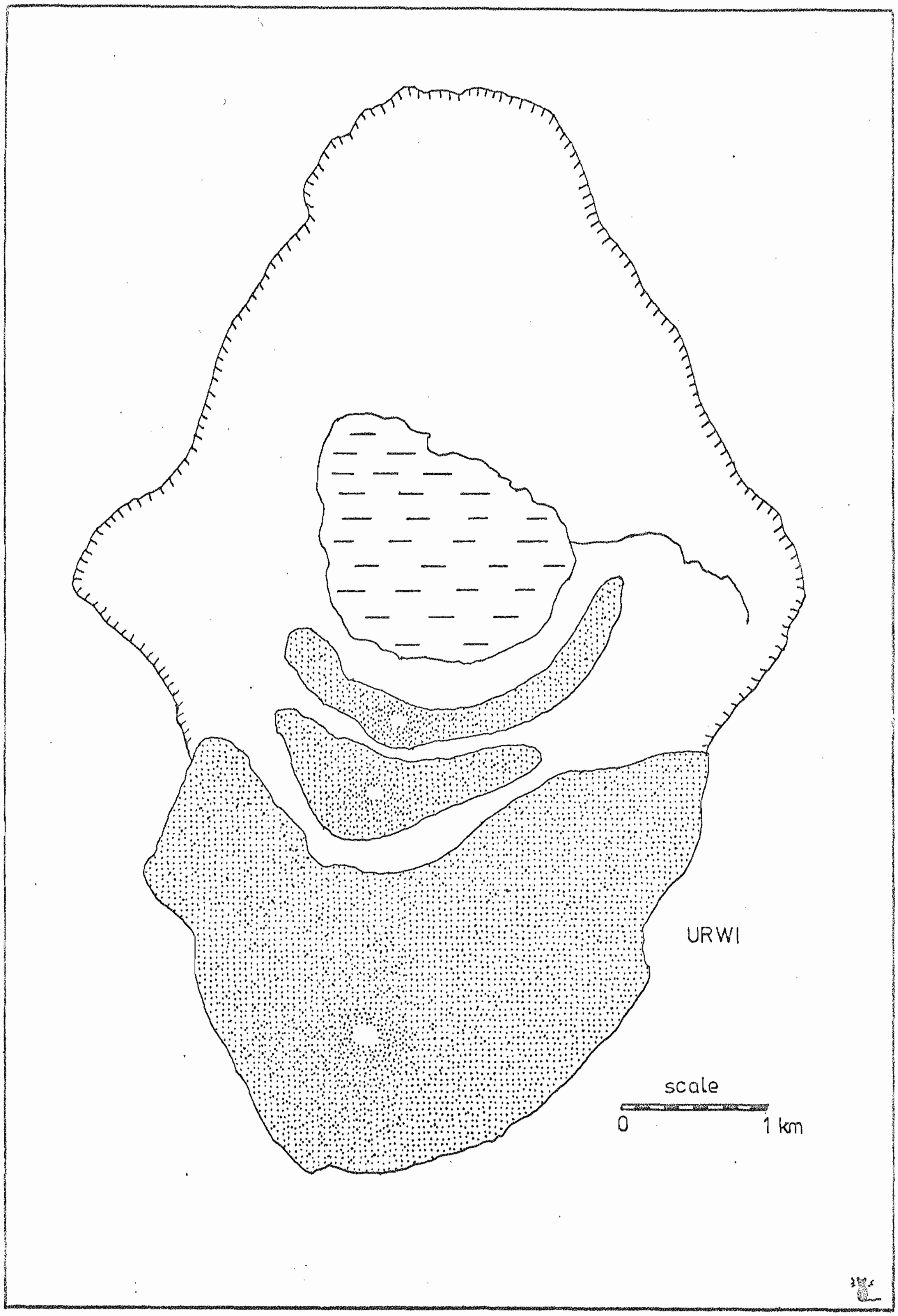


Fig. 3.17 Urwi pan, area 5.

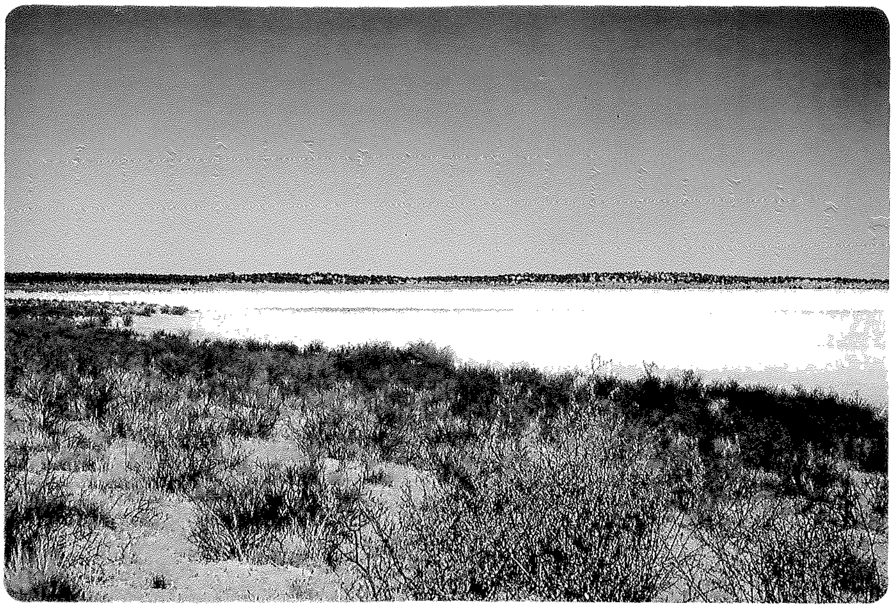


Plate 15. Ukwi pan: view southwest to dunes. Note sharp break of slope around pan edge and silcrete outcrops in pan floor.

Plate 16. Urwi pan: view north over bare clay pan surface from flanks of innermost dune.

dune at Urwi is equivalent to the outer dunes found elsewhere. The innermost dune appears to be equivalent to the inner dunes found at other pans. The middle dune at Urwi is more of a problem, but it does appear to have similarities with the transitional areas between inner and outer dunes elsewhere, and with some of the similar areas at Nwatle and Ukwi pans.

Conclusions

From the foregoing descriptions of the southern Kalahari pans, it is clear that, despite the individual nature of each pan, there are many features that are common to all pans. Inter pan variability becomes insignificant when the whole of the southern Kalahari is considered. Summarising the main topographic features of the pans, the following conclusions can be made.

The pans: the flat central parts of the depressions are occupied by the pans, which may have a surface of bare clay, long or short grasses or low growing succulents and herbs. The pans are regular in shape. Most of them are sub circular or sub elliptical, and highly irregular or very elongated pan shapes are rare in the southern Kalahari. The pans are surrounded by a zone of grey brown clayey sand, often with calcrete nodules which appears to represent a former extension of the pan.

The depressions: the depressions containing the pans are, with few exceptions, isolated and enclosed. Only Masetleng and Pussy, and possibly Mashiaphotsana pans appear to have any links with other pans. Like the pans, the shape of the pan depressions is regular, and is commonly sub circular. The slopes of the pan depression, on the sides not occupied by the dunes, are marked at most pans by a distinct break of slope some 200 to 300 m from the pan edge, associated with a change from red brown sand to grey brown sand and calcretes. At a few of the larger pans, there may be two of the breaks of slope, one near the pan edge and the other at some distance away.

The dunes: on the southern side of all pans is an area of dunes. Commonly there are two dune ridges, separated by an interdunal depression of varying width. The ridge furthest from the pan is composed of red brown sand and is called the outer dune. The other

Plate 17. "Dust devil" at Mpaathutlwa pan - evidence of the sporadic deflation of pan surfaces taking place today.

Plate 18. Khakhea pan flooded to a depth of 20 to 30 cm, early April 1973, following heavy rain a few days previously.

ridge is composed of grey brown sand and is called the inner dune. Exceptionally there may be a single dune ridge formed by the coalescence of the inner and outer dunes, whilst at a few pans three separate ridges may exist. At most pans, the outer dune is the larger of the two dunes, but at Motsobonye, Mashiaphotsana, Kokong, Nwatle and Urwi pans it is poorly developed. In plan, the dunes have a crescentic shape. In the central and western parts of the southern Kalahari, the inner and outer dunes are often offset, with the outer dune being found on the south and southwest of the pan and the inner dune on the south and southeast sides of the pan.

Present geomorphic processes: as far as the writer's observations permit, the evidence for present day geomorphic activity in and around the southern Kalahari pans is slight. The pans are rarely flooded to any extent and for any length of time today, and signs of recent lacustrine processes are largely absent. Equally, evidence of substantial deflation was restricted to a few pans. From this it would appear that the topographic features of the pans are the result of conditions unlike those of the present day.

Thus, to explain the origin and development of the southern Kalahari pans it is necessary to account for the distribution and formation of the depressions that contain the pans, the deposits of the depression floors and the dunes on the southern margins of the depressions.

PREVIOUS HYPOTHESES PUT FORWARD TO EXPLAIN THE ORIGINS OF THE SOUTHERN KALAHARI PANS.

Various hypotheses have been put forward to explain the origins and development of the pans of the southern Kalahari. Passarge (1904) noted the importance of the pans as sources of water for game animals, and suggested that their trampling action was responsible for pan formation. Rogers (1934) acknowledged that game animals appeared to promote the removal of large amounts of material from pans, but concluded that wind, acting on the bare surfaces of pans, was the process by which the pans were formed. Wayland (1952) stated that most pans were formed by wind action during some period in the past and discounted the effects of biogenic action in pan formation.

Boocock and Van Straten (1962) noted that there was no general agreement on the processes of pan formation, but that wind action was the most important factor in maintaining and extending pans at the present time. They suggested that the pans lay in belts that could be related to ancient drainage lines, and that the pans were the remants of ancient sand choked drainage lines. Grove (1969), citing the existence of dunes on the southern side of the pans, suggested that they had been formed by northerly winds.

COMPARISONS WITH SIMILAR FEATURES IN OTHER SEMI ARID AND ARID AREAS.
A wide variety of natural depressions, often containing small seasonally dry lakes, have been described from the semi arid and arid areas of the world. They range in size from the "buffalo wallows" of the Great Plains of the western U.S.A. and the "gnamma holes" of Australia, to the great desert depressions such as the Quattara Depression of Libya and the Sechara Basin of Peru. Consequent upon the wide geographic distribution of such features, a wide variety of hypotheses has been put forward to explain their origin. The most plausible of these are: solution; solution and collapse or settling of underlying strata; dessication of river systems; biogenic action; and deflation.

Solution depressions or dayas cut into level limestone plains of semi arid and arid areas, have been described from North Africa, the Middle East and New Mexico by Mitchell (1974). Commonly, dayas have steep sides and flat, seasonally wet floors. In shape, size and surface features some dayas are not unlike the southern Kalahari pans. However, surface limestone or gypsum outcrops covering a large area seem to be a necessary precondition for the formation of dayas. Formations of this type are absent from the southern Kalahari, so it would appear that a solution origin for the pans there is unlikely, but it is possible that etching of depressions into surface calcretes on the lines suggested by Boocock and Van Straten (1962) may have taken place locally.

Solution of underlying rocks, followed by the collapse of surface strata was advocated by Johnson (1901), Smith (1940) and Frye and Schoff (1942) to explain the origin of the small sub circular depressions of the High Plains of the western U.S.A.. Johnson (1901), Schoff (1939) and Frye and Schoff (1942) also considered the possibility of near surface differential settling of unconsolidated strata as a means of forming small depressions. Requirements for the above hypotheses appear to be weakly cemented sub surface strata and poorly consolidated surface strata. Such deposits undoubtedly do exist in the southern Kalahari. However, the tendency has been for the cementation of these deposits by calcium carbonate or silica, rather than their disintegration by solution and settling. In addition, an examination of the evidence from the U.S.A. by Reeves (1966) suggests that such a hypothesis is untenable, except in very localised examples.

Concentrations of dry lakes in many semi arid and arid areas have frequently been regarded as the remnants of extensive river systems developed under more humid conditions. Progressive dessication, leading to intermittent flows and collapse of sandy banks, results in the isolation of sections of the rivers, which then become local centres of drainage. In the High Plains of Texas, Reeves (1966) has concluded that the larger lake basins have developed along the courses of former river systems. In Western Australia, Gregory (1914), Jutson (1934) and Bettenay (1962) have described lake systems as remnants of Tertiary river systems. In southern Africa, the pans of the western Orange Free State and the Lake Chrissie area have been shown by Wellington (1943, 1945) to be the remnants of former river systems. In the Kalahari, Jaeger (Rogers 1940) concluded that limestone pans lay along the courses of defunct river systems. Examination of the evidence presented in these papers shows that dry lakes that occupy parts of former river systems have a number of distinctive features. They are characteristically elongated and irregular in shape, and have distinctive linear groupings and alignments. Often they can be shown to form a pattern related to present drainage divides and drainage lines.

The influence of animals in creating small natural depressions in semi arid areas has been widely advocated. Darton (1915) suggested that buffalo were responsible for the creation of thousands of small depressions, termed "Buffalo wallows" in the High Plains of Texas. In southern Africa, Allison (1899), Laloy (1905), Passarge (1911) and Flint and Bond (1968) have all suggested that game animals seeking water or salt have promoted the formation of pans and similar small depressions by trampling and destroying vegetation and surface soil, or removing material on their coats. No doubt early investigators were impressed by the large numbers of game animals found at pans and the dust clouds they produced (Hutchinson 1958), but it is difficult to see how the action of game animals, however numerous, could have produced over a thousand depressions in the southern Kalahari, many of them 0.5 km^2 or more in extent and up to 40 m deep.

Closed depressions in arid and semi arid areas have often been regarded as being the products of deflation. In many cases this conclusion is more the result of lack of any evidence other than that the depressions occur in arid or semi arid areas. In discussion of the deflation hypothesis, it is necessary to make the distinction between dry lakes in basins created by deflation, and dry lakes in basins created by other processes, but subject to surface lowering by wind action. The form of both types of dry lake may be similar, but be the result of a very different set of conditions.

Deflation from the surface of seasonally dry lakes to form clay or sand dunes has been described from the U.S.A. by Blackwelder (1931), Reeves (1965) and Bowler (1973); from Australia by Hills (1931), Bettenay (1962), Campbell (1968) and Bowler (1970); from North Africa by Bourlaine (1954) and Coque and Jauzein (1967); and from southern Africa by Rogers (1907) and Jaeger (1939). Such a process is thus of wide occurrence and great significance and gives rise to lake basins that are commonly bordered on their downwind sides by a series of crescentic or lunette dunes, resembling those bordering the pans of the southern Kalahari.

Lake basins created by wind erosion have been described from the High Plains of Texas by Gilbert (1895), Evans and Meade (1945), and Reeves and Parry (1969). These lake basins commonly have a sub circular shape, shallow depth and small size, with a flat floor occupied by a seasonally dry lake. Am area of fringing dunes is found on the southern margins of the basin. In Australia, Twidale (1968) has described clay pans and playas of deflation origin in interdunal corridors in the Simpson Desert. In southern Africa, many investigators have suggested that pans are formed by wind action. Du Toit (1907, 1926) attributed pans in the northern Cape to deflation and Jaeger (1939) stated that the pans of the Namib Desert are the result of wind action. The evidence presented in the literature suggests that lake basins created by deflation are found in areas characterised by level or gently undulating plains, unidirectional strong winds and unconsolidated sandy surface deposits. Deflation basins are commonly well defined, sub circular to sub elliptic in shape; with a tendency to elongate downwind; relatively shallow, rarely more than 50 m deep; relatively small, often less than 5 km across; and generally possess an area of fringing dunes on their downwind side.

CONCLUSIONS

This chapter has described the main features of the topography of the southern Kalahari pans, which are contained in well defined sub circular depressions 10 to 30 m deep and up to 5 km across, with an area of fringing dunes on their southern sides.

The effects of present geomorphic processes upon the pans appears to be minimal, and it appears that the main topographic features of the pans are the result of conditions unlike those of today.

Previous workers in the southern Kalahari have indicated that wind action has played an important part in the development of the pans. Comparisons with similar features elsewhere in the world suggest that this is indeed the case.

The following chapters will attempt to explain the origin and development of the southern Kalahari pans by considering the distribution of the pan depressions, the morphology and composition of the dune complexes, and the composition and extent of the deposits of the pans.

CHAPTER 4.

THE DISTRIBUTION OF THE SOUTHERN KALAHARI PANS

INTRODUCTION

Little or nothing is known about the distribution of pans in the southern Kalahari. Even today, the 1:500000 and 1:1 million maps of the area show only a few of the many pans in the region.

It is not surprising that the comments of previous writers on the distribution of the pans have been brief. Wayland (1952) suggested that the aeolian pans tended to run in belts within which their perceived alignment was more apparent than real, due to the fact that the tracks went from pan to pan. Boocock and Van Straten (1962) stated that the greatest concentration of pans could be found within a 140 km radius of Tshane, and that the pans were distributed in belts related to ancient drainage divides and river systems. Grove (1969), writing with the benefit of aerial photographs not available to earlier investigators, described a 50 km wide belt of pans along the Bakalahari Schwelle, with pans being spaced at 15 km intervals in places.

In view of the above lack of information there is a basic need to describe the distribution of pans in the southern Kalahari with more precision.

Thus, the aims of this chapter are: to describe and analyse the distribution of pans in the southern Kalahari, and to put forward hypotheses to explain the distribution.

THE DISTRIBUTION OF THE SOUTHERN KALAHARI PANS

The only maps covering the whole of the southern Kalahari are at scales of 1:500000 and 1:1 million. As stated above they show only a fraction of the pans to be found in the region.

However, print lay downs (uncontrolled air photo mosaics) at a scale of approximately 1:125000 are available for the whole region. They show all pans that can be detected on the aerial photography of the region.

For the purposes of this study only pans that possessed features described in chapter 3 were mapped. Thus a pan should be contained in a well defined depression with an area of fringing dunes on its southern side. These features, which were possessed by almost all pans in the area, proved easy to recognise on the print lay downs, and enabled the accurate deliniation of the belt of pans along the Bakalahari Schwelle.

Tracings were made from the print lay downs to show all pans of the type defined above. From these maps were made of the total number of pans in each 1/16 ° quadrangle (1/4 of a print lay down); the number of large pans (longest dimension more than 0.5 km); and the number of small pans (longest dimension less than 0.5 km).

This division of the pans into two arbitrary groups was undertaken in order to see if there was any significant difference in distribution of pans of different sizes.

These maps showed the extent of the area containing pans of the type defined in the southern Kalahari, and the distribution of pans within the area.

Fig. 4.1 shows the distribution of all pans in the southern Kalahari that possess the stated features, and illustrates that they lie in a well defined belt. In the east of the area the belt is only 30 km wide and contains relatively few pans (2 to 4 per 1/16 ° quadrangle). It steadily widens out, the number of pans per 1/16 ° quadrangle increasing at the same time, to a maximum width of some 300 km at 22°E. The belt then narrows northwestward to the Namibian (South West African) border at Kule. The form of the pan belt closely parallels that of the watershed.

It will be seen that the number of pans per 1/16 ° quadrangle decreases away from the axis of the watershed. There are few pans north of 23°S, as the Okwa drainage system is approached. Similarly there are very few pans in the southwest part of the southern Kalahari, towards the dune belt along the Nossop river.

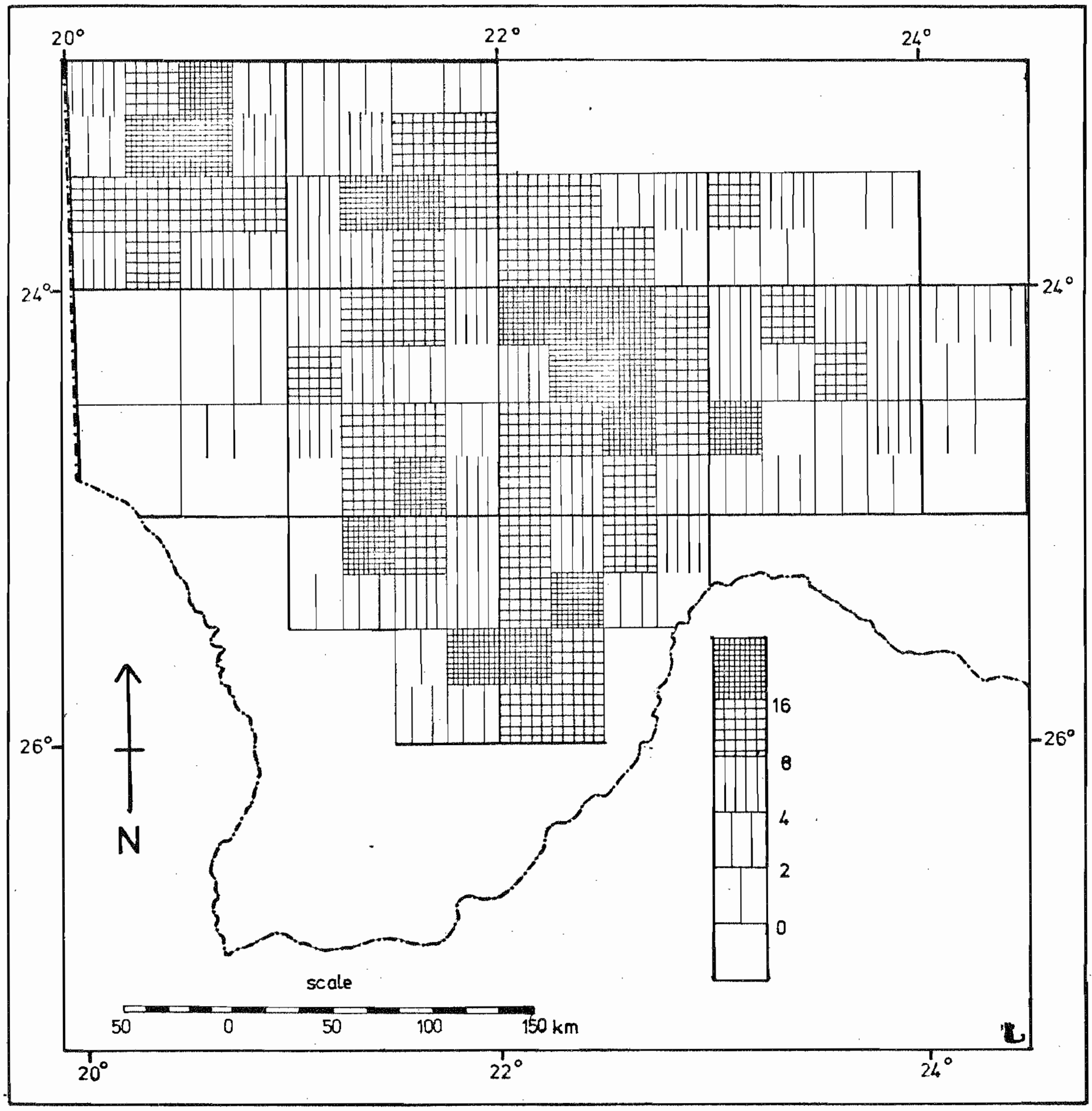


Fig. 4.1 Density of all pans per 1/16 ° quadrangle.

Within the pan belt there is an uneven distribution of pans. The most striking feature is the concentration of pans in the area between Tshane, Kokong and Mabuasehube. Here the density of pans over wide areas reaches 30 per 1/16 ° quadrangle, or 1 pan per 22 km^2. Areas of moderate pan density surround this nucleus, and extend to Tshabong and northwest of Tshane. The existence of this concentration of pans confirms the statement of Boocock and Van Straten (1962) that the greatest density of pans can be found within a 140 km radius of Tshane.

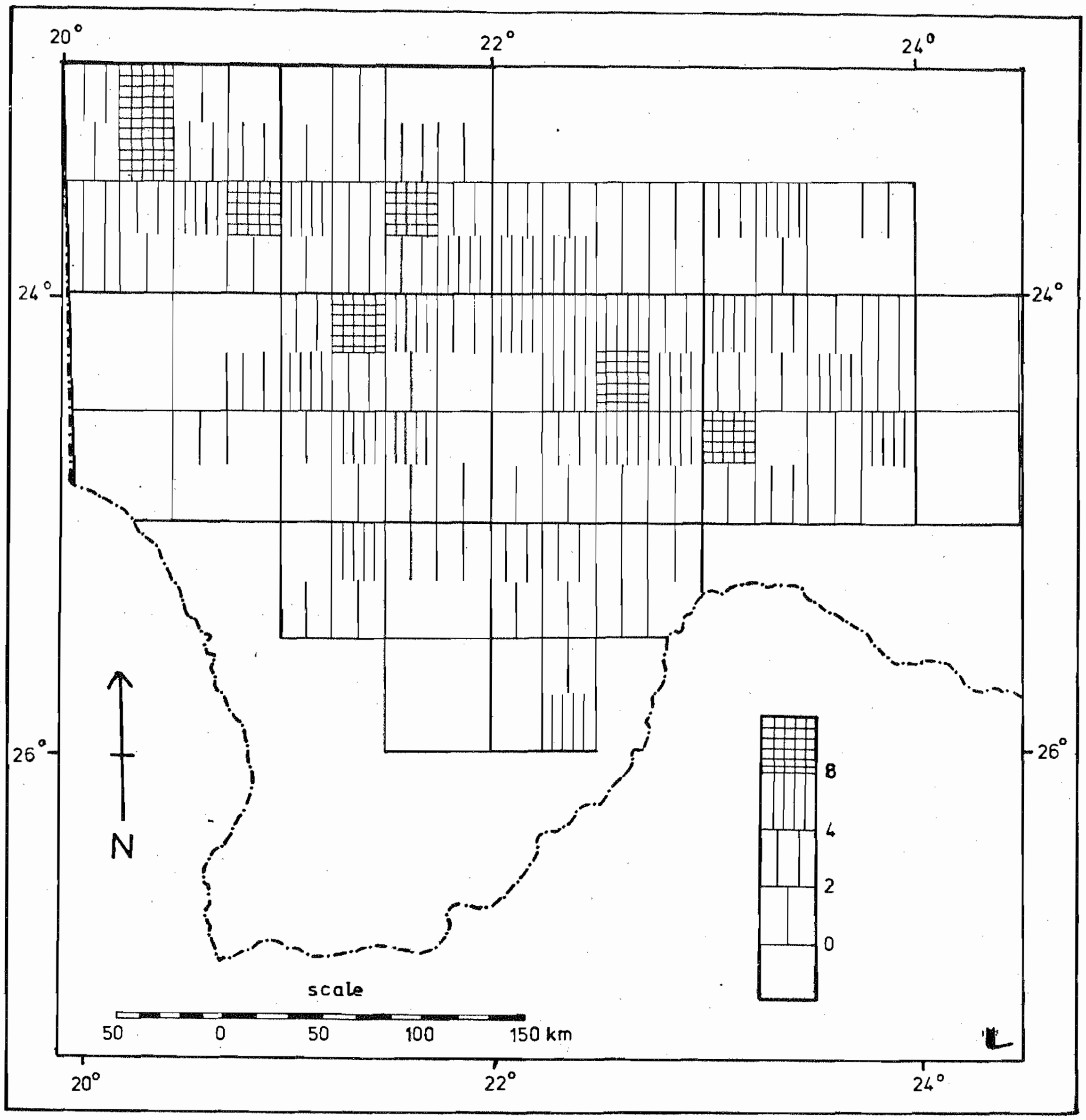


Fig. 4.2 Density of large pans (longest dimension greater than 0.5 km) per 1/16 ° quadrangle.

A second large area of high pan density occurs in the area to the south and east of Kule, centred on Ukwi pan. Further areas of high pan density can be found northwest of Tshane in the vicinity of Manyane pan, and northwest of Tshabong.

Fig. 4.2 shows the distribution of the large pans (longest dimension more than 0.5 km). Large pans occur in relatively small numbers, the maximum density recorded being 14 per 1/16 $^{\circ}$ quadrangle in the area northwest of Kule. They are then scattered at densities of 2 to 4 per 1/16 $^{\circ}$ quadrangle over most of the pan belt of the southern Kalahari. However there is an area where the density of large pans is more than 4 per 1/16 $^{\circ}$ quadrangle. This area stretches continuously from west of Khakhea to west of Tshane and, with a small break, on to the Kule - Ncojane area. It is within this belt, which lies along the axis of the watershed, that all the concentrations of large pans occur, and 6 1/16 $^{\circ}$ quadrangles record more than 8 large pans. Two of these areas are centred on Kokong, one to the west and another to the south east. Further areas of high density of large pans can be found in the vicinity of Manyane pan, northwest of Tshane; around Tshotswa pan west of Tshane; and in the Kule - Ncojane area.

Fig. 4.3 shows the distribution of the small pans (longest dimension less than 0.5 km). Pans of this size are by far the most numerous in the southern Kalahari, and occur widely. They are concentrated into a number of areas in which density reaches more than 20 per 1/16 $^{\circ}$ quadrangle. The most extensive of these occurs north of Tshabong, spanning the track to Tshane. Other more restricted areas of small pans occur in the Motokuse area; southwest of Kokong in the neighbourhood of Mahulitlhake, southwest of Tshane and east of Kule.

Extensive areas of a moderate density, 8 to 16 pans per 1/16 $^{\circ}$ quadrangle, occur in the area between Kokong and Tshane, and in the Manyane pan area north of Tshane.

From the above it is clear that the pans of the southern Kalahari occupy a well defined belt up to 300 km wide, that stretches from Sekoma to the Namibian (South West African) border in the Kule - Ncojane area.

The form of this belt corresponds closely to that of the watershed, which narrows to the east and west from its maximum width at about 22°E. Within this belt there are notable concentrations of pans, particularly in the area between Kokong, Tshane and Mabuasehube. Further, smaller concentrations can be found in the Kule - Ncojane area; in the vicinity of Manyane pan north of Tshane; and in an area northwest of Tshabong.

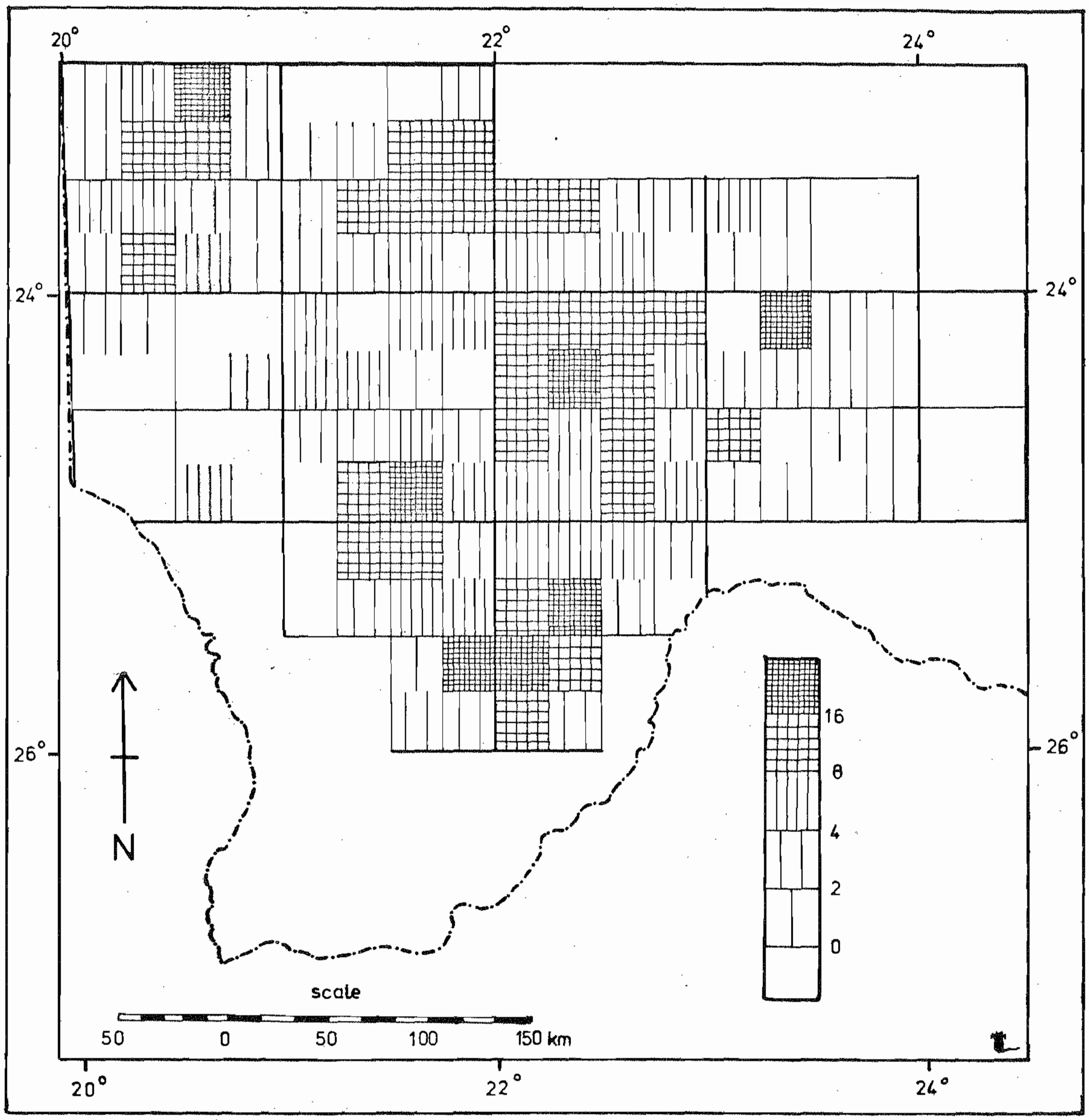


Fig. 4.3 Density of small pans (longest dimension less than 0.5 km) per 1/16 ° quadrangle.

The difference between the distributions of small and large pans appears to be slight. Concentrations of small pans are, with one exception, generally found in areas that contain concentrations of larger pans. The exception is the area immediately north of Tshabong, which contains a notable concentration of small pans.

SPATIAL ANALYSIS OF THE DISTRIBUTION OF SOUTHERN KALAHARI PANS.

For the purposes of this analysis the pans of the southern Kalahari may be considered as a set of points distributed in space.

In view of the large numbers of pans in the southern Kalahari and the wide area over which they are distributed, it was decided to use quadrat methods, despite their limitations, rather than nearest neighbour methods, for analysis of the distribution. Few applications of quadrat methods have been made to problems in geomorphology, although the technique is well established in plant ecology (Grieg Smith 1964) and human geography (King 1969). Most of the geomorphological applications have been in the field of karst morphology, that of McConnel and Horn (1972) being the most applicable to the present problem. The only application of quadrat techniques to arid lands geomorphology known to the writer is Goudie (1970).

Quadrat analysis is a technique for evaluating the arrangement of points in an area, or on a map, that has been partitioned into quadrats, or small subdivisions, and to test the statistical distribution of these points against one or more distribution functions.

Thus a distribution may be identified as random; more regular than random, or more clustered than random. With a random distribution the quadrat mean frequency will be equal to its variance. Thus a more regular than random distribution will have a variance smaller than the mean, and a more clustered than random distribution a variance larger than the mean. In a random distribution of points over a plane, in which any point has an equal probability of occuring at any position, and small subdivisions (or quadrats) have an equal chance of containing a point, the position of any point is in no way influenced by the position of any other point.

A non random distribution is taken to indicate that the points are not mutually independent and that the position of one point is determined by the position of others. This may be a contagious distribution, involving the spread of a phenomenon. In addition certain randomly distributed areas may have more favourable conditions for the existence and development of the phenomena, thus leading to clustering.

In the case of the southern Kalahari we can postulate three hypotheses:

1. The distribution of pans is random.
2. The distribution of pans is clustered to some degree, reflecting either a situation wherby some areas are especially favourable to pan formation; or one in which the pans are linked to each other in some way, perhaps as locally connected drainage systems; or in which the distribution is of randomly distributed clumps in areas favourable to pan formation.
3. The distribution of pans is clustered, as the result of two mutually independant random processes: the creation of conditions favouring pan formation; and the effectiveness of the processes themselves.

A fourth condition of regularity could be postulated, but since the sample variance is larger than the mean, the distribution of pans in the southern Kalahari must tend to be more clustered than regular.

Acceptance or rejection of the hypotheses described above can be made on the basis of whether the distribution is most adequately described by the Poisson, Negative Binomial or Mixed Poisson models respectively.

The Probability Models

If a randomly distributed set of points is sampled by quadrats, then the expected number of points per quadrat (p) is given by the Poisson Series:

$$p = n/Q$$

where n = the number of points and Q is the number of quadrats. Thus the probability that a quadrat contains exactly x points is given by:

$$p(x) = p^x e^{-p}/x!$$

where p = the mean of the observed distribution.
The Poisson model describes a distribution in which points are distributed as a result of a single random process.

Two models for clustered distributions can be put forward. The first is the Negative Binomial, in which the number of points in any quadrat is variable, based on the number of points in any other quadrat.

The probability of a quadrat containing x points is given by:

$$p(x) = \left(\frac{k + x - 1}{k - 1}\right) p^k q^x$$

Where p, a measure of randomness, is given by $\bar{x}/v$, and k, a measure of clustering, is given by $\bar{x}^2/(v - \bar{x})$.

The Negative Binomial model describes situations in which the distribution of points is random, but the density varies over space in response to more favourable conditions in some areas; there are randomly distributed clumps of points; and initially random distribution of points generates further points in close proximity at a logarithmic rate.

A further model is the Mixed Poisson, in which distribution of points is the result of two independant random processes.

The probability of a quadrat containing x points is given by:

$$p(x) = k_1\left(\frac{e^{-Y_1} Y_1^x}{x!}\right) + k_2\left(\frac{e^{-Y_2} Y_2^x}{x!}\right)$$

in which k_1 and k_2 are the probabilities that a point is located as a result of first or second processes, and Y_1 and Y_2 are the parameters for the first and second distributions respectively.

The Mixed Poisson model is appropriate in a situation where the distribution of points is random but is affected by locally favourable conditions randomly distributed.

The expected number of points per quadrat was generated for each of the above distributions using a BASIC programme, written by the writer, and run on the Hewlett Packard HP 9800 Series calculator of the University of Malawi.

The theoretical frequencies were compared to the observed for goodness of fit by the Chi squared one sample test:

$$\chi^2 = \frac{(o - E)^2}{n}$$

Where o = observed frequency in each class, and E = expected or theoretical frequency.

The null hypothesis, that the difference between observed and theoretical frequencies is due to chance, was accepted or rejected at the 0.05 level of significance.

The Statistical Analysis

In seeking an appropriate sampling design, the choice of an appropriate quadrat size presents considerable difficulty, as Grieg Smith (1964) has indicated. There seem to be no satisfactory rules to apply, except that the size of quadrat should be larger than the possible clusters of points, and yet small enough to make the probability of it containing points small. In view of the above, choice of an arbitrary quadrat size does not seem inappropriate, and so a 10 km x 10 km quadrat was chosen.

Placement of the quadrats was achieved by use of the stratified systematic unaligned sampling procedure, described by Berry (1962). By this method, a quadrat was placed in each of the 141 $1/16^{\circ}$ quadrangles in the southern Kalahari study area.

Table 4.1 shows the observed frequencies of pans per quadrat.

Table 4.1

Observed frequencies of pans per quadrat.

No. of pans per quadrat x	Quadrats F(o)
0	74
1	22
2	23
3	13
4	5
5	2
6	1
7	0
8	0
9	0
10	1

M = 1.08. V = 2.36. D = 2.17.

As can be seen from table 4.1, the variance mean ratio for the distribution of pans in the southern Kalahari is larger than one, indicating a clustered distribution.

Not surprisingly the Poisson model did not prove a good fit to the observed distribution. Comparison of the observed and Poisson distributions yielded a χ^2 value of 45.18 indicating rejection of the null hypothesis that the pans are randomly distributed at the 0.05 and also the 0.01 level of significance.

Table 4.2

Results of statistical analysis of pan distribution

No. of pans/ quadrat	Observed Frequency (o)	Expected Frequency (e) Poisson	Negative Bionomial	Mixed Poisson
0	74	48	69	66
1	22	52	34	41
2	23	28	18	15
3	13	10	9	7
4	5)			
5	2)			
6	1)			
7	0 (9	3	11	11
8	0)			
9	0)			
10	1)			

Degrees of freedom = 4

	Poisson	Negative Bionomial	Mixed Poisson
χ^2 =	45.18	6.04	19.25

The Mixed Poisson model proved to be a poor fit to the observed distribution, as can be seen in table 4.2, yielding a χ^2 value of 19.25, indicating rejection of the null hypothesis at the 0.05 and also the 0.01 level of significance.

Although the Mixed Poisson model of two random processes is conceptually plausible, the model is statistically untenable and considerably underestimates the number of points per quadrat at the lower end of the distribution.

The Negative Bionomial model gave the most satisfactory fit to the observed distribution, and underestimated the lower end of the distribution only slightly. Comparison of the expected and observed distribution yielded a χ^2 value of 6.04 indicating acceptance of the null hypothesis at the 0.05 level of significance.

DISCUSSION

The mapped distribution of pans indicates that they are found in a belt up to 300 km wide in the watershed area between Sekoma and Kule. The form of the belt corresponds closely to that of the watershed. Within the belt notable concentrations of pans exist in the area between Tshane, Kokong and Mabuasehube and in the Kule - Ncojane area.

Analysis of the distribution of the pans by quadrat methods indicates that it is strongly clustered and is best described by the Negative Binomial model. In view of this, three conceptual models may be put forward to explain the distribution:

1. An initially random distribution of points generates further points at a logarithmic rate.
2. The distribution consists of random clusters of points.
3. The distribution of points is random, but the density of points varies over space as a response to variations in conditions favouring their location.

It seems unlikely that model 1. is appropriate. There is no evidence to suggest that the formation of a lake basin leads to the formation of other basins nearby as a contagious process. On the contrary, it is more probable that the existence of a basin will tend to concentration of drainage leading to its enlargement, rather than to the creation of further basins. Only when more than one period of basin formation takes place are new basins initiated (Reeves and Parry 1969), the location of which appears to have no relation to already existing basins.

The second model appears at first sight to be acceptable. Inspection of the print lay downs and ERTS imagery of the southern Kalahari shows the pans to be arranged in small clusters of 4 or 5 pans, with other pans scattered at random. However, when looked at at the regional scale, it will be seen that these loose clusters are in themselves clustered. This indicates that model three is the most acceptable explanation of the distribution of the southern Kalahari pans, in which the pans are distributed randomly throughout the region, but their density varies, giving rise to a clustered distribution.

Two hypotheses may be put forward to explain the regional variations in conditions favouring pan formation. Firstly, the pans may be distributed in belts which can be related to the existence of ancient drainage lines and divides (Boocock and Van Straten 1962). Secondly, the evidence of the shape of the pan depressions and the presence of fringing dunes suggests that deflation has played an important role in pan formation. Consequently the location of the pans will reflect the existence of conditions favouring deflation.

There is little evidence available to support the first hypothesis. The form of the clusters of pans is in no way linear and there is no evidence to suggest that the pans of the southern Kalahari form aligned groupings. In addition there are no signs of drainage lines on the ERTS imagery or aerial photography of the southern Kalahari, save for the few north bank tributaries of the Molopo river and some small tributaries of the Okwa and Mmone dry rivers on the northern margins of the study area. No pans can be seen to have any links with these drainage lines. All the river systems that have been recognised in other parts of the Kalahari in Botswana possess well marked valleys, and are easily recognisable on aerial photographs. If such drainage lines did exist in the southern Kalahari, then it would be reasonable to expect them to be visible. In any event organised drainage networks would be unlikely to occur in a watershed area of such wide extent and low relief. A further point of interest is that most, if not all, the river systems in the Kalahari have their sources in areas without a mantle of Kalahari sands. This would suggest that even under conditions of greatly increased precipitation, runoff would have been insufficient to sustain organised drainage systems over much of the Kalahari.

The conditions favouring deflation and the creation of deflation hollows, or blowouts, have been summarised by Melton (1940) and Hack (1941) and include a sub arid climate giving rise to a sparse vegetation cover; unconsolidated, preferably sandy, surface deposits and strong unidirectional winds. Specifically, the existence of deflation hollows is influenced by the existence of bare areas caused by a locally high water table, a local accumulation of water after rainy periods, or by the trampling of game animals.

The southern Kalahari undoubtedly possesses many of the environmental conditions favouring the creation of deflation basins. The surface deposits are unconsolidated Kalahari sands, over which strong winds of constant direction blow. With a slight decrease in present rainfall, vegetation cover would probably decrease sufficiently to give rise to ideal conditions for deflation.

However, the localisation of such basins to a belt along the Nossop - Molopo - Makgadikgadi watershed, and concentration of pans within this belt is more difficult to account for.

Despite the comments of Passarge (1911) and Flint and Bond (1968) the actions of animals cannot be seriously considered as the cause of the depressions containing the 1000 or so pans in the southern Kalahari.

The existence of locally high water tables appears to be more plausible. Glennie (1971) describes deflation hollows and sebkhas fed by groundwater seepage in interdunal areas in the Great Eastern Erg, Algeria. Similar features are described from Tunisia by Coque and Jauzein (1967). In these circumstances deflation is assisted by the creation of bare areas by the seepage of saline groundwater, but is hindered if the water table coincides with the base of the depression. Such a hypothesis appears to have limited application in the southern Kalahari. Over most of the area water tables are found at considerable depths and lie in the pre Kalahari rocks as the Kalahari Beds are a poor aquifer. Only in the Sekoma and Kule - Ncojane areas and at Kokong and Tshane do water tables occur near the surface. On this basis, it would be reasonable to expect concentrations of pans around those areas where pre Kalahari rocks, and thus water tables, are near the surface. However this is not the case, as only in the Kule - Ncojane area is there a large concentration of pans occurring under these circumstances. Elsewhere, in the Sekoma - Khakhea area and at Mabuasehube there are localised concentrations of pans only. In fact, the largest concentration of pans, between Kokong and Tshane, occurs in an area where pre Kalahari rocks are 25 to 50 m below the surface.

Locally, as at Khakhea and in the Sekoma, Tshane and Mabuasehube areas, seepage from groundwater bodies may have created bare areas and thus sites for deflation, but the hypothesis cannot satisfactorily explain the distribution of the southern Kalahari pans as a whole.

The hypothesis that the pans are located in depressions created by deflation from areas kept bare by seasonal accumulations of surface water appears to be more generally applicable. In the southern Kalahari today there are many slight undulations in the sand surface which are floored by greyish or bleached sands and have a relatively sparse vegetation cover. These areas appear to retain some water for a short period after rain. In a watershed area such as the southern Kalahari with a gently undulating surface and very slight regional gradients it is probable that all drainage would be to such areas of local water accumulation. Under conditions in which water persisted for long enough to prevent plant growth such areas would be bare and susceptible to deflation when the accumulated water had evaporated or seeped away.

Additional support for this hypothesis is contained in the following evidence. Grove (1969) noted "faint furrow patterns" on the print lay downs of the southern Kalahari curving round from a northeast - southwest direction north of Kutswe to north northeast - south southwest west of Kokong. Examination of ERTS 1 imagery for the southern Kalahari shows these furrow patterns to be more extensive than Grove thought, and they can be detected in all parts of the southern Kalahari, curving round from northeast - southwest to north - south and even northwest - southeast. They can be clearly seen to link up with the dunes along the Nossop river and in adjacent areas of South Africa and Namibia (South West Africa). The pattern clearly represents the degraded remnants of longitudinal dunes, corresponding to the anticlockwise swirl of dune forming winds around the South African anticyclone. Close examination of the ERTS 1 imagery reveals that pans are situated between these lineaments, rather in the manner of the pans in adjacent areas of Namibia (South West Africa) and South

Africa. This evidence suggests that most of the southern Kalahari pans were originally sited in the corridors between longitudinal dunes. Similar features of a probable deflation origin in interdunal corridors have been described by Flint and Bond (1968) from the Wankie National Park in Rhodesia, and from the Qoz region of Sudan by Warren (1970).

It is thus possible to suggest that the depressions containing the southern Kalahari pans were originally formed as a result of deflation from bare areas which were the sites of water accumulation after rains. The requirements of a sub arid or semi arid climate and a sparse vegetation cover to trap sand, are consistent with this explanation. In a situation in which the dune flanks and interdunal corridors were sparsely vegetated, sand movement and deflation would be localised. Funneling of winds through the corridors would also tend to increase the possibility of deflation in bare areas.

The deflation basins were thus created at the sites of local unorganised drainage systems. Such local drainage systems would in all probability be located at random but be more common along the watershed areas, leading to a concentration of pans there.

Locally, the existence of areas of water accumulation would be determined by undulations in the sand surface, leading to concentration of deflation sites at this scale.

CONCLUSIONS

This chapter has described the distribution of pans in the southern Kalahari. The pans lie in a belt up to 300 km wide along the watershed area between Kule and Sekoma. The width of the belt corresponds closely to that of the watershed. Within the belt of pans the greatest density of pans can be found in the centre of the region, between Kokong and Tshane, with minor concentrations of pans at Kule - Ncojane and northwest of Tshane.

Analysis of the distribution of the southern Kalahari pans by quadrat methods indicates that the distribution is clustered. Clustering occurs at two scales, regional and local, and is best described by a situation in which the distribution of pans is random, but the density of pans varies in response to existence of more favourable conditions in certain areas. Regional scale clustering is accounted for by the increased density of pans in the watershed area. Local scale clustering reflects concentration of drainage towards the centres of broad undulations in the sand surface.

The available evidence suggests that the majority of the pans of the southern Kalahari are contained in deflation depressions created by enlargement of blowouts, the location of which was influenced by local bare areas where seasonal runoff accumulated. It appears that many of the pans probably originated in the corridors between longitudinal dunes, now much degraded, where they formed local centres of drainage. Such unorganised drainage systems would be more common in the watershed areas, which is where the main concentration of pans is to be found. Locally, loose concentrations of pans may be related to broad undulations in the sand surface, concentrating runoff and seepage to a number of centres.

CHAPTER 5.

THE DUNE COMPLEXES

INTRODUCTION

On the southern side of most pans in the southern Kalahari there is an area of crescentic dunes, which rise to a height of up to 30 to 40 m above the pan floor, and extend up to 2 km from the edge of the pan. In most cases two main dune ridges may be identified, which are called the inner and outer dunes.

Previous investigators in the southern Kalahari have briefly noted the existence of the dunes adjacent to the pans, but have said little about their composition or formation. Wayland (1952) noted that sand dunes could be found on the south and southeast sides of pans, composed of material blown from the pan sites. Boocock and Van Straten (1962) noted that most pans had a well defined sand ridge on their south and southwest sides, formed in the case of clay pans by sand carried over the pan floor by the prevailing wind. Grove (1969) stated that dunes, which he compared to lunette dunes, could be found on the south, southeast and southwest sides of most pans.

The aims of this chapter are: to describe the morphology of the dune complexes; to describe the materials forming the dunes; and to put forward hypotheses to explain the origins and formation of the dune complexes.

MORPHOLOGY OF THE DUNE COMPLEXES

The main data sources for this section are the relevant air photography of the pans studied, supplemented by the writer's field observations, and the profiles levelled across many of the dune complexes. The latter, in addition to providing information about dune morphology also served to locate the points at which samples of dune forming material were collected.

General nature of the dune complexes

The topography of the dunes adjacent to southern Kalahari pans has been described in some detail in Chapter 3. Considerable variations in the shape, size and alignment of the dunes exist, but a number of general features may be picked out.

In all cases the dunes are located on the southern side of the pan. However, in some areas the dunes curve around the south and southwest side of the pan, and in others the dunes can be found on the south and southeast sides of the pan. The significance of these variations will be discussed below.

At most pans two dune ridges can be identified. These are termed the inner and outer dunes. The outer dunes can be recognised by their location at some distance from the pan edge; their red brown surface sand; and also by their relatively bare appearance, as they often only support a vegetation cover of grasses and small bushes. The inner dunes can be identified by their location between the pan edge and the outer dune; their grey brown surface sand; and often by their well vegetated appearance, with trees and shrubs up to 5 m high. In many cases the inner and outer dunes form two distinct ridges, separated by a well marked interdunal depression, but the inner dune may merge with the outer dune at one or more places. At a number of pans there is no distinct inner dune, and a single main dune ridge curves around the pan, with red brown sand on its crest and the side away from the pan, and grey brown sand on its panward side. This is the situation at many smaller pans, for example at Bee and Pussy pans, but may also be the case at somewhat larger pans, Sekoma and Kgama pans being the best examples.

However, there are a number of dune complexes that do not conform to the general pattern. At Ukwi and Urwi pans for example, three distinct dune ridges can be identified. In each case their character is different. At Urwi pan there is a massive outer dune of red brown sand, rising some 50 m above the pan datum. Between this and the pan edge are two well developed inner dunes. The innermost dune is a narrow crescentic ridge of grey brown sand, with a sparse grass cover. A narrow, but well defined depression separates it from the middle dune, composed of brown sand, and well vegetated with trees of _Acacia spp._.

At Ukwi the situation is rather different. On the pan edge is a small dune, some 4 m high, composed of very coarse pale sand. This dune appears to be currently receiving sand blown from the pan. Beyond this dune there is a depression, floored by pan surface material. On the far side of this there is a steady rise, to the crest of the main dune ridge of grey brown sand. The outer dune here is of brown to red brown sand and relatively small.

At Mpaathutlwa pan the inner dune is identifiable, but consists of a thin sand cover over an undulating area of massive calcrete. The form of this outcrop strongly suggests that it is the calcreted core of the inner dune, from which the upper parts have been removed to the panward face of the outer dune, which is covered by a spread of grey brown sand.

In a very small number of cases, as at Khakhea, there may be no dune ridge at all, and the dunes are represented by a hummocky accumulation of sand to the south of the pan.

As a general rule the outer is the larger of the two dunes, but occasionally this is not so, as at Kokong and Mashiaphotsana pans in Area 3 and at Ukwi and Nwatle pans in Area 5.

The outer dunes are without exception located on the lip of the pan depression. The inner dunes are located within the depression. There seems to be a general relationship between the size of the dunes and the size and depth of the pan depression, the nature of which is examined below.

The plan form of the dunes.

Although in detail a wide variety of dune forms may exist, two basic types may be recognised. They are the open parabolic or U shaped dunes and the crescentic dunes.

The outer dunes commonly have an open parabolic form, with a broad accumulation of sand at the apex of the parabola and two "horns" extending towards the pan. Three sub types can be recognised. In some cases the dunes are truly parabolic in shape, with a narrow ridge of sand forming two pronounced "horns" extending upwind towards the pan. Dunes of this type are found at Bee, Tatswe, Keng, Khesekwe, Mashiaphotsana and Dead Tree pans. The second sub type occurs when the apex of the parabola becomes infilled, forming a broad transverse crest to the dune, as with the outer dunes at Samane, Kokong, Bosobogolo, Mpaathutlwa and Mabuasehube pans. A further variation exists when the parabola becomes completely infilled by sand to become a transverse shield shaped sand accumulation, as with the outer dunes at Nwatle, Ukwi and Urwi pans.

At a number of pans the outer dune has a weakly crescentic form and consists of a broad transverse sand ridge. Examples of this type of dune occur at Samosadi, Sekoma, Kongwe and Masetleng pans.

The inner dunes commonly have a crescentic form (Plate 19) and curve around the southern sides of the pan. In many cases the inner dune is much less well defined and is much narrower than the outer dune. In many cases it appears that the form of the inner dune is determined by that of the outer dune.

At a number of pans the ideal shapes are distorted. At Samane, Keng and Nwatle pans the western arm of the outer dune is absent. This is the case with the eastern arm at Mashiaphotsana pan. At Khesekwe pan the western arms of the inner and outer dunes merge. Composite forms are relatively rare, although many intermediate shapes can be recognised. The best example of a composite development of dunes is at Masetleng, where the outer dune consists of a shield shaped sand accumulation with an eastern crescentic extension.

Reference to the maps accompanying Chapter 3 will show that there is a general relationship between the shape of the depression containing the pan and some aspects of the dune shape. It would appear that dunes with a strong parabolic form are associated with depressions that are significantly elongated in a north - south direction, as is the case at Bee, Mashiaphotsana, Bosobogolo, Mabuasehube and Nwatle pans. Where there is little elongation of the depression in a north - south direction, and the depression is more nearly circular, or elongated in an east - west direction, the dunes tend towards a weakly crescentic form, as at Samosadi, Mogatse and Masetleng pans.

<u>The dune profiles,</u>

Profiles were levelled across the dunes adjacent to sixteen of the pans studied in detail. They show the cross sectional form of the dune complexes.

Plate 19. Motsobonye pan: view from eastern arm of inner dune to show crescentic form of dunes at this pan.

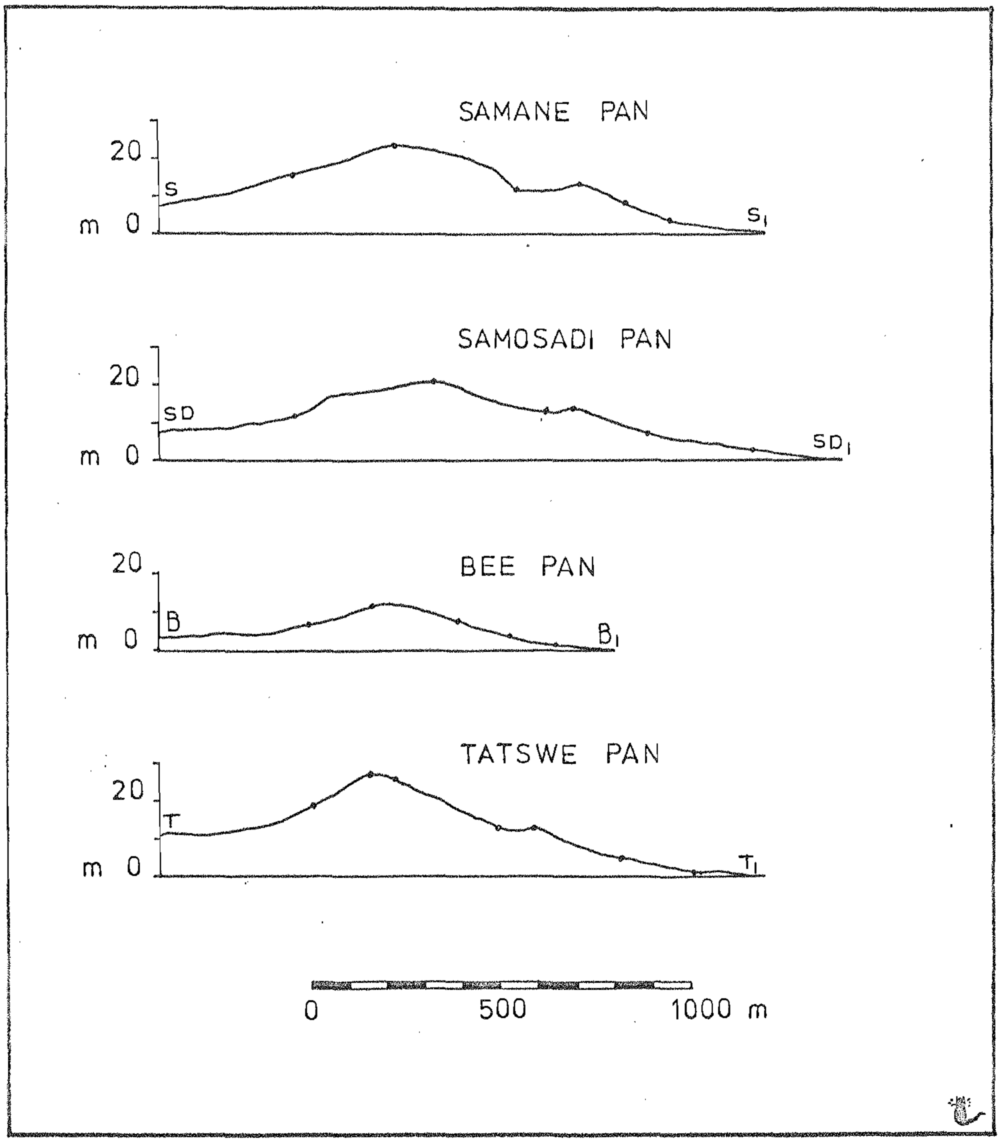


Fig. 5.1 Dune profiles, area 1.

Vertical exaggeration x 10. Points indicate position of samples taken. For profile locations see Fig. 3.4,

The profiles (Figs. 5.1 to 5.5) show clearly that the majority of dune complexes consist of a large outer dune, with a much smaller inner dune superimposed on its panward slope.

The crests of the inner and outer dunes are separated by an interdunal depression of varying width and depth, although in a number of cases the inner and outer dunes merge completely and form a single massive dune ridge.

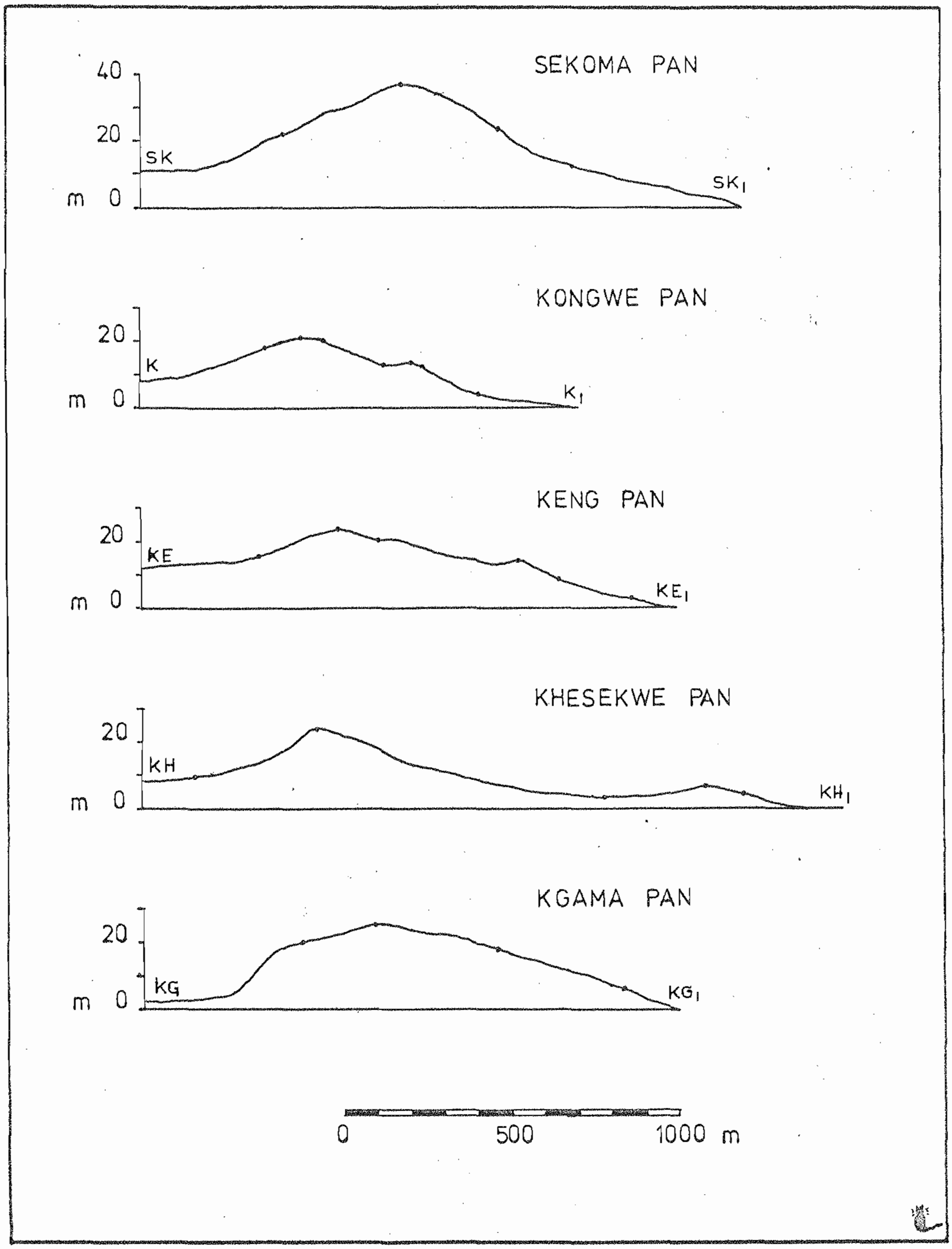


Fig. 5.2 Dune profiles, area 2.

Vertical exaggeration x 10. Points indicate position of samples taken. For profile locations see Figs. 3.6 and 3.7.

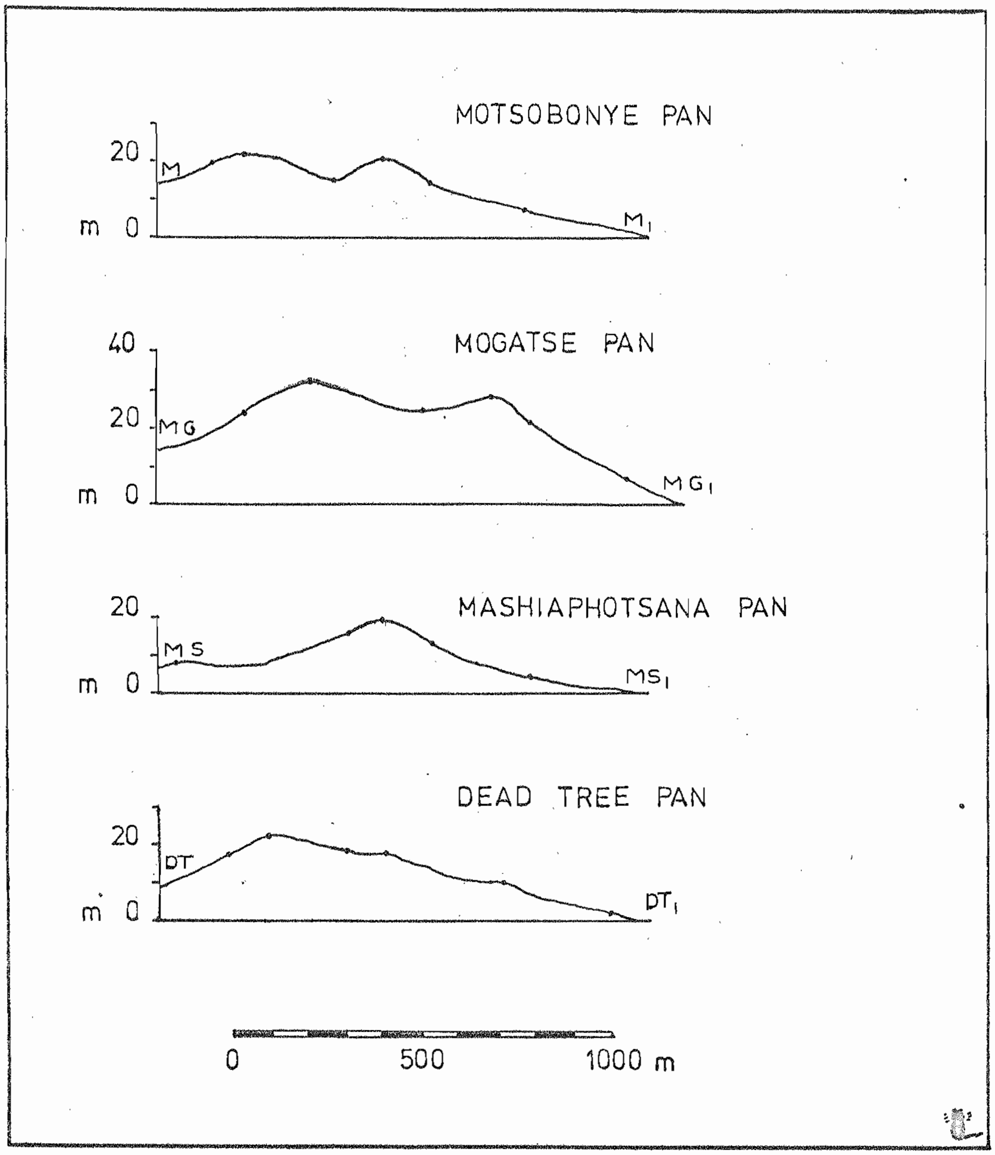


Fig. 5.3 Dune profiles, area 3.

Vertical exaggeration x 10. Points show position of samples taken. For profile locations see Figs. 3.9 and 3.10.

The outer dune generally forms the main part of the dune complex, but a considerable range of sizes exists. The largest dune encountered, but not levelled over, was at Urwi, where the outermost dune rises to some 50 m above pan datum, 2.5 km from the pan edge. The largest dune levelled over was at Mpaathutlwa (Fig. 5.4), rising to 47 m above the pan datum. Other large dunes were encountered at Sekoma (Fig. 5.2), Mogatse (Fig. 5.3),

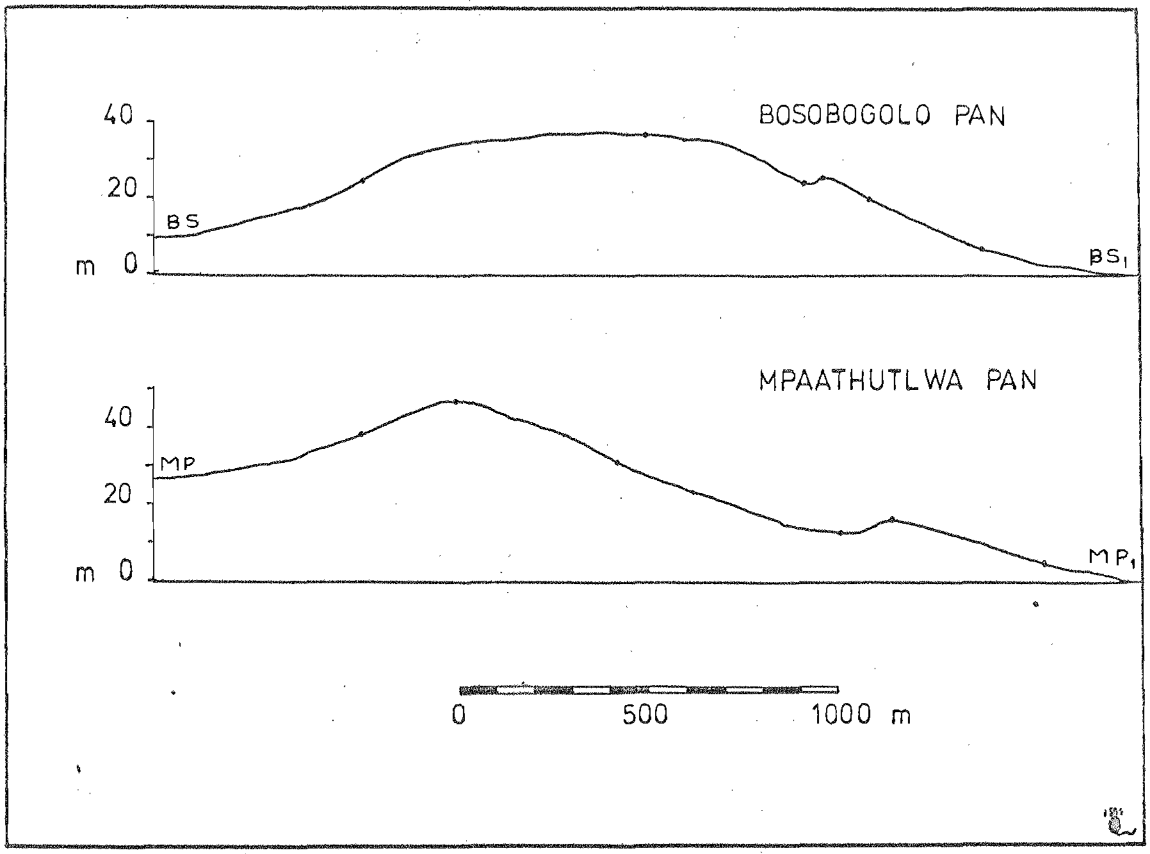


Fig. 5.4 Dune profiles, area 4.

Vertical exaggeration x 10. Points show position of samples taken. For profile locations see Figs. 3.12 and 3.13.

Bosobogolo (Fig. 5.4) and Masetleng (Fig. 5.5) pans. Very small outer dunes are usually associated with the smaller pans, such as Bee and Pussy (Figs. 5.1 and 5.5), with the dunes rising to 12 to 14 m above pan datum. In general, outer dunes rise to heights of 20 to 30 m above pan datum, with their crest lines lying 1 to 1.5 km from the pan edge.

The inner dunes lie on the panward slopes of the outer dunes. Consequently, although their crest lines may lie at some altitude above the pan datum their bulk, as the profiles clearly show, is in the majority of cases small; and they may be rather poorly defined. Inner dunes of some size do exist and are encountered at Khesekwe, Kokong, Motsobonye, Mogatse,

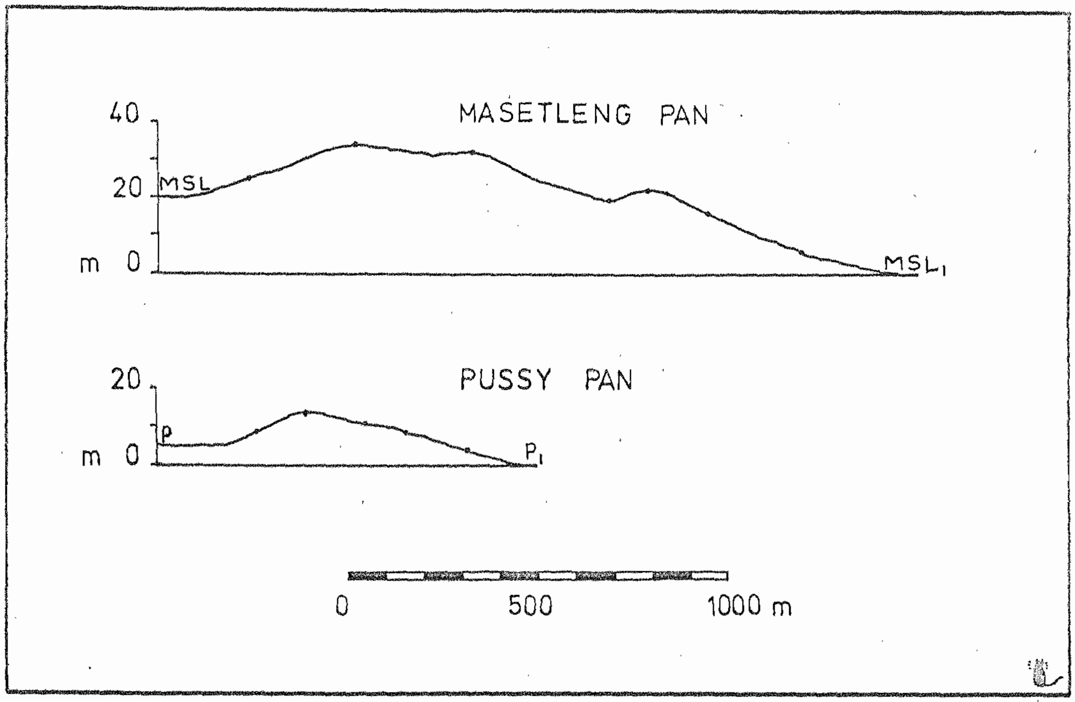


Fig. 5.5 Dune profiles, area 5.

Vertical exaggeration x 10. Points show position of samples taken. For profile locations see Fig. 3.15.

Mashiaphotsana, Masetleng, Nwatle and Ukwi pans. At Nwatle and Ukwi pans they are larger than the outer dunes and form the main part of the dune complex.

The inner and outer dunes are separated by a depression of varying width. The widest encountered was at Khesekwe, where the inner and outer dune crests are 1200 m apart. Generally inner and outer dune crests are separated by some 400 to 500 m.

The profiles of both inner and outer dunes are commonly asymmetric, with steeper slopes being found on the side away from the pan. Slope angles are generally low. Commonly the far slopes of the outer dune have angles of 1.5 to 3 °, and the panward slopes angles of 1 to 2 °. Slopes of the inner dunes are more varied. In some cases their asymmetry is more marked than that of the outer dune, and the slopes away from the pan may vary between 1 and 3.5 to 4 °, but exceptionally may be 5 to 6 ° as at

Khesokwe and Masetleng. Slopes on the panward side of the inner dune are generally 1 to 1.5 ^{o}, locally steepening towards the crest of the dune to 3 to 4 ^{o}.

The slopes of both inner and outer dunes are generally smooth or gently undulating. Gullying of the slopes is rare and takes place only where the vegetation has been removed along game trails or cattle tracks. Except at Kongwe pan, where gullies up to 2 m deep and 3 m wide were noted, their depth seldom exceeds 20 cm.

Alignment of the dunes

The alignments of both inner and outer dunes show that they were formed by winds from a northerly direction.

Some difficulty exists in making precise measurements of the alignments of crescentic dunes. The method adopted is that of Bowler (1970), in which a line was drawn to join the "horns" of the dune. The alignment of the dunes is measured by the orthogonal bisector of this line. The accuracy of this method depends upon the precision with which the dunes have been defined upon the air photographs, which may present some difficulties, particularly with the inner dunes.

The alignments of inner and outer dunes were measured in this way for all pans studied. The results are presented in Table 5.1 and Figs. 5.6 and 5.7.

Table 5.1

Mean dune alignments.

Area	Outer dunes	Inner dunes
1	11 ^{o}	27 ^{o}
2	13 ^{o}	16 ^{o}
3	20 ^{o}	20 ^{o}
4	344 ^{o}	353 ^{o}
5	12 ^{o}	347 ^{o}

Table 5.1 shows that there are differences in dune alignments, both between areas and between inner and outer dunes. In order to

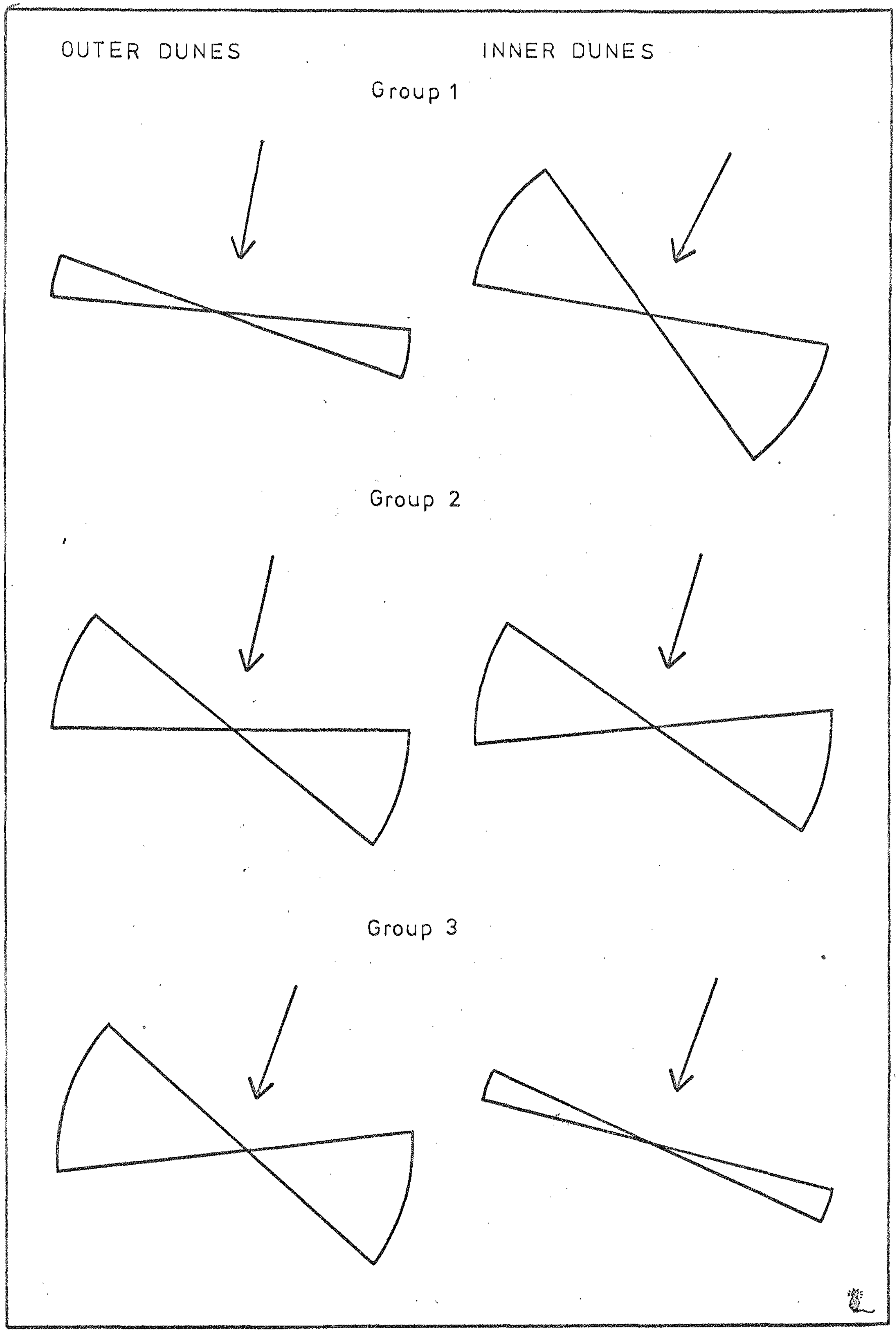


Fig. 5.6 Dune alignments, areas 1, 2 and 3.

Arrows indicate mean dune forming wind direction.

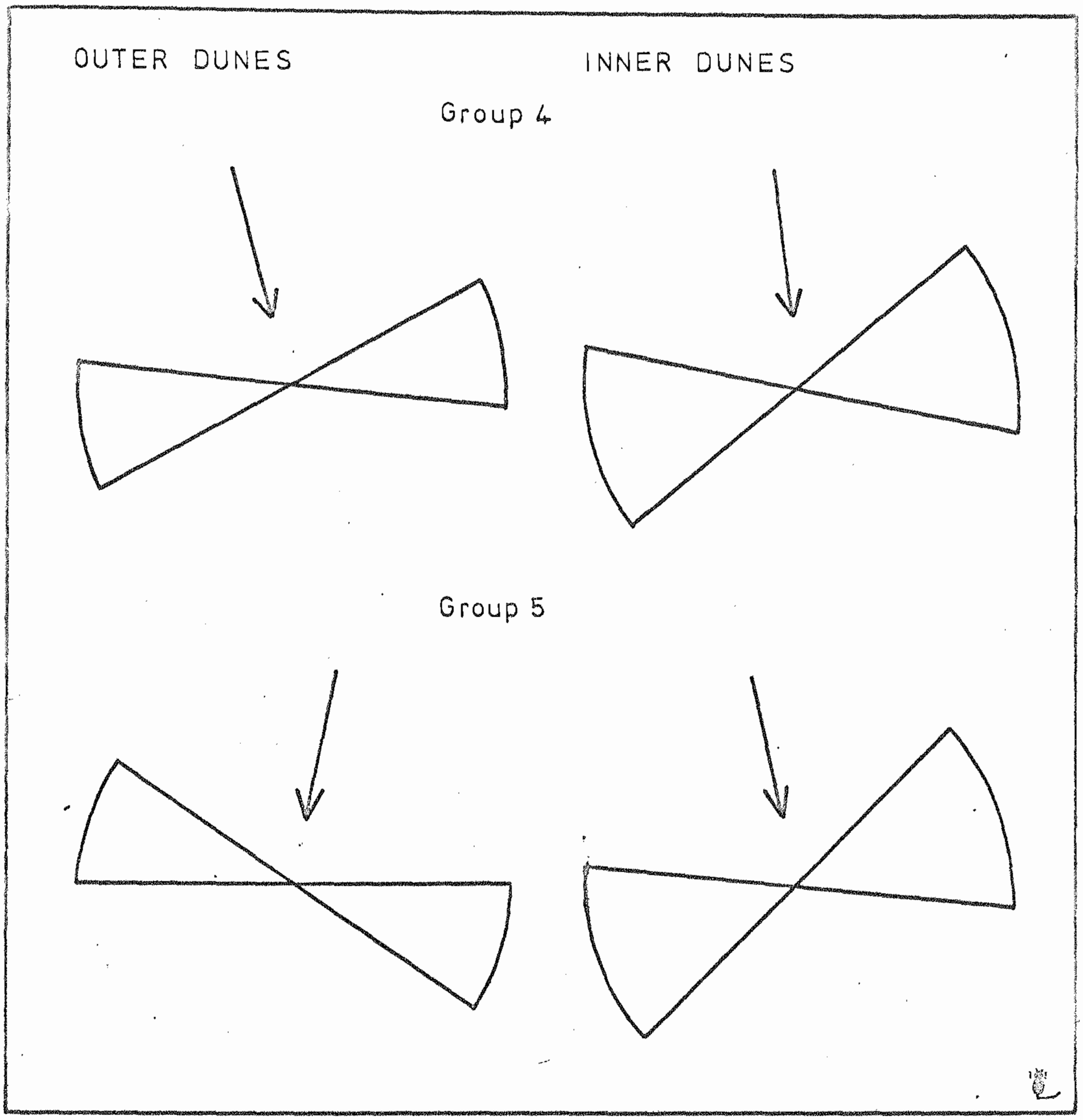


Fig. 5.7 Dune alignments, areas 4 and 5.

Arrows indicate mean dune forming wind direction.

determine the nature of the variability and to test for statistically significant differences in alignments between areas and between inner and outer dunes a two way analysis of variance was performed on the data.

The results of the analysis of variance show that there is a highly significant difference in the alignments of the dunes between areas, but that there is no significant difference in alignments between inner and outer dunes. In addition there is a moderately significant (at the 10 % level) interaction effect, which indicates that the differences in the alignments of inner and outer dunes, although not significant as a whole, are significant in each area, and the magnitude of the difference varies from area to area.

It can thus be stated that statistically significant differences in the alignments of inner and outer dunes exist at a regional level, but that there is no overall significant difference in the alignments of inner and outer dunes.

Regionally, the mean alignments of the outer dunes change from just east of north (011 to 013 °) in areas 1, 2 and 5; to well east of north (020 °) in area 3; and to west of north in area 4. The mean inner dune alignments alter from 16 to 20 ° east of north in areas 1, 2 and 3 to west of north in areas 4 and 5 (347 to 353 °).

The differences in alignment of inner and outer dunes are not statistically significant. They are largest in areas 1 and 5, but the change is not the same in each case. In area 1 the change is towards the east, whilst in area 5 there is a strong shift to the west.

The regional changes in dune alignment are consistent with the current regional change in wind directions within the southern Kalahari, which corresponds to the swirl of winds around the southern African anticyclone in winter. Comparison of dune alignments to the present day winds is hampered by lack of data. Data is available for only three stations within and around the region, Ghanzi, Tshane and Tshabong. Of these, only Tshabong has data for wind speeds as well as directions. Unfortunately, the sheltered site of the station at Tshabong make its data unrepresentative. The percentage frequency of winds from each direction is presented in Fig. 2.6. It can be seen that in the northern part of the southern Kalahari the winds are dominantly from the east and northeast. At Tshane, in the centre of the region, winds are mainly from the north and west. Personal observations suggest that the strongest winds occur in August, at the end of the dry season, and are dominantly northerly in direction.

It would appear that the dunes adjacent to the southern Kalahari pans were formed under a wind regime not unlike that of today. There appears to have been a slight difference in the pattern of wind between the two periods, which was most marked on the edges of the region, particularly in the west of the southern Kalahari.

Relationship of the dunes to the pan depressions.

During the course of the field work in the southern Kalahari it became apparent that a general relationship existed between the size of the dune complex and the size of the pan. Thus the highest and most extensive dunes were located at large and deep pan depressions like Urwi, Mpaathutlwa and Sekoma, whilst small single dune ridges could be found at small pans like Bee and Pussy.

In the absence of contour maps of the pans, no precise estimates of the relative volume of dunes and pan depressions can be made. However, examination of aerial photographs of the pans indicates that, in the majority of cases, the volume of the dunes is approximately equal to that of the pan depression, with some notable exceptions. At Khakhea, no dune complex as found elsewhere exists. In the case of Kgama, Motsobonye and Ukwi pans the bulk of the dunes is small in comparison to the size and depth of the pan depression.

Measures of the height of the outer dune above pan datum, pan depression depth and pan depression area may be used to give an indication of the relationship between the size of the dune complexes and the size and depth of the pan depression. Fig. 5.7 indicates that there is a good correlation between dune height and pan depression depth ($r^2 = 0.90$). A similarly close relationship exists ($r^2 = 0.86$) between dune height and pan depression area.

These relationships indicate that the availability of dune forming material is related to depression size and suggests that the dunes were formed by material deflated from the pan depression.

COMPOSITION OF THE DUNES

The composition of the inner and outer dunes is distinctly different. The outer dune is composed of fine, moderately sorted red brown sand. The material forming the inner dune is grey brown in colour, poorly sorted and consists of quartz sand and up to 25 % silt and clay sized particles.

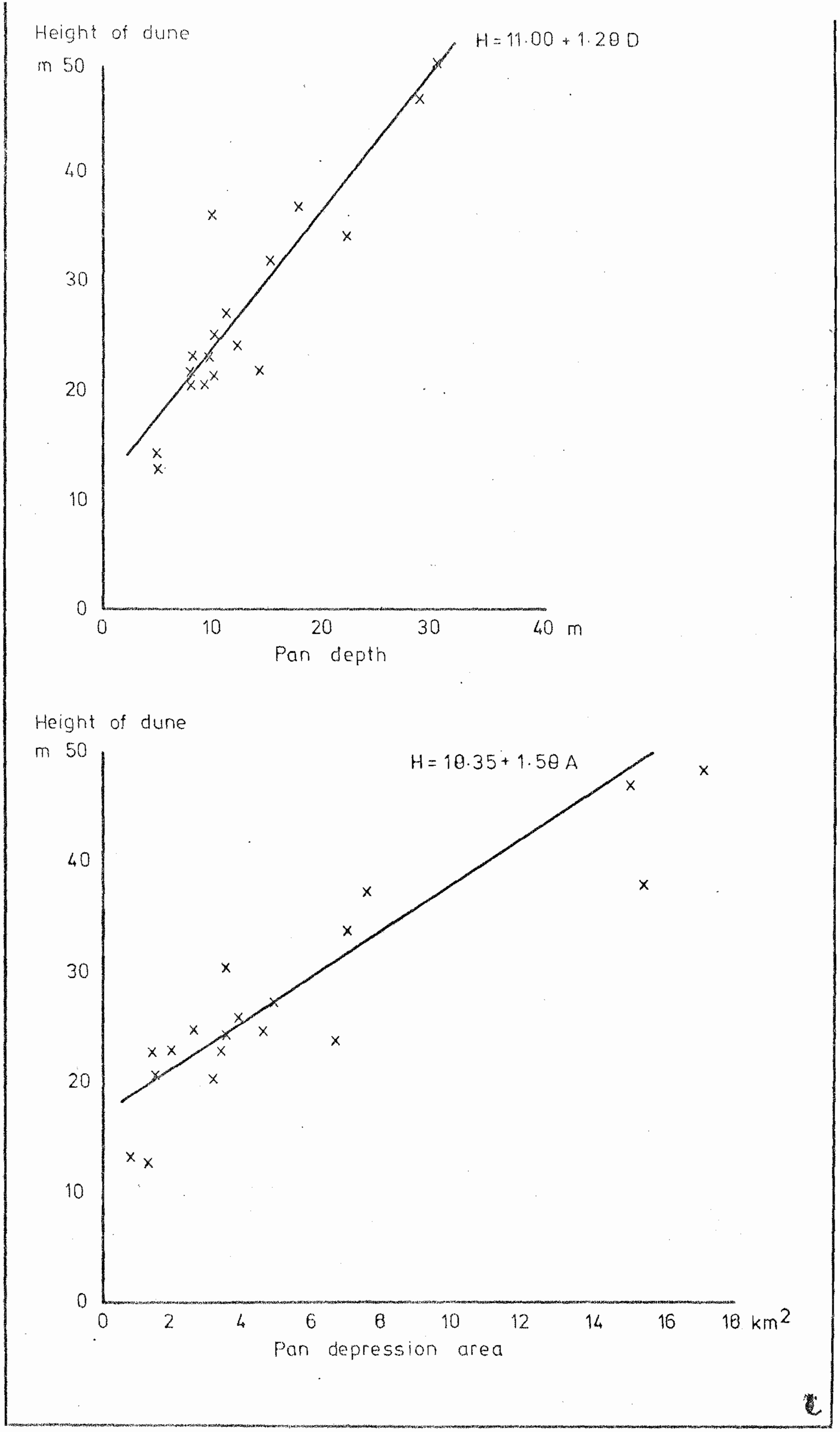


Fig. 5.8. Relationship of dune height to pan depression depth and area.

METHODS OF ANALYSIS

Samples of the dune forming material were taken at depths of 50 cm at intervals along the profiles levelled across the dune complexes, as follows:

Outer dune: crest
outer slope
Interdunal depression.
Inner dune: crest
two samples on panward slope.

Additional samples on panward slopes of outer dune and leeward slopes of inner dunes were taken as circumstances suggested. The location of sampling points is shown on the profiles (Figs. 5.1. to 5.5).

Particle size analysis

Outer dune samples were oven dried as necessary. A sub sample of 100 gms was then placed in a nest of sieves of mesh sizes 0 to 4 phi (1 to 0.063 mm), and shaken in a mechanical shaker for five minutes. It was found necessary to disperse the inner dune samples as they contained a significant proportion of silt and clay sized material. The sub samples of 100 gms were soaked overnight in a 5 % solution of Calgon (sodium hexametaphosphate). Following soaking, the samples were stirred in a mechanical analysis stirrer for five minutes, and then washed through a 4 phi sieve. The residue was oven dried and weighed. The weight loss compared to the original sample weight was taken as the silt and clay content of the sample. Following this the sand was dry sieved as described above.

Computation of sorting and size parameters (phi mean, standard deviation, skewness and kurtosis) was carried out following the method of moments, using a BASIC programme compiled by the writer. These parameters, although mathematically independent, are geologically interrelated and can be used to distinguish between environments of transport and deposition. The full results of the particle size analyses are presented in Appendix 2, and the computer programme in Appendix 3.

Chemical analysis

Approximate measures of the amount of calcium carbonate in inner dune samples were obtained by methods outlined in Black (1965). A 10 gm sub sample of inner dune material was added slowly to an Erlenmeyer flask containing 10 cc of 0.3N HCl, and allowed to stand with occasional swirling for 2 hours, or until the reaction was completed. The weight loss, expressed as a percentage of the original sample weight, is taken as an approximation of the calcium carbonate content of the sample.

$$CaCo_3 \text{content } \% = \frac{\text{weight loss}}{\text{initial weight of sample}} \times 100 \times 2.274$$

Colours were determined using a Munsell Soil Color Chart (Munsell Color Company Inc., 1954).

THE OUTER DUNES

The outer dunes are composed of fine, moderately sorted, unimodal reddish brown or reddish yellow quartz sand.

Despite their having been collected from points up to 500 km apart, the composition of the outer dune samples show a surprising degree of similarity.

Particle size distribution

Following sieving, phi mean grain size, standard deviation, skewness and kurtosis were computed for each sample. The full results are presented in Appendix 2, and as scatter plots in Figs. 5.9 to 5.12.

In addition the cumulative percentage of each sample finer than the standard sieve meshes was plotted. The results are presented in Figs. 5.13 to 5.15. and in Appendix 2.

The mean grain size of most outer dune sands ranges between 2.30 and 2.50 phi. The sands may thus be considered as fine sand. Within each group of pans studied the differences in mean grain size are small. Samples in areas 1 and 3 show little variability with mean grain sizes between 2.36 and 2.40 phi, and 2.32 and 2.45 phi respectively.

However, in area 2 there is more variation, with the sands being somewhat finer at Sekoma and Kgama, with mean grain sizes between 2.49 and 2.53 phi, perhaps reflecting local differences in the source of sand supply. At Bosobogolo and Mpaathutlwa pans in the Mabuasehube area the sands are somewhat coarser, with mean grain sizes in the range 2.25 to 2.37 phi. This may reflect proximity to sand sources in the Dwyka tillites and Waterberg sandstones that outcrop in the area. In area 5 there is a greater degree of variability, reflecting the greater geographical spread of the samples. Mean grain sizes are slightly coarser than in other areas, lying in the range 2.30 to 2.39 phi. Samples from the dunes at Urwi appear still coarser, in the range 2.25 to 2.33 phi.

The phi standard deviations are a good measure of the sorting of the sands. Little variation exists in the sorting of the sands and all can be regarded as moderately sorted, with phi standard deviations between 0.71 and 0.90. Samples for individual dunes have very similar sorting values.

Values for phi skewness indicate that all outer dune sands are strongly positively, or fine, skewed, with values of 0.30 to 1.00 phi. Strong fine skewness is a characteristic of aeolian sands, which have little or no material in the coarser fractions and a "tail" of finer material.

Phi kurtosis values are a measure of the ratio of sorting in the centre and tails of the distribution. All outer dune sands are very or extremely leptokurtic, with phi kurtosis values of 2.72 to 3.80, which indicate a high degree of sorting in the peak of the size distribution curve, a common feature of aeolian sands. Two groups of kurtosis values may be distinguished in Figs. 5.11 and 5.12, those above 3.4 phi and those below 3.2 phi. The higher kurtosis values are common to all outer dunes in areas 4 and 5, and to Samane, Khesekwe, Kgama and Keng pans in areas 1 and 2. It would appear that these high values all occur at pans where the outer dune crest lies at some distance from the pan edge. A greater amount of sand movement is reflected in increased sorting between the centre and "tail" of the distribution curve.

The particle size distribution curves, Figs. 5.14 to 5.16, are typical of aeolian sands, and show little variability. They demonstrate that few samples contain significant amounts of material larger than 1 phi, or smaller than 4 phi. The exceptions appear to be at Bosobogolo and Mpaathutlwa pans, where samples have up to 4 %

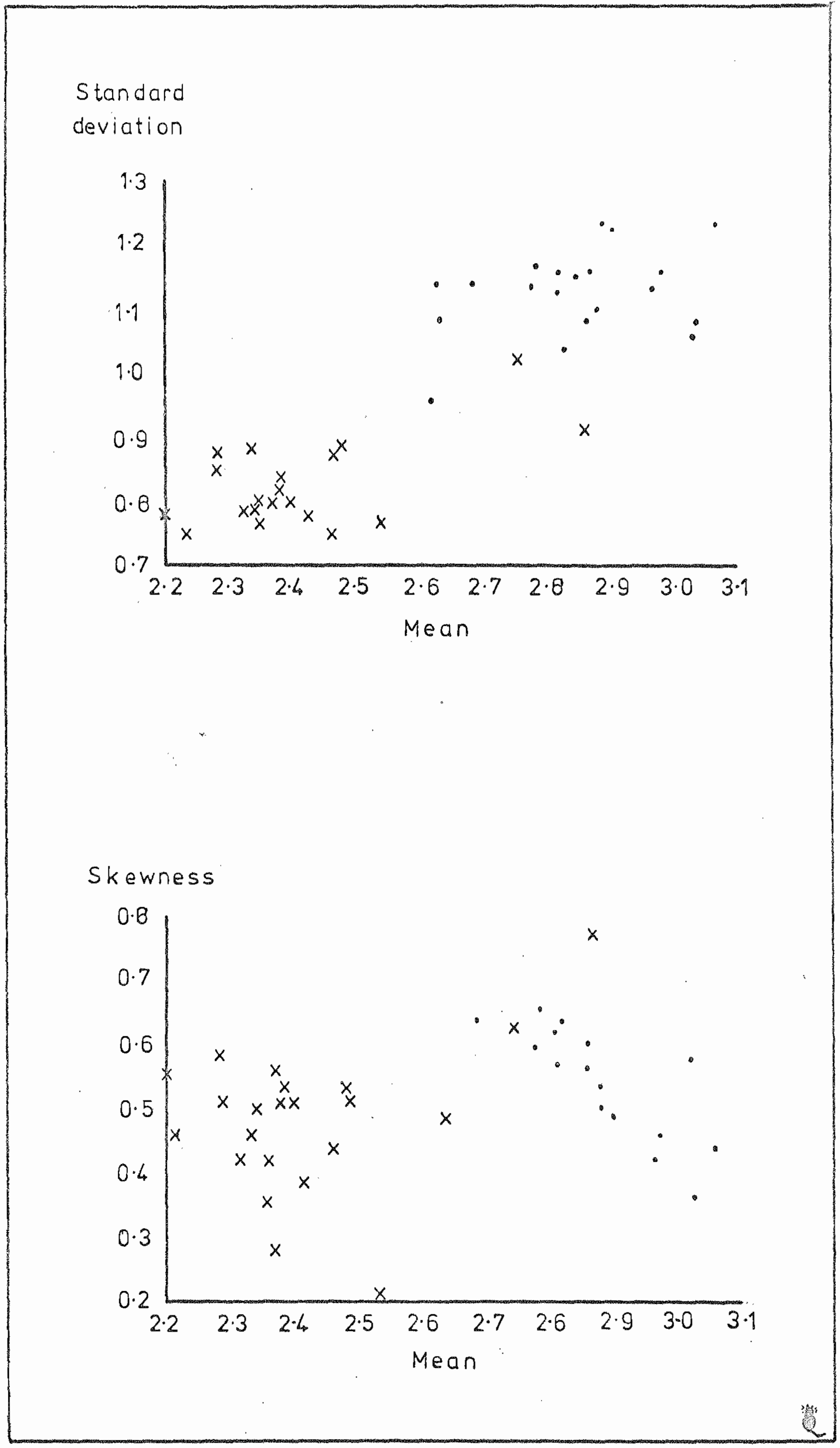


Fig. 5.9 Bivariate scattergrams of dune samples.

Dots: mean of inner dune samples.

Crosses: mean of outer dune samples.

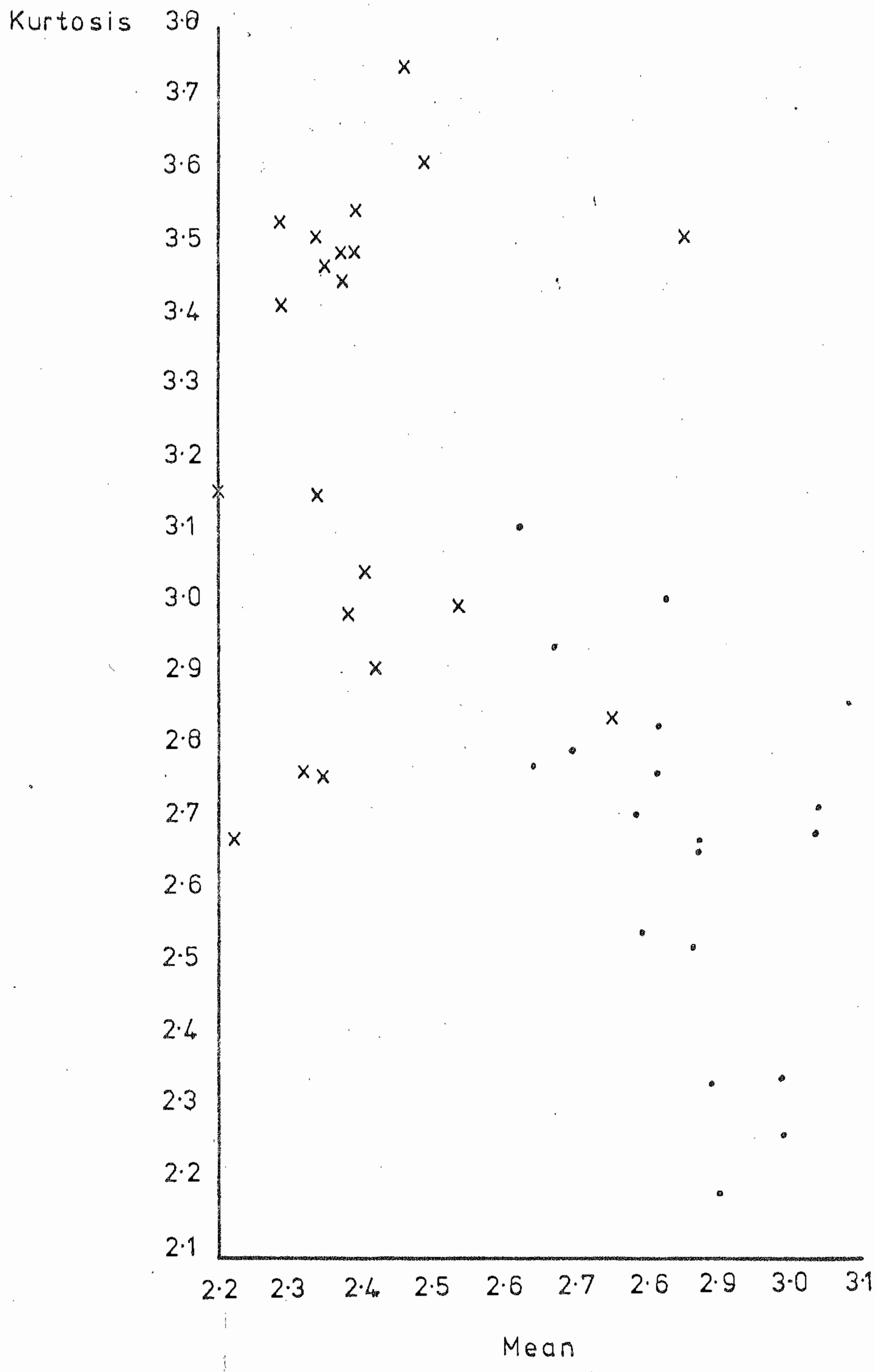


Fig. 5.10 Bivariate scattergram of dune samples.

Dots: mean of inner dune samples.
Crosses: mean of outer dune samples.

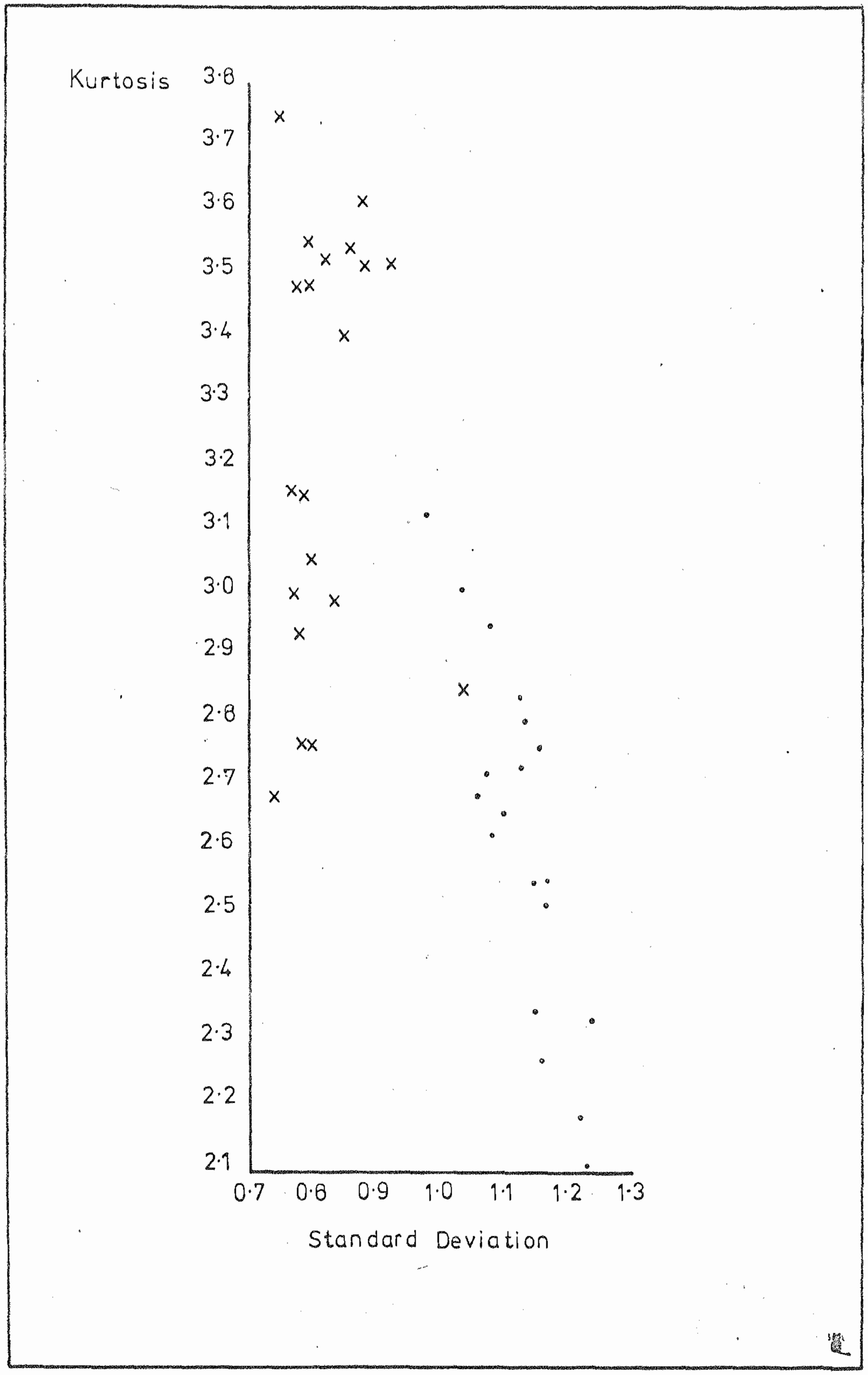


Fig. 5.11 Bivariate scattergram of dune samples.

Dots: mean of inner dune samples.

Crosses: mean of outer dune samples.

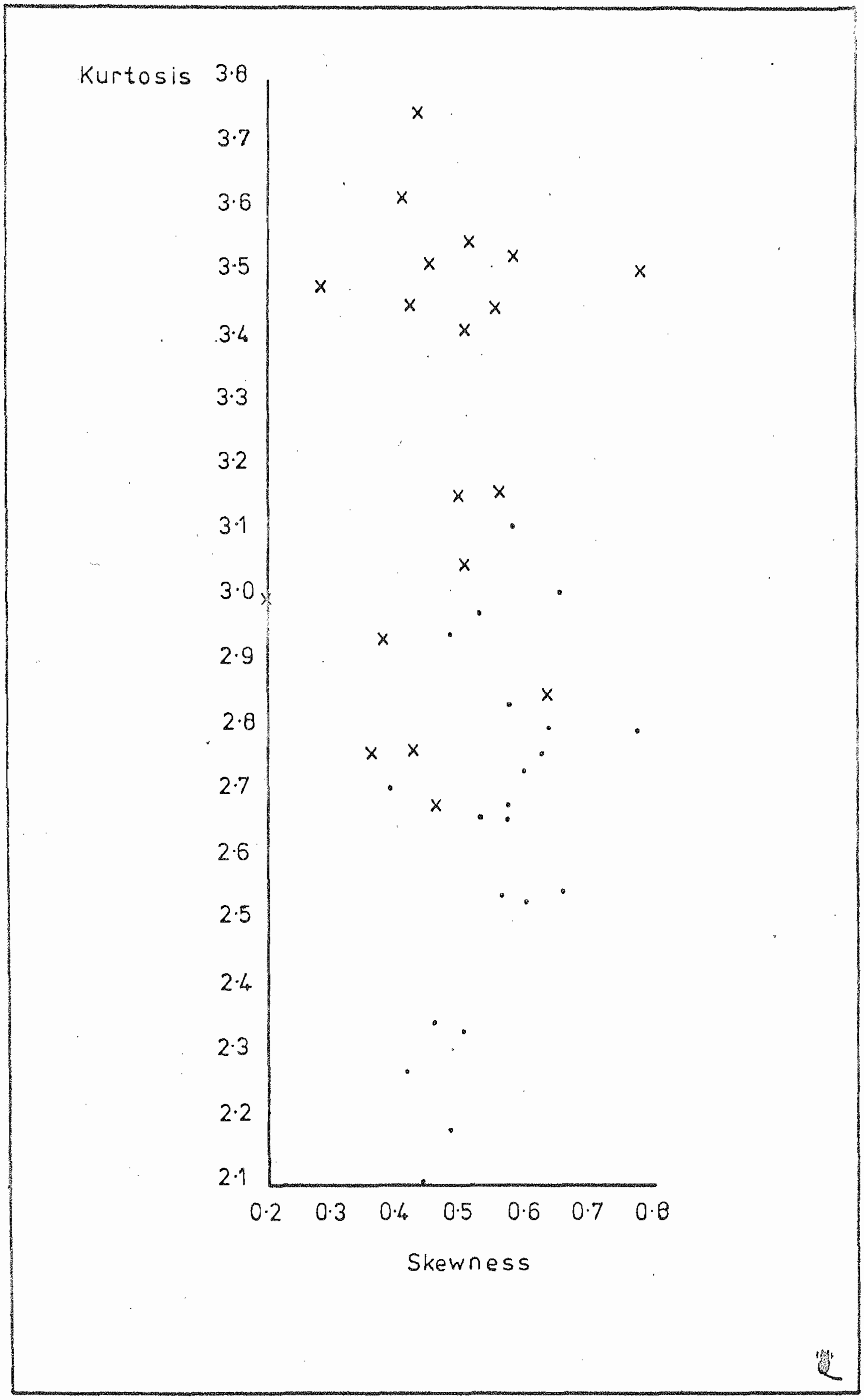


Fig. 5.12 Bivariate scattergram of dune samples.

Dots: mean of inner dune samples.

Crosses: mean of outer dune samples.

of material coarser than 1 phi. Here proximity to local sources of material in Karroo tillites and Waterberg sandstones may be important, demonstrated by the presence of rock fragments in the coarser fractions.

Physical Examination

The colours of the sands were determined with the aid of a Munsell Soil Color Chart. Samples were also examined for frosting, staining and roundness with a binocular microscope.

The colours of the outer dune sands showed little variability. Most samples were reddish brown (Munsell 5YR 4/4, 4/5, 5/3 or 5/4) or yellowish red (5YR 4/6 and 5/6). Yellowish red colours were noted mainly in samples from the drier western areas, in particular from Bosobogolo, Mpaathutlwa, Urwi and Ukwi pans. Microscopic examination of samples showed that the colour is due to a patina of red brown iron oxide (Fe_2O_3) on the larger grains.

The outer dunes are composed almost entirely of quartz grains, (Plate 20). Heavy minerals and other non quartz minerals are rare, except at Mpaathutlwa pan. Most of the grains are well rounded, particularly in the coarser fractions. Although some grains appear to be polished, most of the sands are well frosted, especially in larger fractions.

Internal structures

No natural sections in outer dunes exist to the writer's knowledge, and resources did not permit any extensive excavations in outer dunes. Pits dug to a depth of one metre in the crest of some dunes revealed no visible changes in the sands or other horizonation.

THE INNER DUNES

Superficially the inner dunes appear very different from the outer dunes. They are composed of grey brown sand, with a significant admixture of fine calcareous material and occasional small calcrete nodules. This difference is born out by detailed analysis of the composition of the inner dunes.

Plate 20. Photomicrograph of outer dune sand, Mpaathutlwa pan. Magnification x 20.

Plate 21. Photomicrograph of inner dune sand, Mpaathutlwa pan. Note fine calcareous particles adhering to quartz sand grains. Magnification x 20.

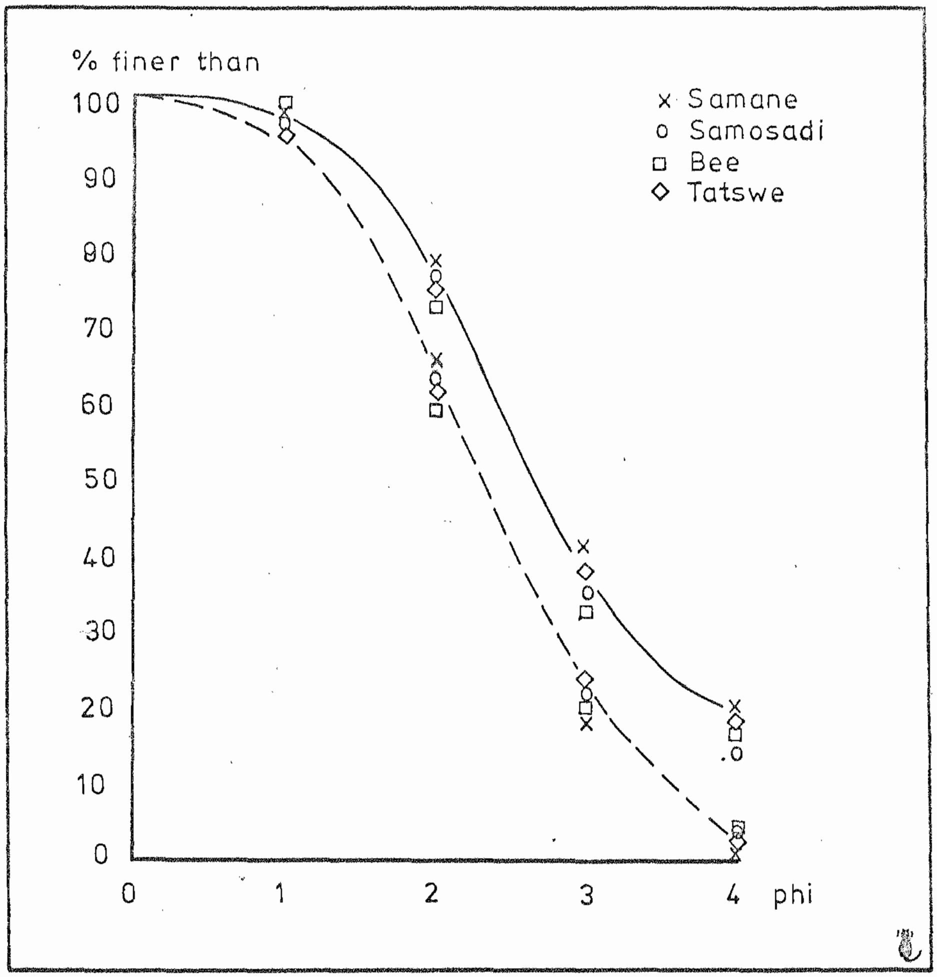


Fig. 5.13 Particle size distribution, area 1 samples.

Solid line: mean of inner dune samples.
Broken line: mean of outer dune samples.

Particle size distribution

Comparison of the grain size and sorting parameters for the inner and outer dunes shows the composition to be rather different. (presented in Figs. 5.9 to 5.12).

The mean grain sizes of inner dune samples have values of between 2.71 and 3.11 phi. The inner dunes are thus composed of material that is finer than that of the outer dunes and may be classified as moderately fine sand. Variability of mean grain sizes within each dune is somewhat greater than for outer dunes, and it is common for the sands to become finer towards the pan edge.

Sorting, as measured by phi standard deviation, is generally poor, with values of 1.00 to 1.30 phi being obtained.

Phi skewness values range between 0.20 and 0.71, and show that the inner dune samples are strongly fine skewed, often with a very long "tail" of fine material present.

Phi kurtosis values between 1.66 and 2.90 show that the ratio of sorting between the "tails" and the centre of the size distribution curves are smaller, and may be described as leptokurtic to very leptokurtic, and indicate poorer sorting of the sands in a lower energy situation.

The particle size distribution curves for the inner dune samples (Figs. 5.13 to 5.15) show that all inner dune samples contain a significant amount of very fine material of silt and clay size (greater than 4 phi). This percentage is always greater than 9 % and commonly is 12 to 15 %. Exceptionally silt and clay contents of up to 26 % may be recorded, in samples taken close to the pan edge. In terms of the standard soil texture classifications, some of the inner dune samples thus approach clayey sands or sandy loams. Inner dune sands thus contain both quartz sand and silt and clay sized material, which gives rise to the poor sorting and finer mean grain size of the samples.

Physical Examination

Apart from containing a moderate amount of silt and clay sized material, inner dunes commonly support a better vegetation cover, perhaps due to their better nutrient status and water retention, and many surface samples contain significant amounts of fine roots and other organic material. Many inner dune samples also contain small fragments or larger nodules (up to 5 or 10 cms in diameter) of calcrete. A common feature of many inner dune sands is the occurence of shells of Xerocerastus schultzei (Boettger) a small xerophytic land snail.

The presence of organic matter and fine material gives the inner dunes a light colour, which varies from brown and greyish brown (Munsell 10YR 5/2, 5/3) through pale brown (Munsell 10YR 6/3) to

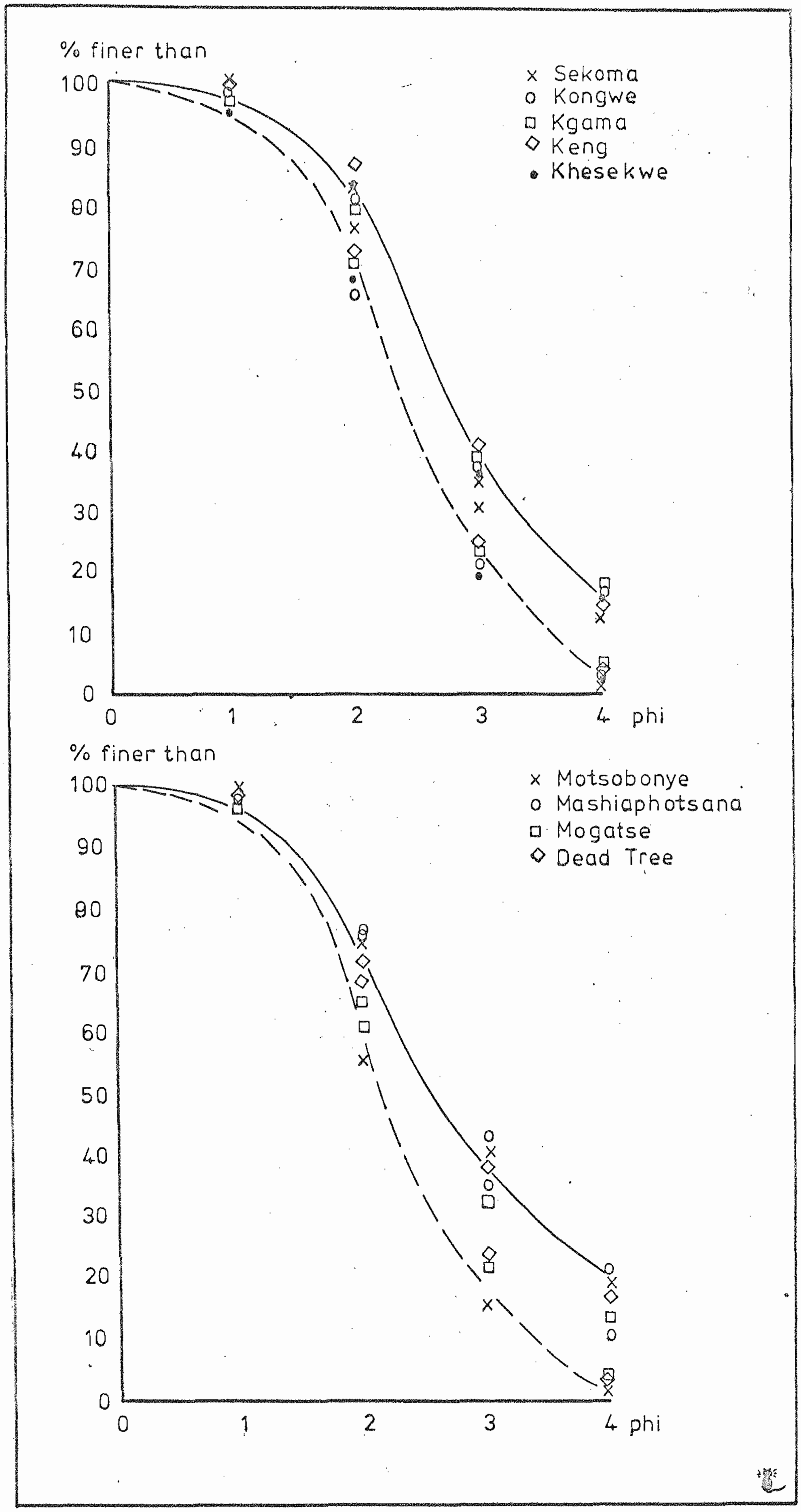


Fig. 5.14 Particle size distribution, area 2 and 3 samples.
Solid line: mean of inner dune samples.
Broken line: mean of outer dune samples.

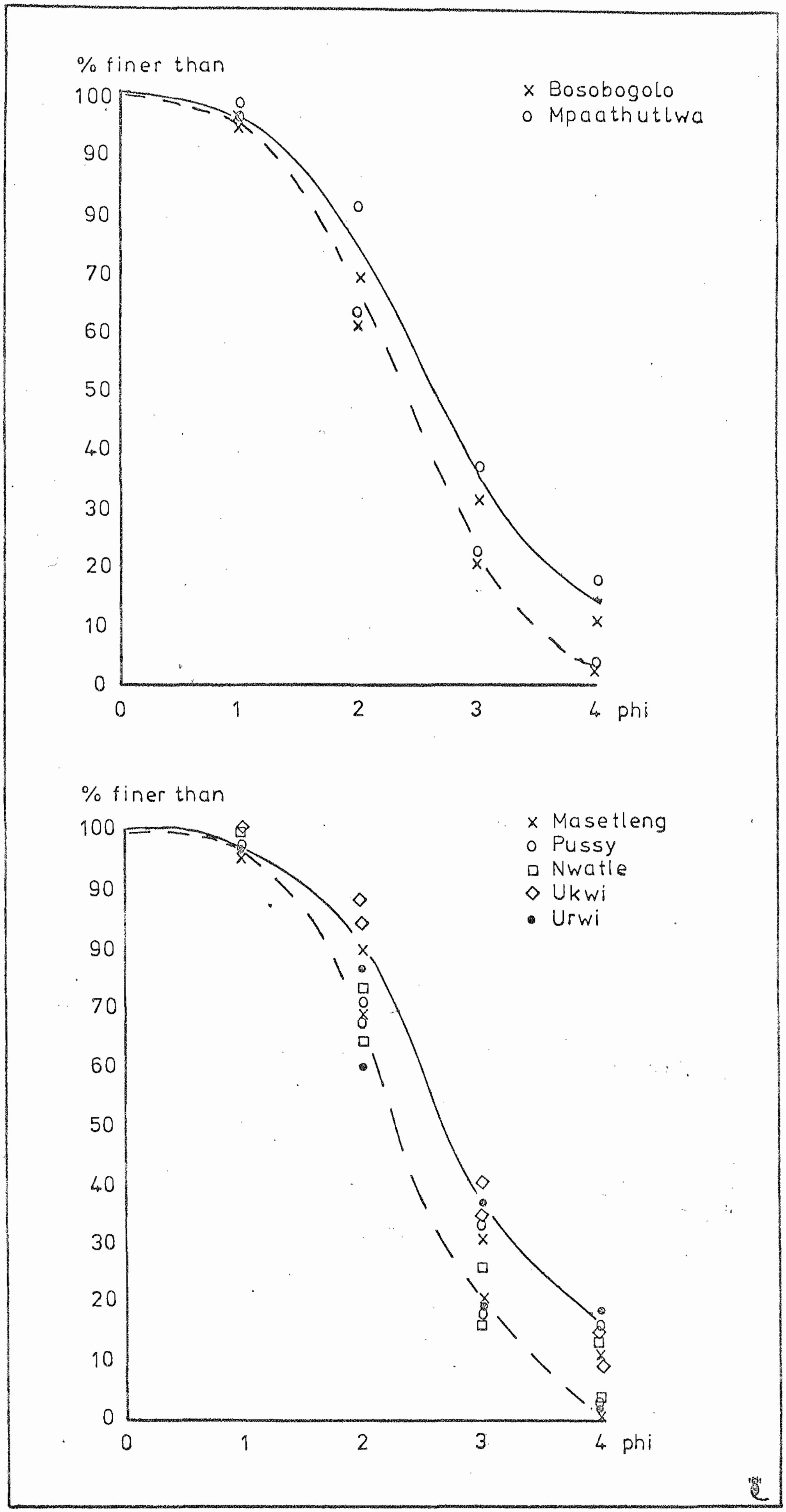


Fig. 5.15 Particle size distribution, area 4 and 5 samples. Solid line: mean of inner dune samples.

a light brownish grey (10YR 6/2). Pale browns and light brownish greys were found to be the most common colours.

Microscopic examination of inner dune samples shows them to be very different to the outer dune samples. The grains are once again rounded to well rounded quartz sands and are commonly frosted, but are bleached with no staining or patina present. Many samples possess grains which are partly coated with very fine whitish probably calcareous material (Plate 21). The amount of this coating increases towards the pan edge, and small sub rounded calcium carbonate grains also occur in this zone. In addition it appears that frosting of grains tends to become more pronounced towards the pan edge.

Chemical analysis

Determinations of the calcium carbonate percentage of the inner dune sands shows them to be moderately to highly calcareous in nature. Calcium carbonate contents in the range of 5 to 15 % are common and amounts of up to 20 or 25 % are encountered occasionally. The calcium carbonate content of samples shows a tendency to increase towards the pan edge.

The calcium carbonate content of the sands appears to occur mainly in a finely divided state, although small fragments of calcium carbonate do occur in many samples. More occasionally larger nodules of calcrete are encountered and may become locally abundant, as at Samosadi, Khesekwe, Kgama, Keng and Dead Tree pans, particularly where calcrete horizons occur near the surface.

It appears that the source of the calcium carbonate in the inner dune sands is probably the fine material that occurs in moderate quantities in all samples. That this is the case is demonstrated by Fig. 5.16, in which calcium carbonate content is plotted against silt and clay content for inner dune samples. From this scatter plot it can be seen that calcium carbonate content of samples increases with the amount of silt and clay present, with a correlation coefficient of 0.56.

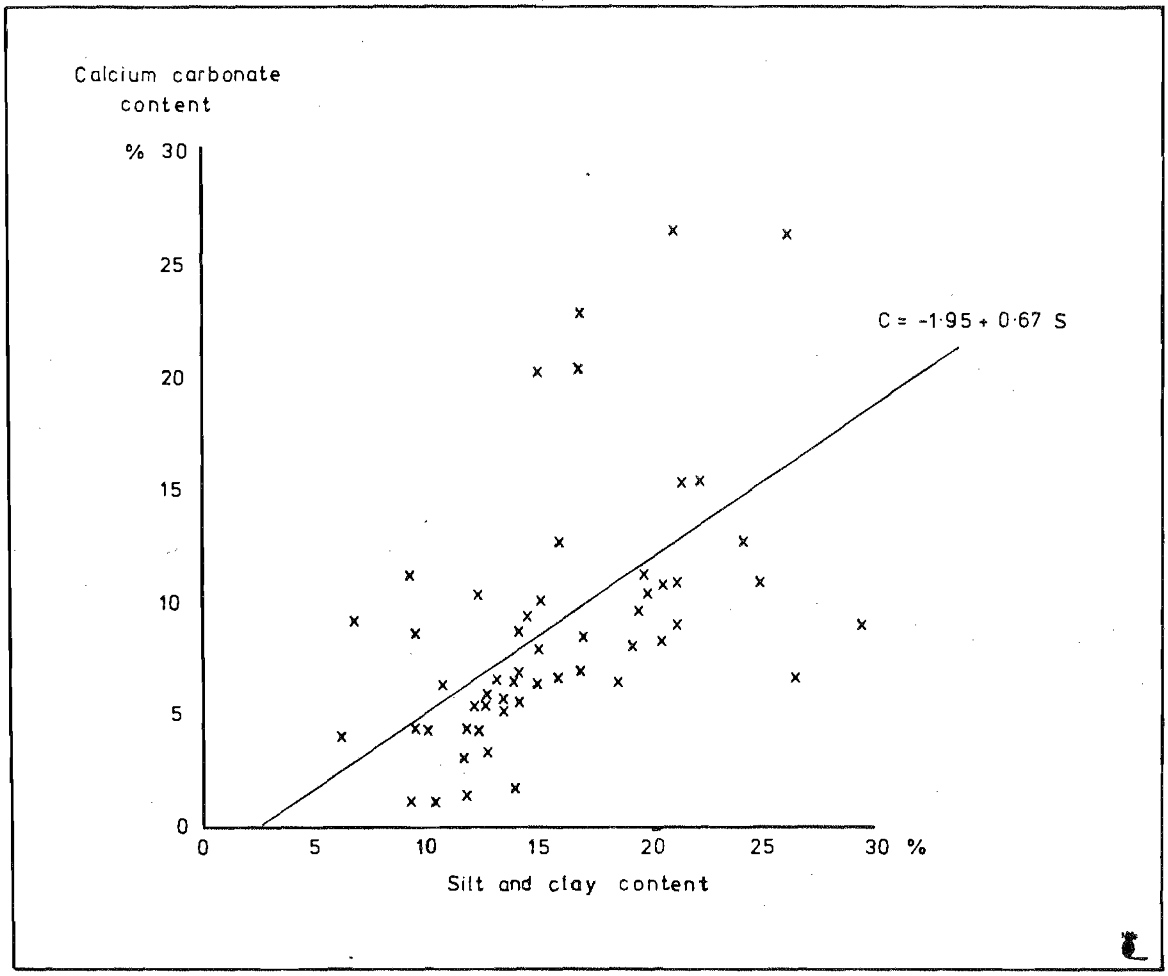


Fig. 5.16 Relationship of calcium carbonate content and silt and clay content of inner dune samples.

Ukwi pan, in addition to its main dune ridge of inner dune type material, possesses a small dune immediately on the pan edge, which appears to be quite active today. The composition of this dune is unlike that of any other dune examined. It consists of light grey (10YR 7/2) moderately sorted fine sand, with a mean grain size of 2.89 phi. The dune contains a significant proportion of coarse material, with 15 % of the sample coarser than 1 phi and 4 % coarser than 0 phi (1 mm). Microscopic examination of the samples shows that the coarser grains are very well rounded, almost spherical, frosted opaque white quartz, unlike any material found elsewhere. The remainder of the sample consists of sub rounded to sub angular quartz grains and occasional sub rounded calcium carbonate fragments. The calcium carbonate content of the dune is moderate, at 12 to 13 %.

Internal structure and composition

The internal structure and composition of the inner dunes was investigated by two means. In conjunction with other work being carried out, the Geological Survey Department drilled several auger holes into the dunes at Kongwe and Sekoma pans to depths of 8 m. (for locations see Fig. 5.17). In addition, detailed studies of the upper 3 m of the inner dunes were conducted by the writer, having dug pits to this depth in the inner dunes at Khesekwe and Samane pans.

The Geological Survey auger holes at Kongwe pan (Fig. 5.18) were drilled in the western arm of the inner dune. Below the upper layers of grey brown sand, the sands were essentially white (10YR 8/2), poorly sorted sands with a mean grain size of 2.85 to 3.20 phi, with a moderate silt and clay content in the range 12 to 15 % to 18 to 20 %, increasing slightly with depth. A layer of sand with a much higher silt and clay content was encountered at depths of 2.5 to 3 m below the surface, containing some 25 to 35 % silt and clay sized material.

Calcium carbonate content increased slightly with depth from 4 to 6 % to about 9 %, but rose sharply to 20 % on contact with calcrete, in which all auger holes bottomed at depths of 5 to 8 m below the surface on the dune crest, and at 3 m nearer the pan edge, indicating that the inner dune at Kongwe is underlain by calcretes.

The single auger hole drilled on the southeastern end of the dune ridge at Sekoma (Fig. 5.17) showed a similar pattern, with a slight increase in silt and clay content downwards, and a layer of material with a high silt and clay content (20 %) at 7 m depth. This hole bottomed in calcrete, at a depth of 8 m.

Detailed examination of pit sections at Khesekwe and Samane pans showed that the detailed picture is not significantly different from the general picture obtained by the Geological Survey.

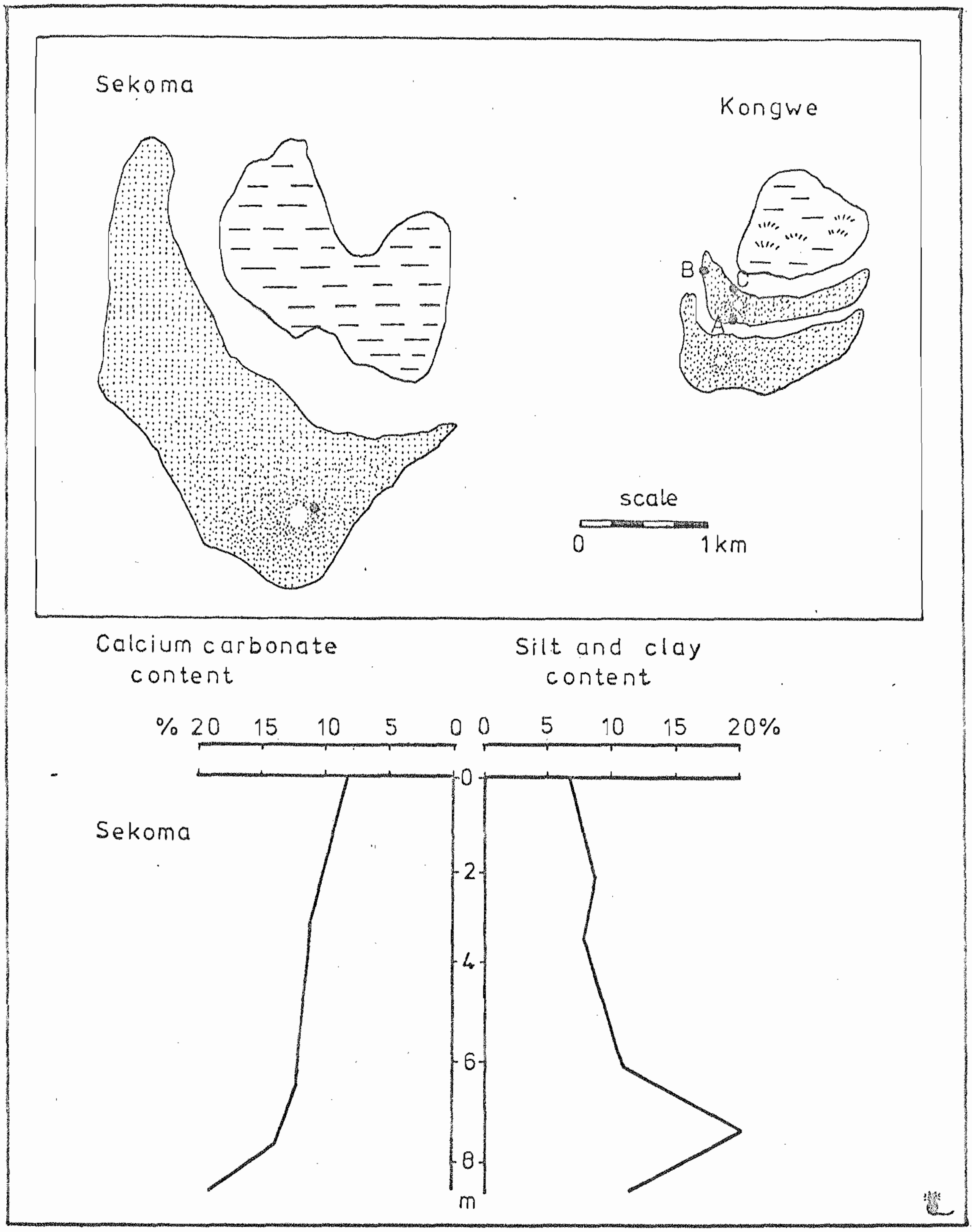


Fig. 5.17 Location of Geological Survey auger holes at Sekoma and Kongwe pans;

Details of auger hole at Sekoma pan.

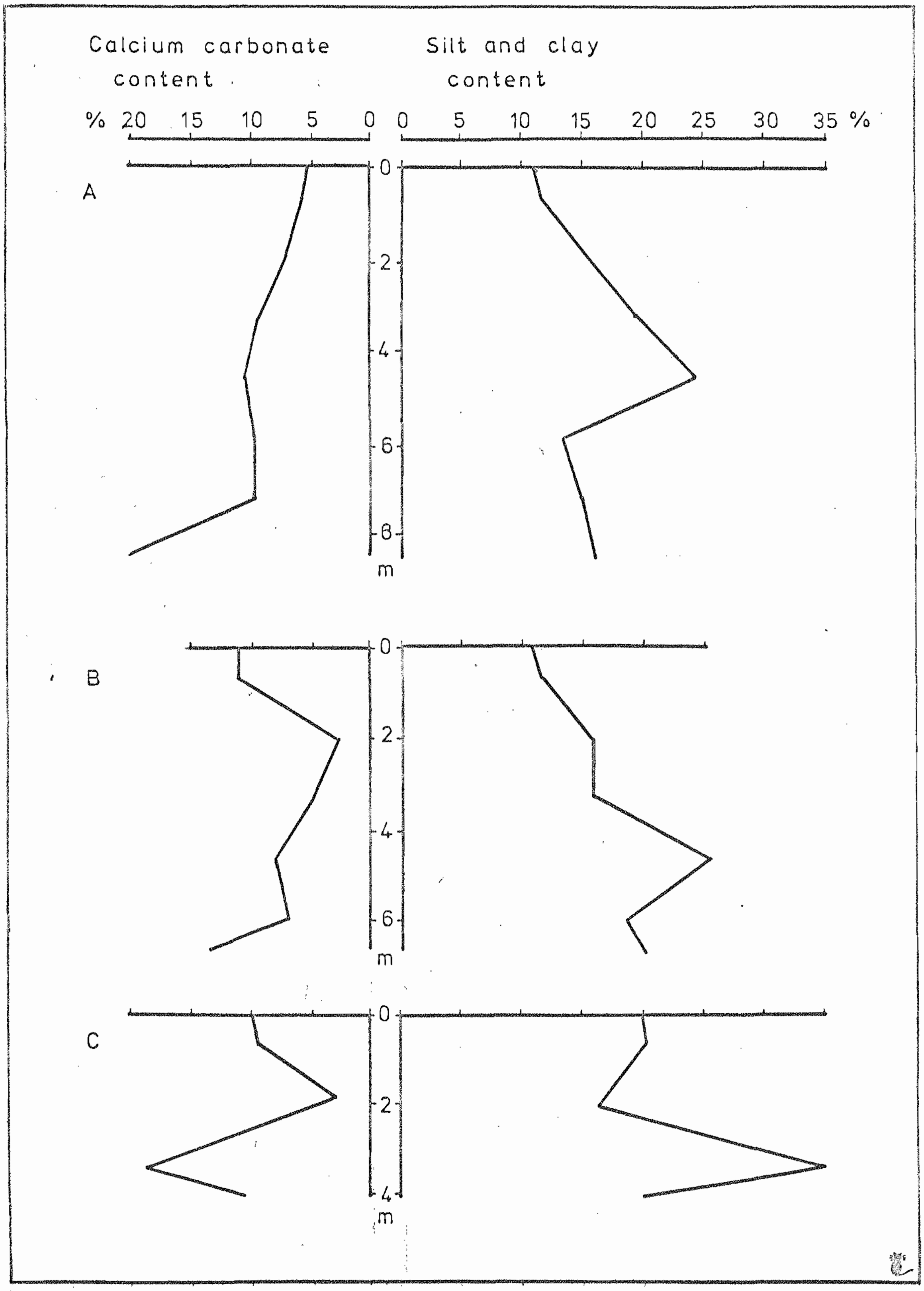


Fig. 5.18 Details of Geological Survey auger hole at Kongwe pan.

For location see Fig. 5.17

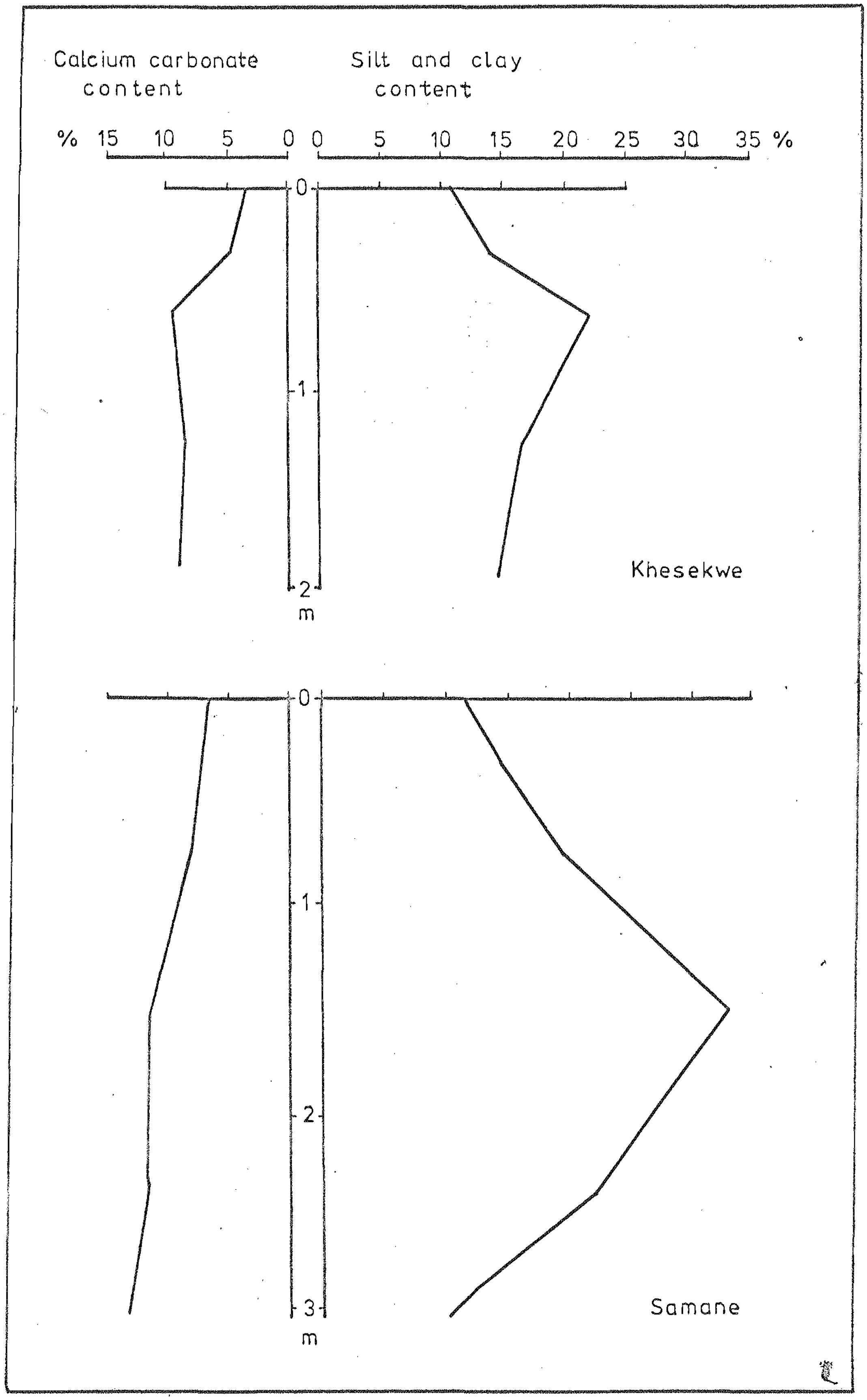


Fig. 5.19 Pit sections at Khesekwe and Samane pans.

At Khesekwe (Fig. 5.19) there was a steady increase in silt and clay content and calcium carbonate with depth. With the increase in calcium carbonate and silt and clay contents, there was a corresponding increase in the compactness of the sands, the lower layers being partially cemented. The upper parts of the profile contained shells of Xerocerastus schultzei (Boettger).

A deeper pit was dug at the crest of the inner dune at Samane pan (Fig. 5.19). Once again there was an increase in calcium carbonate and silt and clay content with depth. Both silt and clay content and calcium carbonate content were moderate in the upper horizons to a depth of 1 m. There was then a sharp increase in both silt and clay content and calcium carbonate content below this, accompanied by increased compaction and slight cementation of the sands. Silt and clay content, but not carbonate content, declined slightly, to around 20 %, at depths of 2.5 to 3 m. The upper horizons possessed abundant shells of Xerocerastus schultzei (Boettger).

The Interdunal Depressions

The composition of the interdunal depressions is very variable, and is indicative of their being a transition between inner and outer dunes.

In some cases the sands of the depression most closely resemble the outer dune material. This is the case at Keng, Mogatse, Dead Tree, Masetleng and Ukwi pans. In others, for example at Samane, Samosadi, Tatswe, Kongwe, Motsobonye and Bosobogolo pans, the interdunal depression is floored by material that is similar to that of the inner dune.

The interdunal depression may be underlain by calcretes, especially where the inner dune lies relatively close to the pan, and the interdunal depression is at a relatively low altitude above pan datum. Extensive calcretes outcrop in the interdunal depression at Khesekwe, Mpaathutlwa and Ukwi pans.

THE ORIGINS OF THE DUNES

The material forming the inner and outer dunes is distinctly different in composition, with the outer dunes being composed of fine, moderately sorted, red brown quartz sand, with a mean grain size of 2.2 to 2.5 phi;

and the inner dunes being composed of grey brown, poorly sorted, calcareous sands, with a mean grain size of 2.7 to 3.1 phi, which contains some 12 to 20 % silt and clay sized material.

It would appear that the sources of the material forming the inner and outer dunes are different, and that the dunes were formed under different conditions, at two periods in time.

Dunes, often called "lunettes" and composed of sand, silt, clay, or an admixture of material, adjacent to small lake basins have been described from most semi arid areas of the world. Elsewhere in southern Africa such dunes have been described from the northern Cape Province by Rogers (1907) and Du Toit (1908). In North Africa dunes adjacent to sebkhas have been described by Bourlaine (1954) and Coque and Jauzein (1967). Dunes of this type are particularly common in Australia where they have been examined in some detail by Bettenay (1962), Campbell (1968), Bowler (1970) and Twidale (1972). Reeves (1965) and Price (1963) report dunes adjacent to playas in western Texas and New Mexico, U.S.A..

Dunes of a parabolic form composed of quartz sand, have been reported from coastal areas (Landsberg 1956), but are also common in some semi arid areas. Parabolic dunes have been described from semi arid areas in the U.S.A. by Hack (1941), Melton (1940) and Hefley and Sidwell (1945); from Tchad (Hurault 1966) and from the Thar desert of Pakistan (Verstappen 1968). Such dunes are commonly associated with blowouts and deflation hollows in pre existing sands fixed by vegetation.

It would appear that the dunes adjacent to the southern Kalahari pans have some similarities with both the dune types described above. Examination of the literature indicates that all dunes fringing small lake basins tend towards a crescentic or parabolic shape, determined by the shape of the lake basin and the material composing them.

The sorting and grain size distribution of the sands of the outer dunes suggest that they were formed under conditions of active sand movement. Bowler (1970) and Twidale (1972) have argued that quartz sand dunes adjacent to small lake basins were formed by deflation of material from beaches created on the downwind side of the lake. Sands were concentrated on the beach by wave action and longshore drifting. Dunes formed in this way are characteristically aligned to wet season wind directions and are indicative of high water levels in the adjacent lakes.

There appears to be little evidence to support this hypothesis in the case of the southern Kalahari pans. The outer dunes appear to be aligned parallel to the strong dry season winds. The bulk of the dunes in relation to the size of the pan depression seems in the majority of cases to be inconsistent with the above hypothesis, and it is difficult to visualise a situation in which the supply of sand by wave action and longshore drifting would be sufficient to promote the formation of dunes of such size.

The parabolic form of most of the outer dunes, their characteristic asymmetry with a steep slip face on their lee sides, their position on the southern margins of the pan depression and the apparent close relationship between the size of the dunes and the size and depth of the pan depressions all suggest that the outer dunes are comparable with the parabolic dunes found in association with blowouts in semi arid areas. Parabolic dunes form initially by the creation of a small transverse dune, where sand is trapped by vegetation, downwind of an area of deflation, or blowout. As deflation continues the depression is enlarged and extends downwind, the transverse dune may move downwind also. The flanks of the dune move slowly, relative to the central portion, and are soon colonised by vegetation, further reducing their mobility. The result is that, as the central portion of the dune moves downwind, it leaves trailing dunes on its flanks, so creating a dune with a parabolic or U shape.

Application of this model to the formation of the outer dunes enables many aspects of their morphology to be accounted for. The variations in the plan form of the dunes may be explained in terms of the amount of downwind movement that has taken place. As has been noted earlier those dunes which have a strong parabolic shape are associated with depressions that are strongly elongated in a north - south direction. Weakly parabolic or near crescentic dunes are associated with near circular or east - west elongated depressions. The amount of dune movement appears to be associated with the size of the depression, and the distance of the outer dune crest from the pan edge increases with pan depression size, reflecting the greater amount of deflation, and hence dune movement that has taken place. Characteristically the outer dunes are asymmetric with steep slopes away from the pan. These slopes have clearly developed as a slip face under conditions of active sand movement.

The origins of the inner dunes are more difficult to account for. The bulk of the material that makes up the inner dune is rounded to well rounded quartz sand, with no staining or patina. This material comprises some 80 to 90 % of the inner dunes. The remainder of the material is silt and clay sized, which is generally moderately calcareous. The quartz grains show signs that the fine material is adhering to them. The position and morphology of the inner dunes shows that they were formed more recently than the outer dunes, by winds from a similar direction. The prescence of shells of Xerocerastus schultzei (Boettger) indicates that inner dunes formed in conditions at least as dry as those of today.

The observations of previous investigators in southern Africa suggest one possible hypothesis to explain the nature of the inner dune material. Du Toit (1907) observed that the dunes adjacent to pans in the northern Cape Province were formed by the movement of red brown sands into the pans by the winds. The sands, having been bleached, were then ejected on the southern side of the pan, together with a certain amount of finely divided calcareous material, to form a dune. Boocock and Van Straten (1962) suggested that the dunes adjacent to the southern Kalahari pans were formed, in the case of bare clay pans, by the accumulation of sand blown across the pans. This hypothesis clearly suggests a process whereby the sands can be bleached and aquire calcareous coatings. However, the size and morphology of the inner dunes are such that it is difficult to envisage their formation by sand movement across the pan alone.

The morphology and composition of the inner dunes suggests that they are very similar to the lunettes or clay rich dunes described by Bowler (1970) and others from Australia. These dunes have a wide range of textures with clay contents ranging from 77 to 20 %, reflecting the composition of the source of the deflated material.

Dunes of this type frequently have a moderate to high calcium carbonate content. Lunettes or clay rich dunes develop by the deflation of peletal clay aggregates and quartz sands from seasonally dry, saline lake beds. The deflated material is trapped by vegetation on the lake margin where it is stabilised by the hygroscopic absorption of moisture by the clays, and wetting during rainy seasons.

The relatively low clay content of the inner dunes (10 to 20 %) gives them greater mobility, and explains some of the sub parabolic forms that exist. The hummocky topography and poorly defined nature of many inner dunes may be explained in terms of a seasonal accumulation of deflated sandy clays and clayey sands that initially formed a sheet of material against the face of the outer dune. Gradual build up of material resulted in the formation of a low dune on the panward slopes of the outer dune. Where the accumulation of material was small, as at many of the smaller pans, no dune formed. After accumulation of the dunes, leaching of carbonates and downward movement of fines took place, resulting in an increase in calcium carbonate and silt and clay content of the dunes with depth, together with some degree of cementation and calcrete formation.

The present surfaces of the southern Kalahari pans are composed of deposits that contain a considerable amount of sand, as Table 5.2 indicates, with most pan surfaces containing some 30 to 60 % sand. Examination of the sand fraction of the pan surface deposits shows that it has many of the characteristics of a wind blown sand. The mean grain size and sorting (Table 5.3) suggest that the pan surfaces contain moderately sorted sands with a mean grain size of 2.3 to 2.5 phi, and a phi standard deviation of 0.76 to 0.90. Clearly, this material has been moved into the pan, or redistributed, by the wind at some time, as the effect of surface wash and fluvial processes alone would be to alter the sorting of the sands. This sand would appear to constitute the material for the formation of the inner dunes.

Thus, it appears that the main sources of the material forming the inner dunes were the sandy clays and clayey sands deposited in the pan depression, the origin of which is discussed below (Chapter 6).

Such sandy calcareous clays are potentially very susceptible to deflation, according to Chepil (1945). They are mechanically very unstable and may easily be eroded by abrasion and surface creep as well as by removal of dust sized particles.

Table 5.2

The composition of the pan surface deposits

	Sand %	Silt and clay %
Samane	50	50
Tatswe	24	76
Sekoma	28	72
Kgama	67	33
Keng	59	41
Khakhea	50	50
Khesekwe	36	64
Motsobonye	67	33
Mogatse	60	40
Dead Tree	29	71
Bosobogolo	69	31
Mpaathutlwa	21	69
Mabuasehube	38	62
Masetleng	48	52
Pussy	46	54
Nwatle	56	44
Ukwi	25	75
Urwi	10	90

The following sequence of events may now be postulated. During the period when the deposits of the pans were being formed sand from the surrounding areas was carried into the depression and incorporated in these deposits. The sands were bleached in this envrionment by reduction of their Fe_2O_3 patina in saline and stagnant water. At the same time many of the sand grains aquired a partial coating of calcareous clays. Subsequently, deflation of these deposits took place. During sand movement much of the silt and clay sized material was lost by abrasion, the amount lost increasing away from the pan. Once active dune movement ceased, redistribution of the fine material and carbonates within the dune took place as a result of leaching and downward percolation of water, leading to an increase in the content

Table 5.3

Mechanical analysis of some sand fractions from pan surfaces

	Mean	Standard Deviation
Samane	2.45	0.81
Kgama	2.50	0.80
Keng	2.53	0.82
Khakhea	2.73	0.80
Motsobonye	2.64	0.81
Mogatse	2.49	0.76
Bosobogolo	2.41	0.78
Mpaathutlwa	2.50	0.81
Mabuasehube	2.27	0.79
Nwatle	2.41	0.76
Ukwi	2.61	0.78
Urwi	2.37	0.78

DISCUSSION AND CONCLUSIONS

This chapter has described the morphology, alignments and composition of the dunes situated on the southern side of the southern Kalahari pans. Hypotheses to explain the origins and composition of the dunes have been put forward.

Two distinct dune ridges or areas of sand accumulation, termed the inner and outer dunes, can be recognised. Their alignments indicate that they were formed by winds from a northerly direction. Although there are no significant differences in alignments between inner and outer dunes as a whole, significant regional variations in dune alignments do exist. The regional differences may be explained in terms of the present day regional shift in wind directions from north northeast in the northern and eastern parts of the southern Kalahari, to north northwest in the southern and western parts of the region. It is interesting to note that the regional change in dune alignments corresponds to a similar pattern observed in the relict dune ridges visible on ERTS imagery.

The composition of the inner and outer dunes is distinctly different. The outer dunes are composed of fine, well rounded, moderately sorted reddish brown quartz sand. The inner dunes, grey brown in colour, are composed of quartz sand with an admixture of 12 to 20 %

silt and clay sized material. It is suggested that the outer dunes are composed of material deflated from the depressions that now contain the pans. The inner dune appears to have been formed as a result of the deflation of calcareous sandy clays deposited on the floor of the pan depression, which were laid down in the period between formation of the inner and outer dunes.

The climatic conditions under which the inner and outer dunes were formed appear to have been unlike those of the present day, as deflation is taking place only sporadically today. Evidence from other parts of the world suggests that parabolic dunes form in sub arid conditions where there is sufficient vegetation to trap sand downwind of blowouts. However, it has been suggested that the pan depressions originated by the deflation of material from areas kept bare of vegetation by seasonal water accumulations. In the case of the southern Kalahari this would suggest a climate with greater runoff and thus greater rainfall, or less evaporation, than the present day, as such accumulations are currently of very short duration. It is thus suggested that the outer dunes formed under semi arid or sub arid conditions as a result of the enlargement of blowouts in places of seasonal water accumulation.

The conditions favouring the formation of clay rich dunes by the deflation of material from the beds of seasonally dry lakes have been summarised by Bowler (1973) and include the presence of a seasonally dry saline water body and strong unidirectional winds during a hot dry season. At the present time water accumulations in the pans of the southern Kalahari are barely sufficient for clay dune formation, as the presence of vegetation cover over all or part of many pans suggests. In addition temperatures during the dry season in the southern Kalahari are much lower than those in areas where clay rich dunes are now forming. The mean daily temperatures during the dry season in the area are 10 to 15 ^{o}C, compared with a mean of 28 ^{o}C in areas of present clay dune formation. It would seem that the inner dunes were formed during a period when the climate was warmer and probably wetter than today.

Comparison of the size and development of the inner and outer dunes indicates that the initial period of deflation, in which the outer dune was formed was, in most cases, the most intense and prolonged. However, locally, as at Nwatle and Mashiaphotsana pans, it does not seem to have been very effective, as the small size of the outer dunes at these pans testifies. The subsequent period of deflation to form the inner dune does not seem to have been as prolonged, as most inner dunes are smaller than the outer dunes. Exceptionally, as at Mashiaphotsana, Nwatle and Ukwi pans, this period of deflation appears to have been the dominant one.

There seems to be little evidence that there has been widespread deflation since the formation of the inner dunes. The only indications of more recent deflation exist at Mpaathutlwa and Ukwi pans. At Mpaathutlwa pan it appears that the inner dune has been removed to rest against the panward face of the outer dune, leaving the calcreted core of the inner dune upstanding. At Ukwi pan, there is the small dune on the pan edge, which may be receiving material even today.

In conclusion it may be stated that the dunes adjacent to the southern Kalahari pans are composed of material deflated from the depressions that now contain the pans. Deflation took place during two periods, the first of which was of longer duration than the second. Between them was an interval in which clays and sandy clays were deposited in the pan depression, the nature and origin of which is discussed below.

CHAPTER 6.

THE PANS AND THEIR ASSOCIATED DEPOSITS

INTRODUCTION

The pans of the southern Kalahari occupy the central parts of shallow, sub circular isolated depressions of probable deflation origin. Three varieties of pan can be recognised: those with a complete grass cover, broken only by scattered waterholes; those with a partial grass cover and more extensive areas of bare sandy clay; and those with a completely bare clay surface. The bare clay pans flood over their entire area after heavy rain to a depth of some 30 cms, whilst other types flood to a lesser extent. Up to 2 to 3 m of sandy clays underlie the pans and there is evidence to suggest that they were formerly more extensive than at present, and may have been up to three times their present size. The outer slopes of the depressions containing the pans are covered by red brown sand as found in the surrounding areas, but the inner slopes are frequently shallowly underlain by calcretes, with a cover of grey brown sand.

Previous investigators in the southern Kalahari have commented briefly on the nature of the pans and their deposits. Passarge (1904), Rogers (1934), Wayland (1952) and Boocock and Van Straten (1962) all described the calcretes and silcretes occuring in the vicinity of the pans. Rogers (1934) and Wayland (1952) noted the existence of calcareous sands and clays on the floors of the pan depressions, which made them impervious to the water which collected there after rain. Van Straten (1955) recognised and described three types of pan surface: grassed, ungrassed and saline.

The aims of this chapter are: to describe the morphology and morphometry of the pans and the depressions containing them; to describe the nature and composition of the pan surfaces, and to describe the composition and stratigraphy of the deposits of the pans and depressions; and to put forward hypotheses to explain their origin.

MORPHOLOGY AND MORPHOMETRY OF THE PANS AND PAN DEPRESSIONS

The general nature of the topography of the pans and the depressions containing them has been described in Chapter 3. This section will concentrate on certain aspects of the morphology and morphometry of the pans and depressions in relation to their origin.

The pans of the southern Kalahari are generally sub circular to sub elliptical in shape and are contained in similarly shaped depressions. They are commonly located in the southern parts of the depressions, which tend to be asymmetric in cross section along their northeast – southwest axes. In many cases the slopes on the northern edges of the depressions are less steep than on the southern side where the dunes are located. Exceptions to this are encountered where there are outcrops of massive calcretes, which form bluffs some 3 to 4 m high, at as Ukwi pan; or where rock outcrops are encountered, as at Khakhea, Kokong, Mpaathutlwa and Mabuasehube pans. The slopes of the depressions fall steadily to the pan at angles of 2 to 3 °. Commonly they are interrupted by a slight break of slope some 200 to 300 m from the pan edge and some 3 to 5 m above the pan datum, forming a slight bench or terrace around the pan. This break of slope is associated with a transition from the red brown sands of the outer slopes to grey brown, slightly calcareous sands which mantle the inner slopes of the pan depression. In many cases the break of slope is marked by the appearance of calcretes, either at the surface, or at shallow depths.

At a number of pans the inner slopes of the pan depression are furrowed by shallow gullies, particularly where calcretes or pre Kalahari rocks are at or near the surface.

Surrounding the pan itself is a zone up to 200 m wide of calcareous sands and calcretes, which appears to represent a former extension of the pan.

Morphometry of the pans and pan depressions

Hutchinson (1957) and Reeves (1968) have described a variety of indices which may be used to describe the morphometry, particularly the shape, of lakes and lake basins. Such indices have been applied to paleolakes in semi arid areas by Reeves (1966) and Killigrew and Gilkes (1973), where they have proved valuable as indicators of the origin and development of the lakes.

For each of the sample of pans studied the following morphometric indices were derived: length width ratio of pan and pan depression, ellipticity of pan and depression, shoreline development of pan and depression; and ratio of pan area to depression area. The values obtained are presented in Table 6.1. All data are taken from the pan maps which illustrate Chapter 3.

The length width ratio of a lake or lake basin is a measure of its elongation, circular basins having a ratio of 1. The length width ratios for the pans of the southern Kalahari range from 1.00, or circular, to 2.26, or moderately elongated. The majority of pans have length width ratios in the range 1.10 to 1.36, indicating a slight to moderate degree of elongation. However, some pans are more strongly elongated, with length width ratios greater than 1.5. The most strongly elongated pans are Nwatle, Masetleng and Pussy, followed by Samosadi, Sekoma, Mabuasehube and Ukwi. The length width ratios of the depressions are lower than those for the pans. In general they are less elongated then the pans they contain. Significantly elongated depressions are encountered at Bee, Sekoma, Kongwe, Nwatle and Pussy pans.

The ellipticity of a lake or lake basin is the ratio of the length of the long axis minus the length of the short axis, to the length of the long axis, or:

$$E = \frac{L - W}{L}$$

Thus, circular basins will have E indices of zero, rising to one as the lake attains an elliptical shape. Ellipticity appears to be a moderately sensitive measure of shape and appears to be a good index of the origin and development of lake basins. The ellipticity of the sample of southern Kalahari pans studied ranges between 0.07 at the near circular Tatswe pan, to 0.56 at the strongly elongated Masetleng pan. The pans appear to fall into two groups, one with a near circular shape with E indices of less than 0.4, and the other more elongated, with E indices of greater than 0.4. Pans with high ellipticity indices and a sub elliptic shape are Samosadi, Sekoma, Kongwe, Bosobogolo, Mabuasehube, Ukwi, Nwatle and Masetleng. Of these Nwatle and Masetleng pans are the most strongly elliptical.

The ellipticity of the depressions containing the pans tends to be low, and is generally smaller than 0.25. In many cases the depressions are more nearly circular than the pans they contain. Exceptions are the strongly elliptical depressions that contain Bee, ble 6.1

n and Depression morphometry

n	Pan Length km	Pan Width	Depression Length km	Depression Width	Length width ratio Pan	Length width ratio Depression	Ellipticity Pan	Ellipticity Depression	Area (km^2) Pan	Area (km^2) Depression	Pan Depression Areas Ratio	Shoreline Develop Pan	Shoreline Develop Depressio
mane	0.75	0.50	1.50	1.40	1.36	1.07	0.27	0.07	0.33	1.18	[illegible]	1.25	1.17
mosadi	1.20	0.70	1.75	1.50	1.71	1.30	0.48	0.23	0.57	1.81	3.17	1.12	1.53
e	0.55	0.45	2.00	1.00	1.22	2.00	0.18	0.50	0.18	1.15	9.70	1.33	1.31
tswe	0.75	0.80	2.80	1.90	1.07	1.47	0.07	0.30	0.43	4.25	9.88	1.08	1.03
koma	2.10	1.25	5.65	3.00	1.68	1.88	0.40	0.47	1.87	15.50	8.16	1.24	1.11
ngwe	1.15	0.75	2.00	1.25	1.53	1.60	0.35	0.38	0.58	1.75	3.02	1.11	1.07
ng	1.15	0.85	2.15	2.00	1.29	1.08	0.19	0.07	0.79	3.25	4.11	1.30	1.09
ama	0.80	0.70	2.60	2.40	1.14	1.08	0.13	0.08	0.39	3.50	8.97	1.02	1.21
akhea	1.65	1.30	2.75	2.45	1.13	1.12	0.21	0.11	1.29	4.00	3.10	1.05	1.30
esekwe	1.00	1.00	2.75	2.45	1.00	1.12	0.52	0.11	0.38	3.69	9.71	2.06	1.17
tsobonye	1.00	0.80	3.00	2.50	1.25	1.20	0.20	0.17	0.65	6.26	9.61	1.07	1.13
kong	1.15	0.95	4.20	3.00	1.21	1.40	0.29	0.17	0.85	8.25	9.71	1.10	1.28
shiaphotsana	1.65	1.30	2.00	1.75	1.27	1.14	0.21	0.13	0.20	3.12	1.57	1.22	1.28
gatse	1.20	0.90	2.60	2.25	1.33	1.16	0.25	0.13	0.73	3.25	4.45	1.13	1.25
ad Tree	0.80	0.70	2.55	1.75	1.14	1.46	0.13	0.31	0.39	2.87	7.36	1.08	1.08
sobogolo	2.24	1.28	3.60	2.48	1.75	1.45	0.43	0.31	2.00	7.12	3.56	1.20	1.06
athutlwa	2.08	1.60	5.20	4.00	1.30	1.30	0.23	0.23	1.72	14.72	8.56	1.05	1.12
uasehube	2.00	1.20	3.20	2.40	1.67	1.33	0.40	0.25	1.95	5.44	2.80	1.22	1.21
i	4.40	2.68	4.00	3.28	1.64	1.22	0.39	0.18	7.45	16.64	2.33	1.24	1.14
i	1.84	1.48	4.00	3.52	1.24	1.44	0.20	0.12	2.10	15.52	7.39	1.05	1.11
tle	1.16	0.56	2.40	1.48	2.07	1.62	0.52	0.38	0.34	4.32	12.71	1.35	1.09
etleng	2.08	0.92	3.40	2.60	2.26	1.31	0.56	0.24	1.45	6.72	4.63	1.12	1.13
sy	0.36	0.20	1.60	0.80	2.00	1.80	0.44	0.50	0.06	0.90	15.00	1.38	1.19

Sekoma, Kongwe, Mpaathutlwa, Mabuasehube, Nwatle, Masetleng and Pussy pans.

The shoreline development of a lake or lake basin is the ratio of the length of its shoreline to the circumference of a circle with the same area as the lake. Thus:

$$SD = \frac{SL}{2\sqrt{A}}$$

Shoreline development is thus unity for a circular lake, and higher values are an indication of the departure of a lake from a circular shape. The values obtained for the pans mostly lie in the range 1.05 to 1.35. As would be expected, those pans with higher ellipticity have higher shoreline development values. Similarly the pan depressions tend to have lower shoreline development than the pans, and a near circular shape.

The ratio of the area of the pan to the area of the depression was determined for the pans studied. A wide variety of values was obtained, ranging from 1.57 to 15.00. Within this range two groups of ratios could be picked out, those pans with ratios of less than 5.00 and those with pan depression areas ratios of more than 8.00. There seems to be no consistent relation of this ratio to any other aspect of pan or depression morphometry, such as pan depth or size. However, it is interesting to note that those pans with lower ratios of pan area to depression area are often grass covered, whilst those with high ratios are often bare clay pans.

Despite the variety of values for the ratio of pan area to depression area, there is a moderately good correlation between pan area and depression area, with a correlation coefficient of 0.72. It is interesting that this compares well with the correlations of playa area to basin area obtained by Cooke in the western U.S.A. (Cooke and Warren 1973).

Direction of elongation of the pans and depressions.

From the above it is clear that most pans are elongated to some extent. To ascertain if this elongation followed a consistent pattern, the directions of the long axes of each pan and depression were measured. The results are presented in Table 6.2. These investigations show that the long axes of the pans may lie in one of two directions; in the range 250 to 320 $^{\circ}$ and in the range 010 to 050 $^{\circ}$. Of these trends the first is more common. It will be noted that these two directions of elongation are nearly at right angles to each other and that they are parallel to, or perpendicular to, the prevailing north to northeast winds of the southern Kalahari. It would thus appear that the pans are elongated in a direction that is either downwind or at right angles to the prevailing wind. The depressions containing the pans are commonly elongated in a downwind direction (020 to 045 $^{\circ}$). The exceptions to this are at Samosadi, Kokong, Mogatse, Masetleng and Pussy pans.

Table 6.2

Orientation of pan and pan depression long axes

	Pan	Depression
Samane	270°	040°
Samosadi	310°	310°
Bee	320°	020°
Tatswe	315°	070°
Sekoma	310°	001°
Kongwe	050°	030°
Keng	050°	050°
Kgama	001°	045°
Khakhea	250°	035°
Khesekwe	270°	040°
Motsobonye	030°	020°
Kokong	315°	290°
Mashiaphotsana	045°	020°
Mogatse	315°	320°
Dead Tree	300°	030°
Bosobogolo	020°	020°
Mpaathutlwa	250°	020°
Mabuasehube	010°	010°
Ukwi	040°	020°
Urwi	300°	002°
Nwatle	020°	025°
Masetleng	290°	290°
Pussy	290°	290°

DISCUSSION

Measures of the morphometry of the pans show that they are sub circular to sub elliptical in shape, and are contained in sub circular depressions. The ellipticity, length width ratios and shoreline development of the pans and depressions are all within the range of values obtained by Reeves (1965) for deflation depressions in western Texas, U.S.A.. The shape of the pans and the depressions containing them is thus a further indication of their deflation origin.

With the exception of Samosadi, Masetleng and Pussy, the pans that are most strongly elongated all have their long axes trending in a north northeast - south southwest direction and are contained in depressions that are strongly elongated in a similar direction. Associated with these pans, which include Tatswe, Dead Tree, Khesekwe and Nwatle pans, are dunes which have a well developed parabolic form. Commonly, those pans that are elongated in an east - west direction are only weakly so, and tend to a near circular shape. Pans with a strong east - west elongation are rare, and tend to be the result of local circumstances, for instance the presence of outcrops of Kanye Volcanic System felsites on the north side of Kokong pan, or the linked depressions of Masetleng and Pussy pans. Reeves (1968) states that depressions of a deflation origin tend to elongate downwind, and this is the case with most of the pan depressions in the southern Kalahari. However, when the basins contain shallow water bodies, the water may be blown by the prevailing winds to the downwind end of the playa, to return by longshore currents, which will erode the ends of the playa, to produce a lake which will be elongated perpendicular to the prevailing winds. This process of end current erosion has been suggested by Reeves (1966) and Killigrew and Gilkes (1973) to explain the shape of lakes in west Texas and western Australia and it would appear that end current erosion may have been important in extending the southern Kalahari pans. However, this process does not appear to be important today, as most pans do not hold water frequently in the middle and late parts of the dry season, when winds are strongest and least variable in direction. Many pans have a near straight lee shore, characteristic of lakes subjected to this form of erosion. Samane, Khakhea, Mogatse, Mpaathutlwa, Masetleng and Urwi pans are the best examples of this. All these pans are slightly elongated in an east - west direction. It does seem that the effect of end current erosion is limited by the shape of the depression and there is little sign of end current erosion having been important at pans such as Nwatle, Bosobogolo and Dead Tree, which have rather narrow basins that limit lateral expansion of the lake.

In addition, it seems probable that the pans have been subjected to further deflation and some infilling after the period when thay may have contained significant quantities of water. This would clearly have modified the then existing form of the pans.

In conclusion, it would appear that the shape of the pans today reflects the operation of both deflation and end current erosion at different stages in their development. The pans that occupied the depressions soon after their excavation by the wind probably took on an elongated form similar to that of the depression. During periods when they were commonly flooded, end current erosion modified the elongated pans to a near circular form. Subsequent deflation has again tended to elongate the basins. The relative importance of the processes is thus reflected in the present shape of the pans.

THE PANS

THE PAN SURFACES

The work of Neal et al (1965) has demonstrated the importance of playa surface types as indicators of the texture, mineralogy and hydrology of playas. It appears that the different surfaces of the pans of the southern Kalahari have developed under rather different conditions. Van Straten (1955) recognised three types of pan surface:

Grassed - with dark sandy clay sediments, low saline concentrations and relatively little calcrete development.

Ungrassed - with a vegetation cover of low growing woody species on dark sandy clays which have good water retention properties.

Saline - with little or no vegetation, saline or alkaline sandy clay sediments. Usually deeply etched into calcareous sandstones, often with extensive calcretes around the pan itself.

The field observations of the writer suggest that Van Straten's classification is capable of some modification. For example, not all pans with no vegetation on them are in fact saline, and many pans in this class are not deeply etched into calcretes. The following working classification of pans is proposed, which divides pans into: Grassed pans; partly grassed pans; and bare clay pans. The bare clay pans may be further subdivided on the basis of the nature of their surface into granular and smooth hard pan surfaces.

Description of surface types

Grassed pans

Grassed pans (Plate 22) have a continuous to discontinuous cover of long or short grasses, mainly Sporobolus spp., Eragrostis spp. and Cynodon dactylon. The length of the grasses seems to depend partly on the amount of game grazing the pan. At one or more places in the pan the grasses may give way to bare areas 10 to 20 m across, which lie 50 to 80 cm below the general pan floor level. These areas fill with water after heavy rains to a depth of 30 to 50 cm, and may be termed the pan pool or waterhole, (c.f. the "pfannenloch" of Jaeger (Rogers 1940)). The deposits underlying the grass pans are invariably sandy clays or clayey sands, light brownish grey in colour, (Munsell 10YR 6/2), with small calcrete nodules present. Clays and sandy clays are exposed in the pan pools. Occasionally, as at Bee and Khesekwe pans, calcretes may be exposed around the pan pool.

Partly grassed pans

Partly grassed pans have a scattered to discontinuous grass cover, together with scattered low growing shrubs and succulents. The areas of bare sandy clays and clays are more extensive, and may cover half the area of the pan. Occasionally, as at Tatswe (Plate 23) and Mpaathutlwa, these areas may lie as much as 50 to 80 cm below the main pan surface level, but generally they lie only some 20 to 30 cm below the general level of the pan. These bare areas hold shallow water bodies after heavy rains, often for some considerable time, and Keng pan was still flooded in June 1972, three months after the last rains in that area.

Bare clay pans

The bare clay pans support little vegetation, although occasionally, for example at Kgama pan, there may be small areas of discontinuous grasses. Two sub types were recognised. The most common sub type has a loose porous clay or sandy clay granular surface (Plate 24) pale

Plate 22. Grassed pan surface at Bee pan.

Plate 23. Partly grassed pan surface at Tatswe pan. Ridge forming skyline is outer dune crest.

brown (10YR 6/3) to light grey (10YR 7/1) in colour. The granular layer may be up to 20 cm thick and overlies compact clays. This surface layer dries out very rapidly after evaporation of the water that may be in the pan, but the underlying clays dry out very slowly. The granular layer tends to become deeper and softer as the silt and clay content of the surface deposits increases. It appears to form by the drying of a 5 to 10 cm layer of liquid mud left after the water has evaporated from the pan. The second sub type (Plate 25) has a hard smooth surface, light grey (10YR 7/1) in colour, with narrow irregular polygonal cracks, forming a crust up to 5 cm thick overlying darker clays. In some cases these crusts may have a distinct shine to them in certain light conditions, apparently caused by their high calcium carbonate content. The hard smooth surfaces also have a distinctive appearance on air photographs, as their high reflectivity gives them a bright white tone. Examples of this surface type were noted at Ukwi, Khakhea and Mpaathutlwa pans.

Areas of the different surface types may be observed at one pan. For example, the bare areas of grassed and partly grassed pans may frequently have granular clay surfaces. Intermediate conditions may occur, and Tatswe pan appears to be transitional between the grassed and partly grassed types. Mpaathutlwa pan appears to be transitional between the partly grassed and bare types.

The distribution of pan surface types

The distribution of pan surface types amongst the sample of pans studied is shown in Table 6.3. Of the pans studied, six were grassed, five partly grassed and twelve bare clay. This appears to be equivalent to the proportions of pans with the three main surface types in the southern Kalahari as a whole, where some 50 % of pans are bare clay, 15 % partly grassed and 35 % grassed. In general, the shallower pans are grassed, and the deeper pans bare. In the sample of pans studied this relationship between pan depth and surface type seems to hold true, as Table 6.4 demonstrates.

The only major exceptions to the relationship appear to be at Mpaathutlwa pan, which is only marginally a partly grassed pan, and at Pussy pan, although some overlap between the categories does exist.

Plate 24. Granular bare clay pan surface, at Sekoma pan.

Plate 25.
Hard smooth bare clay pan surface with polygonal cracks at Ukwi pan.

Table 6.3

The distribution of pan surface types

	Surface types			
	Grassed	Partly grassed	Bare clay	
			Granular	Hard smooth
Samane	X			
Samosadi	X			
Bee	X			
Tatswe		X		
Sekoma			X	
Kongwe		X		
Keng		X		
Kgama			X	
Khakhea				X
Khesekwe	X			
Motsobonye			X	
Kokong		X		
Mashiaphotsana	X			
Mogatse			X	
Dead Tree			X	
Bosobogolo	X			
Mpaathutlwa			X	
Mabuasehube				X
Ukwi				X
Urwi			X	
Nwatle			X	
Masetleng			X	
Pussy		X		

Surface hydrology

All pans flood to some extent following heavy rains, but the nature of the flood waters and the way in which they occupy the pans varies considerably with the nature of the pan surface. The manner of flooding of pans of different types was observed following heavy rains in the Sekoma area in April 1973. Analyses of samples of water taken from Khakhea, Sekoma and Samane pans seven days after the rainfall event, were undertaken by the Botswana Geological Survey

Table 6.5

Chemical analyses by Geological Survey Department of water contained in pans 10th to 14th April, 1973

	Khakhea pan	Sekoma pan	Samane pan
pH	9.4	10.1	8.7
Anions (ppm)			
CO_3^{--}	116	102	20
HCO_3^{-}	672	139	291
Cl^{-}	1671	425	57
SO_4^{--}	257	38	8
F^{-}	2.5	1.5	0.6
Total Anions	2719 ppm	706 ppm	377 ppm
Cations (ppm)			
K^{+}	95	75	70
Na^{+}	1500	362	92
Ca^{++}	17	13	13
Mg^{++}	-	-	8
Total Cations	1612 ppm	445 ppm	183 ppm
Total Ions	4331 ppm	1151 ppm	560 ppm
Conductivity	5600 micromhos per cm	2000 micromhos per cm	640 micromhos per cm

Partly grassed pans, like Keng and Kongwe, were observed to be occupied by 10 to 20 cm deep sheets of water covering up to 30 % of the pan area. Regrettably, the water was too contaminated by cattle to permit analysis.

The bare clay pans appear to hold much more water than other types, and may flood completely to a depth of 50 cm, as was observed at Khakhea and Sekoma. The water in these pans is strongly saline or alkaline. A sample from Khakhea pan was observed to have a pH of 9.4 and a conductivity of 5600 micromhos per cm. The dominant anion was chloride, with bicarbonate, sulphate and carbonate important. The cations were dominated by sodium, with small amounts of potassium and calcium. Clearly, these waters are highly saline. The water contained in Sekoma pan was rather different in composition, being highly alkaline, with a pH of 10.1, and a conductivity of 2000 micromhos per cm. The anions were, like Khakhea, dominated by chloride, with bicarbonate and carbonate as secondary ions. Once again, the dominant cation was sodium, with potassium in small amounts. At Sekoma, in addition to sodium chloride, sodium bicarbonate appears to be an important salt, giving rise to the strong alkalinity.

The water is lost from all pans by evaporation and evapotranspiration, as all pan sediments appear to be impervious at some depth below the surface. The water in the pans appears to level out the surface and fill in holes made by game animals. In the later stages of drying at some bare pans, the top 10 cm of the pan sediments are a liquid mud, but lower down they are compact and only slightly moist. On drying the liquid layer may form a granular surface layer. There is no evidence, in the form of salt crusts, that groundwater reaches the surface of the pans.

THE PAN DEPOSITS

The pans of the southern Kalahari are underlain by a variable thickness of calcareous and alkaline clays, sandy clays and clayey sands. Around the pan edges calcretes and occasional silcretes may occur. They are overlain by calcareous sands, which extend up to 200 m from the pan edge. The nature of the deposits found on the pan edges suggests that they represent evidence of more extensive lakes in the pan depressions.

METHODS OF SEDIMENT ANALYSIS

Particle size distribution

The particle size distribution of the fine textured deposits was determined by the ASTM Bouyoucus hydrometer method as described in Black (1965), following dispersion in sodium hexametaphosphate. In addition all samples were wet seived to determine the distribution of the sand sized particles. Predominantly sandy deposits were wet seived only, following dispersion.

Chemical analyses

Calcium carbonate content was determined gravimetrically using the methods described in Chapter 5. The soluble salines content of pan samples was determined by measuring the electrical conductivity of a 1:5 soil suspension using a MEL conductivity bridge and a dip type cell, following the methods described in Piper (1946). The pH of samples was determined in the same soil suspension with the aid of a Corning/EEL pH meter.

In addition all samples were physically examined in the field and laboratory to determine their colour, structure and fossil content. The sand size (> 0.063 mm) fraction of all samples was examined under a binocular microscope for the shape and composition of the particles.

DESCRIPTION OF THE PAN DEPOSITS

The composition of the pan deposits was investigated by pits dug at a number of pans. Regrettably, time, and the indurated nature of many of the deposits permitted only the upper 1 to 2 m of them to be investigated. Samples of the pan surfaces were obtained at all pans.

Area 1

In this area, pits were dug to a depth of 1 m at Samane and Bee pans. The descriptions of the sections and the composition of the deposits are detailed in Table 6.6, and Fig. 6.1. At both pans the uppermost pan deposits are slightly to moderately calcareous clayey sands. They overlie moderately to highly calcareous blocky clays which occur at depths of 50 to 80 cm below the pan surface. The upper sandy deposits appear to thin out towards the centre of the pans, as comparison of the sections of pits 1 and 2 at Samane indicates, and may be absent altogether in the vicinity of the waterholes, which are floored by calcareous clays (Plate 26). It appears that the upper sandy deposits merge imperceptibly with the calcareous sands of the inner dunes and the inner slopes of the pan depression.

A sample of the pan surface at Samosadi pan shows it to have a similar composition to those of Samane and Bee pans. At Tatswe, a sample was taken from one of the extensive bare clay areas, which are overlain by thin sandy deposits towards the pan edges. Calcretes were found only as occasional small nodules in the deposits at Samane pan, but at Samosadi more massive calcretes may be found in the southeast corner of the pan where they are exposed by deflation. The inner slopes of the northern side of the pan depression at Tatswe are underlain by thin calcretes.

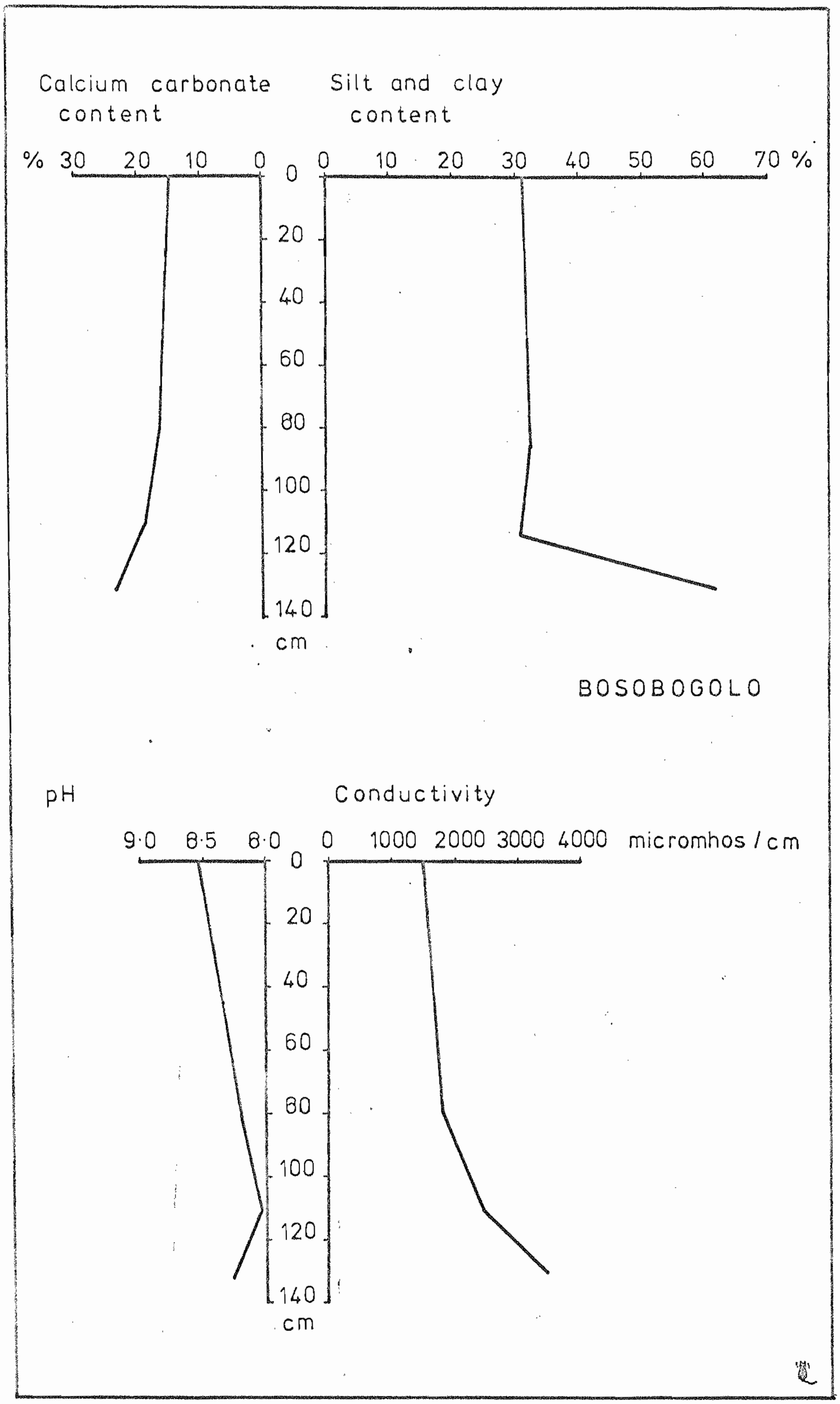


Fig. 6.5 Composition of pan deposits at Bosobogolo pan.

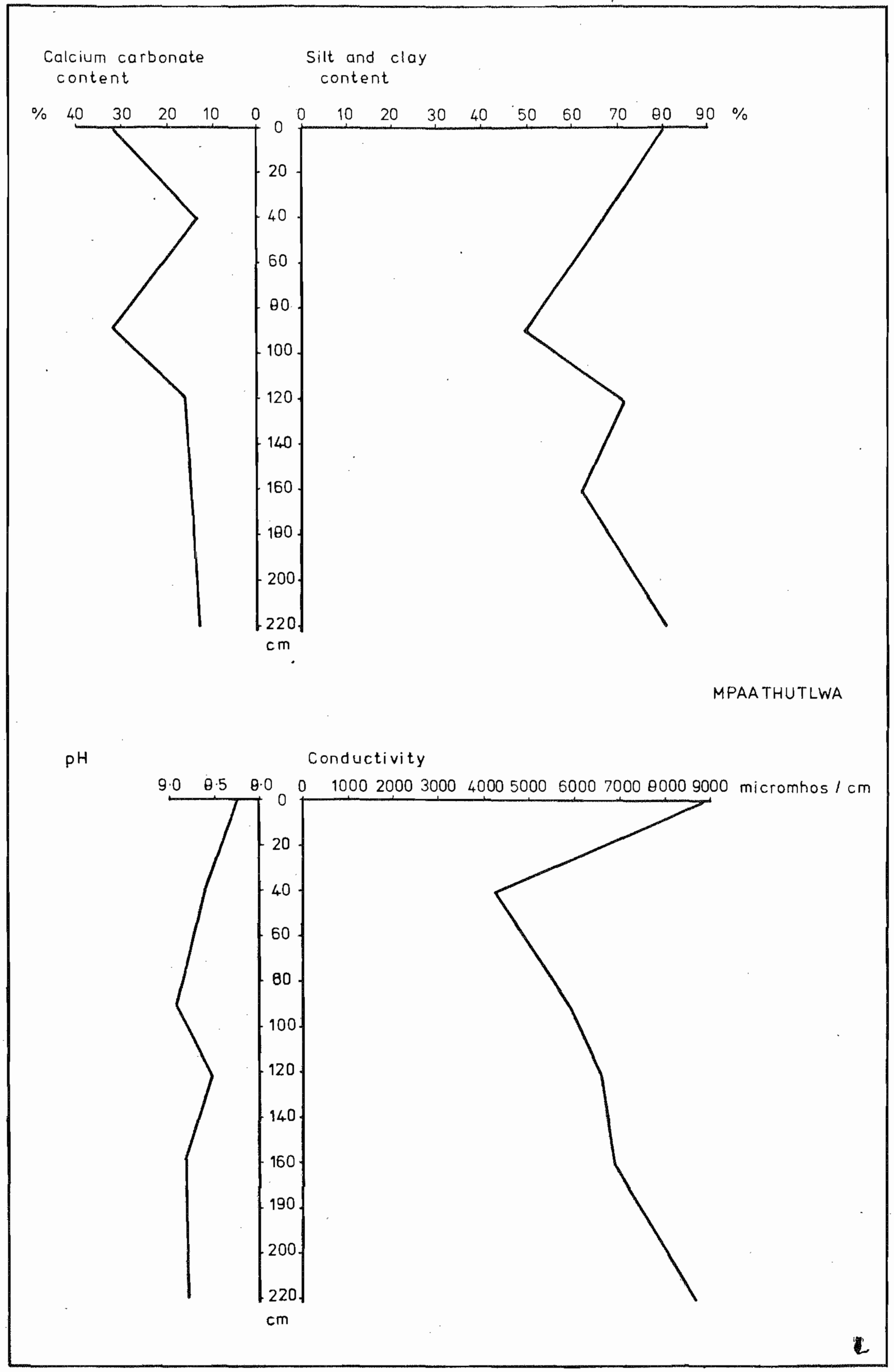


Fig. 6.6 Composition of pan deposits at Mpaathutlwa pan.

Area 5

Pan deposits were examined at Nwatle and Urwi pans in this area.

Nwatle pan has a bare granular clay surface. Below this lies 55 cm of very pale brown clay, passing down into a mixed deposit of pinkish grey and light grey calcareous clays. The sequence of deposits (Fig. 6.7) is in many ways very similar to that observed at Mogatse pan. In Nwatle pan there are "islands" of calcareous clayey sands which stand about 30 cm above the pan surface. They appear to represent residuals of the clayey sands that once overlay the present sandy clays of the pan surface.

The three adjacent pans of Nwatle, Masetleng and Pussy are all noteworthy for the very low (less than 15 %) silt content of their deposits.

A 1.6 m deep pit was excavated at Urwi pan (Fig. 6.8, Plate 28). Below the surface layer of fine granular clay lie 50 cm of greenish blocky clays. Below 90 cm the character of the deposits changes, and the clays are pale grey to white in colour, less saline and more calcareous. The sand content of the deposits is greater, and changes from angular silcretes and calcrete fragments to fine sub rounded quartz sand. A layer of very fine, white calcareous clay separates the two parts of the section. In general the conductivity of the pan deposits is an order of magnitude higher than other pans investigated, apart from Ukwi, and the clays are very strongly alkaline.

Ukwi pan, like Urwi pan, is saline. The surface of the pan is a hard smooth light coloured clay, broken by occasional outcrops of dark green silcretes and Ecca Series sandstones. The sand fraction of the surface is composed of opaque white, almost spherical, quartz grains, identical to those found in the pan edge dune.

Plate 28. Pan deposits at Urwi pan. White calcareous layer above shovel blade divides deposits into upper saline and lower calcareous parts.

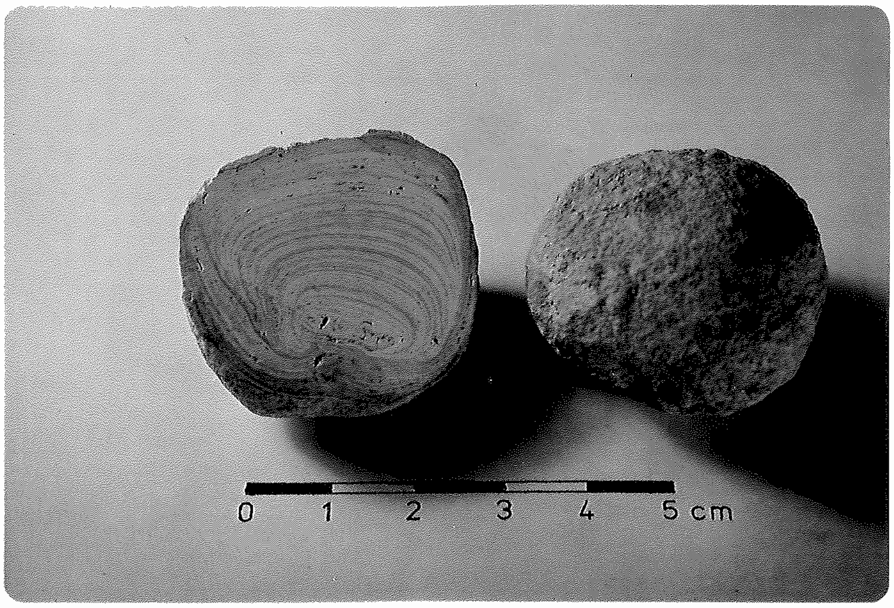


Plate 29. Stromatoliths from Urwi pan. Medial section of stromatolith on left.

Table 6.10

Description and analyses of deposits from pans in area 5

Pit section at Nwatle pan (Fig. 6.7)

1	0 - 5 cm	Light grey (10YR 7/2) blocky sandy clay
2	5 - 60 cm	Very pale brown (10YR 7/2) clay, with small reddish and greenish mottles
3,4	below 60 cm	Pinkish grey (7.5YR 7/2) and light grey (10YR 7/2) moderately calcareous clay (mixed)

Pit section at Urwi pan (Fig. 6.8, Plate 28)

1	0 - 20 cm	Loose fine granular pinkish grey (5YR 6/2) clay
2	20 - 40 cm	Fine granular pinkish grey (5YR 6/2) clay, with many small calcrete inclusions
3	40 - 60 cm	Blocky reddish grey (5YR 5/2) clay
4	60 - 90 cm	Coarse angular blocky very dark grey (5YR 3/1, moist) clay
5	90 - 100 cm	White (5YR 7/1) calcareous clay
6	100 - 120 cm	Light grey (5YR 7/1) clay
7	120 - 150 cm	Light grey (5YR 7/1) calcareous clay
8	below 150 cm	Compact reddish grey (5YR 7/1) clay

Analyses of pan deposits

	Sand %	Silt %	Clay %	Silt + Clay %	Calcium Carbonate %	Conductivity micromhos per cm	pH
Nwatle							
1	56	15	29	44	23.99	1280	10.0
2	38	4	58	62	11.18	5400	10.5
3	54	10	36	46	10.49	5500	10.4
4	60	10	30	40	11.37	2600	10.4
Urwi							
1	10	14	76	90	9.89	37800	8.3
2	18	29	53	82	15.57	25700	8.5
3	26	30	44	74	12.40	32400	8.5
4	23	29	48	77	10.18	37100	8.5
5	9	15	76	91	12.87	22750	8.7
6	22	16	62	78	18.64	11470	8.6
7	32	16	52	68	21.05	22800	8.7
8	23	26	51	77	11.97	15600	8.8
Pan surfaces							
Ukwi	26	29	45	74	12.63	24600	9.8
Masetleng	48	11	41	52	7.98	1148	9.4
Pussy	44	13	43	56	8.27	82	8.4

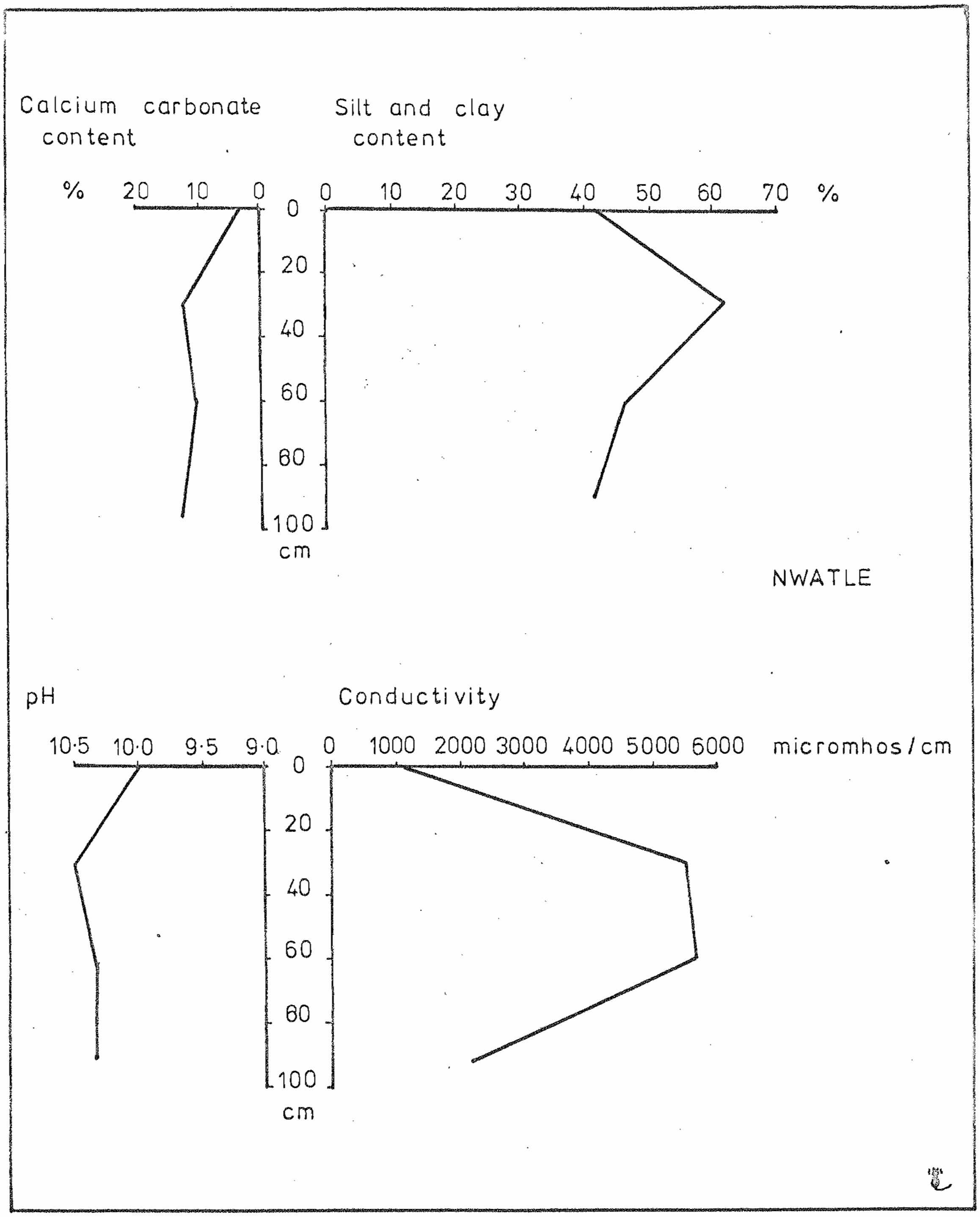


Fig. 6.7 Composition of pan deposits at Nwatle pan.

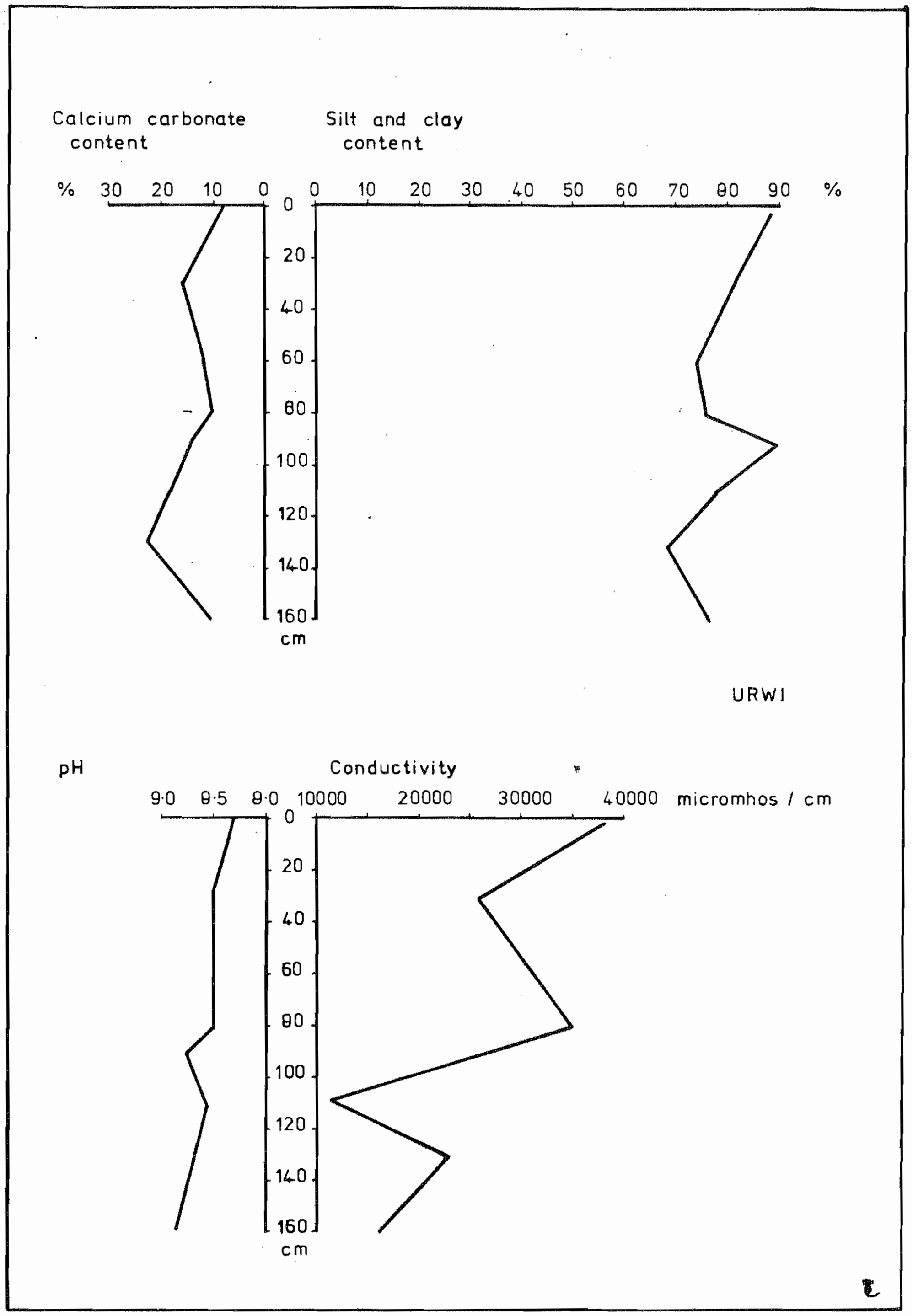


Fig. 6.8 Composition of pan deposits at Urwi pan.

THE COMPOSITION OF THE PAN DEPOSITS

From the descriptions of the pan deposits it is clear that they are dominantly moderately to highly calcareous clays, sandy clays and clayey sands. The distribution of the silt and clay content, calcium carbonate content, conductivity and pH of the pan deposits in the sections observed is illustrated in Figs. 6.1 to 6.8. The main features of the composition of the pan deposits are described below.

Particle size distribution

The pan deposits are in the main composed of material in the sand ($>$ 0.063 mm) and clay ($<$ 0.004 mm) size ranges. Silt sized material (0.004 to 0.063 mm) is a minor or subsidiary component of most pan deposits. Only at Khakhea, Keng, Mpaathutlwa and Mabuasehube pans do the deposits contain 30 % or more silt sized material. In addition the upper metre of the deposits at Mpaathutlwa pan contains significant amounts of silt. At all these pans the high silt content may be attributed to material derived from the weathering of adjacent rock outcrops.

The pan deposits may contain up to 85 % clay sized particles, although most pan deposits contain 35 to 55 % clay.

Where the pan has a bare granular surface, there is a sharp increase in the silt and clay content of the deposits immediately below the surface, and the surface may be considerably more sandy than the underlying deposits. Where the surface is of non granular type, as at Urwi and Mpaathutlwa pans, a decrease in silt and clay content occurs below the surface layer. At grassed pans the pan deposits may be divided into an upper dominantly sandy phase and a lower clayey phase, which are sharply divided.

In all cases much of the clay sized material is composed of colloidal particles with a diameter of 0.001 mm or less. The proportion of colloidal particles in most pan sediments is commonly 80 to 95 % of all clay.

The surfaces of most granular bare clay and grassed pans are sandy clays or clayey sands. Granular surfaces commonly contain 55 to

70 % sand sized material. Grassed pan surfaces are composed of similar material, which may contain 50 to 80 % sand.

Analysis of the sand fraction of the pan deposits shows that it has a similar composition to that of the adjacent inner dunes. Although some sand fractions, as at Mogatse pan, are coarser than dune sand due to the presence of large silcrete and calcrete fragments, the majority of the sand fractions of pan deposits have a mean grain size of 2.29 to 2.50 phi, which is similar to that of the outer dunes, but with a rather different distribution about the mean. It is common to find a high percentage of the sand in the fine sand range (3 to 4 phi), although the modal grain size is still in the medium sand range (2 to 3 phi). Most sand fractions are thus negatively skewed, often strongly so, and have low kurtosis values. The phi standard deviations lie in the range 0.79 to 0.98, indicating a moderate degree of sorting.

The sand fraction of most pan deposits is composed principally of sub angular to sub rounded quartz grains, which may be frosted, but are rarely stained in any way. Sub angular to sub rounded calcrete and occasional silcrete fragments generally form a minor part of the sand sized material, although locally they may be important. Angular fragments of silcrete, calcrete and weathered rock are locally important in the upper deposits at Khakhea, Mpaathutlwa and Mabuasehube pans. A general tendency is for the deposits which have higher sand contents to have higher calcium carbonate contents.

Clay mineral composition

According to Grim (1953) Van de Merwe and Heystek (1971) the dominant clay minerals in the deposits of the southern Kalahari pans are most probably illite with some montmorillonite, which form under conditions of high pH in arid to semi arid climates. Calcite is also likely to be an important constituent, in view of the calcareous nature of the deposits. The greenish colours observed in deposits at Urwi suggest the presence of chlorite or possibly glauconite, found in highly saline conditions.

Calcium carbonate content

The pan deposits at bare clay pans are generally moderately to highly calcareous and commonly contain 10 to 15 % by weight calcium carbonate.

At grassed pans the upper sandy deposits are slightly to moderately calcareous, and the lower clayey deposits are moderately to highly calcareous. The calcium carbonate content of the pan deposits tends to increase with depth from a point immediately below the pan surface to 80 to 90 cm depth.

The surface of granular clay pans may be more calcareous than the deposits immediately below them. At grassed pans there is a sharp increase in calcium carbonate content of the deposits on the contact between the sandy and clayey phases.

The main sedimentation trends for calcium carbonate content of the pan deposits are illustrated in Fig. 6.9. They show that the calcium carbonate content of all deposits is inversely related to their silt plus clay content, and directly related to the sand content. Similar relationships exist in sandy deposits of grassed pans, but there is generally a lower calcium carbonate content. In all cases the calcium carbonate content of the pan deposits is directly related to their colloidal clay content.

Fig. 6.10 shows that the calcium carbonate content of the pan deposits is inversely related to their conductivity. This relationship is particularly well marked in the sub surface deposits at Mogatse, Dead Tree, Nwatle and Urwi pans.

Conductivity

The electro conductivity of the pan deposits indicates that they fall into three groups, based on soluble salines content. The first group includes the sandy deposits at grassed and partly grassed pans, and the surface layers of granular clay pans. These are non saline to very slightly saline, with conductivities of less than 1000 micromhos per cm. The second group includes the sub surface deposits at all bare clay pans, and the clayey deposits of grassed pans, with conductivities between 1000 and 10000 micromhos per cm. These deposits are slightly to moderately saline. The third group consists of the highly saline deposits found at Ukwi and Urwi pans, with conductivities greater than 10000 micromhos per cm.

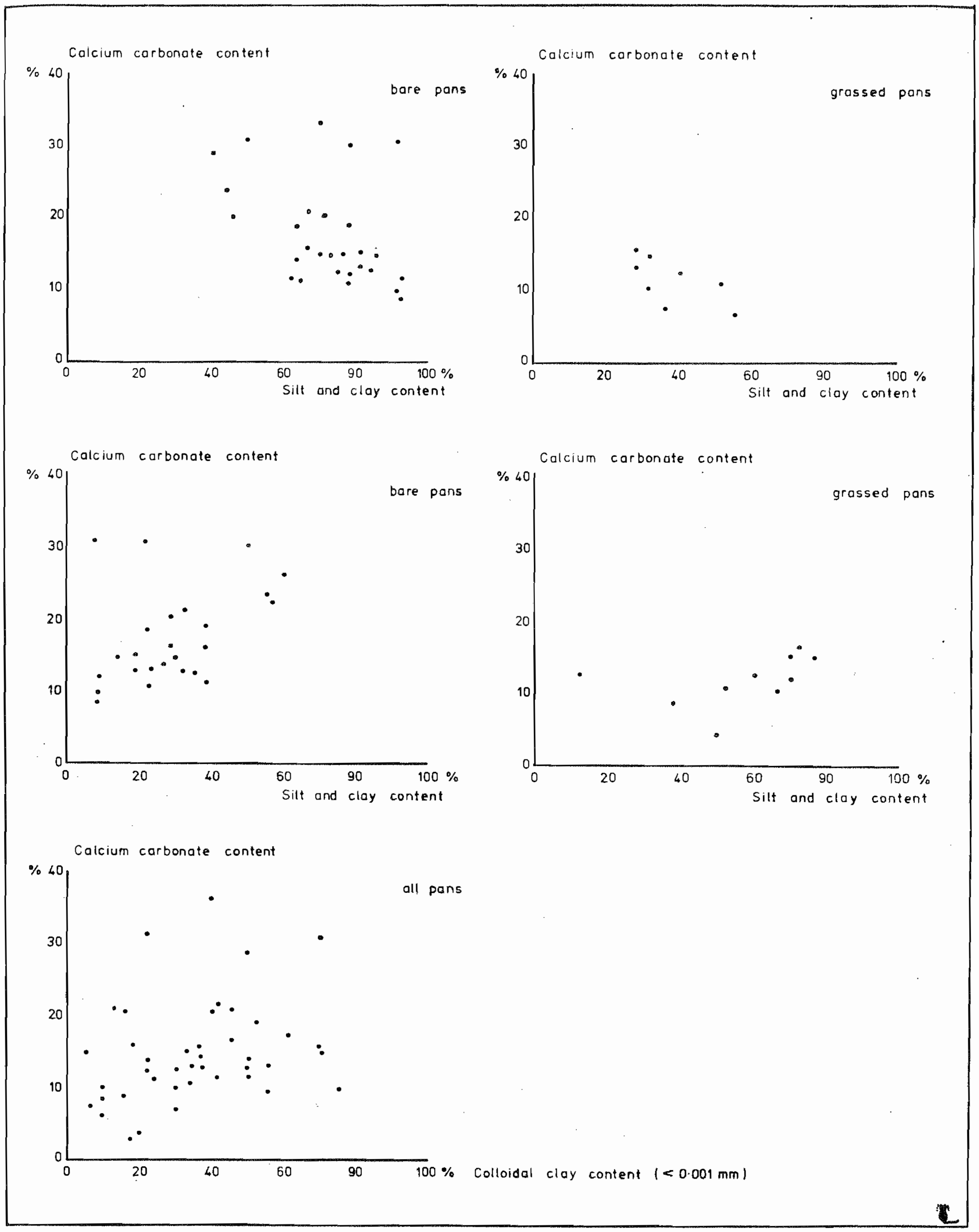


Fig. 6.9 Relationship between calcium carbonate content and silt and clay, sand and colloidal clay content of pan deposits.

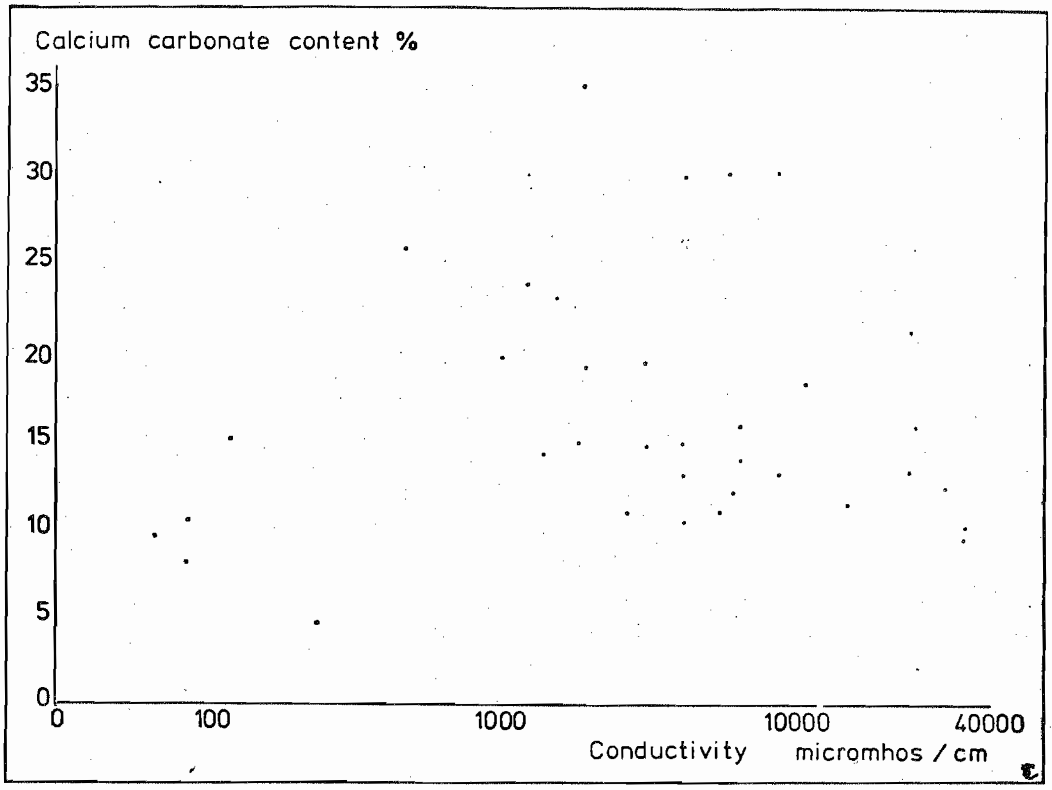


Fig. 6.10 Relationship between calcium carbonate content and conductivity of pan samples.

The distribution of conductivity values in the deposits underlying bare granular clay pans shows that the highest conductivities are found at a depth of 40 to 50 cm below the surface, although at Mpaathutlwa and Urwi pans conductivity values tend to fall from a maximum at the surface. The distribution of conductivity values within the sections observed is irregular, and sub surface horizons may be as saline as those at the surface, reflecting the varied nature of the deposits. At grassed pans there is a sharp increase in conductivity between the upper sandy and lower clayey deposits.

The sedimentation trends for conductivity (soluble salines content) are illustrated in Figs. 6.10 and 6.11. They show that conductivity is directly proportional to the silt and clay content, and colloidal clay content, of the pan deposits.

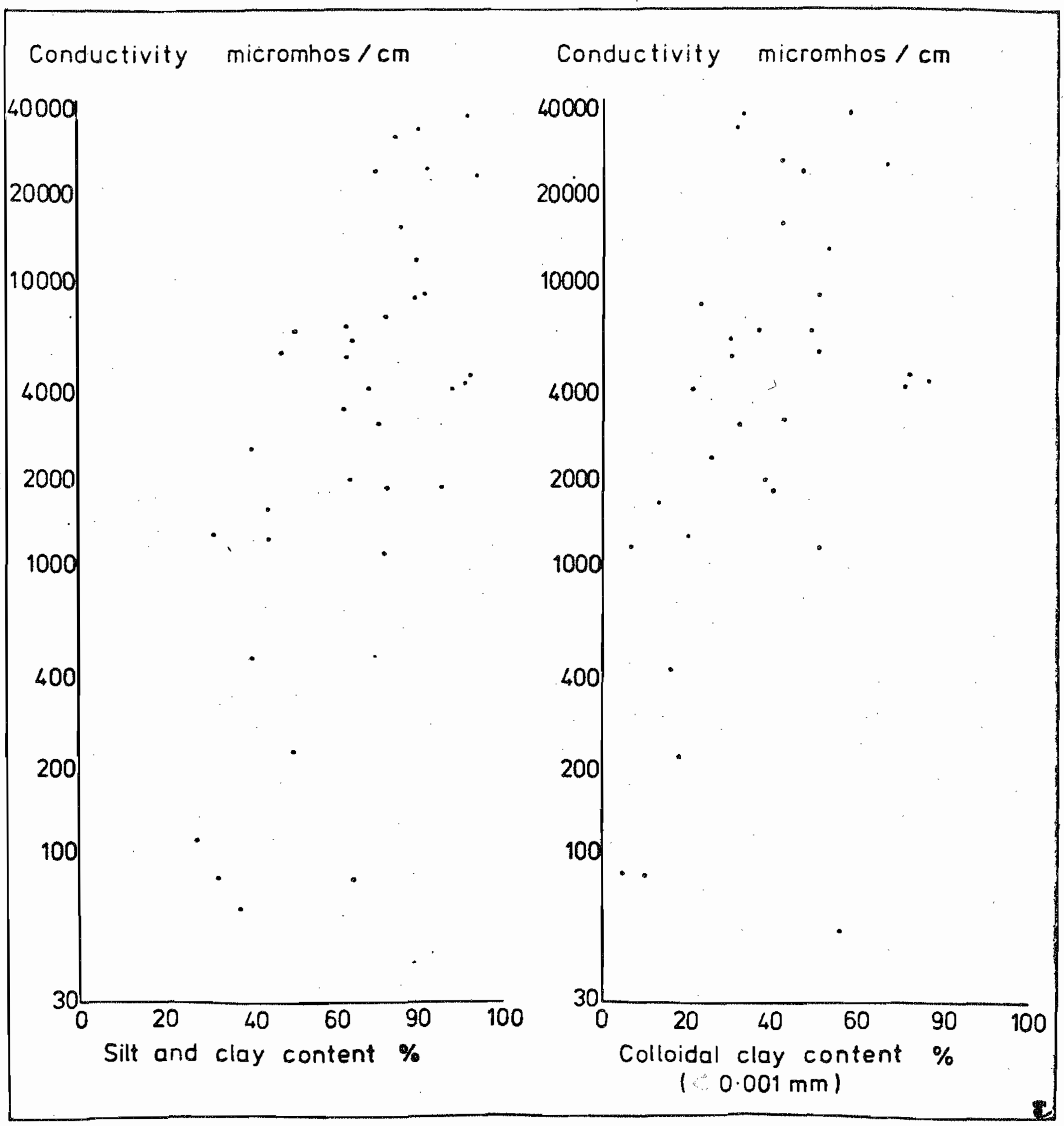


Fig. 6.11 Relationship between conductivity and silt and clay and colloidal clay content of pan deposits.

Conductivity is inversely related to the calcium carbonate, and sand, content of the deposits. It is interesting to note that the direct relationship between conductivity, or water soluble salines, and silt and clay content of the pan deposits is the opposite of that described by Kerr and Langer (1965) from the playas in the Mojave Desert, and by Krinsley, Woo and Stoertz (1968) from Australian playas. In these examples high salt contents are associated with coarse deposits.

pH

Most pan deposits are moderately to strongly alkaline, with pH values of 8 to 10.5, as a result of high calcium carbonate or soluble salts contents. More saline deposits, as at Ukwi and Urwi, tend to have lower pH values, in the range 8 to 8.5. The highest pH values appear to result from a combination of high calcium carbonate content and moderate salinity, as at Dead Tree and Nwatle pans.

There appears to be no consistent pattern to the distribution of pH in the sections examined, although the distribution of pH does follow that of calcium carbonate content in one or two cases.

RELATIONSHIP OF PAN SURFACE TYPES TO COMPOSITION OF PAN DEPOSITS

The pan surface deposits are of very variable texture, as figure 6.12 and Table 6.11 show. There is little relationship between the amount of silt and clay sized material present and the surface type. The surfaces of bare clay pans may contain as little as 33 %, or as much as 90 %, silt and clay. Similarly, the surfaces of grassed pans may contain between 23 and 64 % silt and clay sized material.

Generally the surfaces of bare clay pans are more calcareous or more saline than those of partly grassed and grassed pans. Bare clay pans tend to be slightly to moderately saline, whilst grassed pans are non saline.

An explanation of the surface type at any pan may be given after consideration of the composition of the uppermost pan deposits as a whole. At grassed pans the deposits consist of an upper sandy phase and a lower clayey phase. At bare clay pans, although the surface may be quite sandy, the deposits are predominantly compact and impermeable clays. The sandy deposits at grassed pans allow water to percolate and such pans are locally flooded only. In addition, the presence of a sandy layer effectively prevents capilliary rise of saline water. Bare floored pans flood extensively, and the salinity of the evaporating flood waters is high. The deposits present in grassed pans provide relatively favourable conditions for plant growth, whereas the compact, often saline, clays of the bare pans offer a hostile environment.

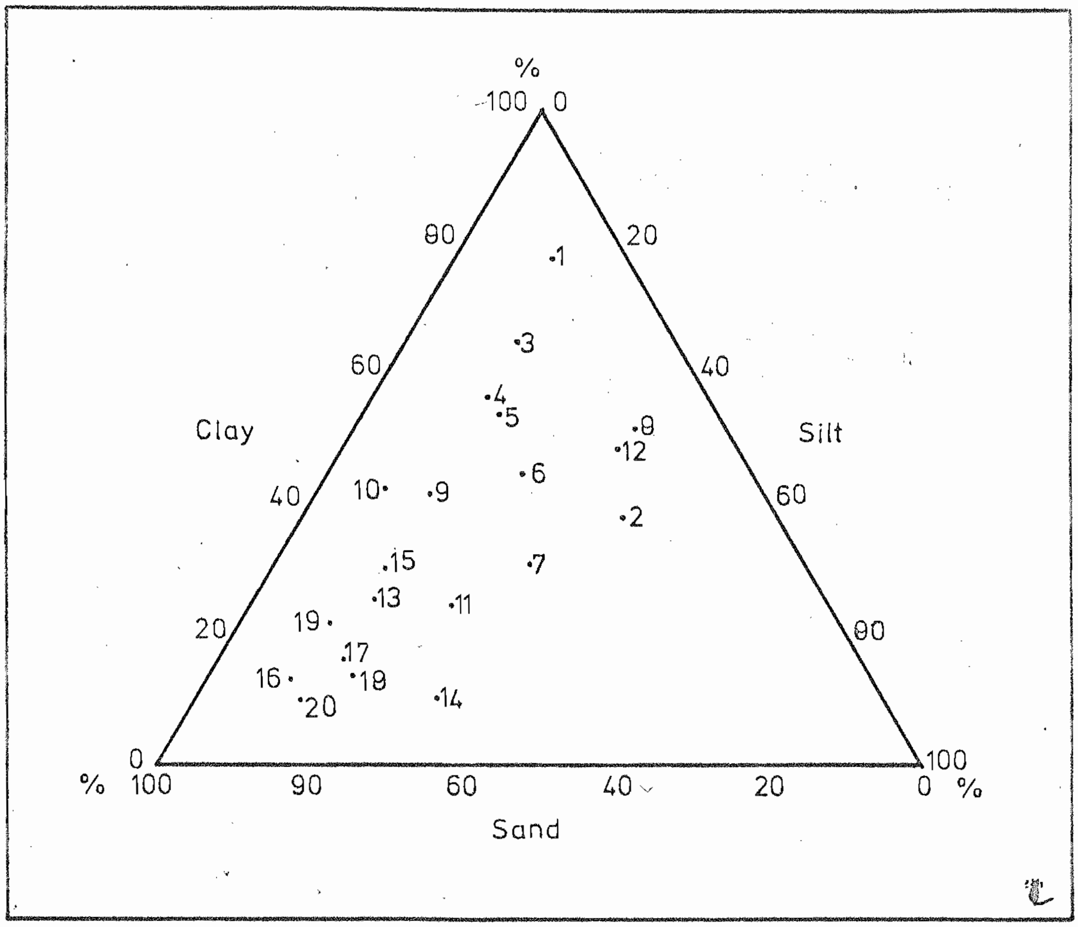


Fig. 6.12 Ternary diagram to show texture of pan surfaces.

For location of samples see Table 6.11.

Consequently, the field classification of a pan surface reflects not only the composition of the surface deposits, but the composition of the upper 1 to 2 m of the pan deposits as a whole.

Table 6.11

Composition of pan surface deposits

		Silt and clay Content %	Conductivity micromhos per cm	Calcium Carbonate Content %	Surface Type
1	Urwi	90	37800	9.89	B
2	Mpaathutlwa	79	8800	33.69	PG
3	Sekoma	79	2000	28.67	B
4	Ukwi	74	24600	12.63	B
5	Dead Tree	71	1080	13.18	B
6	Tatswe	70	338	13.78	PG
7	Khesekwe	64	82	7.89	G
8	Mabuasehube	62	3100	8.42	B
9	Pussy	56	82	15.79	PG
10	Masetleng	52	1148	7.98	B
11	Samane	50	230	4.13	G
12	Khakhea	50	2230	10.49	B
13	Nwatle	44	1280	23.99	B
14	Kongwe	41	120	3.99	PG
15	Mogatse	40	486	20.53	B
16	Mashiaphotsana	37	65	9.97	G
17	Motsobonye	33	2000	18.42	B
18	Kgama	32	4000	7.11	B
19	Bosobogolo	31	1400	14.77	G
20	Samosadi	23	185	8.25	G

Surface types: B - bare; PG - partly grassed; G - grassed.

EXTENT OF THE PAN DEPOSITS

A variety of evidence exists to show that the pan depressions once contained water bodies which covered areas up to three, and exceptionally six, times that of the present pan area.

At some pans, for example Keng, Khesekwe, Mogatse, Dead Tree and Nwatle, the present pan may be bordered by flats up to 100 m wide, which lie 50 to 100 cm above the pan datum and are underlain by calcretes and calcareous clays. Where the pan has a bare clay surface there is a sharp rise from the pan to these areas. At

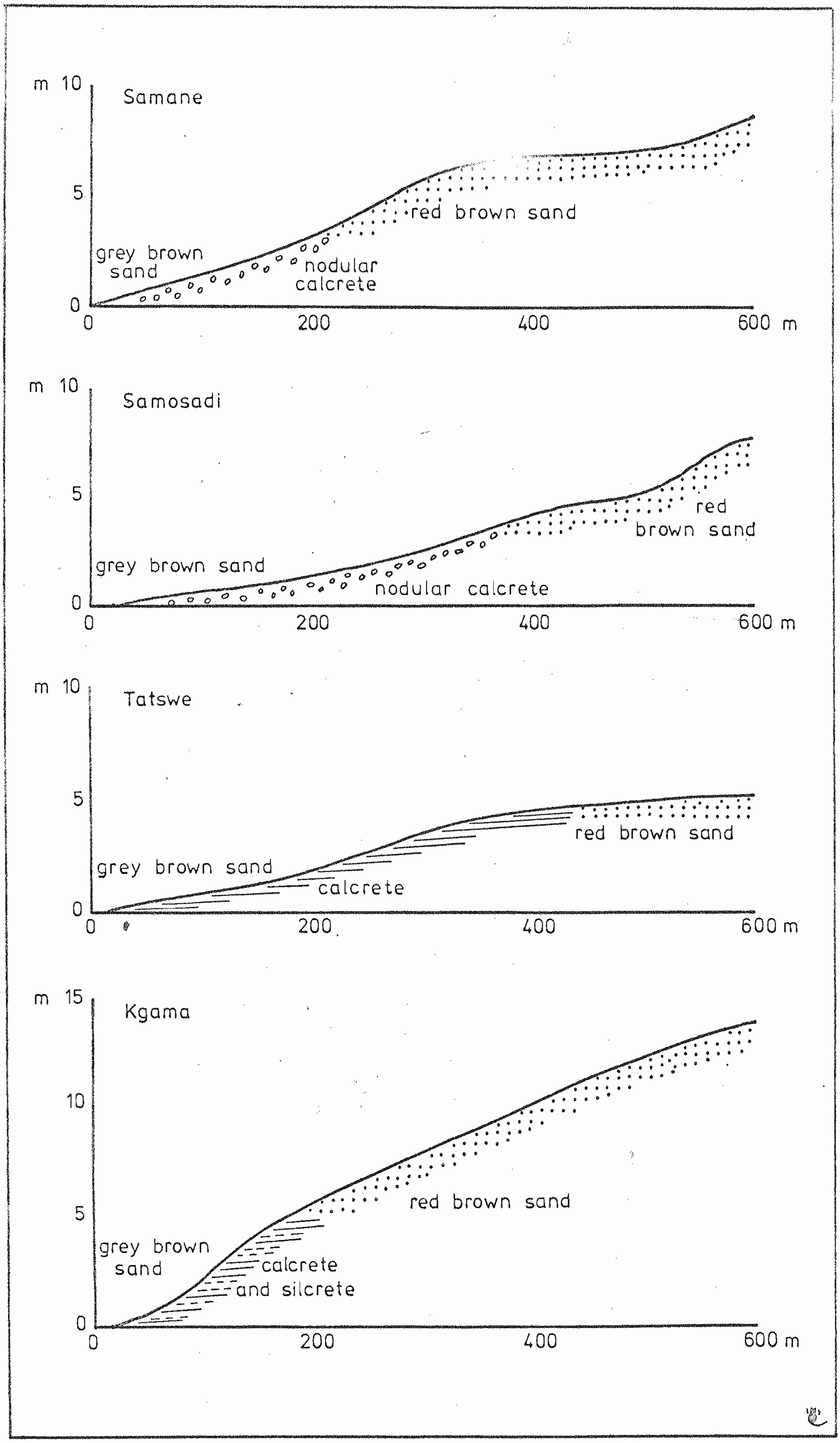


Fig. 6.13 Relationship of deposits on north side of selected pans.

Nwatle pan the flats are particularly extensive, and the pan is separated from the inner dune by an area of slightly calcareous sandy clay 300 m wide, which is underlain at a depth of 80 cm, by a compact calcareous clay, which closely resembles deposits found under the present pan. The composition of the upper sandy clay (63.5 % sand, 36.5 % silt and clay, 5.88 % calcium carbonate) is very similar to that of the deposits forming the upper sandy phase at grass floored pans. On the northern side of the pan, an area of calcareous sands underlain by calcretes and calcareous clays, extends for 700 m from the pan edge. Two hundred metres from the pan edge, 40 cm of clayey sand overlies friable calcretes, which contain fragments of mollusca, whilst 500 m from the pan edge, the sands thicken to 60 cm and overlie compact calcareous sandy clays (73 % sand, 27 % silt and clay, 7.89 % calcium carbonate), which are similar in composition to the calcretes nearer the pan. Deposits of this nature, at depths of 60 to 80 cm, may be found up to 700 m from the pan edge, where they appear to die out suddenly. At this point there is a transition from grey brown sand to red brown sand, accompanied by a vegetation change.

At many pans these flats are not present, and the inner slopes of the pan depression start at or near the pan edge. At bare surfaced pans the edge of the pan is clearly marked, but at grassed pans a slight break of slope is all that marks the pan edge. The inner slopes of the pan depression are composed of grey brown (10YR 6/2) slightly to moderately calcareous sands, with clayey sands around the pan edge. These sands may extend for 300 m from the pan edge on the eastern and western edges of the pan, and to 1000 m from the northern edge of the pan. Their limits may be marked by a break of slope at 3 to 4 m above the pan datum. In all cases the transition from grey brown to red brown sands is marked by a vegetation change, from "pan vegetation" to "Kalahari vegetation", the most notable feature of which is an increase in the grass cover.

Calcrete nodules are often present at the surface of the inner slopes of the pan depression. They usually indicate the presence of more extensive calcretes at a depth of 30 to 50 cm. Commonly calcretes may outcrop at the edges of bare and partly grassed pans, but remain below the surface at grassed pans. Away from the pan the calcretes are more deeply buried and may well be less strongly indurated. The relationships between the deposits on the northern edges of several pans are illustrated in Fig. 6.13.

Table 6.12 shows the composition of selected calcretes from the inner slopes of the pan depressions. Many of the calcretes appear to be indurated clays and sandy clays, and contain 40 to 50 % clay sized material. Some contain fragments of mollusca, as at Samosadi, Tatswe and Mwatle pans. Where the calcretes are exposed around the edges of the present pan they are frequently secondarily cemented with silica, resulting in their being very strongly indurated. In many cases, a transition towards the pan edge from calcretes to silcalcretes and locally silcrete occurs. A good example of this exists at Khakhea, where calcretes 50 to 100 m from the pan edge grade into silcalcretes and silcretes towards the pan.

Not all calcretes on the pan margins can be regarded as indurated pan deposits. At Khakhea massive calcretes 2 to 3 m thick top a 5 m high bluff on the northern side of the pan. Extensive calcretes, often containing angular fragments of Waterberg sandstones may be found around the edges of Sekoma pan. At Ukwi pan massive calcretes form a 4 m high cliff along the northern side of the pan. The massive nature and topographic position of these calcretes indicates that they must be regarded as remnants of local or regional calcretes, through which the pan depression has been excavated.

Calcretes are infrequently found at or near the surface in the vicinity of the inner dune. At Sekoma, Kgama and Ukwi they are probably regional calcretes. At Khesekwe pan calcretes are locally exposed in the interdunal depression, and other parts of this area are underlain by calcretes at a depth of 1 m. Their composition suggests that they are indurated clays and sandy clays deposited when the pan held a much larger water body.

At Masetleng pan a discontinuous zone of calcretes at or near the surface rings the pan at a height of 3 to 5 m above pan datum. The zone is particularly extensive on the north and northwest sides of the pan, and its topographic position suggests once again that the calcretes are indurated pan deposits.

Table 6.12

The composition of calcretes from pan depressions

	Calcium Carbonate %	Insoluble Residue %	Nature of Insoluble Residue
Samosadi	31.25	68.75	Clay and small silcrete fragments
	39.02	60.98	Clay and opaline silica (39 %)
Tatswe	46.83	53.17	Clay
	47.69	52.31	Clay
Sekoma	32.56	67.44	Clay (26.44 %)and Silcrete (41 %)
	29.05	70.95	Sandy clay
	40.00	60.00	Clay
Kgama	53.36	46.64	Clay
	69.52	30.43	Greenish clay (29.43 %) and silcrete (1 %)
Keng	43.69	56.31	Sandy clay
Khesekwe	69.81	30.19	Sandy clay
	69.70	30.19	Sandy clay
	44.65	55.35	Sandy clay (39 %) and silcrete (16.35 %)
Masetleng	30.01	69.99	Sandy clay
Inferred regional calcretes			
Sekoma	19.17	80.83	Quartz sand (31 %) and silcrete (49.83 %)
Kgama	18.64	81.36	Quartz sand (69.5 %) and silcrete (12.36 %)

Deposits and topographic features that can be definitely regarded as marking the shoreline of a lake in the pan depression are rare, and only at Urwi pan was an actual beach deposit located. At Urwi, 50 m from the edge of the present pan, 50 to 60 cm of soft brown sand overlies a sloping deposit of calcareous sandy clay. Set in this matrix are abundant rounded, almost spherical, calcareous nodules 2 to 5 cm in diameter, (Plate 29) which are composed of laminated calcareous and siliceous material. Their general form suggests that they are stromatoliths, or laminated biosedimentary structures (Hofman 1973), which are formed by the trapping and binding of sediment together with the chemical action of blue green algae in shallow saline waters.

Most stromatoliths, both fossil and Recent occur in shallow marine environments, but Stromatoliths from lacustrine environments have been reported from other parts of the Kalahari by Kalkowsky (1908) and, more recently, from the Etoscha pan area of Namibia (South West Africa) by Martin and Wilzewski (1972). They have also been described from many other parts of the world including the Great Salt Lake of Utah, U.S.A. and Ethiopia (Grove, Street and Goudie 1975). Lacustrine stromatoliths appear to form in conditions of moderate salinity that favour more widespread carbonate precipitation.

Topographic features marking the position of shorelines of more extensive water bodies in the pan depressions are rare, due to the unconsolidated nature of the deposits surrounding the pans. However, where massive calcretes outcrop, shoreline features may occur. At Sekoma pan a 2 to 3 m high bench formed in massive calcretes containing sub angular fragments of Waterberg sandstones may be found on the southwest side of the pan, some 100 m from the pan edge. A notch at the base of the massive calcretes on the north sides of Khakhea pan (Plate 6) may be the result of wave action. The bluffs in massive calcretes that occur on the northern sides of Urwi and Ukwi pans may also be the result of wave action in more extensive water bodies. Small notches up to 1 m high occur on the southern edges of Keng, Motsobonye and Ukwi pans and appear to indicate that the pans have recently contained more permanent and extensive water bodies.

Reliable estimates of the depth of deposits in the pan depressions are difficult to obtain. The information that does exist suggests that pan deposits are at most 2 to 3 m thick. The indurated nature of the pan deposits did not permit the writer's investigations to penetrate below a maximum depth of 2 to 3 m. Boreholes drilled in pans are rare and the records for the uppermost deposits penetrated frequently incomplete, but records for a borehole at Tatswe pan show that is penetrates 0.6 m of clays, presumed to be pan deposits, below which are sandstones and silcretes. Wells dug into pans are occasionally encountered. At Khesekwe pan a well in the northern corner of the pan intersects some 2 to 3 m of whitish calcretes and calcareous clays. Wells at Sekoma, Keng and Kgama pans penetrate 1 to 2 m of greenish clays and silcretes that overlie pre Cambrian

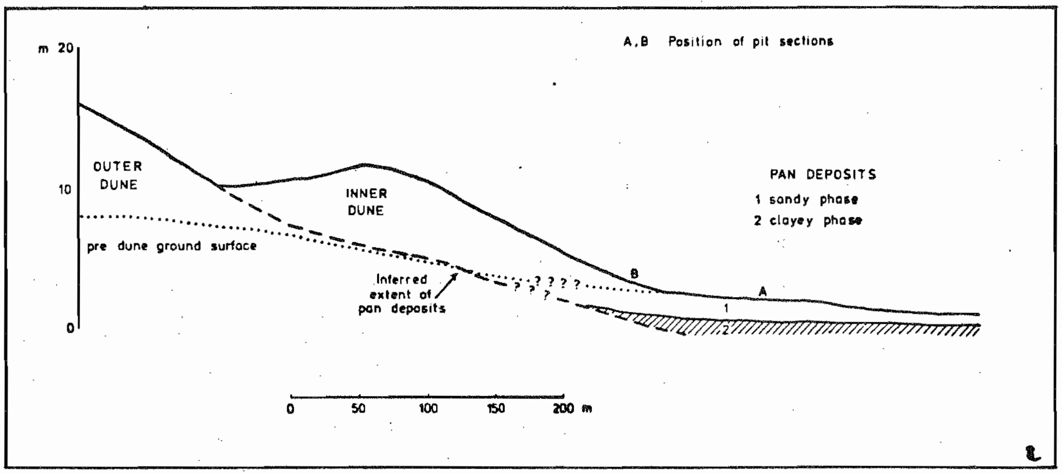


Fig. 6.14 Relationship of pan deposits and dunes at Samane pan.

rocks. At Mashiaphotsana pan a dry well intersects 1.5 m of sandy clays and calcretes overlying green quartz sands. Elsewhere the presence of pre Kalahari rock outcrops in or near the floors of the pan depressions indicates that the depth of deposits is small.

Relationship of pan deposits to dunes

Investigations at a number of pans suggest that the pan deposits underlie the panward slopes of the inner dunes.

The relationship of pan and dune deposits at Samane pan is illustrated in Fig. 6.14. Thirty metres from the pan edge a pit 2 m deep intersected 1.5 m of calcareous sand overlying a calcareous clay. One hundred and fifty metres from the pan edge a further pit section intersects 2.8 m of calcareous sands overlying a calcareous sandy clay, which would appear to mark the limit of the lower clayey phase of the pan sediments.

Similar relationships were observed at other pans. At Bosobogolo pan a pit 30 m from the pan edge intersects 1 m of slightly calcareous grey brown sand overlying a compact calcareous clay

(50 % silt and clay, 12.18 % calcium carbonate), similar to clays intersected by pits in the pan itself. A pit 150 m from the edge of Mpaathutlwa pan revealed 1.25 m of calcareous sand overlying a compact calcareous clay. The shoreline deposits described above from Urwi pan also underlie the inner dune flanks.

THE FORMATION OF THE PAN DEPOSITS

The general nature of the pan deposits suggests that they were laid down in shallow enclosed alkaline water bodies. The particle size composition of the pan deposits indicates that sand and clay sized material are the dominant constituents. This has been held (Motts 1965) to indicate deposits laid down under humid climates in which rock surrounding the lake basin is completely weathered. In the case of the southern Kalahari, the general lack of silt sized material in the pan deposits is the result of an absence of rock outcrops over much of the region and is not necessarily an indication that the pan deposits were laid down under humid conditions. Where rock outcrops do occur in the vicinity of the pans appreciable quantities of silt sized material are present in the deposits. The fine grained nature of the majority of the pan deposits and the presence of colloidal clays, would suggest that runoff was low when they were formed.

Many of the pan deposits have a moderate to high calcium carbonate content, suggesting that chemical precipitation was important in their formation. The high pH, causing precipitation of calcium carbonate, was the result of the evaporation of the lake waters, or photosynthesis by algae, or a combination of both processes.

The sand in the pan deposits may result from aeolian or fluvial deposition. In any event the source material was the surrounding Kalahari sands, and the particle size distribution of the sands, with a high proportion of material in the fine sand fraction, would suggest that the sand in the pan deposits is fluvially reworked.

The irregular distribution of calcium carbonate and soluble salines in the pan deposits indicates that relatively little redistribution of these components has taken place after sedimentation. In any event, the impermeable nature of the pan deposits would make this unlikely. The close inverse relationship between conductivity and calcium carbonate content suggests that the calcium carbonate and soluble salines contents of the pan deposits represent original depositional conditions.

The association of higher calcium carbonate contents with more sandy deposits indicates that they were formed in conditions of relatively high runoff, permiting the transport of coarser material to the pan floors. Higher runoff may have been brought about by a higher rainfall, which would result in more abundant vegetation and hence a higher bicarbonate (HCO_3^{-}) content of the runoff water, which would promote more deposition of calcium carbonate in the pans (Reeves 1968).

The association of higher conductivities with clay rich deposits indicates that they were laid down in conditions of very low runoff. Under these conditions it is probable that the water bodies in the pans evaporated more completely and halite and similar salts were precipitated in addition to some calcium carbonate.

On this basis, the upper sandy deposits preserved in grassed pans appear to have been laid down under conditions of high runoff, resulting in the inwashing of sands from the slopes of the pan depressions, as the water bodies in the pans steadily contracted.

Many of the clayey deposits on the margins of the pans have undergone post depositional calcification, and secondary silicification as a result of pedogenic processes, which indicates the existence of semi arid and subsequently arid climates following their deposition.

STRATIGRAPHY OF THE PAN DEPOSITS

Consideration of the composition and occurence of the different deposits located in and around the pans of the southern Kalahari suggests that they may be divided into an upper, dominantly sandy, phase, and a lower clayey phase.

The upper sandy phase forms the surface deposits at grassed and some partly grassed pans. It is largely absent from the area of the present pan at most partly grassed and bare clay pans, having been probably removed by deflation. Deposits of a similar nature form an anulus of calcareous sands and clayey sands around all pans, extending for up to 1 km from the pan edge on the northern side of the pan and 100 to 200 m from the pan edge elsewhere. The limits of these deposits may be 3 to 5 m above the pan datum.

The lower clayey phase is found at all pans. It is exposed in the waterhole areas and bare clay areas of grassed and partly grassed pans, and forms the surface of bare clay pans. The clayey phase may be tentatively divided into an upper fine grained moderately calcareous part, which is frequently moderately saline; and a lower calcareous part containing rather less soluble salines and more sand sized material. At Mpaathutlwa and Urwi pans there are signs that this may be preceeded by a fine grained, moderately calcareous, saline phase.

A tentative stratigraphy of the pan deposits may be summarised as follows:

Upper sandy phase - coarse grained, slightly to moderately calcareous, non saline.

Lower clayey phase -

1	moderately calcareous, fine grained, saline
2	highly calcareous, sandy, moderately saline
3	fine grained, saline

and appears to represent a situation in which the water bodies in the pans have steadily contracted over a period of time.

CONCLUSIONS

This chapter has described the morphometry of the pans and the pan depressions. The extent and nature of the deposits laid down in the pan depressions has been described.

The pans are sub circular to sub elliptical in shape and are contained in isolated sub circular depressions. The shape of the depressions strongly suggests that they are of deflation origin. The shape of the pans represents a balance between deflation processes which tend to elongate the pan downwind, and end current erosion, which has taken place when the pans contained water and which tends to elongate the pan perpendicular to the direction of the prevailing winds. The three characteristic pan surface types which exist, grassed, partly grassed and bare clay, are all apparently of the surface water discharging type (Motts 1965).

The deposits laid down in the pan depressions are composed principally of clays, sandy clays and clayey sands. The sandy clays and clays are commonly moderately to highly calcareous, and slightly to moderately saline. The composition of the pan deposits suggests that they were laid down in shallow water bodies, with a moderate to high pH. Their extent suggests that the pan depressions were occupied by water bodies with an area 2 to 3 times that of the present pans. The pan deposits may be divided into an upper sandy phase and a lower clayey phase. The upper sandy phase forms the surface of grassed pans and is present around the majority of bare clay pans. It merges with similar deposits on the inner slopes of the pan depression which are frequently underlain by calcretes, calcareous clays and sandy clays. Deposits similar to those of the clayey phase underlie the flanks of the inner dunes. The lower clayey phase may be divided into an upper fine grained saline part and a lower calcareous sandy part.

The composition of the pan surfaces suggests that particle size distribution alone does not determine surface type. Grassed pan surfaces are developed only on the upper sandy phase deposits, which are non saline. Bare clay surfaces appear to be developed in the clayey phase, when the upper sandy phase has been removed by deflation. The impermeable nature of the subsurface deposits prevents water percolation and their salinity offers a hostile environment to plants. Bare clay surfaces are invariably found at the deeper pans, whilst grassed and partly grassed surfaces are associated with shallower pans. The deeper parts, and waterholes, of grassed and partly grassed pans have bare clay surfaces. It is suggested that the pan surface types represent a sequence of development as the pan has been excavated by deflation.

The existence of deposits of lacustrine origin in the pan depressions in the interval between formation of the outer and inner dunes provides clear evidence for a period in which the climate in the Kalahari was substantially wetter than today. The stratigraphy of the deposits indicates that conditions of high runoff and probable permanent lakes, were succeeded by conditions of low runoff and seasonal lakes, which in turn gave way to ephemeral or completely dry lakes or playas. Under present conditions, with an annual rainfall of 300 to 350 mm and an annual evaporation from a lake surface of some 2600 mm, it is not surprising that the pans are occupied by ephemeral lakes and runoff is incidental. Clearly, more extensive and more permanent lakes must be the products of substantially wetter conditions. Given similar evaporation rates to those of today, rainfall amounts of 1000 to 1200 mm per annum, a 3 to 4 fold increase, would be necessary to sustain lakes twice the size of the present pans. Alternatively it is possible that the lacustrine period was accompanied by much reduced evaporation, as a result of lowering of temperature during glacial periods. Assuming a 5 ^{o}C fall in temperature during the late glacial, which other workers in southern Africa have adopted (Butzer 1973), a 30 % reduction of evaporation is probable. Even if this were the case, rainfall would still have to be twice the present amount to sustain permanent lakes of up to 4 km^2 in the pan depressions.

The sequence of calcification and secondary silicification of the deposits on the pan margins are consistent with a gradual dessication of the climate during the deposition of the pan deposits.

In conclusion the pan deposits represent evidence for substantially wetter conditions in the period between the formation of the outer and inner dunes. The uppermost pan deposits appear to represent the source of material for the formation of the inner dunes.

CHAPTER 7.

CONCLUSIONS

The preceeding chapters have described the main features of the geomorphology of the pans of the southern Kalahari. The pans, which are situated in isolated sub circular to sub elliptical depressions 1.5 to 4 km across and 10 to 30 m deep, are underlain by up to 4 m of calcareous and saline clays, sandy clays and clayey sands. There is evidence to suggest that the pan depressions formerly contained water bodies up to 3 times the area of the present pans. On the southern side of the pans is an area of arcuate dune ridges rising to a height of up to 40 m above the pan datum. Two dune ridges can be identified: an outer dune of red brown quartz sand, and an inner dune of grey brown quartz sand and up to 20 % calcareous clay sized material. The inner dune is partly underlain by the pan deposits. The pans may be found in a belt up to 300 km wide along the watershed between the Nossop-Molopo and Makgadikgadi drainage systems.

The aim of this concluding chapter is to draw together the evidence relating to the formation of the pan depressions, the fringing dune ridges, and the deposits of the pan depressions in order to present a coherent picture of the origin and development of the southern Kalahari pans, and to discuss their paleoclimatic implications.

THE ORIGIN AND DEVELOPMENT OF THE SOUTHERN KALAHARI PANS

In detail, the evidence presented in the preceeding chapters suggests that the exact nature of the development of each pan is slightly different. Thus the size and morphology of the fringing dunes can be shown to be a function of the size and shape of the pan depressions. Occasionally the bulk of the outer dunes is much smaller than would be expected. In some examples, such as at Nwatle or Ukwi pans, the bulk of the inner dune is greater than that of the outer dune and indicates that the second phase of dune building at these pans was much more effective than the first. Exceptionally, as at Ukwi and Urwi pans, three phases of dune formation can be recognised. At Urwi all the dunes are inactive, whilst at Ukwi the pan edge dune is still receiving material today. Occasionally, as at Khakhea pan, there may be no recognisable dunes at all, which can be explained in terms of the local circumstances. Khakhea pan is surrounded by outcrops of the Waterberg System, particularly shales and siltstones of the Matsap Beds. The weathering products of these rocks are silt and clay sized particles, which would tend to be removed from the area altogether as dust, rather than move to the edge of the deflation area as saltation sands.

The pan deposits are generally uniform in their composition, although the sequence of deposits underlying the pans does vary. The nature of the pan surfaces may be related to the amount of deflation of the upper sandy phase of the pan deposits that has taken place. Where removal of the sandy phase has been complete, the clayey phase is exposed giving rise to a bare clay surface, but where its removal has been less complete partly grassed or grassed pan surfaces occur.

However, despite the variability in pan shape and size, pan surface composition and the size and morphology of the dunes, the evidence presented shows that there have been three main phases in the development of the southern Kalahari pans. These are illustrated in Fig. 7.1.

Two periods of dune building can be recognised, in which the outer and inner dunes were formed. In the interval between these was a period in which the pans contained shallow water bodies, initially more extensive than at present, but gradually contracting thereafter.

In the following sections the evidence relating to the origin of the pan depressions and to the subsequent development of the pans will be discussed.

THE ORIGIN OF THE PAN DEPRESSIONS

The depressions containing the pans of the southern Kalahari have a distinctive form and distribution. They are isolated, sub circular to sub elliptical in shape, and located in a belt in the watershed area between the Makgadikgadi and Nossop-Molopo drainages. The distribution of the pans is clustered, and is best described by a situation in which the pans are randomly distributed, but their density varies from place to place. The pan depressions do not form any recognisable aligned groupings or patterns and are

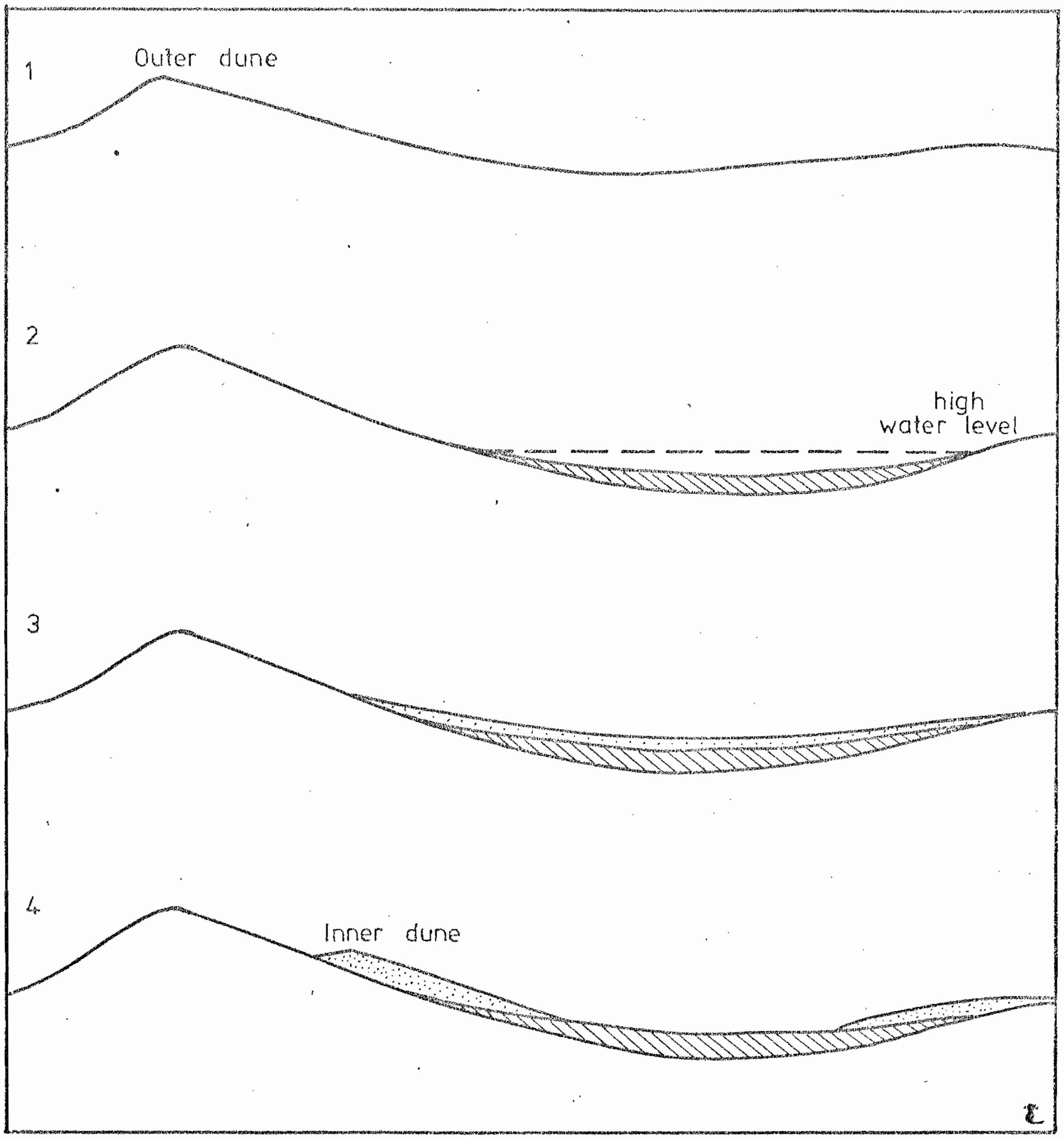


Fig. 7.1. Development of the southern Kalahari pans. (not to scale).

1. Deflation to form outer dune.
2. Deposition of clayey phase of pan deposits.
3. Deposition of sandy phase of pan deposits.
4. Deflation of sandy phase deposits to form inner dune.

characteristically elongated in a north northeast - south southwest direction, parallel to the prevailing winds of today. The evidence of the morphology and distribution of the pan depressions, by analogy with similar features elsewhere in the world, particularly in west Texas, U.S.A., strongly suggests that they were formed by deflation.

Additional evidence for a deflation origin for the pan depressions exists in the form of the fringing inner and outer dunes on the southern edges of the depressions. The sub parabolic form of the outer dunes, their position on the southern edge of the pan depression, and their composition of moderately well sorted red brown quartz sand, suggests that they represent material deflated from the sites of the pan depressions. The inner dunes, with their position against the panward face of the outer dunes, and their composition of mixed grey brown quartz sand and calcareous clays, appear to represent material deflated from the floors of the pan depressions.

A close relationship exists between the size of the dunes and the area and depth of the pan depressions. This provides, in the absence of volumetric relationships, a strong indication that the bulk of the dunes corresponds closely with the amount of material deflated from the depression.

THE DEVELOPMENT OF THE PANS

Following a period of deflation in which the outer dunes were formed, there is evidence, in the form of clays and other lacustrine deposits, which indicates that the pan depressions held water bodies up to 3 to 4 times the area of the present pan. Topographic features or deposits marking shorelines are rare, but clays and sandy clays, thinly covered by sand and often partially or wholly calcified or silicified, may be found 200 to 300 m from the pan edge, and at heights of up to 3 to 5 m above the present pan floor. On the southern side of the pans such deposits underlie the flanks of the inner dunes.

The composition of the pan deposits is variable, indicating fluctuating hydrological conditions, but a lower calcareous to saline clay phase and an upper sandy phase can be recognised. The lower clayey phase is divided into a lower calcareous, coarse grained part, and an upper fine grained, saline part. The sequence of pan deposits shows that high water level conditions in permanent or seasonal lakes were replaced by low water level saline ephemeral lakes. During the time when the pans held extensive water bodies, the shape of the pan depressions was modified by end current erosion. As the water bodies in the pan depressions contracted, the sandy phase was laid down as a wash on the lake margins. This sequence of events seems to be confirmed by the existence of a transition from calcretes to sil-calcretes and silcretes on the pan margins, the composition of which suggests that they are indurated pan deposits, altered as the water bodies in the pan depressions contracted and became more saline. The extremely fine grained nature of the clay fraction of the pan deposits indicates that they were formed as a result of the trapping of inwashed fines, together with carbonate synthesis in relatively shallow permanent or seasonal lakes. Except on the margins of the water bodies, the deposits are characterised by a small amount of sand only, which would seem to indicate conditions of low runoff. The final phase of the contraction of the water bodies in the pan depressions seems to have been one of increased runoff, as the nature of the upper sandy phase indicates.

The composition of the inner dunes suggests that they were formed by the deflation of pan deposits, particularly the upper sandy phase, during the latter stage of the contraction of the pans. At bare clay pans the lower clayey phase is exposed, but at grassed and partly grassed pans all or most of the pan is covered by the sandy phase, and clays are exposed only locally in waterholes or bare areas. This would indicate that the type of pan surface occuring today reflects the balance that existed between the inwashing of material to the pans and the power of the wind to remove it. In this context it is interesting to note that grassed pans are found more frequently in the wetter eastern part of the area.

Following the formation of the inner dunes the pans appear to have dried out completely. However, there is evidence in the form of small, apparently wave cut, notches on the southern side of some of the bare and partly grassed pans, that the pans have held quite substantial quantities of water in recent times, probably during exceptionally wet seasons or periods.

The sequence of events involved in the origin and development of the southern Kalahari pans may be summarised as follows:

Sporadic deflation and seasonal or ephemeral water bodies in pans at present day.

Deflation to form inner dune.

Deposition of pan deposits: Sandy phase

Clayey phase:

Upper saline, fine grained part

Lower calcareous part.

Deflation to form outer dune.

PALEOCLIMATIC IMPLICATIONS

The pans are today virtually fossil landforms, experiencing sporadic deflation from their surfaces, which are flooded seasonally or ephemerally. It is clear that their main features have developed under climatic conditions unlike those of today, and are indicative of the climatic changes that have taken place in the Kalahari during the late Quaternary.

The existence in the pan depressions of lacustrine deposits up to 3 to 4 m thick, and covering an area 2 to 3 times that of the present pan, is clear evidence of a period in which the climate in the Kalahari was substantially wetter than that of today. It is not clear whether this wet phase was the result of higher rainfall alone, or lower evaporation, or a combination of both increased rainfall and lower evaporation. The composition of the pan deposits indicates that runoff was low, suggesting that the existence of the water bodies was the result of reduced evaporation, with a small increase in rainfall. Regrettably, in the absence of present day runoff figures, it is impossible to make precise calculations, using the formulae in Reeves (1968), of the amounts of precipitation and evaporation necessary for the existence of such water bodies.

Evidence from a variety of sources is accumulating to show that the climate of southern Africa was both cooler and wetter some 15000 to 20000 years ago. Butzer (1973) has reported that Alexandersfontein pan near Kimberley contained a 44 km^2 lake, associated with deposits containing Middle Stone Age implements, some 16000 years ago, the result of a 5 °C decrease in temperature and a 150 % increase in precipitation. In the Kalahari, Grove has obtained a date of 20990 ± 1100 B.P. (Gak 4310) for lacustrine sediments from the Makgadikgadi depression when it held a lake some 34000 km^2 in area; fed by rivers draining the highlands of Namibia (South West Africa) and eastern Botswana. Cooke (1975) has reported deposition of dripstone in caves in the Kwihabe Hills during the period 14080 to 17000 B.P.

Elsewhere in southern Africa, Bond (1957) suggests that colluvial deposits at the Khami waterworks site in southern Rhodesia containing Middle Stone Age implements, were laid down under conditions when the rainfall was about 900 mm, compared to the present 635 mm.

A reduction in temperature over much of Africa in the order of 5 to 6 °C is suggested by Moreau (1963) on the basis of the former wide distribution of montane forest habitats, and Hastenrath (1972) has argued for a late Pleistocene snowline depression in the Drakensburg of 1000 to 1100 m, indicating a reduction in temperature of 5 to 6 °C. Palynological studies of deposits at Florisbad, Orange Free State, (Van Zinderen Bakker 1957) suggest a cooler and probably wetter climate around 19000 B.P..

The absence of absolute dates for the pan deposits makes positive correlations impossible, but the available evidence points to a substantially cooler and wetter climate in southern Africa some 15000 to 20000 years ago. If a temperature reduction of 5 °C is assumed then evaporation rates would have been 30 to 50 % lower than at present. Even allowing for a substantial reduction in evaporation rates, an increase in the present rainfall amounts of 100 to 150 % would still have been necessary to sustain permanent lakes in the pan depressions. Thus rainfall amounts in the southern Kalahari would probably have been in the region of 600 to 800 mm, and evaporation rates would have been 1300 to 1820 mm per annum.

It is interesting to compare the situation in the Kalahari at this time with other sub tropical semi arid areas. In Africa north of the equator, the climate was substantially drier than that of today, and dune belts extended far south of their present position, (Warren 1970). However, in the southwest U.S.A. (Galloway 1970) and in Australia (Galloway 1965) high lake levels are recorded, probably the result of much lower evaporation rates than today.

The climatic conditions implied by the inner and outer dunes are more difficult to interpret. Their alignment suggests that the pattern of winds in the southern Kalahari was essentially the same at both periods, and was not significantly different from that of the present day. The inner dune seems to have been formed under conditions of high temperatures and high evaporation, during the final stages of the dessication of the pans after the period of high water levels. During the wet and cool phase in the Kalahari it is probable that groundwater bodies were extensively recharged, as a result of lowered evaporation and increased rainfall. Despite the great depth of the water table today, it is probable that water tables would have been much nearer the surface during the later stages of the humid phase. A variety of evidence exists to show that, between about 15000 and 9500 years ago the climate of Africa as a whole became warmer. Between the northern tropic and the equator the rise in temperature was accompanied by increased precipitation, giving rise to large lakes in the Tchad basin, and the rift valleys of southern Ethiopia and Kenya (Grove and Goudie 1971). In southern Africa, changes in the pollen rain at Aliwal North (Coetzee 1967) indicate a gradual increase in temperature accompanied by somewhat reduced precipitation.

The inner dunes were probably formed about this time, when water tables were still high, temperatures and evaporation rates were also greater than today, giving rise to the shallow saline seasonal water bodies, and rapid drying necessary to create the bare sandy surfaces which supplied the material for the building of the inner dune. At this time a reduction in the vegetation cover associated with the increase in temperature and dessication of climate would probably have promoted the increased runoff which the deposition of the upper sandy phase suggests.

The conditions under which the outer dunes were formed are difficult to interpret. Haok (1941) and Melton (1940) suggest that parabolic dunes in association with deflation basins formed by the enlargement of blowouts in sub arid climates. Reeves (1968) indicates that deflation basins may occur in semi arid to arid climates whenever strong winds blow across unconsolidated sandy surface deposits.

Today, the only sand movement taking place in the Kalahari occurs in the southwest of the region in the dune belts along the Nossop and Auob rivers. Here sand movement is localised and takes place whereever the vegetation is sparse, particularly along the crests of the dunes and in the interdunal corridors. It seems probable that the outer dunes were formed by the enlargement of blowouts created under similar conditions of low precipitation (150 to 200 mm).

The existence of large dune systems, now fixed by vegetation, in the Kalahari (Grove 1969); the invasions of river valleys by aeolian sands reported by Bond (1963) and Mabbutt (1957 a, b) and pollen analysis data from Angola (Van Zinderen Bakker and Clark 1967) all indicate arid conditions in the period 30000 to 40000 years B.P., and it is possible that the formation of the outer dunes dates from the later stages of this period.

CONCLUSIONS

This dissertation has described the main geomorphic features of the pans of the southern Kalahari, with particular reference to the fringing dunes and pan deposits. The distribution of the pans and their morphometry has been analysed. The morphology and composition of these features suggest that they developed under climatic conditions unlike those prevailing in the southern Kalahari today.

The depressions containing the pans of the southern Kalahari can now be said to have originated by the enlargement by deflation of blowouts created under a sub arid climate. Following the deflation of sands to form the outer dunes, there was a long period of cooler and wetter climates, some 15000 to 20000 years ago, during which the shape of the pan depressions was modified by end current erosion in water bodies up to 3 to 4 times the area of the present pans.

During this time calcareous clays and sandy clays were deposited in the pan depressions. The composition of the uppermost pan deposits indicate that the area underwent a steady dessication during the later parts of this period. In the final stages of this dessication the upper sandy phase was laid down, and the inner dune formed by deflation of similar material.

Evidence of periods of climate slightly wetter than the present since the formation of the inner dune exist in the form of small wave cut notches at a height of up to 1 m above pan datum on the southern side of the pan.

The origin and development of the pans of the southern Kalahari can thus be said to represent the influence of changing climatic and hydrological conditions in the area during the late Quaternary.

The stages of the origins and development of the pans of the southern Kalahari can now be summarised, with the suggested climatic conditions existing during the different stages:

Period	Geomorphic features	Suggested climates
Present day	Sporadic deflation and ephemeral water bodies.	Precipitation 300 to 350 mm.
10000 to 12000 yrs.B.P.	Deflation to form inner dune. Deposition of upper sandy phase of pan deposits.	Warmer, with 25 to 30 °C mean dry season temperatures. Decreased precipitation (200 to 300 mm).
20000 to 12000 yrs.B.P.	Extensive water bodies in pan depressions: deposition of clayey phase of pan deposits.	5 °C cooler, Increased precipitation (600 to 800 mm).
Before 20000 B.P.	Deflation to form outer dune.	Decreased precipitation (150 to 200 mm).

APPENDICES

APPENDIX 1

AERIAL PHOTOGRAPHY OF THE PANS STUDIED

Aerial photography taken under the following contracts was used in the study of the southern Kalahari pans.

Areas 1, 2 and 3:	Aircraft Operating Company, 1961 Contract 56/61 S. Scale: 1:50000 approx.
Area 4:	Hunting Surveys (Botswana), 1972 Contract HSB 72 Scale: 1:40000 approx.
Area 5:	Hunting Surveys (Botswana), 1971 Contract HSB/71 W. Scale: 1:40000 approx.

The aerial photographs listed below give stereo cover of the pans studied.

	Strip number	Photo numbers
Area 1		
Samane, Samosadi, Bee	56 BC 11	036, 037, 038
Tatswe	56 BC 12	050, 051
Area 2		
Sekoma	56 BC 10	032, 033
Kongwe	56 BC 9	108, 109
Kgama	56 BC 10	037, 038
Keng	56 BC 9	110, 111
Khakhea	56 BC 8	081, 082
Khesekwe	56 BC 7	142, 143
Area 3		
Motsobonye	56 BC 12	064, 065
Kokong	56 BC 11	058, 059
Mashiaphotsana	56 BC 11	063, 064
Mogatse	56 BC 11	064, 065
Dead Tree	56 BC 11	065, 066

	Strip number	Photo numbers
Area 4		
Bosobogolo	5	4904, 4905
Mpaathutlwa	3	4851, 4852
Mabuasehube	3	4848, 4849
Area 5		
Nwatle	54	4624, 4625
Masetleng, Pussy	53	4199, 4200, 4201
Ukwi	51	4084, 4085
Urwi	48	4955, 4956, 4957

APPENDIX 2

PARTICLE SIZE ANALYSIS DATA FOR INNER AND OUTER DUNE SAMPLES.

This appendix falls into two sections. The first part contains the raw data obtained by the mechanical analyses of the samples. The second part contains the sorting and grain size parameters calculated using the computer programme in Appendix 3.

Samples are located as shown on dune profiles (Figs, 5.1 to 5.5) and are numbered towards pan, i.e. left to right on profiles.

	Weight retained by each sieve (gm)					Silt & clay (Inner dunes only)	Cumulative percent finer than			
	1	2	3	4 phi	Pan		1	2	3	4 phi
Tatswe										
Outer dune										
1	1.2	35.7	40.2	22.7	2.6		98.9	63.7	23.1	0.7
2	0.7	34.5	43.1	22.1	1.3		99.4	65.6	23.2	1.5
3	1.2	43.7	44.6	12.9	0.3		98.8	56.4	13.1	0.6
Interdunal depression	0.6	24.2	36.9	26.6		13.0	99.4	75.5	39.0	12.8
Inner dune										
1	0.3	21.0	43.4	26.3		10.0	99.7	78.9	35.8	9.8
2	0.5	19.2	38.9	27.5		14.6	99.2	74.7	38.0	15.1
3	0.8	25.0	37.3	23.3		15.4	98.2	68.1	37.3	17.3
AREA 2										
Khesekwe										
Outer dune										
1	1.2	32.8	48.4	19.4	2.0		98.8	67.2	20.9	1.9
2	1.8	32.3	47.6	17.2	2.0		98.3	66.3	19.3	1.9
3	1.8	31.2	46.8	19.6	2.1		98.2	67.5	21.3	2.1
Interdunal depression	0.7	21.2	41.7	20.5		16.4	99.4	78.3	36.8	16.4
Inner dune										
1	0.2	13.2	27.1	13.6		8.9	99.6	78.6	35.7	14.1
2	0.7	29.0	42.8	16.5		14.4	99.3	70.9	29.7	13.9
3	2.2	28.3	34.2	15.8		19.6	97.8	69.5	35.4	19.6
Sekoma										
Outer dune										
1	0.7	28.0	47.2	25.3	1.2		99.4	72.1	26.0	1.3
2	0.7	21.6	53.8	27.1	1.2		99.5	78.8	27.2	1.2
Inner dune										
1	0.7	21.1	44.0	22.5		9.1	99.3	78.2	34.4	9.1
2	1.2	17.8	44.4	24.5		13.2	98.8	81.2	37.3	13.1
3	1.1	17.3	47.3	22.6		12.7	98.8	88.8	35.1	12.7

	Weight retained by each sieve (gm)					Sand & clay (Inner dunes only)	Cumulative percent finer than			
	1	2	3	4 phi	Pan		1	2	3	4 phi
Kongwe										
Outer dune										
1	0.6	35.4	45.9	19.6	1.4		99.4	65.0	20.3	1.9
2	1.2	33.2	48.4	20.2	1.4		98.9	67.1	20.6	1.3
3	1.2	39.9	42.7	17.7	1.2		98.9	59.8	17.9	1.1
Interdunal deoression	0.8	20.8	44.6	20.8		13.2	99.2	78.4	39.9	13.1
Inner dune										
1	0.6	18.4	47.4	21.8		12.8	99.4	81.1	34.3	12.7
2	0.7	23.5	41.3	22.6		16.1	99.4	76.7	37.1	15.4
3	1.7	27.1	34.7	16.6		20.0	98.3	71.3	36.7	20.1
Kgama										
Outer dune										
1	3.4	24.8	48.7	20.5	3.8		99.4	70.3	18.7	1.2
2	2.0	25.5	47.6	22.3	2.7		99.2	69.4	22.2	1.4
Inner dune										
1	1.3	22.8	36.4	21.1		15.7	98.6	75.2	37.9	16.2
2	0.8	22.9	37.9	23.3		16.4	98.1	79.5	39.1	15.7
Keng										
Outer dune										
1	0.2	21.2	57.3	20.5	1.5		99.7	78.7	21.8	1.4
2	1.7	30.3	53.0	18.0	1.6		98.4	69.4	18.7	1.6
Interdunal depression	1.0	23.0	57.4	20.3	1.7		99.6	80.6	29.4	7.6
Inner dune										
1	0.3	14.9	53.7	25.5		11.4	99.7	85.6	34.9	10.8
2	0.3	16.4	49.7	24.3		14.9	99.8	84.2	37.1	14.1
3	0.6	8.8	39.0	24.9		26.2	99.4	90.7	51.0	26.0

	Weight retained by each sieve (gm)					Sand & clay (Inner dunes only)	Cumulative percent finer than			
	1	2	3	4 phi	Pan		1	2	3	4 phi
AREA 3										
Motsobonye										
Outer dune										
1	2.1	50.4	41.8	11.0	0.1		98.0	50.2	10.5	0.1
2	0.2	35.9	43.6	18.3	0.6		99.8	63.4	19.2	0.6
Interdunal depression	0.4	23.0	35.3	25.9		15.4	99.6	76.6	41.3	15.4
Inner dune										
1	0.1	24.6	31.6	18.3		25.4	99.9	75.3	43.7	25.4
2	0.7	27.9	35.3	23.1		13.0	99.3	71.4	36.1	13.0
3	1.3	26.6	31.8	23.3		17.0	98.7	72.1	40.3	17.0
Mashiaphotsana										
Outer dune										
1	4.1	23.9	40.5	26.5	9.0		96.9	76.0	35.5	9.0
2	0.7	25.6	37.5	25.2	11.0		99.3	73.7	73.7	11.0
Inner dune										
1	0.3	21.8	29.2	19.6		29.1	99.7	77.9	48.7	29.1
2	0.1	24.3	39.0	26.9		9.7	99.9	75.6	36.6	9.7
3	0.7	22.2	34.2	26.3		16.6	99.3	77.1	42.9	16.6
Mogatse										
Outer dune										
1	1.4	37.2	41.3	20.0	0.8		98.6	61.7	20.6	0.8
2	1.1	36.5	46.7	22.0	1.0		98.9	64.9	21.4	1.0
Interdunal depression	2.8	49.0	38.4	11.4	0.2		97.2	49.1	11.4	0.2
Inner dune										
1	0.5	32.2	39.5	22.1		15.9	99.5	67.5	38.0	15.9
2	0.9	31.2	39.2	20.5		9.2	99.1	67.9	28.7	9.2
3	2.2	40.8	30.0	14.1		12.9	97.8	57.0	27.0	12.9

	Weight retained by each sieve (gm)					Sand & clay (Inner dunes only)	Cumulative percent finer than			
	1	2	3	4 phi	Pan		1	2	3	4 phi
Dead Tree										
Outer dune										
1	0.8	31.8	49.3	23.3	1.7		99.2	69.5	23.4	1.6
2	0.4	31.9	45.8	19.6	0.7		99.6	67.2	20.6	0.7
Interdunal depression	1.1	32.5	47.7	22.1	1.9		98.9	68.1	22.8	1.8
Inner dune										
1	0.5	26.3	40.3	22.7		10.3	99.4	73.3	33.0	10.3
2	0.6	22.8	36.7	23.0		16.9	99.4	76.6	39.9	16.9
3	1.7	27.0	28.5	19.0		26.8	98.3	71.3	42.8	26.8
AREA 4										
Bosobogolo										
Outer dune										
1	3.5	38.1	41.4	16.4	1.4		96.5	58.7	17.7	1.4
2	3.0	39.1	44.3	17.9	2.2		97.2	60.5	18.9	2.1
Interdunal depression	3.6	31.6	46.3	20.0	2.6		96.5	66.2	21.7	2.5
Inner dune										
1	1.6	26.6	39.2	19.0		11.2	96.0	69.4	30.2	11.2
2	3.6	30.6	36.3	17.5		12.0	94.4	65.8	29.5	12.0
3	2.5	23.9	40.3	19.2		14.1	97.5	73.6	33.3	14.1
Mpaathutlwa										
Outer dune										
1	4.0	37.5	44.8	16.8	2.5		96.2	60.7	18.3	2.4
2	3.5	35.7	47.3	18.6	1.9		96.7	63.4	19.2	1.8
3	5.0	31.6	44.6	19.8	3.3		95.2	64.9	22.2	3.2
Interdunal depression	1.7	28.2	45.1	17.7	2.7		98.3	68.7	21.4	2.8
Inner dune										
1	0.5	16.9	45.8	21.7		25.1	99.5	82.6	36.8	25.1
2	1.4	18.3	41.2	16.5		22.8	99.7	81.2	39.5	22.8

	Weight retained by each sieve (gm)					Sand & clay (Inner dunes only)	Cumulative percent finer than			
	1	2	3	4 phi	Pan		1	2	3	4 phi
AREA 5										
Masetleng										
Outer dune										
1	2.2	27.8	56.9	18.3	1.0		97.9	71.7	18.2	0.9
2	2.1	27.6	50.5	20.0	1.6		97.9	70.8	21.2	1.6
3	4.6	34.1	46.3	17.7	1.9		95.6	63.0	18.7	1.8
Interdunal depression	2.2	31.9	50.3	17.0	1.6		97.9	66.6	18.1	1.6
Inner dune										
1	0.6	19.1	51.9	22.6		5.8	99.4	80.3	28.4	5.8
2	1.4	20.5	41.9	19.0		18.0	98.6	78.1	36.2	18.0
Pussy										
Outer dune										
1	2.3	31.5	55.2	18.7	1.2		97.9	67.0	18.3	1.1
2	4.6	34.7	54.3	8.6	1.0		95.5	42.9	19.3	1.0
Inner dune										
1	3.0	28.6	49.4	18.4	2.0		97.0	68.8	20.1	2.0
2	2.2	22.8	43.7	18.5		12.8	97.8	75.0	31.3	12.8
3	4.3	24.3	37.1	15.2		19.1	95.7	71.4	34.3	19.1
Nwatle										
Outer dune										
1	2.4	38.8	51.2	15.3	1.0		98.9	71.0	21.0	1.6
2	1.5	25.2	49.8	19.7	2.2		97.8	62.1	15.0	0.9
Inner dune										
1	2.0	26.5	56.0	18.6		1.1	98.1	72.6	18.9	9.2
2	2.4	21.9	43.8	18.8		13.1	97.6	76.5	34.2	1.7

	Weight retained by each sieve (gm)					Sand & clay (Inner dunes only)	Cumulative percent finer than			
	1	2	3	4 phi	Pan		1	2	3	4 phi
Ukwi										
Outer dune	0.2	12.5	52.1	26.0	9.2		99.8	87.3	35.2	9.2
Interdunal depression	2.3	29.3	49.0	23.0	1.8		97.8	70.0	23.5	1.7
Inner dune										
1	0.9	13.3	45.9	31.7		8.2	99.1	85.8	39.4	8.2
2	2.1	21.4	40.3	23.7		12.5	97.9	76.5	36.2	12.5
3	0.9	14.9	38.6	24.4		20.2	99.1	84.2	45.6	20.2
4	1.7	4.3	36.7	34.0		23.8	95.5	58.2	23.7	22.8
Pan edge dune										
1	1.1	13.3	41.9	31.7		8.7	85.7	42.2	9.3	8.7
2	14.5	23.3	31.4	22.4		8.4	85.5	62.2	30.8	8.5
Urwi										
Outer dune										
1	3.5	39.5	42.3	16.3	1.9		98.6	58.5	17.5	1.8
2	2.5	37.9	43.7	18.5	2.7		97.6	61.6	20.1	2.6
Interdunal depression	2.5	29.2	46.4	23.0	4.2		96.7	58.2	19.9	7.7
Middle dune										
1	1.6	29.5	49.6	22.4	3.2		98.5	70.7	24.1	3.0
2	2.5	33.5	48.3	21.6	3.4		97.7	67.1	28.9	3.1
3	2.5	29.0	46.4	23.5	4.2		97.6	70.0	25.9	4.0
Interdunal depression	3.3	30.4	35.0	16.7		14.6	96.7	66.3	31.3	14.6
Inner dune										
1	0.4	17.0	49.7	23.7		9.2	99.6	82.6	32.9	9.2
2	0.5	14.7	43.4	21.3		20.1	99.5	84.8	41.4	20.1
3	3.7	26.5	39.5	17.7		12.6	96.3	69.8	30.3	12.6
4	6.4	27.3	30.0	15.5		13.8	93.6	66.3	36.3	13.8

APPENDIX 2

PARTICLE SIZE ANALYSIS DATA FOR INNER AND OUTER DUNE SAMPLES

Samples are located as shown on dune profiles (Figs. 5.1 to 5.5) and are numbered towards pan, i.e. left to right on profiles.

AREA 1

	Mean	Standard Deviation	Skewness	Kurtosis
		(phi units)		
Samane				
Outer Dune				
1	2.36	0.80	0.57	3.46
2	2.38	0.79	0.54	3.44
Interdunal Depression	2.80	1.15	0.60	2.50
Inner Dune				
1	2.91	1.01	0.54	2.90
2	2.98	1.26	0.44	2.03
3	3.05	1.20	0.41	2.11
Samosadi				
Outer Dune				
1	2.41	0.80	0.49	3.09
2	2.38	0.80	0.52	3.01
Interdunal Depression	2.94	1.20	0.54	2.21
Inner Dune				
1	2.71	0.90	0.71	3.53
2	2.89	1.12	0.56	2.52
3	3.02	1.28	0.36	1.96
Bee				
Outer Dune				
1	2.36	0.81	0.53	3.09
2	2.42	0.85	0.22	2.87
Inner Dune				
1	2.74	1.06	0.73	2.95
2	2.75	1.13	0.69	2.70
3	2.94	1.29	0.44	2.01

	Mean	Standard Deviation	Skewness	Kurtosis
		(phi units)		
Tatswe				
Outer Dune				
1	2.38	0.83	0.38	2.72
2	2.40	0.81	0.43	2.85
3	2.18	0.72	0.45	2.75
Interdunal Depression	2.83	1.10	0.54	2.58
Inner Dune				
1	2.79	1.01	0.64	3.00
2	2.93	1.10	0.50	2.54
3	2.85	1.15	0.56	2.45
AREA 2				
Khesekwe				
Outer Dune				
1	2.40	0.81	0.54	3.50
2	2.37	0.82	0.53	3.63
3	2.40	0.83	0.47	3.48
Interdunal Depression	2.89	1.15	0.60	2.49
Inner Dune				
1	2.85	1.10	0.66	2.69
2	2.71	1.14	0.79	2.78
3	2.82	1.28	0.54	2.19
Sekoma				
Outer Dune				
1	2.49	0.79	0.25	2.83
2	2.57	0.75	0.16	3.17
Inner Dune				
1	2.73	1.00	0.69	3.19
2	2.87	1.07	0.57	2.84
3	2.85	1.05	0.64	2.99

	Mean	Standard Deviation	Skewness	Kurtosis
		(phi units)		
<u>Kongwe</u>				
Outer Dune				
1	2.37	0.79	0.52	3.13
2	2.38	0.79	0.41	3.19
3	2.28	0.79	0.56	3.16
Interdunal Depression	2.81	1.08	0.68	2.84
Inner Dune				
1	2.84	1.05	0.70	2.96
2	2.87	1.14	0.59	2.50
3	2.87	1.28	0.52	2.14
<u>Kgama</u>				
Outer Dune				
1	2.48	0.90	0.43	3.70
2	2.50	0.85	0.39	3.53
Inner Dune				
1	2.86	1.18	0.53	2.43
2	2.86	1.11	0.61	2.63
<u>Keng</u>				
Outer Dune				
1	2.53	0.72	0.45	3.81
2	2.39	0.78	0.43	3.68
Interdunal Depression	2.40	0.77	0.53	3.57
Inner Dune				
1	2.86	0.97	0.77	3.29
2	2.92	1.05	0.69	2.81
3	3.31	1.16	0.27	1.98

AREA 3

	Mean	Standard Deviation	Skewness	Kurtosis
	(phi units)			
Motsobonye				
Outer Dune				
1	2.09	0.71	0.47	2.72
2	2.33	0.75	0.44	2.64
Interdunal Depression	2.91	1.14	0.50	2.38
Inner Dune				
1	3.07	1.30	0.37	1.77
2	2.76	1.13	0.62	2.57
3	2.87	1.22	0.47	2.24
Mashiaphotsana				
Outer Dune				
1	2.75	1.00	0.65	2.95
2	2.76	1.08	0.60	2.75
Inner Dune				
1	3.20	1.32	0.20	1.66
2	2.77	1.03	0.63	2.85
3	2.94	1.16	0.44	2.30
Mogatse				
Outer Dune				
1	2.32	0.80	0.37	2.71
2	2.37	0.79	0.36	2.80
Interdunal Depression	2.08	0.73	0.49	2.87
Inner Dune				
1	2.76	1.16	0.68	2.51
2	2.60	1.05	0.77	3.08
3	2.51	1.20	0.88	2.82

	Mean	Standard Deviation	Skewness	Kurtosis
	(phi units)			
Dead Tree				
Outer Dune				
1	2.45	0.80	0.42	3.14
2	2.38	0.76	0.35	2.73
Interdunal Depression	2.43	0.82	0.46	3.24
Inner Dune				
1	2.71	1.05	0.71	2.93
2	2.91	1.17	0.52	2.33
3	3.04	1.46	0.28	1.77
AREA 4				
Bosobogolo				
Outer Dune				
1	2.25	0.84	0.45	3.31
2	2.30	0.86	0.57	3.51
Interdunal Depression	2.38	0.88	0.41	3.47
Inner Dune				
1	2.68	1.10	0.69	2.91
2	2.60	1.17	0.66	2.82
3	2.76	1.16	0.58	2.68
Mpaathutlwa				
Outer Dune				
1	2.29	0.88	0.55	3.64
2	2.32	0.85	0.41	3.44
3	2.37	0.93	0.42	3.45
Inner Dune				
1	3.11	1.20	0.44	2.07
2	3.02	1.25	0.44	2.10

AREA 5

	Mean	Standard Deviation	Skewness	Kurtosis
		(phi units)		
Masetleng				
Outer Dune				
1	2.39	0.75	0.18	3.54
2	2.42	0.80	0.30	3.48
3	2.30	0.86	0.36	3.44
Interdunal Depression	2.35	0.80	0.42	3.62
Inner Dune				
1	2.67	0.88	0.73	3.85
2	2.90	1.18	0.54	2.41
3	2.86	1.32	0.44	2.24
Pussy				
Outer Dune				
1	2.37	0.77	0.27	3.46
2	1.99	0.77	0.84	4.30
Inner Dune				
1	2.39	0.83	0.35	3.64
2	2.73	1.12	0.64	2.91
3	2.80	1.29	0.47	2.30
Nwatle				
Outer Dune				
1	2.43	0.78	0.43	3.50
2	2.26	0.77	0.41	3.43
Inner Dune				
1	2.82	1.16	0.58	2.62
2	2.41	0.75	0.20	3.59

	Mean	Standard Deviation	Skewness	Kurtosis
		(phi units)		
Ukwi				
Outer Dune				
1	2.86	0.92	0.79	3.52
Interdunal Depression	2.44	0.83	0.28	3.26
Inner Dune				
1	2.87	0.93	0.48	3.37
2	2.79	1.11	0.51	2.78
3	3.09	1.17	0.38	2.23
4	3.35	1.10	0.13	2.47
Pan edge Dune				
1	2.89	0.96	0.41	3.22
2	2.41	1.25	0.29	2.56
Urwi				
Outer Dune				
1	2.25	0.85	0.55	3.52
2	2.33	0.87	0.62	3.55
Interdunal Depression	2.29	0.90	0.64	3.51
Middle Dune				
1	2.48	0.86	0.52	3.56
2	2.42	0.89	0.54	3.53
3	2.50	0.92	0.51	3.47
Interdunal Depression	2.66	1.22	0.63	2.58
Inner Dune				
1	2.79	0.96	0.75	3.40
2	3.06	1.15	0.51	2.27
3	2.65	1.16	0.61	2.82
4	2.61	1.29	0.52	2.48

APPENDIX 3

COMPUTATION OF SORTING AND SIZE PARAMETERS FOR DUNE SAND SAMPLES.

Computation of the sorting and grain size parameters in Appendix 2 was carried out by the method of moments.

The formulae used to derive phi mean, standard deviation, skewness and kurtosis from the raw data were taken from Friedman (1961) and were as follows:-

Mean = $f.p/s$

where f is the weight of sand retained by a sieve of given size; p is the mid point of each grain size grade in phi units; and s is the total sample weight.

Standard deviation = $\sqrt{\frac{f(p-m)^2}{s}}$

Skewness = $\sqrt[3]{\frac{f(p-m)^3}{s}}$

and kurtosis = $\sqrt[4]{\frac{f(p-m)^4}{s}}$

where m is the sample mean.

Calculation of the grain size and sorting measures was carried out using a Basic programme compiled by the writer, and run on the University of Malawi Hewlett Packard 9830 series computer.

The programme used is set out below:-

```
10   REM MECHANICAL ANALYSIS STATISTICS
20   FIXED 2
30   PRINT "MEAN", "S. DEVIATION", "SKEWNESS", "KURTOSIS"
40   DIM X  100  ,  P  100
50   PRINT
60   FOR I = 1 TO
70   S1 = S2 = S3 = S4 = S5 = 0
80   J = 1
90   READ P[ J] ,  X[ J]
```

```
100  IF X [J] = 999 THEN 280
110  IF P [J] = 6 THEN 160
120  S1 = S1 + X   J
130  S2 = S2 + P   J * X   J
140  J = J + 1
150  GO TO 90
160  M = S1/S2
170  FOR L = 1 TO J - 1
180  S3 = S3 + ((P [L]- M)↑2)  *  X [L]
190  S4 = S4 + ((P [L]- M)↑3)  *  X [L]
200  S5 = S5 + ((P [L]- M)↑4)  *  X [L]
210  D = SQR (S3/S1)
220  S = D↑(-3)  *  (S4/S1)
230  K = D↑(-4)  *  (S5/S1)
240  NEXT L
250  PRINT M, D, S, K
260  NEXT I
270  DATA 0.5, 1.9, 1.5, 34.1, 2.5, 46.3, 3.5, 17.9, 5, 1.7, 6, 1
280  END
```

BIBLIOGRAPHY

BIBLIOGRAPHY

ALISON, M.S. 1899: On the origin and formation of pans. Trans. geol. Soc. S. Afr. 4, 159 - 161.

BAILLIEUL, T. 1972: Analysis of some sand overlying the Morapule coalfield. Unpublished report. Geological Survey, Lobatse, Botswana.

BAILLIEUL, T. 1973: Reconnaissance sand survey - western Ngamiland. Unpublished report. Geological Survey, Lobatse, Botswana.

BERRY, B.L.J. 1962: Sampling, coding and storing flood plain data. United States Department of Agriculture, Farm Economics Division, Agricultural Handbook 237

BETTENAY, E. 1962: Salt lake systems and associated aeolian features in the semi arid regions of Western Australia. J. Soil Sci. 13, 10 - 17.

BLACK, C.A. (ed.) 1965: Methods of soil analysis. American Society of Agronomy, Madison (Wisconsin) U.S.A.

BLACKWELDER, E. 1931: The lowering of playas by deflation. Am. J. Sci. 21, 140 - 144.

BLAIR RAINS, A. and YALALA, A.M. 1972: The central and southern state lands, Botswana. Land Resources Study 11. Land Resources Division.

BOND, G. 1957: The geology of the Khami Stone Age sites, southern Rhodesia. Ocassional Paper, National Museum of Southern Rhodesia 3, 44 - 45.

BOND, G. 1963: Pleistocene environments in southern Africa. In: Howell, F.C. and Bouliere, F. (eds.) African Ecology and Human Evolution, Viking Fund Publications in Anthropology. Aldine, Chicago., 308 - 334.

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.

BOULAINE, J. 1954: La sebkha de Ben Ziane et sa "lunette" ou bourrelet. Rev. Geomorph. Dyn. 5, 102 - 133.

BOWLER, J.M. 1970: Late Quaternary Environments: a study of lakes and associated sediments in southeastern Australia. Unpublished Ph.D. thesis, Australia National University.

BOWLER, J.M. 1973: Clay dunes: their occurence, formation and environmental significance. Earth Sci. Rev. 9, 315 - 338.

BUTZER, K.W., FOCK, G.J., STUCKENRATH, R. and ZILCH, A. 1973: Paleohydrology of late Pleistocene Lake Alexandersfontein, Kimberley, South Africa. Nature London 243, 328 - 330.

CAHEN, L. and LEPERSONNE, J. 1952: Equivalence entre le system du Kalahari du Congo Belge et les Kalahari Beds d'Afrique australe. Mem. Soc. Belge. de Geol. Paleontol. Hydrol. Sec 8, 4, 1 - 64.

CAMPBELL, E.M. 1968: Lunettes in southern South Australia. Trans. Roy. Soc. S. Austr. 92, 85 - 109.

CHEPIL, W.S. 1945: Dynamics of wind erosion. Soil Sci. 60, 305 - 320, 397 - 411, 475 - 480; Soil Sci. 61, 167 - 177, 257 - 263, 331 - 340.

COETZEE, C.B. 1960: Geology of the Orange Free State gold fields. Mem. Geol. Surv. S. Afr. Pretoria.

COETZEE, J.A. 1967: Pollen analytical studies in East and southern Africa, Pt.II southern Africa. Paleoecology of Africa. 3, 100 - 123.

COOKE, H.J. 1975: The paleoclimatic significance of caves and adjacent landforms in the Kalahari of western Ngamiland, Botswana. Geogrl. J. 214.

COOKE, R.U. and WARREN, A. 1973: Geomorphology in Deserts, Batsford.

COQUE, R. and JAUZEIN, A. 1967: Geomorphology and Quaternary geology of Tunisia. Petroleum Exploration Society of Libya, 9th Annual Field Conference, 227 - 257.

DARTON, N.H. et al. 1915: The Santa Fe Route, Pt.C of Guidebook of the western United States. Bull. U.S. Geol. Surv. 613, 1 - 94.

DU TOIT, A.L. 1907: A geological survey of the eastern part of Griqualand West. Ann. Rept. Geol. Comm. C.G.H. 10, 87 - 176.

DU TOIT, A.L. 1908: Geological survey of parts of Mafeking and Vryburg. Ann. Rept. Geol. Comm. C.G.H. 11, 125 - 192.

DU TOIT, A.L. 1926: The Mier Country. S. Afr. Geogr. J. 9, 21 - 26.

DU TOIT, A.L. 1927: The Kalahari and some of its problems. S. Afr. J. Sci. 24, 88 - 101.

DU TOIT, A.L. 1954: The Geology of South Africa (3rd ed.) Cliver and Boyd.

EVANS, S.L. and MEADE, G.E. 1945: Quaternary of the Texas High Plains. University of Texas Publ. 4401, 485 - 507.

FLINT, R.F. and BOND, G. 1968: Pleistocene sand ridges and pans in western Rhodesia. Bull. Geol. Soc. Am. 79, 299 - 314.

FRIEDMAN, G.M. 1961: Distinction between dune, beach and river sand from textural characteristics. J. Sedim. Petrol. 31, 514 - 529.

FRYE, J.C. and SCHOFF, S.L. 1942: Deep seated solution in the Meade Basin and vicinity, Kansas and Oklahoma. Trans. Am. Geophys. Un. 23, 35 - 39.

GALLOWAY, R.W. 1965: Late Quaternary climates in Australia. J. Geol. 73, 603 - 618.

GALLOWAY, R.W. 1970: The full glacial climate in the southwestern U.S.A. Ann. Ass. Am. Geog. 60, 245 - 256.

GILBERT, G.K. 1890: Lake Bonneville, U.S. Geol. Surv. Monographs, 1.

GILBERT, G.K. 1895: Lake basins created by wind erosion. J. Geol. 3, 47 - 49.

GLENNIE, K.W. 1970: Desert sedimentary environments. Dev. in Sedimentology 14, Elsevier.

GREGORY, J.W. 1914: The lake system of Westralia. Geogrl. J. 43, 656 - 664.

GRIEG-SMITH, P. 1964: Quantitative Plant Ecology, Butterworths.

GRIM, R.E. 1953: Clay Mineralogy, McGraw Hill.

GROVE, A.T. 1958: The ancient erg of Hausaland and similar formations on the south side of the Sahara. Geogr. J. 124, 526 - 533.

GROVE, A.T. 1969: Landforms and climatic change in the Kalahari and Ngamiland. Geogrl. J. 135, 191 - 212.

GROVE, A.T. and GOUDIE, A.S. 1971: Late Quaternary lake levels in the Rift Valley of southern Ethiopia and elsewhere in tropical Africa. Nature London 234, 403 - 405.

GROVE, A.T., STREET, F.A. and GOUDIE, A.S. 1975: Former lake levels and climatic change in the Rift Valley of southern Ethiopia. Geogrl. J. 141, 177 - 202.

GOUDIE, A.S. 1970: Notes on some major dune types in southern Africa. S. Afr. Geogr. J. 52, 93 - 107.

HACK, J.T. 1941: Dunes of the western Navajo country. Geogrl. Rev. 31, 240 - 263.

HASTENRATH, S. 1972: A note on Recent and Pleistocene altitudal zonation in southern Africa. S. Afr. J. Sci. 68, 96 - 101.

HEFLEY, H.M. and SIDWELL, R. 1945: Geological and ecological observations of some High Plains dunes. Am. J. Sci. 243, 361 - 376.

HILLS, E.S. 1939: The lunette, a new landform of aeolian origin. Aust. Geogr. 3, 15 - 21.

HOFMAN, H.J. 1973: Stromatolites: characteristics and utility. Earth Sci. Rev. 9, 339 - 373.

HURAULT, J. 1966: Etude photo - aerienne de la tendance a la remobilisation des sables eoliens sur la rive nord du Lac Tchad. Rev. Inst. Francais de Petrole. 21, 1837 - 1846.

HUTCHINSON, G.E. 1957: A Treatise on Limnology, vol. 1, Geography, Physics and Chemistry. Wiley.

JACKSON, S.P. and TYSON, P.D. 1971: Aspects of weather and climate over southern Africa. Ocassional Paper 6. Dept of Geography and Environmental Studies, University of the Witwatersrand, Johannesburg.

JAEGER, F. 1939: Die Trochenseen der Erde, Petermanns Mitt. Ergunzuugschaft 236.

JOHNSON, W.D. 1901: The High Plains and their utilisation. Rep. U.S. Geol. Surv. 21.

JUTSON, J.T. 1934: (2nd ed. 1950): The physiography of Western Australia. Bull. Geol. Surv. West. Austr. 95.

KERR, P.F. and LANGER, A.M. 1965: Mineralogical features of Mojave Desert playa crusts. In: Neal, J.T. (ed.) Geology, Mineralogy and Hydrology of U.S. playas. Air Force Cambridge Research Laboratories Environmental Research Paper 96, 31 - 72.

KALKOWSKI, E. 1908: Oolith und Stromatolith in nord-deutshen Bund-Sandstein. Z. dt. Geol. Ges. 60, 68 - 125.

KING, L.J. 1969: Statistical Analysis in Geography, Prentice Hall.

KILLIGREW, L.P. and GILKES, R.J. 1974: Development of playa lakes in southwestern Australia. Nature London 247, 454 - 455.

KRINSLEY, D.B., WOO, C.C. and STOERTZ, Y.E. 1968: Geologic characteristics of seven Australian playas. In: Neal, J.T. (ed.) Playa surface morphology: Miscellaneous investigations. Air Force Cambridge Research Laboratories Environmental Research Paper 238, 59 - 103.

LALOY, L. 1905: Les actions biologiques dans la geologie du Kalahari. La Nature 33, 378 - 379.

LANDSBERG, S.Y. 1956: The orientation of dunes in Britian and Denmark with respect to the wind. Geogrl. J. 122, 176 - 189.

LEWIS, A.D. 1936: Sand dunes of the Kalahari within the borders of the Union. S. Afr. Geogr. J. 19, 23 - 32.

McCONNELL, H. and HORN, J.M. 1972: Probabilities of surface karst. In: Chorley, R.J. (ed.) Spatial Analysis in Geomorphology, Methuen, 111 - 134.

MABBUTT, J.A. 1957 a: Some Quaternary events in the winter rainfall area of Cape Province. In: Clark, J.D. (ed.) Proc. 3rd Pan Africa Cong. Prehist. Livingstone, 1955, 6 - 13.

MABBUTT, J.A. 1957 b: Physiographic evidence for the age of the Kalahari sands of the S.W. Kalahari. In: Clark, J.D. (ed.) Proc. 3rd Pan Africa Cong. Prehist. Livingstone, 1955, 123 - 126.

MABBUTT, J.A. 1968: Aeolian landforms in central Australia. Austr. J. Sci. 6, 139 - 150.

MARTIN, H. and WILCZEWSKI, N. 1972: Algen - Stromatolithen aus der Etoscha - pfanne, Suidwest - Afrikas. Neues Jahrbuch Geol. Pal. Monatsheft 6, 12, 720 - 726.

MEIGS, P. 1953: World distribution of arid and semi arid homoclimates, Reviews of Research on Arid Zone Hydrology, UNESCO Paris, 203 - 209.

MELTON, F.A. 1940: A tentative classification of sand dunes. J. Geol. 48, 113 - 173.

MITCHELL, C.W. and WILLIMOTT, S.G. 1974: Dayas of the Moroccan Sahara and other arid regions. Geogrl. J. 140, 441 - 453.

MOREAU, R.E. 1963: The distribution of tropical African birds as an indicator of past climatic changes. In: Howell, F.C. and Bouliere, F. (eds.) African Ecology and Human Evolution, Viking Fund Publications in Anthropology, Aldine, Chicago, 28 - 42.

MOTTS, W.S. 1965: Hydrologic types of playas and closed valleys and some relations of hydrology to playa geology. In: Neal, J.T. (ed.) Geology, Mineralogy and Hydrology of U.S. playas. Air Force Cambridge Research Laboratories Environmental Research Paper 96, 73 - 104.

MUNSELL COLOR COMPANY INC. 1954: Munsell Soil Color Charts.

NEAL, J.T. (ed.) 1965: Geology, Mineralogy and Hydrology of U.S. playas. Air Force Cambridge Research Laboratories Environmental Research Paper 96.

PARIS, R. 1968: Kalahari pans: a preliminary study. Mss. Dept. of Wildlife and National Parks, Gaborone, Botswana.

PARIS, R. 1970: Important role of the Kalahari pans. Afr. Wild Life. 24, 234 - 237.

PASSARGE, S. 1904: Die Kalahari, Reimer, Berlin.

PASSARGE, S. 1911: Die pfannen formigen hohlformen der Sudafrikanischen steppen. Petermanns Mitt. 57, 130 - 135.

PEEL, R.F. 1966: The landscape in aridity. Trans. Inst. Br. Geogr. 38, 1 - 23.

PIKE, J.G. 1972: Rainfall over Botswana. In: Proc. Conference on sustained production for semi arid lands. Botswana Notes and Records, Special Edition, 1, 69 - 75.

PIPER, C.S. 1946: Soil and Plant Analysis, Interscience Publishers, New York.

POLDERVAART, A. 1957: Kalahari sands. In: Clark, J.D. (ed.) Proc. 3rd Pan African Cong. Prehist. Livingstone, 1955, 106 - 114.

PRICE, W.A. 1963: Physico-chemical and environmental factors in clay dune formation. J. Sedim. Petrol. 33, 766 - 778.

REEVES, C.C. 1965: Chronology of west Texas pluvial lake dunes. J. Geol. 73, 504 - 508.

REEVES, C.C. 1966: Pluvial lake basins of west Texas. J. Geol. 74, 269 - 291.

REEVES, C.C. 1968: Introduction to Paleolimnology, Elsevier, Amsterdam.

REEVES, C.C. and PARRY, W.T. 1969: Age and morphology of small lake basins, southern High Plains Texas and eastern New Mexico. Tex. J. Sci. 20, 349 - 354.

ROGERS, A.W. 1908: Geological survey of parts of Vryburg, Kuruman, Hay and Gordonia. Ann. Rep. Geol. Comm. Cape of Good Hope, 12 (1907) 9 - 122.

ROGERS, A.W. 1934: The build of the Kalahari. S. Afr. Geogr. J. 17, 3 - 12.

ROGERS, A.W. 1935: The solid geology of the Kalahari. Trans Roy. Soc. S. Afr. 23, 165 - 176.

ROGERS, A.W. 1936: The surface geology of the Kalahari. Trans.Roy. Soc. S. Afr. 24, 57 - 60.

ROGERS, A.W. 1940: Pans - a review of Die Trochenseen Der Erde. S. Afr. Geogr. J. 22, 55 - 60.

RUSSELL, I.C. 1885: Geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada. U.S. Geol. Surv. Monograph, 2.

SAVORY, B.M. 1965: Sand of Kalahari type in Sesheke District, Northern Rhodesia. In: Snowball, G.J. (ed.) Science and Medicine in Central Africa, Pergamon Press, 189 - 200.

SCHOFF, S.L. 1939: Sediments and groundwater resources of Texas County Oklahoma. Bull. Geol. Surv. Oklahoma. 59

SMITH, G.I. 1968: Late Quaternary geologic and climatic history of Searles Lake, Southeastern California. In: Morrison, R.B. and Wright, H.E. (eds.) Means of Correlation of Quaternary Successions, Univ. of Utah Press, Salt Lake City, 293 - 310.

SMITH, H.T.U. 1940: Geologic studies in S.W. Kansas. Bull. Geol. Surv. Kansas. 34, 1 - 240.

TWIDALE, C.R. 1972: Evolution of sand dunes in the Simpson Desert, Central Australia. Trans. Inst. Br. Geogr. 56, 77 - 110.

VAN DE MERWE, C.R. and HEYSTEK, H. 1955: Clay minerals of South African soil groups, 3: Soils of the desert and adjoining semi arid areas. Soil Sci. 80, 479 - 494.

VAN STRATEN, O.J. 1955: The geology and groundwaters of the Ghanzi cattle route. Ann. Rept. Geol. Surv. Bech. Prot. 28 - 38.

VAN ZINDEREN BAKKER, E.M. 1957: Pollen analytical investigation of the Floisbad deposits. In: Clark, J.D. (ed.) Proc. 3rd Pan African Cong. Prehist. Livingstone, 1955, 56 - 67.

VAN ZINDEREN BAKKER, E.M. and CLARK, J.D. 1962: Pleistocene climates and cultures in N.E. Angola. Nature London 196, 639 - 642.

VERSTAPPEN, H.Th. 1968: On the origin of longitudinal (seif) dunes. Zeit. fur Geom. N.F. 12, 200 - 220.

WARREN, A. 1970: Dune trends and their implications in the central Sudan. Zeit. fur Geom. Supp. 10, 154 - 180.

WASHBOURN-KAMAU, C.K. 1971: Late Quaternary lakes in the Nakuru - Elmenteita basin, Kenya. Geogrl. J. 137. 522 - 535.

WAYLAND, E.J. 1952: More about the Kalahari. Geogrl. J. 119, 49 - 56.

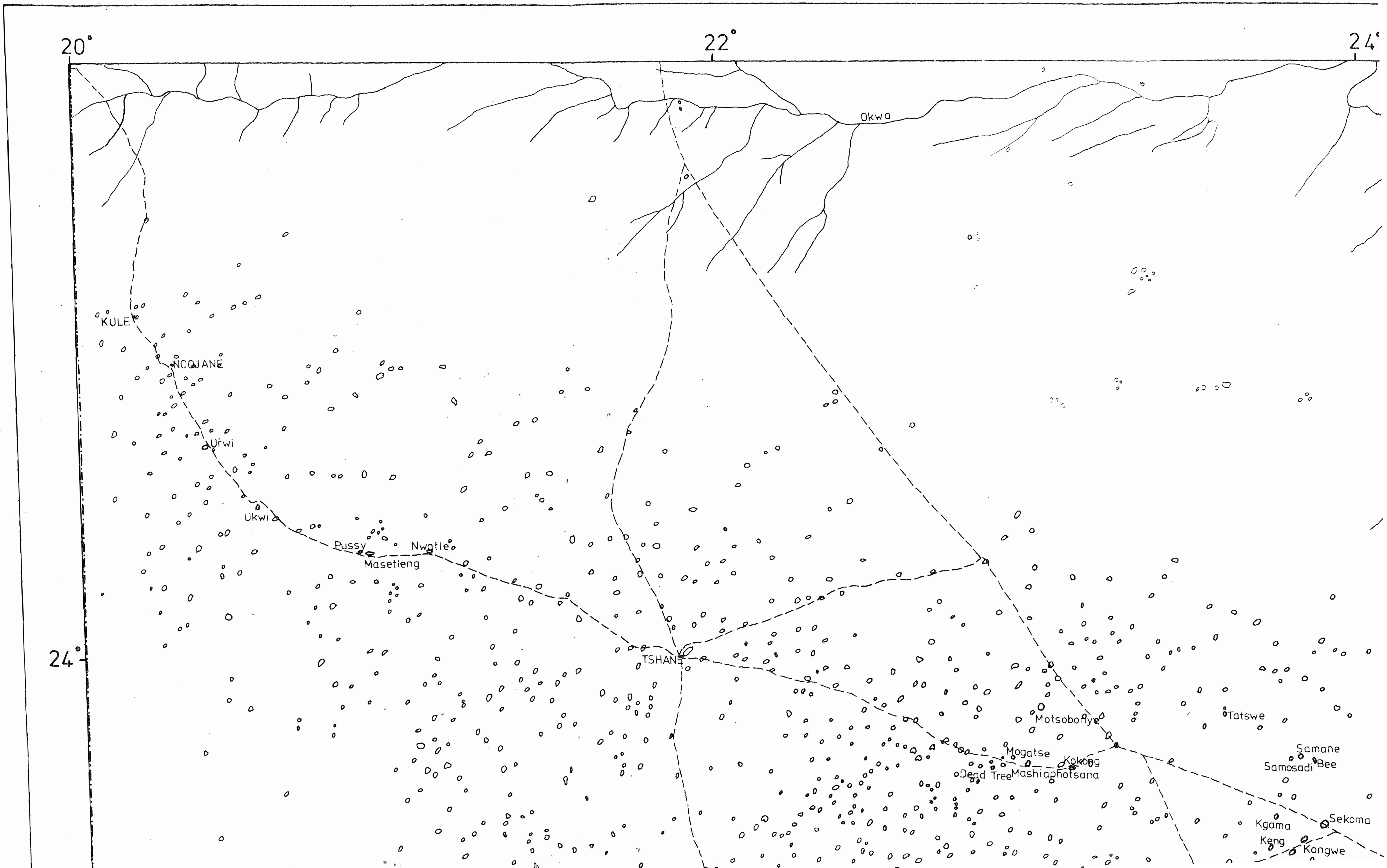
WAYLAND, E.J. 1954: Outlines of prehistory and Stone Age climatology in the Bechuanaland Protectorate. Mem. Acad. R. Sci. Colon. Sci. Nat. red. 8 25(4).

WELLINGTON, J.H. 1943: The Lake Chrissie problem. S. Afr. Geogr. J. 25, 50 - 64.

WELLINGTON, J.H. 1945: Notes on the drainage of the Western Free State sandveld. S. Afr. Geogr. J. 28, 73 - 77.

WELLINGTON, J.H. 1955: Southern Africa - a Geographical Study, vol. 1 Physical Geography., Camb. Univ. Press.

WERTHER, R. 1935: Die Kalahari, Leipzig Mus. Landkerk, wiss Veroff. N.F. 3, 35 - 94.



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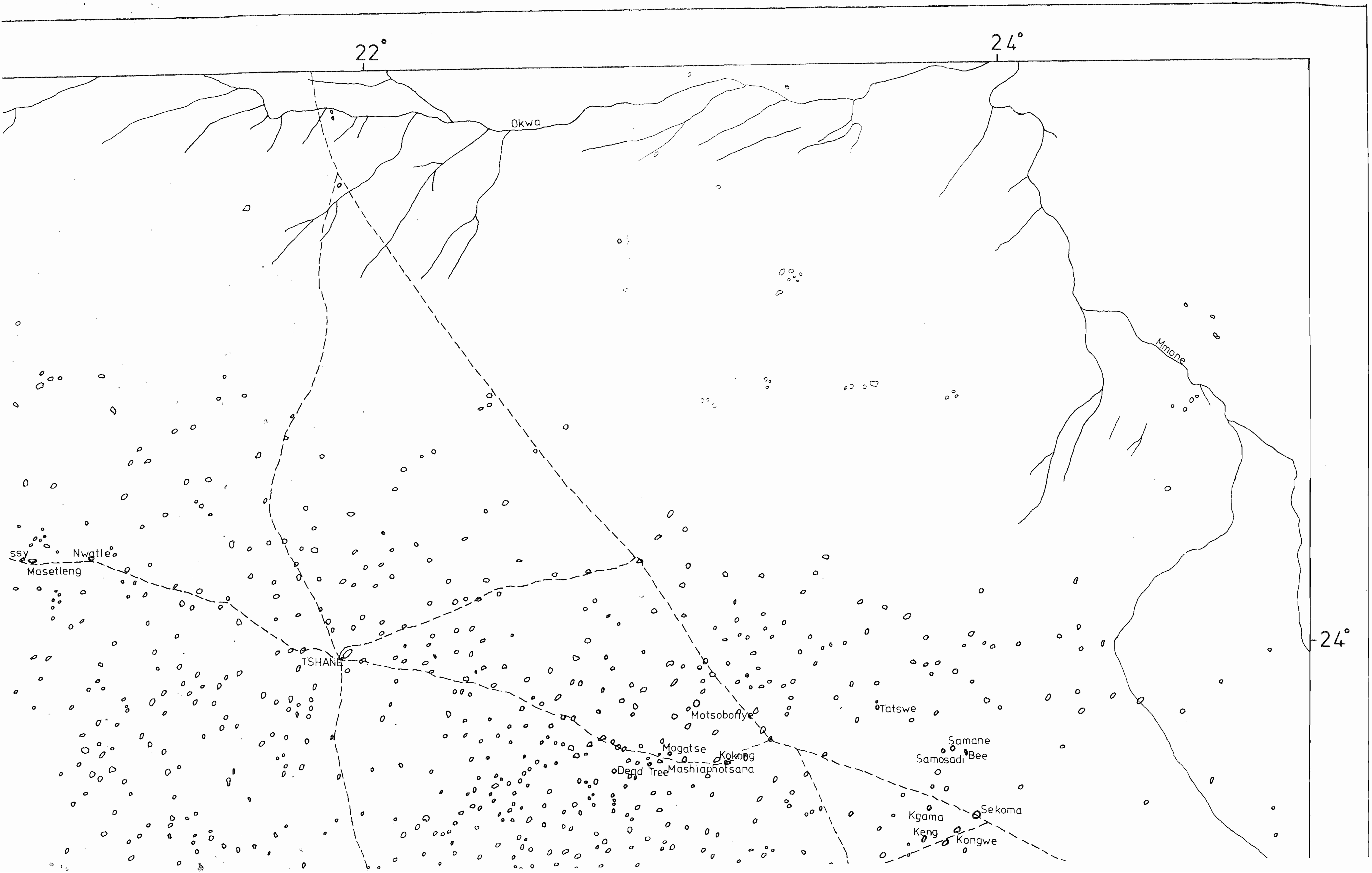
Kokong
Dead Tree
Mashiaphotsana
Kgama
Sekoma
Keng
Kongwe



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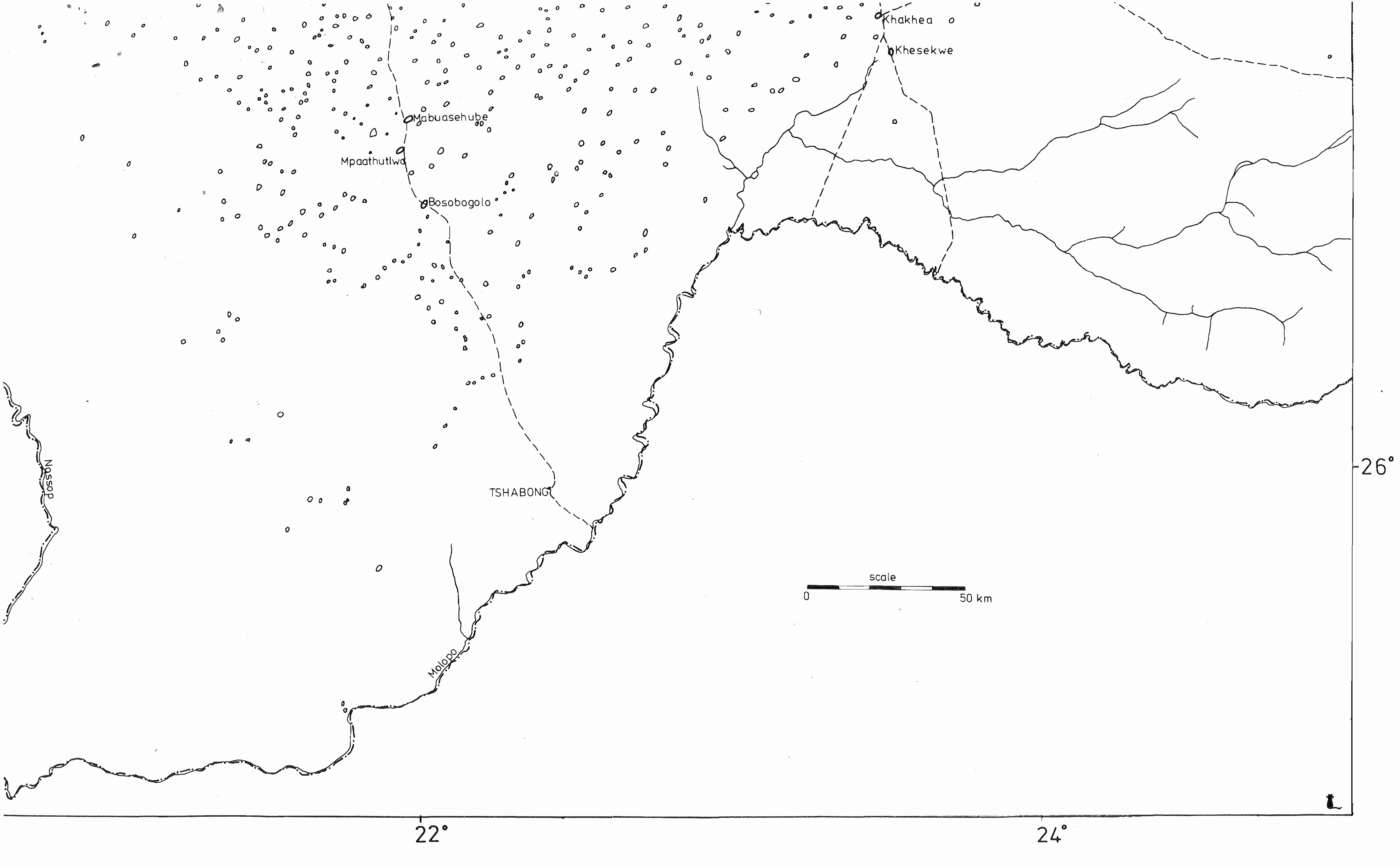

Khakhea
Khesekwe
Mabuasehube
Mpaathutlwa
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Nossop
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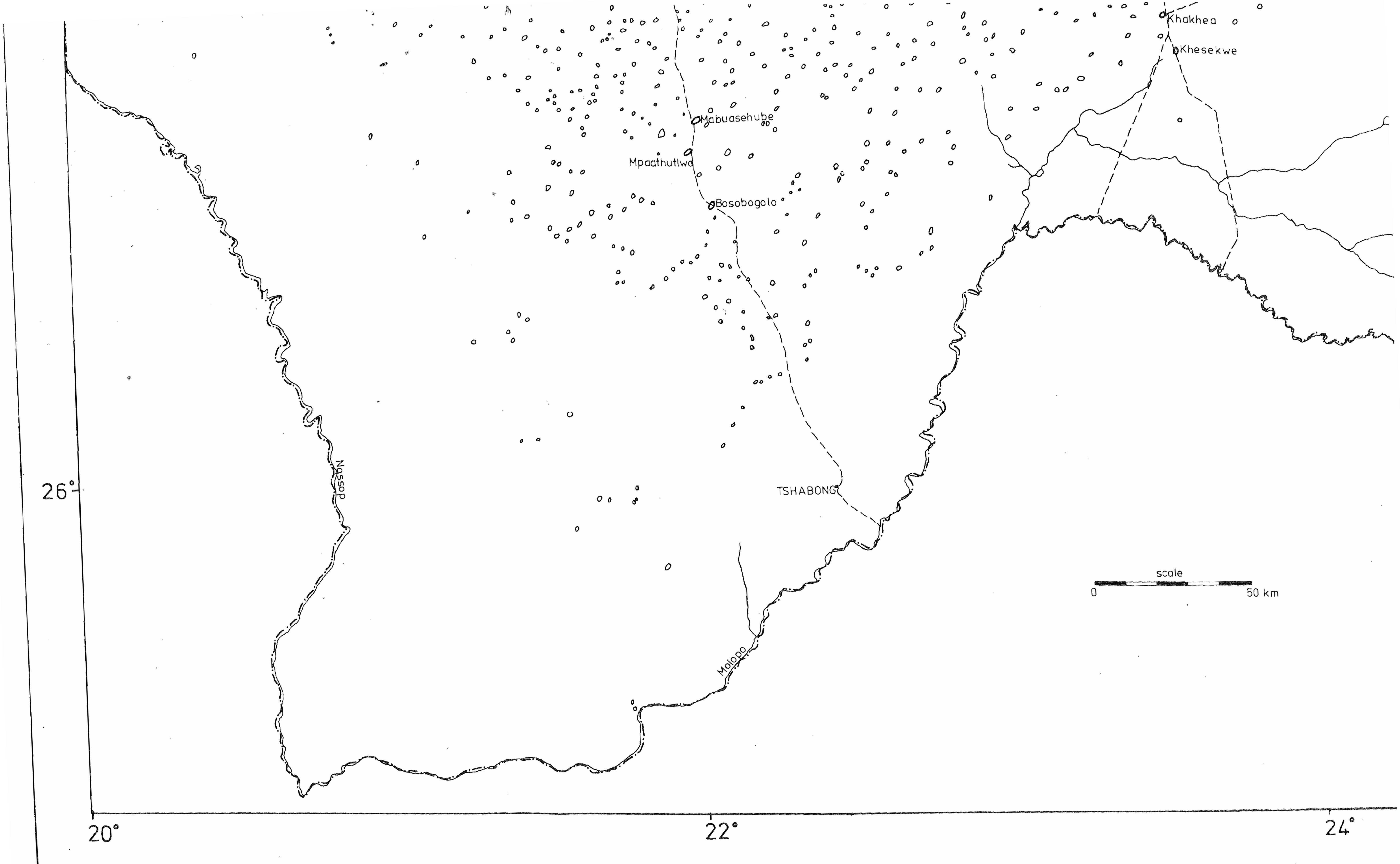
Khakhea
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