ABSTRACTS

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FOREWORD

The Kalahari has fascinated all who have been fortunate enough to spend weeks or months in its sandy wastes. The continual problem of water in a land which is saturated at depth, the unceasing dune fields covered in vegetation which seemingly contradict accepted models of dune formation, the lush, luxuriant swampy wastes of the Okavango and the vast shining white expanses of the pans like Sua, Magadigadi and Etosha all form part of the whole which is the mystique of the Kalahari.

The questions of how, when and why fill the minds of geologists and geomorphologists working in the area today - these questions no different to those that confused Passarge, du Toit and King. Their early attempts to explain the causes and sources of this great sand accumulation are not very much different to the present some state of knowledge. However, recent groundwater development and deep exploration has increased our understanding considerably.

Why do we struggle with our understanding of the Kalahari? The single most important factor in controlling the amount of research into this desert has been the severe logistical problems of working in that remote and forbidding area. Secondly, there is an attitude that very little of an economic nature is present. That has of course changed. Today we see the importance of groundwater and minerals. Furthermore without an understanding of the Kalahari itself geophysical interpretation of the underlying geology is fraught with difficulties.

The Kalahari has been extremely reticent with it’s divulgence of ages, dates and what it is about. Duricrusts, which make up only a fraction of any area in the Kalahari comprise some of the most persistent landforms. The limited drilling which has been conducted, has as primary objective to get through the sand as soon as possible with the result that samples are very rarely collected and if so are even more poorly logged.

An understanding of the lithological controls are only revealed after thorough understanding of the mechanisms by which the Kalahari formed. Although our understanding of these mechanisms is still severely limited, the recent advances
in disparate fields such as climatology, geology and botany as well as major developments in groundwater drilling has far increased our knowledge of the major blank areas on our maps.

With these developments in mind a symposium providing a forum for the discussion of the Kalahari Group was convened in November 1992 under the auspices of the Geological Society of Namibia. These collected abstracts form the bulk of papers presented at the Kalahari Symposium 1992 in Windhoek. This conference was successful in its goals which were to increase general understanding of the Kalahari as well as providing a forum for the many workers in the area to interact. It is hoped that this will not be the last and that continuing research will be presented in the near future.

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Windhoek  
November, 1992

OVERALL TECTONICS, MODERN BASIN EVOLUTION AND GROUNDWATER CHEMISTRY OF THE OWAMBO BASIN

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The Tertiary-Quaternary Kalahari Group is found throughout much of southern Africa. This paper deals with the Owambo Basin which lies in north-west Namibia and extends across into southern Angola. The basin attains maximum thickness of about 500 metres in central Owambo, thinning to the north west and south, and extending into other Kalahari basins east and north.

Evidence from aerial photography, field work and satellite imagery suggests that the basin has been erosional and not depositional in its recent past. This is evidenced by extensive faulting throughout the basin and the development of an almost universal rock platform underneath a very thin veneer of modern sediments. The age of the faulting is uncertain but it probably dates from at least the Cretaceous through to the very recent. Some of the larger faults are almost certainly due to basement reactivation.

Faulting is caused by extensive uplift in the west of the basin along the craton margin. The extent of uplift cannot be determined but basal Kalahari Group sediments are found at 1300 metres elevation in the west compared with an average elevation of about 1100 metres for upper Kalahari sediments in the main part of the basin. This suggests that uplift in the west was at least 400 metres at the modern basin’s margin and probably much more. The basin originally extended much further west and has been removed by erosion. Uplift was almost certainly episodic.
It would appear that uplift has occurred across much (if not all) of the central and western Owanbo Basin (it is recognised to have taken place at least as far east as Eenhana and Okankolo). This is evidenced by the presence of brittle rock fracture (faulting), hard/semi-consolidated rocks at shallow depth throughout this part of the basin and clear evidence of tectonic movement (particularly folding) in several exposures.

Prior to the most recent phases of uplift, the Owanbo Basin probably drained to the sea via a drainage to the south of the basin. This is evidenced by all the palaeo-drainages which flow south and west. These drainages include the Cuvelai, Oshigambo, Nipele and Omuramba Owanbo Rivers. In addition there are several drainages present under the modern dune fields that originally flowed from the Angolan highlands through into the Etosha Basin.

That uplift was episodic can be demonstrated by the presence of a clear regional step in basin elevation. This step is of the order of only a few metres but is clearly reflected on the satellite photography and by the vegetation. To the west of this step are the grasslands and palm belts while to the east are the forest areas. It is believed that this step represented a major pulse.

The palaeo drainage across the Etosha pan floor (which drained from east to west) is possibly the remnants of this drainage system. The size of the Hoanib River and the fact that it still has the lowest potential outlet level on the south-west basin margin makes it a very likely contender. Drainage would have been via the Beestevlakte (a very broad sand-filled valley) and the Khwarib Schlucht (a large 30 kilometre-long series of gorges). There is no clear evidence that the Cunene River played any role in draining the Etosha Basin at this stage.

Continued uplift possibly combined with a period of lower drainage volumes closed this outlet to the sea generating a saline body of water at least 45 metres deep. This would give the lake a surface area greater than 82,000 square kilometres or larger than Lake Victoria. If the lake was currently full it would be the second biggest inland body of water in the world after the Caspian Sea. Evaporation progressively salinised the waterbody and all of the sediments underlying it.

Uplift in the west, as well as closing the south-western outlet rejuvenated all westward flowing drainages, including the lower reaches of the proto-Cunene, and decreased the gradient of westward flowing rivers (causing them to become largely dormant). As the Cunene drainage assumed its modern form, so it removed by river capture many of the headwaters of the Etosha Lake system. This had the double effect of substantially reducing the water flow into the system and almost certainly allowed water from Lake Etosha to escape to the sea via the 110 metre outlet of the Mui River. This outlet is still preserved in the Etaka and Mui Rivers which are one and the same (the Mui drains north, the Etaka drains south). This caused a geologically recent stabilisation of the system at the 110 metre level, generating the 110 metre shorelines seen at the eastern side of the Andoni Flats and in the west at Okondeka. As the water level dropped so the lower shorelines were generated. It is apparent that as the water dissolved salts and flushed them towards the base of the Etosha Pan, so salinities are found to increase in the groundwaters towards the pan centre.
Three hydrogeologically different aquifers were identified within the project area of central Owambo:

1. The Discontinuous Perched Aquifer. This aquifer was encountered in the northern part of the project area and is very shallow (1-10 metres). It is essentially rainwater accumulating at the base of porous units (e.g., modern sand dunes) in contact with the underlying harder rock units. Water quality is very good but the water volumes present and yields are very small. These are locally tapped by "Omuifima" - cone-shaped holes dug in the sand, typically with a brush fence around them. These systems cannot be developed as reliable rural water sources.

2. The Middle Shallow Aquifer. This aquifer varies from about 1 metre deep in the south of the area (adjacent to the Etosha Pan) to as deep as about 40 metres in the north. It can be considered as part of the underlying deep aquifers but is excluded on account of its very variable water quality. Essentially it is a saline aquifer (salinity is probably due to dissolution of soluble evaporites inherent in the system and connate saline water) that has numerous freshwater lenses floating on the upper surface. These freshwater lenses are created by irregular recharge points (faults, animal holes, etc.). This aquifer is therefore extremely variable in nature.

3. The Deep Aquifer. This aquifer lies from about 50 metres downwards and is a continuum with the Middle Shallow Aquifer. Field evidence shows that below about the 1130m topographic contour (maximum lake stillstand) this aquifer is always saline and salination extends several hundred metres through the sediment pile. Above this contour, water quality progressively improves until above about the 1400m topographic contour, this aquifer is of a good quality.

All three aquifers have a very distinct hydrochemistry but dissolution of evaporitic salts within the system is universal to all three. All three water types have high Na+, HCO₃, Cl- and SO₄, which are typical of basins that have undergone high evaporitic conditions. To prove the point, sediment samples were collected and dissolved over 10 days. Analyses of the water samples showed that Na+ was combining in a 1:1 ratio with SO₄, Cl- and HCO₃. This demonstrated that the more saline fluids are derived by dissolution of evaporitic salts while the less saline are derived by dissolution and mixing processes. Mixing is of essentially
The Cunene River has captured its modern headwaters. Lake Etosha drains to the sea via the Etaka and Cunene Rivers. This creates the well-developed 1100m shoreline (depth of water was ± 23m).

The upper portion of the Etaka River flows both north and south. The western oshanas are recent Cunene overflow channels. The Omaombo Ovambo, Akazu, Nipele and Oshigambo Rivers are dormant. Current climatic conditions only generate small flows in the Ekauma River.

Saline fluids and meteoric groundwater. This explains the rapid variation of water quality seen throughout central Ovamboland.
THE QUATERNARY GEOMORPHOLOGY OF THE KALAHARI

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Interpretation of the Kalahari Group sediments, first attempted by Passarge at the end of the nineteenth century, has proved to be a difficult task. The sediments show a high degree of homogeneity, particularly the Kalahari Sand, lack fossils and have low rates of organic preservation. They are frequently highly altered, and there has been much confusion in distinguishing the products of post-depositional modification from true stratigraphy.

Geomorphological studies carried out in the Kalahari south of the Zambezi River over the past twenty years have contributed greatly to the understanding of processes active in the Kalahari Basin, and, through a suite of approximately 300 radiocarbon dates, of the environmental conditions prevailing in the Late Quaternary. This, in turn, has allowed greater insight into the nature and relationships of the Kalahari sediments.

The oldest Kalahari landforms appear to be the networks of dry valleys (megachannels) which drain towards the centre of the basin, or southwards towards the Orange River. Although there is limited evidence for sporadic surface flow in these valleys, particularly in the Kuruman-Auob-Nossob system, their formation can be largely attributed to groundwater activity along selected flow paths. Pans are also formed by groundwater activity, rather than aeolian action as previously thought.

The complex suites of duricrusts associated with these two landform types are evidence of this groundwater activity.

Studies of the Okavango Delta and the associated Makadigkadi-Mababe-Ngami palaeolakes has provided evidence for episodes of wetter climates in the Late Quaternary, although hydrological patterns have been much modified by tectonic activity in the Kalahari Rift and Gwembe Trough. Two major palaeo-lake levels, the Lake Palaeo-Makadigkadi stage at 945 m asl. and the Lake Thamalakane stage at 936 m asl. indicate major changes in the Middle Kalahari region. Evidence from Drotzky’s Cave in Ngamiland has been used to differentiate local from regional climatic signals.

The dominant dune form is the linear dune, which occurs in three major fields in the Southern and Middle Kalahari. These fields have previously been assumed to be fossil features activated during periods when precipitation has decreased below c.150 mm p.a. This hypothesis is difficult to sustain given the latitudinal extent of the dunes, and the lack of chronological data currently available for the existence of episodes drier than present. Recent research suggests that linear dunes are sand transporting dunes with little bedform movement, and are capable of functioning at higher precipitation levels and a vegetation cover up to 30%. As such they are persistent and probably ancient features in the landscape.

Radiometric dating has provided good chronological control of environmental changes over the past 20,000 years, with strong evidence for a major wet phase throughout the region at 16,000-13,000 BP, followed by lowering of groundwater tables and accompanying duricrust formation to 10,000 BP. The early Holocene experienced conditions similar to the present, while minor wet episodes have occurred throughout the last 5,000 years, notably around 2,000 BP. The radiocarbon chronology has been extended back to 50,000 years, but the period before the Last Glacial Maximum (c. 18,000 BP) has provided less certain results.

An interesting feature of the Quaternary climatic chronology is that it is out of phase with Africa north of the Equator, and with other arid and semi-arid regions of the tropics. This divergence from global patterns has not yet been satisfactorily explained, but is likely to arise from the northward movement of the monsoonal belt during periods of hemispheric forcing.
Present research is concentrating on the extension of the palaeoclimatic record to 300,000 BP through the use of Th/U dating on cave speleothems, and the dating of ‘drier’ episodes using thermoluminescence and optical luminescence on dune sediments.

PALLYGORSKITE AND DOLOMITE IN LATE NEOGENE PALUSTRINE SEDIMENTS, NORTHWESTERN TRANSVAAL, SOUTH AFRICA

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The fluvial sediments of the Rooibokkraal Formation and associated lacustrine argillites comprising the Zuurverdiend Member accumulated in parts of the northwestern Transvaal on the margin of the Kalahari region, probably during the late Neogene period. The accumulation of thin, yet widespread sedimentary cover and formation of diverse duricrusts associated with the Rooibokkraal Formation is discussed in the context of regional calcritization in response to changing environmental conditions.

Landscape processes in the area changed from active fluvial channel and distal ephemeral lacustrine processes to those dominated by pedogenic calcritization. The development of thick calcrite profiles within gravelly and sandy sediments and weathered granitoid bedrock occurred initially in areas surrounding poorly-drained depressions. Preferential removal of Ca during a long period of calcrite formation in these areas concentrated Mg in groundwater-feeding poorly-drained areas. Further evaporative concentration of magnesium during periodic emergence of the palustrine margins of ephemeral lakes resulted in breakdown of smectitic clays and neoformation of palygorskite. Permanent desiccation of palustrine mudflats led to development of replacive, pedogenic powder dolcrete within the palygorskite/smectite clay deposits.

Although accumulation of the Rooibokkraal Formation was probably contemporaneous with part of the Kalahari Group succession, no lithostratigraphic correlation has been attempted. It is suggested that a broader lithostratigraphic grouping is needed before attempting to correlate Cainozoic sediments in the region.
GAMMA-RAY SPECTROSCOPY FOR THE MEASUREMENT OF THE RADON EMANATION RATES FROM SAND CONTAINING HEAVY MINERALS

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Radon gas emanating from minerals containing uranium diffuses through the overburden and reaches the atmosphere. The rate of diffusion can be measured and mapped and can provide information regarding both the underlying formations and characteristics of the overburden such as porosity and depth. A measurement of the $^{222}$Rn loss rate can relate the radon fluxes to such factors as the $^{226}$Ra concentrations of the overburden, the soil type, the moisture content and the vegetation. The results of radon monitoring can therefore provide useful information for geological, mineralogical and environmental interpretation.

This paper describes a method for the determination of radon loss that was originally developed to monitor the rate of radon emission from tailings dumps produced as by-products in the extraction of heavy minerals from sand deposits. Although this project had the objective of protecting the public and the environment from radioactive exposure, the methods are widely applicable to the study of overburden and underlying rock as was described above.

The present study is part of a research programme aimed at addressing these important questions in the case of an environmental study. It sought to answer the following questions:

a) The nature and composition of the radioactive by-products produced.

b) The potential hazard of the radon emanation.

c) Ways of reducing the rate of production of the radon.

d) In particular what is the emanation rate of radon and hence the emanation index.

The procedure to be described involves the determination of radon adsorbed on activated charcoal using a container in the shape of a marinelli beaker. The radon gas from the sample is allowed to build up for a set period of time in this container. The activity of the decay products of the $^{222}$Rn was then measured using both a NaI(Tl) detector and a Ge detector.

A layer of silica gel is used to reduce the effects of humidity on the adsorption. A space between the charcoal and the surface produces a fixed volume that is sampled by the charcoal. The radon activity is measured by means of the gamma-ray activity from the radon daughter products $^{214}$Pb and $^{214}$Bi. A similar method has been described by Perisko and Wicke (1988).

The natural gamma-ray activity measured can be related to the emanation of radon and this in turn is related to the emanation coefficient, defined as the ratio of the radon released to the total radon formed within the sample. This coefficient depends on a number of factors including the porosity, mineral species, radium mineralogy, particle size and interstitial or pore water content. It will be described and evaluated.

References:

WHERE ON EARTH ARE WE? (Applications of GPS satellite navigation in Botswana)

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The development of portable and affordable satellite positioning systems has greatly improved navigation in the Kalahari Desert, and is of great interest to all geoscientists working in remote areas.

As a result of rapid development of satellite technology since the early 1960s, several satellite navigation systems came into use. TRANSIT of SATNAV was developed by the United States Navy, while ARGOS, SARSAT and STARFIX are examples of civilian and commercial systems. The former Soviet Union also designed its own GLONASS system, the future of which is perhaps uncertain.

The Global Positioning System (GPS or NAVSTAR) has been developed by the US Ministry of Defence in the 1970s to eventually replace the TRANSIT system. The full GPS satellite constellation consists of 21 operational and 3 spare satellites and should be completed in 1993 (Figure 1). As of this date, there are 17 operational satellites in orbit, enabling 24 hour 2-dimensional position fixing. Until the complete constellation is operational, 3-dimensional positioning may be available only part-time.

Early positioning instruments using the TRANSIT satellites were bulky and required several days of recording to achieve 1 m accuracy. The development of

the GPS technology launched navigation and surveying into a new era. There are

NAVSTAR GPS satellite orbits

21 satellite constellation
20,183 km above the Earth
12 hour orbits, visible 20 minutes

Figure 1 - GPS satellite constellation
two levels of accuracy of GPS instruments: Coarse Acquisition (CA) used primarily for navigation; and Precise Positioning Service (PPS) Systems employed for survey applications.

CA receivers are more common in the earth sciences because of their low cost, portability and real-time positioning capabilities. The standard technology of these CA instruments is easily capable of 100 m in seconds. This accuracy may be improved to perhaps 5 m by recording the data over a period of about 20 minutes and analyzing the statistical variation of position with time (Figure 2).

The new GPS technology is very quickly becoming established in applied earth sciences in Botswana. During recent field work in the Okavango Delta, three different GPS instruments were used for mapping the occurrence of Acacia spp and Salvinia molesta (Kariba Weed), borehole surveying, water sampling of the Boro River system, and game tracking. The Geological Survey of Botswana use GPS receivers for navigation in the Kalahari, and point positioning for regional gravity surveys.
The possible users of GPS are myriad. The civilian uses of this technology are perhaps more imaginative and diverse than those foreseen by the original military designers. In the future, GPS may be used for navigation of automobiles through city streets, or may be available in wristwatch sized versions for the weekend camper. Instrument manufacturers predict a US$6 billion market for GPS by 1996.

![scatter of GPS positions]

Figure 2 - variation of position with time

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**THE USE AND MISUSE OF GEOPHYSICS FOR BOREHOLE SITING IN THE KALAHARI**


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In the last two decades, geophysics has played an increasingly important role in the siting of boreholes for groundwater. In areas with extensive alluvial cover such as parts of the Kalahari, this increase appears to have been more prolific. Both consultants and contractors continuously search for the perfect modern day “black box” that will replace more traditional techniques that perhaps may operate on a slightly less scientific basis.

With this increase in the use of geophysics for borehole siting, there has been a steady increase in the number of non-geophysicists utilising these methods. While often this does not pose a problem if these individuals have a suitable background in science to understand the physics of the problem at hand, there have been numerous instances of the wrong geophysical method being utilised to measure the wrong physical parameter in the search for groundwater. When proper data has been collected, it has often been incorrectly interpreted. Both non-geophysicists and geophysicists have been guilty of this transgression.

This talk serves to outline the different geophysical techniques available for siting boreholes in various aquifer types and the proper manner in which they should be employed. The discussion is primarily confined to the more conventional techniques currently employed in Botswana (magnetics, VES, EM and gravity) under the assumption that more sophisticated and expensive methods such as controlled source audio-magneto tellurics (CSAMT), reflection seismic and time-domain EM would not be employed in siting bores.

Potential field methods such as magnetics and gravity, are only effective if there is a sufficient lateral contrast in the respective physical properties of the various units within the survey area. Ground surveys with these methods are
generally best suited in defining structure, which in turn tend to be the best drill targets in fractures and fractured-porous aquifers. The resolution of structural features with these methods is primarily a function of survey quality and choosing of the appropriate station interval for the anticipated target. Given the high cost of detailed gravity surveys, this method is less appropriate for siting individual boreholes; however, it is generally very applicable in regional scale work for defining prospective areas for more detailed follow-up, especially in the Karoo.

![Figure 1 Common Mistake
Siting VES on a fault](image)

Electromagnetic profiling has proven itself to be one of the most effective and successful methods for the siting of boreholes in Botswana. Although the equipment is relatively straightforward to operate, the choice of the proper cable length and operating frequencies is critical to the success of a survey. Typically the cable length chosen is either too short to allow the signal to penetrate to the anticipated target depth, or the longest cable available is used. This latter configuration decreases resolution and further increases an already conductive background response which in turn dominates and masks the anomalous response. With the exception of porous aquifers, EM profiling is generally effective in all aquifer types in Botswana, provided the survey is properly designed.

VES is perhaps the most widely used geophysical technique in groundwater work and borehole siting, and not surprisingly is the most abused. Interpretation of this data is based on the assumption that the area being surveyed is void of any lateral discontinuities; however, these soundings are quite often sited on inter-
Primary porosity type aquifers in the Kalahari beds are perhaps the most difficult target for geophysics, particularly with electrical techniques where current penetration is limited.

Fractured and karst type aquifers provide a small total resource, but are locally important because they occur in the densely populated area of eastern Botswana.

![Fractured-Porous Aquifer](image)

Figure 2 - borehole 6767 regional geophysics

Traditional and non-scientific methods such as water divining have been popular historically and continue to be used as an alternative to modern techniques. The effectiveness of these alternative siting methods, and the scientific explanation thereof, remains a mystery ...

In this paper we present several geophysical case histories of different aquifer types to demonstrate the effectiveness of each geophysical technique in the Kalahari environment.
One of the most important techniques for mapping regional geology and structure has proven to be detailed aeromagnetic surveys. Potentially water-bearing fault zones and dolerite dykes overlain by Kalahari beds can be effectively located with this method.

Gravity and magnetics, electrical soundings, and electromagnetic profiling techniques have proven to be the most effective combination of borehole siting methods for exploration of the important fractured-porous type aquifers in the Karoo Basin (Figure 2).

In judging the effectiveness of a particular technique, two different types of success are defined: technical success and utilization success. A borehole is a technical success if the geological and geophysical interpretation is explained. A borehole is judged a utilization success only if it meets the needs originally intended.

ISOTOPE HYDROLOGY OF SEMI-ARID REGIONS: LESSONS FROM THE KALAHARI

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The sand-covered Kalahari threistland is devoid of surface water, except for the inland Okavango delta in the north-west. Annual rainfall, ranging from 200 mm in the south-east to 600 mm in the north-east is highly variable. Groundwater, mostly phreatic to partly-confined, is held mainly in horizontally-bededed, Carboniferous to Jurassic sedimentary Karoo aquifers. Traditionally, diffuse recharge was regarded as negligible, except in areas where the sandy, unconsolidated Tertiary to Recent Kalahari Beds cover is <6 m or during floods in ephemeral streambeds. Low piezometric gradients towards sedimentary basin centres were taken as evidence of sub-regional flow away from such "recharge areas".

Groundwater levels, at depths of 20 m to over 200 m, tend to follow the Kalahari/pre-Kalahari interface. Regional groundwater gradients are directed towards drainage levels, such as the Makgadigadi salt flats in the north-east. Although this dry lake clearly received groundwater drainage in pluvial times, at present groundwater levels lie below the perched brine level in the lake floor.

Environmental isotope and hydrochemical studies have been conducted over a period of more than 20 years in a number of areas of the Kalahari, usually as part of groundwater development projects. Most of the data was gathered from existing, low-yielding supply boreholes, usually poorly documented. Hence, a semi-statistical approach is usually adopted. Even in specially-drilled project boreholes, integrity of e.g. depth controlled samples was rarely assured.

A selection of these studies is briefly discussed. Various features of this semi-arid environment become apparent from the overall conclusions, leading to some important insights into hydrological processes which may have validity in other semi-arid to arid environments.
1. Gordonia. A relatively fresh groundwater occurrence was assumed to be fed from ephemeral river flood infiltration by underflow over a distance of some 40 km. Radiocarbon and hydrochemistry in numerous wells exhibit no trends as evidence of such underflow. Stable isotope values in groundwater near to and further from the river are quite different. This leads to a model of diffuse recharge through thick sand cover occurring only during exceptionally intense rainfalls, whilst evapotranspiration balances infiltration completely due to expanding vegetation activity during prolonged wetter periods, with much lighter isotope signal, when the river flows.

2. Kweneng. A histogram of \(^{14}\text{C}\) values in numerous wells shows most frequent values around 55 pMC. Values 10 pMC are all associated with confined conditions. The latter cases are all Na-HCO\(_3\), Cl dominant, whilst unconfined groundwater shows various transitions between Ca and Na dominance. There are no clear regional isotopic or hydrochemical trends, which suggest little or no regional flow. Regional permeabilities are thus much smaller than measured in pump tests. An overall model proposes isotopic (80 - 60 pMC) and chemical (Ca-Na) depth stratification.

3. Serowe. The intensively faulted and intruded Karoo sequence forms a low escarp with thick Kalahari cover to the west of Serowe. Groundwater levels show a mound to the west of the scarp. Deeper and confined groundwater is fresher and Na-HCO\(_3\) dominant; in shallower groundwater, salinities increase westwards with decreasing piezometric gradients. For the fresher groundwater of the mound, recharge estimates based on \(^{14}\text{C}\) values, chloride balance, mound stability and modelling roughly agree (3 - 12 mm a\(^{-1}\)). Further west, \(^{14}\text{C}\) recharge estimates are unchanged, all other tend to 0. Aquifer structure is therefore important in salination and chloride balance should be applied with caution.

4. Tsetse/Shitwa. In this extremely flat area, deep Kalahari Beds cover intensively faulted quartzite and arkose rocks. Groundwater gradients are low and ill-defined. Mineralisation ranges up to 15 000 mg/l, independent of the \(^{14}\text{C}\) distribution which is continuous from 80 pMC to 5 pMC. Stable isotope values show some pre-recharge evaporation, but little geographic dependence. The actively recharged water therefore carries a palaeosalinity, which even in pluvials will be imperfectly flushed due to the structure.

5. Jwaneng. The highly productive Jwaneng mine well field produces Ca-HCO\(_3\) dominant water in the Kweneng district with Na-Ca - HCO\(_3\), Cl groundwater. Below the featureless Kalahari cover, the field taps a Karoo coarse sandstone delta which partly subcrops and becomes confined below increasingly thick mudstones north-westwards, with \(^{14}\text{C}\) values increasing from 55 - 75 pMC. This apparent paradox leads to the concept of recharge in the south-east, producing flow lines north-westwards, boreholes progressively tapping only the upper aquifer. Leakage into the overlying aquitard, reversed during pumping, may explain the unusually low drawdowns observed over 12 years of increasing exploitation (5x10\(^{6}\) m\(^3\)/a). Groundwater flow in the delta aquifer, as opposed to near-static conditions outside, is ascribed to ongoing recharge and its asymmetrical structure.

Conclusions

1. In such factors as groundwater mobility, mineralisation and chemical type, as well as aquifer development, aquifer structure is of fundamental importance.

2. Diffuse groundwater recharge is ubiquitous and generated by exceptionally intense rainfall events (e.g. Uhlenhorst, Namibia (1961): 489 mm in 24 hours).

3. The contribution and influence of localised recharge sources (e.g. floods in rivers) is limited to their immediate vicinity.

4. The principal loss mechanism is evapotranspiration, even through tens of meters of sand cover.

5. Such losses imply increasing salination, which maybe reset during major recharge periods (pluvials), here too structure is of major importance.

6. Evapotranspirative salination disqualifies chloride balance recharge estimates. Although \(^{14}\text{C}\)-bearing alkalinity also builds up, \(^{14}\text{C}\) is more reliable, as radioactive decay and calcite precipitation act as sinks.
GEOLOGY AND GEOMORPHOLOGY OF AN AREA CENTRED ON THE LOWER ORANGE AND MOLOPO RIVERS: TOWARDS A REMOTE SENSING - GIS SOLUTION

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The objective of this study is to investigate the evolution of geomorphology, specifically drainage, as a function of lithology, structure, tectonics, stream piracy, and climate change. The study also aims to better model the source and transport of alluvial diamonds.

Even though the Kalahari and Bushmanland region typically receives no less than 120 mm of rainfall per annum, it boasts a highly developed drainage system. Notable rivers include the Molopo, Kuruman, Nossob, Aoub, Bak and Kourop. This paradox has received relatively little attention over the past sixty years, this possibly being due to the lack of effective regional-scale geological and geomorphological mapping and analyzing tools. Literature shows that remote sensing and Geographic Information Systems (GIS) have been successfully applied in various geological mapping and exploration studies.

In this study, satellite images (SPOT XS and LANDSAT Thematic Mapper TM) and geophysics (aeromagnetic and gravity) were processed to enhance the geology and geomorphology. The following techniques were utilised to enhance the satellite images: Principal Component Contrast Stretching (PCS), Kauth-Thomas Vegetation Transformation (KTT) and Fast Fourier Transformations (FFT). The first, applied to both the SPOT and TM data, produced well contrasted false-colour composites (RGB: SPOT 321 & TM 754). These images effectively depict lithology, structure and landform. The second technique involved an intensity-hue-saturation representation of the KTT greenness component written as hue and the PCS TM band 4 written as vegetation in tones of blue, green and red respectively and proved useful in mapping drainage. In the third method,

Attempts were made to remove the masking effects of the linear dunes which cover large areas of the region. This technique involved the building of a frequency domain image using a two-dimensional forward FFT, the placement of a user-defined directional wedge, reducing the frequency components within it, and reconstructing a dune-free image by an inverse FFT. The aeromagnetic data were registered and processed at Anglo American Corporation’s Geophysical Division by P.B. Leggatt. The aeromagnetic image depicts broad subsurface geology, and correlates well with that depicted in the satellite images. The images also provided information of hidden structure beneath the Nama, Karoo and Kalahari rocks.

The data sets, once registered and correctly projected, were interpreted interactively on-screen for numerous geological and geomorphological features, including geology, palaeo-drainage and landsurfaces. The integration of image processing, image and map registration, projection and interpretation within a GIS has resulted in a very effective mapping, analytical and cartographic tool, able to manage large regional-scale geological and geomorphological studies.

I would like to thank and acknowledge Dr A.A. de Gasparis, Mr E.O. Kostlin and Mr P.B. Leggatt of Anglo American Corporation, and Mr M.C.J. de Wit and Dr J. Ward of De Beers for providing data, logistical support and guidance.
STUDY METHODS APPLIED IN THE INVESTIGATION OF KALAHARI GROUP SEDIMENTS

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The selection of an area of interest in Botswana is followed by a study of Landsat TM images of that particular area. Certain features on the images are highlighted for investigation in the field. The study area is then traversed and outcrops and borrow-pits are logged in detail. Boreholes in the area are logged by means of chips or cores and a geophysical borehole logger. Since most of the work in the Kalahari is done above the water table, Natural gamma and density are the most useful geophysical logs. The geophysical logs are useful in defining contacts and small upward fining and coarsening sequences in the Kalahari Group, which are often difficult to recognize with chip-logging. The upward fining and coarsening sequences are in turn useful in the interpretation of the depositional environment for the sediments.

A geological map of the area is then compiled, digitized and entered into a GIS (Geographic Information System). The GIS is used to compare and overlay different sets of data in order to better understand the data. For example, the geological map can be superimposed on the Landsat TM images or topographic maps and even moulded to the topography for a 3-D view. Prospecting results are also superimposed on the geology to aid in the understanding of those results.

Considerable attention is given to Kalahari Group sediments as an understanding of their depositional environments is imperative in order to prospect for deposits hidden under the Kalahari Group.

EVOLUTION OF THE EAST HERERO HYDROGEOLOGICAL REGIME

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Many of the hydrogeological, topographical and Kalahari Group phenomena that are evident today are inconsistent with the current hydrological and hydrogeological regime.

Some of these phenomena include:
- the size and courses of the omurambas;
- the apparent contradiction in groundwater age, chemical quality and distribution;
- the formation of thicknesses of calcretes in the Middle Kalahari formations;
- the incision of the omurambas through these calcretes and in some cases into bedrock.

These phenomena are explained in terms of the evolution of the groundwater regime. It is apparent that the area has been subject to significant climatological and environmental change over the last 40,000 years (Figure 1) after the Upper Kalahari Quaternary dunes were emplaced. Heavy rainfall periods saturated the Kalahari formations to within metres of the surface probably more than once during this period. Further evidence for near surface saturation are stalactites and stalagmites in caves in the Tsodilo Hills in Botswana.

Due to the extreme wavelength of the upper dune system, unconfined aquifer water levels in these sands would mimic topography. Groundwater flow directions were then controlled by the dune and regional topography. Internal drainage after rapid infiltration of rainfall was toward local base levels defined by interdune corridors which carried and controlled surface flow (Figure 2).
Stage 1. Regional hydrologic base level was the paleo-Ngami lake in Botswana. When climatic conditions became dry and hot, and internal drainage reduced groundwater levels to a point where direct recharge by precipitation through significant thicknesses of Kalahari sands was no longer possible, the phreatic surface continued to drop under natural groundwater head and hydraulic gradient conditions.

Stage 2. As water levels dropped, the topographically lowest interdune area would begin to drain a greater volume of water derived from lateral internal flow captured from topographically higher interdune areas. These dried up as the water table dropped below their base. Flow volumes in these proto-omurambas increased and significant erosion and downcutting began. (Figure 2).

Stage 3. When hydraulic gradients and groundwater flow velocities decreased regional calcrite formation took place in the Middle Kalahari layers. Drilling evidence indicates an increase in the calc content of the sands with depth until the regional duricrust layers are intersected. These tend to mimic both surface and bedrock topography as evidenced by the exploration drilling profiles. These duricrust layers were formed at the water table interface and achieved thicknesses of 40-60m as the phreatic surface slowly subsided.

Stage 4. As dewatering of the Kalahari beds progressed, a combination of surface flow during wet episodes, lateral internal drainage, and uplift resulted in downcutting of the omurambas through the pedogenic duricrust layers as evidenced east of the 20° meridian.

Stage 5. With further dewatering and the latest dry period waning flow conditions in the omurambas deposited fluvialite sediments fining upward toward zones where infiltration into bedrock structure occurred.

It is probable that this sequence of events occurred partially several times before complete dewatering of the Kalahari Group formations occurred.

Once the Kalahari formations had been dewatered, recharge to the basin continued predominantly by throughflow from the southwest and to a lesser extent the north and south. Low permeabilities of the bedrock formations around the basin...
margins and higher outflow rates into Botswana resulted in a declining water level in the centres of the basin. This is largely the situation today, with steep groundwater gradients around the basin margins where throughflow is taking place and a central portion which has dewatered under natural residual hydraulic head.

This conceptual model explains the rather erratic distribution of groundwater ages and chemistry. Most water was introduced into the basin over relatively short intense periods. Major age groups as identified by Vogel (1979) correlate broadly with the major wet periods identified by paleo-climatic studies. In this case we would expect to have an age stratification with depth and unless hydrochemical and isotopic sampling could accurately ascertain the source of the sample, random sampling could produce a confusing picture.
PROCESSES IN THE FORMATION OF THE OKAVANGO FAN DELTA.

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Over the last six years, a multidisciplinary team from the University of the Witwatersrand has been carrying out research to establish the nature of the processes which underpin the Okavango Delta. From this work it has become evident that the environmental factors controlling the Delta can be divided into two broad categories:

(i) External variables, which include graben faulting, which is the ultimate reason for the Delta’s existence; the geology of the catchment area of the Okavango River, which controls water quality and the nature of the particulate sediment; the semi-arid nature of the environment, which is responsible for the high evaporative rate; and groundwater leakage which prevents the accumulation of hypersaline groundwater;

(ii) Internal processes which operate within the constraints imposed by the external variables and have produced the present form of the Delta. Biotic processes dominate this latter category, with specialized plant communities fulfilling specific functions. These various communities regulate the dispersal of particulate sediment and water. They also control water loss through transpiration, thereby regulating chemical sedimentation, which is the dominant aggradational process in the Delta at present. The action of biological agencies induces even aggradation of the land surface and shapes the topography of the Delta, ensuring widespread distribution of water, and localizing, and hence minimizing the impact of, the accumulation of toxic salts. Far from being catastrophic, changes in water distribution are actually brought about by plant communities and constitute an essential self-renewal strategy in the system.

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CHRONOSTRATIGRAPHY IN THE KALAHARI GROUP - RELEVANCE TO INTRACRATONIC BASIN MODELLING.

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Tertiary age strata of the Kalahari Group occur as largely semi- to unconsolidated sediments in southern and central Africa. These terrestrial sediments have a mixed fluvial and lacustrine origin and are covered by aeolian sands. In Namibia the Kalahari Group is present in the eastern, northern and southern parts of the country. Two broad basins are present in the north - the Owambo Basin (Miller, 1990) and the Herero Basin (Albat, 1978). The southeastern parts of the country are separated from the north by the Ghanzi Ridge which extends from Witvlei through to Maun in Botswana. This prominent topographic high formed during the Damaran Orogeny and appears to have been an important boundary since then.

Three units of formational status are recognized to comprise the Kalahari Group in the Owambo Basin. Post-Karoo sediments such as the Nanzu Formation underlie these units and can also be considered to be part of this sequence. The Kalahari sediments are from the base upwards: the Beiseb Formation which consists of red clays, gravels and grits; the Okukonva Formation, which consists of red and brown calcareous sandstones; and the Andoni Formation consisting of green, usually non-calcareous clay-rich sands and sandy clays (SACS, 1980).

Similar units were identified in the Herero Basin (Albat, 1978). These are the Tsumkwe Formation consisting of reddened gravels, grits and sand; the Eiseb Formation consisting of silcretized quartz sands and the Omatako Formation consisting of ferricretes. All are overlain by recent, unconsolidated aeolian sands of the Gordonia Formation (SACS, 1980).

In the Kavango region red clay is usually noticed below fluvialite sandstones and grits which are discontinuously covered by green clay-rich sands possibly
equivalent to the Andoni Formation. A calcrite horizon is usually encountered at the junction with the overlying unconsolidated aeolian sands.

A single formation, the Weissrand Formation, is recognised in the southeastern parts of the country (SACS, 1980) and consists of calcretes and gravels. Reddened sandstones and calcritised siltstones do, however, underlie parts of this unit. A variable thickness of unconsolidated dune sand again covers the sequence.

All these divisions are based upon significant changes in lithology, however, few actual exposures exist in the Kalahari and most data is sourced from hydrological percussion drilling. Local divisions have therefore often been based upon calcretes or other duricrusts. Traditional sedimentary analyses should therefore be considered with care as:

i. the pervasive presence of duricrusts severely alters the nature of the sediments. Chemical expansion as well as alteration can severely change the nature of the original rock.

ii. The rarity of fossils and dateable remains severely limits correlation of units identified.

Chronostratigraphy or sequence stratigraphy has had a large amount of success in the oil industry in delineating stratigraphic sections to a great degree of accuracy. Most of the work is based upon seismic sections, however, units have been well constrained using microfossil dating. Correlation is therefore a well developed tool.

Of primary importance in utilizing sequence stratigraphy is the identification of unconformity bounded surfaces or UBS’s combined with hierarchical ranking. This effectively enables one to subdivide the entire sequence into correlatable units. In the majority of cases the unconformity bounded surface will constrain an age to the overlying sequence.

Recently the applicability of chronostratigraphic analysis has been successfully applied to the Witwatersrand Basin (Winter, 1990). Understanding of the continuous structural dynamics of this basin has been well advanced through this

Figure 1: Erosion and deposition changes.
technique. The Witwatersrand is well suited to chronostratigraphy as detailed borehole logging, seismic surveys and mining development has constrained UBS divided units very well. Importantly the Witwatersrand Basin is devoid of any fossiliferous material. The Kalahari Group/Basin with its limited exposures is therefore well suited to chronostratigraphic interpretation and identification of Unconformity Bounded Surfaces will depend on:

i. Major lithological changes - here the protolith must be properly identified as a duricrust overprint could severely alter the appearance of the rock.

ii. Identification of the local or regional nature of the duricrusts identified. Are they recognisable as aquifers/aquaculides? This could also have important consequences with respect to palaeoclimatic interpretation.

iii. Reworked calcrites. These are important to identify and are often masked by the recementation and formation of nodular and concretionary calcrites.

iv. Correlation with off-shore sediments. Gaps, breaks and hiatuses must have terrestrial equivalents on the grand scale.

The Kalahari Basin began to form immediately after the break-up of Gondwanaland when isostatic rebound caused margin uplift to produce an intracratonic depocenter. This depocenter rapidly filled up with material eroded from the continent’s edges. The effect of this is well illustrated by the narrow drainage system flanking the Namibian coastline. However, in times of increased uplift, elevated precipitation or major regression the base level would have been radically dropped and major rivers would have flowed out of the basin eroding and transporting material to the coast. The Orange River was the major conduit for sediments being eroded and transported from the western parts of this interior basin.

The lower Orange River has well developed gravel terraces which can be correlated on grounds of their elevation and relative distance from the mouth as well as tributaries of the river. These gravels have been dated at their oldest to be mid-Miocene in age (Corvinus and Hendey, 1978). The terrace tops also represent UB surfaces. It should be possible to correlate these units with major events in the offshore sediments of the Orange Basin. Oil exploration off the coast of Namibia will soon enable accurate subdivision of these sediments and hopefully chronostratigraphic subdivision of the offshore sediments will enable correlation of the major UB’s occurring in the Kalahari Group itself.

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THE ETJO AND KALAHARI SEDIMENTS OF THE OWAMBO BASIN

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This analysis of the post-Karoo succession in the Owambo Basin is based largely on a reinterpretation of the cores of the following deep boreholes drilled in the late 1960s: ST-1 (Hedberg, 1979); Nanzi (borehole no. 9074), Olukonda (9124), Okankolo (9197), Ombalantu (9262), Beiseb Pan (9296) and Okasnama-kanan (9563) (Hugo, 1969). The late Proterozoic Owamboland Formation forms the pre-Karoo basement within the Owambo Basin. Figure 1 shows the distribution of Dwyka, Prince Albert and Etjo Formations as well as basalt of the Karoo Sequence.

Etjo Formation
Hugo (1969) correlated a succession of red beds and hard light grey to yellowish, well-bedded sandstone which overlies the Prince Albert and Owamboland Formations in the central and northwestern parts of the Owambo Basin with the Stormberg Series of the Karoo Sequence, i.e. with the Etjo Formation of central Namibia. However, the hard, light grey, well-bedded sandstone which occurs between the depths of 257 and 394 m in the Nanzi borehole and which has a well-developed 7 m thick basal conglomerate is quite distinct from the red beds that occur at similar depths in the other boreholes. The light grey sandstones in the Nanzi borehole are the only rocks that can be correlated with the Etjo Basin. The red beds belong to a totally different formation.

Kalahari Sequence
The Kalahari Sequence is subdivided into four formations: a basal, red, fine-grained Ombalantu Formation, a conglomeratic Beiseb Formation, a red Olukonda Formation and an upper Andoni Formation. The thickness of the Kalahari Sequence is shown in Figure 2.
Ombalantu Formation

The logs given by Hugo (1969) name the various red lithologies encountered immediately above definitive Karoo and Owamboland rocks as sandstone or siltstone with varying amounts of clay, shale, clay and unconsolidated sand. The log of the Okasanakana Pan borehole (9563) describes the red shale as having a gritty appearance due to abundant spherical centres of silicification. These are between 1 and 2 mm in diameter and are a common feature of all the red cores described as "sandstone" or "siltstone". In some cores these silicification centres occur within a fine filigree latticework of silicification veinlets, in other only the filigree latticework is present. The so-called red sandstones, siltstones and shales are finely laminated in places with small-scale, well-developed crossbedding being common. In places there are a few, small, irregular patches up to 10 cm thick in which the red colouration is reduced to a light grey colour. Close examination shows, however, that most of the red "sandstones", "siltstones" and "shales" are in fact red semiconsolidated but friable, variably silicified mudstones consisting almost entirely of clay. Even the silicification centres can be ground down with the fingers to a clay-sized powder. Some of the mudstone contains variable amounts of silt and sand-sized grains.

These mudstones are not sufficiently indurated to warrant use of the term shale. The lack of induration and the presence of interbedded red unconsolidated sands in the Ombalantu borehole which were washed out in abundance with the drilling water clearly indicate that this succession is younger and less lithified than the Karoo Sequence. It is tentatively referred to in this paper as the Ombalantu Formation and apart from the above unconsolidated sands and local interbedded units described below consists largely of red mudstone. The basal two metres are pebbly in the Beiseb Pan borehole. In most holes, sections of the mudstone contain scattered angular fragments up to 2 cm across of pink to white very fine-grained limestone or siltstone. Thin layers of light brown sandstone and siltstone and white nodular pan limestone up to 20 cm thick are present in places, particularly in the Beiseb Pan borehole. Irregularly-shaped nodules of white calcite up to 4 cm across are present in places. Gypsum crystals and casts of gypsum crystals occur in the upper part of the formation in the Ombalantu borehole. Not known from outcrop, it is suggested that the Ombalantu Formation forms the base of the Kalahari Sequence, is Cretaceous in age and is possibly equivalent to the red,
cross-bedded Kwango sandstone beds of Zaire and Angola (Furon, 1963; Haughton, 1963).

The Ombalantu Formation has a broad elongate suboutcrop extending from the Andoni-Beiseb area in the southeast to Ombalantu in the northwest (Fig. 3). The beds may also occur west of the Etjo inselberg of the Nanzii borehole because the overlying Kalahari succession also contains abundant clay in this region. Deposition of the Ombalantu Formation consisted mainly of the accumulation of fine clastics in a shallow, low-energy, deltaic environment in a restricted continental basin in which there was sufficient evaporation to produce gypsum. In the Beiseb Pan area, gritty and pebbly material was introduced at an early stage from the basin margins. Thick aeolian sands accumulated marginal to the lake in the northwest.

**Beiseb Formation**

The Beiseb Formation reaches a maximum thickness of 30 m, is widespread, was intersected in all boreholes and represents a period of rapid and extensive input of material from the basin margins into the basin. It is generally reddish in colour but light green to white in the Nanzii and Okasnanakana boreholes. The formation consists of well-rounded clasts of brown and grey sandstone and mudstone and grey and black chert (some oolitic) up to 12 cm in diameter that are set in a matrix of fine- to medium-grained, argillaceous, calcareous to dolomitic sandstone which is very hard where well-cemented by carbonates or silica. Dolomite layers are interbedded in the ST-1 borehole. The lowest 5 m of the Ombalantu borehole contain gypsum crystals up to 5 cm long.

The calcrite-cemented basal parts of the Kalahari Sequence that outcrop in the Tsumkwe-Garn area and along the Weissrand of southern Namibia may be equivalent to the Beiseb Formation.

**Olukonda Formation**

The Olukonda Formation is a friable, poorly consolidated, reddish brown, poorly sorted, massive sand and sandstone up to 120 m thick that contains a few thin gritty and pebbly layers. In the Ombalantu borehole, 35 m of dark red sticky clay that becomes progressively more sandy upwards overlies the red sands. The formation has only a limited distribution and, like the Ombalantu Formation, has
a broad elongate suboutcrop extending from Beiseb in the southeast to Ombalantu in the northwest (Fig. 3).

**Andoni Formation**

The Andoni Formation occurs throughout the Owambo Basin as a cover to all underlying units and consists of interbedded white medium-grained sand, light greenish clayey sand and green clay. The sand, in zones between 10 and 200 m thick, is unconsolidated, slightly pyritic or hematitic and, near the top of the section, contains numerous irregularly shaped dolicrite and calcrite nodules up to 30 cm across. Silcrete nodules occur in the east and become more abundant in the northeastern part of Namibia. Sorting improves upwards in the sequence. Polished and frosted, angular to subrounded grains of quartz make up 90% of the sand; chalcedony, feldspar and chert are minor components. Burrows occur in cemented sand of the Beiseb borehole.

The clay layers interbedded in the sand are between a few centimetres and 155 m thick (Ombalantu borehole). They are often sandy or silty and calcereous and are generally pyritic. Thin limestone layers up to 10 cm thick, some of which are laminated, occur interbedded in the clays. Oolitic layers between 2 and 10 cm thick and ostracod shells and impressions occur in the clays of the Beiseb and ST-1 boreholes. Unidentified bone fragments were found in clay from the Nanzi borehole.

Calcrite lenses occur locally at or near the top of the Andoni Formation.

A thin cover of reddish brown aeolian sand in the west and southeast may be Recant in age (SACS, 1980).

More than half of the Andoni Formation consists of light green clay or sandy clay over a broad region that extends due south of Ombalantu for some 200 km. The section underlying the present-day Etosha Pan contains more than 25% clay (Fig. 4). The clay-rich parts of the Ombalantu, Olukonda and Andoni Formations falling within the triangle defined by Ombalantu, Beiseb and borehole 5-1 may therefore define the Cretaceous and Tertiary limits of an inland lake that resembled the Okavango swamps of Botswana. The Olukonda lake appears to have been
5. Schematic section of the Kalahari Sequence between the Beiseb and Ombalantu boreholes.

located slightly north of the position of the Ombalantu lake but during deposition of the green Andoni clays the lake was located further south and beneath the present-day Etosha Pan. A schematic section of the Kalahari Sequence between the Beiseb and Ombalantu boreholes is shown in Fig. 5.

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PAN TYPES AND GEOLOGY: SOME OBSERVATIONS FROM BUSHMANLAND, NAMIBIA

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Introduction

Pans are distinctive, mostly Late Cainozoic to contemporary geomorphic elements, that are widespread in the Kalahari environment. Here we draw attention to a variety of pan types in Bushmanland, north-east Namibia, and their apparent association with the underlying geology.

Much of Bushmanland lies on a broad, flat watershed (c. 1150 m above sea level) between the north to north-east draining Nhoma and the south-east draining Daneib watercourses. Pans are well developed in the area north-north-east, south-south-east and south-east of Tsumkwe where the cover of Kalahari sands is thin to absent. This paucity of largely aeolian reworked sands is attributed to the presence of the low but prominent Aha Hills further west which acted as a trap and buffer to the westward movement of Kalahari sands. The variety of pan types in Bushmanland include:

1. **Pans underlain by pedogenic hardpan calcrete** - notably the large Nyae-Nyae and Khabi systems, Nama Pan, Gauutsch Pan and Tjokwe Pan. The pedogenic calcrete, mostly well-cemented and in places jointed, represents a calcereous palaeosol formed in gravels, grits and sands that have been derived largely from the east, i.e. the Aha Hills. These sediments mark the last stage of infilling the c. 300 m deep Cainozoic basin between about Tsumkwe and the western border of Bushmanland. The calcrete not only provides a firm base to these pans but has also contributed to the sand-sized sediment forming lunettes on the western margin of the larger pans, in particular Nyae-Nyae and Khabi. These pans also display palaeo-shorelines reflecting higher water levels, similar to those recorded elsewhere in the Kalahari. In addition, some pans, e.g. Nama and Gauutsch Pan, have minor, cliffed shorelines within their present perimeters, indicating more constant water levels in the recent geological past. Nyae-Nyae and Khabi Pans occupy a large north-south depression, the overall configuration of which may be controlled by structural/neo-tectonic subsidence within the Cainozoic basin.

In rare place the calcrete has been affected by local sinkhole formation which has given rise to the almost circular to oval depressions marking the Xae/see and Te-Barka Pans to the south-west of Khabi.

2. **Pans underlain by Mokolian granite** - notably Makuri Pan, Gimsa Pan, Kirkii Pan and Halfway Pan. The distribution of these comparatively small pans is governed largely by the intersecting joint patterns in the underlying basement granite. *Acacia Kirkii* trees are restricted locally to these pans, pointing to their characteristic high clay content which is probably a consequence of the weathering of feldspars in the granite.

3. **Pans underlain by Karoo-age basalt/dolerite sills and dykes** - notably the Klein and Groot Doeb Pans. Aeromagnetic survey results of north-eastern Namibia highlight the presence of a dyke swarm of presumed Karoo-age striking roughly south-east to north-west from Botswana into Namibia. Klein and Groot Doeb Pans may represent selective chemical weathering of the basic intrusions and volcanics.

4. **Pans in the sandveld north of Tsumkwe**. Localised depressions in the pale grey sand country commonly possess a rim of ferricrete. This ferricrete rim represents bog-iron formation as a result of fluctuating water table effecting the leaching of iron oxide coatings from aeolian sand grains, as well as the weathering of heavy mineral grains.

5. **Pans along poorly developed drainage lines** - notably pans in the Baraka area and in the interdunes of the sand covered area in north-east Bushmanland. Although not strictly correlated with the underlying bed-rock geology, these pans appear to owe their origin to animal activity - initially territorial, then the resultant browse/trample effect of herbivores, followed by wallowing in the localised
clay-rich are to form a depression that may be modified and/or maintained by aeolian deflation and subsequent wallowing.

The occurrence and distribution of many of the pans can therefore be linked to the underlying geology of the region, an appreciation facilitated by the thin Kalahari sand cover. Furthermore the presence of higher, relict shorelines in the Nyae-Nyae/Khabi system is a potentially important palaeoclimatic indicator in an area situated between and higher than the Etosha and Makgadigadi Pan systems.
METHODS IN KALAHARI GROUNDWATER INVESTIGATION OF KAVANGO

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With the passage of time things known to be "true" are often found not to be quite so. Initial understanding of geological and sedimentary processes becomes modified as successive layers of information are "peeled" off and with each so the truth also is transformed. With geology there are very few absolutes and all of our understanding of genesis is through inference. With this cast body of tertiary (cretaceous) to recent terrestrial sediment the earliest workers relied on scattered exposures of elements of the stratigraphy. With the passage of time scattered drilling revealed more, and understanding of the unit increased. When we were appointed to carry out a groundwater investigation in Kavango and Bushmanland the understanding with which we approached the Kalahari has undergone a metamorphosis as newer information has presented itself and enabled the evaluation of earlier concepts. Basically we have been shown - in no uncertain terms - that we did not know that much to start with and the further we go the more profoundly different the emerging picture.

As mentioned the reason for our involvement in the Kalahari of this area was primarily the EEC funded groundwater investigation awarded to Namibian Groundwater Development Consultants by the Department of Water Affairs. The project has basically comprised 2 phases, the first a compilation of available information of the occurrence and utilization of groundwater in the area supplemented by a field reconnaissance survey aimed at determining the status quo of supply and demand. This first phase survey resulted in the formulation of a pretty clear picture of the Kalahari in Kavango and Bushmanland.

Unfortunately we were also asked to design and implement a more practical second phased investigation in which the wonderfully clear (and simple) understanding achieved during Phase 1 could be both tested and added to - this quietly scrambled several fundamental concepts but also presented an explanation for certain obscured phenomena. In a nutshell - we were chastised for presuming to know the truth regarding the Kalahari of our study area!

Levels of knowledge
We will now take a look at the Phase 1 exercise and the manner in which we were lulled into such a sense of false security.

Our TOR called for a compilation of available information regarding groundwater in the Kalahari. For this we accessed the Department of Water Affairs' database - for borehole and groundwater information - and carried out a fairly extensive literature survey. This was compiled in the form of a report in which we took the liberty to reach some conclusions. During the field survey that followed we visited 90% of the waterpoints in the area and established certain physical parameters while recording other socio-economic data. Pumping rates, water test levels, physical location and physiography were recorded at each water point, in addition to collecting water samples for hydrochemical analysis. At the completion of this a final report (Phase 1) was put together. From this most of the conclusions reached in the desk study were confirmed.

1. Geology and Isopachs
2. Surface of bedrock
3. Bedrock structures (Aeromag?)
4. Piezometric surface
5. Rest levels
6. Hydrochem (TDS, HARD, F)

In essence the Phase 1 survey had shown the following:

1. The Kalahari (aquifer) was a relatively homogeneous sandy to silty body that reached in excess of 350 m along the basin axis, tapering eastwards to the bedrock high on the Botswana border.

2. Borehole yields did vary due to changes in permeability resulting from the distribution of layers of differing grain size matrix content.

3. Groundwater chemistry reflected the influence of bedrock.