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REPUBLIC OF BOTSWANA

GEOLOGICAL SURVEY DEPARTMENT

(DIRECTOR: DR C.R. JONES)

Bulletin Series

BULLETIN 7

A SUMMARY OF THE GEOLOGY, SEISMICITY, GEOMORPHOLOGY AND HYDROGEOLOGY OF THE OKAVANGO DELTA

by

D.G. HUTCHINS, B.Sc., M.Sc., L.G. HUTTON, B.Sc. MRIC.,
S.M. HUTTON, B.Sc., C.R. JONES, B.Sc. PH.D. and
E.P. LOENHART, DR.RER.NAT.

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FOREWORD AND SUMMARY

In recent years, considerable attention has been focussed on the Okavango Delta as a possible primary water source which could be harnessed to assist in the agricultural and industrial development of Botswana. The region has also attracted the attention of geologists, as it is known to be an area of active crustal movement, having an average of three appreciably-sized earthquakes per year. Conventional geological investigations are made difficult on account of the thick sand cover which conceals much of the bedrock in the region, but since 1970 the Geological Survey Department has undertaken a number of geophysical and other remote-sensing surveys which have led to a much better understanding of the geology, structure, seismicity and geomorphology of the delta.

The Department is receiving an increasing number of requests for information on the geology and hydrogeology of the Okavango region, especially with regard to the seismic hazard, and in Bulletin 7 much scattered information has been collected together and summarised. Full references are given to the detailed papers upon which much of the present report is based, and those readers wishing to enquire more deeply into specific subjects of interest are referred to the publications cited. Unpublished Geological Survey Reports are available for inspection in the Library at Geological Survey HQ, Lobatse, or photocopies can be supplied, at cost, on request. The prospecting results carried out by Mining Companies formerly holding prospecting rights in Ngamiland may also be inspected at Lobatse.

This Bulletin summarises what is known of the solid geology in the region surrounding the delta and inference is made from geophysical investigations on the extension of the different bedrock units under the swamps. The structure, seismicity and geomorphology are elucidated from the results of remote-sensing surveys, and there is a summary of the limited information available on the hydrogeology and water chemistry of the delta.

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31st March 1976

1 INTRODUCTION

By its classical shape and the fact that it is amongst the largest of inland deltas in the world, the Okavango has attracted the attention of geographers and geologists for many years. Surprisingly, however, until very recently little detailed work was undertaken in the region with the result that geologically the Okavango still remains poorly known. This lack of detailed attention may be ascribed to the logistic problems of remoteness and inaccessibility and to the thick spread of superficial deposits which conceal the solid geology of the region.

Following early topographical accounts of nineteenth century travellers interest was focussed on the swamp region by the publication of the dubious proposal (Schwarz, 1920) to harness the perennial surface waters of northern Botswana for ponding in the Makgadikgadi basin to induce a wetter climate over southern Africa. This was followed by the two major scientific expeditions of Du Toit (1926) and MacKenzie (1946) organised through the Union Government of South Africa to assess the validity of the Schwarz scheme and to investigate inter alia the irrigation and agricultural potentialities of the region as a whole. The two expeditions collected valuable geomorphological and geological information which provoked speculation on the origin and history of the swamps. Du Toit (1926, 1927, 1933) was the first investigator to suggest that the delta had a tectonic connection with the East African rift system.

In 1948, a Geological Survey Department was established in the then Bechuanaland Protectorate and this provided the basis for a systematic investigation of the geology of the entire territory. Reconnaissance visits were made to Ngamiland, but the scarcity of bedrock exposures in the region did not invite detailed mapping. In addition, unlike other areas in the concealed Kalahari where some idea of the solid geology accrued from the drilling of boreholes to bedrock in the search for water, wells drilled in the swamp regions encountered aquifers in the superficial formations and did not penetrate bedrock. The tectonically active nature of the region was, however, realised from the high incidence of earthquakes (McConnell, 1959) and photogeological investigations (Jones, 1962) led to the recognition of tectonic control lines affecting the superficial formations and revealing the structural conditions responsible for the delta. The northeasterly trending impounding faults at the distal end of the delta were first shown on a geological map by Green (1966).

In more recent years, private sector prospecting in the areas surrounding the swamps (Johannesburg Consolidated Investment Co. Ltd., Anglovaal South West Africa, Ltd., South Africa Vendôme Co. Ltd., and United States Steel), detailed Geological Survey mapping in the vicinity of Lake Ngami (Thomas, 1973), and geophysical investigations have led to a much better understanding of the geological conditions obtaining in the Okavango region. Bedrock lithologies have been inferred with a fair degree of reliability from regional geophysical surveys, including gravity, seismic refraction traverse and airborne magnetics. The major structural elements have been determined by the interpretation of gravity and seismological data supported, where surface features are manifest, by photogeological and satellite imagery (LANDSAT 1) studies. Satellite imagery has also contributed towards an appreciation of the geomorphology and geological history of the region.

The remote-sensing techniques available to the geophysicist have, however, provided the bulk of information now available on the geology of the Okavango. This work stemmed, initially, from airborne magnetic surveys conducted by the prospecting companies. Later, the Geological Survey undertook a regional gravity survey of Ngamiland (Reeves, 1973), followed by seismic refraction traverses into the Delta (Greenwood and Carruthers, 1973). Prompted by the high incidence of earthquakes in the area and the implications that these could have on the stability of the swamp waters, a micro-earthquake study was undertaken by Scholz (1975) under the sponsorship of the FAO/UNDP (BOT 71/506) project which is investigating the Okavango as a primary water source. This resulted in an appraisal of the seismic state of the Delta and led to more detailed consideration of the relationship between the controlling tectonics and the East African rift system. It was concluded that the seismicity and faulting of the Okavango marked a southwesterly extension of the Luangwa branch of the rift belt.

Whereas remote-sensing techniques have provided a tolerable indication of the geology and geomorphology of the Okavango, little is known of its hydrogeology. As an ancillary study of the FAO/UNDP project currently in progress, plans have been drawn up for a full-scale investigation of the groundwater resources, and it is hoped that these investigations will commence in 1977. The hundred-or-so wells and bore-holes in the swamps and its

environs tap aquifers in the superficial deposits, and only a limited amount of hydrogeological data is available from these. Recent sampling has, however, allowed research into the chemistry of the waters, and a broad classification has been possible which suggests that the groundwater is partly fossil.

2.1 GEOLOGY

The key to the solid geology of the Okavango lies in the surface outcrops in the areas surrounding the swamps and in the several available bore-holes which have penetrated the sub-Kalahari basement. This information is shown on the map at Fig.1. This map also provides an interpretation of bedrock geology based on geophysical evidence over the concealed areas.

The oldest rocks are granitoid gneisses of the Archaean Basement Complex. Outcrops occur in the Xangwa Valley and near the Chobe River. Geophysical evidence suggests that the rocks extend in a wide belt northeastwards from near the Aha Hills through the swamp region to the north of the Gomare fault.

The variably metamorphosed strata of the overlying Damara supergroup form the Aha, Koanaka and Tsodilo Hills. They comprise quartz schists, quartzites and dolomitic marbles of late Pre-Cambrian age. The strata constitute an eugeo-synclinal facies which may be equivalent in age to the miogeosynclinal Ghanzi Formation building the Ghanzi ridge to the south. In the country lying between the Ngamiland fence at the Kuke Gate and Lake Ngami, bedrock is reasonably well exposed, and the quartzites, shales and limestones of the relatively unmetamorphosed Ghanzi Formation occur overlying the Kgwebe Formation. The latter comprises two members - a quartz-feldspar porphyry which gives way, laterally, northwards to the Toteng diabase. Seismic and bore-hole evidence indicates that the diabase is thick and widespread in the Maun area, but the porphyry occurs again in the Goha and Gubatsaa Hills. Radiometric dating of the porphyry has given an average age of a little over 900 million years (Boocock, 1968).

The Ghanzi Formation is composed predominantly of quartzites and arkosic quartzites with subordinate dark shales and limestones. It is a near-shore succession and bears stratigraphic similarities and possible structural relationships with the Katangan rocks (Late Pre-Cambrian to Lower Palaeozoic) of the Zambian copper belt and the copper-bearing Tsumis Formation of South West Africa. The strata which are folded into large isoclinal structures extend in an almost continuous outcrop from Mamuno on the South West African Border to Lake Ngami, and they also form the Haina and Shinamba Hills.

Faulted outliers of Karroo supergroup strata (Late Palaeozoic to Mesozoic) occur in the region south of Lake Ngami and geophysical evidence suggests that they occur extensively under the central parts of the Okavango. The succession consists of sandstones, shales and coal seams of Ecca age underlying Stormberg basalts. The basalts are exposed near the Chobe and Ngwezumba rivers to the northeast of the swamps and have been encountered in bore-holes near Maun and to the south of Lake Ngami.

Overlying the bedrock in thicknesses of up to 300 m, but probably averaging considerably less, are vast expanses of deltaic and windborne, medium to fine-grained sands and silts of Cenozoic age which are collectively known as the Kalahari beds. Associated with these semi-consolidated layers of detritus are hard concretionary lenses of calcrete and silcrete. Little is known of the structure and succession of the superficial formations. Some information on the surface nature of the deposits is given in the following paragraph.

Pale brown sand, capped with silcrete, predominates on the low ridges north of Maun and east of the Thamalakane fault. South of Maun the sand is fine to medium-grained and very white. At Maun it is overlain by about a metre of grey sand. The islands within the swamp, where they are not salt-encrusted, are formed of white sand. Sand on the Ghanzi ridge is fairly dark brown. The Ngami lakebed deposits are dark grey, infertile silts with a low phosphorus content. Pipe sandstone occurs 12 km north of Toteng on the Maun road and in a river terrace above the bridge at Toteng. It is a pale yellowish-white, fine-grained sandstone only partially consolidated. The pipes are cylindrical cavities which may be empty, or contain loose sand or silcrete nodules. In the terrace at Toteng, transported angular pebbles of quartz and a rather altered ironstone occur.

2.2 SEISMICITY AND RIFTING

The Okavango Delta lies within an area of continuing earthquake activity (Reeves, 1972a). In the nine-year period September 1965 to August 1974, a total of 38 events in the vicinity of the Delta have been detected by the Rhodesian Meteorological Services. All Okavango events of magnitude 3,0 or greater on the Richter Scale should have been detected by the Rhodesian seismograph network during this period and located to an accuracy better than 50 km. The epicentres are plotted at Fig.2. The magnitude of the 38

events are distributed as follows:-

5,0 - 5,9	1
4,0 - 4,9	4
3,0 - 3,9	26
Less than 3,0	7

Larger events have been recorded in the past. During the period May 1952 - May 1953 inclusive, the early South African seismographs recorded one magnitude 6 and 21 magnitude 5 events. The magnitude 6,7 earthquake of 11th October, 1952, reportedly caused damage to buildings at Maun. It has also been suggested that the earthquakes of 1952 caused a change in the drainage pattern of the Delta (Pike, 1970).

In an attempt to delineate the seismicity of the Okavango Delta and environs, a micro-earthquake investigation was conducted in 1974 (Scholz, 1975). The Maun-Toteng area was found to be the most active region studied, with most of the activity related to the northeasterly striking Thamalakane and Kunyere faults (Figs. 1 and 2). A composite focal mechanism for the well-located events in this area indicates normal faulting, with the nodal plane dipping 60° to the northwest. If this dip is taken to be correct, all well-located hypocentres in the area are found to lie on the faults.

Considerable activity was observed in the region of the Mababe depression, and several events occurred in the region of the Chobe River. Activity decreased southwest of the Lake Ngami and central delta region and was virtually non-existent in the upper delta.

There is therefore strong seismic evidence for rifting in the Okavango. The focal mechanism for Okavango events is similar to that of the largest Kariba event (Gupta, *et al.*, 1972) and the persistent northeast trends of seismicity and faulting suggest that the activity is the southern end of the Luangwa Valley - Kariba Gorge zone of seismicity, and may mark an incipient arm of the East African Rift System, (Scholz, *op cit*).

There is little direct geological evidence to support the rifting hypothesis. Ngamiland is a region of extremely low topographic relief and the solid geology is nearly everywhere concealed by Kalahari sands and recent fluvial sediments.

2.3 STRUCTURE: OTHER GEOPHYSICAL EVIDENCE

In an effort to delineate the geological structure of the Okavango, several geophysical

surveys have been undertaken since 1970 by the Geological Survey Department. A gravity survey of Ngamiland was first conducted, and by 1971 some 1 000 gravity stations had been established, (Reeves, 1973). Fig.3 is a Bouguer anomaly map showing the variations in gravity over the Okavango and its geological interpretation.

The two distal boundary faults, the Thamalakane and Kunyere faults, are substantiated by the results of the gravity survey, although the anomalies they produce are confused by the proximity of a series of two-dimensional gravity highs paralleling these faults. This anomaly was drilled at Ghautsa Rapids (CR2) and after passing through Kalahari beds and Karroo basalt, the hole intersected strongly epidotised diabase at 70 m. Blebs of native copper in the core created some economic interest (Reeves, 1972b). The formation has been correlated with the Toteng diabase which outcrops at Toteng and is associated with the largest of the family of anomalies. Thomas (1969) places the Toteng diabase in the Kgwebe formation and the anomalies parallel the observed occurrence of Kgwebe porphyry. Similar two-dimensional gravity highs occur near porphyry exposed at the Goha and Gubutsa Hills (Reeves, 1974).

The lack of geological control has restricted quantitative evaluation, but preliminary interpretation of the gravity data in the vicinity of the distal faults suggested that the throw could be as much as 1 000 metres. Evidence for an increasing thickness of sedimentary cover within the swamps, away from the boundary faults, is provided by the series of gravity lows which extend from the Lake Ngami - Tsau region, through Lion Island to the Selinda Spillway gravity low in the northeast.

Northwest of the swamps and south of the Tsodilo Hills, there is a large triangular gravity low. This occurs in an area where the sand cover is known to be thin, and isolated outcrops of granite basement occur further southwest in the Xangwa Valley. Reeves (1974) attributed the anomaly to either an upwarp of granitic basement, or a large intrusive granite. Alternatively, it could represent a suite of post-tectonic granites associated with the Damaran orogeny, but there is no direct evidence to support this speculation.

To provide additional control, particularly in the vicinity of the distal faults, a seismic refraction survey was conducted in 1972 (Greenwood and Carruthers, 1973). The information provided by these investigations is given at Fig.4. Along the Thamalakane fault, seismic results give the throw of the fault as 115 m at Shokwamokwa and 120 m at Sakapane. The seismic results indicate

a 1,9 km/sec layer which probably represents the Toteng diabase.

The thickness of Kalahari cover increases to over 300 m across the Kunyere fault. The Kalahari cover overlies a layer of intermediate seismic velocities ranging from 3,6 km/sec to 4,4 km/sec. These velocities possibly represent Karroo sediments. Further into the Delta, Karroo velocities indicate thicknesses of 300 m at Muchaba pan, 180 m at Lion Island and 100 m at Hubu, overlain by Kalahari sediments ranging from 140 m at Hubu to over 250 m at Muchaba pan and Lion Island.

North of Muchaba, in the vicinity of Nokaneng, a seismic velocity layer ranging from 5,7 km/sec to over 6 km/sec underlies approximately 140 m of Kalahari sediments. This layer is thought to be intrusive basement and has a similar velocity to the Toteng diabase. The Karroo strata to the south are probably downfaulted against this basement, and the Bouguer anomaly map (Fig.4) provides evidence which supports this idea.

The presence of Karroo sediments and volcanics contributes towards the theory that rifting extends through the Okavango region. Recent aeromagnetic coverage suggests that Karroo volcanics occur in the region of the Selinda Spillway, downfaulted by the Gomare-Chobe fault. The faulted Karroo basins appear to extend northeastwards into Zambia along the zone of seismicity mentioned earlier.

A recent magnetometer array study of South West Africa, Northern Botswana and Rhodesia has detected a conductive zone at lithospheric depths paralleling the Thamalakane and Kunyere faults and colateral with the line of the Luangwa - Kariba Rift (De Beer, *et al.*, 1975). The conductive zone bifurcates south of the swamps, one arm continuing southwestwards into the central Kalahari, the other running westwards across South West Africa in the direction of the Walvis Bay ridge. Both extensions of the conductive zone are associated with seismic activity and could follow lines of weakness within the African continental plate. The faulting in the Okavango is probably associated with the Damaran orogenic belt which separates the Congo and Rhodesian cratons.

2.4 STRUCTURE: SATELLITE IMAGERY INTERPRETATION

Remote sensing techniques, including satellite imagery (LANDSAT 1) interpretation, have confirmed that the distal end of the Okavango Delta is confined by two extensive northeast-trending faults.

Photogeological studies by Jones (1962) and Vermaak (1962) surmised that the Gomare ridge, which marks the northwest boundary of the trough southwest of the Delta, is also a fault. Satellite imagery shows marked tonal contrasts across this ridge and also that the seif dunes to the west are abruptly terminated by this line. The line itself is visible only intermittently and disappears to the southwest. The disposition of major fault lines suggests therefore that the Okavango might lie across a rifted graben.

The detailed satellite imagery interpretation at Fig.5 shows four marked linear trends and at least one further "minor" one. Ground truth derived from ground survey is not available since accessibility is very difficult. Data from the current aeromagnetic survey of Botswana may confirm some or all of these trends. The value of LANDSAT data for detecting linear trends is beyond question (NASA, 1973). Because cultural, geomorphological and lithological features can appear as linear trends, it has become customary for geologists to refer to "linears" which have been deduced from satellite imagery interpretation and not backed by ground truth. This avoids rigid classification of the trends as tectonic lineaments. Selection of the trends was based on visible changes in tone and alignment of drainage channels in the Delta. Some of the trends were concealed by the high summer vegetation, while others were accentuated.

The trend which controls impounding of the swamps is northeasterly. Satellite imagery shows that this trend can be divided into two directions - the faults associated with the Ghanzi ridge at 58° and the Thamalakane and Kunyere faults trend at 38° . The Gomare fault and its probable extension along the southeastern side of the Linyanti swamps (Chobe fault) has a trend midway between these values. There is a possibility that the 38° trend on the Kunyere fault crosses the 58° trend in the neighbourhood of Toteng. The geophysical investigations referred to above have confirmed the two-directional trend of the faults and that downthrow occurs on the side of the Delta.

Originally described as a secondary trend (Akehurst, 1973), many linears have an orientation on an axis varying from directions at 133° to 155° . Reeves (1974) confirmed that magnetic anomalies of northeasterly trends were truncated along well-defined lines more or less at right angles to the major northeast faults. He ascribed this pattern to underlying control by the Damaran rocks on which has been superimposed relatively minor tectonic activity of the present day.

A prominent trend also lies on an axis at 78°. Post-Karoo dykes stated by Reeves (op.cit.) to trend at 110° have not been identified on satellite imagery.

The lines on the map may well be an over-simplification; the true structure is probably in the nature of an en echelon fault pattern as suggested by Reeves (op.cit.).

It is impossible to distinguish lithological types on the imagery although SMH would like to propose that as in other areas bluish-white patches on the false-colour imagery may be Kalahari calcrete or silcrete. Faulting seems to have affected some of these outcrops. Bedrock is visible in the Tsodilo Hills, the Aha Hills, the Kgwebe Hills and possibly in some of the fossil valleys west of the Delta. Sub-surface bedrock is apparent on the Ghanzi ridge which plunges beneath the cover near Toteng. The geological strike is generally parallel to the boundaries of the ridge which is approximately 40 km wide. Fold trends in the Aha Hills lie close to the direction at 70°.

2.5 ECONOMIC GEOLOGY

Sulphide mineralisation is associated with the Ghanzi Formation to the south and east of the swamps. Coal is known to occur in downfaulted blocks of Karroo strata near Lake Ngami. As these strata probably extend under the swamps, it is logical to assume that the mineral deposits also occur beneath the Okavango. The delta also forms the repository for vast quantities of water-borne detritus which contains a minor fraction of heavy ore minerals. Such minerals include rutile and ilmenite which have been derived by weathering of the granites of the Angolan highlands. Other minerals, including diamonds, could occur, but as yet no concentrations of placers of economic significance have been encountered.

The reports of early travellers to Ngamiland include references to gold, copper and other base metals, but it was not until 1962 that serious prospecting was started by the Johannesburg Consolidated Investment Company. The company's geological mapping programme did not reveal any mineralised zone and the concession lapsed. At this time, the idea that the Ghanzi beds represented a continuation of the copper-bearing Tsumis Formation of South West Africa and marked a link with the Katangan rocks of the Zambian copper belt was actively considered. Anglo Vaal South West Africa (Pty) and from 1971 a consortium headed by United States Steel Corporation have held concessions over the entire strike belt of the Ghanzi Formation between the South West African border

and the Shinamba Hills. Regional geochemical surveys have revealed copper anomalies which drilling has shown are related to narrow stratal zones of sulphide mineralisation lying at the top of the main arenaceous facies and below dark shales. The mineralisation has proved to be remarkably persistent along strike for some 300 km and appears to be genetically related to shallow palaeobasins. It comprises disseminated cupriferous sulphides mainly chalcocite and bornite, with subordinate chalcopyrite and pyrite associated with sphalerite and argentiferous galena. Diagenesis has led to the development of economically significant zones of concentration along the axes of folds and at present these mark the target areas for evaluation by the prospecting companies. The ultimate origin of the copper probably lies with the intrusives of the Kgwebe Formation and the presence of native copper in Toteng diabase from a diamond drill core (CR2) tends to support this contention.

The dominant geomorphological feature of Ngamiland is the Okavango Delta, a broadly triangular area extending over some 16 000 km² of country. The use of the term "delta" is convenient and based on the classical morphology which the feature develops, but in the normally accepted sense of the word (Pitty, 1971), the deposit is not built up by a river debouching into a body of little disturbed water, and perhaps a more correct physiographic description would be "alluvial fan".

The Delta is fed by the Okavango River, draining southeastwards from the Angolan highlands. On satellite imagery, the drainage system appears to anastomose, although according to the UNDP/FAO (1971) working map there are six main channels along which outlet flow occurs. Water also moves in mass amongst the expanses of reed. During the seasonal flood, water flows into peripheral channels and pools and dwindles chiefly through evapotranspiration as the flood subsides. Most of the water entering the Delta is eventually lost through evapotranspiration and infiltration, although some escapes along the Boteti River, only to drain into the Makgadikgadi pans. It has been estimated that only 5% of the inflow at Shakawe reached Maun (Pike, 1970). Other outlets are southwest to the Ngami depression via the Nhabe (Lake) river and Kunyere River and northeast to the Linyanti and the Mababe depression via the Magweqana (Selinda spillway) and the Thamalakane. Water flows into the Ngami and Mababe depressions only in years of good flow. According to Standish-White (1972) most of the sediment load is blocked by the Kunyere fault, while the Thamalakane fault forms the barrier to the Delta waters.

The Okavango spreads its waters out over a slope of approximately 0,25 metres per kilometre between Shakawe and Maun (SWECCO, 1973). Lack of topographic data makes it impossible to state whether this is a uniform gradient; apparently many of the lagoons in the Delta have been stable for up to 20 years (SWECCO, op.cit.) and this may reflect topographic and hence structural control. On the other hand, fault movement is believed to have caused diversion of the drainage within the last century, although insufficient evidence is available to confirm this.

Du Toit (1926) supposed that the Okavango, Linyanti and Zambezi rivers once flowed in parallel direct lines to the Indian Ocean prior to uplift along the Kalahari axis. This recent line of uplift passes southeast of the Makgadikgadi

pans and forms the watershed between the endoreic drainage to the west and the drainage to the ocean to the east. It was proposed that the Okavango once flowed continuously with the Boteti into a giant Lake Makgadikgadi (Greater Makgadikgadi), which had its outlet to the Limpopo by way of the Motloutse River. Subsequent faulting, trending northeast with downthrow to the northwest, created the barrier ridges that dammed the Okavango and gave rise to the Mababe depression. The Kalahari uplift probably belongs to the same period of neotectonic activity. The Linyanti River was diverted by faults on a similar trend and took its present course into the Zambezi. Du Toit thought that it might ultimately have captured the Magweqana waters from the Savuti. Rogers (1934) believed it more likely that there was a link between the Okavango and Zambezi rather than the Limpopo on the basis that certain distinctive fresh water snails occur only in the Okavango-Zambezi system.

The geomorphological map at Fig.6 drawn from LANDSAT imagery shows the connection with the Zambezi via the Magweqana and Linyanti, although it is obvious that the main direction of flow is towards the Makgadikgadi depression. The imagery clearly shows a strandline marked topographically by a fossil beach 10 to 13 m high to the west of Ntwetwe pan. Rather than attributing the desiccation of Greater Makgadikgadi purely to a drier climate, the shrinking of the lake may be accounted for by faulting in Ngamiland which ponded the waters of the Okavango and created the Delta. Greater Makgadikgadi may have come into being only after uplift along the Kalahari axis. Grove (1969) suggested that the capacity of the Okavango was just enough to fill the Ngami and Mababe lakes and that only a river the size of the Zambezi could fill Greater Makgadikgadi. He envisaged southwesterly flow along the Linyanti-Savuti channel and the Magweqana which was later cut off either by dunes or faulting at Kasane.

Flow in the Okavango Delta formerly extended over a greater area than today. This is demonstrated by the abandoned drainage channels visible on LANDSAT imagery. The retreat of the waters may be the result of several causes. Evapotranspiration may have increased due to changes in solar energy; the flow in the Okavango may have decreased because of declining rainfall in the Angolan highlands; rainfall over the Delta, which provides some recharge, may have decreased, or there may have occurred an increase in infiltration within the Delta caused by recrudescant tectonic activity.

Evidence for climatic deterioration may be deduced from inter-dune channels, now dry, which once drained run-off from the Aha Hills eastwards. These fossil valleys fed their waters into a network of channels

southwest of the Okavango. Water also drained into the area from the south, contributing to a presumed northeasterly flow. The channels in the west split over the Gomare ridge, which is a tectonic feature, to form a palaeo-swamp basin west of the present delta. The significance of the ridge lies in the fact that the west-northwest-trending seif dunes are abruptly truncated by it, thus dating the movement as being relatively recent. It is possible that this basin was inundated at the time the fossil rivers of the central Kalahari flowed into Greater Makgadikgadi. The divide (line D-D1) from the present delta is quite precise. No streams appear to cross it from either side.

Seif dunes comprising rolling, longitudinal sand ridges about 1,75 km wide trending approximately 102°, occur mainly to the west and north of the Okavango. South of the Aha Hills, the trend veers to 80°. A smaller dune field to the southeast of the delta also has a trend about 80°. Grove (op.cit.) states that the dunes formed in a drier climate than the present under prevailing easterly winds. Supporting evidence for this occurs where sand has been blown up against the eastern side of the Tsodilo Hills. Satellite imagery shows that the dunes have been cut by tributaries of the larger inter-dune rivers, such as the Xadum and Xangwa, north of the Aha Hills. In the area immediately bordering the delta, the dunes have been eroded by former flood waters. South of the "panhandle", this zone can be 2 - 10 km wide. Between the delta and the Linyanti, there are no dunes, but there is evidence of old drainage channels indicating that this area once formed an extension of the swamps.

The former extents of Lakes Ngami and Mababe are clearly marked by ancient strandlines. Both lakes were once considerably larger than they are at present. The Ngami depression is estimated to be an eighth of its previous size. There is evidence that delta channels have encroached on its former surface, now defined by the Tautse flats.

The flood plain of the Boteti River, distinguished on LANDSAT imagery as a pale-coloured zone of pans, abandoned channels, cutoffs and strewn sediment, does not extend for more than 3 km on either side of the river.

The head of the delta is permanently flooded. It is proposed here that the limit of the permanently flooded area can be identified on end-winter LANDSAT imagery by means of outlining the areas of climax riparian vegetation - this is shown at Fig.6 (Sept. 1972, imagery). Another indication of the extent of the permanent delta is the intensity of drainage channels. In densely vegetated areas, it is rarely

possible to distinguish the course of the channels, whereas oxbows and lagoons are more easily detected. Thus it is inferred that where the network of channels is dense it lies outside the perennial swamp because it does not support extensive vegetal growth in winter. Similarly, the extent of flourishing vegetation at high summer (January, 1973) has been used as a guide to outline the farthest limit of active Delta drainage. With care, it should be possible to define these boundaries more precisely. Certainly, ground truth and computer techniques would greatly increase the accuracy of interpretation. High-summer imagery also shows that the summits of the seif dunes are relatively better vegetated than the intervening hollows.

Study of satellite imagery of Ngamiland provides a basis for establishing a sequence of geomorphological events. During Tertiary times, longitudinal sand dunes formed in a desert régime with winds from the east. It is not clear whether the Okavango was flowing strongly at this time or not. Northeast faulting, with downthrow on the northwest side, disturbed dune formation. Ridges created by the faults held inflowing water back and diverted a good deal of it to Lakes Ngami and Mababe and possibly even further afield to the Zambezi. A wetter climate about or at this time is indicated by the presence of interdune channels and a much more extensive delta and lake system. It is not clear how the drainage network southwest of the present delta fits into the picture. Trapped between the Gomare and Ghanzi ridges, much of the water may have been lost through infiltration. The slope would appear to have been to the northeast since the faulting dies out southwestwards and the dune field becomes continuous. Following this phase, the climate became drier leaving fossil river channels in the desert and strandlines marking shrunken lakes. Desiccation of the Okavango may have been additionally aggravated by infiltration within the delta along lines of neotectonic activity.

4.1 HYDROGEOLOGY

As indicated in the Introduction, little is known about the geology of groundwaters of the Okavango, and this section is devoted mainly to a preliminary statement on the chemistry of surface and underground waters.

There are records of some hundred-or-so boreholes and wells in the Okavango and vicinity in Geological Survey, but there is little hydrogeological information relating to them, and what is available is not particularly reliable. The aquifers which have been penetrated nearly all lie in the superficial formations at depths averaging between 10 and 40 m. The main aquifers are coarse sands and calcretes in which the water is retained by enclosing clayey and silty horizons. Yields vary greatly between a few litres and 260 litres per minute with an average of around 40 litres per minute. Sixty percent of the boreholes yield fresh or good quality water, with the remainder yielding brackish or saline water, usually from the deeper boreholes.

Obviously some surface water percolates downwards through the sands and along neotectonic fractures to charge underground aquifers. No idea of the amount of surface water lost in this manner exists. However, Baillieul (1973) estimated that the permeability of surficial sands could range from 100 to 450 gallons per day per foot² and McCann (1974) deduced a transmissivity of about 180 000 gallons per day per foot² in the aquifer just north of the Kunyere fault. The latter value appears rather high and on the basis of Baillieul's permeability figures, requires an aquifer thickness of 122 - 550 m which actually occurs in the delta area itself. Outside the delta, lower permeability corresponding to reduced aquifer thickness can be assumed for the Kalahari Beds. Coarser grained river deposits are likely to have higher permeability and thus afford river water infiltration to the Kalahari Beds' aquifer. This is supported by rest water levels of 20 - 30 m below the surface southwest of the delta (Nokaneng-Tsau) and about 6 m below the surface southeast of the delta (Maun). All the figures are estimates, and quantification of hydrogeologic parameters is urgently needed (McCann, 1974). McCann (*op.cit.*) suggests that on account of the distribution of saline water around the south and west sides of the delta, the groundwater flow is mainly east towards the Linyanti River. The chemistry of the groundwaters on the other hand seems to indicate that much of the water away from the seepage effects of the river channels is fossil and that direct infiltration is minimal.

4.2 CHEMISTRY OF RIVER AND SWAMP WATERS

Okavango swamp waters are derived from two sources. The principal one is the Okavango River while the lesser one is the contribution made by rain falling over the swamps.

The contribution to salinity from rainfall is small compared to that from the river, but is worthy of further investigation. It has been estimated that the total dissolved solids (TDS) content of rainwater is between 2 and 10 ppm, consisting mainly of dissolved carbon dioxide, oxygen, traces of ammonia, nitrous oxides and chloride ions. The salinity of the Okavango River at Mohembo gauging station is estimated to be between 20 and 30 ppm TDS, but this is dependent on seasonal flow and needs monitoring.

In general, it would be expected that the salinity of the river channel waters increases due to evaporation as the waters progress through the swamps. Only 50 samples (approximately) from the interior of the delta system have been analysed so far, and the generally low TDS content makes the analysis of the dissolved ions analytically difficult. An assessment of the composition changes in the water chemistry needs the collection of further basic data before any quantitative interpretation can be hazarded. Water quality monitoring is at present being carried out by the UNDP/FAO project.

The water in the various river outlets suffers seasonal variation related to the state of flooding, but the TDS values of the Thamalakane River at Maun fluctuate between 80 and 200 ppm when the river is flowing. There are insufficient analyses to make a definitive statement. Study of the Boteti River system should yield interesting facts about the influence of evaporation on the chemistry of the river water.

Salt-encrusted islands occur in the swamps. The salts are mainly sodium carbonate and sodium bicarbonate. Analyses of the composition of the salts and the composition of the stagnant pool waters surrounding the islands indicate a strong inter-relationship. The available analyses are supplied in Table 1. The extent of salt formation in the delta will have an effect on the overall salt balance of the system. The saturation point for the formation of these surficial evaporites needs to be investigated.

However, a substantial amount (possibly 80%) of the salt content of the incoming water may be lost as the floods progress across the swamps. Bearing in mind the increased salinity caused by evaporation, the precipitation rate within and on exposed protrusions of land in the swamps is very considerable. The process whereby the progressive desalination of waters occurs is imperfectly understood and merits further study.

Although there is insufficient data for sound analysis, the predomination anion in the waters analysed so far is the bicarbonate (HCO_3^-) with only small amounts of chloride and sulphate. The predominating cations are calcium and sodium with potassium and magnesium contributing significantly to the total. The distribution of individual ion values within the swamps may be useful in defining areas in which salt encrustation is likely to take place and also in locating buried deposits such as calcrete.

Very few reliable analyses of trace elements in Okavango waters have been made. The analytical difficulties of measuring trace amounts of metals and nutrients at the microgramme per litre level are great and results should be viewed with caution. The nutrients which could be expected in the swamp area, such as ammonia, nitrate and phosphate have not yet been determined accurately, but investigations are currently in progress. Concentrations of these nutrients have an important bearing on the plant productivity of different areas. The presence of bacteria such as Nitrosomas and Nitrobacter may be easier to detect than actual nitrite and nitrate concentrations. The presence of ammonia (NH₃) and the ammonium ion (NH₄⁺) can be expected from the decomposition of green plant protoplasm (Behnke, 1975) and should be the easiest determinable variety of all the nitrogen species.

Of the dissolved silica measurements that have been made, the general trend shows that the further the waters progress through the swamps, the higher is the concentration of dissolved silica. This may be due either to evaporation or solution of channel deposits which are mainly sand. The more alkaline water is, the more dissolved silica it can carry; the pH of the swamp waters varies from 6,8-7,5 and may be a controlling factor of SiO₂ content, but again there is not enough evidence on which to make a categorical statement.

Dissolved oxygen measurements are also being made which, allied to nutrient measurements, could help elucidate vegetation patterns.

The colour of the waters may be due to several factors which require further investigation. Some waters are markedly brown.

4.3 CHEMISTRY OF GROUNDWATERS

This evaluation is based on analyses of 43 bore-hole waters and 11 waters from hand-dug wells or springs made at the Geological Survey over the last 20 years. A further four samples were recently provided by the UNDP/FAO team.

Little or no information exists on the geological and hydrogeological conditions of the aquifer(s) tapped, nor on the technical conditions of the bore-holes and wells, such as whether there is any casing, the rate of pumping, the method of sampling, and so on. Only Kalahari beds have been penetrated, but there are no bore-hole logs detailing depth and type of strata.

The waters analysed have been divided into three main groups on the basis of their TDS (Fig.7). Group "A" waters are defined as fresh with a TDS of less than one gramme per litre - this group

constitutes 49% of the samples. Group "B" waters are brackish with a TDS of between one and five grammes per litre, while Group "C" waters are saline with a TDS of over five grammes per litre. Groups "B" and "C" together comprise 51% of the analyses. In addition, Group "A" waters are characterised by a high proportion of bicarbonate anion (greater than 65 epm %), Group "B" waters by a wide-ranging bicarbonate content with a corresponding increase in chloride and/or sulphate anions between 10% and 50%, while Group "C" waters have chloride or sulphate anions prevailing. Within Group "A", two sub-groups can be distinguished - one with calcium and magnesium predominating, the other with sodium predominating. The former group is indicative of recent origin, either through rain recharge or river infiltration. The latter group is assumed to have evolved through base-exchange processes from the former group over a lengthy period of geological time. The base-exchange process is effected between the groundwater and the adjacent geological formation.

In certain bore-holes, which have been sampled twice, there seems to be a fluctuation between Group "A" and Group "B" waters, which indicates that the two groups co-exist in stable equilibrium. The prevalence of one type or another depends on current recharge conditions. The sodium-dominated waters of Group "A" are the transitional link between Group "A" and Group "B" waters. In the case of one bore-hole at Sehitwa, water type is influenced by seasonal recharge with surface water from Lake Ngami. Lake water is subject to evaporation which tends to increase the sodium values and the carbonate and bicarbonate concentrations.

Groundwater derived from river infiltration always has a predominance of calcium and magnesium and bicarbonate ions. Shallow, hand-dug wells seem to have abundant calcium and magnesium. The calcium-dominated Group "A" waters also occur in the Nokaneng and Maun areas (Fig.7) which indicates that recharge by river infiltration only takes place locally. However, between these two areas, north of Lake Ngami, sodium-dominated waters of Group "A" occur, often in close association with waters of Groups "B" and "C" which, by evidence of their composition and salinity are quite old waters.

A field of Group "B" waters occurs in the midst of saline waters in an area south of Maun, while Group "A" waters with predominating calcium and magnesium are found in the area of the

Odiakwe camp. This indicates that recharge is taking place outside, and independently of, the Okavango system. In the first case, Group "C" waters are presumably being diluted by rainwater, while at Odiakwe the waters must be derived directly from recent rainfall.

4.4 ISOTOPIC COMPOSITION OF WATERS

Only few data are available but show interesting comparisons with the hydrochemical results. Four radiocarbon and tritium values of Okavango area groundwaters have been published by Mazor et al. (1974). The ^{14}C values range between 54,3 and 98,7 pmc (percentage modern carbon). The recent age of the latter sample (Toteng store, no. 1242) is supported by an elevated tritium content of 15,8 TU whereas the other samples have less than 1,2 TU. Model ages calculated by Mazor et al. (op.cit.) have resulted in 1 750 - 3 600 years for three groundwaters of which the main salt component is either NaHCO_3 or Na_2SO_4 . These waters may be attributed to groups "A" (with sodium domination) and "B".

Some stable isotope determinations quoted in Mazor et al. (op.cit.) and Jennings (1974) are given below:

	$\delta\text{D}(\text{‰})$	$\delta\text{O}^{18}(\text{‰})$
Groundwaters	-28,8/+3,3	-2,9/+1,8
Rivers (Thamalakane, Kunyere, Nghabe)	-29,7/+40	-2,3/+12,2
Lake Ngami	+32/+58,4	+8,3/+12,8

River waters show a wide range of fluctuation in stable isotope composition. Sampling was conducted during late summer in 1970 and 1972, the values reflecting varying stages of flooding and evaporation. Lake Ngami waters (both 1970 values), clearly indicate extreme evaporation. On a plot depicting the relationship between $\delta\text{D}(\text{‰})$ and $\delta\text{O}^{18}(\text{‰})$, groundwaters fall on a line located between rain and surface waters. The isotopically heaviest groundwater, the only one with positive values, is Toteng no. 1242. The assumption that this particular sample represents groundwater recharged by highly evaporated surface waters, probably from Lake Ngami, is in good agreement with the high tritium and carbon-14 concentrations mentioned above.

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APPENDIX

CORED BORE-HOLE LOGS CR1 - CR5

DRILLER: Mr. W. Burgoffer - March 1970 to
January 1971

With the exception of CR-1, the bore-hole cores have not been logged in detail by a geologist. Cores are available for inspection at Lobatse.

CR-1: MATLAPANEN BRIDGE Alt. 937 m 760,7 B, 7793,2 N

0 - 153 m : Sand with occasional limestone
and minor clay - Kalahari Beds

CR-2: GHAUTSA FALLS Alt. 933 M 740,1 E, 7770,3 N

0 - 43 m : Calcrete, silcrete and sands -
Kalahari Beds

43 - 69 m : Vesicular basalt - Karroo

69 - 70 m : Agglomerate - Karroo

70 - 238 m : Toteng Diabase, with some copper
mineralisation

CR-3: TSANAKUNA Alt. 933 m 744,8 E, 7776,4 N

0 - 59 m : Sands, silcrete and calcrete -
Kalahari Beds

59 - 83 m : Vesicular basalt - Karroo

83 - 91 m : Sandstone, presumed Cave Sandstone

91 - 135 m : Toteng Diabase

CR-4:TOTENG Alt. 930 m 703 E, 7705 N approx.

0 - 15 m : Sand, calcrete and weathered
diabase

15 - 64 m : Toteng Diabase

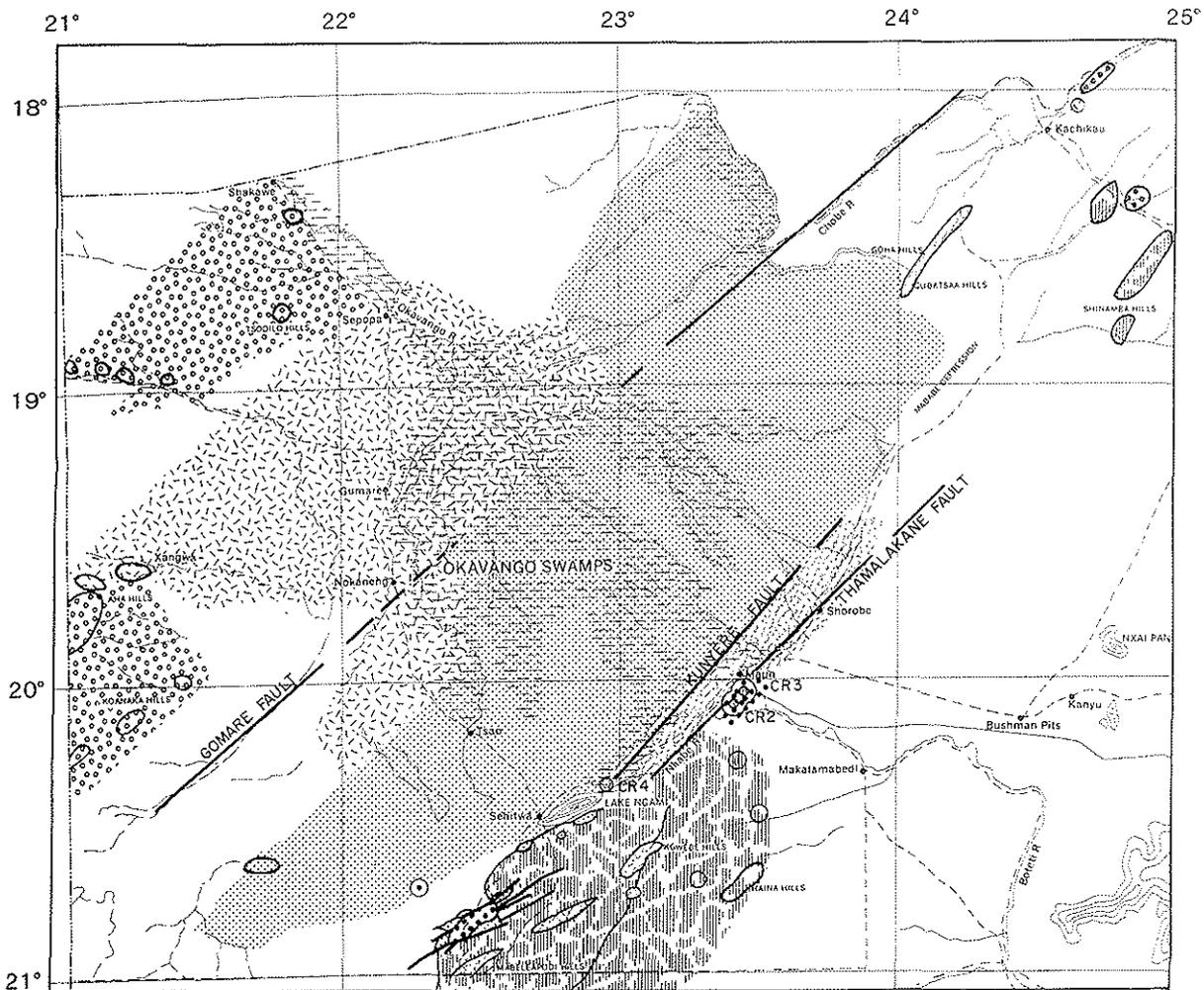
CR-5: OLD FRANCISTOWN RD. Alt. 938 m 776,4 E, 7793,5 N

0 - 150 m : Sands, calcrete, silcrete -
Kalahari Beds

TABLE 1

COMPARISON OF CHEMICAL COMPOSITION OF SALT CRUST
AND ADJACENT POOL WATER FROM THE OKAVANGO SWAMPS

	<u>Buffalo Pools: Crust</u>		<u>Buffalo Pools: Water Sample</u>		
	<u>Soluble Material</u>	<u>% of total</u>	<u>% equivalent weight</u>	<u>e.p.m.</u>	<u>% per equivalent weight</u>
				<u>e.p.m.</u>	
CO ₃ ⁻⁻	18,42	0,614	52,814	86,0	
HCO ₃ ⁻	16,52	0,27	22,058	81,7	
Cl ⁻	Trace	-	0,423	-	
SO ₄ ⁻⁻	0,33	-	0,790	-	
Na ⁺	16,87	0,733	65,250	89,0	
K ⁺	2,10	-	9,750	-	
Ca ⁺⁺	0,06	-	0,349	-	
Mg ⁺⁺	0,01	-	0,329	-	
SiO ₂	0,02	-	-	-	
<u>Insoluble Material</u>					
SiO ₂	22,68				
Fe ₂ O ₃	0,17				
Al ₂ O ₃	1,87				
TiO ₂	Trace				
CaO	0,49				
MgO	0,27				
Loss on ignition	<u>20,24</u>				
Total:	<u>100,05</u>				



GEOLOGICAL LEGEND

-  Karroo lavas : basalt
-  Karroo sediments : sandstone, shale and coal seams
-  Ghanzi Formation : quartzite, shale and limestone
-  Kgwebe Formation : quartz - feldspar porphyry and diabase
-  Damara Supergroup : quartz schist, quartzite and marble
-  Basement Complex : granitoid gneiss
-  Rocks outcropping at surface

 Boreholes with number

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SCALE 1:2000000

20 10 0 20 40 60 80 100 km

FIGURE 1: SOLID GEOLOGY SHOWING SURFACE OUTCROPS, BOREHOLES TO BEDROCK AND INTERPRETED BEDROCK GEOLOGY IN CONCEALED AREAS

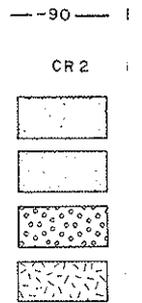
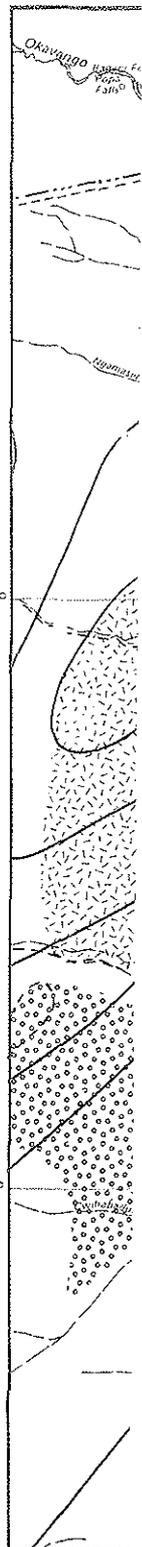
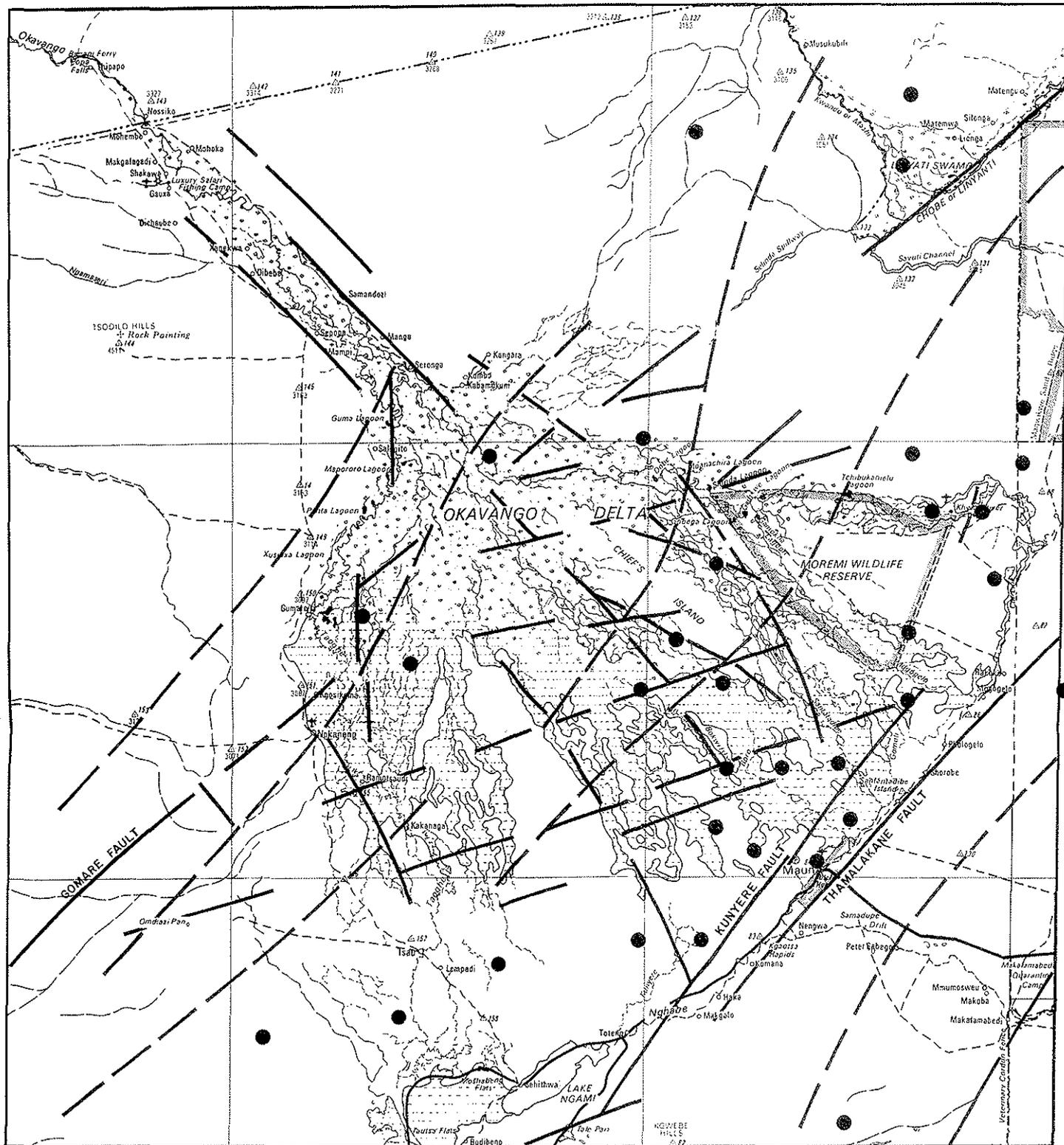


FIGURE 3



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LEGEND

SCALE 1:1000000

- Earthquake epicentres registered by the Rhodesian Seismograph Network
- Main faults and linears determined by photogeological and satellite imagery interpretation and geophysical investigation
- - - Regional tectonic trends suggested by geophysical evidence

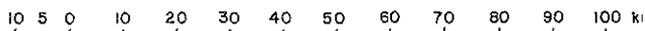
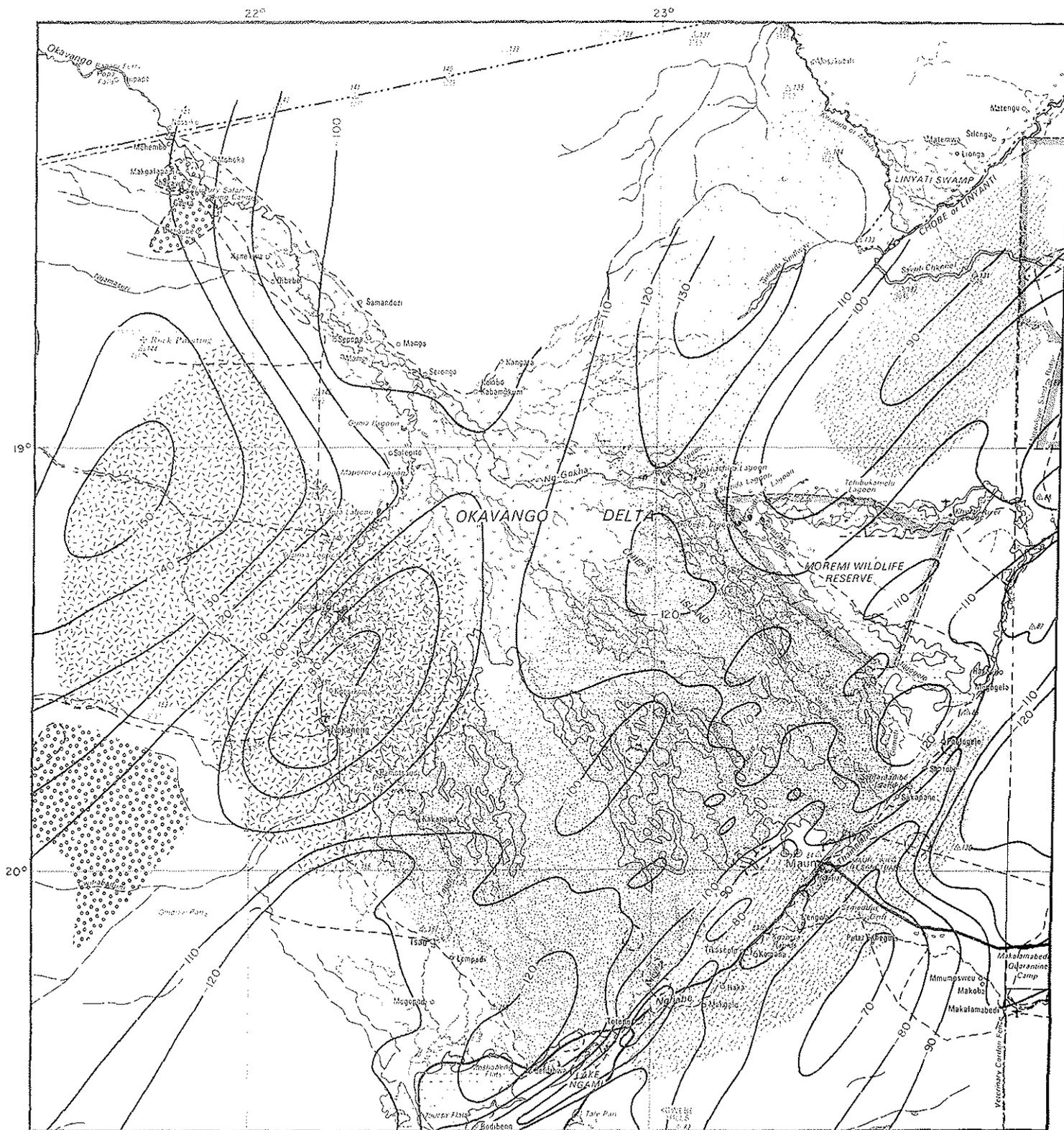


FIGURE 2 MAIN STRUCTURAL ELEMENTS AND EARTHQUAKE EPICENTRES IN THE OKAVANGO

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LEGEND

- 90 — Bouguer contours with gravity value of 10 milligal intervals
- CR 2 Borehole
-  Immediate bedrock Karroo
-  Immediate bedrock Kgwebe formation
-  Immediate bedrock Damara supergroup
-  Immediate bedrock granitic gneisses
- - - - - Confirmed by borehole/seismic evidence

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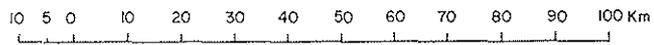
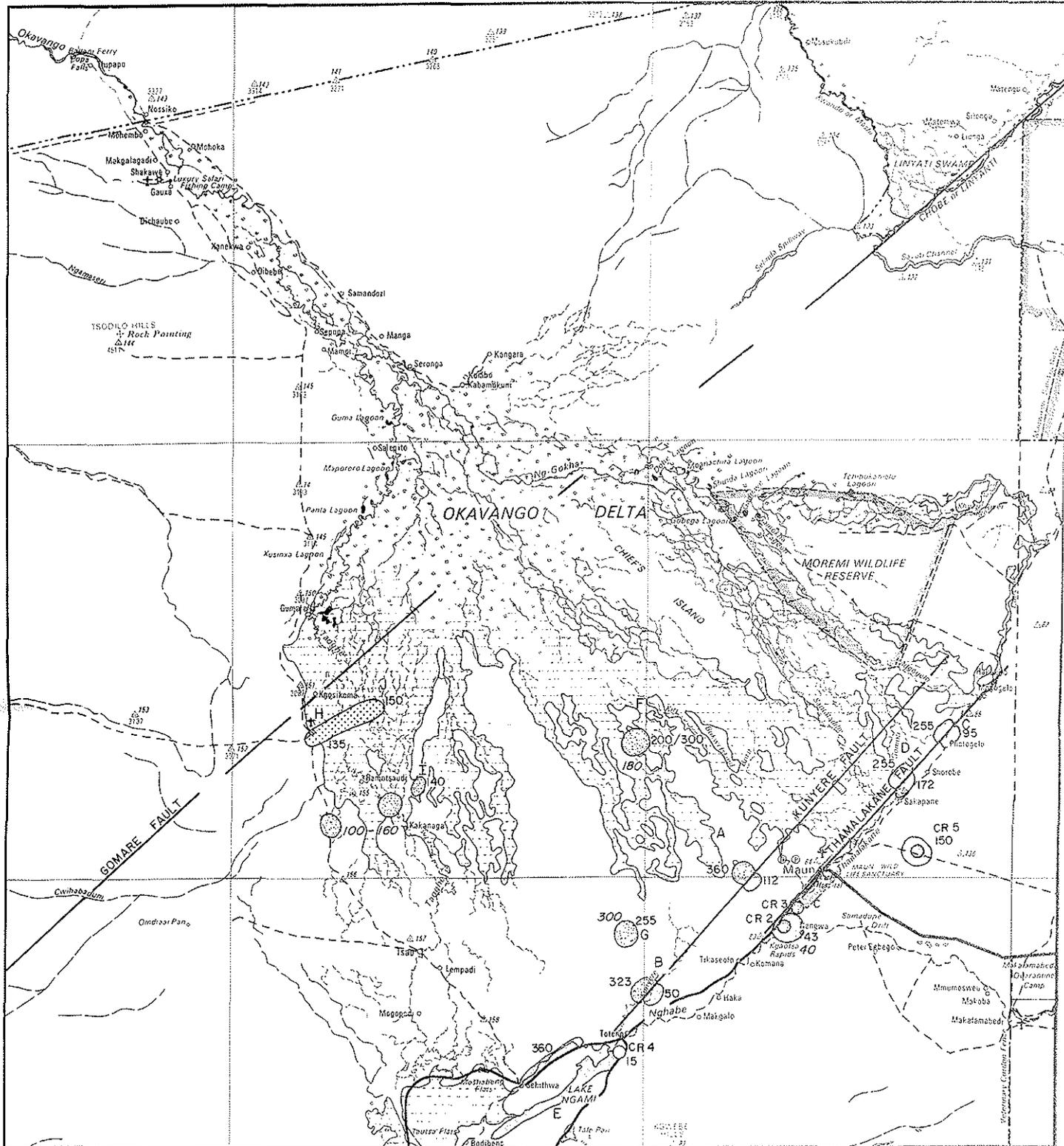


FIGURE 3 GRAVITY MAP OF OKAVANGO WITH GEOLOGICAL INTERPRETATION



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LEGEND

- | | | |
|-------------------------------|-----------|--|
| Seismic refraction traverses: | ○ CR 2 | Borehole |
| A Marape | 255 | Indicated thickness of Kalahari beds in metres |
| B Xobogo | 180 | Indicated thickness of Karroo beds in metres |
| C Shokwomdkwa | [Pattern] | Indicated Karroo bedrock |
| D Sakapane | [Pattern] | Indicated Kgwebe formation bedrock |
| E Lake Ngami | [Pattern] | Indicated basement gneiss bedrock |
| F Lion Island | | |
| G Muchaba Pan | | |
| H Xa xa | | |
| I Hubu | | |
| J Xa xa East | | |

SCALE 1:1 000 000

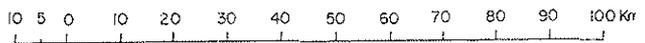
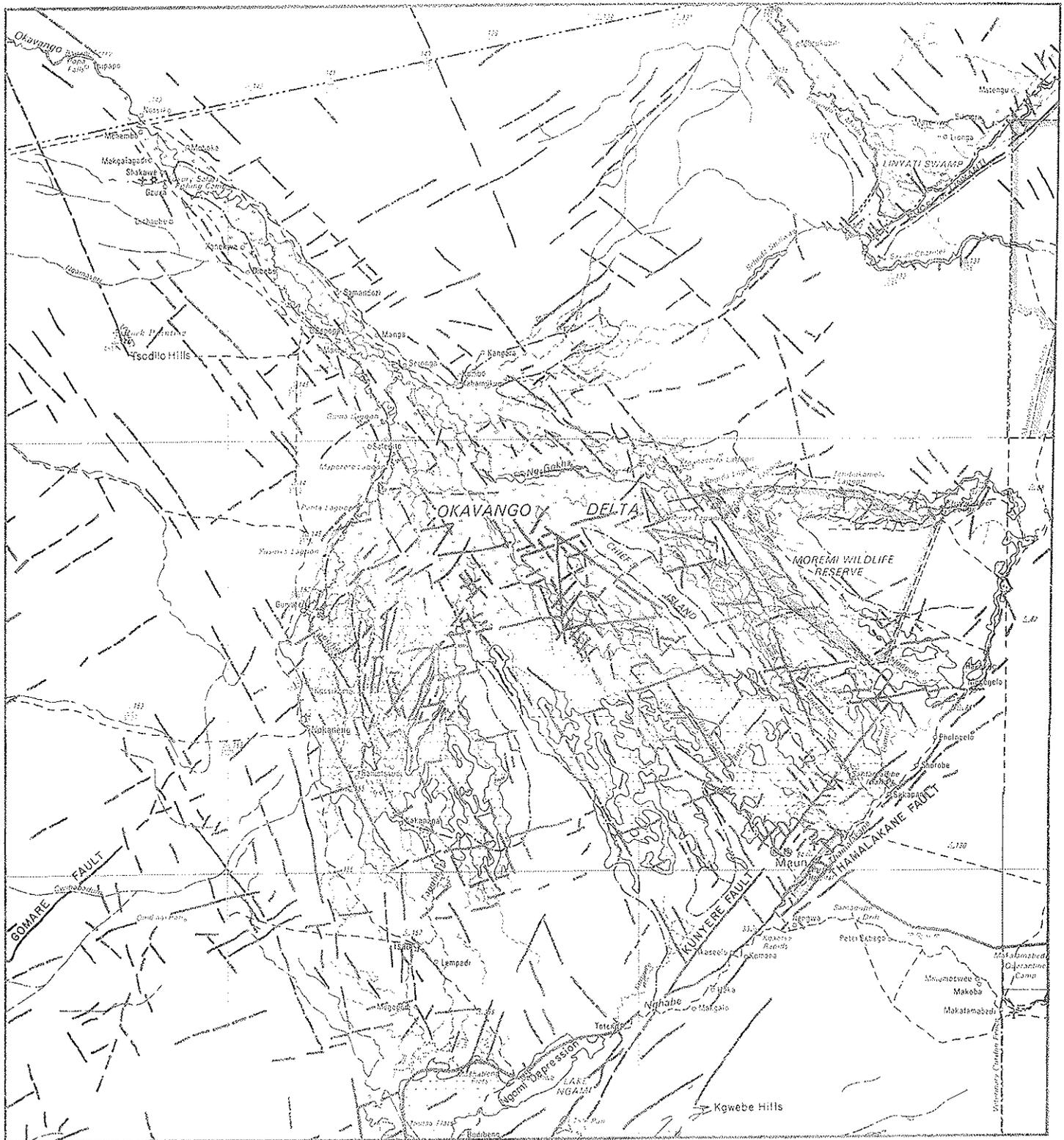


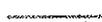
FIGURE 4. BEDROCK AND STRUCTURAL INFORMATION FROM SEISMIC REFRACTION TRAVERSES

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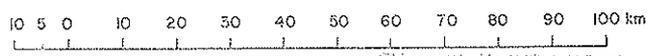


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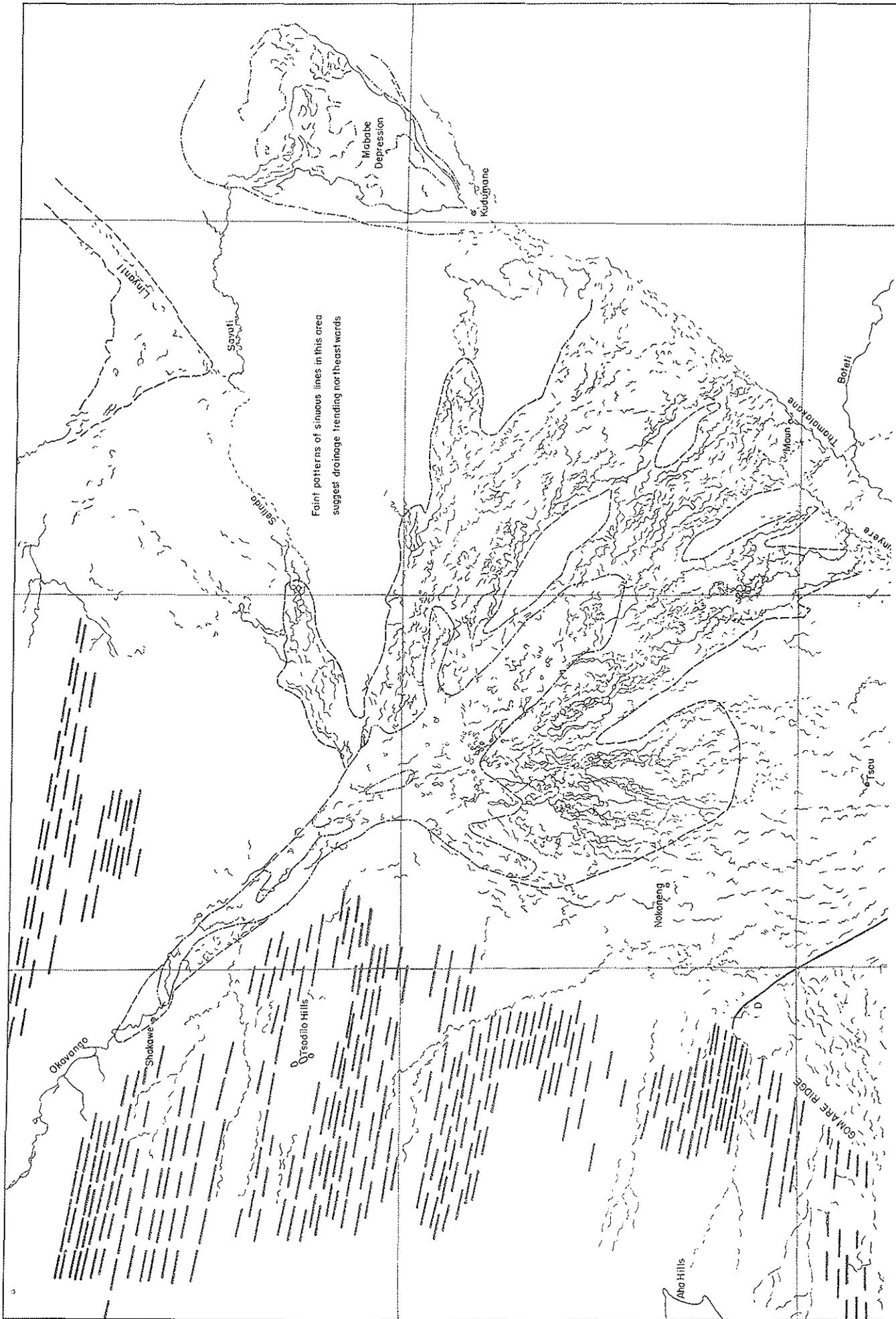
-  Linears : assumed tectonic significance
-  Linears : uncertain tectonic significance
-  Hills, fold trends
-  Drainage channels, lake outlines
-  Approximate outline of active delta drainage area and Linyanti swamps defined by high summer (Jan 1973) vegetation

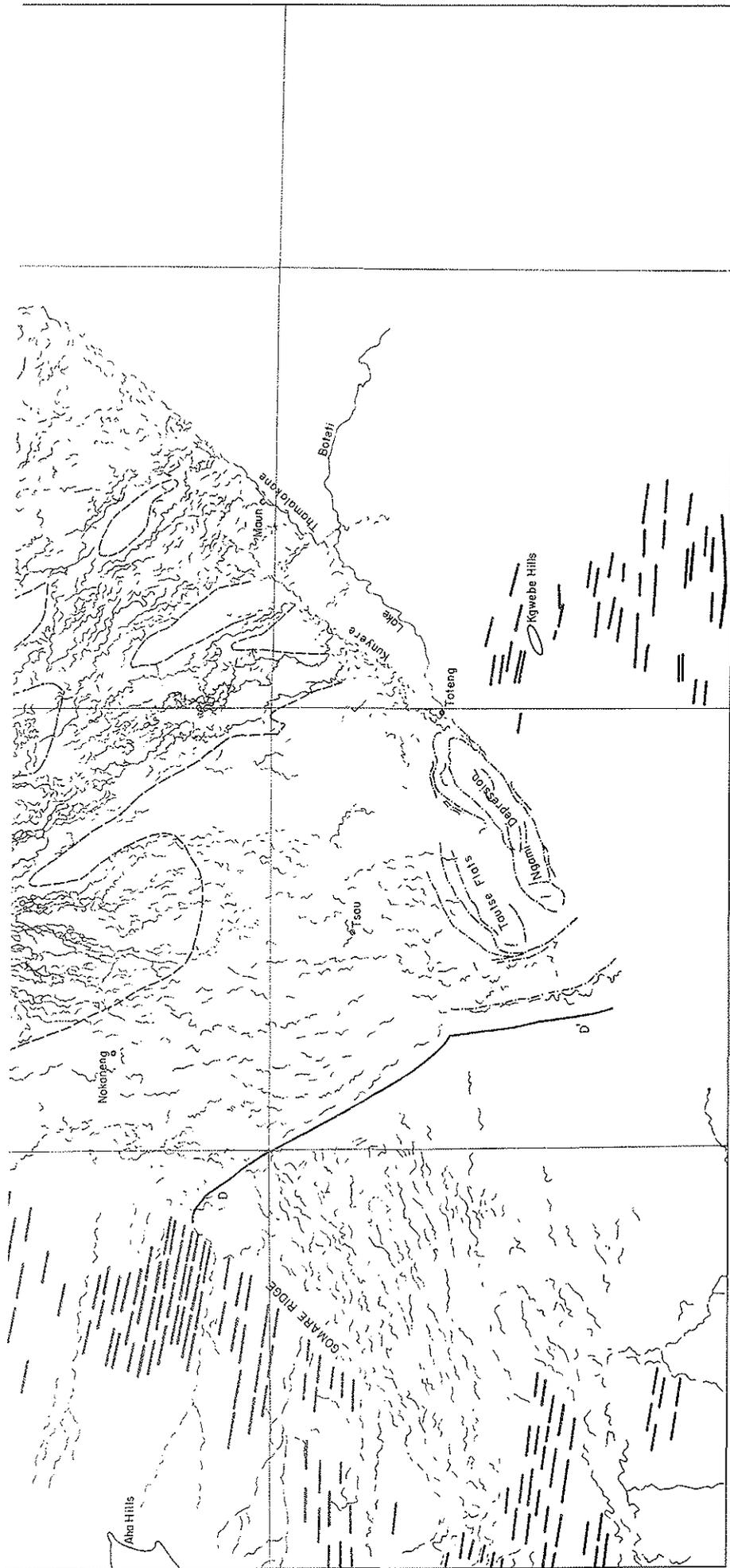
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FIGURE 5 SATELLITE IMAGERY (LANDSAT 1) INTERPRETATION OF THE OKAVANGO SHOWING TECTONIC LINEARS AND OTHER FEATURES

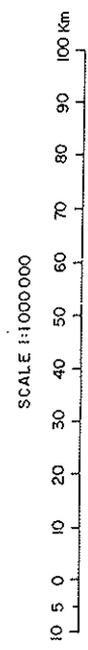




GS.Dwg. 20/76

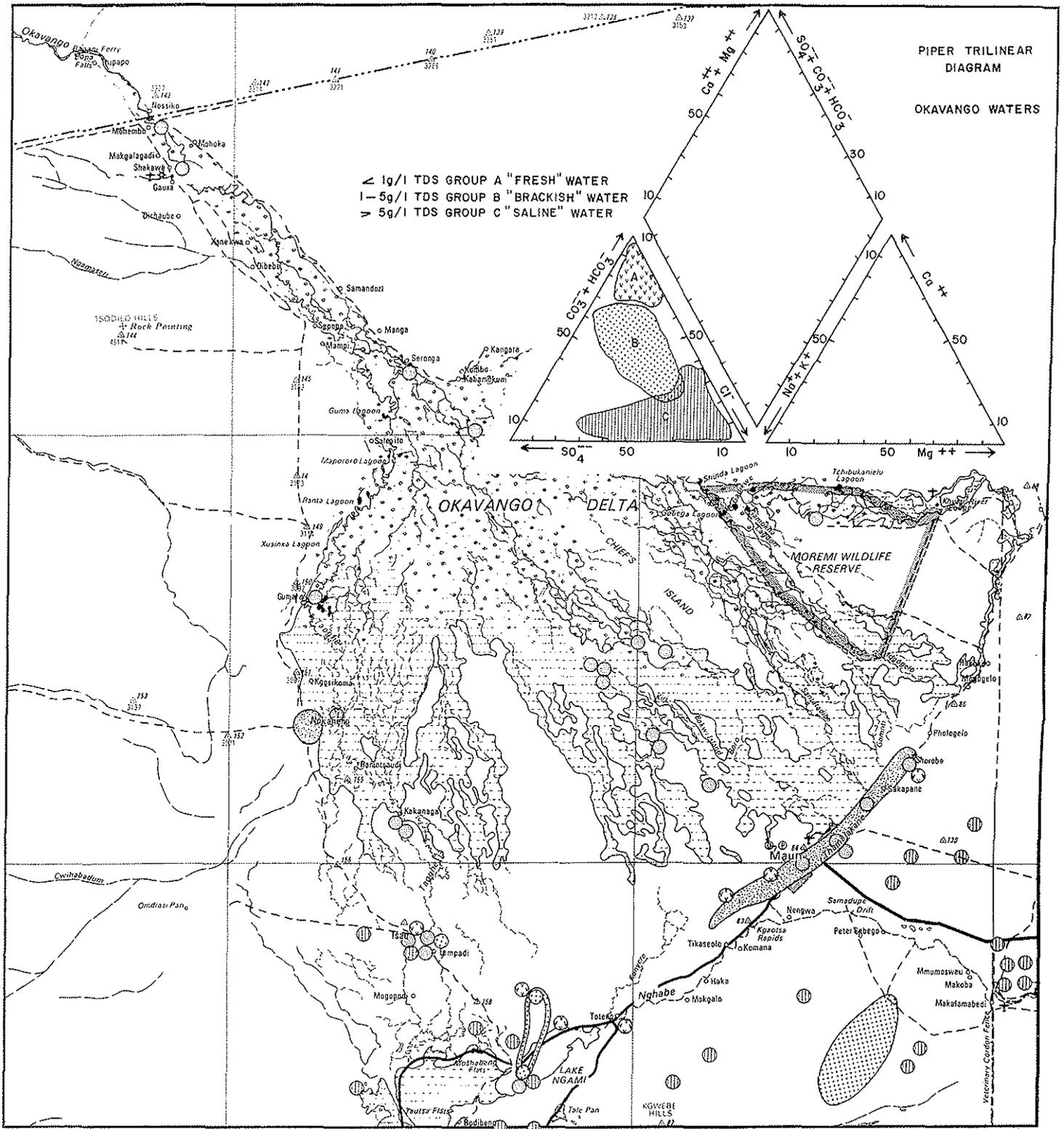
LEGEND

- Drainage channels, perennial, ephemeral, dry (Sept. 1972 imagery)
- Strandlines, lake outlines, tonal variations in lake beds
- Drainage divide D D'
- Self dunes
- - - Approximate outline of active delt drainage area and Linyanti swamps defined by high summer (Jan. 1973) vegetation
- Postulated limit of permanently flooded swamp winter (Sept 1972) imagery



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FIGURE 6 GEOMORPHOLOGY OF NGAMILAND AS INTERPRETED FROM LANDSAT I. IMAGERY



GS. Dwg. 21/76

LEGEND

- Sample stations for river and swamp waters
- ⊙ Group A groundwaters (TDS $< 1g/l$)
- ⊕ Group A groundwaters recharged from rivers
- ⊗ Group B groundwaters (TDS $1 - 5g/l$)
- ⊖ Group C groundwaters (TDS $> 5g/l$)

SCALE 1:1 000 000

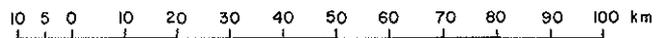


FIGURE 7 SURFACE AND GROUNDWATER SAMPLE STATIONS AND HYDROGEOCHEMISTRY OF THE OKAVANGO

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