

THE HYDROGEOLOGY OF BOTSWANA

by

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A B S T R A C T

Botswana covers an area of 570 000 km² and has a population of about 600 000. It is estimated that three-quarters of the human and livestock populations are dependent on ground water, with an estimated 26 x 10⁶ m³ of water from this source being used annually. Details of the physiography, climate, denudational and depositional surfaces and geology are given:-

Ground water occurs in both primary and secondary aquifers under both water-table and artesian conditions at varying depths from less than 1m to over 300m. The water-bearing properties of the various aquifers are described with the basalt/Cave sandstone contact providing the greatest number of successful boreholes and the sedimentary rocks of the Pretoria Group providing the highest yields (208,45 litres/minute). The shallowest water is found in the Kalahari Beds and the deepest in the Ecca Group.

Detailed descriptions are given of the hydrogeology of the Central Kalahari, Lobatse, Orapa and Serowe. In the Lobatse area, estimates of the average monthly recharge rate have been made as well as estimates of the total storage capacity of the various ground-water basins. The percentage of annual rainfall contributing to ground water has also been calculated. An annual recharge rate has also been calculated for Serowe while the total amount of water in storage in the important Cave sandstone aquifer has been estimated. Hydrogeological details of the Kalahari Beds, basalt/Cave sandstone aquifer and Middle Ecca aquifers are given following core drilling programmes.

ERTS photography was used to assist in obtaining a figure of 56 x 10⁶ m³ of extractable water present in storage in the "sand rivers" of eastern Botswana.

Detailed aquifer tests on a variety of aquifers are described and show that the secondary aquifers generally present often behave in a similar fashion to primary aquifers.

Approximately 5 000 boreholes are presumed to be present in Botswana. It is estimated that 17% of the successful boreholes have yields in excess of 150 l/min. The siting of boreholes using geological/geophysical aids has resulted in an increase in the success rate of nearly 25%. New geophysical techniques for the location of ground water have been investigated and ground geophysical methods used include electrical resistivity, inductive and conductive electromagnetic, Afmag, self-potential and seismic reflection and refraction methods. The well-tried resistivity method remains the most successful technique but self-potential, Afmag and seismic methods have given encouraging results.

Extremely detailed studies using environmental isotopes are described. These have enabled quantitative estimates of ground-water storage and turnover times to be made; have given ground-water flow rates; have outlined areas of recharge; have enabled permeabilities to be calculated; have enabled a clearer picture of recharge mechanisms through the unsaturated zone to be built-up; and have provided important evidence of areas in which recent recharge has contributed to ground-water supplies. The studies have shown that measurable amounts of tritium are present over far wider areas than originally anticipated and thus more recharge is taking place than thought earlier from laboratory tests and hydrogeological considerations. In Lobatse a water balance model is proposed and calculations based on this model indicate that some leakage, hitherto unsuspected, between several of the ground-water basins, take place. The carbon-14 method has, in addition, helped outline areas of recharge (Central Basin, Lobatse) which tritium had failed to do and has shown by using combined ^3H and ^{14}C data that mixing of young and old waters takes place. In the Kalahari, radiocarbon has been used to calculate ground-water flow rates, permeability and transmissivity. The oldest ground water in Botswana has an age of 33 700 years.

Isotopic studies in the unsaturated zone have shown that water moves given rates downward at a rate of between 31 and 41 cm per year.

Studies of water levels in boreholes have shown that nearly all boreholes show responses which can be directly correlated with seasonal recharge and hence the nature and frequency of recharge can be estimated. In addition, storage capacity and safe yield have been estimated using long term water level changes and knowing the amount abstracted from the basin. The rapid responses shown in some boreholes indicates surprisingly rapid recharge. Two boreholes in Botswana showed effects of the Tulbagh earthquake on 29th September 1969. The disturbance of semi-diurnal fluctuations in boreholes could possibly be used as an early warning device to predict catastrophic earthquakes.

A preliminary annual safe yield for ground-water supplies in Botswana is estimated to be $4 \times 10^9 \text{m}^3$ per annum.

Tree roots have been found in boreholes at depths greater than 68m. This emphasises the role vegetation can have in causing transpirational losses from ground-water supplies.

Irrigation from boreholes is unlikely to be profitable unless exceptionally large supplies are obtained or water be present at very shallow depth. Underutilised boreholes, e.g. boreholes drilled specifically for cattle ranching, could also be profitably used for irrigation.

Details of ground-water chemistry and examples of fresh water overlying saline, saline water overlying fresh, chemical stratification with depth and changes in quality with time are given. The distribution of fluoride rich waters in Botswana is also given.

This thesis has therefore attempted to outline the current status of hydrogeological research in Botswana and it is hoped that this will lay the foundation for later, more detailed and quantitative, studies. These will become even more vital than at present, as it is estimated that all readily available surface water resources in eastern Botswana will be fully utilised by the late 1980's and the country will rely even more heavily on ground water than at present.

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GENERAL NOTES

The grid co-ordinates referred to in the text can be found in Figures 3 and 7.

Abbreviations used.

cumecs	-	cubic metres per second.
epm	-	milliequivalents per million.
gpd	-	gallons per day.
gph	-	gallons per hour.
l/min	-	litres per minute.
m ³	-	cubic metres (1 m ³ = 220 gph).
m ³ /m	-	cubic metres per month.
mar	-	mean annual run-off.
mg	-	million gallons.
my	-	million years.
pmc	-	per cent modern carbon.
ppm	-	parts per million.
tds	-	total dissolved solids.

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"Water shortage hampers economic expansion at every turn. It limits the number of cattle that can be economically grazed, the types of crops that can be economically grown, the yields of those that are grown. It prevents consideration of certain types of industrial activity, or restricts them to locations that are disadvantageous, on other grounds. And it predetermines the safe centres of expansion of population and administration" (Economic Survey Mission Report, 1960).

Drought, and hence thirst and hunger in man and beast, is the underlying motif in Botswana. The writer gratefully acknowledges the permission of Stanley Hall of Lobatse to reproduce his poem "Desert Storm" given below, which expresses the feelings of all who have experienced the frequent droughts in this arid but fascinating country.

WATER- THE LIFE-BLOOD OF BOTSWANA.

Pl. 1

Bushwomen filling ostrich egg shells with water at a well in the Kalahari.



Pl. 2

Cattle watering - Kgwebe hills. (C.4).



Pl. 3

Cattle watering from sand river north of Serowe. (E.7).



Pl. 4

Stock watering at well on pan in Kalahari. (F.



Pl. 5

Bushmen drinking from author's water bottle
in Kalahari.



Pl. 6

Bushwoman arriving at well in Kalahari to
fill her bag of ostrich-egg shells with water.



Pl. 7

Mokgalakgadi woman drawing water from a well
in the Central Kalahari.



Pl. 8

Motswana women fill their goatskin water



Pl.9

Bushmen drawing water from a well - Kgwebe hills. (C.4).



Pl.10

Water in sand rivers constitutes an important source of ground water.- Cattle watering in the Mahalapshwe River. (F.7).



Pl. 11

Filling up water drums at Lone Tree Borehole.
(E.3).



Pl. 12

Xangwa Spring. (B.2).



Pl. 13

Kalahari Desert Storm.

DESERT STORM

Braggart black the bellied clouds
 Shoulder the sun to eclipse,
 And mass in funereal crowds
 To cast their souls to
 The shrivelled earth
 Shimmering in the
 Wilting heat
 Neath droughted dust.
 A whisper at birth
 Now sibilant strength,
 The vagrant wind spirals
 Through brooding bush.
 Voice of the suns' dying glare,
 While armour limbed
 The stirring thorns
 Claw the rumbling air;
 Horized violet veil
 Umbilicals the land,
 Promise to straw crisp grass
 And dormant root.

The first drops die
 In dusty shroud
 As the rain splits
 The roaring sky,
 Gathering strength from
 Clashing cloud,
 Misting down in sheeting flood
 Churns the smoking red soil
 To earth blood.
 Trickling, rushing in gathering rout,
 Fingers of life probe
 The wounds of drought,
 As the sodden land reflects
 The pewter sky.
 Growls the thunder deep and distant,
 The rain pecks puddles and stops.
 Droop and dripping trees
 In silent homage.
 The rain washed air vibrates to
 The languid music of serpentine
 Streams
 And the heavy sensuous smell
 Of hot
 Wet earth.

Stan. Hall

Lobatse, Botswana, 1972.

PREFACEHydrogeology

Hydrogeology was defined by Mead (1919) as "a study of the laws of the occurrence and movement of subterranean waters and which presupposes or includes a sufficient study of general geological limitations which must be expected in hydrographic conditions and of the modifications due to geological changes".

Period of Research, Object and Scope of Study

This thesis represents the results of 18 years of study and research into various aspects relating to the hydrogeology of Botswana. During the first fourteen years, dating from January 1956, the writer was employed initially as a geologist and later as a Senior Geologist and then Deputy-Director of the Botswana (Bechuanaland) Geological Survey. During the greater part of this fourteen year period, the writer was engaged on hydrogeological work and was directly responsible for the initiation and supervision of hydrogeological records and research in Botswana. During the last four years, the writer has continued to be associated with research in Botswana, particularly with regard to the studies involving the use of environmental isotopes, and has in addition made numerous trips to Botswana to update information.

The purpose of this thesis is to set down the results of pioneering studies initiated and supervised by the writer, relating to ground water in Botswana, in the hope that it may lead to a better understanding of the complicated

processes governing its occurrence, movement and location in Botswana, and in so doing, that it may lay the foundation for subsequent more detailed quantitative studies by other workers, as well as assisting the planning of water resource and utilization studies.

This whole thesis is the writer's original work, except where specifically indicated to the contrary in the text.

INTRODUCTION

Botswana is a large semi-arid tableland, situated at an average height of about 1000 m above sea level. The country is characterised by its large size; its relatively small population of just over 600 000 people; the predominance of the cattle industry in the country's economy; the chronic shortage of water with dependence mainly on ground water supplies and the limited potentialities for arable agriculture. Recent mineral discoveries have given rise to great potential in the mining and industrial fields and hence considerable attention is now being focused on the rational utilisation of Botswana's limited surface and underground water resources which are so essential to the nation's development. In addition, the extremely rapid demographic growth rate, rising standards of living and hygiene and improved farming methods, have led to a marked increase in the demand for ground water.

Despite a vast body of water in the Okavango Swamps, there is a general shortage of water elsewhere, and the traditional sources of water over the greater part of the country are hand-dug wells, boreholes or water held in storage in the large, ephemeral, sand-filled river courses. Because approximately 84 per cent of the surface area of Botswana is covered by an absorbent mantle of sands of Kalahari type, and because evapotranspiration exceeds the rainfall, no perennial rivers and only a handful of springs have their origin in the country.

As a result, it is estimated that at least three-quarters of the country's human and cattle populations are dependent on ground water. This includes not only the rural population of Botswana, but every single major town or village in the country, with the solitary exception of the capital, Gaborone, while both the major diamond and copper-nickel mining enterprises were seen through their early stages on ground water.

DESCRIPTION OF BOTSWANABackground

On the 27th January, 1885, the British Government proclaimed Bechuanaland a British Protectorate, extending as far north as latitude 22°S and westwards to longitude 20°E. Shortly afterwards, the area south of the Molopo River was proclaimed a Crown Colony and given the name British Bechuanaland. This became part of the Cape Colony in 1895. The northern boundary of the Protectorate was extended to its present position between 1892 and 1899. In 1899, the British Government was prepared to transfer the Protectorate to the British South Africa Company (B.S.A. Company), but following strong protests in 1895, from the three principal Tswana paramount chiefs, the British Government abandoned their intention of handing the whole territory over to the Company, and it was agreed that the strip of land required for the railway would be ceded to the Company by the Chiefs; that the tribal lands should be demarcated; and that only lands outside the tribal areas would come under the control of the B.S.A. Company. In 1904, all the land held by the B.S.A. Company was declared to be Crown Land, with the exception of the Tuli, Gaborone, and Lobatse Blocks. Following a long period commencing with the establishment of separate African and European Advisory Councils in 1920, progressive responsibility was given to the people of Bechuanaland, culminating in the country becoming the Independent Republic of Botswana on 30th September, 1966.

Location

The Republic of Botswana is a large landlocked country, situated in central southern Africa, with an area of 569 800 square kilometres (km^2), and is the same size as Kenya and a little bigger than France. It is bounded in the north by the Caprivi Strip, Angola and Zambia, in the west by South West Africa, in the south and south-east by the Republic of South Africa and in the northeast by Rhodesia. It lies between latitudes 17° and 27° south and between longitudes 20° and 30° east. (See Fig. 1). The country is divided into two almost equal northern and southern halves by the Tropic of Capricorn.

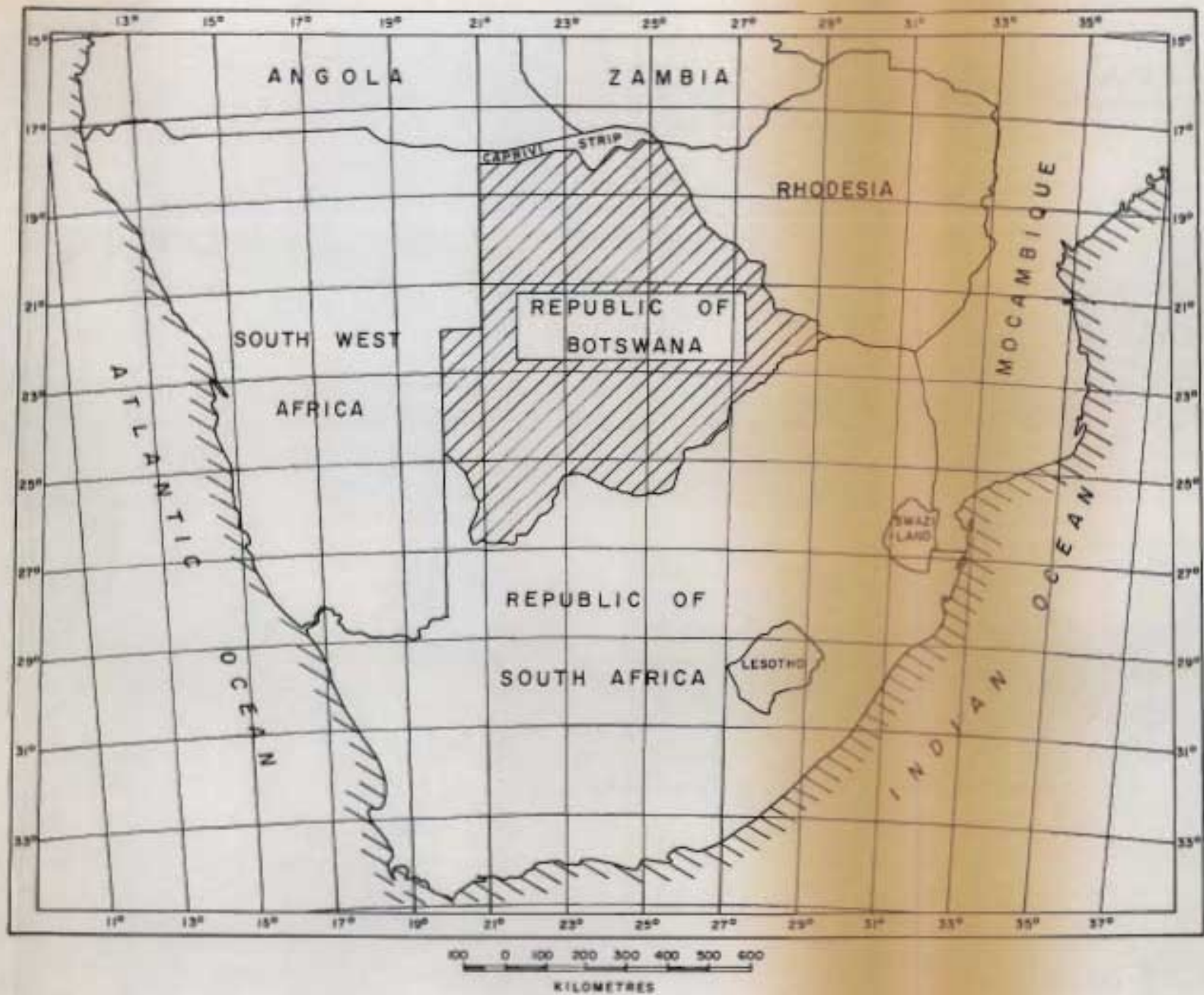


Fig. 1 BOTSWANA — LOCALITY MAP

Population and Employment

A census of population held in 1964, showed that the country's inhabitants numbered 543 525, comprising 535 373 Africans, 3 921 Europeans, 3 489 persons of mixed race and 382 Asians. The 1971 population census arrived at a total of 630 379, which is an increase of 16 per cent. Overall population density is $\frac{1}{4}$ 1 person per square kilometre. Growth in population since 1964 has thus been between 2 and 3 per cent per annum. Should this growth rate be maintained, the population by the year 2 000 will be about one and a half million. The Botswana Government is aiming to reduce this rate gradually over the next three decades to a figure of half a per cent and in so doing, keep the population down to a figure of just over 1 million by the year 2000. This would result in a 50 per cent higher per capita income than if the present trend were to continue.

The majority of the population leads a pastoral and agricultural existence, living in central villages, the largest being Serowe (45 560), Kanye (43 379) and Molepolole (34 711). The main business centres are the capital Gaborone (18 800), Francistown (21 083) and Lobatse (12 362), all situated along the line of rail. Although large scale mining will be in progress by the middle seventies, these operations will be essentially capital intensive projects and the main increase in

.... / employment

employment will be due to a substantial increase in private sector activity in response to the mining development. At present, 60 per cent of the population is engaged in the hand-to-mouth existence of subsistence agriculture. At any one time, about 46 000 Batswana are temporarily absent from Botswana and are mostly engaged in working on mines in South Africa.

The seat of government is the newly established capital of Gaborone, which is a modern and fast-growing town.

Land Utilisation

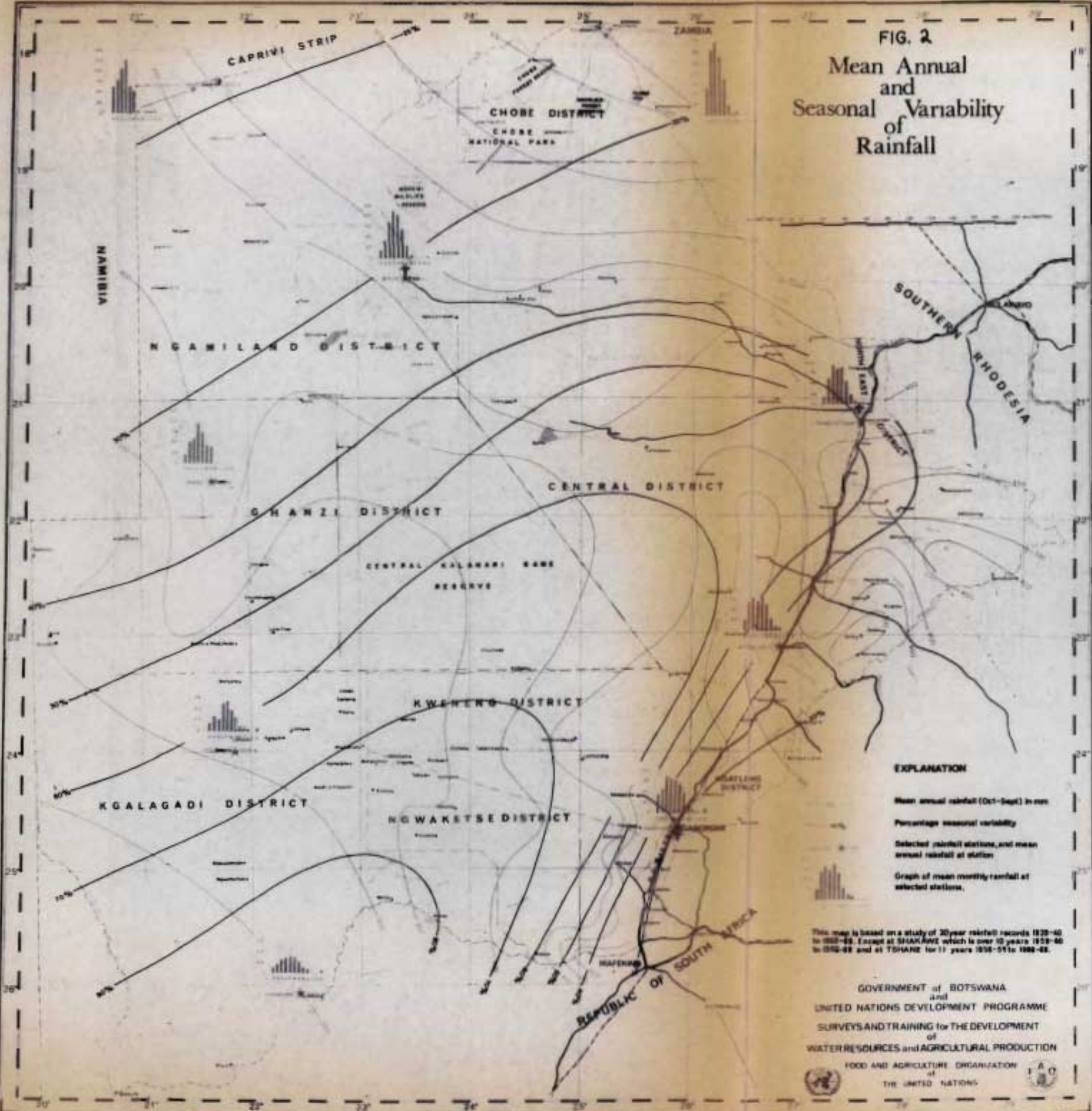
Botswana is divided into eight districts (278 000 km²), six freehold farming blocks (22 100 km²) and State Lands (273 000 km²), which are largely uninhabited sandveld. The various districts are shown on Fig. 2.

Pastoral and agricultural activities have long been traditionally carried out by villagers in separate areas with cultivated tribal lands, usually starting a few miles from the villages and in the case of the larger villages, stretching in any direction for up to forty-eight kilometres. The grazing areas, consisting of scattered cattle posts, are usually situated beyond the "lands" areas and draw their water from boreholes, hand-dug wells or from wells in the sands of ephemeral rivers. Each cattle-owning family maintains a cattle post which may be shared with other members of the extended family. Small cattle owners are encouraged to form syndicates to pay for boreholes. Grazing areas are traditionally unfenced. Traditionally families were granted areas in which they could graze their cattle or plough by the Tribal Authority. There is an increasing tendency for people to make permanent homes at their lands or cattle posts and to abandon the former system whereby lands areas were only inhabited during the crop growing season and cattle posts left largely in the care of servile tribesmen or younger male members of the family.

It is estimated that there are 4,45 million hectares



FIG. 2
Mean Annual
and
Seasonal Variability
of
Rainfall



of land suitable for cultivation in eastern Botswana; of this area, only one tenth or less is under cultivation. Most of the country except the extreme southwestern portion, where bare sand dunes occur, offers good grazing. The national herd of cattle is estimated to be approximately 2 million head, while the carrying capacity is estimated to be 2,5 million head, depending on the provision of sufficient watering points.

Physiography

Altitude

Although Botswana is generally regarded as a vast plateau, it can be divided into two main physiographic regions, consisting of a large central saucer-shaped plateau (but excluding the inland deltaic area of the Okavango Swamps in the northeast), now almost completely mantled by sands of Kalahari type, and an eastern Bushveld region. These two regions are generally separated by a clearly defined escarpment below which, in the east, several late Tertiary and younger cyclic denudational surfaces can be recognised. These will be described later in more detail. The crest of this escarpment varies in altitude from 1 097 metres to 1 341 metres above sea level.

Of the two regions, the eastern Bushveld region has the most favourable rainfall (apart from a rain shadow area in the extreme northeast between the Shashe and Limpopo Rivers), and the most suitable agricultural land. Consequently, about 80 per cent of the population is distributed here in the vicinity of the line of rail from the Republic of South Africa to Rhodesia. Drainage from this section is ephemeral and forms part of the Limpopo catchment.

The southern portion of the Kalahari area slopes gently towards the Molopo and Nossob Rivers on the borders of the Republic of South Africa and South West Africa respectively.

..../(This point

(This point is at an altitude of 823 metres). The main part of the Kalahari, however, slopes very gently towards the ancient internal drainage centre of the Makgadikgadi Depression at an elevation of 914 metres. This vast endoreic drainage system is now fed only occasionally by overflow from the Okavango-Boteti-Lake Xau (Dow) system and from a number of southwesterly or westerly draining ephemeral rivers west of Francistown which debouch into the eastern or Sua section of the Makgadikgadi.

In the eastern region, the lowest point (518 metres) is at the confluence of the Limpopo and Shashe Rivers. The highest point in Botswana is in the southeast at Ootse Hill (1 491 metres).

Further detail regarding the altitude of hills in Botswana is given in the description of the morphology of Botswana.

The depths to ground water in the two main physiographic regions are, in general, markedly different with the eastern bushveld region, having depths to water of about one third that of the central Kalahari region.



Pl. 14

The Kalahari - Dikgomo di kae hills on central skyline. (G.5).



Pl. 15

Main road across Kalahari. Note deep sand.



Pl.16

The Kalahari - Note fairly dense vegetation cover.



Pl.17

Sunrise in the Kalahari



Pl. 18

The Kalahari.



Pl. 19

A well in banded ironstone (Griquatown)
Moseeje. (H.5).

The Kalahari Region

The Kalahari is a great sandy plain, which extends from the Orange River near Upington as far as 1° north latitude in the lower Zaire basin and thus forms the largest continuous sand surface in the world. Although known as a desert, it is almost entirely covered with grass and woodland, and is more correctly termed a thirstland which is practically devoid of surface water and which is well nigh uninhabited, except for a few hardy bands of Bushmen and Bakgalakgadi. The latter lead a similar hunter-food gathering type of existence to that of the Bushmen. The Bakgalakgadi may in addition keep a few cattle and some goats and are hence confined to areas where water is available from wells or boreholes. The Bushmen on the other hand are able to do completely without water as such, and can obtain their moisture from the stomach content of animals and from a variety of melons and other watery plants.

The Kalahari is generally so flat that one often has the illusion that the land rises gently in the direction in which one is travelling - only to have the same illusion when returning.

The Kalahari may be defined as a large saucer-shaped basin separated in the east by a clearly marked escarpment from the Limpopo catchment area. Towards the Makgadikgadi Depression, this boundary becomes indefinite, whilst the Kalahari extends northwards into Rhodesia near Wankie, westwards into South West Africa and southwards into the



Pl.20

View across Mababe Depression. Gubatsaa
hills in distance.

Northern Cape Province.

In Botswana, the rim of the Kalahari attains its maximum elevation along its eastern and northwestern margins.

In the east, the most prominent hills are Kwagkwe (G.6, 1 472 metres); Kgoro (H.6, 1 371 metres); Lobutse (G.6, 1 374 metres); and Dikgomo Di Kae (G.5, 1 199 metres). Further north, the Shoshong hills (E.7, F.7) attain a maximum height of 1 348 metres, while the Mokware hills (E.7, south of Serowe) reach a maximum height of 1 316 metres.

In the southern Kalahari, only two small hills emerge from beneath the ubiquitous sand cover - at Yaaneng (H.4) and at Motsoje (H.5. See Plate 19) (both are formed by resistant Griquatown banded ironstone).

In the central western portion of the Kalahari in Botswana a resistant rib of northeasterly striking Ghanzi Group sedimentary rocks and associated silicic lavas interrupts the general monotony of the plain and runs from Mamono (E.1) on the South West African border, past Ghanzi to south and southeast of Lake Ngami. Prominent hills (Mabeleapudi, Ngwenelekau, Shulabompe, C.3) of quartz feldspar porphyry, run from the veterinary cordon fence separating the Ghanzi and Ngamiland Districts to the Kgwebe Hills, (C.4) while prominent quartzite hills form the Tsau (D.3) and Haina Hills (C.4) along a line further southeast.

Northeast of the Kgwebe Hills, after a gap of 250 km, similar rock types form the Gubatsaa (Plate 20) - Coha Hills



Pl.21

Tsodilo hills. (A.2).



Pl.22

Alab dunes - North of Makgadikgadi.



P1.23

Barchan dunes - Makgadikgadi Pan. (c.6).

(porphyry) (A.5) and the Shinamba Hills (A.5, Ghanzi Formation quartzite).

In the area west of the Okavango delta, prominent hills (Aha, (B.2) and Koanaka, (C.2)) are formed by Outjo facies dolomite of the Damara Supergroup, while the Tsodilo hills (A.2) of ferruginous and micaceous quartzite (Damara Supergroup) reach a height of 1 375 metres and form one of Botswana's most famous landmarks (Plate 21).

Sand dunes. - Examination of aerial photographs of Botswana reveal a number of extensive dunefields which are now fixed by vegetation, except in the extreme southwest. The major dunefields are present: in the extreme southwestern portion of Botswana between the Molopo and Nossob Rivers; west and north of the Okavango Swamp, where massive alab dunes reach heights of several tens of metres above the intervening trough and run in dead straight lines for scores of kilometres; and north of the Makgadikgadi where low linear dunes similar to those described by Flint and Bond (1968) extend into western Rhodesia (Plate, 22, B.7). Barchan dunes are present on the western Ntwetwe Pan section of the Makgadikgadi (Plate 23, C.6).

The dunes of Botswana have been described in detail by Grove (1969).

It is interesting to note that sand is often piled high on the eastern side of many of the hills in northwestern Botswana. e.g. Tsodilo, Koanaka and Goha Hills. In the

Goha Hills, the difference in elevation between the sand on the eastern and western margins is 43 metres. This fact, together with the general easterly trend of the alab dunes, leads to the conclusion that prevailing winds at the time of the dune formations were roughly easterly in direction in northern Botswana. In the southwestern portion of Botswana, the dunes have a northwesterly trend and are regarded by Grove (1969) as having been formed by dominant northwesterly winds.

Pans. - Early descriptions of pans in the Kalahari were given by Passarge (1904) and Jaeger (1939). More recent descriptions have been given by van Straten (1955), Boocock and van Straten (1962) and Grove (1969). Apart from the occasional fossil river course, pans form the most distinct morphological features in the Kalahari. They range in size from a few metres in diameter to the vast pans of the Makgadikgadi.

They are widely distributed throughout the sand-covered area of Botswana, but two areas in particular contain remarkable concentrations of pans - viz. a broad strip coinciding with the drainage divide separating the Molopo and Makgadikgadi drainage basins (termed Bakalahari Schwelle by Passarge) and the area between Lake Xau (D.5) and Ghanzi (D.2). The lowest point of the pan depression may lie up to 21 metres below the surrounding plain. Most pans in central Botswana have a sand ridge on their southwestern margin pointing to their being shaped by northeasterly winds. The mode of origin of these pans is still obscure, but Boocock and van



Pl.25. Sekoma Pan after exceptional rains. (G.4).



Pl.25a Tshane Pan. (F.2).



Pl.26

Tshabong Pan (note percussion drill)(I.3).



Pl.27

Okwa Fossil Valley just E. of Main Ghanzi

Straten (1962) suggest that the majority were formed along the lines of sand-choked and fossilized drainage systems. Although this is probably the case in the area west of Lake Xau, a study of the air photographs of the Bakalahari Schwelle area shows no trace of either ancient drainage lines or a linear orientation of the pans.

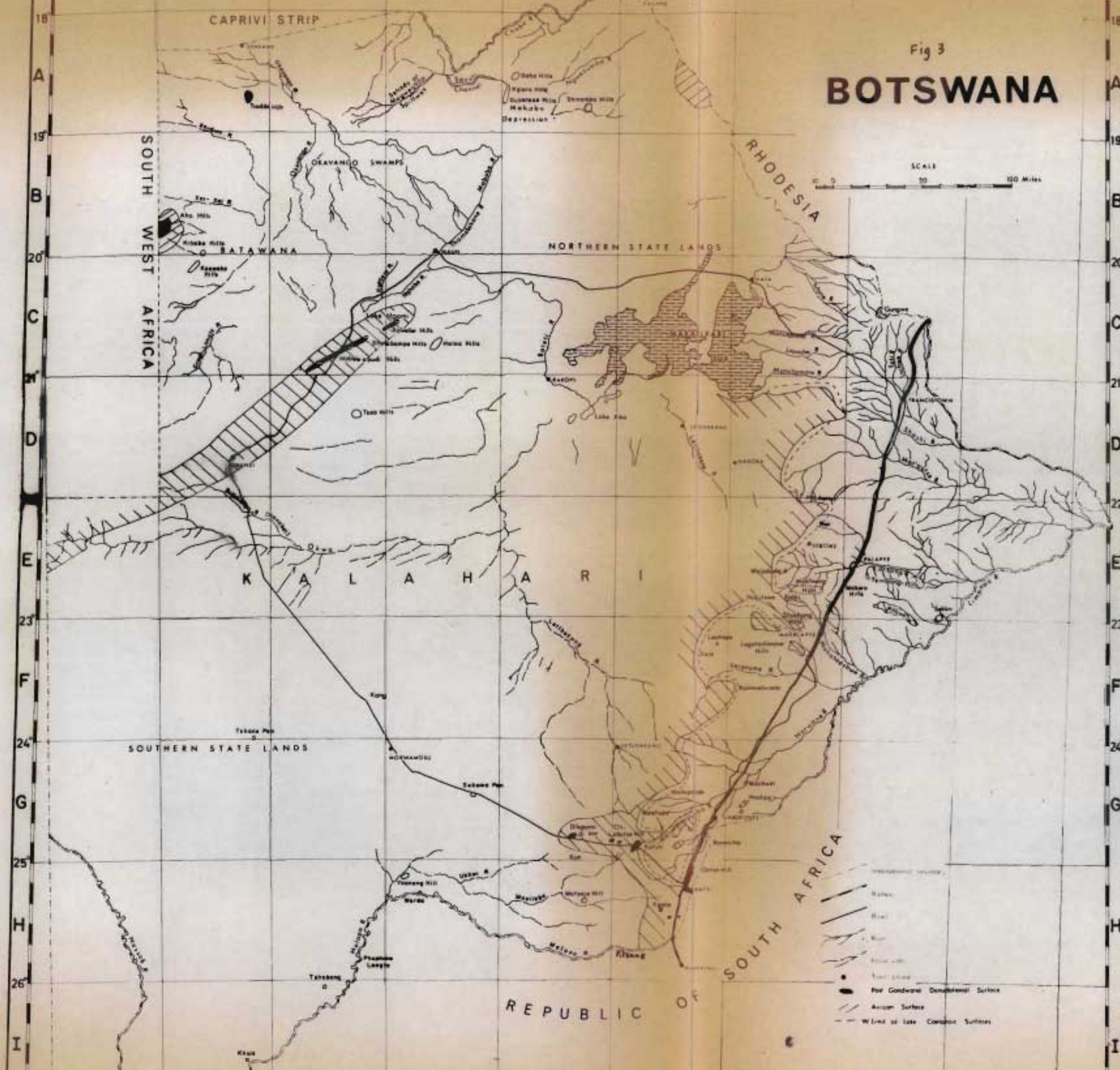
Plates 24-26 show two typical pans in the central Kalahari.

Pans in the south-central Kalahari occasionally yield ground water at shallow depths, whereas in the surrounding Kalahari sandveld water is only found at deeper levels below the Kalahari Beds. Such shallow perched water table wells may be found at Sekoma, Kukong, Kang, Tshane, Hukuntse and Lehututu Pans and derive their water by infiltration from accumulations of rainwater in the pans. Elsewhere in the extremely flat Kalahari region, very little concentration of rainwater can occur and most rainfall is probably lost to evapotranspirative processes.

Fossil River Valleys. - Fossil river valleys, known locally as mokgatcha, dum or omuramba, form one of the most prominent geomorphological features in the otherwise monotonous expanse of the Kalahari (Fig.3). These may be incised up to 100 m below the surrounding plain (Plate 27) and, apart from limited localised flow noted by the writer in the headwaters of the Okwa and Moselebe valleys and by M.T. Jones (personal communication) in the Letlhakana valley near Orapa, have probably carried no water in historic times. The Molopo River, which forms Botswana's

Fig 3

BOTSWANA



southern boundary, is partly fossil with no flow having been recorded in recent times further west than Phephane Laagte (H.3). Evidence of considerably greater flow having taken place in the past along this river is afforded by a 30 m deep gorge cut through quartzite at Khuis (I.2) and a similar gorge cut in banded ironstone (Kraaipan Formation) near Pitsane. (H.6).

Two fossil valleys, the Ukhwi (H.5) and Moselebe (H.5), which form a tributary to the Molopo, are present in the south.

The three main fossil valleys in the Central Kalahari, the Okwa and Hanahai (Buitsivango, E.2) and the Letlhakeng (F.5) valleys are separated from the Molopo basin by a broad swell rising to an elevation of 1 200 to 1 300 m called the Bakalahari Schwelle by Passarge (1904).

The Okwa river system probably once formed one of the principal rivers feeding the former Great Makgadikgadi Lake.

On the eastern margin of the Kalahari, only two major fossil valleys are present - these are the Letlhakana valley (D.6) and the Serurume valley (F.6).

West and southwest of the Okavango Swamps are a number of long shallow fossil valleys which formerly drained into the Okavango. The chief valleys in this section, from south to north, are the Groot Laagte, (C.2), the Xai-Xai valley (B.2) and the Xaudum valley (A.2, B.2).

These previously strong-flowing rivers probably formed the main recharge source for the chief aquifers underlying the Kalahari during Pleistocene times.

Eastern Bushveld Region. - This eastern "bushveld" region, which is largely composed of rocks of the Basement Complex assemblage, lies to the east of the main scarp which forms the margin of the Kalahari. The country is generally extremely flat and is broken only by occasional inselbergs (Plate 28) or by ranges of more resistant quartzite and dolerite hills such as the Matsiloje hills (D.8), the Makhware (E.7), Shoshong (F.7), Makoro (E.8, Plate 29), Tswapong hills (E.8) and the Ootse - Lobatse hills (H.6).

The Bushveld region is drained by a number of broad, normally dry, sandy river beds which can, however, come down in spate after heavy rains (Plates 31,31). These ephemeral rivers are probably the main source of recharge to the boreholes and wells in the vicinity of the river courses, while their sandy beds form an important aquifer in Botswana (See section on Sandriver Storage).

The rivers are described in more detail in the section on drainage.

This eastern region has better communications; comparatively good soils; a more favourable rainfall and shallower ground water than the country to the west and hence the majority of the population is concentrated here.



Pl.28 E. Bushveld Region. Modipe Hill (gabbro) on skyline. (G.7). Note well-planed Late-Tertiary Denudational Surface.



Pl.29 Makoro hills. (E.8).



Pl.30 Dry Motloutse River Bed. (D.8).



Pl.31 Shashe River in flood. (D.8).

Drainage Systems

Three main drainage systems can be recognised within Botswana. These are: a portion of the Limpopo basin; the Okavango-Makgadikgadi basin and the Molopo-Nossob basin. In addition the Chobe River forms part of the northern boundary of Botswana. It is noteworthy that all of Botswana's major rivers are partly or wholly external in their origin. Jennings (1971) gave a detailed description of the hydrology of Botswana.

The Limpopo Basin

The total catchment of the Limpopo River up to the point where it leaves Botswana is 179 020 km², of which 77 700 km² are in Botswana. The main tributaries within Botswana are the Notwane (F.7), Metsemotlhaba (F.8), Motloutse (D.8, Plate 30) and the Shashe Rivers (D.8. Plate 31). All are ephemeral and flow at most for a few months every year. Even though these rivers are of an ephemeral nature, they convey large quantities of flood water annually (Plate 32) to the Indian Ocean via the Limpopo River. Because of the concentration of population in this area and as a result of recent mineral discoveries occurring in or relatively near to this basin, serious consideration is now being given to the conservation and utilisation of this water. The very large Shashe Dam was completed recently and supplies the Selebi-Pikwe mining complex. Other large dams have been built on the Notwane (Gaborone Dam) and the Nuane Rivers (for Lobatse).

The Okavango Basin

The perennial Okavango River rises in Angola, crosses the Caprivi Strip and at Shakawe, where it enters Botswana, has a catchment of 137 270 km². The Okavango is the largest river in Southern Africa after the Zambezi, and has an estimated mean annual discharge of 11 881 x 10⁶ m³. Below Shakawe, the Okavango forms a large delta covering 16 835 km² from which most of the water is lost by evapotranspiration. Small quantities however, (5 per cent of inflow) spill over in several channels into the Thamalakane River which forms a drain at the base of the delta (Plates 32-36). The delta-shaped swamp is bounded on its southern margin by a low N.E.-S.W.trending ridge which runs for hundreds of kilometres and is undoubtedly caused by faulting. This has resulted in the Okavango River backing up against the fault and forming a delta. The hydrography of the Okavango Basin is extremely complex with water occasionally spilling over via the Magwegana (or Selinda) spillway (A.4) into the Chobe River. The Chobe River itself may spill via the Savuti Channel (A.4) into the Mababe Depression. This Depression also occasionally receives overflow in the south from the swamps via the Mababe River (B.4) or in the northeast from the ephemeral Ngwezumba River (A.5).

The Thamalakane River (B.4) flows first southwest past Maun into the Boteti River (C.4) which then leads away to the southeast past Rakops (290 km away from Maun by water) to Lake Xau and occasionally into the Makgadikgadi Depression



Pl. 32

Thamalakane River. (B.4).



Pl. 33

Thamalakane River. (B.4).



Pl. 34

Aerial view of Okavango Swamp.



Pl. 35

Boteti River - dry.

(322 km) from Maun. When the Thamalakane River reaches a discharge rate of 5,5 cumecs, in addition to flowing down the Boteti River, it also flows southwestwards as the Lake River (Nghabe, C.4) into Lake Ngami. In addition, the Kunyere River with 30 per cent of the total swamp outflow, joins the Lake River at Toteng (C.3) and is the major feeder to Lake Ngami.

Flow through the Okavango swamps takes 3 to 5 months with maximum levels at Shakawe (A.2) in late March and at Maun (B.4) in June-August. The water in the Okavango swamps is very clear, has a very low dissolved solids content and carries no suspended silt at any time of the year.

The Okavango swamps have evoked considerable interest over the years and especially following publication of the controversial book "The Kalahari: or Thirstland Redemption" (Schwarz, 1920). Other studies have been made by Stigand (1923), du Toit (1925), Jeffares (1938), Mackenzie (1946) and Brind (1954). Their researches have shown conclusively that the formation of a vast interior lake would have little beneficial effect on the climate of Southern Africa as Schwarz believed. A comprehensive survey of this area has recently been completed by the Food and Agricultural Organisation of the United Nations. The project was jointly financed by the Botswana Government and the United Nations Development Project (Special Fund).

Apart from the Lake Xau overflow into the western Makgadikgadi, a number of ephemeral rivers flow into the eastern or Sua Pan



Pl. 36 Boteti River in flood. (Note clear water).



Pl. 37 Merging of Zambezi and Chobe River Floodwaters near Kasane. (A. 6).

section of this ancient internal drainage centre. The Okwa-Letlhakeng drainage system (E.4, G.5), with its catchment of approximately $93\,240\text{ km}^2$, must once have contributed large quantities of water to the Makgadikgadi. This system is now fossil except for the limited flow in the Okwa in the vicinity of the South West African border after exceptional rains.

The Chobe River

The Chobe River forms part of the northern boundary between Botswana and the Caprivi Strip and has a catchment of $145\,040\text{ km}^2$ above its junction with the Zambezi River. No hydrological data for this large river are available, but the flow has been estimated at $3\,659 \times 10^6\text{ m}^3$ (Mackenzie, 1946). The Chobe River receives large quantities of water from the Zambezi swamps lying upstream of the confluence at Kasungula (Plate 37).

The Molopo-Nossob Basin

The Molopo and Nossob Rivers which form the southern and southwestern boundaries of Botswana are ephemeral rivers rising east of Mafeking and in South West Africa respectively. The lower portion of the Molopo River has been dry for the past 25 years and the sand-covered catchments in Botswana contribute no run-off to the ephemeral flow.

Climate

General Characteristics

Botswana has a semi-arid climate which may be classified as being of low-latitude hot steppe type with summer rainfall (B. Shw. of the Köppen classification). The sparse rainfall is associated with abnormally dry subsiding air masses (superior air) and horizontally diverging wind systems of the subtropical anticyclones. As a result of the dry climate and high potential evaporation, there is no surplus of water with which to maintain a constant water supply from rainfall and hence no permanent streams or rivers and only a handful of springs originate within Botswana. The climate is characterised by severe seasonal temperatures with large diurnal temperature ranges and extremely variable rainfall, high evaporation and low humidity.

Circulation, Pressure Systems and Air Masses

The climate of Botswana, situated as it is in the centre of the Southern African sub-continent, is controlled by the regional climate of southern Africa as a whole, which is bounded on the west by the Atlantic Ocean with its cold Benguella current and on the east by the Indian Ocean with its warm Mocambique and Agulhas currents.

During the winter months from April to September, anticyclonic conditions persist for lengthy periods, and are broken only by occasional tongues of low pressure from the south or southeast which pass up the coast. The anticyclonic

conditions result in exceedingly dry north-westerly winds causing warm, dry sunny days with temperatures rising above 20°C , followed by clear cold nights during which radiation is active and hence temperatures drop rapidly and often to well below freezing point. (Pike 1971).

During the summer months from October to March, a weakening of the anticyclones permits the entry of moist maritime air from the Indian Ocean. Tropical Continental air, originating from the sub-tropical high pressure belt and modified during its passage over the hot, humid eastern coastal belt, is uplifted across the Great Escarpment and being warm and moist, gives rise to conditions conducive to the development of thunderstorms in eastern Botswana. During the late summer months, the tropical low pressure system over the interior may link with the temperature low in the south, resulting in fairly widespread rains as the temperature low moves up the southeast coast. Widespread general rains, however, occur only when a cool, heavy air mass from the South Atlantic Ocean forms a wedge extending northwards against the Drakensberg Range and its lower layers are warmed by contact with the warm Agulhas current, the air mass becomes unstable and with a low pressure system present over Botswana there is an enormous influx of humid air into the interior (Pike, 1971).

In northern Botswana as far as latitude 20°S , rain falls mainly as the result of the Equatorial air mass, forming part of the Inter Tropical Convergence Zone, moving into the area.

Rainfall

A glance at the isohyetal map (Figs.2,3) of Botswana, shows that there are three distinct rainfall regions which are a direct result of the weather processes affecting the country and which have been described earlier. These three zones may be described as follows:-

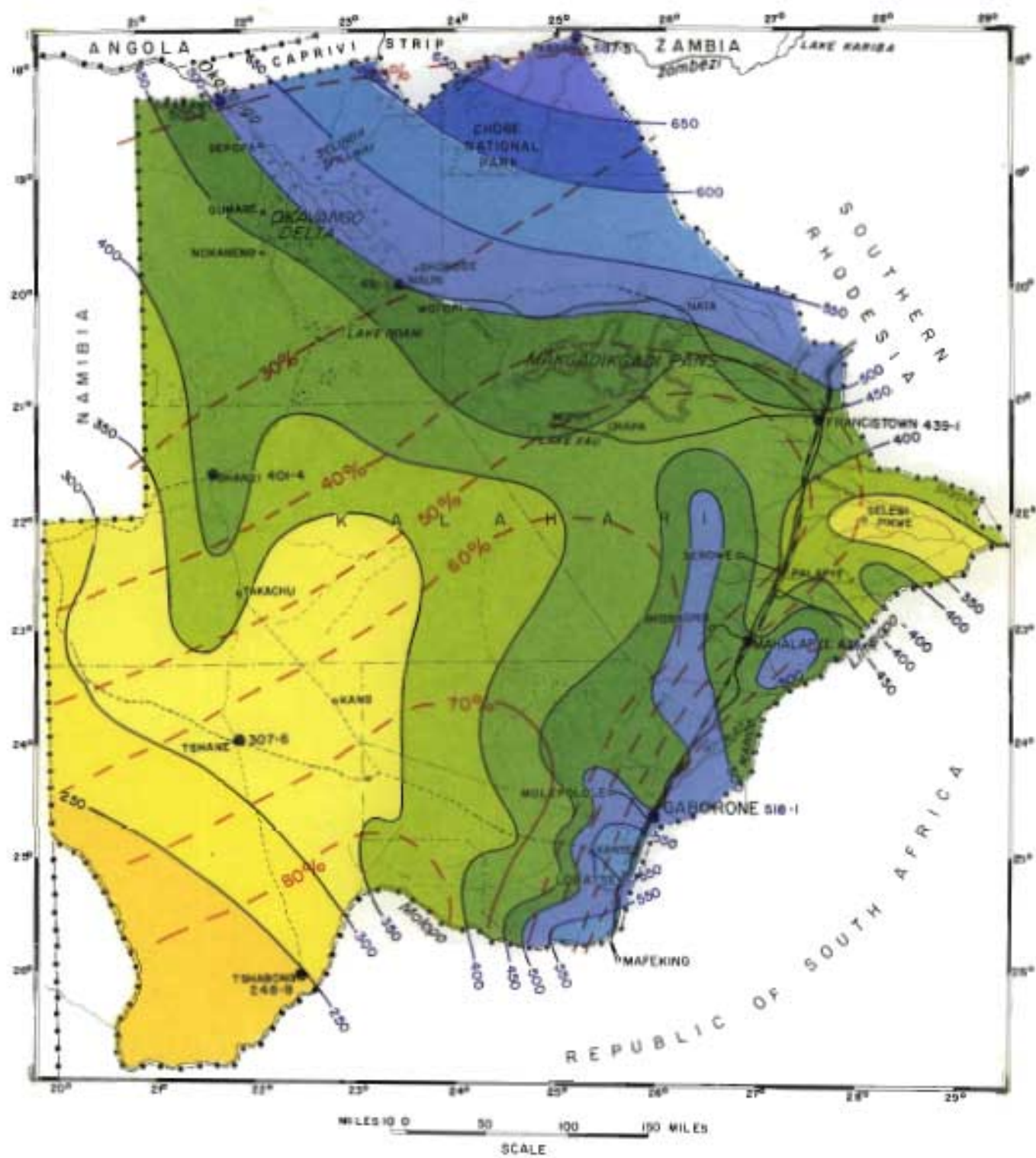
- i) Northern
- ii) Eastern
- and iii) Kalahari

The Northern Zone stretches to $20\frac{1}{2}^{\circ}\text{S}$, and shows a steady decline in rainfall from 650 mm to 450 mm. It closely reflects the southern limits of the Inter Tropical Convergence Zone and also shows a decrease westwards towards the arid zone of South West Africa whose climate is affected by the cold Benguella current.

The western limit of the Eastern Zone approximates with the erosion scarp separating the Kalahari from the Limpopo watershed. The rainfall in this Eastern Zone is derived mainly from moist easterly air originating over the Indian Ocean, and varies from 550 mm in the southeast to 350 mm in the north. The rainfall decreases steadily west of the Kalahari scarp.

The Eastern and Northern Zones are separated by a drier belt extending westwards up the Lower Limpopo and Motloutse valleys.

The Kalahari Zone is an extension of the arid zone of southern South West Africa and the northern Cape Province.



Mean Annual Rainfall

Fig-4

- 400 MEAN ANNUAL RAINFALL (OCT-SEPT) IN MM.
- 60% PERCENTAGE SEASONAL VARIABILITY FROM MEAN ANNUAL RAINFALL.
- 687-5 SELECTED RAINFALL STATIONS AND MEAN ANNUAL RAINFALL IN MM.

NOTE
 THE MEAN ANNUAL RAINFALL IS BASED ON A THIRTY YEAR PERIOD 1939-40 TO 1968-69 EXCEPT AT SHANAKE FOR TEN YEARS AND TSHANE FOR TWELVE YEARS

Rainfall in this zone is highly variable (the annual coefficient of variation ranging from 50-80 per cent), with mean annual totals of 250 to 350 mm. (Pike 1971) (Fig. 2).

Rainfall thus varies from 150 mm in the southwest to nearly 700 mm in the extreme north. It has been estimated that the mean annual rainfall for Botswana is just less than 400 mm. However, average figures for rainfall can be very misleading as in any year at a given place the rainfall may be less than half or more than double the average for that area (See Fig.2 showing mean seasonal variability).

Rainfall Variability and Distribution

Pike (1971) has given monthly rainfall means for the 30 year periods 1939/40 - 1968/1969 (See Table 1) and also coefficients of variation and probability of exceedence for a number of stations in Botswana (Tables 2,3). As a result of a study of the rainfall distribution and variability and combining this with the presence of soils suitable for agriculture, he concluded that less than 5 per cent of Botswana may be considered as potentially arable, and even here the risk of crop failure may be put at approximately 4 in 10 years.

Rainfall Intensity

The maximum rainfall intensity known to the writer in Botswana was when 292 mm of rain fell in $3\frac{1}{2}$ hours in Ghanzi in October 1963. Rainfall intensities of 165 mm in 3 hours and 114 mm in $1\frac{1}{4}$ hours have also been recorded at Francistown.

TABLE 1

RAINFALL : MONTHLY MEANS mm

1939/40 - 1962/69

STATION	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	TOTAL
KASANE	17.7	66.9	155.0	187.3	138.7	91.6	27.2	1.5	3.3	0.0	0.2	1.4	687.5
HAUN	16.0	47.1	86.8	117.0	107.2	73.7	32.8	6.2	1.4	0.0	0.2	2.4	491.1
FRANCISTOWN	19.1	61.8	91.5	84.7	86.9	54.1	22.4	6.7	3.6	0.5	0.4	3.1	439.1
GHAZI	19.3	48.4	59.7	93.9	72.2	50.9	41.8	8.7	1.8	0.6	0.5	3.2	401.4
MAKALAPYE	29.5	70.1	82.6	73.0	91.8	67.5	33.7	12.9	6.3	0.6	1.4	7.2	476.4
GABORONE	43.8	58.7	87.9	81.7	80.6	68.6	51.4	15.3	10.5	4.4	3.1	12.9	518.7

TABLE 2
RAINFALL CHARACTERISTICS

STATION	30 Year Average	MAXIMUM		MINIMUM		MODE	Stand-ard Devi-ation	Coeff. of Vari-ation	Probability of Exceedence %				
	mm	mm	%	mm	%				mm	mm	%	200	400
KASANE	687.6	1,040.6	151.3	379.1	55.1	651.4	181.1	26.3	100	97	57	27	3
MAUN	491.1	872.6	177.7	267.5	54.5	488.0	150.0	30.5	100	67	20	3	-
GHANZI	401.4	720.8	179.6	114.7	26.6	375.7	160.3	39.9	90	40	20	-	-
FRANCISTOWN	439.1	923.0	210.2	113.7	25.9	412.6	178.7	40.7	93	53	17	3	-
NAHALAPYE	476.4	913.4	191.7	228.7	48.0	464.2	159.5	33.5	100	60	17	7	-
GABORONE	518.7	927.2	178.8	307.7	59.3	495.3	148.6	28.6	100	77	27	7	-

TABLE 3

RAINFALL : MONTHLY COEFFICIENT OF VARIATION

(%)

STATION	Seasonal Mean mm	% Coeff. of Variation							
		October	November	December	January	February	March	April	Season
KASANE	687.55	112.4	50.5	49.2	54.7	69.8	70.8	122.1	26.3
MAUN	491.1	103.2	61.6	55.7	60.9	70.5	76.4	102.2	30.5
FRANCISTOWN	439.1	86.0	64.6	73.6	87.3	86.8	112.4	97.8	40.7
GHANZI	401.4	129.5	67.4	68.7	98.2	78.6	81.5	103.4	40.0
MARALAPYE	478.4	97.3	55.3	83.8	75.7	99.1	80.9	106.2	32.9
GABORONE	516.7	65.9	56.6	70.2	54.7	95.0	88.8	112.0	28.6

This type of extremely intense rainfall results in rapid run-off and consequent concentration of water and hence often probably leads to periods of major replenishment.

Schalk (1961) recorded a maximum intensity of 489 mm in 12 hours near Uhlenhorst in South West Africa in an area with an average annual rainfall of 250 mm. During this storm an average of 400 mm of rain fell over an area of 116 km² or an average of 250 mm over an area of 944,6 km². An estimated 45 per cent or $106 \times 10^6 \text{ m}^3$ of water infiltrated as ground-water recharge.

Drought Frequency

Drought and hence thirst in both man and beast are common in Botswana and result in widespread famine and destruction of grazing land.

Pike (1971) gives the following annual drought frequency probability:-

Kasane	1 year in 20
Maun	1 year in 10
Ghanzi	1 year in 7
Francistown	1 year in 7
Mahalapye	1 year in 8
Gaborone	1 year in 15

A drought year is defined as one in which rainfall is less than 60 per cent of the mean annual rainfall.

Evaporation

Evaporation from open water surfaces varies from 1,7 to 1,9 metres per annum, with maximum daily rates up to 7 mm.
(Table 4)

TABLE 4

EVAPORATION - OPEN WATER mm

1958/59 - 1967/68

10 - Year Mean

STATION	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Seasonal TOTAL
KASANE	203.9	191.8	179.0	178.6	176.0	173.8	161.6	126.7	101.1	98.1	120.5	163.9	1877.1
MAJH	214.5	200.1	198.3	199.0	171.6	169.1	134.0	105.5	87.0	91.9	126.1	168.8	1860.0
FRANCISTOWN	215.5	204.4	201.2	203.3	177.9	179.8	135.5	104.9	78.4	85.0	124.1	171.1	1886.1
GHANZI	181.3	188.6	192.7	195.5	186.4	175.8	145.9	95.7	63.3	63.0	94.8	143.1	1726.1
MAHALAPYE	197.5*	198.5*	203.8	212.8	181.6	165.3*	123.9*	91.4*	68.0*	77.6*	109.6*	154.9*	1785.1*
GABORONE	196.1	200.7	210.9	214.1	179.5	160.7	112.6	80.2	58.6	59.0	100.9	149.4	1731.7

* 9 year mean only.

Past Climatic Changes

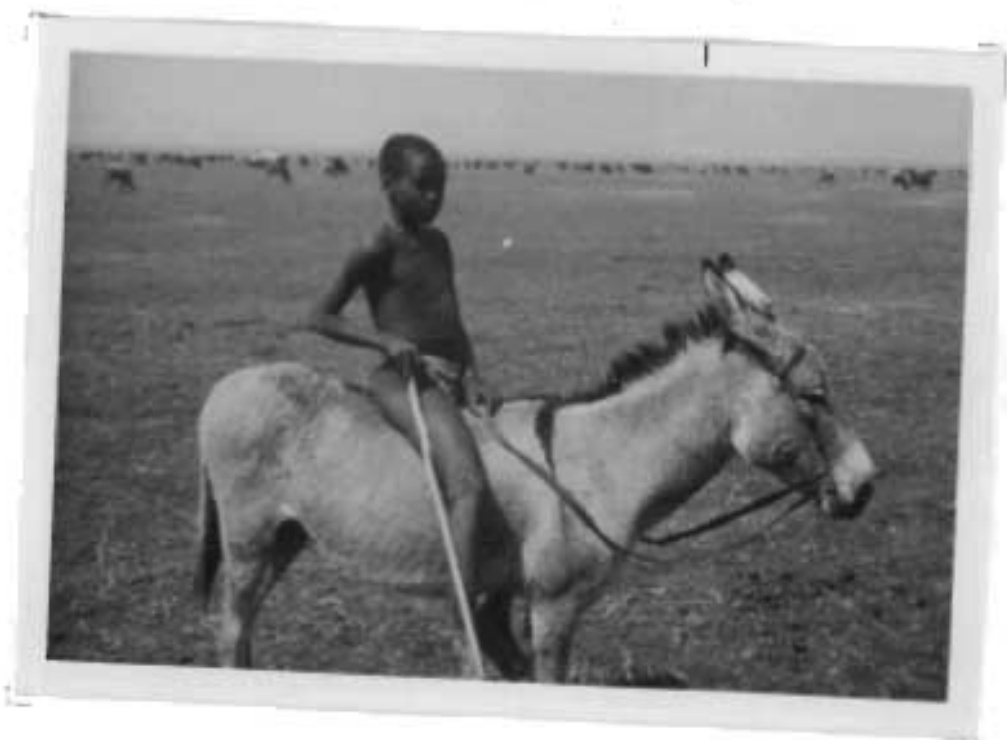
Wayland (1948, 1952, 1954) was the first to appreciate that the Kalahari climate had undergone great vicissitudes in the past and also recognised that these changes have had a marked influence on the underground water resources of the country.

Evidence cited by Wayland (1948) of climatic changes during relatively recent times was; that the hills of Botswana when viewed from a considerable distance appeared imposingly high, yet appeared to lose half their height when viewed from the base - this was due to gently sloping pediments leading up to the base of the hills. These conditions, indicative of desert climates, together with patches of wind-blown Kalahari sands, extend over a huge area extending as far north as Zambia, Angola and Zaire and indicate a far greater extent to a former great Kalahari desert. Dune features are also very widespread in Botswana, but except in the extreme southwestern parts of Botswana, are now invariably fixed by vegetation.

Other evidence of climatic changes quoted by Wayland (1948) are the numerous long dry river courses; the ancient cataracts of the lower Molopo River; the well-developed gravels with stone tools; the stalactites and stalagmites of Drotsky's cave (Plate 38) with later red wind-blown sands. Wayland (1948) also noted the presence of well-rounded boulder gravels underlying 21 metres of surface limestone which are in turn overlain by Kalahari sand. These gravels contain water worn implements derived from



Pl. 38 Stalactite, Drotsky's Caves - Kihabe hills.
(B.2).



Pl. 39 Lake Ngami flats - Underlain by Saline
Ground Water.

pre-existing gravels as well as implements later than the gravels.

Wayland (1948) concluded that the desert topography had taken millions of years to produce, but superimposed on this desert region were a number of wet climatic phases which could in all probability be related to the Glacial and Interglacial periods of the higher latitudes.

An examination of air photographs for the siting of water boreholes in Botswana, shows clearly defined former strand-lines up to 50 km west of the Makgadikgadi and of the present margin of Lake Ngami. In addition, the western northern and northwestern margins of a former vast lake occupying the Mababe Depression, are also very clearly discernable. These former vast lakes must surely have been formed during more humid periods, though suspected rift type faulting (Reeves, 1972) could in some cases have had a marked influence on the hydrography of the region. For example, movement of only a few metres along the presumed fault line forming the southeastern margin of the Chobe swamp from which the Savuti Channel takes off, could result in virtually the whole of the flow of the very large Chobe (Linyati) River being diverted into the former Mababe Lake. (A.5).

Recent important indirect evidence of climatic fluctuations has come about as a result of exploration for uranium in an area covered by Kalahari Beds in the south-central Kalahari.

Dalrymple (1972) states that minor uranium mineralisation present in the upper and middle Ecca Group of the Karoo Supergroup appears to be directly related to the position of the water table. As uranium has been detected up to 15 m above the present water table, this is regarded by the writer as important evidence of the lowering of the water table by this amount, since the period when the fossil drainage systems were active flowing rivers.

Effects of past Climates on Ground Water Supply in Botswana

Wayland (1948) was the first to recognise the influence of past climates on ground-water supply in Botswana and stated "past climates have had long range effects, some of which still affect the economy of our lives and even provide a threat for the future".

Wayland recognised three wet phases, of which the first was the most intense, separated by very long dry periods. These extremely dry periods were regarded by Wayland as undoing the good of the pluvial periods and were also regarded by him as being responsible for the prevention of any progressive results which the rains would have achieved, as far as ground water supplies are concerned.

In addition, the relatively short humid periods favourable for chemical weathering along joint planes have been insufficient for deep-seated weathering to take place and hence ground-water storage in joints is relatively limited. Another factor mentioned by Wayland which adversely affects ground-water supplies, is the sealing off of joints near the

surface by the precipitation of surface limestone. This not only prevents replenishment by present day rainfall but water from a previous pluvial below the sealed off surface layer will be gradually lost by transpiration, by hydration of certain minerals and by normal leakage.

Perhaps the most serious result, however, of past climatic fluctuations has been the concentration of saline groundwater beneath the former vast lakes of the Makgadikgadi, Mababe and Ngami and possibly southwest of the Okavango Delta, so that the chances of finding potable groundwater beneath any of these former large lakes covering areas of 34 000 km², 320 km² and 1000 km² respectively are regarded by the writer as being extremely remote. (Plate 39).

Soils

Van Straten (1959) was the first person to summarise available information on soils in Botswana. This work was revised later the same year by Van Straten and De Beer(1959). Further work was carried out by Bawden and Stobbs (1963), Bawden (1965), Blair-Rains and McKay (1968), Mitchell (1968) and Siderius (1972). The latter was the first to apply the modern concept of soil classification by using genetic soil horizons. (See Fig. 4).

The soils of Botswana may be divided into five main units. (After U.N.D.P. Map 1972). These are:-

1. Limpopo Unit

These soils consist of dark, red-brown, medium-textured soils of varying depth associated with dark coloured clayey soils and medium-to-fine-textured brown-grey mottled soils in depressions, with inclusions of lithosols in very sandy soils. The soils may be regarded as ferruginous.

These soils are largely derived from the pre-Kalahari age geological formations. Their distribution coincides closely with the Late Tertiary and Quaternary denudation surfaces.

2. Makgadikgadi Unit

These soils consist of brown and grey soils of medium-to-coarse texture, with inclusions of vertisols and other fine-textured clayey soils in depressions. These soils are often highly saline and alkaline and are associated with the large internal drainage basin of the Makgadikgadi Depression.

3. Kalahari Unit

These have the widest distribution of all soils in Botswana and consist of yellow, reddish-brown and grey usually deep soils of sandy texture. They are often underlain by calcrete with inclusions of dark coloured, fine-textured soils in depressions.

4. Chobe Unit

Soils in this unit consist of reddish-brown, yellow and grey sandy soils associated with medium-textured, reddish-brown soils, dark clayey soils and vertisols in depressions. The vertisols may be saline and alkaline.

5. Okavango Unit

Soils in this unit have varying textures associated with greyish-brown coarse-textured soils developed on the Kalahari sand and calcrete. These soils are often saline and alkaline.

Soils and their influence of infiltration

The medium-textured soils of the Limpopo Unit (1), which coincides with the eastern (Bushveld) physiographic region, favour rapid infiltration and hence ground water is regularly replenished and occurs at relatively shallower depth than in the Kalahari area.

The fine-grained sandy soils of the Kalahari unit (3) have long been regarded (See chapter on Recharge and Safe Yield) as preventing recharge of ground water where they exceed 9 m in thickness. As a result ground water supplies are often hard to obtain and are encountered at greater depth than in the Limpopo Unit. Isotopic studies have shown that in general, Kalahari ground waters are much older than in the east, but nevertheless the presence of measurable amounts

of carbon-14 and even tritium indicates geologically recent recharge. (See also Chapter on Isotopes).

GOVERNMENT OF THE REPUBLIC OF BOTSWANA
and
UNITED NATIONS DEVELOPMENT PROGRAMME

GENERALIZED SOIL MAP of BOTSWANA

EXPLANATION



- 1
- 2
- 3
- 4
- 5

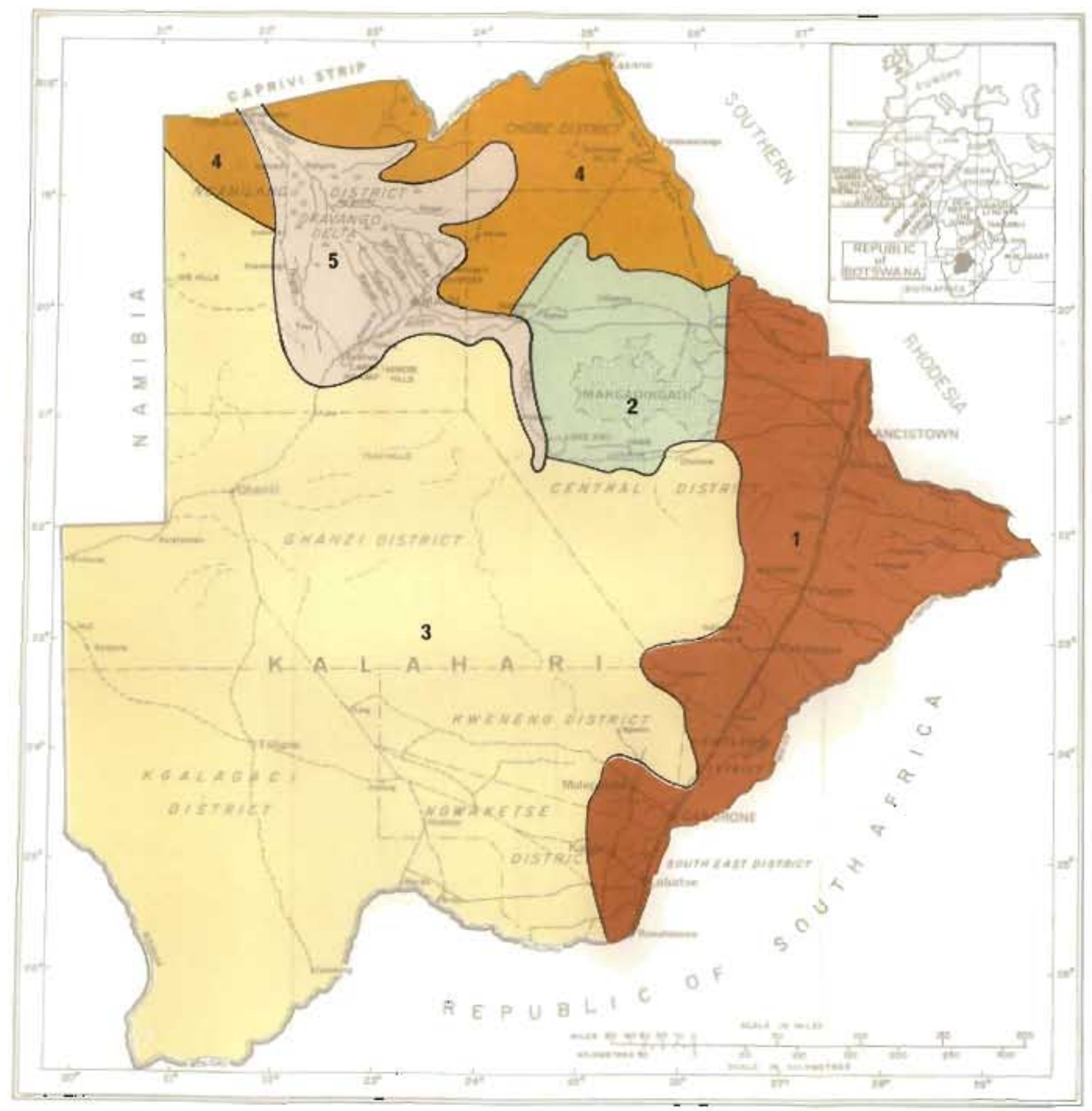
LIMPOPO UNIT: dark reddish-brown, medium textured soils of varying depth associated with dark coloured clayey soils and medium to fine textured brown-grey mottled soils in depressions, with inclusions of lithosols and very sandy soils.

MAKGADIKGADI UNIT: brown and grey soils of medium to coarse texture with inclusions of vertisols and other fine-textured clayey soils in depressions, often highly saline and alkaline.

KALAHARI UNIT: yellow, reddish-brown and grey usually deep soils of sandy texture often underlain by calcrete, with inclusions of dark coloured, fine textured soils in depressions.

CHobe UNIT: reddish brown, yellow and grey sandy soils associated with medium-textured, reddish-brown soils, dark clayey soils and vertisols in depressions; the latter often saline and alkaline.

OKAVANGO UNIT: alluvial soils of varying texture associated with greyish-brown coarse textured soils developed on Kalahari sand and calcrete, often saline and alkaline.



Vegetation

Pioneering work on vegetation in Botswana was carried out by De Beer (1962) who produced the first provisional vegetation map. This map was revised by Weare and Yalala (1972) and again by the United Nations Development Team (1972). A description of the main vegetation types and their distribution is given on Fig. 6.

Details of plants and their relationships to ground water are given in the chapter on phreatophytes.

CYCLIC DENUDATIONAL SURFACES IN BOTSWANA

Following the pioneer demonstration by Dixey (1938) that African landscapes could be widely interpreted in terms of denudational cycles, many local studies were made by Cahen and Lepersonne (1952), Mabbut (1955), McConnell (1956), Dixey (1942, 1955), King (1951, 1955), King and Fair (1954) and many others. The results of these were not always in harmony and in fact different ages for a single land-surface could be obtained when the surface was traced in different directions. This earlier confusion was partly due to the fact that researchers did not always appreciate the magnitude of earth movements that have deformed the various cyclic surfaces in relatively late geologic time (Pleistocene). This confusion has now been resolved by King and King (1959) and King (1962) and they have confirmed Dixey's (1942) view that the Highveld surface of the Transvaal is not of Gondwana age, but is due to planation in the early Tertiary culminating in the Miocene. (King's early Tertiary or African surface = Dixey's Miocene or mid-Tertiary peneplain).

Wayland (1948) was probably the first to remark that the hills of Botswana were perched on the apices of long, low-angle rises or pediments typical of desert lands. McConnell (1956) and Jennings (1970) have given detailed descriptions of the geomorphology of Botswana.

The landscapes of Botswana fall clearly into two contrasted types - erosional, wherein elevated areas become eroded

and are moulded under the pediplanation cycle (i.e. by scarp retreat and growth of pediments), and depositional.

Successive elevations relative to sea level will therefore result in new denudational cycles working their way progressively inland from the coast. The denudational surfaces can also be studied by mapping and section drawing. The study of depositional surfaces can be undertaken by stratigraphic study of continental type formations ranging in age from Karoo to Quaternary aided by borehole logs. "Borehole geomorphology", is a particularly valuable method in areas where terrestrial deposits are found.

CYCLIC DENUDATIONAL SURFACES

Two main cyclic erosional surfaces are clearly represented in Botswana (Fig. 3). These are:-

- (i) A high surface occurring at elevations of 1 128 metres to 1 341 metres, the eastern boundary coinciding roughly with Wellington's (1946) boundary between the Kalahari Basin (Region 1) and the Limpopo-Sabi Depression (Sub Region 6A). This scarp is also roughly coincident with du Toit's (1953) Kalahari-Rhodesia Axis. (This forms the divide between the Limpopo drainage and the endoreic drainage to the Makgadikgadi Depression). This surface can be traced without break from the Transvaal Highveld and is thus the African landsurface.
- (ii) An extremely well-planned surface occurring below the escarpment with occasional inselberg-like outliers of

the higher surface. This surface is undoubtedly polycyclic and can be correlated with the three Late Cainozoic surfaces 1, 2 and 3 found in Rhodesia (King, 1962). This was formerly known as the Victoria Falls or Coastal Plain Cycle.

McConnell (1956) regards the summit levels in southeastern Botswana at about 1 372 metres and 1 463 metres, e.g. Kanye (G.6), Lobatse (H.6) and Ootse (H.6), as belonging to cycles of a polycyclic Gondwana landscape while he correlates an intermediate surface at 1 280 to 1 311 metres with Mabbut's (1955) intermediate surface of end-Cretaceous age. A later widespread surface (African) dips westwards beneath the Kalahari sands.

The Tsodilo (A.2), Aha (B.2), Kwebe-Mabeleapudi hills (C.3) in northwestern Botswana are probably uneroded residuals of the African surface and are thus probably also of Gondwana age. North of Mamona (E.1) on the South West African border there is a magnificently planed erosion surface of probable post-Gondwana age standing at an elevation of over 1 280 metres. The scarp leading to this surface is 60 metres high.

The above dating is thus in accordance with Cahen and Lepersonne's (1952) and Mabbut's (1955) African surface, dipping eastwards beneath the deposits of the Kalahari on the western side of the continent. Similarly in the east the African surface dips westwards beneath sediments of the Kalahari. In the Serowe area (E.7) the Stormberg basalt at the top of the escarpment (overlain by silcrete and

Kalahari type sands), occurs at an elevation of about 1 250 metres. At Letlhakane (D.6), northwest of Serowe, this same surface has been downwarped to about 1 006 metres. In the south, the African surface west of Kanye dips gradually westward. This surface reappears along the Ghanzi ridge (D.2) in western Botswana.

The Early Tertiary Denudational Surface

The eastern boundary of the Early Tertiary surface runs to the south of Lobatse and thence past Kanye along the divide between the headwaters of the Molopo and Limpopo River systems.

At a point 14 km north of Kanye, the escarpment runs in a northwesterly direction and then swings due north some 24 km west of Moshupa. The escarpment in this region overlooks the headwater drainages of the Metsemotlhaba river. The scarp then swings in an east-northeasterly direction south of Molepolole (G.6) and then swings back to a point north-west of Molepolole whence it runs north-south and then north-east to link up with the Ramoselwana escarpment (F.7, silcrete overlying basalt). From Ramoselwana, the escarpment runs east-west and then in a semicircle round Suje (F.6) and then to the west and north-west of Lephepe (F.6, silcrete and sands capping basalt \pm 1 219 metres above sea-level). The scarp then trends in a northeasterly direction to link up with the Hukutswe scarp (E.7, silcrete containing gastropod fossils capping Cave Sandstone). The gastropoda are unfortunately of no use as regards dating the silicified deposits forming the base of the Kalahari beds. The scarp

from Hukutswe to Mashoro (E.7) is of classic form with a crest scarp, debris slope and pediments. From Hukutswe the scarp which is 91-122 metres high runs east-west and links up with the Shoshong hills (E.7) and with the Legatadimane hills (F.7) forming an outlying extension to the south. The maximum elevation in this area is 1 348 metres.

From the diabase capped hills in the Shoshong area the scarp can be traced in a northerly direction to the Kaliki area (E.7, 1 219 metres), where a thin capping of Kalahari type sands and silcrete overlies Basement Complex Granites. In the same general area the Early Tertiary cycle planes Ecca (Karoo Supergroup) sedimentary rocks.

An eastward promontory of the African cycle occurs in the Makhware hills (E.7), which reach a maximum height of 1 353 metres. Here erosion has bevelled quartzites and diabase (Shoshong Formation).

From west of Moijabana the escarpment swings in a great arc towards Serowe. Here the Loale and other rivers have cut back by headward erosion into the escarpment which forms the Loale Plateau 122 metres above the country to the east. The scarp in this region is locally either of Stormberg basalt or Cave Sandstone.

To the west of Serowe and northwards past Paje (E.7), an extremely well-defined break up to 152 metres high occurs between the Early and Late Tertiary erosional surfaces. (Plate 40). North of Paje the scarp suddenly swings westwards and then

north and later northeast as far as longitude 27°E where a silcrete capped scarp overlying Basement Complex limestone and granitic rocks occur. This scarp (137 metres high) overlooks the great plain excavated by the headwaters of the Motloutse River (D.7). (See Fig. 3).

The Late Cainozoic Denudational Cycles

This well-planed surface is to be found everywhere east (Plate 41) of the main escarpment which forms the boundary with the African surface (Plate 28). The Late Cainozoic surfaces consist of at least three separate cycles, the boundaries of which are generally not clearly defined except at Mochudi (G.7, Plate 42) and Palapye (E.8) where scarps separate the first and second cycles. These cycles have consequently not been differentiated on the accompanying map. (Fig. 3).

This cycle is also represented by valley incision of the Molopo, Okwa, Boteti and Nata River (C.7) systems elsewhere in Botswana.

Depositional Cycles

Following the disruption of Gondwanaland a cyclic series of upwarps inland from the Continental margins resulted in tilting towards a central Continental depression (the Kalahari), and as a result, sediment from the surrounding higher land accumulated, with a thickness of up to 198 metres in the area immediately north of the Molopo River. Elsewhere the Kalahari Beds in Botswana seldom exceed 60 metres in thickness. However, recent drilling, gravity and



Pl. 40

Escarpment North of Serowe separating "African
from Late-Tertiary surface.

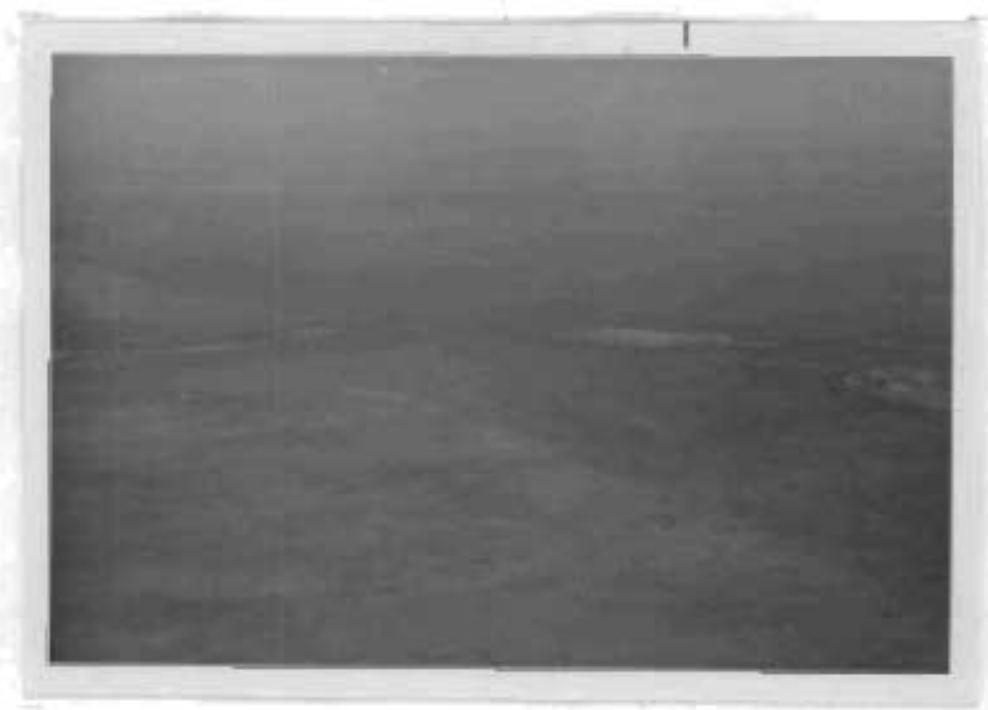


Pl. 41

Aerial view of Late-Tertiary surface S. of
Francistown.



Pl. 42 Scarp separating Late-Tertiary surfaces -
Mochudi. (G.7).



Pl. 43 Former strandline (50 km west of Makgadi-
kgadi) cut by Boteti River. (C.5).

resistivity work in the Okavango swamp area, had indicated a very considerable thickness of Cainozoic beds possibly thousands of metres thick.

In the Molopo area, the succession consists of gravel (calcreted), overlain by marl, sand, silcrete, calcrete and younger sand. In the central Kalahari, the gravels and marls are usually absent. No attempt has been made to correlate the depositional cycles with the denudational surfaces, as no diagnostic fossils have been found in the Kalahari Beds to date.

Relationship Between Erosion Cycles and Water Table

Marked differences are present in the depth to the water table on different denudational surfaces, with depths to water increasing progressively with older surfaces.

Geomorphological History

Following erosional periods in pre- and intra- Karoo times, a number of cycles of erosion probably took place during Jurassic, Cretaceous and early Tertiary times. The latest cycle has at present by far the greatest extent and perfection of bevelling.

Following the early Tertiary cycle of erosion, uplift in the form of gentle upwarping (roughly along du Toit's (1953) Kalahari-Rhodesia axis) occurred. This initiated a new cycle of erosion, active during Late Tertiary times, to the east of the axis with a corresponding phase of deposition of debris occurring west of the axis of uplift in the Kalahari and culminated in a period in which the Kalahari was reduced to an arid sandy desert. Similar warping also took place on the South West African side of the Kalahari Basin.

Depositional phases also appear to have occurred on the Late Cainozoic pediplain which still has remnants of sand and calcrete lying on this surface in a number of places. West of Palapye, sands and sandy calcrete with pebbles of basalt and silcrete form a superficial deposit up to 33 metres thick.

The basalt and silcrete pebbles appear to be of fluvial origin with a possible later aeolian redistribution of the red sands. The nearest basalt outcrop (capped by silcrete) occurs on the escarpment some 50 kilometres to the west. The

uppermost red sands carry Stone Age implements in the Serowe and other areas (Wayland, 1954 and McConnell, 1959). These sands are thus of Pleistocene age.

The age of the silcrete forming the base of the Kalahari beds must therefore be Miocene or Pliocene, as the silcretes overlie the Early Tertiary erosional surface and are older than the implementiferous Pleistocene sands.

In the Kalahari Basin, evidence of further climatic oscillations of earth movements is afforded by the now fossil river valleys, such as Letlhakane, Letlhakeng, Okwa, Buitsivango and Molopo system, which have cut down through Kalahari beds. In the Okwa valley, a number of distinct terraces can be discerned, the lowest of which contain artefacts while they appear to be absent from the highest terrace. Very clearly defined former lake shorelines (strandlines) can be found in the Mababe area, west of Lake Ngami and west of the Makgadikgadi. (Plates 43, 44).



Pl. 44 Old strandline west of Sua Pan, Makgadikgadi.
(C.6).



Pl. 45 Losi migmatite. (F.7).

THE GEOLOGY OF BOTSWANA

Botswana is underlain by a varied assemblage of geological formations ranging in age from early Pre-Cambrian to Recent. Most of the older formations crop out in the eastern part of Botswana, while the central part of Botswana is mainly blanketed by Kalahari Beds. Older rocks crop out again in the northwestern part of Botswana. Rock types range from ultramafic to felsic intrusives and extrusives; highly metamorphosed igneous and sedimentary rocks, and unmetamorphosed sedimentary types such as shale, mudstone siltstone, sandstone grit and limestone. (See Figs 7 and 8).

The following formations are present in Botswana:-

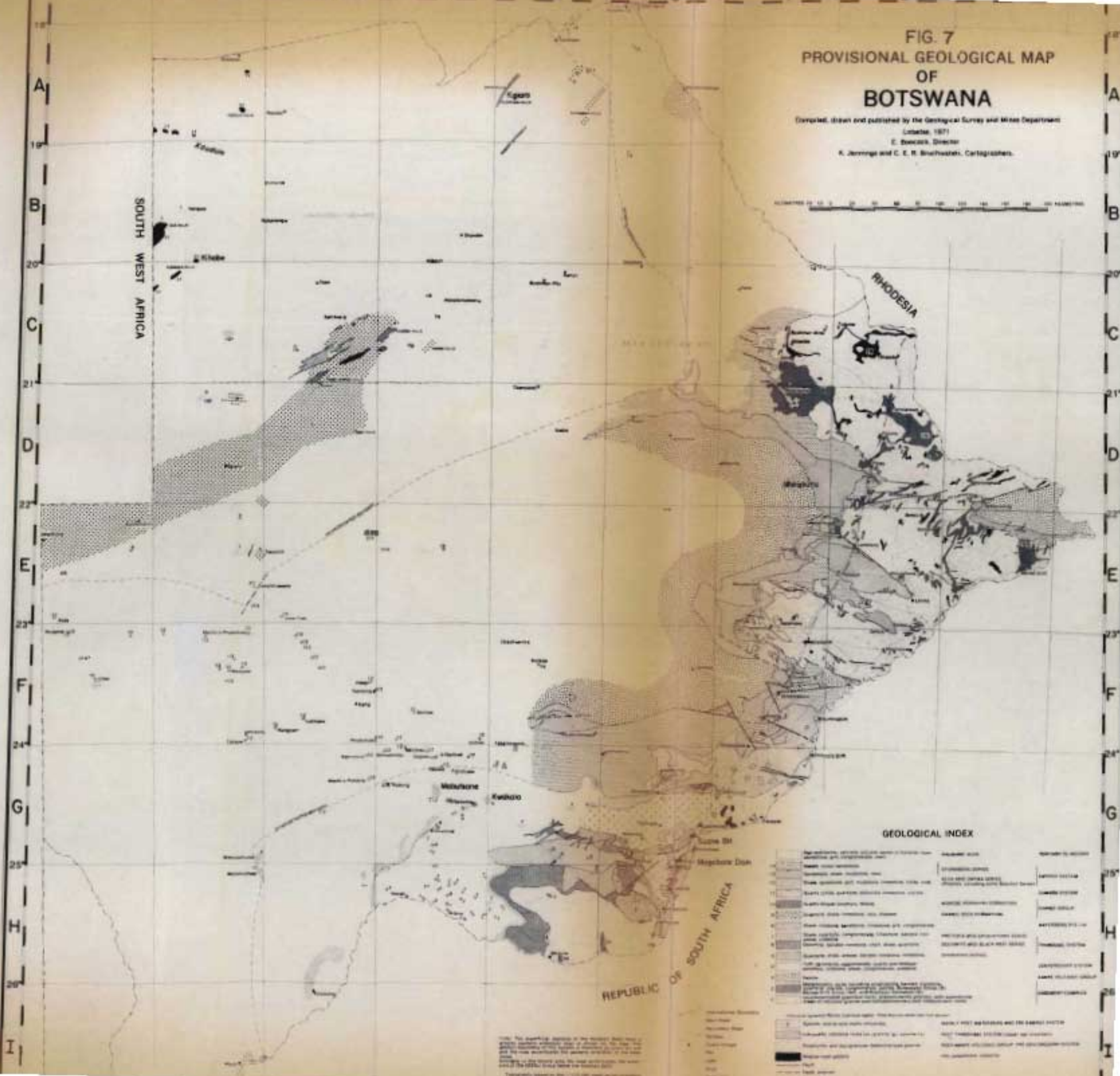
Table of Geological Formations

MESOZOIC TO RECENT	KALAHARI GROUP	Calcrete, silcrete, ferricrete, sands of Kalahari type, sandstone conglomerate, marl
KAROO SUPERGROUP	{ STORMBERG GROUP	Basalt, sandstone, shale, mudstone, marl
	{ ECCA GROUP	Shale, mudstone, sandstone, grit, limestone.
	{ DWYKA GROUP	Tillite, shale, sandstone
DAMARA SUPERGROUP		Quartz-schist, biotite schist, quartzite, dolomitic limestone, marble
	GHANZI GROUP	Shale, limestone, quartzite, diabase, quartz feldspar, porphyry, felsite
WATERBERG SUPERGROUP		Shale, siltstone, sandstone, grit, conglomerate, limestone, lava.

	} <ul style="list-style-type: none"> PRETORIA AND GRIQUATOWN GROUPS DOLomite GROUP BLACK REEF GROUP 	Shale, siltstone, conglomerate, limestone, banded ironstone, andesite
TRANSVAAL SUPERGROUP		Dolomite, banded ironstone, chert, shale, quartzite
		Quartzite, shale
?	SHOSHONG GROUP	Quartzite, shale, arkose banded ironstone, limestone
VENTERSDORP SUPERGROUP		Tuff, ignimbrite, agglomerate, shale, quartz and feldspar porphyry, siltstone, shale, conglomerate, andesite
	KANYE VOLCANIC GROUP	Felsite
BASEMENT COMPLEX		Metamorphic rocks including amphibolite, banded ironstone, schist, quartzite, marble, conglomerate, granitoids
<u>INTRUSIVES</u>		
Post-Karoo		Karoo dolerite
Post-Waterberg and pre-Karoo Supergroup		Syenite, diorite and diabase
Post-Transvaal Supergroup		Ultramafic intrusives, granite, syenite
Post-Kanye Volcanic Group, pre-Ventersdorp Supergroup		Gaborone-type granite
Pre-Gaborone granite		Modipe-type gabbro

FIG. 7
**PROVISIONAL GEOLOGICAL MAP
 OF
 BOTSWANA**

Compiled, drawn and published by the Geological Survey and Mines Department
 Lobatse, 1971
 E. Swickard, Director
 K. Jennings and C. E. B. Bruchwiler, Cartographers.

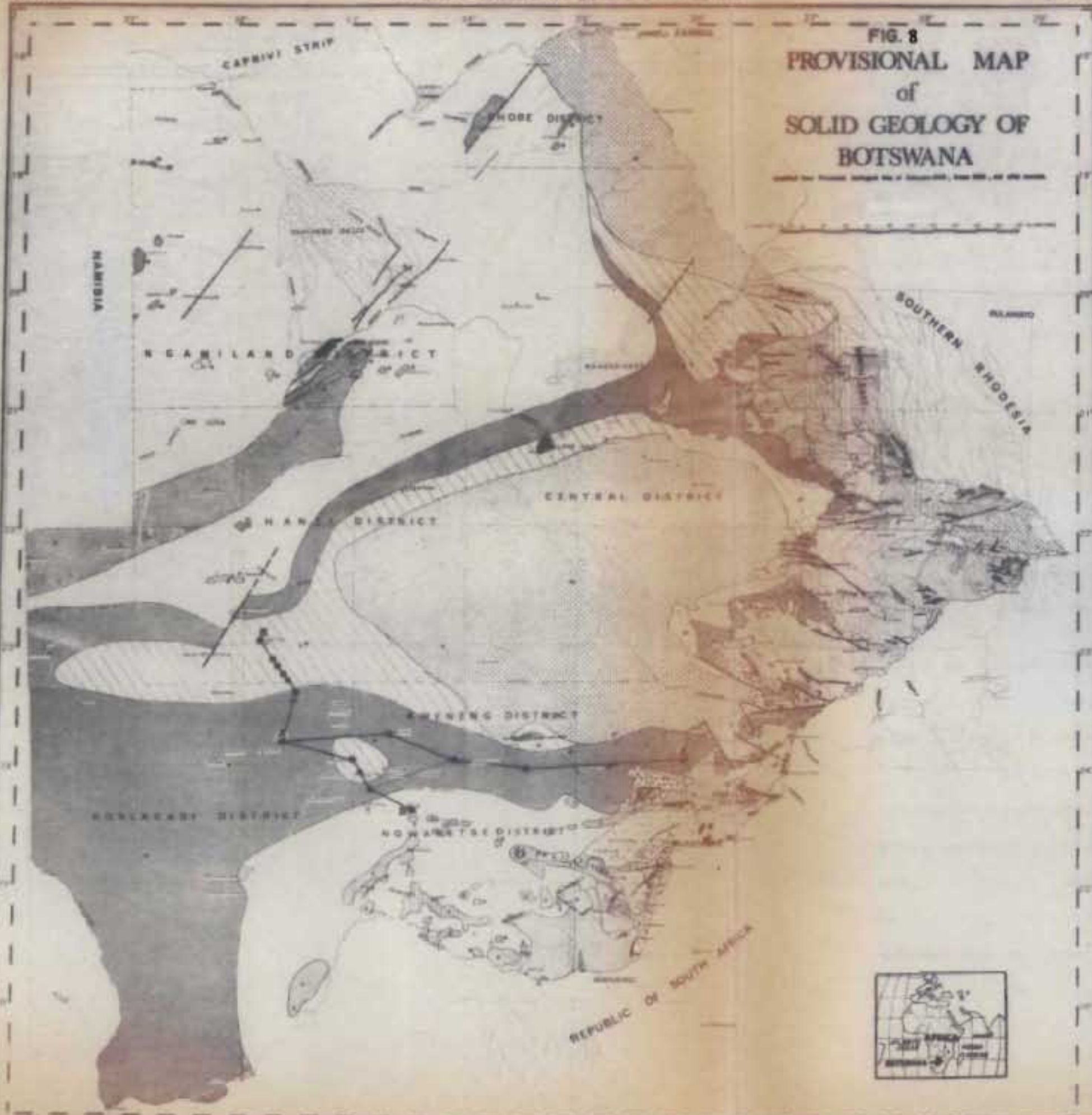


GEOLOGICAL INDEX

Pre-Cambrian rocks (granite, gneiss, schist, etc.)	Quaternary deposits (alluvium, etc.)	Unconformity
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)
Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)	Beaufort Group (sandstone, shale, etc.)

This map is a preliminary geological map of Botswana and is not intended to be used as a basis for any legal or administrative action. It is based on the geological survey of Botswana conducted by the Geological Survey and Mines Department from 1960 to 1970. The map is published by the Geological Survey and Mines Department, Lobatse, Botswana, 1971.

FIG. 8
PROVISIONAL MAP
of
SOLID GEOLOGY OF
BOTSWANA

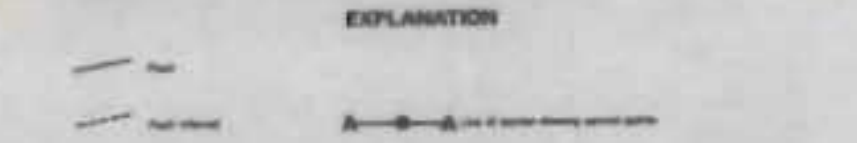


GEOLOGIC UNITS

19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]	[Symbol]
19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

EXPLANATION

[Symbol]	[Symbol]	[Symbol]	[Symbol]
[Symbol]	[Symbol]	[Symbol]	[Symbol]
[Symbol]	[Symbol]	[Symbol]	[Symbol]
[Symbol]	[Symbol]	[Symbol]	[Symbol]



BASEMENT COMPLEX

Rocks of the Basement Complex assemblage crop out over extensive areas in Eastern Botswana. They occupy a number of discrete areas north of Mabule in the upper Molopo River; crop out along the Limpopo River from near Gaborone to Olifant's Drift; and are present over a vast area in the eastern portion of the Central and the whole of the North East Districts. Isolated inliers occur south of the Ntwetwe and Sua sections of the Makgadikgadi; along the Okwa Valley south of Ghanzi; and north of the Aha Hills and in the vicinity of the Xangwa spring.(B.2).

The Basement Complex is comprised of a complex assemblage of early pre-Cambrian, Archaean metamorphic rocks, including varied gneissic, granitoid and granitic rocks which are areally predominant, with associated major belts and more minor remnants of metamorphosed mafic and ultramafic intrusive and extrusive rocks and metasedimentary rocks.

Two major geotectonic domains can be recognised in the Basement Complex of northeastern Botswana. These consist of ancient, stable cratonic nuclei ("the cratons"), traversed by younger highly metamorphosed and granitised "mobile" or "orogenic" belts. Although these orogenic belts tend to encircle the cratonic areas, they nevertheless form an integral part of the crystalline shields. Within Botswana, the Limpopo and Shashe orogenic belts which are characterised by high grade metamorphism, are surrounded by Archaean cratonic areas characterised by greenschist to

.... / amphibolite

amphibolite facies of metamorphism. The cratonic areas contain "schist belts" consisting predominantly of meta-volcanic and metasedimentary rocks, surrounded by extensive areas of granitic rocks. The distribution of the main "schist belts" is shown on the accompanying geological map (Fig. 7).

The Limpopo Belt has an east-northeasterly trend and extends from beneath the younger cover of Karoo sedimentary rocks across northeastern Botswana, through the southern part of Rhodesia into Mozambique.

Plate 45 shows migmatitic rocks at Losi quarry near Mahalapye (F.7).

Plate 46 shows a sheared Basement Complex conglomerate northwest of Matsitama (C.7).



Pl. 46

Basement Complex conglomerate.



Pl. 47

Venteradorp shale with Botswanaella.

KANYE VOLCANIC GROUP

Rocks assigned to the Kanye Volcanic Group extend in an arc commencing from some 60 kilometres northwest of Kanye in the west, through Kanye southeastwards to south of Pitsane and thence northwards to south of Gaborone. A second belt extends eastwards from Molepolole to just west of Mochudi. An isolated inlier occurs 60 kilometres west of Molepolole in the vicinity of Kgari Hill.

The group consists mainly of felsitic lavas and tuffs. The felsites are generally massive, fine-grained, closely jointed rocks. They vary in colour from black to grey or purple. There is generally a gradual transition from the typical felsites forming this Group to the true mobilised Gaborone granite.

These rocks probably represent original rhyolitic lavas and silicic tuff but most signs of lithological differentiation have been suppressed as a result of recrystallisation and low grade metamorphism associated with later thermal events. The felsites have a quartzo - feldspathic composition with approximately equal quantities of soda and potash feldspar present. Magnetite and amphibole occur in accessory quantities (Crockett, 1970).

VENTERSDORP SUPERGROUP

The Ventersdorp Supergroup, which has an age of about 2 300 m.y. (Snelling & Rex, 1967), consists of a variable thickness of siliceous pyroclastic rocks and argillaceous sedimentary rocks. They occur in a belt surrounding the rocks of the Transvaal System in southeastern Botswana and south and west of Kanye.

Crockett (1971) has divided the Ventersdorp Supergroup into three assemblages. The Lower Volcanic Assemblage, consisting of siliceous and potash-rich volcanic rocks of both flow and pyroclastic origin. The overlying Mogobane Assemblage consists mainly of argillites, shales and siltstones with some conglomerate and sandstone. The Upper Volcanic Assemblage consists predominantly of andesitic lavas.

Plate 47 shows Ventersdorp shale with Botswanella, a bacteria produced concretion.

THE TRANSVAAL SUPERGROUP

Rocks of the Transvaal Supergroup have an age of about 2 000 m.y. (from indirect dating only) and crop out in two main separate areas in southeastern Botswana, where they form the western edge of the main Transvaal Basin, and in southern Botswana where an extensive area is underlain by Transvaal rocks. These form the northward continuation of the Northern Cape Basin. This latter basin is largely concealed by Kalahari Bed cover but extensive drilling for water in the farming area north of the Molopo River has now proved that a large part of this vast area is underlain by Transvaal Supergroup sedimentary and volcanic rocks. Minor outcrops are also present between Molepolole and Mochudi. The Shoshong Group west of Mahalapye may be a correlate of the Transvaal Supergroup. (Pl.48). Boocock (1961), Crockett (1969) have given detailed accounts of the Transvaal Supergroup in Botswana.

The Transvaal Supergroup may be up to 6 000 metres thick. It overlies unconformably, rocks of the Ventersdorp Supergroup or the Kanye Volcanic Group.

The Transvaal Supergroup has been divided into three groups. These are the Black Reef Group, the Dolomite Group, and the Pretoria Group, which consists of a cyclic alternation of argillaceous and arenaceous rocks with an interbedded volcanic horizon.

Black Reef Group

The Black Reef Group unconformably overlies the Ventersdorp Supergroup, the Kanye Volcanic Group or Basement Complex rocks



pl. 48

Banded ironstone (Shoshong Group).



pl. 49

Waterberg conglomerate - Tswane. (E.2).

and generally consists of thin pale-coloured quartzitic sandstone with minor intercalated argillaceous beds. A basal conglomerate is sometimes present. The maximum recorded thickness is less than 30 metres thick.

Dolomite Group

The Dolomite Group consists of a very thick succession of dolomitic limestones and limestones which contain massive chert horizons towards the top. Intercalated shale, quartzite and shaly dolomite have been noted, but constitute only a very minor portion of the whole succession. Stromatolitic and oolitic beds occur at numerous horizons in the succession. Ferruginous red and brown shales overlie the dolomitic rocks in the Lobatse area and form the highest member of the Dolomite Group. In the Northern Cape Basin the dolomite is overlain by banded ironstone, which on the farm Knapdaar, immediately north of the Molopo River, is estimated to be 200 m thick. East of Lobatse in the Linokana area of the Republic of South Africa, the ferruginous shales grade laterally into banded ironstone. Other isolated outcrops of banded ironstone are present at Yaaneng, Moteoji and Oki hills in southern Botswana. (H.4).

Pretoria Group

Timeball Hill Formation

A chert conglomerate of possible glacial origin known as Bevet's Conglomerate, forms the lowest member of the Timeball Hill Formation. Overlying this is a succession of shale overlain by the thin, sugary Polo Ground Quartzite horizon and then a succession of shales until the main reddish-brown Timeball

Hill quartzite is reached. This resistant band generally forms prominent hills.

Daspoort Formation

This consists of shale with the contemporaneous Ongeluk (andesitic) lava, normally underlain by chert conglomerate frequently with a thin quartzite band. Shale of variable thickness overlies the lava followed by the Daspoort quartzite which may have a lower and an upper ferruginous band.

Magaliesberg Formation

This consists of shale with a dolomitic limestone horizon in the upper third of the shale succession capped by quartzite which may form three separate quartzite bands or may coalesce to form a single band. The quartzite is generally hard and white, but towards the top of the stage may become a soft, friable, medium- to coarse-grained sugary sandstone.

Smelterskop Formation

This stage consists of an alternation of argillaceous and quartzose beds which generally form lower ground than the more resistant Magaliesberg quartzites. Conglomerate beds are also present in the Lobatse area. Several boreholes on Lobatse Estates have penetrated this stage and have revealed the presence of considerable amounts of pyrite in the shaley beds.

Intrusives

Intrusive dykes and sills of diabase are common in the Pretoria Group. In the Northern Cape Basin a large positive

gravity anomaly has been found to be due to intrusive mafic and ultramafic rocks.

WATERBERG SUPERGROUP

Rocks of the Waterberg Supergroup are present in the Tsabong (I.3) area in the southern Kalahari and extend in a great arc north-northwestwards to the west of Khakhea, then north-eastwards through Mabutsane and thence eastwards past Ditlhako, Jwana, Molepolole to Mochudi and into the Republic of South Africa. These rocks form an unbroken link between the Matsap Beds of the northern Cape Province and the Waterberg Supergroup of the Transvaal. A further area extending for 100 kilometres west of Kanye in southeastern Botswana, (G.6) is underlain by Waterberg Supergroup sedimentary rocks and has been traced in boreholes further westwards until it links up with the Waterberg Supergroup west of Khakhea (G.4). Waterberg Supergroup sedimentary rocks are also present near Ootse, north of Lobatse, where they form impressive hills and west of Gaborone where they form thin cappings to the hills. Further extensive outcrops are present forming a discontinuous range of hills extending from north-east of Serowe, southeastwards past Palapye and Moeng (Chwaping Hills) to Lerala (E.8). A parallel range extends from west of Mokoro siding to Sefare and Selika in the Central District.

The Waterberg System has been described by Cullen (1958, 1960), Boocock and van Straten (1962), Jones (1963, 1965, 1966), Green (1963, 1965), Jennings (1963, 1965). Crockett and Jennings (1965) have remarked on the marked lithological similarity between the coarse-grained purple quartzite with conglomerate bands of the older Sedimentary and Volcanic

Formation in the Okwa Valley near Tswane (south of Ghanzi in northwestern Botswana) with rocks of the Waterberg System in eastern Botswana. (Plate 49, E.2).

The Waterberg Supergroup varies from a few metres in thickness to several hundreds of metres. The succession comprises essentially arenaceous and rudaceous terrestrial sedimentary rocks consisting of coarse boulder conglomerates, conglomerates, coarse-grained feldspathic grit and sandstone, quartzitic sandstone or quartzite. Pebbly bands with pebbles of vein quartz and rounded jasper inclusions are characteristic of the Waterberg arenites. Flagstone sandy shale, shale and siltstone may also be present. These finer-grained clastic rocks generally overlie the coarser sandstones and conglomerates.

The rocks of the Waterberg Supergroup are of late Precambrian age and have been dated by indirect methods, in the Republic of South Africa at about 900 m.y.

They are unfossiliferous and unmetamorphosed, except locally where diabase dykes and sills have metamorphosed the shales to dense hard hornfelsic rocks which break with a conchoidal fracture. Contact minerals include cordierite, feldspar, staurolite and sillimanite, while in places recrystallisation has resulted in micrographic intergrowths of quartz and feldspar.

The Waterberg Supergroup rests with an unconformable contact on older formations (Transvaal Supergroup west of Kanje and near Ootse, Kanye Volcanic Group, Ventersdorp Supergroup), whilst further north it rests on the Basement Complex.

GHANZI GROUP

The Ghanzi Group is confined to northwestern and northern Botswana. It has been subdivided into a Ghanzi Beds Formation and an older Kgwebe Porphyry Formation, which forms a belt in the centre of the Ghanzi Beds Formation outcrop area.

Rocks of this Group are present continuously along a northeasterly trending belt extending from Mamono on the South West African border in western Botswana to the Lake Ngami area. Low groups of hills comprising the Tsao and Haina (Dinokwana) hills protrude through a thick sand-covered tract to the east of the main zone of outcrop. The presence of rocks of this group beneath Kalahari Beds has also been proved by water boreholes south and southeast of Maun and west of Makalamabedi and they probably extend northeastwards to link up with outcrops in the Shinamba Hills and Ngwezumba Valley areas in northern Botswana. Further northeast, they are overlapped by Stormberg Group (Karoo Supergroup) lavas. The Gubatsaa -Goha line of hills of quartz porphyry stretch from the western edge of the Mababe Depression to the northeastern edge (Plate 20). These are identical in appearance and metamorphic fabric (i.e. strongly cleaved) to the porphyries forming the Mabeleapudi, Ngwenalaku, Kgwebe range of hills southeast of Lake Ngami and which together with minor diabase, sandstone, grit and conglomerate, form the Kgwebe Porphyry Formation. The porphyry is generally reddish in colour and may show flow textures. The porphyry from the Kgwebe Hills has been dated at 895 ± 35 m.y., while that from the Goha Hills was dated at 960 ± 50 m.y.

The Ghanzi Formation consists of fine-grained brown, reddish-brown, purple and grey calcareous and feldspathic quartzitic sandstone and quartzite, marly shale, shale and grey limestone. These rocks generally dip at steep angles and have a marked NE-SW lineation and fracture cleavage.

The Kgwebe Porphyry Formation appears to have formed a core to the surrounding, strongly isoclinally folded, Ghanzi Formation sedimentary rocks (Thomas, 1969).

DAMARA SUPERGROUP

Rocks assigned to the Damara Supergroup form isolated inliers in the Ngamiland District, west of the Okavango Swamps. These rocks form some of the most prominent hills in Botswana, where they crop out to form the Tsodilo (Plate 21) and Aha Hills. The Koanaka-Kihabe Hills (Plate 50) also form a low but impressive rib of hills in an otherwise completely featureless plain.

The rocks in the Aha - Koanaka hills consisted of highly foliated dolomitic limestones, which can be correlated with similar dolomites of the Outjo facies of the Damara Supergroup in the Tsumeb-Otavi areas of South West Africa. In the Aha Hills area, the Damara Supergroup overlies unconformably Basement Complex granitic rocks which crop out just north of the hills.

Along the Xaudum poorly exposed calcareous siltstone, marly shale, limestone and quartzite occur. (A.2).

The Tsodilo Hills consist of micaceous and ferruginous quartzites.

Air photographs of the area south of the Aha Hills show that the Damaran rocks have been folded into closed anticlinal and synclinal structures. Elsewhere these rocks are covered by sands of Kalahari type, which show pronounced linear dune features.

Mafic lavas encountered in two core boreholes drilled southwest of Maun and now altered to epidosite, are

.... /probably

probably the equivalent of the volcanic and pyroclastic upper portion of the Nosib Formation, which underlies the youngest Abenab Stage of the Damara Supergroup in northern South West Africa.



Pl. 50

Dolomitic limestone - Koanaka hills. (C.2).



Pl. 51

Cave sandstone.

KAROO SUPERGROUPDistribution

Rocks of the Karoo Supergroup dating from Late Carboniferous to Liassic, cover a large area of Botswana. They occur in an extensive sedimentary basin, which extends N.E.-S.W. through the central Kalahari and parts of eastern Botswana linking up with the Karoo Supergroup of the northern Cape Province in the southwest, of South West Africa in the west and of Rhodesia in the northeast. An easterly extension of the Karoo Supergroup in Botswana extending eastwards from between Dibeets and Mamabule links with the Karoo Supergroup of the Waterberg Coalfield in the Transvaal. An isolated outcrop area in the extreme east of Botswana, west of the Shashe-Limpopo Rivers confluence links with the Karoo Supergroup rocks in the northern Transvaal and the southern part of Rhodesia (Tuli trough). The distribution of the Karoo Supergroup is shown in Figs. 8 and 9. Much of the knowledge concerning the known distribution of the Karoo Supergroup has resulted from extensive drilling programmes for water in the sand-covered Kalahari area.

Previous Work

Early work on the Karoo Supergroup in Botswana was carried out by Passarge (1904), Molyneux (1903, 1907), Lamplugh (1907), Rogers (1907, 1935), du Toit (1916), Maufe (1922) and MacGregor (1930).

More recent descriptions have been given by Poldervaart (1950), Green and Poldervaart (1952), Wright (1958), van Straten (1959), Green (1957, 1958, 1961, 1963(a), 1965(a), 1969), Boocock and van Straten (1962), Gerrard (1963),

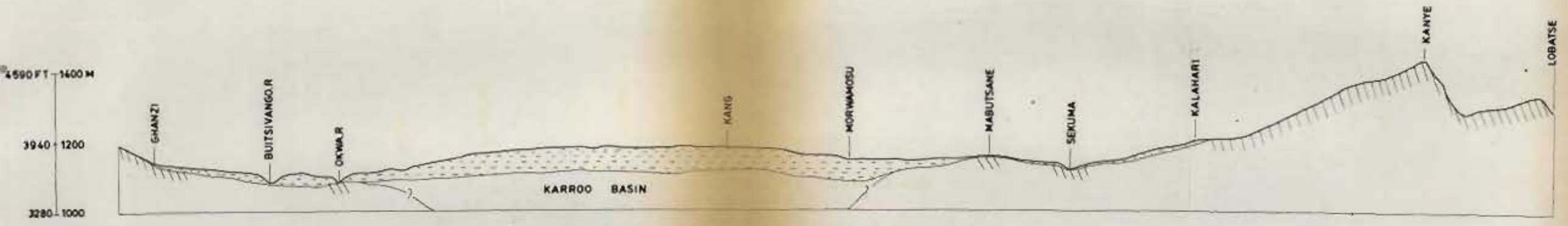
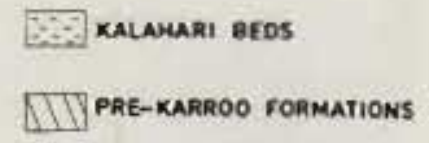


FIG 9 SECTION ACROSS KALAHARI GHANZI TO LOBATSE



Jennings (1963, 1965), Crockett (1965), Mason (1967), Jones (1968), Thomas (1969), Bennett (1970), Stansfield (1970).

The most comprehensive account of the Karoo Supergroup in Botswana as a whole has been given by Green (1966).

Stratigraphy

Because of the paucity of exposures in Botswana and a consequent dearth of palaeontological evidence, subdivision of the Karoo Supergroup has largely been based on lithostratigraphic evidence. The remarkable uniformity of the Karoo Supergroup over huge areas has enabled correlations to be made with type areas in the Republic of South Africa.

GENERALISED STRATIGRAPHIC TABLE OF THE KAROO SUPERGROUP (After Green 1966)

Lithostratigraphic Sub-Division	Maximum Known Thickness	Designation	
Purple, grey or black massive to amygdaloidal basalt	1315'	Drakensberg Lava Formation	} Stormberg Group
Orange, reddish or white aeolian sandstone	483'	Cave Sandstone Formation	
Mottled, reddish and green mudstone, marl and calcareous sandstone	228'	Red Beds Formation	
Feldspathic sandstone and grit	50'	Molteno Beds Formation	
Grey or pale reddish and green, non-carbonaceous mudstone	440'	Not subdivided	} Beaufort Group
Carbonaceous mudstone and coal	452'	Upper Formation	} Ecca Group
Feldspathic sandstone, coal mudstone	540'	Middle Formation	
Fine-grained siltstone and sandy shale with some sandstone	304'	Lower Formation	

Ecca Group

The Ecca Group has been subdivided into a Lower, a Middle and an Upper Formation. The Lower Formation is apparently of rather restricted development with sedimentation restricted to isolated basins, whereas the Middle and Upper Formations were laid down over far more extensive areas. There is a considerable amount of evidence to indicate that the Ecca Formation was frequently deposited on a very uneven land surface, which, in the area south of Serowe, towards the Makhware Hills, has a relief probably exceeding 300 m. Other areas where a considerable amount of pre-Karoo relief has been proved, are west of Letlhakeng, where a line of core boreholes drilled as part of a hydrogeological research programme encountered Waterberg Supergroup sedimentary rocks within an area of the Ecca Group (Bh 1130 Ditlhako, Fig. 10). Kgari hill (felsite) south of Letlhakeng, (G.5) probably reflects a resurrected pre-Karoo surface while there is much coincidence of moderate pre-Karoo relief west of Seruli in the Central District. (D.8).

The Lower Ecca Formation consists mainly of siltstone and sandy shale.

The Middle Ecca Formation, consisting of medium- to coarse-grained feldspathic sandstone and grit, which is sometimes pebbly, coal and mudstone, has a wide distribution in Botswana.

Overlying the yellow, white or cream coloured feldspathic sandstones of the lower part of the Middle Ecca Formation, is a succession of coal, shale and mudstone. Van Stratén (1959) has subdivided this succession in the Morapule area

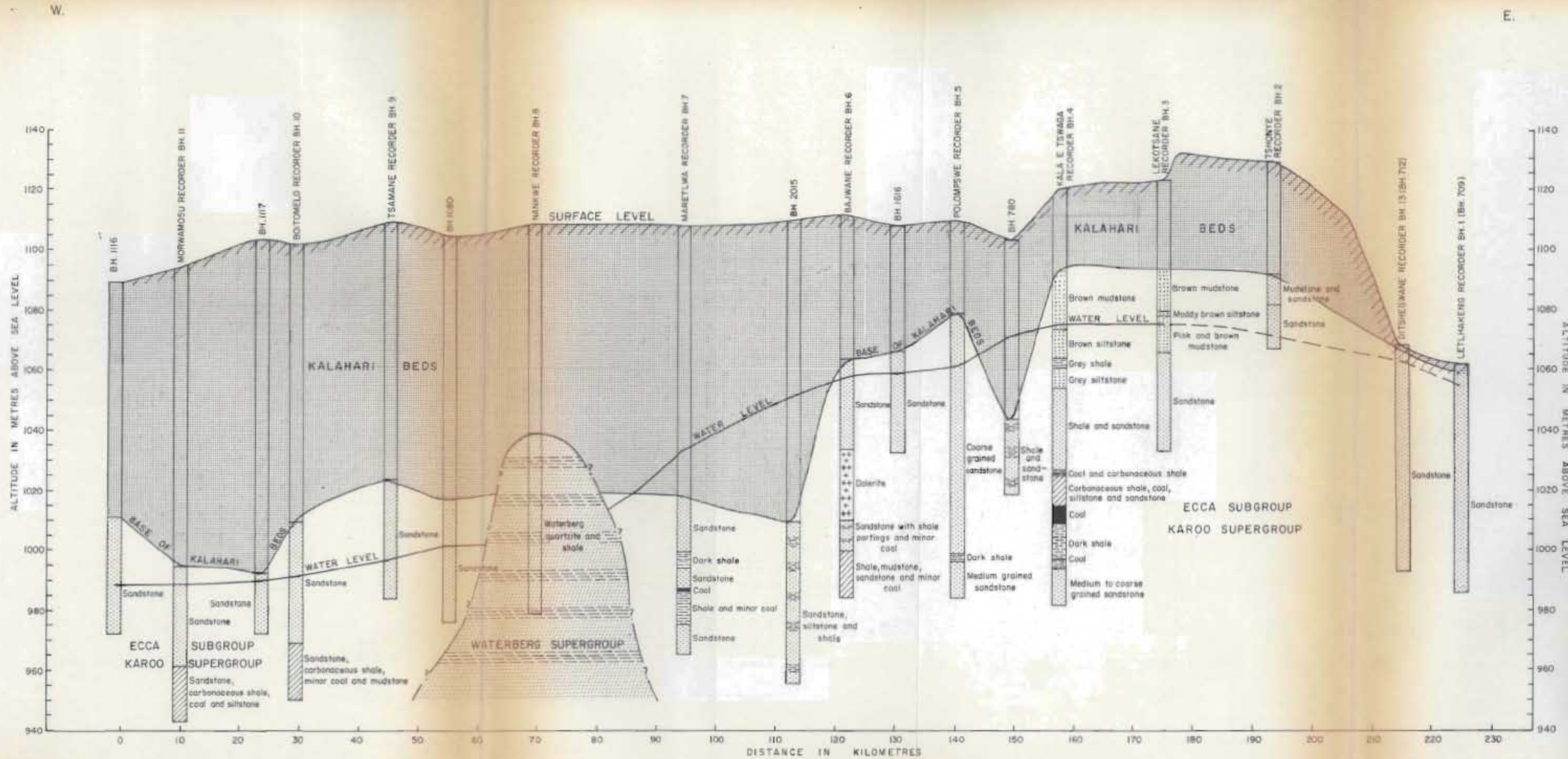


Fig. 10 HYDROGEOLOGICAL SECTION ACROSS CENTRAL KALAHARI RESEARCH AREA

into 3 zones with the "Basal (Coal) Zone", which has a remarkable thickness of coal varying from 4,6 to 9 m, being the most important economically. This is overlain by black shale and a pale-coloured siltstone "marker horizon". Following the practice adopted in the Waterberg coalfield of the Transvaal, the highest sandstone band and hence the "siltstone marker" horizon has been taken as defining the top of the Middle Ecca Stage.

Further south, at Mamabule, two economically important coal seams, averaging 2,4 and 5,48 m thick (Green, 1966) are separated by about 15 m of sandstone and overlain by mudstone and sandstone.

The Upper Ecca Stage consists predominantly of carbonaceous mudstone, shale and coal. In the Morapule area, two thin and laterally impersistent coal seams are present within this stage. The presence of lenses and nodules of limestone in light-grey Upper Ecca strata, west of Mahalapye at the foot of the Lebung escarpment has been noted (Jennings, 1958).

The Beaufort Group

Strata which may be assigned to the Beaufort Group on a lithological and successional basis, are present in the Makgadikgadi area, in the extreme east of Botswana, in the Palapye and southern Tuli block areas and the Kalahari. The Beaufort Group normally consists of greyish-white or blue-grey non-carbonaceous mudstone and siltstone, but in the Kautse area (south of the Makgadikgadi), siltstone, calcareous sandstone and limestone are developed.

In the area about 30 kilometres north of Kang in the Central Kalahari, a succession of about 131 metres thick, of brown mudstone, brown to red-brown and grey, shaly siltstone, fine-grained grey sandstone and pyritic siltstone intersected in a water borehole below about 60 metres of Kalahari Beds cover is considered to belong to the Beaufort Group. Green (1966), on the basis of a study of borehole intersections in the Central Kalahari, has suggested the widespread presence of Beaufort Group sedimentary rocks in the Kalahari region overlying the carbonaceous Upper Ecca Formation and overlain in turn by the Cave Sandstone Formation of the Stormberg Group.

The Stormberg Group

The Drakensberg Lava and Cave Sandstone Formations are widely developed in Botswana. The Red Beds Formation has however only been recognised in the Bobonong-Tuli area (Mason, 1965), and near Lebung (Jennings, 1958).

The Red Beds Formation

The Red Beds Formation consists of maroon and green mottled mudstone, siltstone, red shale and calcareous sandstone.

Cave Sandstone Formation

The Cave Sandstone Formation has a very widespread distribution throughout Botswana and is the undoubted lithological equivalent of the Cave and Bushveld Sandstone of the Republic of South Africa and the Forest Sandstone of Rhodesia. The top of this Stage is marked by extensive outpourings of basaltic lava forming the Drakensberg Lava Formation, while the base

is generally marked by an unconformity with the underlying beds which are normally the carbonaceous Upper Ecca Formation.

The sandstone varies in colour from white and pink to buff, pale-yellow, brown and greenish-white. It is generally slightly feldspathic, fine-grained to medium-grained, non-micaceous and massive. The sandstone is only feebly cemented and the rock is therefore often extremely friable. Bedded varieties do, however, occur towards the top of the succession and large scale cross-bedding (with foreset planes up to 12 m in length) is of frequent occurrence. Small scale cross-bedding has also been noted. In some areas the normal fine-grained sandstone contains scattered larger, well-rounded "millet seed" grains, while in other areas the Cave Sandstone consists of a closely bedded alternation of coarse and fine sand layers. (Plates 51,52).

The Cave Sandstone attains a maximum thickness of 147 m in Botswana and contains thin intercalated maroon shale bands towards the base. The basal sandstone often grades into a pink marly sandstone. The Cave Sandstone has been observed to overlap directly into Waterberg Supergroup sedimentary rocks near Serowe, while south of Maun the Cave Sandstone overlaps onto pre-Karoo epidiosites, which can probably be correlated with the Nosib Formation of South West Africa. Elsewhere the Cave Sandstone is underlain by pink and maroon or pale blue Ecca Group shales or Beaufort Group sedimentary rocks in the Central Kalahari.

Slickensiding, shearing, silification and jointing are common in the vicinity of dykes and it is probable that most dykes



Pl. 52 Cave sandstone showing cross-bedding - Serowe.



Pl. 53 Polygonal jointing in Cave sandstone - Tehebatsweu.

were intruded along pre-existing fault or shear planes. Thin silicified joint planes (up to one-half inch in width) are often present some distance from the dykes. Xenoliths of Cave Sandstone, up to 25 feet in diameter, occur fairly frequently in dolerite dykes cutting the Cave Sandstone. Columnar joining in Cave Sandstone has been noted occasionally along dolerite dyke contacts. Large scale polygonal jointing some eight feet across occurs at Tehebetsweu (Plate 53) and on flat outcrops. A number of linear belts of denser vegetation extending for several miles and often hundreds of feet wide show up clearly on air photographs and are found on both Cave Sandstone and basalt. These tree lines are developed along zones of closely spaced parallel joint planes along which deeper soil has developed allowing preferential growth of trees and shrubs. The tree lines thus mark major joint planes which trend NE-SW or NNW-SSE, along the main escarpment, separating the eastern Bushveld zone from the Kalahari.

The Cave Sandstone-basalt contact varies from an extremely smooth plane to one which undulates markedly. Present day erosion has frequently exposed basalt lying at a lower level than the Cave Sandstone. Similar extrusion on an uneven landscape of the Cave Sandstone was noted by Van Eeden and others (1955) in the eastern Lowveld area in the Republic of South Africa. The Cave Sandstone is generally indurated for up to 15 cm in the contact zone and is harder with a red, brown or maroon colouration.

Drakensberg Lava Stage

Recent water boreholes drilled in the Central Kalahari which have encountered basaltic lavas, have now established that there is probably a continuous sheet of lava extending beneath the Kalahari cover from the outcrop areas in eastern Botswana near Lephepe and along the escarpment near Serowe for a distance of more than 400 km westwards thus confirming Poldervaart's (1952) contention that they probably form one of the largest single areas of basalt on the African continent. In the north, there is probably a continuous sheet of lava from the Maitengwe River (B.7) to Panda ma Tenga and Kasane. Further extensive outcrops are present in the extreme east of Botswana in the Bobonong-Tuli area.

These basalts were termed "Loalemandelstein" by Passarge (1904), who correctly correlated them with the Batoka basalts at the Victoria Falls and the basalts of the Stormberg Group in South Africa. The basaltic flows were apparently preceded by a period in which erosion of the Cave Sandstone took place as the lavas were extruded over a surface with relief of up to 20 m in the Serowe area (Jennings, 1965).

The basalt varies in thickness, but attains a thickness in excess of 400,91 m north of Lephepe (Bh. 1351), while the maximum recorded thickness in the Tuli-Bobonong area is over 249,39 m (Bh. 1578, Semolale). In the central Kalahari area, the greatest recorded thickness is 210 m, while in northern Botswana, no boreholes have penetrated the basalts and hence, because of the shallow water table, the maximum

recorded thickness is about 100 m.

It is a fine-grained dark-grey, black, brown or purple amygdaloidal or massive rock. No intercalated sandstone bands have been noted in the Serowe area, though occasional intercalated sandstone bands have been noted in boreholes drilled southwest of Makoba (northwest of Serowe). The amygdales which vary in size from less than one centimetre to over 15 centimetres in diameter, consist of crystalline quartz, chalcedony, agate, chlorite, serpentinite, calcite and a variety of zeolites. In places the amygdales consist entirely of oval, blackish-green, chlorite pellets.

Occasionally, numerous unfilled vesicles may impart a pumiceous texture to the lava. The basalt frequently shows spheroidal or tabular weathering on exposed faces. Massive varieties are often cut by later irregular intrusions of amygdaloidal basalt though the reverse also occurs. Orange to purple, current-bedded, sandy tuff bands up to 76 cm thick have been noted occasionally.

The basalts are mainly tholeiitic types with an intersertal texture. However, subophitic, porphyritic, poikilitic and glomeroporphyritic textures were also noted. They are generally fine- to medium-grained rocks consisting of lime soda plagioclase, clinopyroxene and magnetite. Small amounts of olivine occur as euhedral microphenocrysts now generally pseudomorphed by iddingsite, pleochroic green to brown bowlingite with high birefringence, serpentinite, or an apparently isotropic green mineral which is probably

serpophite or chlorophaeite. Orthopyroxene occurs but is uncommon.

The extensive distribution of the lavas in horizontal flows suggests eruption from fissures rather than central type volcanoes. Some of the dykes found cutting the basalt may have acted as feeders to higher horizons which have since been removed by erosion.

Relationship to underlying and overlying rocks

The basalt appears to overlies the Cave Sandstone stage in places, e.g. Serowe, with a slight unconformity, whereas elsewhere, e.g. Debeeti and Fort Tuli areas, alternations of basalt and sandstone occur over a thickness up to 45 m with the sandstone bands being about 60 cm thick in the lower part of the section, but diminishing in thickness upwards. These observations accord well with the generally accepted conclusion that the youngest deposits of the Cave Sandstone period were deposited contemporaneously with the outpourings of basaltic lava. The thinner bands of sandstone were noted to contain amygdales similar to those of the lavas (Green, 1954). In the Kachikau area of northern Botswana, Rogers (1935) noted that Stormberg lavas overlap directly onto Basement Complex granite.

The basalts are overlain unconformably in the Kalahari region by sediments which belong entirely to the Kalahari deposits. In other areas no formations other than recent deposits and alluvium cover the basalts and hence they have been subjected to erosion since Liassic times.

KALAHARI BEDS

A glance at the geological map (Fig. 7), shows the vast areal extent covered by the Kalahari Beds, especially as it should be borne in mind that the map accentuates the westerly extension of the older rocks.

The Kalahari Beds consist of unconsolidated, white to pink-coloured aeolian sands, silcrete, calcrete, ferricrete, conglomerate, limestone and marl and attain their greatest known thickness of 156 m in a borehole north of the Molopo, while a thickness of 150 m has been proved in a hydrogeological research core borehole drilled on the faulted southeastern margin of the Okavango Swamps. Gravity work carried out during the last three years has indicated that the Kalahari Beds could be up to 1000 m thick in this area, (C. Reeves, personal communication, 1972).

Natural sections through the Kalahari Beds are extremely limited and occur only along the escarpment near Serowe and along some of the fossil river valleys.

The Kalahari Beds are best developed in the southern Kalahari along and north of the Molopo River. These beds consist of basal gravels which are overlain by a thick succession of red marl. This marl is overlain by a considerable thickness of sandstone with minor silcrete and calcrete and unconsolidated sands. In the southern Kalahari the sands appear to be both of fluvial and aeolian origin.

The basal member of the Kalahari Beds in the Serowe area is a massive to poorly bedded, white, greenish-white or

red-brown, soft, friable sandstone normally characterised by numerous tubular holes resembling root holes which cut the sandstone at various angles. Root holes are occasionally found filled with a younger, now lithified, red sand. Wayland (1954) regards these tubular holes as being formed by roots at depth (possibly 15 to 21 m) on forested dunes. This sandstone can probably be correlated with the "Pipe" Sandstone occurring in Rhodesia (Maufe, 1938). False bedding and concentric banding were noted occasionally. The sandstone is often silicified to form an extremely hard, pale grey, buff to honey-coloured silcrete which breaks with a conchoidal fracture (Plate 54). The "Pipe" sandstone is overlain in turn by a chalcedonic silcrete (sometimes with small freshwater gastropod and pelecypod fossils).

Passarge (1904) regarded the silcretes as being Oligocene in age while Newton (1920) regarded the age of fossils from the Gwampa chalcedony found in a similar stratigraphic position to that in the Serowe area as Late Cretaceous, but admitted that the obscure fossiliferous remains were of so restricted a character that they presented little evidence as to their geological age. Wayland (1954) however, regarded these beds as being late Pliocene or early Pleistocene. Dixey (1941) also regarded similar silicified surface deposits in Zambia, Angola and Zaire as being formed during the intense and widespread period of aridity that prevailed in the end-Tertiary and early Pleistocene.

The chalcedonic silcrete is overlain in the Serowe area



Pl. 54

Silcrete on edge of Serurume fossil valley.
(F.7).



Pl. 55

Peleng Spruit in rare flood - Lobatse.

with a sharp break by a horizon of ferricrete varying from 30 cm to 3,65 m in thickness. The ferricrete consists of ferruginous nodules cemented together and now often partly converted to limonite. It often grades into a cellular, ferruginous sandstone. Ferricrete boulders containing numerous tubular fragments of chalcedony were noted.

The ferricrete is overlain by 6 m or more of fine-grained red, brown or grey unconsolidated sand. These sands of Kalahari type can probably be correlated with the Plateau Sands of Cahen and Lepersonne (1952). A Chelle-Acheulean handaxe was found partly covered by these sands, but it is more probable that the handaxe was covered by a subsequent redistribution of the plateau sands and is therefore of little use in dating the sands. Wayland (1953) regards the accumulation of the sands of the Kalahari type as having brought to an end the period when the Chelle-Acheulean type of culture was evolved in Africa. However, the Chelle-Acheulean tools found by Wayland were found east of the high-lying plateau in sands which are undoubtedly younger than those mantling the plateau. Cooke (1957) regards the Kalahari type sands as probably Pliocene in age as does Martin (1958). Mabbut (1957) also regarded the sands as being of Upper Tertiary age.

A line of boreholes drilled as part of a hydrogeological research programme between Letlhakeng and Morwamosu in the southern central Kalahari (Kweneng District) has provided some detailed sections on the hitherto virtually unknown Kalahari Beds. Detailed logs of these boreholes

will be given in a later section on the hydrogeology of this region. The most interesting feature however, provided by these boreholes, is the presence of a fairly thick succession of a basal conglomerate in some of the boreholes. These conglomerates have a calcareous cemented, sandy matrix.

INTRUSIVES

MODIPE TYPE GABBRO

A number of large gabbroic intrusives are present in an area east and northeast of Gaborone (G.7). These gabbro bodies generally form resistant hills (Plate 28). They pre-date the Gaborone granite and are approximately 2 600 million years old (Evans and McElhinny, 1966).

GABORONE GRANITE COMPLEX

The Gaborone granite is confined to the southeastern part of Botswana and crops out westwards from Gaborone to west of Thamaga, where it disappears beneath Kalahari Beds. A further large triangular area between Ootse, Lobatse and Kanye has been intruded by this granite. It is surrounded by a near continuous zone of the Kanye Volcanic Formation, which has been intruded by the younger Gaborone granite. This has been dated at circa 2 800 million years. Crockett (1968) noted that because of the gradational nature from felsites of the Kanye Volcanic Group through granophyric rocks to the coarse-grained porphyritic granite forming the Central Gaborone Granite Assemblage it was

groups of ancient acid igneous rocks.

POST-TRANSVAAL SUPERGROUP INTRUSIVES

Intrusive granitic, (Mmathete granite) and syenitic rocks are found northwest (G.5), south and somewhat southwest of Kanye (H.6), while ultramafic intrusives are known to be present in wells and boreholes near Sekoma Pan (Oikhe and Keng Pans, D.7) and near Bray (D.8) north of the Molopo River.

These intrusives which are olivine, enstatite peridotites, are of post-Transvaal age but their upper age limit is unknown. They generally do not form good aquifers. In the sand-covered Molopo area, the ultramafic intrusives invariably give unpotable water supplies to boreholes drilled into them. The syenitic rocks and Mmathete granite are usually hard and impermeable rocks. However, by using the electrical resistivity method successful boreholes can be sited in basins of decomposition.

POST-WATERBERG AND PRE-KAROO SUPERGROUP INTRUSIVES

Post-Waterberg mafic intrusives are found in widely separated areas - all in eastern Botswana but west of the railway line. These areas are north of Molepolole (G.7), 20 km south of Shoshong (F.7), and in the Makhware hills south of Serowe.

The intrusives, (Jennings, 1963) vary in composition from dolerite (Hangnest and Downes Mountain types) to diorite granophyric diorite and red hornblende granophyre.

The post-Waterberg, pre-Karoo intrusives generally occur as sills or dykes interbedded within or cutting the Waterberg and Shoshong Groups. They seldom exceed 130 m in thickness. They form notoriously poor aquifers and boreholes drilled into them seldom provide adequate supplies.

STRUCTURE

Four main structural epochs have been recognised in Botswana. These are, (a) Post-Basement Complex (and earlier than the oldest unmetamorphosed sediments), (b) post-Transvaal and pre-Waterberg, (c) post-Waterberg and pre-Karoo and (d) post-Karoo.

GROUND WATERGround Water and the Hydrologic Cycle

The enigma of the hydrologic cycle has been known since earliest Biblical times and led Solomon to observe that "all the rivers run into the sea; yet the sea is not full, unto the place from whence the rivers came, thither they return again"(Ecclesiastes Chap.1, para.7).

The extraordinary properties of water require little emphasis. This odourless, colourless and tasteless substance has great stability; is a powerful solvent and source of chemical energy. It is the only substance on earth that occurs in vast quantities and can exist in three forms - ice, vapour and liquid; it is a powerful agent which has been moulding the face of the earth for thousands of millions of years; it determines the climate; forms the soil on which agriculture is dependent and has other remarkable properties, such as its property of expansion and lighter density when frozen; and its ability to absorb and release more heat than most other substances.

Water that infiltrates the soil may be pulled back to surface by capillary action, and be evaporated; it may be absorbed by plant roots and then be transpired by the plant back to the atmosphere; or it may penetrate, under the action of gravity, through the soil after this has attained field capacity, until it reaches the level of

the zone of saturation. This water is known as ground water or phreatic water and has been used in the form of spring discharge and from wells by man from the earliest days to the present. Subsurface water in interstices above the zone of saturation (i.e. in the zone of aeration or unsaturated zone) is known as vadose water. The zone of aeration may be subdivided into a soil water zone, an intermediate and capillary fringe immediately in contact with the water below the water table.

Ground water constitutes an integral part of the earth's water circulating system known as the water or hydrologic cycle. This endless cycle is generally regarded as commencing with the oceans which cover three-quarters of the earth's surface. The sun's radiation on the ocean causes water to evaporate. As water vapour is only 0,62 times as heavy as an equal volume of air, it rises into the upper regions of the atmosphere. The temperature of the ascending vapour gradually decreases until the air becomes saturated and the vapour condenses and precipitates to earth or the oceans. The precipitated water may be intercepted by plants, it may run over the surface of the ground into streams and rivers, or it may infiltrate into the ground, as described earlier. The ground water flows out of rocks as springs or seeps into streams (gaining (influent) streams) and thence flows back to the oceans, or it may seep underground directly back to the oceans. Losing (influent) streams lose water to ground-water storage. This complicated process, involving the atmosphere, hydrosphere and lithosphere, has been in progress throughout the earth's history.

Because surface waters can be seen and tremendous amounts of money have been spent on dams, aqueducts and irrigation canals, it is seldom realised that less than three per cent of the fluid fresh water resources of the earth are present as surface water, with more than 97 per cent - an estimated 8 million cubic kilometres (Leopold and Davis, 1968) being present as ground water. Because of the invisible nature of ground water; its relative inaccessibility; the difficulty in assessing ground-water resources; the general lack of knowledge concerning its mode of occurrence and location; the importance of ground water has often been overlooked. This is especially the case in the search for ground water where man's actions have often been governed by romanticism and mysticism rather than by reason. As a result, the ancient cult of dowsing or water divining still has an enthusiastic following, even in highly developed countries such as the United States and Great Britain. Even the inhabitants of Botswana have a term "dupametse" which means "to witch out water".

Importance of Ground Water

Ground water has assumed an especially important role in Botswana for a number of reasons. Among these are:-

1. The virtual absence of any run-off over at least 84 per cent of the country and hence the absence of any rivers and streams. Because evapotranspiration exceeds rainfall, no perennial rivers rise within Botswana.
2. The relatively low cost of drilling and equipping boreholes compared to the building of expensive surface reservoirs. These could not be afforded in the past because of the country's straitened finances.
3. Dams in Botswana, furthermore, have the disadvantage that there is a dearth of good natural sites resulting in long walls in relation to the volume stored. Surface area and hence evaporation loss is thus high in relation to volume stored. Sedimentation is high because of the sandy soils, lack of vegetal cover and high rates of run-off and erosion following the high intensity rainfall storms occurring in Botswana. Finally, the low and variable rainfall leads to considerable uncertainty of supply.

4. In the past, the predominantly rural economy of the country, with an almost complete lack of any major industry, together with the relatively small population even in the largest towns, has not justified the construction of large and expensive dams. This has, however, changed with the development of major diamond and copper-nickel mining activity at Orapa and Selebi-Phikwe respectively, and the establishment of the new capital at Gaborone.

The estimated ground water usage in Botswana is given in Tables 5, 6 and 7.

It is calculated that a total of approximately $26 \times 10^6 \text{ m}^3$ of ground water is used annually in Botswana.

TABLE 5
RHODESIA RAILWAYS GROUND WATER USAGE IN BOTSWANA

<u>WATERING POINT</u>	<u>ANNUAL CONSUMPTION m³</u>	
LOBATSE	50 000 *	
MAHALAPYE	248 565	
MOLOTOANA	99 280	
MORALE	116 070	
MOSOMANE	132 495	
OTSE	165 710	
PALAPYE	20 000 4	Includes dam supply
PALLA ROAD	49 640	
SHASHE	414 275	
TSAMAYA	58 035	
TSHESEBE	<u>66 430</u>	
	<u>TOTAL:</u>	<u>1 420 500</u>

* During the 14 year period ending 1970 the Rhodesia Railways used an average of 30,500 m³ p.a. of ground water. Present consumption is estimated at 50,000m³.

~~4~~Total consumption including dam supply is 198,925 m³ p.a. Ground water consumption is estimated at 20,000m³ p.a.

TABLE 6ESTIMATED DOMESTIC AND INDUSTRIAL WATER USAGE IN BOTSWANA

LOCALITY TYPE	POPULATION	ESTIMATED ANNUAL CONSUMPTION ^{m³}
URBAN POPULATION	48 267	110512
VILLAGE	285 784	2276189
LANDS	141 608	
CATTLE POSTS	73 936	
FREEHOLD FARMS	17 484	
OTHER	866	
MINING TOWNSHIP	6 000 est.	109500
	<u>TOTAL:</u>	<u>2496201</u> Say 2500000

Urban Population (Consumption based on figures for Serowe 15723 use 360 000m³ p.a., i.e. 22896 m³ per annum per capita.

Village, Lands Population etc Consumption estimated at 12 litres per day (Mining Township Consumption estimated at 50 litres per day.

As approximately 75 per cent of the population is estimated to be dependent upon ground water then the estimated annual domestic/industrial usage from this source is 1875000 m³.

TABLE 7

SUMMARY OF TOTAL ESTIMATED
ANNUAL GROUND WATER USE IN BOTSWANA

TYPE OF USAGE	m ³ PER ANNUM
DOMESTIC & INDUSTRIAL USE	1 875 000
RHODESIA RAILWAYS	1 420 500
LIVESTOCK	20 035 926
IRRIGATION (TULI BLOCK) ESTIMATED	2 000 000
TOTAL:	<hr/> 25 331 426 <hr/>

PRINCIPLES OF OCCURRENCE OF GROUND WATERS

In order to evaluate the ground water resources of Botswana, it is necessary to appreciate that these resources occur in two essentially different types of aquifers. Of these two aquifers, one consists mainly of hard-rock crystalline formations consisting of igneous and metamorphic rocks and the other consists of granular sedimentary rocks or unconsolidated formations. The unaltered sedimentary rocks form primary or original aquifers while the crystalline rocks, because of their lack of pore space, only form secondary aquifers.

Primary aquifers generally hold water in the granular pore spaces of the rocks. These are often interconnected over considerable distances and the aquifer thus behaves as a homogeneous unit. These primary aquifers generally form extensive, uniform aquifers having a general water table or piezometric surface. Because of their homogeneous geohydrological properties and their lateral extent the siting of boreholes is often not critical or limited to narrow zones.

Secondary aquifers consist of joints, fissures, faults, decomposed zones and solution channels. These aquifers are thus, in theory, of limited lateral extent and of limited capacity. In actual practice however, aquifer evaluation tests initiated by the writer have indicated relatively great lateral extent and much greater hydrological continuity than had been anticipated (see chapter on Aquifer Tests).

Ground water can only occur when the host rock contains sufficient interconnected openings to permit the movement and storage of water.

THE WATER-BEARING PROPERTIES OF THE VARIOUS
GEOLOGICAL FORMATIONS IN BOTSWANA

BASEMENT COMPLEX GRANITOID ROCKS

The various granitoid type rocks found in Botswana invariably give a very high percentage of blank or low yielding boreholes where no geological/geophysical aids are used (probably less than 40 per cent successful), yet on the other hand they give a very high percentage of successful boreholes (over 70 per cent) when proper siting using geology and geophysics is used.

Water occurs in these granitoids either in basins of decomposition or in jointed, fractured or faulted zones. Both main types of aquifers are extremely amenable to their detection by geophysical techniques - the former by electrical resistivity and the latter by electromagnetic or self-potential methods and hence the high success ratio of boreholes using these aids or by taking cognisance of jointed and fractured zones following surface geological inspection. The lack of intergranular pore space makes the granitoids of no use whatsoever as a primary type of aquifer.

Yields obtained using geophysical aids vary from about 15 to over 228 litres per minute and average 72 litres per minute.

The quality of water obtained in this sort of aquifer is generally good.

BASEMENT COMPLEX GREENSCHIST BELT ASSEMBLAGE

Rock types in these "schist belts" consist of altered basaltic and intermediate lavas - now greenschists, amphibolites, felsic lavas, pyroclastics, ultramafic intrusives and extrusives and metasedimentary rocks.

These rocks have generally been subjected to intense folding and greenschist facies metamorphism. As a result of several periods of deformation the more competent rocks are often well jointed and moderately deep drilling to well below the expected isopiezometric level for the area will often result in high yielding boreholes. In many cases boreholes were sited initially by siting in decomposed basins delineated by resistivity surveys. For example, in Francistown, all boreholes were stopped soon after penetrating to just below the depth of decomposition as indicated by the resistivity survey. Later however, these boreholes were continued to a depth approaching 100m despite the fact that water levels in the area were generally less than 15m and despite the fact that in many cases water supplies of up to 76 litres per minute had been obtained at depths of less than 30 to 45 metres. The majority of boreholes then gave yields of about 228 litres per minute or more thus proving that additional supplies of water were encountered in joint planes below the decomposed zone.

KANYE VOLCANIC GROUP

The acid lavas (felsites) forming this Group are notoriously poor water-bearers and a very high percentage of blank or low yielding boreholes has been drilled in these rock types. As numerous diabase dykes intrude these felsic lavas and give rise

to tree and shrub lines growing on the more weathered diabase ("aars") numerous boreholes have been sited by water diviners in the middle of the dykes with scant success.

The few successful holes sited within this formation have been sited in the fractured country rock adjacent to diabase intrusions. In some cases where these fractured zones are broad enough, they can be detected by resistivity surveys.

Good water supplies were also obtained on the contact between felsites and a diabase sill northwest of Kanye.

The quality of water encountered in this Group is always good.

VENTERSDORP SUPERGROUP

This Supergroup consists of tuff, ignimbrite, agglomerate, quartz and feldspar porphyry, siltstone, shale, conglomerate and andesitic lava. Both acid and intermediate lavas, like those of the Kanye Volcanic Group, are extremely poor aquifers and hence give rise to a high percentage of blank boreholes. The pyroclastics and sedimentary rocks constitute slightly better aquifers than the lavas, but nevertheless, because of low secondary porosity, seldom give rise to high yielding boreholes. An exception is the Suane borehole (Bh 1225, 551/mm) just west of the main road halfway between Ramotswa and Gaborone (G.6).

TRANSVAAL SUPERGROUP

Black reef group

The Black Reef Group consisting of quartzites, quartzitic sandstones and minor conglomerates is seldom sufficiently well developed to give water supplies. Where it is sufficiently thick, moderate (\pm 38 l/min) yields of good quality water can be obtained.

Dolomite group

This very thick succession of dolomite rocks with interbedded cherts is generally a poor water bearer where it is unweathered. However, where basins of decomposition can be located by electrical resistivity (preferably less than 10 000 ohm - centimetres) very good yields - sometimes in excess of 228 litres per minute, can be obtained. Strong supplies of water can be expected to be present in solution channels within weathered dolomite, but as there is no means of detecting these channels from surface this potentially large and valuable source of ground water can be neglected. Only a single borehole on Lobatse Estates (H.6) is known to have intersected a 2 metre cavity containing a very strong supply of water. The driller also reported "river sand" to be present in the cavity. This borehole which was privately drilled is now equipped only with a windpump and is used for cattle watering, and could probably be used should there be a shortage of water for township supply in the future. A nearby borehole to the above (number 1997) was reported to blow air at certain times. This is probably caused by atmospheric pressure changes in cavities in the dolomite above the water table. As can be expected, the Dolomite Group yields water of a moderate quality with fairly high dissolved calcium and magnesium salts and hence the water is generally "hard".

The Pretoria group

This group consists mainly of shale, quartzite, conglomerate, limestone, banded ironstone and andesite (Ongeluk lava) of which

shale and quartzite are predominant. Both the shale and quartzite form extremely good aquifers. On Lobatse Estates the quartzite (Magaliesberg Stage) forms an extremely good aquifer and numerous boreholes with both a high yield and a very high storage capacity have been drilled in this horizon. Boreholes penetrating these quartzites in the Central and Northern basins on Lobatse Estates have proved the mainstay of Lobatse water supply since 1962. These boreholes produce up to 1140 litres per minute and have transmissivities of up to 620m^2 per day.

Not many holes are known to have been drilled in the Ongeluk andesite lavas, but those in the Lobatse area (H.6) and Western Bangwaketse (G.5) produce good yields. Some 30 km further west however, a number of blank boreholes were drilled in the same horizon.

In the sand covered Molopo area (H.5) a number of good yielding boreholes have been reported in banded ironstones. Further eastwards no boreholes are known to have been drilled in this horizon.

The limestone bands present in the Magaliesberg Stage of the Pretoria Group are of insufficient thickness to form important aquifers on their own, though boreholes penetrating alternating beds of shale, limestone and quartzite have given good yields. Water quality in boreholes drilled in Pretoria Group Beds is generally of excellent quality. A number of boreholes drilled in Magaliesberg quartzites have total dissolved solids content of less than 100 parts per million.

GHANZI FORMATION

This formation consists predominantly of quartzite, quartzitic sandstone, shale, greywacke and subordinate limestone. Throughout the main area of outcrop, excellent supplies of water are generally obtained at shallow depths of less than 30 m. These supplies of water are undoubtedly obtained from an intricate interconnected joint and fissure system within the tightly folded pre-Cambrian sediments. Martin (1961) has noted that identical sediments in South West Africa (Tsumis Group) also give good yields but that there is a marked drop off in successful boreholes where the Kalahari Bed cover exceeds more than about 10m. Similar conditions obtain in Botswana and an analysis of hundreds of electrical depth probes in Ghanzi Beds showed that wherever Kalahari Bed cover exceeded about 15m the chances of encountering low yield or blank boreholes rose significantly. The abovementioned analysis however, only included relatively shallow boreholes of less than 60 metres depth and should conditions in the Klein Aub Mine in Ghanzi Formation correlates in South West Africa be any criterion, then deep boreholes of up to 300m should be considered in sand covered areas in Botswana. At this mine the deeper levels ($\pm 300\text{m}$) have encountered much more water than the higher levels in a number of high yielding fissures with water present under very high pressures.

One of the most puzzling features of the water-bearing properties of the Ghanzi Formation is the abrupt change as one proceeds from Latitude 21 degrees South in a northeasterly direction. Here the success rate of boreholes sited, even using geophysical aids, drops suddenly to about 30 per cent. The only possible explanation is that this drop in success ratio coincides with

(combretum) and that all available rain water which would normally infiltrate beyond the root zone to replenish the ground water is transpired by the heavy tree growth. The best chances of obtaining successful supplies of water appear to lie in careful photogeological studies to outline joint zones in the noses of the tightly folded sediments and then to site boreholes on these joint planes. Optimum resistivity values as found from yield-resistivity curves in the Ghanzi area i.e. less than 10 000 ohm - centimetres, do not hold good north of Latitude 21 degrees South.

A study of the hydrograph on an observation borehole in Ghanzi village indicates a slight but steady decline in ground water level during the dry months followed by a steady rise in the rainy season. It appears therefore that some replenishment occurs in most years whilst it is only in exceptional years, such as October 1963, when 292 mm fell in $3\frac{1}{2}$ hours, that major replenishment occurs.

An analysis of the water quality data on 45 boreholes drilled in Ghanzi Beds in the Ghanzi district shows that the total dissolved solids content varies from 344 to 2476 p.p.m. with an average of 840 p.p.m.

WATERBERG SUPERGROUP (INCLUDING MATSAP FORMATION)

The Waterberg Supergroup consists of pre-Cambrian age shales, siltstone, sandstone, limestone, grit, conglomerate and quartzite. Of these only the shale, siltstone, sandstone and quartzite members attain any appreciable thickness and hence are of any importance as regards their water-bearing properties. Of these latter, only the sandstone/quartzites are of significance as aquifers.

The shale and siltstone members are generally too fine grained to yield appreciable quantities of ground water, and also have insufficient secondary porosity and permeability to constitute important aquifers.

Two important townships in Botswana - Palapye (E.8) and Molepolole (G.6) are completely dependent on water supplies obtained from this Supergroup as is the important Secondary School - Moeng College situated in the Chwapong Hills (E.8).

Another village - Kanye is largely dependent on water obtained from boreholes in Waterberg Supergroup sandstone.

At three of the abovementioned localities, a thick shale/siltstone succession (at least 100m thick) overlies a basal sandstone horizon with minor conglomerate. Numerous blank or low-yielding boreholes were drilled in the argillite/semi-pelite succession before it was realised that only deep boreholes sited to intersect the underlying arenites were likely to be able to provide adequate water supplies.

At Palapye the few successful boreholes drilled into the shale horizon generally produce water of such poor quality that they are unpotable or only marginally potable.

Further West in the Kalahari (G.4) a number of high yielding potable boreholes have been drilled; at Kwakala (No. 1201, yield 137 l/min), Ghia (No. 1542, yield 19 l/min), Konkwa (No. 1174, yield 44 l/min), Mabutsane (No. 1102, yield 114 l/min) and Khakhea (No. 281, yield 129 l/min). These boreholes were sited where there was an absence of overlying Kalahari Beds cover and often because of their favourable apparent resistivity range (10 - 30 000 ohm - centimeters). These boreholes are all noteworthy for the exceptionally good quality of their water (Kwakala Bh., 104 p.p.m. total dissolved solids). The

presence of appreciable quantities of tritium in water from these boreholes indicates that modern recharge is taking place. Further to the southwest where the Kalahari cover exceeds 100m or more, a large number of boreholes drilled within the Molopo Farming Block have virtually all given poor quality or unpotable water. The reason for this is not clear, but is probably related to poor recharge conditions caused by thick overburden and very low rainfall.

Still further to the southwest in the Tshabong area, (H.3 and I.3) high yielding potable boreholes have been drilled where Waterberg/Matsap Supergroup quartzites again crop out.

KAROO SUPERGROUP

Dwyka group

This Group consists of Upper Carboniferous age tillite, shale and minor sandstone, but because of its limited distribution and thickness does not form an important aquifer in Botswana. Boreholes known to be sited in Dwyka tillite are situated southwest of Palapye (E.7,8) and at Mashi a Potsana (G.3) in the Kalahari. This latter borehole yielded highly saline water.

Ecce group

The Ecce Group consists predominantly of Upper Carboniferous to Triassic age sandstone with minor coal beds. Because of their impermeable nature, the shales form an extremely poor aquifer, and furthermore often yield only saline supplies of water e.g. Boritse Pan (F.4), Kang (F.3.), Katswene (F.3) and in numerous privately drilled boreholes in the area between Serowe and Palapye (E.7). On the other hand, the coarse grained gritty sandstones form moderately good aquifers throughout

Botswana e.g. Dukwe area (C.7), south of Palapye (E.8), near Dibete (F.7) and westwards into the Kalahari as far as Morwamoso (F.6, G.6, F.5, G.5 and G.4) and even further northwest near Ncojane (F.1). The shales can generally be distinguished from the sandstones because of their lower electrical resistivity and hence geophysical resistivity surveys in sand-covered areas often result in a high success ratio of boreholes drilled.

The quality of water encountered in Eccca sandstone and grits is generally moderately good, but deteriorates westwards and at Kamelane (G.3) Kangyane and Lotlhake (F.3) is unpotable.

STORMBERG GROUP

Cave sandstone

The Cave Sandstone beds of Triassic age consist of about 100m of fine to medium-grained, well-sorted aeolian sandstone underlain by a thick succession of shales which form an aquiclude. The sandstone and the contact zone with the overlying Stormberg basaltic lavas form Botswana's most consistent and important aquifer in the Central District area (D.6 and 7, E.6 and 7, F.7) and in the central Western Kalahari around Lone Tree and Manyane (E.3 and F.2 and 3).

This aquifer probably extends all the way between the Lone Tree area and Serowe (F.7) though only one successful borehole (No. 1461) (E.4) has been drilled in this area. A further important aquifer is present in a downfaulted trough in Ghanzi Formation southwest of Lake Ngami (C.3) and in the extreme eastern corner of Botswana (E.9).

The quality of water encountered in the Cave Sandstone is generally of excellent quality in the Serowe area (E.7), but deteriorates towards Orapa (D.6). In the Lone Tree (E.3) area, the water

.... / is of

is of good quality (but hard), but deteriorates again around Manyane (F.2).

One of the two known artesian boreholes in Botswana was drilled in the Cave sandstone aquifer at Mashoro (D.7). This borehole (No. 141) flowed at only 0,76 litres per minute but gave a pumped yield of 152 litres per minute.

Stormberg Basalt

Stormberg basalts of lower Triassic age are distributed over an extremely widespread area in Botswana, but with the exception of the Morukuru area (D.7) the lavas do not form an important water bearing formation. The use of the electrical resistivity method does enable basins of decomposition to be detected, but these generally do not yield very large supplies (38 l/min) and they are furthermore susceptible to rapid depletion because of their limited areal extent. In the Morukuru area water appears to be encountered both in the basalt which is more uniformly decomposed than elsewhere and also probably on the contacts between different lava flows. The basalt attains a maximum known thickness (in excess of 401m) north of Lephepe in Bh. 1351 (F.6). An artesian water supply was encountered in basalt at Bobonong (D.9) in borehole 1561. Water in this borehole flowed over the casing at a rate of 15,2 litres per minute while it gave a pumped yield of 228 litres per minute.

Dolerite Dykes

Post-basalt dolerite dykes (Liassic) are present wherever Karoo strata have been encountered. These dykes do not generally form favourable water-bearers as the dolerite itself is relatively

..../fine-grained

fine-grained with little intergranular porosity. They also have little secondary porosity imparted through shearing and jointing. In Botswana very few boreholes have been sited on dolerite contacts in normally impervious Eccca shales. As the demand for additional supplies of ground water arises in areas of Botswana underlain by a thick succession of shales boreholes will, no doubt be sited on dyke contacts. The presence of dolerite dykes in Kalahari covered areas in the western Kweneng District has been detected by magnetic surveys, but no boreholes have as yet been sited on the dyke contacts. The only two boreholes known to be sited on dyke contacts (No. 1454, E.8 and No. 976, E.7) proved blank and low yielding (3,8 l/min) respectively.

KALAHARI BEDS

The Kalahari Beds range in age from Cretaceous to Recent. They consist of unconsolidated red sand, calcrete, silcrete, marl, sandstone and conglomerate (calcreted). These Beds cover almost 85 per cent of Botswana, but their thickness is such that, except in certain parts of northern Botswana, north of latitude 20 degrees 30' South and the south-central part of Botswana in the Molopo farms area, they do not form an aquifer of any consequence. Other exceptions to this are at Kang (F.3) where two shallow boreholes obtain poor quality water in Kalahari calcretes in a perched water table related to the pan depression and also at Tshane (Plate 25, F.2, - shallow hand dug wells) and Lehututu (F.2, - shallow boreholes in calcrete) where similar perched conditions obtain but where the water quality is better.

In the northern Kalahari there is a considerably higher rainfall and extensive beds of calcrete occur at or near surface in the Odiakwe-Gweta area (C.6). Consequently supplies of good quality water, but often with a high fluoride content, are obtained at shallow depth.

Elsewhere in the Northern Kalahari where the unconsolidated sand cover is considerably thicker than in the Odiakwe-Gweta area, boreholes in the Kalahari Beds generally give no water at all or are low yielding and/or saline. In close proximity to the Okavango Swamps where recharge from the annual flood is possible, good supplies of good quality water can be obtained in unconsolidated Kalahari sand. Recent seismic investigations by the Geological Survey have indicated a considerable thickness of Kalahari sediments beneath the Swamps and thus a very considerable quantity of water is probably present in storage beneath the swamps. Should a scheme to export or exploit large quantities of water from the Okavango ever be considered, this ground water could be utilized during periods when little surface water is present in the Swamps. It would have the added advantage of being regularly replenished by the annual Okavango flood emanating from the Angolan highlands.

In the Southern Kalahari region (Molopo farming block) the Kalahari Beds attain a considerably greater thickness than elsewhere in Botswana (other than beneath the Okavango Swamps). As a result of this, the detection of deep Kalahari sediment infilled basins for ground water supply by electrical resistivity and gravity methods has resulted in numerous high yielding boreholes with moderately good water quality being drilled. In particular the deepest portion of these old basins which contain sandstone and conglomerate (often now a calcreted conglomerate)

form particularly favourable aquifers some of which have been pumped continuously for longer than ten years with no obvious signs of depletion. In this region the Kalahari Beds, when of sufficient thickness, form a better aquifer than the underlying granitic, ultramafic or shaley rocks (Pretoria Group, Transvaal Supergroup).

See Table 8 for summary of data on aquifers in Botswana.

TABLE 8

AQUIFERS IN BOTSWANA

Geological formation:	Age	Lithology	Occurrence of aquifers	Yield litres per minute	Observations
Kalahari Group	Cretaceous (?) - Tertiary - Recent	Predominantly unconsolidated red sand, calcrete, silcrete marl, sandstone and conglomerate	None Primary aquifer in sands and gravels where Kalahari Beds in Southern Kalahari (N of Molepo R) are 100m thick	Av. 95,75 l/min. Av. bh depth 36,26m	Saline supplies often encountered under fresh water. Only in N. Kalahari and extr S. Kalahari
Karoo Supergroup Stormberg Group	Triassic - Jurassic	Basalt, Cave sandstone and dolerite dykes.	In zones of basaltic decomposition and flow contacts. Lava - sandstone contact. Joints act as conduits Primary aquifer in Cave sandstone.	Av. yield 99,81 l/m Av. yield 127,36	Av bh depth 72,21m Always fresh water. Av. bh depth 109,079
Ecca Group	Upper Carboniferous. Triassic.	Shale, sandstone	Middle Ecca sandstones. (Joints in sandstone act as main conduits)	200 - 3,000 Av yield 102,59 l/min	Water often saline Av. borehole depth 137,72m
Dwyka Group	Upper Carboniferous	Tillite	Unimportant.	Small	Often saline
Damara Supergroup	Late Precambrian (± 500 my)	Quartz schist, quartzite, dolomite.	Unimportant.	Virtually no boreholes drilled.	Good water potential in N.W. Ngamiland. Grazing limitations however.
Ghanzi Group	Precambrian C900my	Quartzite, gneiss, shale limestone.	Permeable zones in sandstone or fissures and joints in quartzites	Av. yield 97,99 l/m	Av. bh depth 62,83m No aquifers under thick sand Good aquifer in outcrop areas except in Ngamiland.
Waterberg - Matsop Supergroup	Precambrian	Quartzite to sandstone, conglomerate, shale	Shattered zones and joints in quartzites and sandstones.	Av. yield 75,84	Fresh water. Av. bh depth 86,27 m

TABLE 8 (Continued)

Geological formation:	Age	Lithology	Occurrence of aquifers	Yield litres per minute	Observations
Transvaal Supergroup Pretoria Group	Precambrian (From 2000m.x)	Quartzite shale, banded ironstone, andesite	In decomposed dolomite zones, and in quart- zites and shales	Av.yield 208,45 l/min.	Av. depth 113,29m
Dolomite Group		Dolomite, chert and Black Reef quartzite.		Av.yield 198,30 l/min.	Av. depth 69,92m
Ventersdorp Supergroup	Precambrian C 2300 m.y.	Tuff, ignimbrite, agglomerate, por- phyry, siltstone, shale, conglomerate, andesite.	Secondary aquifer in joints etc.	Av.yield 53,89 l/min	Av. borehole depth 74,
Kanye Volcanic Group	Precambrian 3 000 m.y.	Acid volcanics (fel- site, porphyries).	In shattered zones near dykes contacts. In decomposition zones.	Av.yield 26,032 l/min.	Av. depth 58,43m
Basement Complex	Early Precambrian	Granite, gneiss, amphibolite, acid and mafic lavas, meta sediments etc.	In granitic decom- position zones and joints. In secondary joint planes, fissures, etc. in "schist belts".	Av.yield 72,34 l/min.	Av. depth 56,58m
<u>Intrusive Igneous Rocks</u>					
Diabase/dolerite	Precambrian/ Liassic	Dolerite, diabase	Joints and decomposed zones in dolerite/ diabase.	Av.yield 64,9 l/min.	Av. depth 65,85m
Gaborone-type granite	{ Post-Kanye Volcanic Group C 2800 m.y. Pre-Ventersdorp Supergroup	Porphyritic equi- granular Sapakivi type granite	Joints and decomposed zones in granite.	Av.yield 48,76 l/min.	Av. depth 56,58m

The aquifers producing the highest percentage of successful boreholes are the basalt/Cave sandstone contact (97,4 per cent), the Pretoria Group (87,17 per cent) and the Dolomite Group (82,43 per cent). The aquifer producing the highest percentage of blank boreholes is the Kanye Volcanic Group (42,1 per cent).

The shallowest water is on average likely to be encountered in the Kalahari Beds (18,09m); in diabase/dolerite (19,20m) and the Kanye Volcanic Group (20,62m). The deepest water is likely to be encountered in the Eccca Group (65,25m). Because of the shallow depth to water, irrigation schemes, (where costs are critical for their viability) using ground water derived from the Kalahari Group are likely to have the greatest chance of being financially successful.

The average depth of successful boreholes is likely to be least in Kalahari Beds (36,26m) and greatest in the Eccca Group (137,72m).

There is a greater chance of encountering saline water in boreholes drilled in the Kalahari and Eccca Groups than in any other Groups.

STATISTICS RELATING TO THE WATER-BEARING PROPERTIES
OF THE VARIOUS GEOLOGICAL FORMATIONS

An analysis of statistics relating to all government-drilled boreholes drilled between 1929 and the present (official number 2 500) is summarised in Tables.9-12. All boreholes assigned official borehole numbers, but which were abandoned for technical reasons (deflection of borehole etc.); or boreholes drilled for test purposes, such as commissioning of new rigs; training of operators; brine testing boreholes etc, were omitted from the calculations. Successful boreholes were defined as boreholes with potable quality water, arbitrarily taken as less than 5 000 p.p.m. total dissolved solids, and with yields exceeding 7,6 litres per minute (100 gallons per hour). (See also Table 12a).

CONCLUSIONS

Botswana's highest producing aquifers are sediments of the Pretoria Group (Transvaal Supergroup, 208,45 l/min); quartzites and dolomitic limestones of the Dolomite Group (Transvaal Supergroup 198,3 l/min) and the three main aquifers of the Karroo Supergroup - the basalt/Cave sandstone contact (Stormberg Group 127,36 l/m); the Eccca Group (102,36 l/min) and the Stormberg basaltic lavas (99,81 l/min). The poorest aquifer is the Kanye Volcanic Group with an average of only 26,03 l/min.

..../The

T A B L E 9

AVERAGE BOREHOLE YIELDS FOR VARIOUS GEOLOGICAL FORMATIONS IN DECREASING ORDER (l/min).

1.	2.	3.	4.	5.	6.	7.	8.
PRETORIA GP.	DOLOMITE GP.	STORMBERG GP BASALT/CAVE SST.	ECCA GP.	STORMBERG GP. BASALT	GHANZI GP.	KAL. GP.	STORMBERG GP CAVE SST.
208,45	198,30	127,36	102,59	99,81	97,99	95,75	79,03

9	10	11	12	13	14
WATERBERG GP.	BASEMENT	DIABASE/DOL.	VENTERSDORP GP.	GABORONE GRANITE	KANYE VOLCANIC GP.
75,84	72,34	64,9	53,89	48,76	26,03

T A B L E 10

AVERAGE DEPTHS OF SUCCESSFUL BOREHOLES IN VARIOUS GEOLOGICAL FORMATIONS (INCREASING DEPTH-m)

1.	2.	3.	4.	5.	6.	7.	8.	9.
KAL. BEDS	BASEMENT COMP	KANYE V.GP.	GABORONE GRANITE	GHANZI GP.	DIABASE	TRANSVAAL S.G.	STORMBERG BASALT	VENTERS- DORP S.G.
36,26	56,58	58,43	61,97	62,83	65,85	69,92	72,71	74,51

10.	11.	12.	13.	14.
WATERBERG S.GP.	STORMBERG GP. BASALT/CAVE SST	CAVE SST.	PRETORIA GP.	ECCA GROUP
86,27	109,07	11,66	113,29	137,72

T A B L E 11
AVERAGE DEPTH TO STATIC WATER LEVEL FOR DIFFERENT GEOLOGICAL FORMATIONS (m)

1.	2.	3.	4.	5.	6.	7.	8.
KAL. GP.	DIABASE	KANYE V. GP.	BASEMENT COMP.	BASALT	WBG. GP.	TVL. DOLOMITE	GABERONE GRAN
18,09	19,20	20,62	23,20	26,63	27,57	28,22	28,54

9.	10.	11.	12.	13.	14.
VENT SGP.	GHANZI GP.	BASALT/CAVE SST.	PRETORIA GP.	CAVE SST	ECCA GP
29,85	31,92	37,82	44,58	54,68	65,25

T A B L E 12
PERCENTAGE SUCCESSFUL BOREHOLES DRILLED IN VARIOUS GEOLOGICAL FORMATIONS

1.	2.	3.	4.	5.	6.	7.
BASALT/CAVE SST.	PRETORIA GP.	DOLOMITE GP.	VENTERSDORP S.GP.	WATERBERG S.GP.	BASALT	KAL GP.
97,4	87,17	82,43	76,0	75,11	72,65	65,07

8.	9.	10	11.	12.	13.	14.
CAVE SST.	GHANZI GP.	BASEMENT COMP.	GAB. GRANITE	DIABASE	ECCA	KANYE VOLC G
64,77	59,15	57,2	42,52	42,42	42,20	42,10

TABLE 12a

BOREHOLE STATISTICS ON VARIOUS GEOLOGICAL FORMATIONS IN BOTSWANA

	BASSETT COMPLEX	KAIYE VOLCANIC GROUP	CARBONIFEROUS GRANITE	VENTERSDORP S. GROUP	TRANSVAAL S. GROUP DOLDRITE & S. REEF Gps.	TRANSVAAL S. GROUP PRETORIA Gp.	WATERBERG S. GROUP	GHANZI GROUP	KAROO S. GROUP STORMBERG Gp. BASALT	KAROO S. GROUP STORMBERG Gp. BAS./CAVE Set.	KAROO S. GROUP STORMBERG Gp. CAVE Set.	KAROO S. GROUP ECCA & OUKA Gps.	DIABASE/DOLERITE INTRUSIVES	KALBAR
NO. OF BOREHOLES	472	57	87	28	74	76	209	71	128	154	78	250	59	61
NO. SUCCESSFUL	220	24	37	19	61	68	157	42	93	150	49	110	42	36
NO. BLANK	202	33	50	6	13	10	82	29	35	4	27	132	57	25
NO. SALINE (INCL. 1% BLANK TOTAL 480VC)	3	1	1	-	-	-	3	3	3	2	2	22	-	1
AVERAGE YIELD (LITRES/MIN)	72,34	26,03	40,76	53,89	100,30	208,45	75,84	97,99	95,81	127,36	79,03	102,99	64,9	61
AVERAGE DEPTH SUCCESSFUL BHS.	86,58	58,43	61,97	74,51	69,62	113,29	66,27	62,63	72,21	109,07	111,65	137,72	65,65	36
AVERAGE DEPTH ALL BHS.	97,99	51,97	65,82	71,63	70,78	116,27	86,60	66,79	75,74	109,37	105,85	115,82	60,63	41
AVERAGE DEPTH WATER STRUCK	34,32	31,17	43,63	38,55	35,92	57,50	40,35	41,07	38,66	61,32	67,72	97,05	30,79	23
AVERAGE DEPTH TO STATIC WATER LEVEL	23,20	20,62	20,94	29,85	28,22	44,58	27,97	31,92	26,63	37,82	54,68	65,25	19,20	18
% SUCCESSFUL	57,2	42,1	42,52	76,8	82,43	87,17	75,11	59,15	72,65	97,4	64,77	42,20	42,42	60

DETAILED GROUND-WATER STUDIES AND INVENTORIES1. HYDROGEOLOGY OF THE CENTRAL KALAHARIINTRODUCTION

Prior to the establishment of the Geological Survey in 1949, comparatively little was known of the sub-Kalahari Beds geology in the Central Kalahari. With the need to develop ground water supplies in this inaccessible region however, a fair knowledge of the geology and hydrogeology of the area has been built up.

Previous descriptions of the geology or hydrogeology of the Kalahari have been given by Passarge (1904), du Toit (1916), MacGregor (1932), Rogers (1934, 1935, 1936), Debenham (1948), Wayland (1953) van Straten (1953, 1954, 1955), Crockett and Jennings (1965), Mazor et al (1974, 1974a) Boocock and van Straten (1962) gave a particularly detailed and valuable account of this area.

PHYSIOGRAPHY

The central Kalahari is a vast featureless Kalahari-sand covered plain standing at an average elevation of about 1 000m. This plain rises to over 1200m on its eastern and northwestern margins. The Kalahari has a good cover of trees, scrub and grasses. Because of this the country is eminently suitable for cattle ranching if ground water can be found.

The only features breaking the monotony of the central Kalahari are low fixed sand dunes, pans and, in some areas, fossil river valleys. In the northern Kalahari the area is traversed by the semi-perennial Boteti River which links the Okavango Swamps with Lake Xau.

RAINFALL AND CLIMATE

Rainfall over the central Kalahari drops off progressively from the eastern Kalahari towards the central area (470mm to 300mm) and also towards the southwest and averages only 150mm at the Molopo-Nossob confluence. The climate consists of a hot rainy summer season alternating with a long dry winter often with severe frosts in the southwest. Rainfall for the five year period ending 1971/1972 is shown in Table 12. (See Fig. 11).

TABLE 13

SEASONAL RAINFALL IN MM MEASURED AT OBSERVATION BOREHOLES ACROSS KALAHARI (KWENENG)

Place	Co-ordinates Lat S Long E	Mean (5yrs)	Seasonal rainfall				
			1967/8	1968/9	1969/70	1970/1	1971/2
Lethakeng	24°07' 25°01'	459,28	468,5	387,9	397,9	412,2	629,9
Tshonya Pan	24°08' 24°51'	400,36	526,1	349,0	202,9	251,7	672,1
Lekotsane	24°09' 24°39'	472,72	537,5	481,2	229,8	374,1	741,1
Kalaetswago	24°11' 24°31'	307,12	359,6	300,7	191,0	205,7	478,6
Majwane	24°11' 24°12'	402,18	567,1	308,8	346,7	240,7	547,6
Tsamane	24°07' 23°26'	398,42	422,4	323,7	273,3	308,6	664,1
Botsomelo	24°06' 23°16'	463,3	417,4	447,5	344,5	528,9	578,2
Norwamosu	24°05' 23°05'	293,18	290,60	139,2	188,3	319,6	528,2

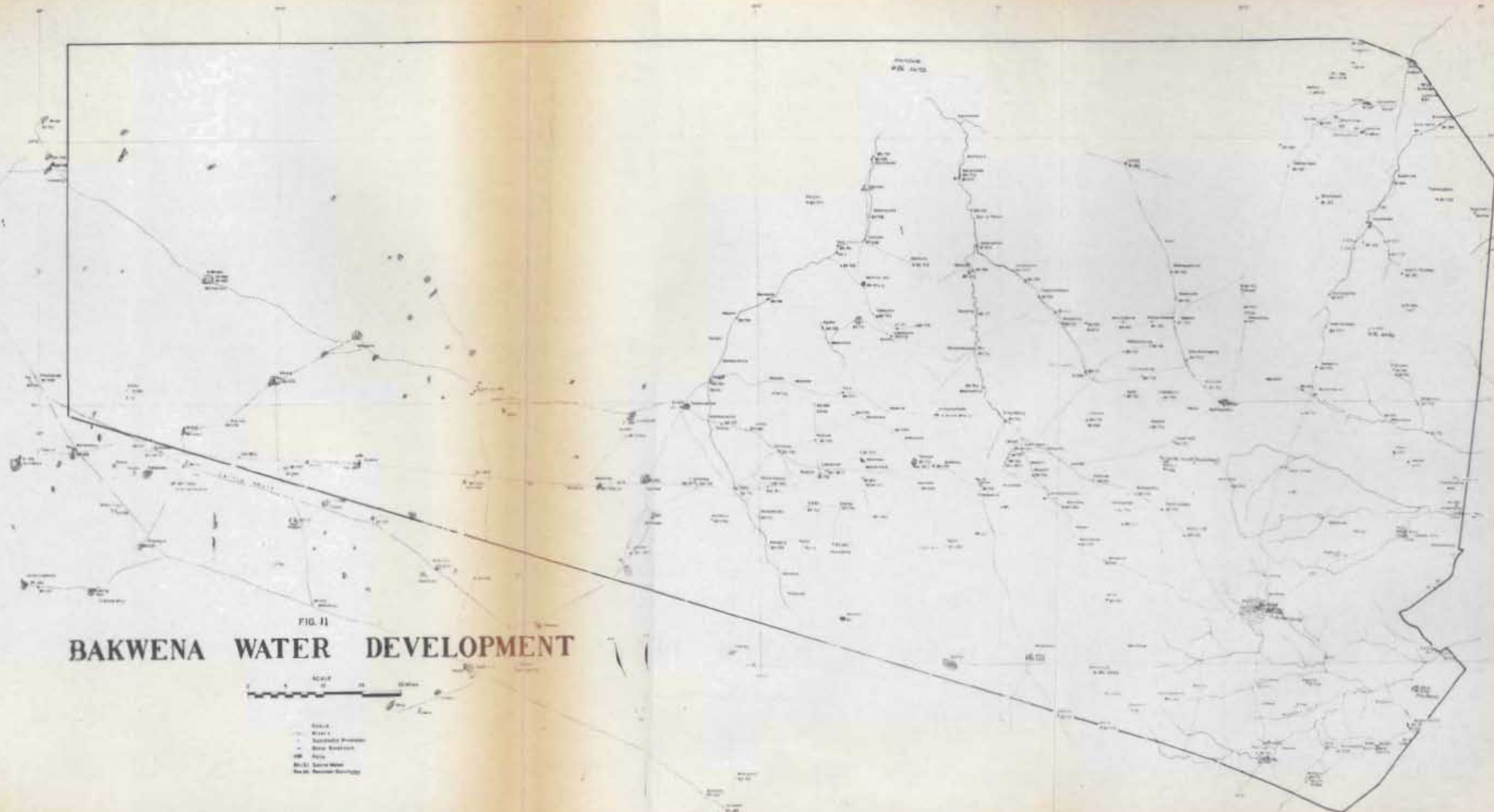


FIG. 11

BAKWENA WATER DEVELOPMENT



- Dam
- Weir
- Siphon Power
- New Dam
- Road
- R.R.
- Sewer Main
- Water Supply Main

GEOLOGY

The following generalised stratigraphic column is present in the Kalahari:-

Kalahari Beds	
	} Stormberg Group
Karoo Supergroup	} Ecca Group
	} Dwyka Group
Ghanzi Group	} Kgwebe Porphyry Formation
	} Ghanzi Beds Formation
Waterberg Supergroup	} Pretoria and Griquatown Groups
Transvaal Supergroup	
	} Dolomite and Black Reef Groups
Kanye Volcanic Group	
Basement Complex	
Intrusives.	

Details of the individual geological formations will not be given here as they have been comprehensively described by Boocock and van Straten (1962). Subsequent core boreholes, drilled as part of the hydrogeological research programme, have given valuable new information on the Kalahari Beds. These are described in the logs given under the section on Hydrogeological Research.

HYDROGEOLOGY

The water-bearing properties of the various geological formations have been described in a separate chapter which also gives statistical data on boreholes drilled in these formations.

Hydrogeological Research

As the better watered eastern portion of Botswana has become overgrazed and with an increase in the national herd, expansion of cattle ranching westwards into the Kalahari sandveld has taken place. Martin (1961) had given field evidence to show that ground water in South West Africa becomes difficult to obtain wherever the cover of loose dune sand exceeds a certain limit. Van Straten (1955), on the basis of laboratory experiments carried out at the Geological Survey, showed that when the thickness of unconsolidated sand cover consistently exceeds 6 metres there is little possibility of recharge under present climatic conditions. Accordingly it was thought highly probable that the majority of boreholes drilled in the greater portion of Botswana were utilising fossil underground water supplies unless recharge took place in favourable intake areas in the east and then migrated westwards. As this area had been chosen for relatively intensive development of underground water supplies for the

cattle industry, it was decided to establish a series of $2\frac{1}{2}$ inch (45mm) cored observation boreholes through the Kalahari Beds into the aquifers being developed in the Middle Ecca Group of the Karoo Supergroup. This line of observation boreholes, sited at 8 to 16km intervals, extends for 193 km from south of Letlhakeng to Morwamosu in the central Kalahari and probably represents one of the first approaches in research in Southern Africa into the behaviour of aquifers being exploited in such an environment. It was recognised that under present utilisation of these ground-water resources, considered on presently known hydrogeological data to be of fossil origin, few results were likely to accrue for many years. It was, however, considered important to initiate hydrogeological studies at an early stage to anticipate possible intensive utilisation of these ground-water resources in the future. The core boreholes not only give detailed sections through the hitherto virtually unknown Kalahari Beds, but show that, despite the relatively porous nature of the Middle Ecca Group grits, water movement takes place mainly along narrow joints varying from 1.5mm to 6.35mm in width which act as water conduits. The observation boreholes were initially equipped with 6-monthly or monthly water stage recorders together with rain gauges at selected stations. These automatic recorders did not function satisfactorily because of the narrow diameter of the boreholes and water levels were then measured electrically at two

In this rather remote area it was not possible to record daily rainfall figures. To test the accuracy of unmonitored rain gauges, an experiment was carried out utilising two adjacent standard rain gauges in Lobatse over a 15 month period. One rain gauge was read daily and the second at monthly intervals. The experiment showed that under evaporation conditions experienced in the Lobatse area, there was less than 2% difference between monthly totals and totals determined from daily readings. Accepting this factor, it was considered that monthly totals determined from these rain gauges established on individual observation boreholes could give a relatively reliable estimate of monthly rainfall data without incurring excessive financial expense in arranging for daily figures to be recorded. Rainfall data from the various stations shown in Fig. 11 are given in Table 13 .

A geological section showing the core drilling and water levels in the various boreholes is given in Fig.

Typical logs of two of the core boreholes drilled in this area are given in Appendix 1.

As no accurate topographic maps were available for the area, accurate barometric levelling was carried out on all borehole collar elevations (these were tied in to the existing trigonometrical network). Isopiezometric contour maps, topographic contours and contours of the base of the Kalahari Beds were prepared

..../and

and are shown in Figs.12, 13, 14 and 15. The isopiezometric results were somewhat surprising as it was generally accepted that recharge of the important Middle Ecca Group aquifer took place in an area of limited exposures of Ecca sandstone, south and east of Letlhakane. The isopiezometric data, however, showed conclusively that recharge takes place further to the west in an area where the Kalahari Beds are approximately 30m thick. This area coincides with the highest ground topographically and the brief five year rainfall record shows that this area has a markedly higher rainfall than elsewhere. Carbon -14 and tritium datings of ground water from this area have confirmed this and it appears that we thus have incontrovertible proof of recent recharge through at least 30 metres of Kalahari Bed cover. (Not necessarily Kalahari sand).

Water levels in boreholes.

Water level measurement in boreholes was commenced between 1965 and 1967 and results are plotted in Figs.16-21. These hydrographs show surprisingly little change in water level despite the fact that a number of the observation boreholes are situated within 6 - 20m of equipped (pumping) boreholes. Several hydrographs - that of recorder boreholes 1 and 6 at Letlhakeng and Bajwane respectively and borehole 1988 (Figs.16, 17, 19) show definite cyclic fluctuations of levels. The Bajwane borehole showed an overall rise in level between 1966 and the end of 1968 (unfortunately details of water fluctuations

FIG 12
BAROMETRIC LEVELLING - KWENENG.
TOPOGRAPHIC CONTOURS INTERVAL, 10' HEIGHTS RELATIVE TO SEA LEVEL.

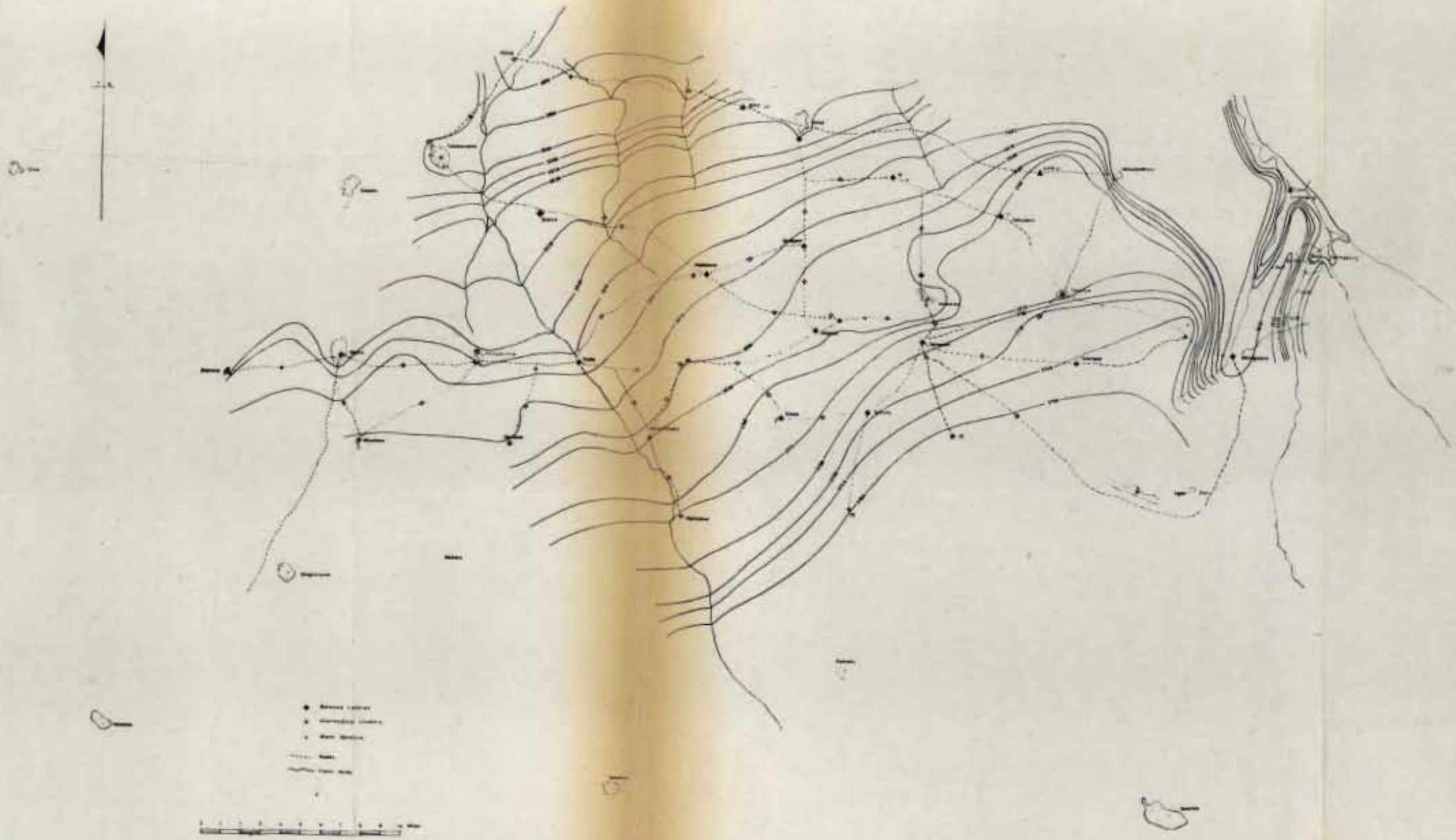
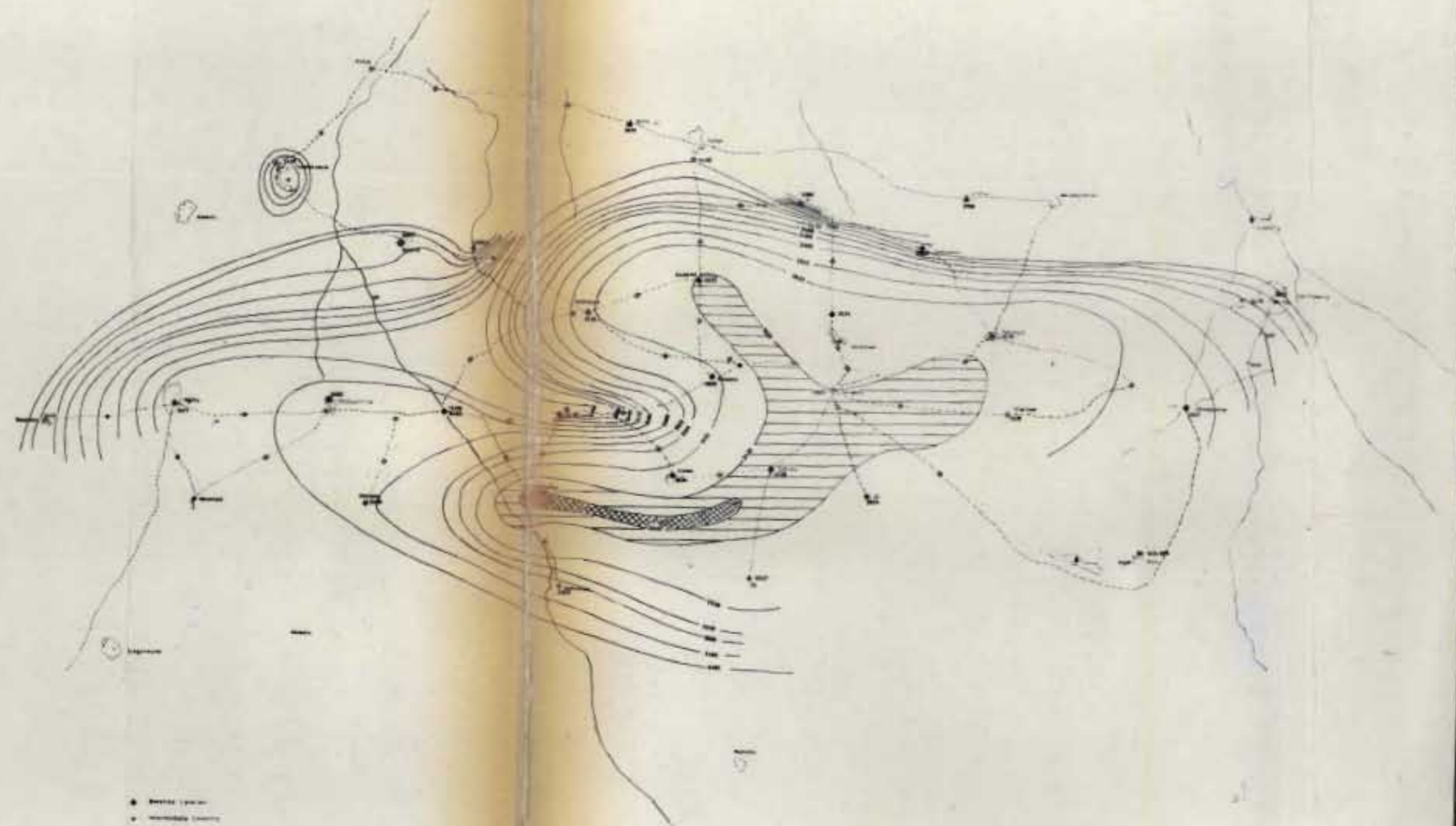


FIG 13
BAROMETRIC LEVELLING - KWENENG.
ISO PIEZOMETRIC CONTOURS 10' INTERVALS. HEIGHTS RELATIVE TO SEA LEVEL



9

10

10

10

BAROMETRIC LEVELLING - KWENENG.

CONTOURS OF BASE OF KALAHARI BEDS. CONTOUR INTERVAL 25 FT.
ALL HEIGHTS RELATIVE TO SEA LEVEL.

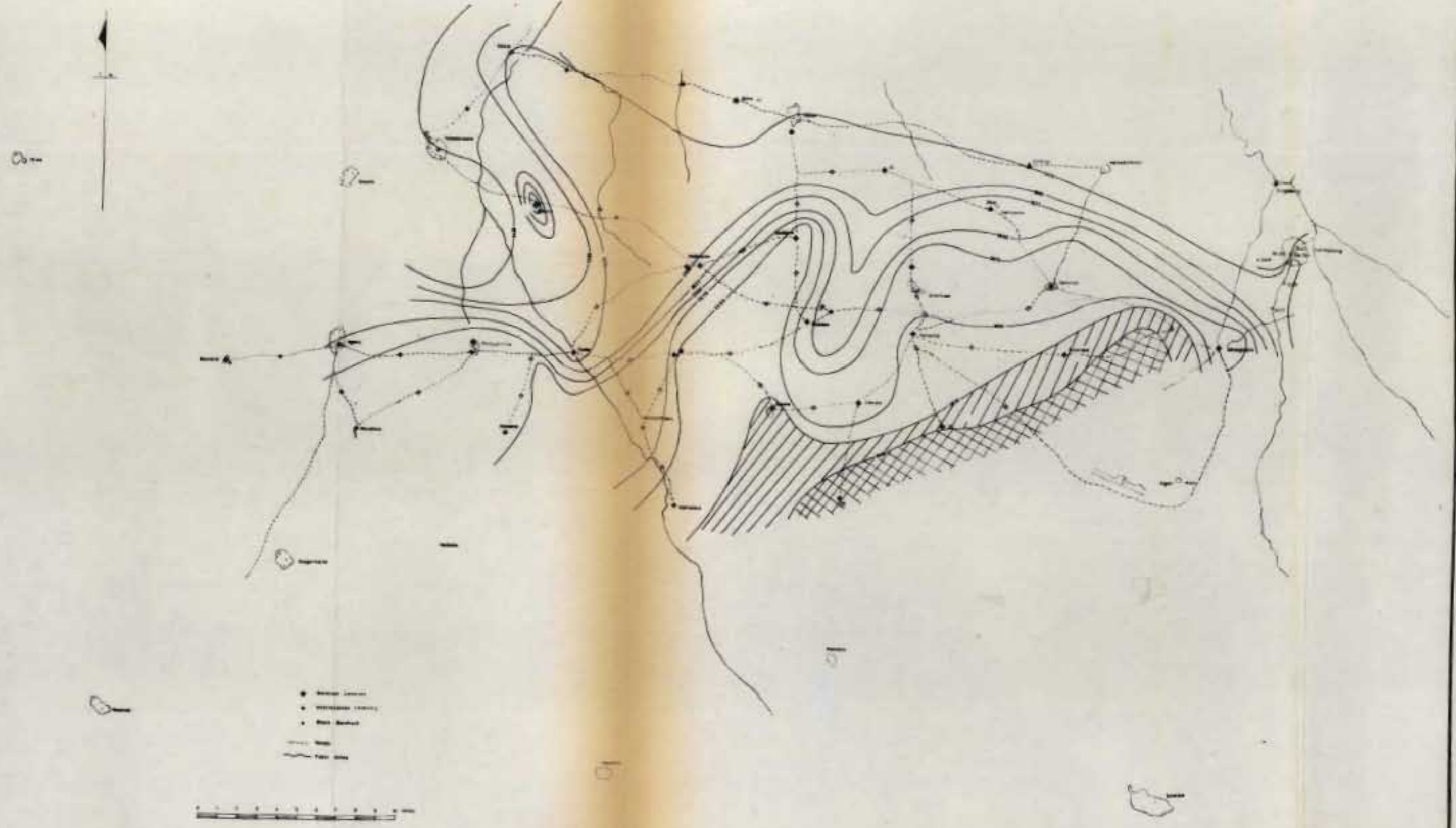
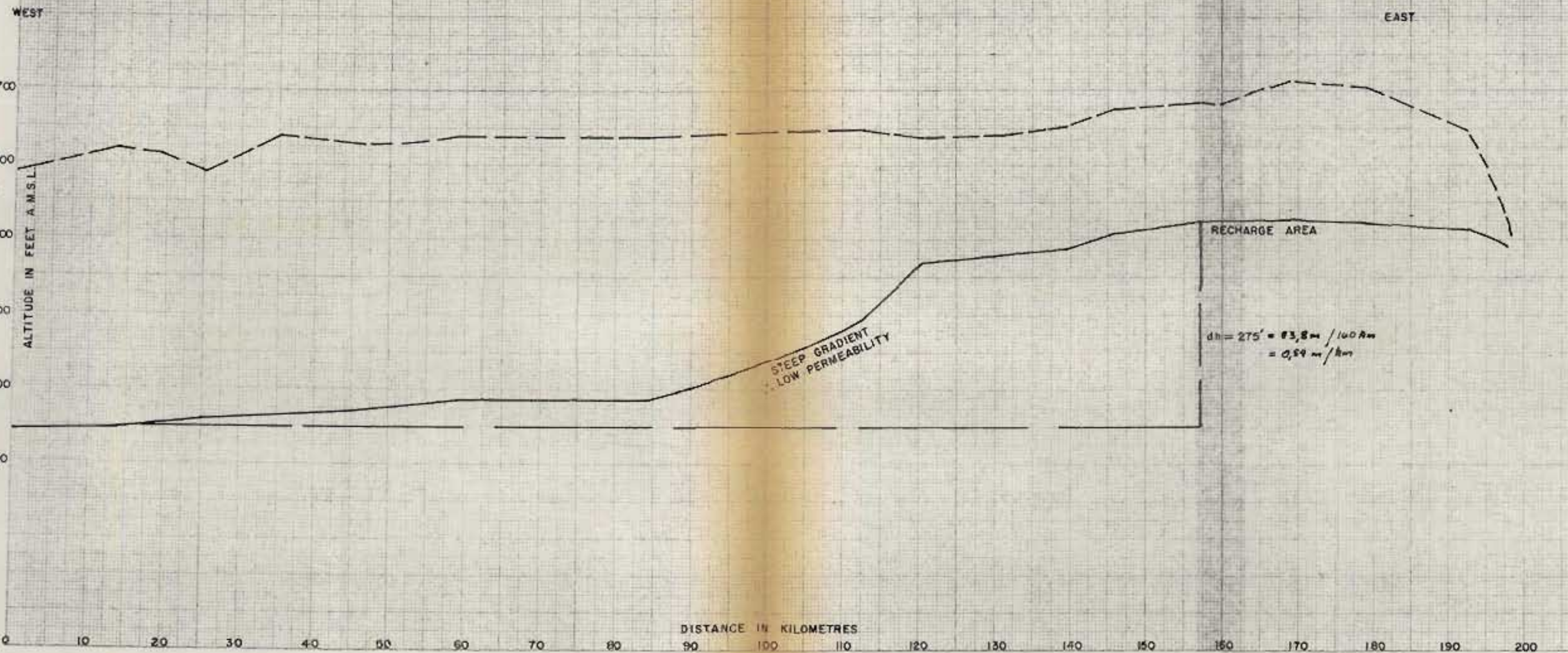


Fig. 15 SECTION AND PIEZOMETRIC PROFILE - C. KALAHARI



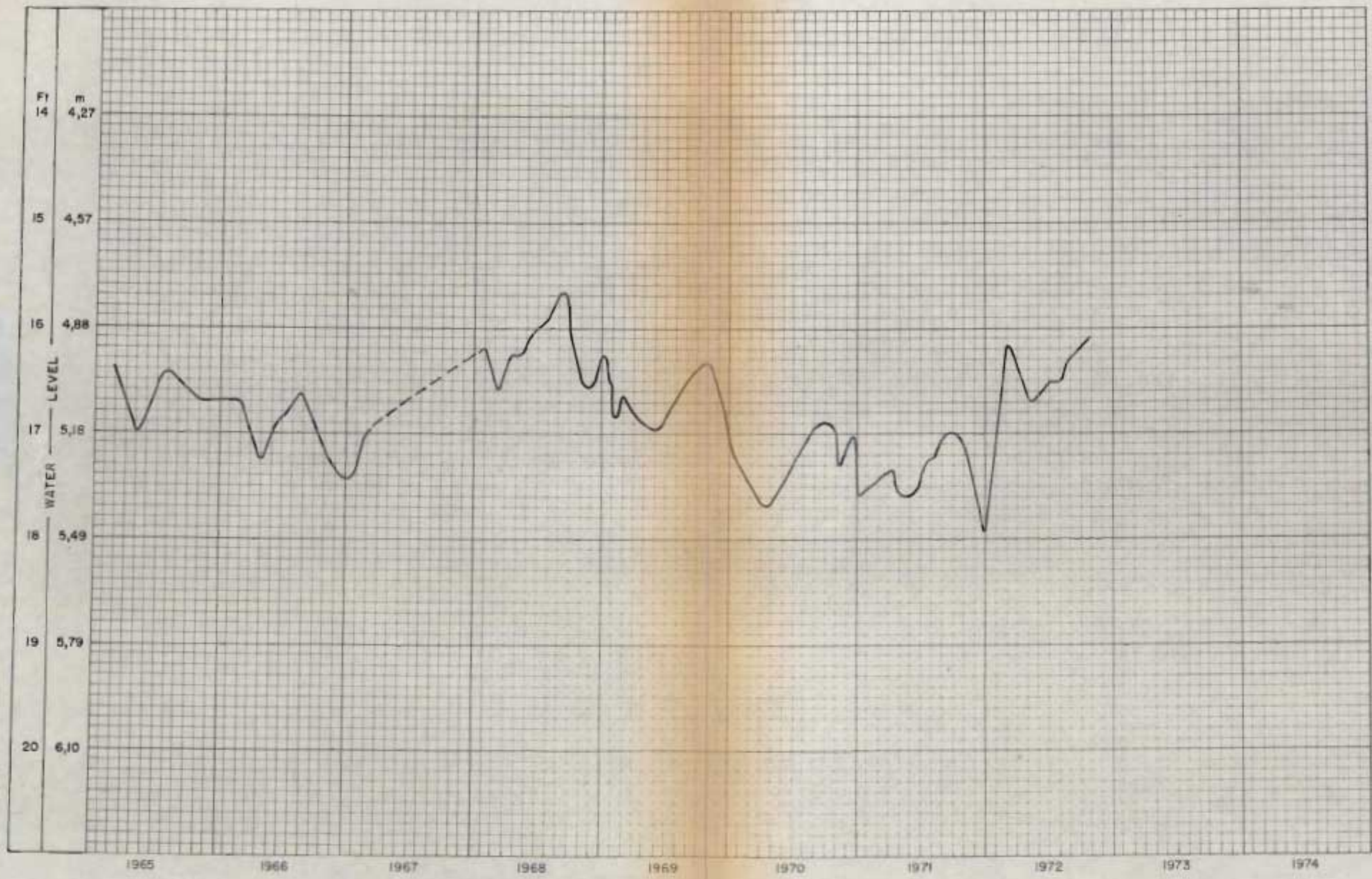


Fig. 16 HYDROGRAPH RECORDER BH 1 - LETLHAKENG - KWENENG

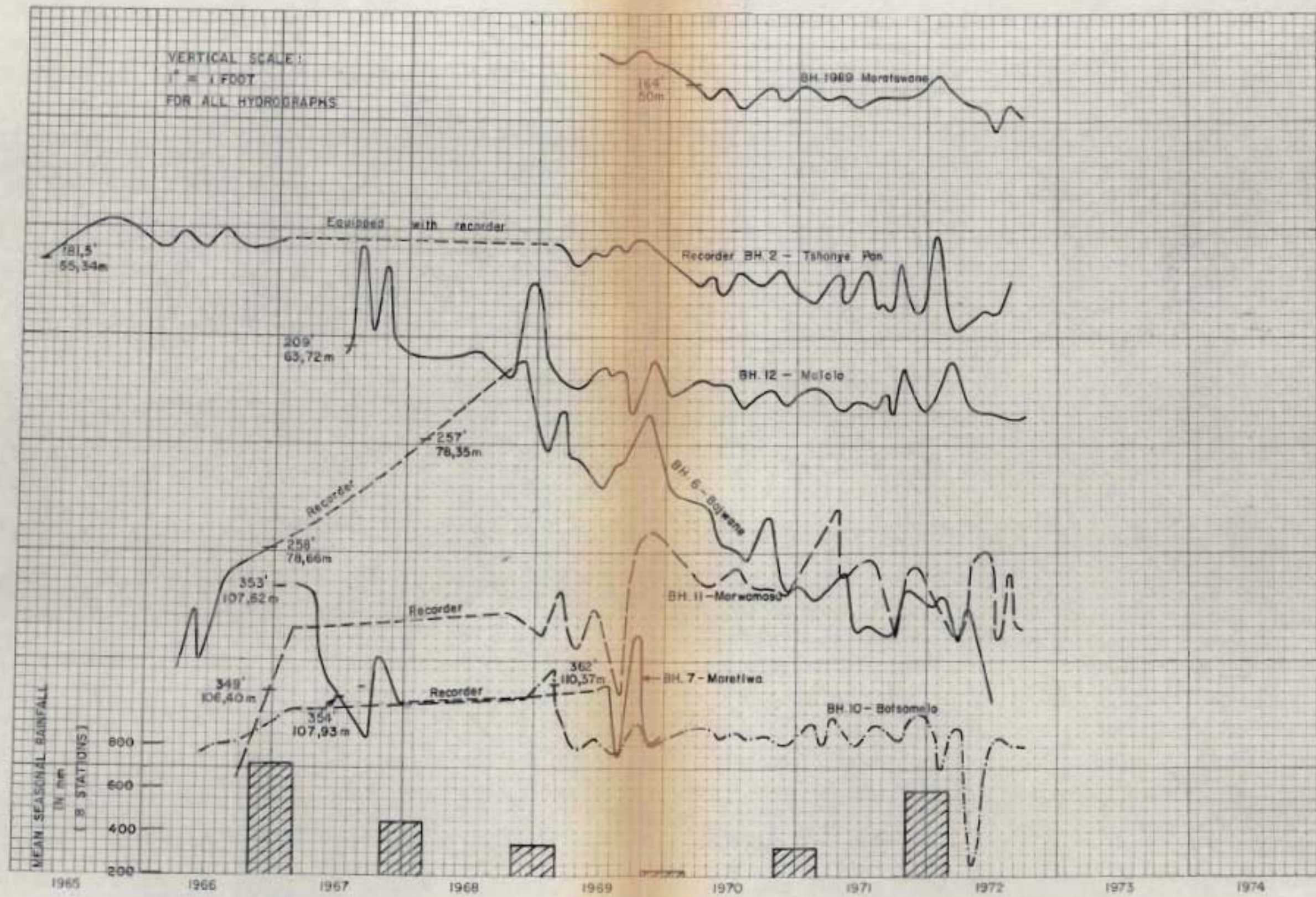


Fig. 17 HYDROGEOLOGICAL RESEARCH BOREHOLES ACROSS KALAHARI - KWENENG DISTRICT

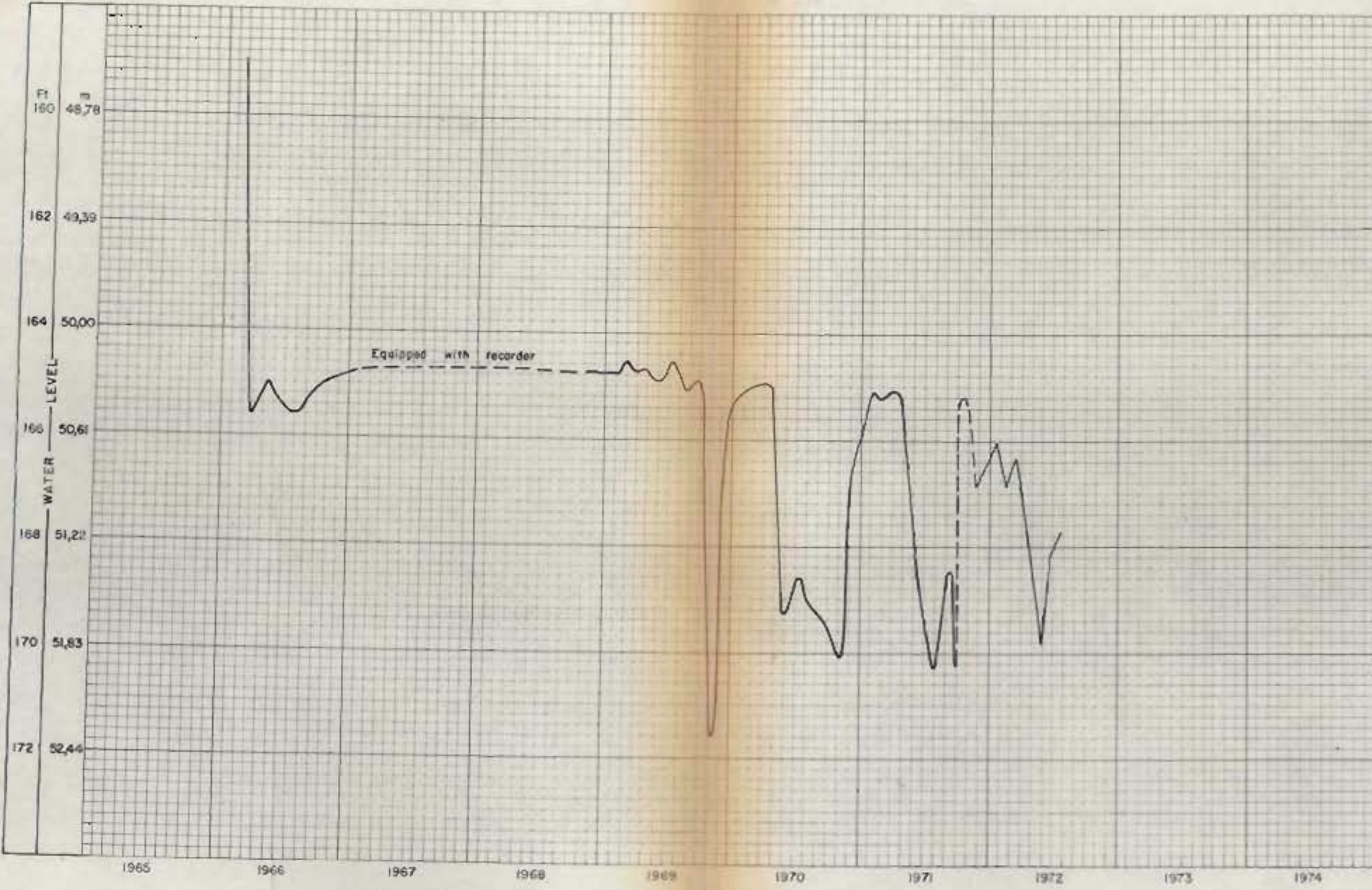


Fig. 18 HYDROGRAPH RECORDER BH 4 - KALA E TSWAGA - KWENENG

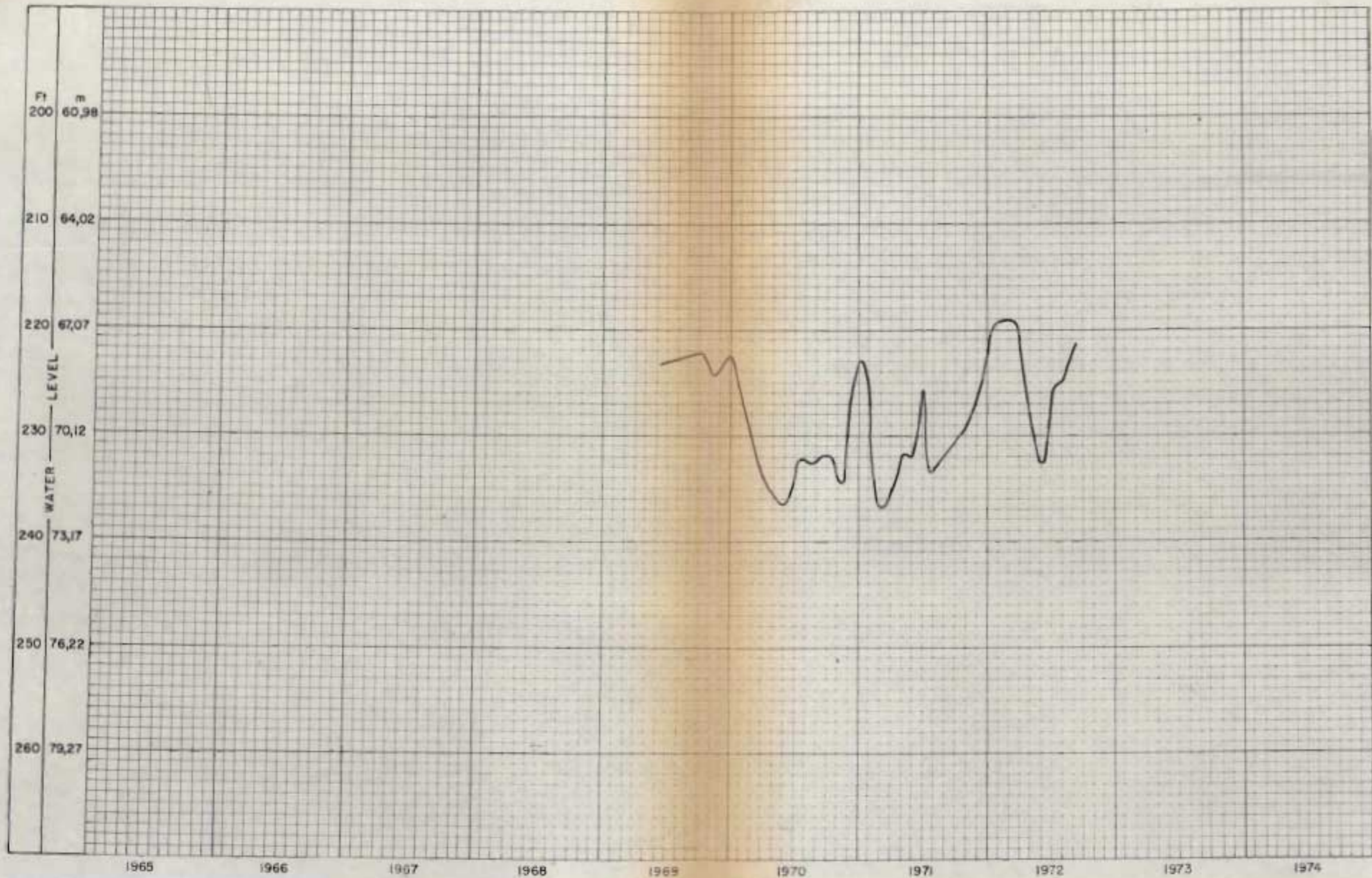


Fig. 11 OBSERVATION BH.1988 - MATLHOKOLA - KWENENG

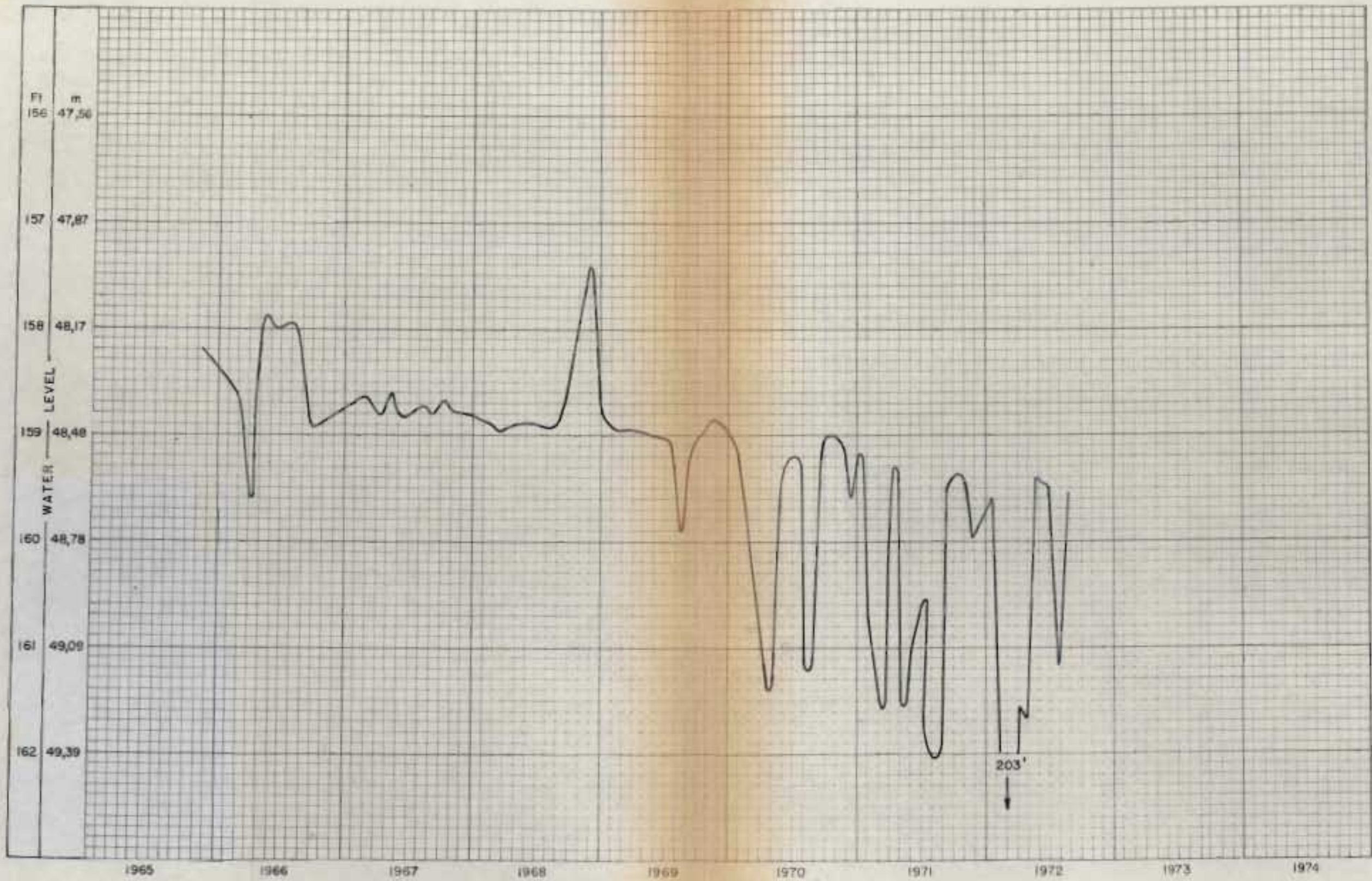


Fig. 20 HYDROGRAPH RECORDER BH.5 — POLOMPSHWE — KWENENG

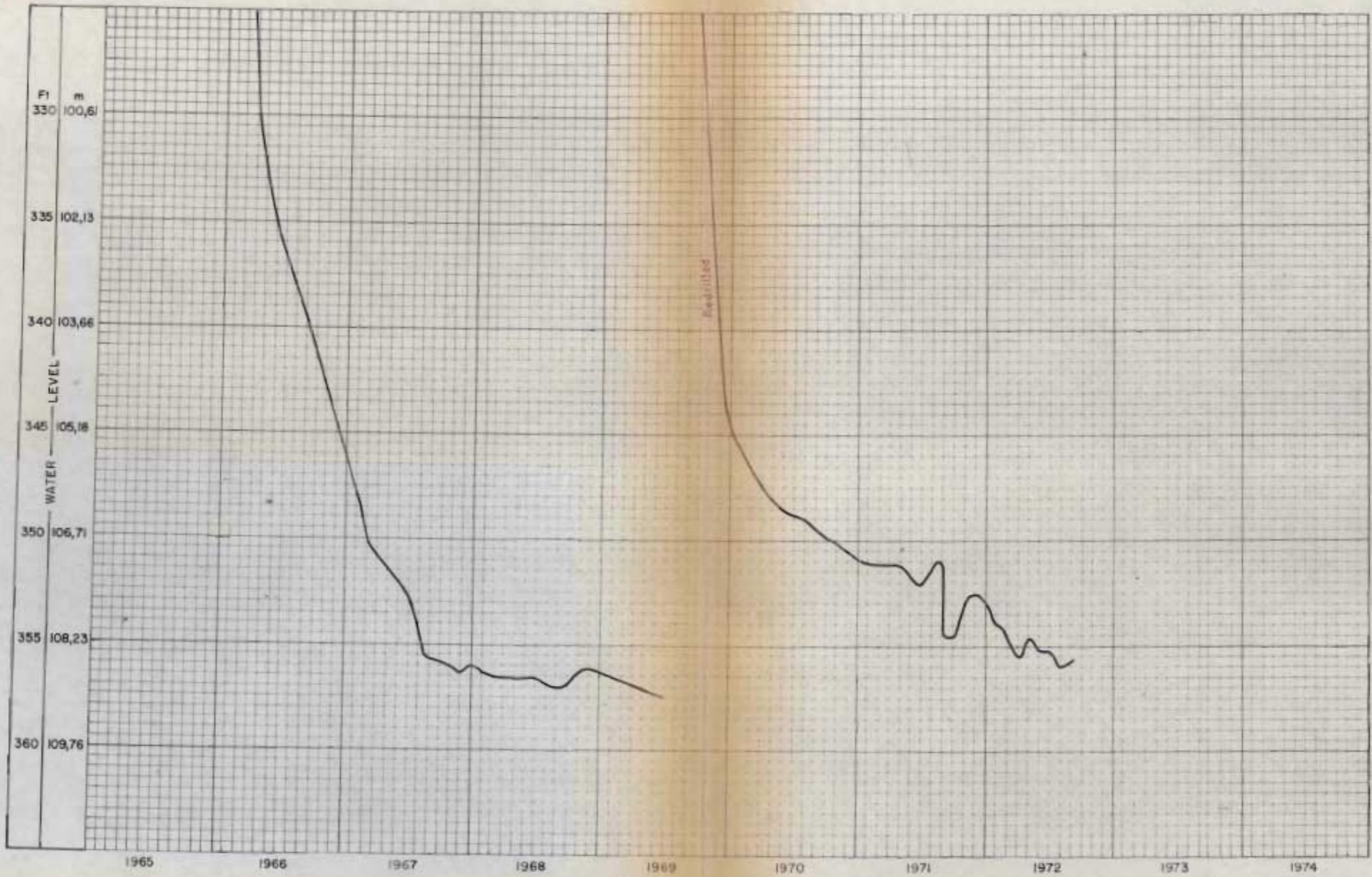


Fig 2.1 HYDROGRAPH RECORDER BH.8 - NANKWE - KWENENG

within this period are lacking because of the malfunctioning of the six-monthly automatic water stage recorder) and then a general recession from the beginning of 1969 till present with superimposed seasonal rises due to recharge events. These peaks are displaced four to eight months after the end of the rainy season (Fig. 17). The observation borehole at Letlhakeng (Fig. 16) clearly shows seasonal recharge events with peak levels between August and November i.e. four to eight months after the end of the rainy season. This lag probably represents the time taken for rainfall to infiltrate to the water table.

There is very little overall drop in water levels in all observation boreholes in the Kalahari. (Fig.17). For example, in observation Borehole 11 in close proximity to Borehole 858 (Morwamosu) water level fluctuations from 1966 to 1972 vary between 105,88 and 106,68m and there appears to be only a very minor overall recessionary trend of at most 15cm between 1969 and 1972. This is counteracted by an apparent overall rise in water levels between 1966 and the end of 1968 due probably to the good 1966/67 rainfall season. During the six year period between the end of 1966 and the end of 1972 an estimated $48\ 180\text{m}^3$ (10,5 million gallons) of water was pumped from the nearby borehole (400 people using 10 litres per day + 600 cattle using 30 litres per day for six years). Boreholes 4 (Fig. 18) and 5 (Fig. 20) do, however, show fluctuations in water level in response to heavy pumping of nearby boreholes. Borehole 8 (Fig.21) shows a gradual recession in water level.

This borehole was the only borehole drilled in impermeable Waterberg Supergroup shale and quartzite and the recession shown is due to the loss of the drilling water in the core borehole into the low permeability surrounding sediments. The rise in level at the end of 1969 occurred when the hole was redrilled because of collapse of a portion of the borehole.

It would appear therefore that the line of observation boreholes sited at strategic intervals across the important Central Kalahari ranching area has already commenced to provide invaluable evidence that recharge is taking place at least in the eastern Kalahari area, and that, despite the relatively heavy pumping of water from important cattle watering points, no alarming drop in water levels is taking place as had been feared earlier. Confirmatory evidence will also be presented later, from isotopic measurements (^{14}C and tritium) that present day recharge is indeed taking place at least in certain areas of the Kalahari thus refuting to a certain extent the earlier contention by Martin (1961) and van Straten (1955) that no recharge takes place in the Kalahari.

Environmental Isotope Studies

Details of data accumulated by collaborative studies between the writer and Dr. J.C. Vogel of the Council for Scientific and Industrial Research, and the Nuclear Physics Research Unit of Witwatersrand University (Mazor et al 1974)

are presented in the Chapter on Environmental Isotopes, and only a brief summary of the most important results will be given here: -

Carbon - 14

Results of an intensive water sampling programme for isotope analysis in the western Kweneng District have given rather unexpected results in that relatively much younger waters were encountered - a number with post 1952 tritium. In the Mabutsane Borehole (1102) repeat water sampling has indicated that recharge of this borehole took place between 1968 and 1972. Carbon - 14 measurements back up in excellent fashion deductions made from a research programme in which isopiezometric contours were plotted and from which potential recharge areas were deduced.

Tritium

Tritium values in the Central Kalahari area are generally less than 2 T U indicating little post-bomb (1952) recharge. Exceptions do however occur and the Mabutsane Borehole (1102) indicates much post-bomb recharge in an area of Waterberg Supergroup Sandstones in the Central Kalahari. Other boreholes Khakhea (Sample 82), Tshane (Samples 72, 73), Tsabong (Sample 79), Maitlo a Phuduhudu (Sample 671), Phuduhudu (Sample 48) and Ncojane (Sample 76) all indicate post-bomb recharge. Of the above boreholes, Khakhea, Tshane, Ncojane and Maitlo a Phuduhudu are situated within or adjacent to

major pan depressions where localised concentrations of rain run-off occur or in the case of Maitlo a Phuduhudu adjacent to a fossil valley. The Tsabong borehole is sited on thin sand cover overlying Matsap quartzites which crop out nearby. The Phuduhudu borehole (Sample 48) is therefore the only borehole in the Central Kalahari providing evidence of recent recharge through approximately 56 m of Kalahari Beds cover.

Stable Isotopes

Stable isotope measurements indicate little change in recharge conditions from that of present day has occurred during the time span of radio-carbon datings (\pm 40 000 years). These conditions are intense rainfall accompanied by low evaporation.

HYDROCHEMISTRY

Boocock and van Straten (1962) have divided the ground waters in the Kalahari into three groups. Group A consists of fresh to weakly mineralised saline, bicarbonate waters characteristic of the calcretes and sileretes of the Kalahari Beds, potable waters from the Middle Ecca and Cave Sandstone - basalt aquifers (Karoo Supergroup), and of water from the Waterberg Supergroup and Ghanzi Groups. Group B consists of weakly mineralised to highly mineralised magnesium and calcium chloride waters found near pans; in Upper Ecca Subgroup shales beneath thick sections of Kalahari sand;

in the Middle Ecca Subgroup sandstones northwest of Kukong; and in wells and boreholes tapping the Kalahari Beds in the lower Molopo and Nossob Rivers. Sodium is the dominant cation but magnesium and calcium are present in higher concentrations than group A as are chloride and sulphate anionic constituents. Group C consists of weakly to highly mineralised sodium carbonate waters encountered in Kalahari Beds; in some Karoo aquifers, occasionally in older rocks, usually near pans or impeded drainages. Dissociated sodium carbonate is frequently present in these waters. Carbonate is, however; only a minor anionic component. Sodium is the dominant cation with only minor calcium and magnesium present.

Selected analyses of waters from the Central Kalahari are shown in Table 14 .

TABLE 14

SELECTED ANALYSES OF GROUND WATERS FROM THE CENTRAL KALAHARI

Water type	Group A	Group A	Group B	Group C	Group C
Bh No.	1102	770	858	994	1500
Locality	Mabutsane	Mamatlaku	Morwamosu	Depth 630' Boritse Pan	Kang Pan
Date	17.1.63	30.4.62	17.5.68	31.3.58	16.6.65
pH	7,55	8,3	7,7	8,65	8,6
CO ₃ ⁻⁻	-	-	-	1375	150
HCO ₃ ⁻	479	181	514	4679	604
Cl ⁻	46	68	1617	35291	544
SO ₄ ⁻⁻	13	37	348	7360	74
F ⁻	2	1	1	33	6
Total anions	540	287	2480	48720	1378
K ⁺	55	4	53	-	33
Na ⁺	85	30	1175	28324	715
Ca ⁺⁺	25	39	63	-	2
Mg ⁺⁺	40	31	67	423	1
Total cations	205	104	1358	28747	751
Sum total	745	391	3838	77467	2129
Tds	536	316	3704	77768	1832
Theor. Tds	502	299	3677	75165	1822
K	800	380	5500	-	2800
¹⁴ C p.m.c.	92,1 [±] 1,4	66,28	31,92	-	67,7 [±] 1,2
T U	10,8 [±] 1,2	-	0,8 [±] 0,4	-	0,0 [±] 0,2

Repeated sampling of water from a number of boreholes in the Central Kalahari show only minor variations and no overall deterioration in quality. An example of this is shown in Table 15 .

TABLE 15

RESULTS OF REPEATED WATER ANALYSES
ON BH. 858, MORWAMOSU, CENTRAL KALAHARI

Date	30.4.62	17.1.63	12.9.63	8.4.65	27.4.66	20.3.67
Total dissolved solids in ppm.	3835	3935	4100	4197	4106	3810

Date	8.12.67	21.3.68	17.5.68	6.1.69	28.3.72
Total dissolved Solids in ppm.	3963	3709	3838	3753	4005

Because of the lack of alternative water supplies, water of a quality normally regarded as unpotable for stock and humans is often used as the sole source of supply. At Tsetseng, for example, humans and stock use water during the dry season with a total dissolved solids content of 12592 parts per million (Boocock and van Straten, 1962). The Kalahari thus represents a fruitful field of research for the investigation of limits of tolerance to humans and stock to various dissolved chemical constituents.

APPENDIX 1KWENENG HYDROGEOLOGICAL RESEARCH PROGRAMMECORE BOREHOLE AT LEKOTSANA OR (MOGAGARAPE)

0' - 4'	No Recovery.
4' - 24'	15'7" Core. 4'5" Lost. Hard, compact grey-white slightly sandy limestone (calcrete) 1st 4'6" of core rather fragmentary. In places however the core is porous showing a mammillary silica-coating on the irregular joint surfaces.
24' - 30'	6' Recovery no core lost. As above.
30' - 43'7"	7" 12'7" Core. No core lost. Mottled sandy calcrete with numerous irregular chert bands and inclusions.
43'7" - 56'5"	No core lost. 12'10" core. 10'4" Mottled calcrete. 2'6" Mottled calcrete conglomerate with sub-rounded pebbles of dolerite, quartzite, vein quartz mylonite, mid-Ecca sandstone ferruginous quartzite etc. Some pebbles are cut by calcite veins.
56'5" - 75'3"	18'10" core. No core lost. As above - pebble size up to 2". The calcrete may be partly replaced by silica.
75'3" - 83'6"	5' Core. 3'3" Core lost. 3'9" As above, with several fairly well rounded pebbles of ferruginous quartzite (Daspoort?) at base (up to 2" in diameter) - Core fragmentary.
79'0" - 80'3"	Grey-white calcrete now replaced by silica to form a dull white silcrete. Remainder core lost.
83' - 6" - 96'	6'8" Core. 5'10" lost. Silcrete grading downwards into dull grey-white to pink marl.

BASE OF KALAHARI BEDS

96' - 116'	10' Core. 10' Core lost. Core rather broken. 1'0" Brown to pink-brown mudstone (Ecca). 1" Very calcareous mudstone-probably calcretised by solutions along a joint plane from overlying calcretes. 2'1" Brown mudstone.
------------	---

116' - 146'	19'9" Core 3" Core lost. 13'8" Brown mudstone. 0'0 $\frac{3}{4}$ " Ferruginous and calcareous sandstone lens. 6'0" Fragmentary core of brown mudstone.
146' - 156'	10' Core. None lost. Broken core of muddy, brown siltstone.
156' - 186'	12'9" Core. 17'3" lost. Brown mudstone grading after 2 feet into mottled pink to brown mudstone with ferruginous staining. Plant fragments occur in last 3 feet.
186' - 196'	No core recovery.
196' - 206'	1'8" Core. 10'4" Core lost. 1'8" Med-coarse grained grey feldspathic mid-Ecca grit.
206' - 216'	0'2" Core. 9'10" Core lost. 2" As above.
216' - 227'	6' Core. 4' Lost. 6' Grey medium-grained feldspathic grit.
227' - 236'	7'10" Core. 2'2" Lost. As above.
236' - 252'	13'10" Core. 2'2" Lost. As above, but grey to rusty brown in colour and with occasional clay lenses.
252' - 296'6"	44'6" 13' Core. 30'6" Lost. Very coarse grey gritty micaceous feldspathic Ecca grit with occasional clay lenses.
296' - 302'3"	No core lost. As above.

END OF HOLE

APPENDIX 2RECORDER BOREHOLE KALA E TSWAGA

- 0 - 18' No core recovery - sand?
- 18 - 25' 6'4" Core 8" Core lost.
0'7½" Red brown, friable, slightly calcareous med-grained sandstone - fragmentary core.
0'8" Hard calcrete - fragmentary core
3'9" Calcrete conglomerate with numerous well rounded to sub-angular pebbles up to 2" in diameter - pebbles appear to consist mainly of felsite and sandstone (some fine-grained pink siltstone with coarse grains-resembling a quartz porphyry. Dolerite is also present.
- 25 - 36' 10'11" Core 1'1" Core lost.
3'0" Core of hard calcrete conglomerate END of N.X.C.
1'0½" Calcrete conglomerate.
6'11" Mottled, red-brown sandstone cut by intricate vein work of calcite veins, some now replaced by opaline silica. Occasional small pebbles +/- ¼" diameter of dark felsite occur.
- 36' - 46' 8' Core 2' Core lost.
5'0" Red brown fine-grained sandstone becoming less calcareous.
3'0" Brown sandstone with occasional veins of chalcedonic or opaline silica (core fragmentary).
- 46 - 56' 7'8" Core 2'2" Core lost.
7'8" Grey to light - brown, fine-grained partly calcareous sandstone. Core fragmentary.
- 56 - 62' 2'4" Core. 3'8" Core lost.
2'4" Fine-grained, partly calcareous light brown sandstone. Core fragmentary.
- 62' - 67' 4'9½" Core. 2½" Core lost.
As above.
- 67 - 76' 9'0" Core. No core lost.
9'0" Grey-brown, fine-grained sandstone with veins of white calcite, apparently along shear planes, in the sandstone.

76 - 86 9'9" Core 0'3" Core lost.
9'9" Light-brown, fine-grained sandstone with bands and irregular patches of white calcrete.

BASE OF KALAHARI BEDS

86 - 96' 4'4" Core
4'4" light brown siltstone grading downwards into a brown mudstone. Core fragmentary.

96 - 106' 8'7" Core. 1'5" Core lost.
8'7" light brown mudstone, calcareous in parts. Core broken.

106 - 116' 9'3" Core. 0'9" Core lost.
9'3" As above with 0 $\frac{3}{4}$ " calcite band 3' from top.

116 - 126' 9'1" Core. 0'11" Core lost.
9'1" light-brown mudstone.

126 - 131' 3'6 $\frac{1}{2}$ " Core. 1'5 $\frac{1}{2}$ " Core lost.
As above.

131 - 136' 5' Core. No core lost.
As above.

136 - 146' 7'5" Core. 2'7" Core lost.
As above.

146 - 156' 9'7" Core. 0'5" lost.
9'7" Grey-brown mudstone with red mottling and bands.

156 - 166' 10'0" No core lost.
10'0" Grey mottled mudstone grading into a banded siltstone.

166 - 176' 10'0" No core lost.
10'0" Banded siltstone with small ferruginous nodules.

176 - 193' 16'4" Core. 0'8" Core lost.
12'3" As above.
4'1" Dark grey micaceous shale with lighter calcareous bands.

193 - 196' 3'0" Core. No core lost.
3'0" Grey shale.

196 - 204'6" 8'6" Core. No core lost.
8'6" Grey shale grading downwards into a pale grey siltstone.

204'6" - 212'6"	8'0" Core. No core lost. 8'0" Pale grey shaly siltstone.
212'6" - 216'2"	3' Core. No core lost. 3'8" Grey brown banded siltstone.
216'2" - 226'	9'10" Core. No core lost. 9'10" Grey-brown muddy siltstone grading into grey-green shale.
226' - 236'	9'8" Core. 0'4" Core lost. 9'8" Grey-green shale grading into reddish shale all with numerous thin siltstone partings. Occasional ferruginous nodules and lenses occur.
236' - 246'	10'0" core. No core lost. Red-brown silty shale grading downwards into a grey-green shale with numerous thin ($\frac{1}{8}$ ") calcite bands and lenses occur.
246' - 256'	10'0" Core. No core lost. 10'0" Grey shale with thin siltstone partings.
256' - 266'	9'6" Core. 0'6" Core lost. 9'6" Grey shale with siltstone partings.
266' - 276'	9'7" Core. 0'5" Core lost. 9'7" Grey silty shale.
276' - 286'	9'6" 0'6" Core lost. 1'6" Grey siltstone with plant fossil at base. 8'0" Grey siltstone.
286' - 296'	10'0" No core lost. 10'0" Grey micaceous muddy siltstone.
296' - 301'	4'6" Core. 0'6" Core lost. 4'6" As above.
301' - 306'	4'2" 0'8" lost. 4'2" Grey shale.
306' - 316'	9'7 $\frac{1}{2}$ " Core. 8'6" Grey micaceous shaly siltstone with plant fossil at base. 1'1 $\frac{1}{2}$ " Grey shale with siltstone partings.
316' - 236'	9'2" Core. 0'9 $\frac{1}{2}$ " Core lost. 0.11" Pale grey shale with siltstone partings. 2'0" Carbonaceous shale. 4'10" Pyritic coal with vitrinite bands and some carbonaceous shale. 1'5 $\frac{1}{2}$ " Grey shale with thin siltstone partings grading into pale grey siltstone.

- 326' - 336' 9'1" Core. 0'9" Core lost.
7'3" Pale grey siltstone grading into fine-grained grey sandstone with pyrite nodules and numerous thin dark grey shaly partings.
1'10" Medium-grained gritty micaceous sandstone.
- 336' - 346' 9'2½" Core. 0'9½" Core lost.
9'2½" Fine-grained sandstone with numerous dark grey shaley partings.
- 346' - 349' 3'0" Core. No core lost.
3' As above.
- 349' - 353'8" 4'8" Core. No core lost
4'8" Carbonaceous shale and coal.
- 353'8" - 356' 2'0" Core. 0'4" Core lost.
0'5" Grey carbonaceous shale.
1'0½" Mainly vitrinitic coal with some grey shale.
0'6" Grey carbonaceous shale.
- 356' - 366' 10' Core. No core lost.
10'0" Coal with minor thin shale bands.
- 366' - 372' 6' Core. No core lost.
6'0" Mainly bright, banded pyritic coal with some intercalated shale bands up to 3" thick.
- 372' - 385' 13'0" Core. No core lost.
0'10½" Bright and dull pyritic coal with siderite spotting.
2'3" Shaley coal
1'3" Dark grey micaceous shale.
2'2" Grey micaceous finely laminated siltstone to 2'¼" in diameter occur.
1'10½" Grey micaceous siltstone with numerous plant fragments.
0'3" shaley coal
2'6" Dark grey shale with thin vitrinite stringers.
1'10" Light grey shale with plant remains.
- 385' - 394' 8'9" core. 0'3" Core lost.
1'1½" Dark grey shale with numerous bright coal partings less than ½" in diameter.
2'8" Dark grey shale with plant remains.
0'4½" Grey micaceous shaly siltstone.
1'0½" Grey micaceous shale with plant remains.
0'3½" As above with much siderite spotting.
3'3½" Grey micaceous shale with plant remains.

493' - 404'	10' Core. No core lost. 2'9" Grey micaceous shale with thin micaceous siltstone intercalations towards the base. 0'1" vitrinitic coal with $\frac{1}{4}$ " thick pyrite layer. 1'4" Dark grey carbonaceous shale with plant remains. 0'1" Bright vitrinitic coal. 1'2" Dark grey carbonaceous shale. 0'2" Vitrinitic coal with siderite spotting. 1'10" Dark grey carbonaceous shale. 2'8" Carbonaceous shale alternating with shaly pyritic coal.
404' - 408'	4'4" Core. 0'4" Excess core. 1'10" Carbonaceous shale alternating with shaly pyritic coal. 2'6" Dark grey carbonaceous shale.
408' - 411'	2'11" Core. 0'1" Core lost. 2'11" Dark grey mudstone.
411' - 421'	9'10 $\frac{1}{2}$ " Core. 1'2" Core lost. 3'8" Dull and bright pyritic coal. 0'5" Carbonaceous shale. 2'10" Cross bedded siltstone. 3'3 $\frac{1}{2}$ " Carbonaceous pyritic shale.
421' - 432'	10'10" Core. 2" Core lost 1'8" Dark grey pyritic shale with thin bright coal partings. 7'2" Light grey micaceous siltstone with occasional plane remains. 2'0" Grey, micaceous medium-grained to coarse-grained Ecce grit.
432' - 442'	10'0" Core. No core lost. 10'0" Grey, micaceous medium-coarse-grained Ecce grit.
442' - 452'	5'3 $\frac{1}{2}$ " Core. 4'8 $\frac{1}{2}$ " Core lost. As above.
452' - 460'	4'10" Core. 3'2" Core lost. As above.

END OF HOLE

NOTE: Borehole 1867 nearby was drilled to a depth of 145m (475ft), encountered water from 107m onwards (352ft). Static water level was 51m and the tested yield 67,5 litres per minute (900 g.p.h.).

2. THE HYDROGEOLOGY OF THE LOBATSE AREAINTRODUCTION

Lobatse is a small village spread roughly for a distance of 5 km along the line of rail from South Africa to Rhodesia, and is completely surrounded by a group of low hills. It is situated at an average elevation of about 1220m above sea level, while the surrounding hills reach a height of 1427m. Lobatse is situated some 74 km south of the capital, Gaborone, in southeastern Botswana only 10 km from the border of the Republic of South Africa.

The development and precise date when Lobatse was founded is veiled in obscurity, but must have been closely allied to the completion of the railway line at the end of the last century, as the older part of the town developed round the railway station.

However, it was only during the 1940's that a rapid expansion commenced with the establishment of a creamery (Imperial Cold Storage Company) which was later replaced by the Abattoir. The Abattoir was established in Lobatse in 1954 by Bechuanaland Protectorate Abattoirs Limited and still later a subsidiary company - the Export and Canning Company, was formed to handle the canning and marketing of meat. Killing commenced on 20th September 1954. The first full year of operation of the abattoir was thus in 1955 and there has been a steady expansion ever since. In 1963 the Government agreed to convert the Bechuanaland Abattoirs Limited into a statutory corporation and as a result, the

Bechuanaland (now Botswana) Meat Commission was formed. The Commission now handles all meat exports from Botswana and in 1973 the value amounted to R31,3million. These exports constitute a high percentage of all exports from the country and hence Lobatse plays a vital role in the economy of the country. The provision of an assured water supply for the town is therefore of considerable national importance. Other industries in the town consist of a maize mill, cap and helmet factory, clothing factory and brickyards. Manganese mining is carried out some six miles east of Lobatse at Gopani and also 35 miles west of Lobatse at Kgwakwe. Lobatse is the commercial banking centre for the Molopo and Lobatse block farming communities and is the headquarters of the Government Geological Survey and the Posts and Telegraphs Departments. Lobatse also forms an important administrative centre for Rhodesia Railways and is also a vital watering point for the long dry haul by the Railways (steam) to the north of Lobatse.

The population of Lobatse is 12,920 (1971 Population Census).

HISTORY OF LOBATSE WATER SUPPLY

The Lobatse area probably represents one of the most intensely studied ground-water areas in Southern Africa. Wayland (1944) was the first to give an outline report on ground-water supplies in Lobatse. In this report, he mentions that the water supply derived from hand-dug wells, to that part of Lobatse township in the neighbourhood of the Government offices (i.e. D.C.'s Office area), was

inadequate. He also gave the first geological description and expectation of available water in the various rocks under the conditions obtaining in Lobatse. Wayland concluded that the shortage of water could be solved by one of two alternatives - viz:-

- (1) to drill in "good ground" outside the demand area and to pipe the supply to it, or
- (2) pipe water from existing boreholes yielding good supplies.

This latter alternative was preferred by Wayland and in fact water was laid on from the two existing government boreholes G1 & 2, situated at the entrance to the Imperial Cold Storage Company (Abattoir). These two boreholes were later (1956) recommended by Geophysical Surveys to be closed down in view of overpumping that was taking place from the restricted area covered by the Abattoir.

It is interesting to note that Wayland's (1944) report was the first documented note of a water shortage in Lobatse - a trend which was destined to continue to the present and, with the continued phenomenal increase in water consumption in Lobatse, will undoubtedly continue in the future.

Lobatse has been dependent for the greater part of its history on ground-water supplies and has experienced a series of water crises due to rapidly increasing consumption from ground-water reserves of relatively limited storage capacity and with limited annual replenishment. There has been a phenomenal increase in water consumption from

approximately 1 million gallons per month (m.g.m, $4545m^3$) in 1952, to over 20 m.g.m. in 1972. ($90,909m^3$).

TABLE

WATER CONSUMED IN LOBATSE 1952-1972
(Million gallons per year)

Year	Ground Water	Source of Water		Total Exclusive of Railway Dam
		Nuane Dam	Railway Dam	
1952	12	-	?	12
53	14	-	?	14
54	31,41	-	?	31,41
55	50,60	-	?	50,60
56	54,0	-	?	54,0
57	61,89	-	?	61,89
58	63,51	-	?	63,51
59	70,85	-	6,92	70,85
60	61,15	-	8,02	61,15
61	61,37	-	4,99	61,37
62	70,0	-	4,31	70,00
63	88,82	-	7,74	88,82
64	106,38	-	5,2	106,38
65	20,5	96,39	6,18	116,89
66	18,29	113,05	?	131,34
67	17,32	101,70	?	119,02
68	18,05	130,23	?	148,28
69	43,8	?	?	
70	127,91	Dam dry in May		?
71	94,44		?	
72			?	
1976			Estimated by	352
1978			Gibb(1969)	402
1980				454

Factors leading to this greatly increased water consumption in the 1950's were:- The rapid growth of the township since the opening of the Abattoir and later the Canning Factory; the use of larger quantities of water by the Abattoir than was originally planned; the rapid expansion in the size of the Government township; the establishment of both European and Indian schools with boarding facilities and the High Court in Lobatse; a rapid increase in the size of the African townships resulting from a large influx of people to the village

following a series of disastrous droughts in the country; the development of secondary industry in Lobatse and an expansion in the size of the Rhodesian Railways community in Lobatse. Another factor was that up to 1955 the pumping of ground water by the four main users - viz. Government, Railways, the Abattoir and private sector was largely uncontrolled.

In 1950, four boreholes in Lobatse were sufficient to meet the town's needs. (Personal communication, C. Boocock). The first Government boreholes were completed in 1937. It soon became obvious that further supplies would be needed and the Geological Survey, and Geophysical Surveys Limited independantly carried out magnetic, electromagnetic and electrical resistivity surveys to delineate further favourable ground-water areas. These surveys resulted in a number of high yielding boreholes being drilled in the mid 1950's. It was during this period that the majority of boreholes supplying the township were drilled.

In January 1955, the Government established a system of quarterly water meetings to provide a forum for discussion by the main water consumers in Lobatse - viz. Government, Railways and the Meat Commission (Abattoir) of general water use policies. These meetings resulted in a considerable degree of cooperation between the various water users, and, as a result of an early decision, all boreholes were equipped with meters and a number of observation boreholes were set up in which regular water level recordings could be made. As a result of this

far-sighted policy, extremely detailed records on the performance of virtually all boreholes contributing to Lobatse Water Supply are available and these have enabled detailed hydrogeological observations to be made, especially with regard to storage capacity, porosity, rates of infiltration and safe yield.

The borehole supplies developed up to 1957, derived their water from two main ground-water basins:- The original development took place in the western basin which is a valley area containing a thick cover of alluvium underlain by dolomitic limestone with occasional chert bands (Dolomite Group, Transvaal Supergroup). When it became obvious that overpumping was taking place from closely spaced boreholes in this basin, where water levels were falling at an alarming rate, development of boreholes was carried out in the valley east of a major fault running along the centre of the Lobatse Valley. This so-called eastern basin consists of a weathered diabase sill underlain by Magaliesberg Stage quartzite and sandstone (Pretoria Group, Transvaal Supergroup).

By 1957, when 250 000 m³ gallons of water were used in Lobatse compared with 212 273 m³ for 1955, it was realised that a water crisis was again looming up and consequently on 7th May 1958, approval was given to Government to proceed with a drilling programme on the farm Woodlands (Lobatse Estates), which was then owned by the British South Africa Company. The farm was later sold to Mr. C. Hurvitz, who agreed to a water servitude on the farm in return for the payment of the sum of R10 000. Ground-water supplies were

developed in three discrete geological basins on this farm. Drilling was completed in 1959 and the boreholes were brought into supply between 1960 and 1962. However, total ground water abstraction had risen to 318 181 m³ per annum by 1962 and the new supplies were unable to cope with the increased demand, and once again "water capital" became overdrawn, with a resultant rapid drop in water levels in the newly developed areas on Lobatse Estates.

At the same time as drilling was in progress on Lobatse Estates, detailed geophysical surveys were carried out near Ootse (Waterberg Supergroup shale and sandstone) in the Bamalete Reserve, approximately 22,4 km north of Lobatse. A number of boreholes were drilled, but the yields, ranging from 22,7 - 151 litres per minute, were disappointingly low and were considered insufficient to justify the expense of the lengthy pipeline to Lobatse. A similar programme involving a number of holes penetrating shale and quartzite of the Daspoort Subgroup of the Pretoria Group (Transvaal Supergroup) on Lobatse also proved a failure.

As all the intervening land with good ground-water potential was privately held ground, it became obvious that only a surface reservoir could relieve the critical water supply position. Consequently, the Nuane Dam with a capacity of 2 466 600 m³ (542 million gallons) with an estimated net sustained draft of 320 661 m³ per annum (71 million gallons per annum or 0,2 million gallons per day (m.g.d.)) was completed and filled in November 1964. It was pointed out by the consulting engineer, that during many years of average rainfall, the draft could be increased by two or three times.

this amount. In designing the dam for this draft, it was intended that the surface reservoir at Nuane would be used in conjunction with the existing ground-water system. The latter being used to supplement supplies from Nuane during years of low rainfall and allowed to recover during those years when the dam was capable of meeting the full requirements of Lobatse. Despite the intention that the boreholes be used in conjunction with the surface supply, most boreholes were allowed to fall into disuse and as a result, most of the ground-water basins showed large recoveries in water levels.

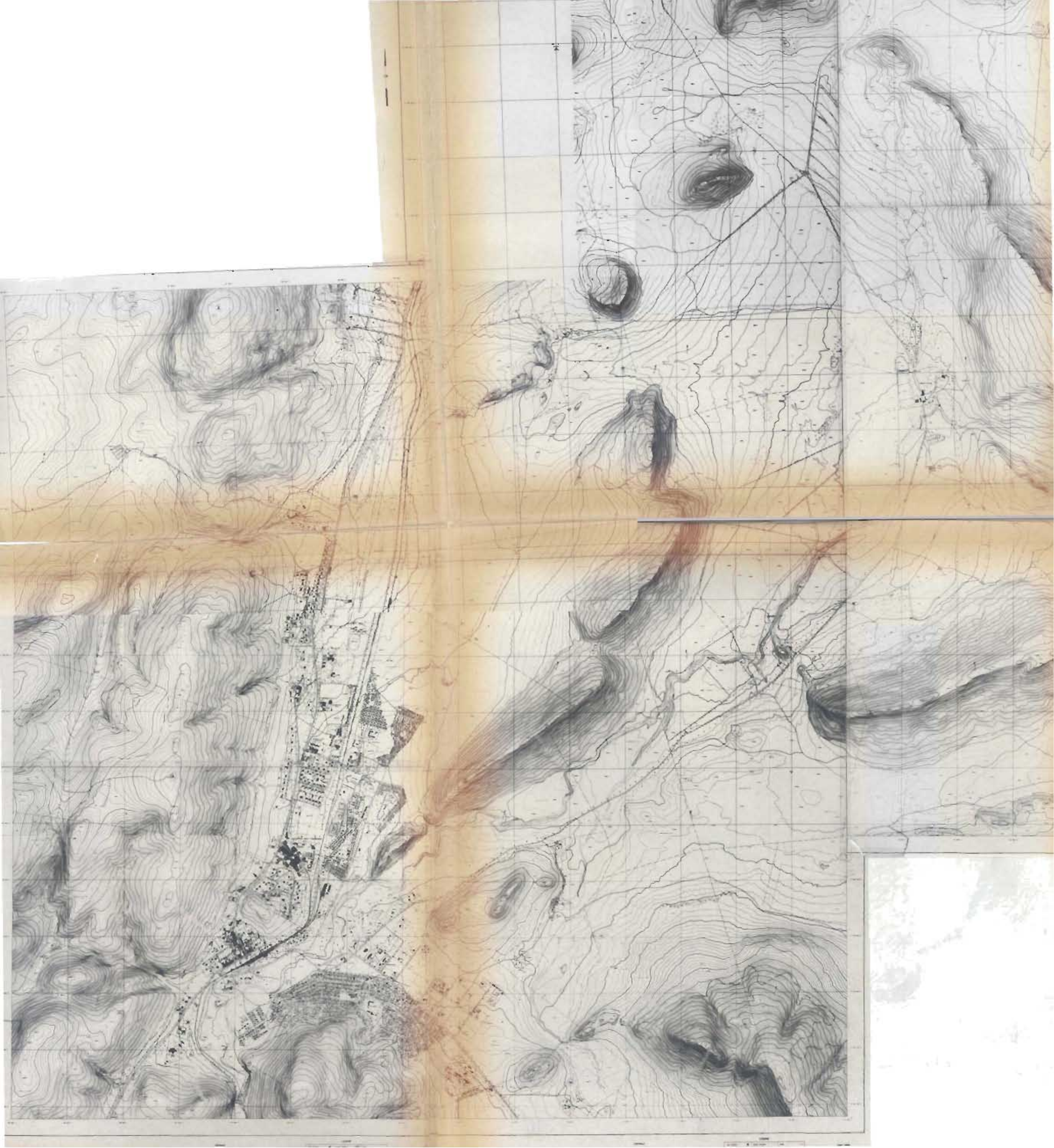
Because of extremely low run-off during the 1967/1968, 1968/1969, and 1969/1970 rainy seasons, and because of increasing water use, the Nuane dam dried up completely in May 1970, and once again the town became completely dependent on ground water. This had been anticipated by the Geological Survey, which completed an emergency water boring programme in March 1970. This resulted in a further 13 productive boreholes being commissioned and these boreholes together with the older ones saw the township through until the following two rainy seasons when sufficient water entered the dam to enable the conjunctive use of ground and surface water to maintain a sufficient supply of water for the township.

In addition to drilling by the Government and by the Abattoir for domestic and industrial water, a number of high yielding boreholes were drilled by the Rhodesian Railways in the vicinity of the railway station (railway sub-basin) from 1928 onwards.

TOPOGRAPHY AND DRAINAGE

Lobatse is pleasantly situated in the headwater region of one of the ephemeral tributaries (the Peleng River) of the Limpopo River system at an altitude of about 1220 metres above sea level. It is surrounded by low hills averaging 1372 m in height and which attain a maximum of 1427 m above sea level. There is a marked geological control of the topography, with the range of hills to the west and south consisting of resistant Ventersdorp Supergroup felsites and quartz porphyries and Black Reef Group quartzites (Transvaal Supergroup). The ranges of hills east and northeast of Lobatse consist of dip slopes of quartzites of the Magaliesberg Subgroup of the Pretoria Group (Transvaal Supergroup). The Lobatse valley forms part of the late-Tertiary denudational surface. This valley which lies north of the village of Lobatse trends approximately N.N.E.-S.S.W. and has a length of over 5 km. The width of the valley in its central portion is 2,4 km from east to west. There are no major surface drainage channels in the valley, and thus run-off of rainfall is reduced to a minimum within the valley itself. The general slope of the ground is from north to south, but in the extreme northeastern corner of the valley the ground slopes from southwest to northeast. The difference in elevation between the northern and southern ends of the valley is 30m. (See Fig. 22).

Because of the large number of farm dams and the Railway Dam (13636 km^3 capacity) in the catchment of the ephemeral Peleng River (catchment $92,2 \text{ km}^2$), very little flow takes



place along this river and sustained flow resulting from the spillage of the Railway Dam has only occurred thrice in the past seventeen years. Brief flow does, however, occur every year along the tributary which joins the Peleng River just south of the Lobatse Estates southern basin (catchment 67,6 km²) and probably constitutes the major recharge source for this ground-water basin. A number of small stream courses drain the hills west of the main dolomite basins and debouch into a series of gravel fans overlying the dolomite. No perennial springs are found and, as there appears to be little leakage from the various ground-water basins, each basin may be regarded as a compact unit in which geohydrological data can be accumulated.

Geomorphology:

The present day floor of the Lobatse valley has no surface drainage and represents an old valley which is now choked by aggradation due to a change in base level. The valley floor comprising the Lobatse Estates ground-water area has had a similar geomorphological history. Only the Peleng Spruit, which forms a headwater drainage of the Limpopo River system, is now actively incising into the alluvial valley fill due to a later change in base level. (Pl. 55).

The ridge forming the western flank of the Lobatse valley possesses a more or less parallel series of youthful stream courses which only flow for short periods following heavy rains.

The Boswelatlou stream is the only one with a catchment to the west of the crest of the ridge. The toes of these streams are characterised by small alluvial fans which coalesce with the valley floor. These fans absorb all

interfluvies passes into the valley through the extensive scree at the foot of the Ventersdorp - Black Reef ridge. (Plates 56, 57).

This water finds it's way, by sub-surface drainage, into the thick cover of alluvium overlying the irregular sub-alluvial dolomite surface. No surface drainage leaves the area west of the railway line (Western Basin), and accordingly the area forms a compact basin in which an accurate picture of the hydrogeology can be built up.

East of the railway line, precipitation drains either north or south, and has little or no effect on the ground-water supply west of the fault.

Springs:

Early records indicate that springs once existed (probably in the Peleng River course, in the vicinity of the Railway station), and old inhabitants of Lobatse can recall permanent deep pools in this now completely dry river bed. It is also known, from Wayland's (1944) report, that hand dug wells once made a contribution to the towns water supply but were already failing - probably due to the general lowering of the water table following the construction of the railway dam in a narrow constriction between the hills just to the south of Lobatse.

HYDROMETEOROLOGY

Rainfall

The climate is essentially dry, i.e. potential evaporation from the soil and vegetation exceeds the average annual



Pl. 56

{ Gullies draining Lobatse hill after heavy
rain - a major cause of

precipitation. As a result of this rainfall deficiency there is no surplus of water with which to maintain a constant ground-water supply and hence no permanent streams originate within the area. The semi-arid climate can be classified as being of low-latitude hot steppe type with summer rainfall (B. Shw of the Köppen classification). This type of climate is characterised by relatively severe seasonal temperatures and large diurnal temperature ranges, with extremely variable rainfall so that the average cannot be depended upon. It is significant that there are more years when rainfall is below average than above, interspersed with the occasional humid year which tends to raise the average. Precipitation is mainly of the convectional type with thunderstorms, with occasional large contributions from frontal type conditions.

The mean seasonal rainfall (July to June) for Lobatse for the 17 year period up to 1971/72 was 547,88 mm, while the mean annual rainfall at Lobatse Estates from 1932-1967 was 566,42 mm. Rainfall variability on Lobatse Estates ranged from 56 to 173 per cent of the mean annual rainfall (low 322,07 mm, high 995,93 mm).

As can be seen from the table of mean monthly rainfall for Lobatse Estates and Lobatse given below, most rain falls during the six month summer period from October to April, with 76 per cent of the rain falling between November and March.

/TABLE.....

TABLE 15

Mean Monthly Rainfall
Lobatse Estates (1932-67)
and Lobatse (38 year period)

	<u>Lobatse Estates</u>		<u>Lobatse</u>	
	<u>ins.</u>	<u>mm.</u>	<u>ins.</u>	<u>mm.</u>
January	3,76	95,50	3,77	95,7
February	3,81	96,77	3,66	92,9
March	3,04	77,22	3,13	79,6
April	1,87	47,50	1,70	43,2
May	0,64	16,26	0,71	18,1
June	0,14	3,56	0,38	9,8
July	0,22	5,59	0,21	5,4
August	0,08	2,03	0,08	2,1
September	0,49	12,45	0,65	16,5
October	1,81	45,97	1,72	43,8
November	2,66	67,56	2,97	75,5
December	3,80	96,52	3,96	100,5
TOTAL	<u>22,30</u>	<u>566,93</u>	<u>22,94</u>	<u>583,1</u>

For purposes of estimating ground-water recharge a detailed analysis of seasonal rainfall recorded from the 1954/5 season (i.e. 1st July - 30th June) until the 1971/72 season is given in Tables.

Key to Table:

- A = Monthly rainfall total.
- B = Number of days in month on which rain fell.
- C = Total monthly rainfall in falls exceeding 25 mm per day.
- D = Number of days in month with falls exceeding 25 mm per day.
- ΣA = Seasonal total for A. (This varies from 339,34 to 902,21 mm per season).
- ΣB = Seasonal total for B. (This varies from 39 to 87 days of rain per season).
- ΣC = Seasonal total for C. (This varies from 70,61 to 476,25 mm.)
- ΣD = Seasonal total for D. (This varies from 2 to 14 days per season).

ΣA means Mean seasonal rainfall for period 1954/5 to 1971/1972 = 547.88 mm.

ΣB mean= Mean seasonal number of days, rainfall period
1954/5 to 1971/1972 = 59 days.

ΣC mean= Mean seasonal total of rainfalls of 7,25 mm. per
day = 213,10 mm.

ΣD mean= Mean seasonal total of number of days of heavy
rain = 5,72 days.

Evaporation

Evaporation measurements using a Class "A" pan for Gaborone for the period 1958-1968 gave an average of 2077 mm, with a minimum of 1575 mm in 1958 and a maximum of 2550 mm in 1965.

Temperature, dew-point, wind speed and sunshine data are also available for Gaborone and from this it is possible to estimate open water evaporation using the Penman method.

Results as obtained by Gibb (1969) are given below in Table 18.

Run-off

In the absence of reliable run-off figures, extrapolation, using Midgeley's (1952) estimate of Zone 1 (Forest, East coastal sand and bush belt, Kalahari sandveld, Northern Transvaal sandveld and Dolomitic Flat Areas) has to be resorted to. Thus for an area with a mean annual rainfall of 548,64 mm, the corresponding run-off has been estimated as 18 acre-feet per square mile ($8571,26 \text{ m}^3$ per km^2). Thus, for the Nuane Dam, with a catchment area of 220,15 square kilometres, the mean annual run-off can be estimated as 1,500 acre-feet ($1\ 886,964 \text{ m}^3$).

TABLE 17
 RAINFALL DATA LOCUSTE IN IN
 1954/55-1973/74

	JULY				AUGUST				SEPTEMBER				OCTOBER				NOVEMBER				DECEMBER				JANUARY				FEBRUARY				MARCH				APRIL				MAY							
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D								
1954/5	-	-	-	-	-	-	-	-	-	-	-	-	2.30	2	-	-	103.12	11	31.76	1	71.88	11	44.70	1	149.08	12	87.63	2	291.94	16	127.00	3	30.32	5	-	-	36.07	5	-	-	1.02	2	-	-	27.60	2	-	-
1955/6	-	-	-	-	-	-	-	-	-	-	-	-	118.12	9	85.78	2	71.68	8	38.30	1	124.71	12	88.29	2	30.83	8	-	-	236.47	12	147.34	3	37.16	10	-	-	-	-	-	-	42.18	7	-	-	-	-	-	-
1956/7	-	-	-	-	-	-	-	-	8.82	2	-	-	64.04	9	27.43	1	34.79	4	27.43	1	85.37	7	-	-	89.29	7	27.94	1	132.22	9	88.07	1	82.24	6	24.7	1	8.10	5	-	-	4.31	1	-	-	48.02	2	-	-
1957/8	79.19	4	47.48	1	-	-	-	-	75.18	8	-	-	84.07	7	30.48	1	90.08	7	-	-	105.15	8	38.60	1	147.08	5	87.58	2	81.70	6	-	-	60.71	10	-	-	10.72	6	-	-	-	-	-	-	-	-	-	-
1958/9	-	-	-	-	-	-	-	-	27.84	8	-	-	43.46	2	24.83	1	79.24	7	30.22	1	120.90	8	88.53	2	133.60	9	82.55	2	94.10	5	-	-	87.68	3	56.84	1	89.18	4	20.72	1	56.29	3	56.82	2	-	-		
1959/60	5.32	2	-	-	-	-	-	-	-	-	-	-	17.50	4	-	-	54.81	5	-	-	132.08	12	82.23	2	72.84	11	42.88	1	89.01	9	-	-	10.74	1	42.87	1	25.97	6	-	-	2.24	2	-	-	7.62	1	-	-
1960/1	8.85	2	-	-	3.81	2	-	-	3.30	1	-	-	28.82	4	-	-	102.35	11	-	-	179.20	12	87.15	2	30.27	5	-	-	120.12	8	100.48	3	42.94	8	-	-	179.07	8	130.81	1	80.71	8	-	-	19.20	2	-	-
1961/2	24.00	2	-	-	5.04	1	-	-	-	-	-	-	19.70	3	-	-	64.08	8	-	-	44.24	6	-	-	70.20	7	48.07	2	63.78	7	27.18	1	77.22	4	20.91	1	121.22	4	124.33	2	-	-	-	-	-	-		
1962/3	-	-	-	-	1.27	1	-	-	2.79	1	-	-	20.22	2	-	-	124.27	14	70.81	2	24.20	4	-	-	110.09	11	31.75	1	7.11	1	-	-	20.87	7	-	-	89.07	6	-	-	22.86	1	-	-	24.09	2	-	-
1963/4	-	-	-	-	-	-	-	-	-	-	-	-	128.27	8	84.58	2	87.37	6	66.82	2	3.81	2	-	-	84.11	10	37.24	1	31.75	8	-	-	40.89	7	-	-	0.31	1	-	-	-	-	-	-	3.08	2	-	-
1964/5	-	-	-	-	-	-	-	-	-	-	-	-	94.42	8	-	-	21.57	3	-	-	129.03	11	70.41	2	71.91	7	-	-	24.29	5	-	-	4.24	2	-	-	44.01	7	-	-	-	-	-	-	-	-	-	-
1965/6	1.27	1	-	-	-	-	-	-	-	-	-	-	20.18	1	-	-	41.85	5	-	-	12.48	2	-	-	124.48	12	32.12	2	129.29	12	44.90	1	-	-	12.95	1	-	-	14.10	1	-	-	40.71	2	-	-		
1966/7	-	-	-	-	-	-	-	-	17.27	2	-	-	31.49	5	-	-	25.08	6	-	-	190.11	15	88.27	1	245.82	15	225.86	7	231.84	15	88.85	2	67.08	12	-	-	214.39	18	140.48	4	3.58	2	-	-	-	-	-	-
1967/8	-	-	-	-	32.00	2	-	-	6.50	1	-	-	88.82	7	-	-	28.44	11	-	-	81.21	10	-	-	87.58	11	-	-	22.28	8	-	-	183.84	12	80.88	2	101.09	12	-	-	20.78	2	-	-	1.77	2	-	-
1968/9	-	-	-	-	1.27	2	-	-	-	-	-	-	1.27	2	-	-	82.89	11	-	-	70.81	9	40.84	1	33.27	2	-	-	82.89	9	-	-	82.89	9	-	-	82.89	9	26.1	1	65.02	5	84.81	2	22.26	7	-	-
1969/70	-	-	-	-	2.02	1	-	-	1.52	1	-	-	49.78	8	-	-	7.87	7	-	-	110.74	12	44.19	1	74.2	12	28.05	1	63.18	5	28.22	1	19.81	4	-	-	23.11	2	-	-	5.98	2	-	-	6.04	2	-	-
1970/1	8.40	1	-	-	-	-	-	-	10.01	2	-	-	7.26	2	-	-	77.07	9	31.78	1	110.08	9	49.02	1	188.99	18	86.16	2	87.82	7	26.88	1	21.24	7	-	-	89.02	7	29.87	1	14.22	4	-	-				
1971/2	8.25	1	-	-	-	-	-	-	13.2	4	-	-	74.18	-	25.85	-	84.22	12	27.88	1	27.88	11	-	-	220.41	25	121.87	8	62.5	8	-	-	144.07	12	81.82	2	72.10	5	-	-	6.18	-	-	-	2.54	1	-	-
1972/3	-	-	-	-	-	-	-	-	14.1	2	-	-	7.8	2	-	-	87.1	4	31.2	1	41.7	8	-	-	84.8	10	-	-	101.3	12	20.4	1	71.4	8	53.4	2	28.7	6	21.1	1	-	-	-	-	-	-		
1973/4	-	-	-	-	-	-	-	-	42.7	2	4.4	1	92.6	7	28.0	1	115.2	12	81.8	2	86.1	8	-	-	204.8	18	89.4	2	110.2	17	22.1	1	122.0	14	-	-	81.2	12	-	-	1.20	1	-	-	-	-	-	-

A - ft
 B - days
 C - mm
 D - days

TABLE 18

DETAILED ANALYSIS - LOBATSE RAINFALL 1954/5 - 1973/4

	ΣA mm	ΣB days	ΣC mm	ΣD days	$\frac{\Sigma C}{\Sigma A} \%$	$\frac{\Sigma D}{\Sigma B} \%$	$\frac{\Sigma C}{\Sigma A \text{ mean}} \%$	$\frac{\Sigma D}{\Sigma B \text{ mean}} \%$
1954/5	703,58	66	291,08	7	25,27	10,61	51,12	12,53
1955/6	651,76	62	309,63	8	47,50	12,90	54,37	14,32
1956/7	489,97	48	179,58	5	36,65	10,42	31,53	8,95
1957/8	764,29	65	184,15	5	24,09	7,69	32,33	8,95
1958/9	643,89	51	358,14	10	55,62	19,61	62,89	17,90
1959/60	430,02	56	146,56	4	23,62	7,14	25,74	7,16
1960/1	747,27	68	296,42	6	39,66	8,82	52,01	10,74
1961/2	499,36	46	237,49	6	30,61	13,04	41,70	10,74
1962/3	406,15	53	102,36	3	25,20	5,66	17,98	5,37
1963/4	383,28	39	190,35	5	49,90	12,82	33,50	8,95
1964/5	389,13	43	70,61	2	13,05	4,65	12,40	3,58
1965/6	393,95	40	152,91	4	38,81	10,00	26,85	7,16
1966/7	902,21	89	476,25	14	52,79	15,73	83,63	25,06
1967/8	582,17	86	93,98	3	10,30	3,49	16,55	5,10
1968/9	403,86	53	133,35	4	33,10	7,59	23,50	6,80
1969/70	339,34	54	115,06	3	34,00	5,55	21,1	5,26
1970/1	578,87	64	218,19	6	37,69	9,37	40,02	10,52
1971/2	683,77	87	281,94	8	41,23	9,19	51,72	14,03
1972/3	422,30	56	147,10	4	34,83	7,14	26,84	7,01
1973/4	791,20	90	294,1	7	37,17	7,77	53,66	12,27

TABLE 19

PENMAN ESTIMATE OF OPEN-WATER EVAPORATION AT GABORONE

(25°40'S, 25°35'E, 983m)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	TOTAL
Mean air temperature (°C)	25,8	25,1	23,4	20,3	16,1	12,8	12,7	15,5	19,9	23,2	24,4	24,9	
Mean dewpoint temperature (°C)	14,7	14,9	12,9	10,1	5,4	1,1	0,4	1,9	3,6	7,1	10,9	13,1	
Mean sunshine (hours/day)	8,9	9,3	8,7	8,4	9,3	8,8	9,6	9,7	9,9	10,0	8,9	9,1	
Mean wind run (miles/day at 6m)	125	88	96	104	69	89	95	104	139	178	177	144	
E _o (mm/day)	7,64	6,81	5,75	4,45	3,07	2,69	2,99	3,83	5,87	7,60	7,73	7,71	
E _o (mm)	237	192	178	133	95	81	93	119	176	236	232	239	2011
E _o (inches)	9,3	7,6	7,0	5,2	3,7	3,2	3,7	4,7	6,9	9,3	9,1	9,4	79,1

Geology.The Lobatse Valley: (Figures 23 and 24).

The western flank of the Lobatse Valley is formed by resistant, siliceous, potash-rich tuff, ignimbrite and amygdaloidal andesite with a prominent, intercalated quartz- or less commonly, quartz-feldspar porphyry sill. These rocks have been assigned to the Ventersdorp Supergroup and dip uniformly eastwards at about 30 degrees.

A thin veneer of much younger, Black Reef Group grit and quartzite, unconformably overlies the Ventersdorp pyroclastics. These form the lowermost member of the Transvaal Supergroup and are conformably overlain by the Dolomite Group which forms the floor of the valley west of the railway line although exposures are limited to the northern and southern extremities of the area. This Group consists of dark blue dolomite with intercalated stratiform chert bands. Both groups dip to the east at about 20 degrees.

The eastern flank of the valley is formed by a northeasterly trending group of northwesterly dipping (30-60°) sediments of the Pretoria Group, which were emplaced by a complex gravity slide at the end of Transvaal Supergroup times. This major north-south trending gravity fault brings Smelterskop Subgroup sediments (top of Pretoria Group) into juxtaposition with the Dolomite Group and runs approximately parallel and adjacent to the railway line in the

/vicinity....

FIG. 23

GEOLOGY OF LOBATSE AREA

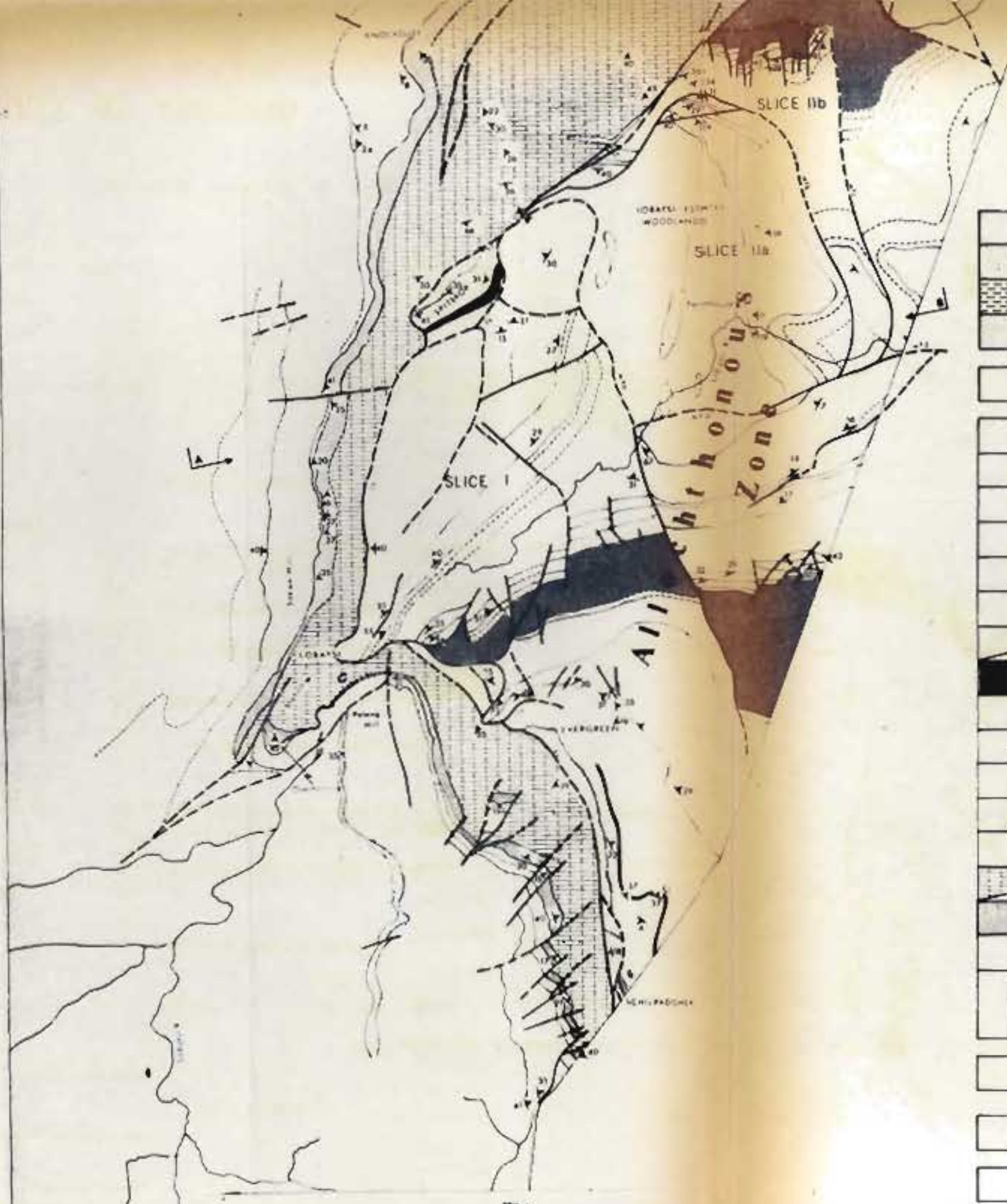
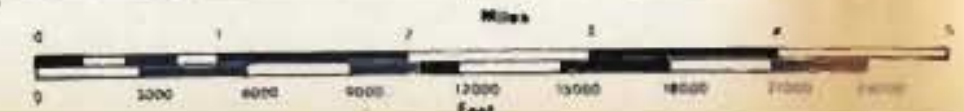


TABLE OF GEOLOGICAL FORMATIONS

	Sandstone, conglomerate	W4 Unit	} WATERBERG SYSTEM
	Silty conglomerate	W3 Unit	
	Shale, siltstone	W2 Unit	
	Chert & oolite-bearing conglomerate, quartzite	W1 Unit	
	Chert-bearing breccia	Oxley Breccia Formation	
	Quartzite, shale, silty conglomerate	Smalterskop Stage	} PRETORIA SERIES
	Quartzite	Magaliesberg Stage	
	Shale		
	Limestone, marl	Dorpert Stage	
	Shale with intercalated thin sand		
	Quartzite		
	Ferruginous flagstone and basal quartzite	Timbell Hill Stage	} TRANSVAAL SYSTEM
	Ampelite (Dorpert level)		
	Chert-bearing conglomerate	Upper Stage	
	Shale with intercalated quartzite bands		
	Quartzite	Lower Stage	
	Shale with intercalated thin sand, quartzite and basal Breccia conglomerate		
	Ferruginous shale	DOLOMITE SERIES	} VENTERSDORP SYSTEM
	Dolomite, bedded chert & lower shale		
	Quartzite, gnl	BLACK REEF SERIES	
	Ampelite (Dorpert level)		
	Shale, siltstone	UPPER VOLCANIC SERIES	
	Tuff, sandstone, conglomerate	VOLCANIC SERIES	
	Tuff, sandstone, conglomerate	LOWER VOLCANIC SERIES	
	Tuff	Kanya Volcanic Group	SWAZILAND SYSTEM?
	Diorite	Bushveld Igneous Complex?	POST-TRANSVAAL, PRE WATERBERG SYSTEM
	Quartz & quartzite breccia	Plantation Porphyry	VENTERSDORP SYSTEM

INTRUSIVE ROCKS



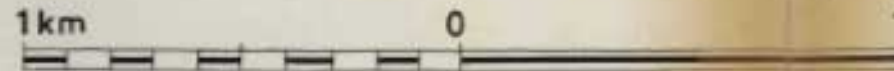
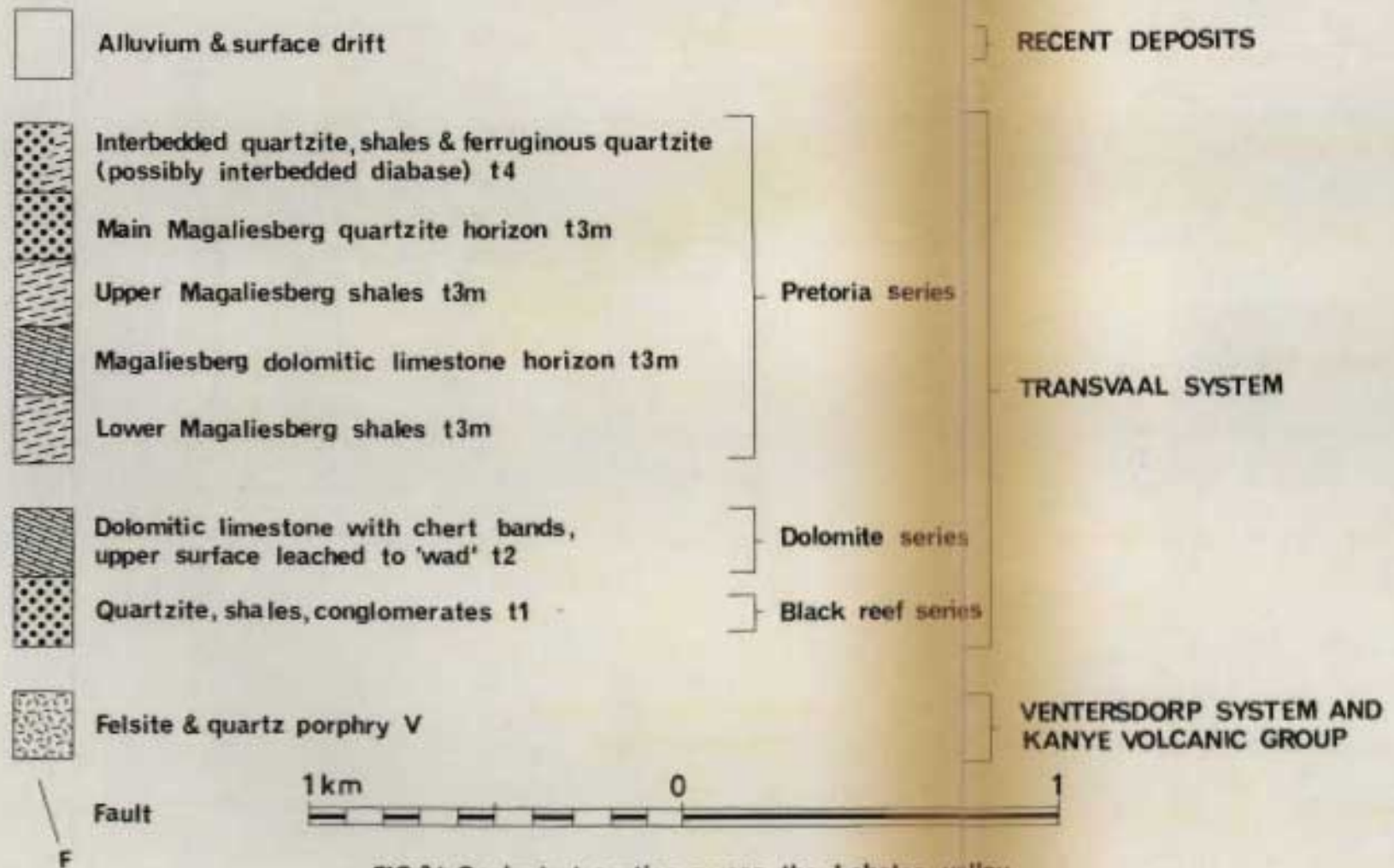
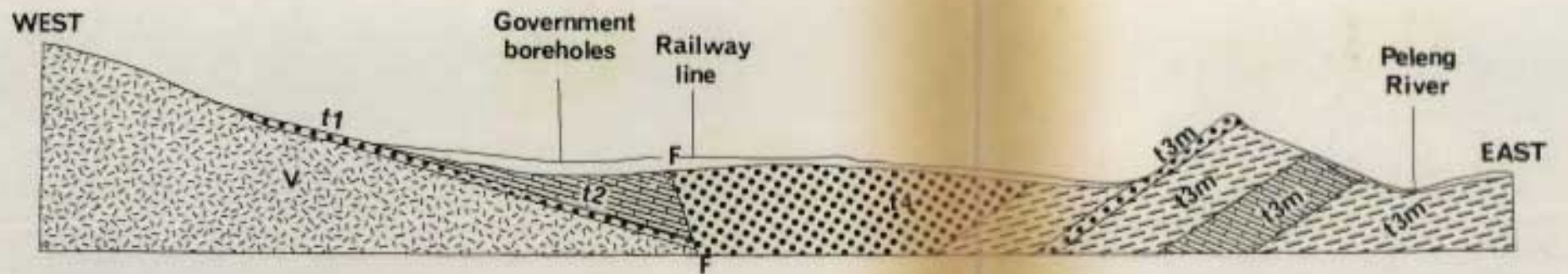


FIG.24 Geological section across the Lobatse valley

vicinity of Lobatse village but trends in a northeasterly direction further north. This fault can be traced on the ground northwards from the vicinity of the Lobatse-Zeerust road but disappears beneath surface cover about 1,2 km to the north.

Most of the dolomite west of the railway line is overlain by an extensive cover of recent deposits consisting of porous and permeable rubble, gravel and colluvial soil which attain a thickness of up to 30 m. This considerable thickness of recent deposits is not present overlying the Pretoria Group east of the railway line. (See Plate 58).

Immediately below the alluvium the dolomite is highly leached and consists of relatively unconsolidated manganeseiferous "wad", which extends to a depth of about 27 to 41 m. The solid dolomite beneath the wad consists of an irregular surface of basins and ridges whose positions are controlled by planes of stratification and jointing. Where the dolomite is undecomposed and unfissured, it forms a hard crystalline impermeable formation which is a very poor bearer of ground water.

The Lobatse Eastern and Lobatse Estates Central and Northern Basins are situated in the Magaliesberg or Smelterskop Subgroups of the Pretoria Group (the latter overlies the former). The main quartzite horizon of the Magaliesberg Group forms the crest of the hills forming the eastern flank of the above three basins. This horizon is composed of three quartzite bands with interbedded shale and thin dolomitic limestone. The quartzite is predominantly hard, white and sugary but passes upwards into a sandy, rather friable



Pl. 58

Porous soil and gravel at foot of hill -
Lobatse, Western basin.



Pl. 59

N. Koketso measuring water level in
bh. 952, Lobatse Western basin.

quartzitic sandstone. The quartzites dip in a generally westerly direction and are overlain by sediments forming the Smelterskop Subgroup and consist of interbedded, sometimes highly pyritic, argillaceous and quartzose horizons with intrusive diabase sheets. A persistent ferruginous quartzite band forms the lowest member of the quartzose horizons. The Lobatse Estates Central and Northern Basins have up to 30 m of sandy alluvium overlying the Pretoria Group sediments.

The Lobatse Estates Southern Basin is situated in argillaceous and quartzose rocks of the Daspoort Subgroup. The rocks comprising the aquifer consist of a thick succession of dark grey shale over a thin ferruginous quartzite horizon.

Structure:

Crockett (1969) has described a climactic collapse of the basin floor at the end of the Transvaal Supergroup times which triggered off extensive gravity sliding along the flanks of the basin. Much of the Pretoria Group succession developed in the present area was originally situated somewhat centrifugally from its present position with respect to the centre of the basin. Two stages of gravity sliding took place in which the momentum of gravity-slipped allochthons was absorbed by a complex pattern of reverse and transcurrent faults which are widely developed especially in competent rocks. This tectonic instability continued on a decreasing scale into post Waterberg Supergroup times.

/The.....

The large fault separating the Lobatse eastern and western ground-water basins was formed by a major gravity slide while a transcurrent fault separates the Lobatse Estates southern and central basins. A further gravity slide separates the central and northern basins on this farm.

HYDROGEOLOGY

The systematic collection of hydrogeological data in the Lobatse area was commenced in 1956 and continues at present. At present eight observation boreholes are equipped with automatic water stage recorders while water levels in a further forty-nine boreholes are measured at daily, weekly or monthly intervals using electrical gauges. Virtually all production boreholes are equipped with meters, which are read at monthly intervals, and hence exact amounts of water abstracted from all ground-water basins are known. (See Plate 59).

Groundwater Basins

Eight geologically discrete groundwater basins are to be found in the Lobatse area (Fig. 25).

The Lobatse area may be divided into an eastern and western basin. The western basin may be subdivided from south to north into the Railway Sub-Basin, the Botswana Meat Commission Sub-Basin, the Government Sub-Basin, Going Sub-Basin and the Pitsanyane Sub-Basin, all occurring in the Dolomite Group (Transvaal Supergroup), but disconnected by topographic highs of solid dolomite.

A further basin is to be found in the Dolomite Group north of the Teachers Training College.

The aquifer in the western basin is a zone of alluvium overlying decomposed dolomite with relict chert which overlies the solid dolomite and chert of the Dolomite Subgroup (Transvaal Supergroup). The decomposed dolomite is overlain by up to 30 m of soil, gravel, alluvium and "wad".

The Lobatse Eastern Basin, situated in Pretoria Group (Transvaal Supergroup) is separated from the Western Basin by a major fault which runs approximately along the line of rail. This fault forms an aquiclude and effectively separates the widely differing rock types of the eastern and western basins.

Three important basins situated in Pretoria Group sedimentary rocks and separated by faulting, are to be found on Lobatse Estates. These three basins are denoted the Lobatse Estates Southern, Central and Northern Basins.

Lobatse Western Basin

The Railway Sub-Basin (D.C.'s Office Sub-Basin).

This sub-basin is situated in the Dolomite Group of the Transvaal Supergroup, but is separated from the main Lobatse Western basin by a prominent dolomite kopje, which lies at the northern end of the Railway Sub-Basin and separates this basin from the main Lobatse Western Basin.

Thirty-three boreholes have been drilled by the government, the railways and by private owners in this basin. However, the entire amount of water abstracted from this basin comes from one government and four railway boreholes. Since 1957, when meters were first installed, a total of 531 818m³ (117 mg.) (till 1st June 1970) has been pumped from this basin. (See Table).

TABLE 20

Railway Basin Abstractions
(Millions of gallons)

Year	Railways		Government		Total	
		m ³		m ³		m ³
1957	14,80	67272	4,75	21591	19,54	88818
1958	6,76	30727	7,64	34727	14,41	65500
1959	6,60	30000	7,35	33409	13,94	63364
1960	0,85	3864	5,99	27227	6,82	31000
1961	2,65	12045	2,05	9318	4,70	21363
1962	1,53	6955	2,00	est.9090	3,53	est.16045
1963	5,10	23182	3,88	17636	8,98	40818
1964	2,56	11636	2,01	9136	4,56	20727
1965	3,10	14091	-	-	3,10	14091
1966	2,70	12273	-	-	2,70	12273
1967	2,19	9955	-	-	2,19	9955
1968	4,06	18455	-	-	4,06	18455
1969	20,36	92545	-	-	20,36	92545
1970 (end May)	13,70	62272	-	-	13,70	62272

Daily or monthly water levels have been measured on five observation boreholes since October 1967.

The Lobatse Western Basin

The main western basin may be defined as extending from the northern end of the Agricultural Department plantation, west of the Lobatse-Gaborone road, to the dolomite kopje

south of the Abattoir, and bounded on the west by impermeable felsites forming the north-south running hill west of the village, and on the east by the Dolomite-Pretoria Group fault running roughly underneath the railway line.

The shale, quartzite and conglomerate of the Black Reef Group (Transvaal Supergroup), which form the western margin of the basin, dip eastward at 30 to 40 degrees beneath the conformably overlying dolomite and chert beds (Dolomite Group). The Black Reef Group is in turn underlain by tuff, ignimbrite, andesite and quartz porphyry (Ventersdorp Supergroup) dipping eastwards at about 30 degrees. The fault forming the eastern margin of the basin brings Magaliesberg Group sedimentary rocks into juxtaposition with the Dolomite. The throw of this fault must therefore amount to many hundreds of metres.

Although recent drilling has shown that there is little justification for subdividing this basin into the Botswana Meat Commission and Government Sub-Basins, they will be treated separately, as boreholes in this basin are situated in two widely separated areas. A total of 2217 130m³ (487,77 mg.) has been pumped from this basin (1953-1972).

TABLE 21

Lobatse Western Basin Abstractions

(Sum of Lobatse Government and B.M.C. Sub-basins)

	<u>Million Gallons</u>	<u>m³</u>
1953	14,49	65 860
1954	27,25	123 863
1955	46,3	210 455
1956	54,0	245 454
1957	36,6	166 363
1958	30,82	140 090

1959	36,78	167 181
1960	34,42	156 454
1961	30,62	139 181
1962	28,13	127 863
1963	26,00	118 181
1964	23,81	108 227
1965	6,53	29 682
1966	3,27	14 863
1967	1,87	8 500
1968	3,59	16 318
1969	3,00	13 636
1970	39,80	180 909
1971	22,38	101 727
1972	18,21	82 772

The Botswana Meat Commission Sub-Basin

This sub-basin is situated just north of the dolomite kopje, which separates it from the Railway sub-basin. Five production boreholes supplying the Botswana Meat Commission and one observation borehole are situated in this sub-basin. Monthly or weekly static water level measurements have been taken in borehole A.6 (Fig. 26) since May 1956, while over 950 000 m³ (209 mg.) of water have been pumped from this sub-basin since the inception of metering in April 1957. (See Table 22).

The Government Sub-Basin

This basin originally contained five production boreholes drilled by government for township supply. An additional four boreholes were recently brought into use while there are eight observation boreholes in the area. Monthly water level observations have been taken at borehole 629 since 1st April 1959, while an estimated 681 818 m³ (150 mg.) have been pumped from this sub-basin since 1953 (see Table 23).

WATER PUMPED x 10⁶ GALLONS PER YEAR

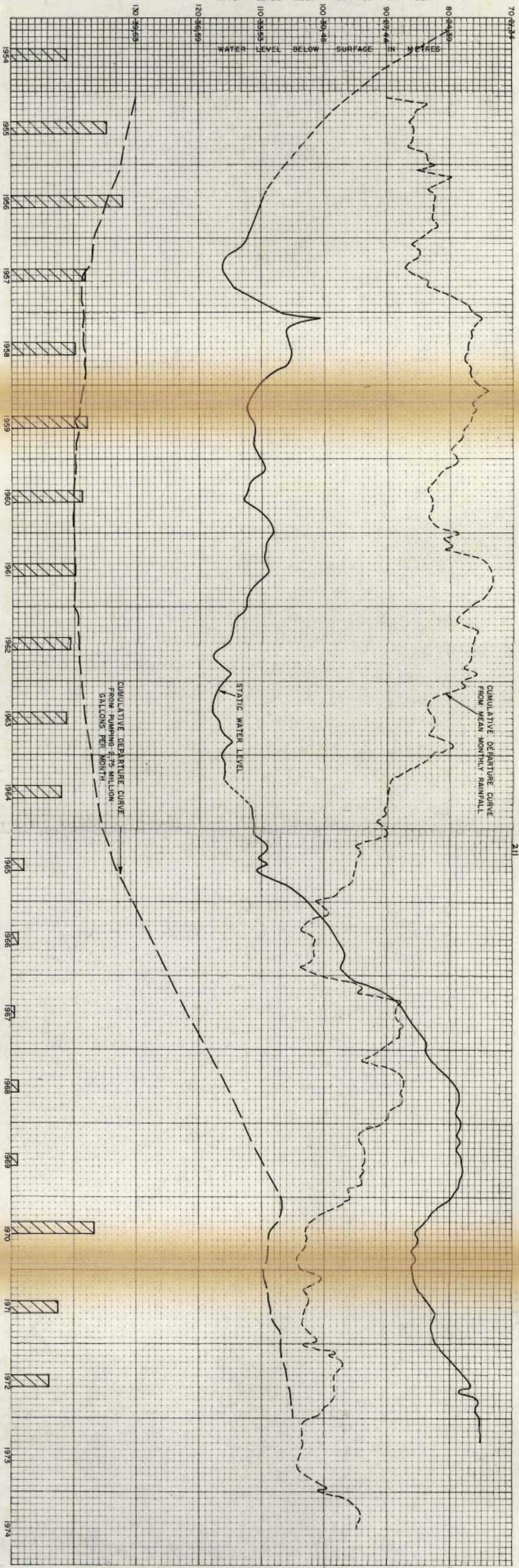


Fig. 2.6 HYDROGRAPH: BH. A6 LOBATSE WESTERN BASIN - YEARLY PUMPING FIGURES AND DEPARTURE CURVES.

T A B L E 22

BOTSWANA MEAT COMMISSION WESTERN BASIN ABSTRACTIONS (Millions of Gallons)

Pumping boreholes A1, A2, A3, A4, A5

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC	TO
1953				0,35	0,44	0,49	0,50	0,58	0,81	0,80	0,35	0,17	4,
1954	0,33	0,77	0,71	0,78	0,76	0,72	0,77	0,96	2,07	3,03	4,35		15,
1955													32,
1956	21,87 January to August												37,
1957				3,05	2,83	2,68	1,93	2,09	1,67	1,31	0,97	1,33	20,
1958	1,42	1,37	1,70	1,38	1,53	1,26	1,28	1,74	2,02	2,22	2,16	2,08	18,
1959	1,86	2,00	1,94	1,82	1,89	1,52	1,82	1,70	2,14	2,15	1,81	1,17	20,
1960	1,90	2,00	1,86	1,88	1,71	1,73	1,98	1,12	1,35	1,39	1,22	1,20	18,
1961	1,43	1,32	1,40	1,39	1,41	1,44	1,54	1,68	1,85	1,87	1,71	1,53	17,
1962	1,13	1,96	2,00	1,76	1,57	1,80	1,72	2,02	1,95	1,59	1,04	1,09	19,
1963	1,75	1,28	1,47	1,40	1,63	1,46	1,47	1,17	1,25	1,17	1,11	1,80	16,
1964	1,41	0,84	1,38	1,19	1,49	1,37	1,13	0,92	0,86	0,70	0,74	0,66	12,
1965	0,80	0,97	0,97	1,38	1,26	0,74	0,70	0,51	0,38	0,11	0,01	0,10	6,
1966	0,48	0,14	0,34	0,46	0,45	0,11	0,57	0,20	0,71	0,61	0,62	0,24	3,
1967	0,25	0,24	0,19	0,14	0,13	0,13	0,11	0,10	0,00	0,11	-	0,11	1,
1968													1,
1969													1,
1970	1,38	1,40	1,03	1,24	1,80	2,21	1,75	1,62	1,67	1,52	1,24	1,36	18,
1971	1,06	2,19	2,06	1,53	1,46	0,70	1,46	0,53	0,83	0,62	0,73	0,73	13,
1972	0,23	0,08	0,03	0,04	0,07	0,02	0,03	-	0,21	0,09	0,03		
1973													

T A B L E 23

LOBATSE GOVERNMENT SUB-BASIN ABSTRACTIONS (Millions of Gallons)

Pumping boreholes 665, 2261, 2268, 2278, 2302, P. 212 2302

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG	SEP.	OCT	NOV.	DEC.	TOTAL
1953													10,00 est.
1954													12,00 est.
1955													14,00 est.
1956													16,20 est.
1957													16,00 est.
1958													12,25
1959													16,18
1960													16,29
1961													13,06
1962													8,49
1963													9,03
1964													10,94
1965													-
1966													-
1967													-
1968					0,08	0,19	0,30	0,36	0,35	0,33	0,33	0,66	2,59
1969	1,06	0,84	0,10	-	-	-	-	-	-	-	-	-	2,00
1970	-	1,28	0,95	4,00	4,64	1,20	1,50	1,51	1,41	2,36	1,27	1,50	21,62
1971	0,40	0,65	0,50	0,62	0,79	0,50	0,47	0,50est	0,50est	0,50est	0,50est	1,50est	7,43
1972	1,00est	1,00est	1,00est	1,50est	1,54	2,50	1,80	1,85	1,81	1,48	-	-	-

Going and Pitsanyane Sub-Basins

These dolomite basins are situated north of the Western Sub-Basin and contain a small number of privately drilled boreholes with widely varying yields. Water from only one borehole is available for township supply.

The Teachers Training College (T.T.C.) Basin

A large number of privately owned and three productive government boreholes have been drilled in this dolomite basin. During the period 1957 to 1961 a total of over $863\ 63\ \text{m}^3$ (19 mg.) (Table 24) and an estimated $136\ 364\ \text{m}^3$ (30 mg.) were abstracted from government and private boreholes respectively. Owing to overpumping during this period, a number of boreholes showed signs of drying up, and pumping from this basin virtually ceased from 1962 onwards. Following the good rains in 1966/67 water rest levels have now been restored.

The Lobatse Eastern Basin

This basin is separated from the western basin by a major fault which must have a considerable throw as it brings lower Dolomite Group dolomite (W.Basin) into juxtaposition with Magaliesberg Subgroup shale, quartzite and dolomitic limestone and mafic intrusives.

All boreholes in this basin except 2261, were drilled by the Meat Commission. Accurate abstraction figures (Table 25) and water level observations for this basin have been made since pumping commenced in October 1957. A total of over

TABLE 24

PUMPING FIGURES FROM GOVERNMENT BOREHOLES T.T.C. BASIN IN GALLONS

1957	2,435,250
1958	4,916,550
1959	4,374,220
1960	3,340,150
1961	4,034,600

TABLE:25 LOBATSE EASTERN BASIN ABSTRACTIONS (Millions of Gallons)

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	TOTAL
1957										0,43	1,24	1,64	3,31
1958	0,90	0,84	0,69	0,91	1,44	1,27	1,35	1,78	1,26	1,39	1,16	1,27	13,36
1959	2,14	1,89	1,71	1,60	1,46	1,73	1,56	1,68	0,98	1,35	0,61	0,58	15,14
1960	1,07	1,59	1,72	1,56	1,12	0,95	0,70	0,52	0,83	0,80	0,54	0,50	10,82
1961	0,53	0,96	0,97	0,87	0,92	0,93	1,15	1,22	1,28	1,00	1,06	0,60	10,94
1962	0,55	0,87	0,92	0,80	1,10	0,89	0,90	0,75	0,90	0,68	0,58	0,75	9,13
1963	0,78	0,78	0,85	0,82	0,70	0,79	0,71	0,40	0,24	0,26	0,33	0,37	6,25
1964	0,41	0,38	0,97	0,82	0,81	0,69	0,54	0,66	0,78	0,78	0,49	1,04	7,95
1965	1,32	1,16	1,72	0,70	0,67	0,61	0,74	0,59	0,55	0,84	0,90	0,60	9,06
1966	0,91	0,92	0,92	0,80	0,64	0,90	0,75	0,95	0,86	1,17	1,19	1,14	10,15
1967	1,18	1,09	0,91	1,11	1,10	0,99	1,01	0,86	0,84	0,83	-	0,85	10,79
1968	0,83	0,80	-	-	-	-	-	-	-	-	-	-	10,00 est.
1969	-	-	-	-	-	-	-	-	-	-	-	-	5,00 est.
1970	-	-	-	-	-	0,01	0,38	0,23	-	-	0,09	0,03	0,74
1971	0,60	0,47	1,06	0,73	0,81	0,46	0,35	0,41	0,22	0,14	0,29	0,32	5,86
1972	0,32	0,20	0,20est	0,20est	0,23	0,22	0,20est	0,20	-	-	0,09		

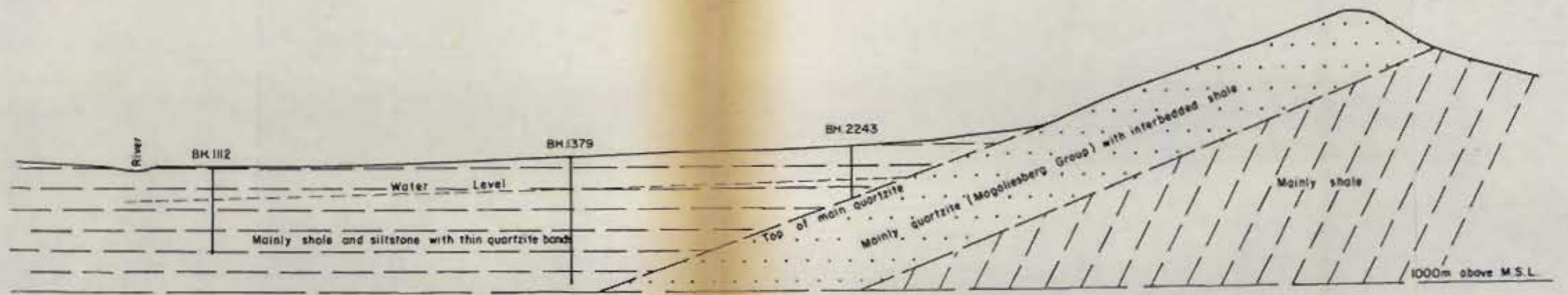


Fig. 35 HYDROGEOLOGICAL SECTION ACROSS LOBATSE ESTATES CENTRAL BASIN

SCALE— 1cm = 50 Metres or 1:5000

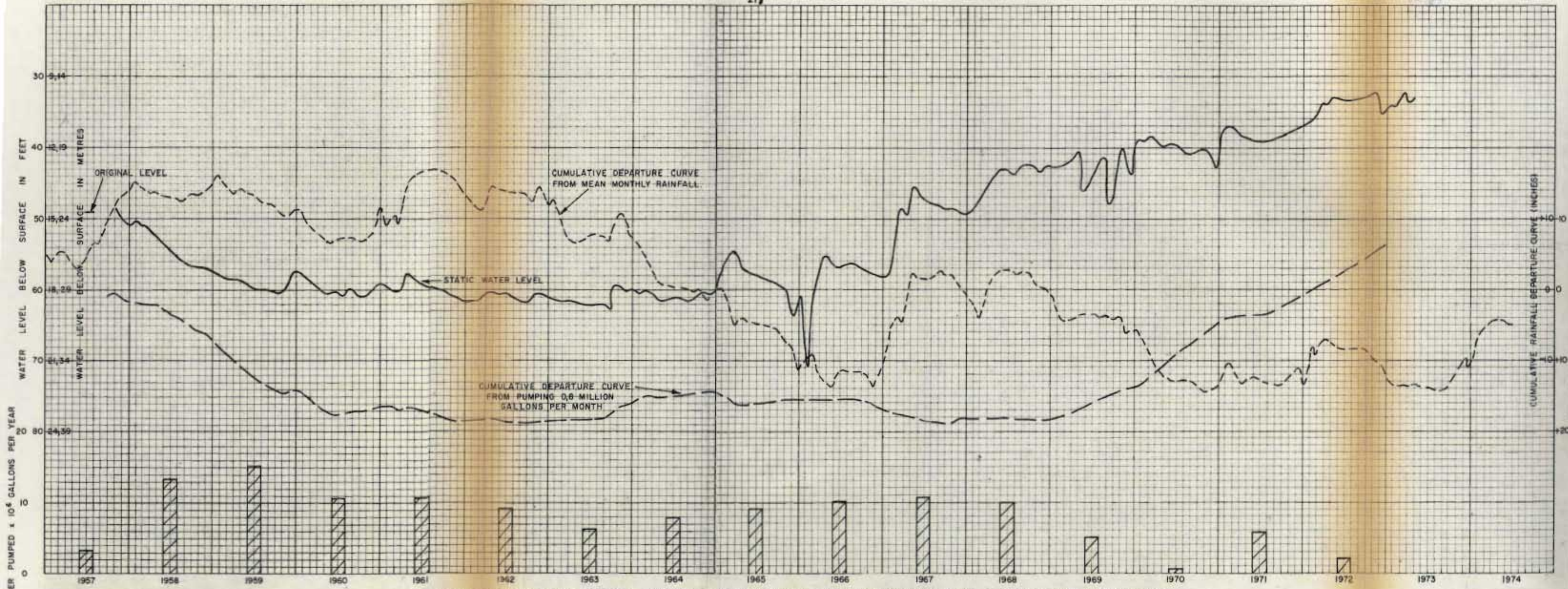


Fig. 17 HYDROGRAPH: BH. X4 (P772)-LOBATSE EASTERN BASIN-YEARLY PUMPING FIGURES AND DEPARTURE CURVES.

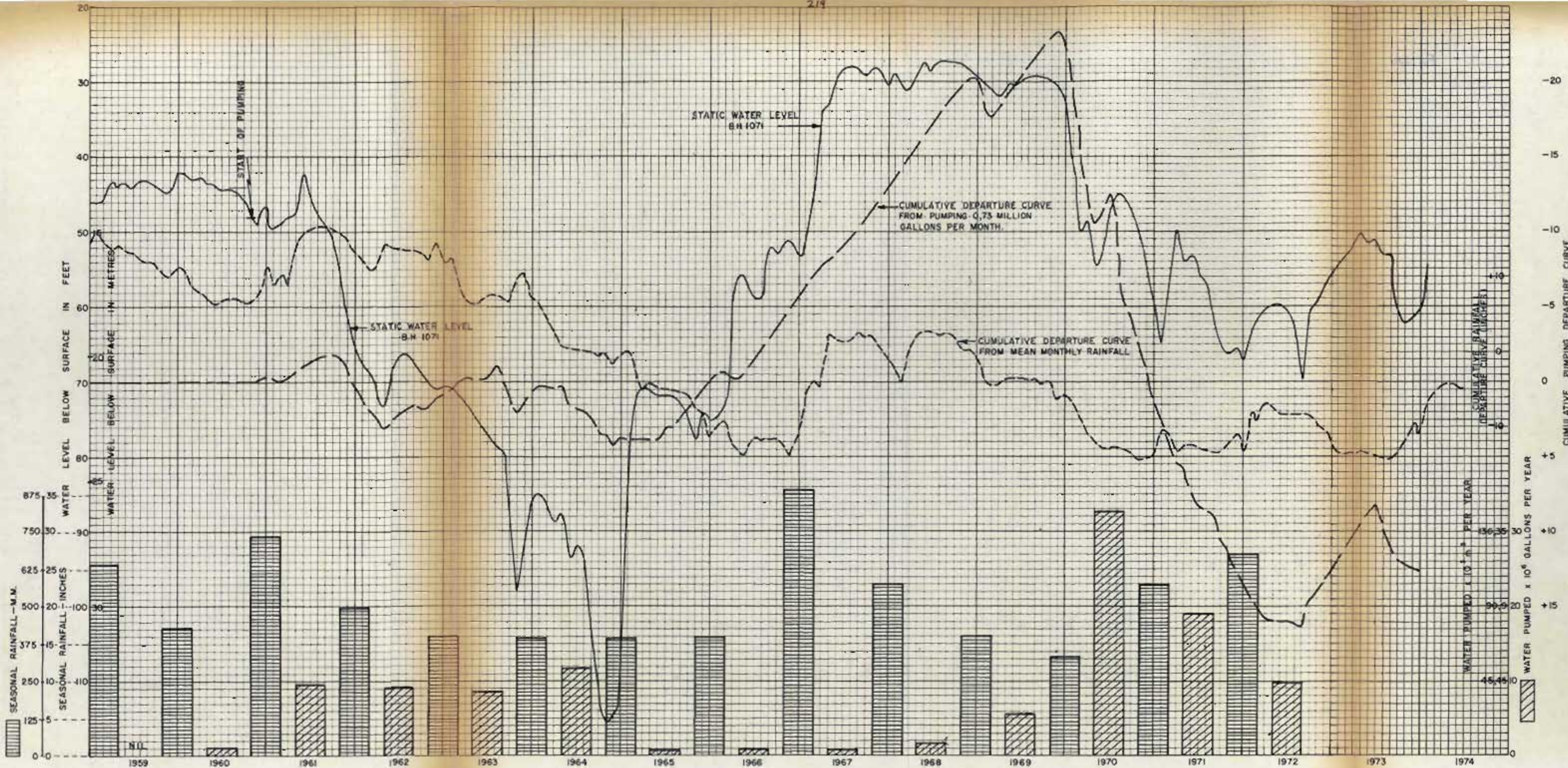


Fig. 28 HYDROGRAPH BH.1071 - LOBATSE ESTATES SOUTH BASIN SEASONAL RAINFALL AND YEARLY PUMPING FIGURES AND DEPARTURE CURVES

TABLE:26 LOBATSE ESTATES SOUTH BASIN ABSTRACTIONS (Millions of Gallons)

MAIN ABSTRACTION BOREHOLES:- 1010, 1077,1326, 1077

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
1960											0,52	0,53	1,05
1961	0,86	1,00	0,47	0,22	0,36	0,47	0,56	0,56	0,67	0,93	1,50	1,94	9,53
1962	1,50	1,44	1,25	1,36	0,30	0,44	0,25	0,46	0,95	0,64	0,05	0,60	9,24
1963	0,40	0,20	0,49	0,73	0,94	0,29	0,09	1,30	2,27	1,74	0,05	0,03	8,51
1964	0,41	0,79	0,81	0,66	2,03	0,86	0,90	0,96	1,76	1,02	1,36	0,35	11,86
1965						0,04		0,10	0,08	0,09	0,05	0,19	0,55
1966	0,22	0,56	0,98	0,84	0,17	0,01	0,03	0,09	0,01	0,05	0,08	0,06	0,87
1967	0,02	0,02	0,11	0,24	0,46	0,09	0,09	0,28	0,01	0,01	0,02	0,01	0,35
1968	0,03	0,06	0,01	-	0,01	0,04	0,06	0,04	0,08	0,11	0,38	0,60	1,42
1969	2,92	1,11	0,17	0,01	0,04	0,06	0,08	0,03	0,03	0,24	0,31	1,62	5,62
1970	3,41	3,85	4,80	2,57	0,08	0,05	1,64	6,26	1,82	2,46	2,32	3,14	32,40
1971	1,82	2,07	2,46	0,95	2,33	1,69	1,06	0,96	2,54	1,37	1,71	1,71	18,98
1972	1,71	1,50	1,33	0,94	0,94	0,56	0,16	0,38	0,54	0,11	0,1	0,0	8,27
1973	-	-	-	-	-	-	1,79	2,35	1,76	1,07	0,93	0,93	8,83

T A B L E 27

LOBATSE ESTATES CENTRAL BASIN ABSTRACTIONS (Millions of Gallons)

Main abstraction bhs :- 1379, 1414, 1429, 2265, 2270 2271

Observation borehole :- 1412

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
1961	-	0.22	0.27	0.22	0.12	0.05	0.19	0.23	0.27	-	-	-	1.57
1962										0.45	0.78	0.66	2.89
1963	1.89	2.36	2.78	2.33	2.27	1.63	1.65	1.52	1.52	1.41	2.56	3.89	25.94
1964	4.66	2.60	4.75	4.38	3.45	4.40	3.91	4.61	3.61	3.60	4.13	0.43	44.52
1965	0.20	0.11	-	-	0.11	0.11	0.15	-	-	0.03	0.01	0.43	1.16
1966	0.04	0.04	0.04	0.46	0.84	0.73	0.03	0.14	0.20	0.13	0.14	0.16	1.30
1967	0.21	0.08	0.25	0.14	0.08	0.07	0.21	0.08	0.16	0.10	0.24	0.24	2.12
1968	0.12	0.18	0.15	0.10	0.39	0.10	0.10	0.05	0.10	0.05	0.05	0.13	1.57
1969	0.97	0.13	0.05	0.04	0.07	0.05	0.07	0.53	1.79	1.89	2.29	3.04	10.92
1970	2.36	6.15	4.62	4.75	9.26	8.69	11.18	6.02	10.44	10.24	8.45	7.74	85.49
1971	6.19	6.95	7.16	3.43	5.10	3.19	1.15	1.22	3.96	3.74	3.42	6.00	51.51
1972	6.00	5.10	3.80	3.12est	3.72	4.30	4.44	3.67	1.22	1.21	1.00		

An emergency drilling programme was recently completed in the central and northern basins, and a number of high yielding boreholes with minimum yields ranging from 912 - 1368 litres per minute were developed at the foot of the Magaliesberg quartzite dip slope following detailed geophysical surveys.

The Lobatse Estates North Basin

This basin is situated in an identical geological situation to the Central Basin, but is separated from it by a fault. Detailed pumping figures are available for the entire pumping history of this basin (401 318 m³)(88,29 mg.) (Table 28), but unfortunately no water levels could be measured during this period.

GROUND WATER REPLENISHMENT (RECHARGE) AND SAFE YIELD

Infiltration and recharge studies can be made by use of lysimeters or preferably from studies of ground water table fluctuations coupled with statistics of rainfall, area of catchment and amount of water extracted from the ground-water basin. Infiltration calculations can also be made in catchment basins of known area and low evaporation and where accurately gauged permanently flowing rivers occur. In these latter basins, calculations are based on the assumption that the yearly flow of rivers in the basin is equivalent to the yearly replenishment of underground water.

Replenishment depends on a number of factors such as the amount of rain, the intensity of rainfall, the period of

/duration.....

TABLE: 28 LOBATSE ESTATES NORTH BASIN ABSTRACTIONS (Millions of Gallons)

MAIN ABSTRACTION bhs 1126, 1331, 1463, 2254,
2262, 2264

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
1962										0,64	0,85	0,77	2,26
1963	1,60	0,65	0,79	1,25	1,60	0,57	1,13	1,12	1,59	1,40	0,90	0,54	13,14
1964	0,72	1,93	1,55	0,66	0,50	0,37	1,21	1,29	1,62	1,58	1,52	0,73	13,68
1965	0,10												0,10
1966													NIL
1967													NIL
1968													NIL
1969								0,15	0,38	0,14	0,23		0,90
1970	-	0,15	0,10	0,25	1,20	0,06	0,29	2,20	1,53	0,14	1,40	1,96	9,28
1971	2,99	3,99	5,10	1,50	1,56	2,71	1,83	1,07	3,58	1,19	3,85	3,40	32,79
1972	3,40	2,24	0,81	3,72	0,82	1,56	0,19	1,14	0,82	1,44			

duration of the rainy season, the climate, topography, the nature of the surface cover, the nature and structure of the geological formations; the vegetal cover and runoff. Of the above factors, man can only control the nature of the surface cover and the vegetation.

In the Lobatse area, these studies are simplified by the fact that no permanent springs are found in the area, and as, in most instances, the water table exceeds a depth of 30 m, there can be no significant losses by evapotranspiration. Furthermore, all the ground water basins appear to lose minimal amounts of water by subsurface leakage and hence the basins may be regarded as virtually closed systems.

Early calculations of recharge

Early reports by Geophysical Surveys Limited from the Lobatse Abattoir based recommendations for pumping on safe yields as determined by one of three methods - viz.

- 1). By analogy with the Slurry area east of Mafeking, where similar geological and climatic conditions prevail. In the Slurry area, no measurable recharge of the ground-water reservoir was found to exist when the annual rainfall was less than 483 mm. (19 ins.) The first 483 mm. of rainfall are lost to surface run-off, evapotranspiration and the soil-moisture zone whereas any rainfall in excess of this contributed to the recharge of the ground-water reservoir. Geophysical Surveys used a figure of 516 mm. for the effective average annual rainfall for Lobatse and so obtained a figure of $177\,727\text{ m}^3$ per year for the total Lobatse Valley catchment of $5,3\text{ km}^2$, assuming a recharge of 33 mm. This method is not considered reliable by the writer because the amount of

replenishment is unlikely to depend simply on the total rainfall as the run-off which governs recharge is dependent on a number of variables such as vegetation cover, wetness of catchment, intensity and frequency of rainfall etc.,.

2) Once again an analogy is made with thirteen catchments studied in South Africa, with fairly low evaporation, which indicates that an average of between 4 and 7 per cent of the average annual rainfall over the whole catchment area penetrates to the water table. Assuming a mean of 5,5 per cent for the Lobatse Valley, Geophysical Surveys Limited calculated, using the same average annual rainfall of 516 mm, that 28,45 mm of rainfall per year would reach the ground-water reservoir. Thus for the same catchment area of 5,3 km², 150 455 m³ would be recharged per annum. This method as used by Geophysical Surveys is regarded as being useful to obtain an idea of the order of the probable amount of recharge.

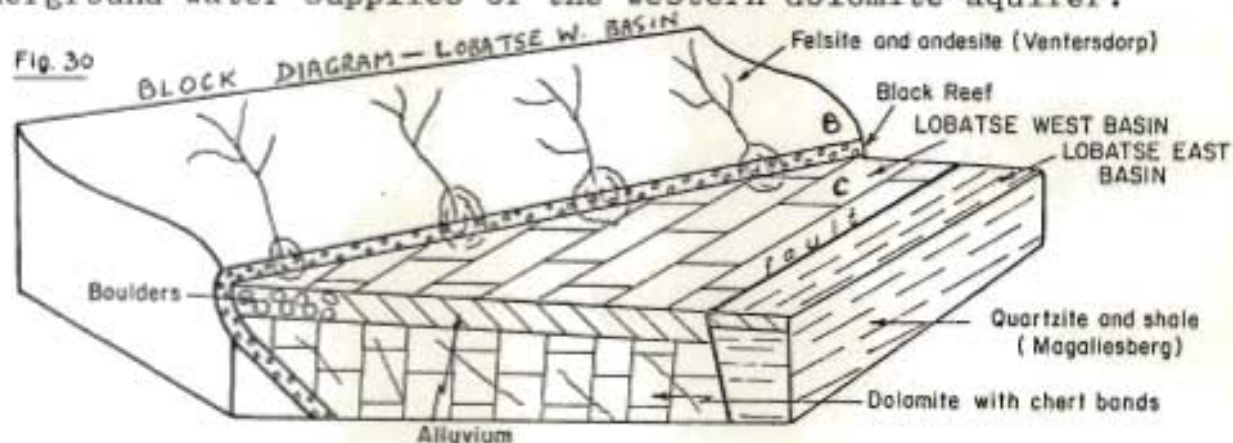
3) Geophysical Surveys assumed that large amounts of moisture would be retained in the porous rubble and alluvium overlying the dolomite aquifers (i.e. on the flat valley-floor) and considered that only 2 per cent or 10,41 mm of rainfall falling directly on the valley-floor, reaches the ground-water reservoir. Thus, the direct recharge of the aquifers under the valley-floor amounts to 18 636 m³. Due to the surface run-off being allowed to percolate directly into the aquifers on the hill-slopes, it was considered possible that 10 per cent or 51,56 mm per year makes it's way to the ground-water zone. Thus, the annual recharge off the hills amounts to approximately 180 454 m³ and the total

recharge thus becomes $199\ 090\ m^3$. This estimate is regarded by the writer as being calculated using arbitrary estimates which are unlikely to be of use in estimating accurately the actual amount of water recharged.

The above three methods used gave an average possible recharge for the western catchment area of $175\ 909\ m^3$.

Use of Long Term Hydrogeological Data

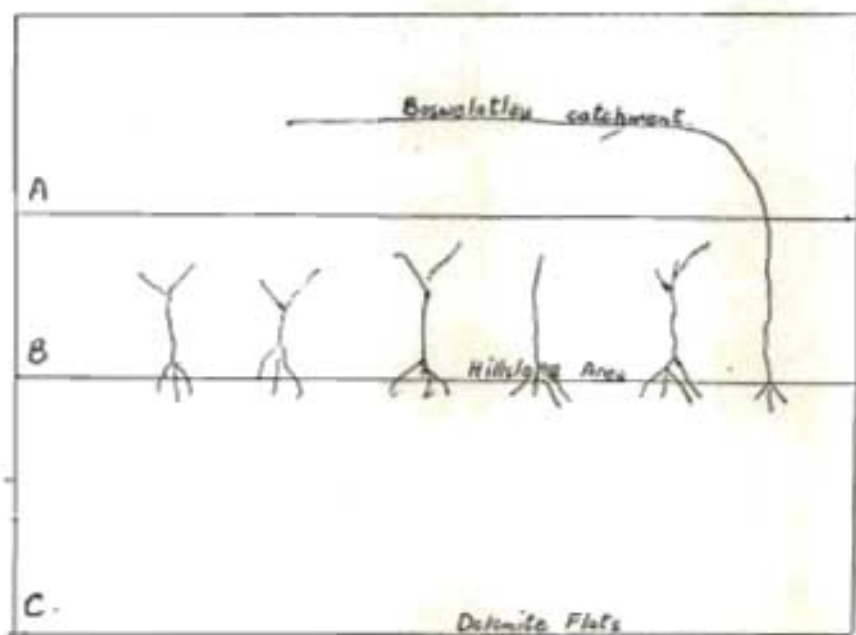
A study of the topographic map of the Lobatse area (Fig.22) shows that the catchment area of the Lobatse western groundwater basin can be divided into three main areas as shown schematically in Fig.29, with rainfall on any or all of the three main areas able to infiltrate to recharge the underground water supplies of the western dolomite aquifer.



The respective areas of the three main catchments which may be termed the Boswelatlou catchment (A), the hillslope area (B) and the dolomite flats (C), are $4,3\ km^2$, $7,3\ km^2$ and $2,83\ km^2$ respectively. (See also Fig. 30).

In actual practice recharge from the Boswelatlou catchment is small because of the poor run-off characteristics of the soil in this catchment and consequent almost complete lack of flow far enough to consistently recharge the dolomite

/aquifer.....

SCHEMATIC DIAGRAM - LOBATSE WESTERN BASIN CATCHMENTFig. 29

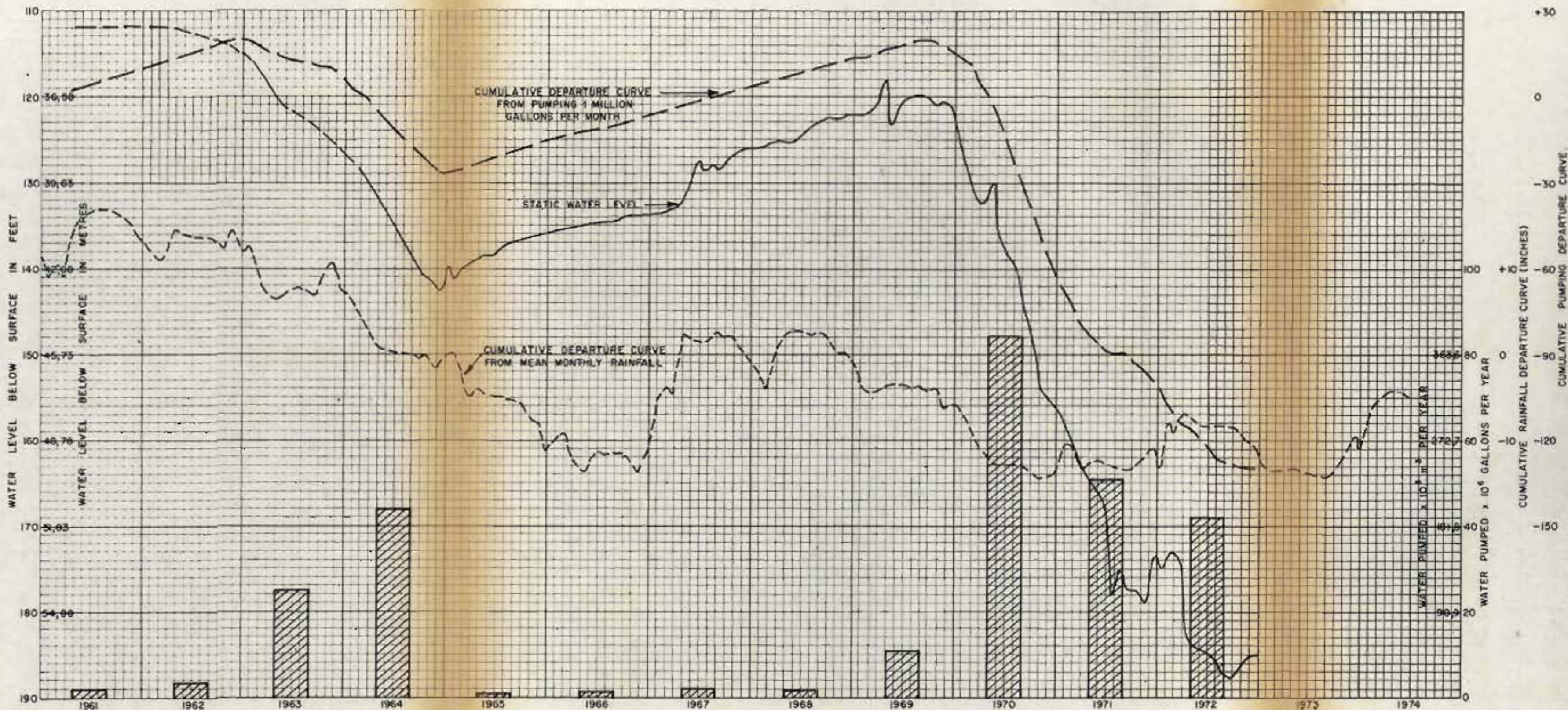


Fig. 31 HYDROGRAPH: BH 1412 — LOBATSE ESTATES CENTRAL BASIN — YEARLY PUMPING FIGURES AND DEPARTURE CURVES.

aquifer (C). In addition the relative flatness of the area forming the dolomite flats, the lack of any surface drainage, the very thick soils overlying the aquifer and the depth to the water table (30m) also preclude any appreciable amount of rainwater from direct infiltration reaching the water table. Far and away the greatest amount of recharge is presumed to derive from run-off from the hillslope area concentrating in a number of small gulleys and infiltrating directly into the gravel fans at the edge of the dolomite basin.

Jennings (1970) took fairly long term data available of pumping figures for the Lobatse western basin and using the hydrograph for the tally hole A.6 (Fig.26), two dates were selected (1.6.56 and 28.2.65) when water rest levels in borehole A.6 were the same depth below ground level.

During this period of 105 months, 1 315 000 m³ of water were pumped from the basin. Therefore, assuming that no leakage from the basin takes place, the abstraction and amount of water recharged must be in balance, and the recharge or

$$\begin{aligned}
 \text{safe yield} &= \frac{1\,315\,000\text{ m}^3}{105} \text{ per month} \\
 &= 12\,524\text{ m}^3 \text{ per month (2,75 m.g. per month)} \\
 &= 150\,286\text{ m}^3 \text{ per annum (33 m.g. per annum)}
 \end{aligned}$$

This figure compares reasonably well with that obtained by Geophysical Surveys Limited in 1956 - viz. 175 909 m³, but is regarded as a far more reliable figure than the earlier estimates, which are largely based on assumed figures derived from catchments elsewhere. The only major possible weakness in the above calculation lies in the fact that

/with.....

with the erratic rainfall pattern, the 105 month period may not be a truly representative average period as far as ground-water recharge is concerned, and hence may give a safe yield which is lower or higher than average. Care should be taken therefore to ensure that safe yield (recharge) calculations are made over as long a period as possible to cater for the variable rainfall. Care should also be taken to ensure that the period chosen does not start or end in the middle of the rainfall season. This will prevent errors in the calculations caused by a possible time lag between rainfall and recharge. An analysis of the rainfall period used above, gave seasonal rainfall totals of:-

489,96, 764,29, 643,89, 430,00, 747,27, 499,36, 406,15, 383,28 and 389,13 mm respectively. This represents an average of 528,32 mm which is slightly below average. It should also be noted that 6 of the 9 years were of sub-average rainfall. The calculated recharge figure could thus be slightly conservative. Similar safe yield (average recharge) calculations for different ground-water basins in Lobatse are given in Table 29.

Ground Water Recharge

As far as estimation of conditions favourable for recharge is concerned, it was thought probable that $\frac{\sum C}{\sum A_{\text{mean}}}$ (Table 18) expressed as a percentage would be the most diagnostic. Values for $\frac{\sum C}{\sum A_{\text{mean}}}$ per cent ranged from a low of 12,4 per cent in 1964/65 to a high of 83,63 per cent in 1966/67, with an average of 37,71 per cent (18 years). However, comparison of $\frac{\sum C}{\sum A_{\text{mean}}}$ values from 1957/58 to 1971/72 with the estimated semi-quantitative amount of recharge gauged

T A B L E 29

SAFE YIELD (RECHARGE) CALCULATIONS, LOBATSE AREA

PERIOD AT BEGINNING AND END OF WHICH WATER LEVELS WERE SAME	TIME PERIOD IN MONTHS	WATER ABSTRACTED BY PUMPING OVER THE SAME PERIOD m ³	CALCULATED AVERAGE MONTHLY RECHARGE (SAFE YIELD)	
			m ³ /m	m.o.m
<u>LOBATSE RAILWAY SUB-BASIN (Bh 1276 (D.C.2.) Fig)</u>				
1.3.68 - 15.10.68 (Fig)	7½	9 550	1 273,33	0,26
1.10.67 - 15.5.68	7½	9 675	1 289,98	0,26
Regarded as being unreliable because of short period used.				
<u>LOBATSE WESTERN BASIN (Bh A.6 Fig)</u>				
1.5.56 - 28.2.65 (Fig)	105	1 315 000	12 523,81	2,75
1.11.54 - 1.2.67	147	1 644 909	11 189,86	2,46
<u>LOBATSE EASTERN BASIN (Bh x Fig)</u>				
1.11.59 - 1.11.64 Bh x 1	60	218 633	3 643,89	0,80
1.2.54 - 31.1.67	95	387 702	4 038,97	0,88
1.10.59 - 1.10.64 Bh x 4	60	221 232		
<u>LOBATSE ESTATES SOUTHERN BASIN (Bh 1071 Fig)</u>				
31.5.60 - 31.12.66	79	189 090	2 393,56	0,52
31.5.60 - 31.12.69	115	222 682	1 936 36	0,42
1.11.61 - 1.8.66	55	155 500	2 827 27	0,62
31.7.67 - 15.6.69	23	27 545	1 197 62	0,26
1.10.61 - 30.6.73	141	465 364	3 300,45	0,72
<u>LOBATSE ESTATES CENTRAL BASIN (Bh 1412 Fig)</u>				
1.3.64 - 1.6.67	39	185 182	4 748,20	1,04
Regarded as a little high as it includes the exceptional 1966/1967 season				

from hydrographs for the Lobatse basins, shows that no correlation can be made between the above postulated recharge parameter and the actual recharge. e.g. for 1964/1965 $\frac{C}{\Sigma A_{\text{mean}}}$ was only 12,4 per cent, yet "moderate to large" recharge took place in all four main ground-water basins in Lobatse. See Table 30 and Figs.26,27,28,31.

An extremely useful recharge inventory has been given for the period 1923-1968 by Bredenkamp and Vogel (1970) for a dolomite aquifer in the northern Cape situated in a similar climatic zone to that of Lobatse. Major recharge events since 1954 in this area took place in 1956 (3 times mean annual recharge (m.a.r.)), 1957 (2½ times m.a.r.), 1961 (2.8 times m.a.r.) and 1967 (6.6 times m.a.r.). This data has been plotted in Fig.32 .

Calculation of Proportion of Rainfall Contributing to the Ground-water Recharge Component

During the same period used earlier for the recharge (safe yield) calculation for the Lobatse western basin (1.6.56 to 28.2.65) a total of 4679,95 mm (184,25 in.) of rain fell and a total of 1 315 000 m³ water was abstracted. The catchment of the Lobatse western basin is clearly defined by geological and topographic boundaries and measures 7,3 km² (2,82 square miles) in extent.

$$\begin{aligned} \therefore \text{Per cent of rainfall infiltrating} \\ \text{as recharge component} &= \frac{1315\ 000}{7,3} \times \frac{100}{467950} \\ &= 3,84\% \text{ say } 4,00\% \end{aligned}$$

Put another way, a long term average of 3,84 per cent of the mean season rainfall (548 mm) or 21 mm of rainfall infiltrates to the water table.

TABLE 30

SEMI-QUANTITATIVE ESTIMATES OF RECHARGE SEASONAL RAINFALL AND RAINFALL

FALLING IN HEAVY PRECIPITATION DIVIDED BY MEAN RAINFALL

SEASON	ESTIMATED RECHARGE FROM HYDROGRAPH				SEASONAL RAINFALL IN mm	$\frac{\sum C}{\sum A}$ % MEAN
	LOB. EST. S. BASIN	W. BASIN	E. BASIN	LOB. EST. C. BASIN		
1956/7	No data	Nil	No data		490	31.53
1957/8	" "	Large	Very small		764	32.33
1958/9	Small	Nil	Nil		644	62.89
1959/60	Small	Small	Moderate		430	25.74
1960/1	Moderate	Moderate	"		747	52.01
1961/2	Very small	Very small	Small		499	41.70
1962/3	" "	Moderate	"		406	17.98
1963/4	" "	"	Moderate	Nil	383	33.50
1964/5	Large	"	Mod.-Large	Moderate	389	12.40
1965/6	"	"	Moderate	Nil	394	26.85
1966/7	Major	Large	Major	Major	902	83.63
1967/8	Small	Moderate	Large	Nil	582	16.55
1968/9	Very small	Nil	Very small	Large	404	23.50
1969/70	Nil	"	"	Moderate	339	21.1
1970/1	Moderate	Moderate	Moderate	Nil	579	40.02
1971/2	"	Mod.-Large	Moderate	Large	684	51.72
1972/3	"				422	26.84
1973/4	"				791	53.66

Fig. 32 GRAPH SHOWING ESTIMATED PORTION OF SEASONAL RAINFALL CONTRIBUTING TO GROUND WATER STORAGE IN W. TRANSVAAL AND LOBATSE AREAS

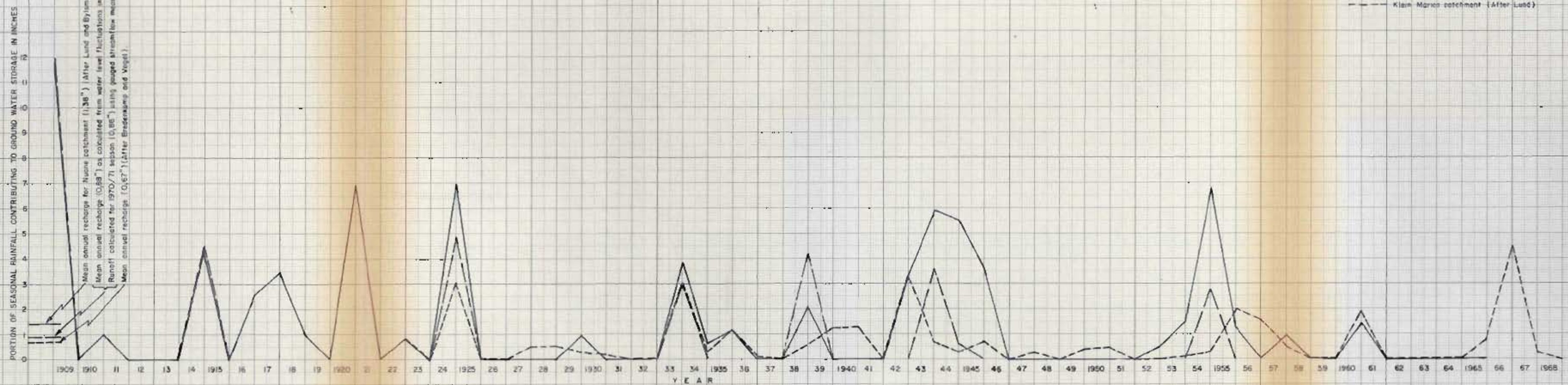
PORTION OF SEASONAL RAINFALL CONTRIBUTING TO GROUND WATER STORAGE IN INCHES

1909 1910 11 12 13 14 1915 16 17 18 19 20 21 22 23 24 1925 26 27 28 29 1930 31 32 33 34 1935 36 37 38 39 1940 41 42 43 44 1945 46 47 48 49 1950 51 52 53 54 1955 56 57 58 59 1960 61 62 63 64 1965 66 67 1968

Y E A R

Mean annual recharge for Nuene catchment (1.38") (After Lund and Bylisma)
 Mean annual recharge (0.88") as calculated from water level fluctuations in Lobatse West basin
 Runoff calculated for 1970/71 season (0.86") using gauged streamflow measurements - Lobatse West basin
 Mean annual recharge (0.67") (After Bredenkamp and Vogel)

— Nuene (Lobatse) catchment (After Lund and Bylisma)
 - - - (After Bredenkamp and Vogel)
 - - - Klein-Maria catchment (After Lund)



111111 111111

Calculations of Safe Yield Using Assumed Recharge

Calculations of safe yield for the various ground-water basins have been made assuming a recharge of 4 per cent of the average rainfall (559 mm) or 22 mm per annum falling on the hill slopes. This figure of 4 per cent was obtained from the relation of long term observation of water levels to abstraction and rainfall figures in the Lobatse Western Basin. It has been assumed that no recharge can take place through the thick soil cover overlying the actual ground-water basins. This latter assumption is regarded as valid, as field observation has shown that the moisture from 25 mm rainfall generally only penetrates about 150 mm in the thick soils forming the flat floor of the Lobatse valley.

On this basis the safe yield for the Lobatse area is as follows:-

Railway Sub-Basin (7,17 km ²)	= 155 000 m ³ /annum or 12 917 m ³ /m
Lobatse Western Sub-Basin (7,27 km ²)	= 157 727 m ³ /annum or 13 144 m ³ /m
Going Sub-Basin (6,78 km ²)	= 146 364 m ³ /annum or 12 197 m ³ /m
Pitsanyane Sub-Basin (8,9 km ²)	= 192 273 m ³ /annum or 16 023 m ³ /m
Teachers Training College (T.T.C.) Sub-Basin (1,63 km ²)	= 37 273 m ³ /annum or 3 106 m ³ /m
Lobatse Eastern Basin (2,09 km ²)	= 45 455 m ³ /annum or 3 788 m ³ /m
* Lobatse Estates South Basin	= 37 273 m ³ /annum or 3 106 m ³ /m
Lobatse Estates Central Basin (1,94 km ²)	= 42 273 m ³ /annum or 3 523 m ³ /m
Lobatse Estates North Basin (2,46 km ²)	= 54 091 m ³ /annum or 4 508 m ³ /m
TOTAL	<hr/> 867 729 or 72 311 m ³ /m = 15,91 m.g.m.

* The safe yield for the Lobatse Estates south basin has

been calculated from long term observation of water levels and not from the catchment area which is not clearly defined.

It is interesting to note that the safe yield for the Lobatse East Basin ($3\ 644\ \text{m}^3/\text{m}$ or 0,81 million gallons per month), calculated from water level fluctuations and abstraction figures, compares extremely well with the figure obtained ($3\ 788\ \text{m}^3/\text{m}$) using an assumed recharge rate and known catchment area. This is regarded by the writer as confirmatory evidence of the reliability of the method used for calculating recharge.

Of the other two basins where the safe yield calculations can be checked using geohydrological observations, there is again a good correlation for the Lobatse Estates Central Basin, viz. $4\ 748\ \text{m}^3/\text{m}$ versus $3\ 523\ \text{m}^3/\text{m}$. However, for the Railway Sub-Basin, there is a large discrepancy due probably to the very short period (of sub-normal rainfall) over which recharge calculations have been made.

A Possible New Method of Estimating Ground-water Recharge

Lund (personal communication, 1973) has recently kindly supplied the writer with synthesised, long term run-off data for certain catchments in Botswana derived using a method developed primarily as a practical solution to the problem of reservoir yield determination in arid areas such as Botswana, where there is a paucity of hydrological and meteorological data. This method is based on the proposition that for a particular depth of rain falling over a reasonably long period, run-off will depend primarily on the wetness of the catchment. This is done by calculating the wetness of

the catchment by a water balance for a unit of time taken to be one month (Lund and Bylsma, 1972). With short term run-off records, a set of characteristic curves for the catchment are drawn up relating to rainfall and evaporation data over this limited period. These characteristic curves are then used to synthesise probable run-off records from the whole period over which rainfall and evaporation data, (or wet and dry bulb) are available. In order to produce the run-off figures, it was necessary to write a computer program involving the solution of five simultaneous equations for each month starting from the earliest years. An iterative procedure was used owing to the discontinuous nature of the rainfall/run-off relationship. Since run-off forms a small part of the water balance equation $SR = R - (\Delta SM + (INT + ETV))$ or $SR = F(R, SMAV)$, it is set at zero for the first iteration of each month, and only included in the second iteration when the first value of SMAV for that month has been obtained.

Symbols Used

SR:	Surface run-off.
R :	Average rainfall over catchment.
ΔSM :	Change in soil moisture state over month.
INT:	Sum of rainfall intercepted by vegetation and surface detention.
ETV:	Evapotranspiration from the soil mass and vegetation.
SMAV:	Average soil moisture state of the catchment and taken to be the average soil moisture in the top 0,7-1,0 m of the soil mass.
ETP:	Evaporation from a Symons pan.
C:	A constant usually taken as 0,7.

With the value of the calculated run-off over the catchment, a new value of SMAV is calculated and the procedure continued until the water balance equation is satisfied. Of the five basic equations for the solution of the problem it was found that evaporative processes play a major role in the analysis and care had to be taken to see that the heat budget equation was satisfied, i.e. $C \cdot ETP \geq ET + ETV$.

During normal months this relationship is satisfied, and the excess evaporating energy is used to heat the atmosphere.

During months of high rainfall, where the soil has reached field capacity, and there is low evaporating energy, there is an excess of moisture available which is assumed by the writer to be lost to ground-water storage.

We now thus have a possible method for determining amounts of recharge from long term rainfall and pan evaporation (or wet and dry bulb temperature) measurements and hence invaluable quantitative data can be synthesised for any area. This data can be of great use for sound long term resource planning.

Using this method, data covering the Nuane catchment immediately west of the Lobatse western ground-water basin, was synthesised and used to determine major recharge events in Lobatse. This has been plotted on Fig. 32 together with a long term recharge compiled from long term spring flow measurements by Bredenkamp and Vogel (1970) for a dolomite catchment in South Africa in a similar climatic zone to that of Lobatse. The calculated recharge for the Lobatse western basin for the 1970/1971 and 1971/1972 seasons as estimated by stream flow gauging, is also shown on the same figure. While there are some discrepancies between the curves, it appears that the

/above.....

above method could be useful for estimating ground-water recharge in developing, semi-arid countries which lack long term run-off data or detailed hydrogeological records. This data could be a particularly useful aid for assisting decisions as to whether ground-water resources should be supplemented by expensive surface water storage schemes.

Recharge Studies Using Gauged Weir Measurements

Although long term records of water level fluctuations, ground water abstraction figures and rainfall are available for Lobatse, there was an urgent need for the establishment of gauging weirs at various localities in the vicinity of the Lobatse ground-water basins in order to obtain a better idea of the mechanism of recharge and to provide an independent check on recharge calculations obtained from these long term measurements. This had however, proved impossible prior to 1970, because of the shortage of funds. In this year, however, the Geological Survey in conjunction with the Department of Water Affairs and the United Nations Development Fund, erected a single weir on a typical gully, (the "hospital gully") on the hill to the west of the Lobatse western ground-water basin. This gully, together with a number of similar gullies, form the sole source of recharge to the western ground-water basin. By accurately determining the catchment area of each gully and because geological conditions, vegetation and hence run-off characteristics are considered to be identical for all the gullies, it was considered that the total ground water recharge would be calculated by extrapolation from the one gauged catchment. See Fig. 22 for catchment areas and Plates 60 and 56, which show the gauging weir and typical gullies



Pl. 60

Gauging weir - Lobatse Western basin.



Pl. 61

Pumping installation - Orapa 8 Mile Wellfield.

in flood following exceptionally heavy rains.

These gullies normally carry no flow whatsoever, but because of the scrubby vegetation with sparse grass and soil cover, and even, in many places, a complete lack of soil cover, considerable volumes of water are channelled into the gullies and debouch onto the alluvial fans at the foot of the hillslope. These fans consist of large, angular to sub-rounded boulders, pebbles and cobbles set in a highly permeable and porous coarse sandy matrix. Further away from the foot of the hillslope, the inclusions become smaller, but nevertheless the material overlying the dolomite up to distance of 200 m from this point may contain boulders up to 15 cm and more in diameter (See Plate 58). Because of the permeable nature of this fill, only exceptionally heavy and prolonged periods of rain (e.g. 1966/1967) have resulted in flow from any of the gullies reaching the main road situated at a distance of 100 to 300 m from the foot of the hill, otherwise all run-off sinks in immediately into the porous material at the toes of the gullies.

It appears therefore that the scree zones at the foot of the hillslopes form an ideal natural medium for recharging the important underlying dolomite aquifer, while the shale-quartzite sandstone aquifers elsewhere which form the Lobatse Eastern and Lobatse Estates aquifer are probably replenished in a similar way by run-off from the surrounding hills.

The Gauging Weir

The weir was constructed of solid concrete, into which a quarter inch steel plate was set and was built on a solid quartz-feldspar porphyry foundation. The gauging section

consists of a conventional rectangular weir with a Vee notch set in it's base to measure small flows. This rectangular weir is 6 feet long while the right-angled V notch has a height of 1 foot (See Plate 60). Discharge measurements were made with an automatic water

level recorder. During the 1970/71 season, no flow took place within the rectangular section, while in 1971/72 flow topped the V-notch on only 5 occasions. The maximum recorded flow was at a rate of 5 295 m³ per hour for 24 minutes following a period from 9 - 29th March, 1972 in which a total of 144,2 mm (5,67 inches) of rain fell on 13 separate days with a maximum rainfall of 81,7 mm (3,22 inches) in one day. During January 1972, when the first recorded flow of the season was measured, a total of 231,8 mm (9,13 inches) fell on 24 separate days of which rainfall exceeding 10 mm fell on 9 days, with a maximum intensity of 33,8 mm (1,33 inches) being recorded in one day.

Calculations of the amount of run-off from the Lobatse Hospital gulley were carried out for the 1970/71 season by Robins (1971) with certain additions and corrections by the writer, and for the 1971/72 season by the writer.

Gauging Formulae

The writer has followed Robins (1971) and used the formulae $Q = 2,49H^{2.48}$ for the V-notch, while for the rectangular flat spill the writer has used the formula $Q = 3,33 L.H^{1.5}$ where Q = discharge in cubic feet per second (cusecs)

H = head in feet above the bottom of the notch

L = total width of spill (6 feet)

Where flow was restricted to the V-notch, the writer used the rating curve supplied by Robins. Where flow topped the V-notch, the writer used the rating curve derived from the above formula. This curve gives both flow through the V-notch and for the rectangular spill.

Discharge Calculations

Figure 33 shows the hydrographs for the two flow periods in the beginning of 1972. Figure 34 shows the relationship between discharge and rainfall for the 1970/71 rainfall season.

Extrapolation to calculate total run-off contributing to Lobatse Western Ground-water Basin

Examination of aerial photographs and a recently published topographic map of Lobatse to the scale of 1 : 5,000 show that there are eight principal gullies draining into the western basin. As the gullies are similar in character, it is considered that by extrapolating the discharge from the known catchment area of the hospital gulley, a fairly reliable measure of the total run-off from all the gullies could be obtained by simple proportion.

e.g. If run-off from the hospital gulley catchment of 145 700 m² is 17 409 m³, then the run-off from a similar gulley, say that opposite the tennis courts with a catchment of 116 900 m² will be

$$17\ 409 \times \frac{116\ 900}{145\ 700} = 13\ 968\ \text{m}^3$$

The gullies draining into the western basin are designated, from north to south:- Boswelatlou (?) Lamont's gulley (A), Hospital Gulley (B), Gulley opposite Geological Survey (C), Gulley opposite Tennis Courts (D), Gulley opposite B.M.C.

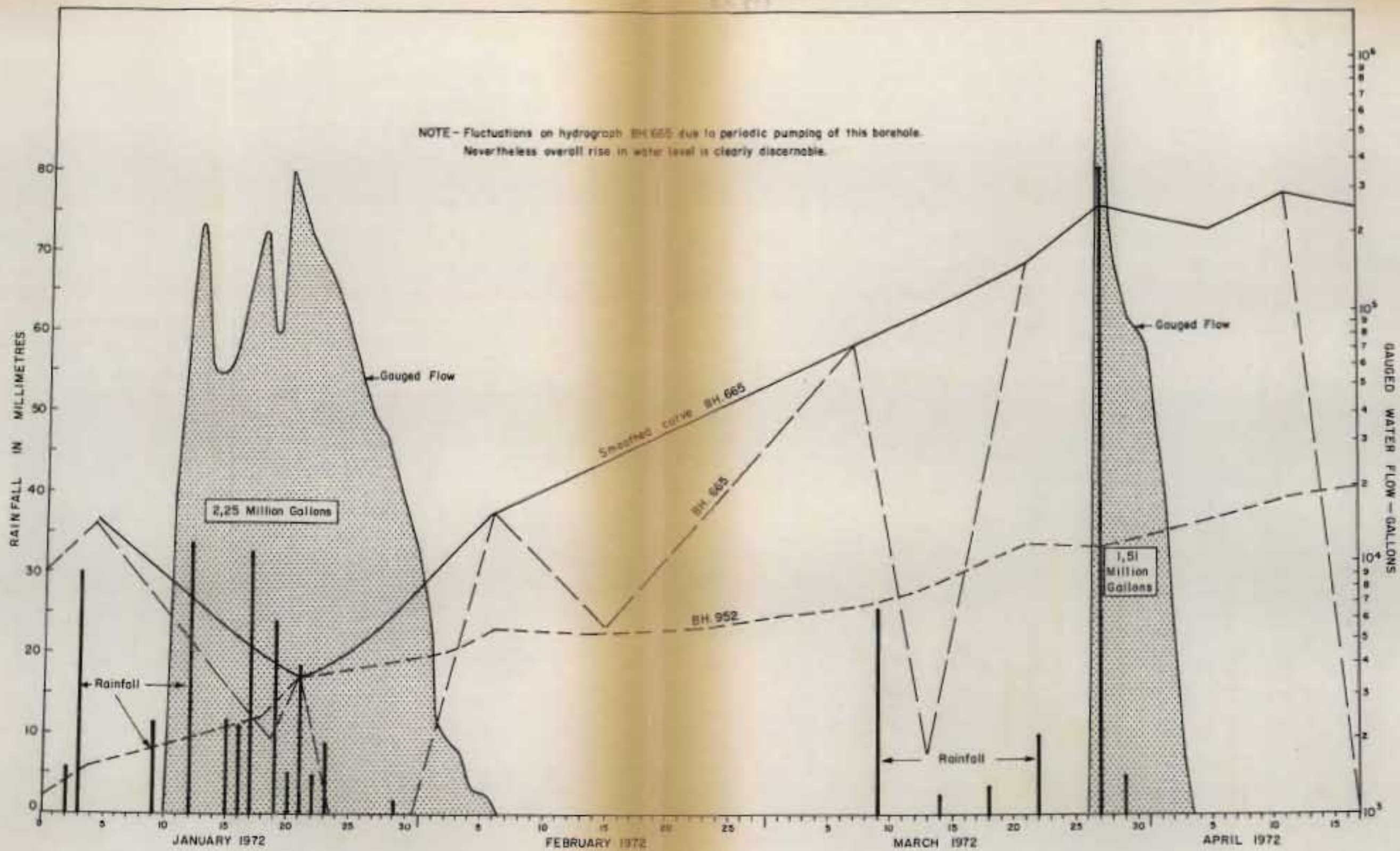
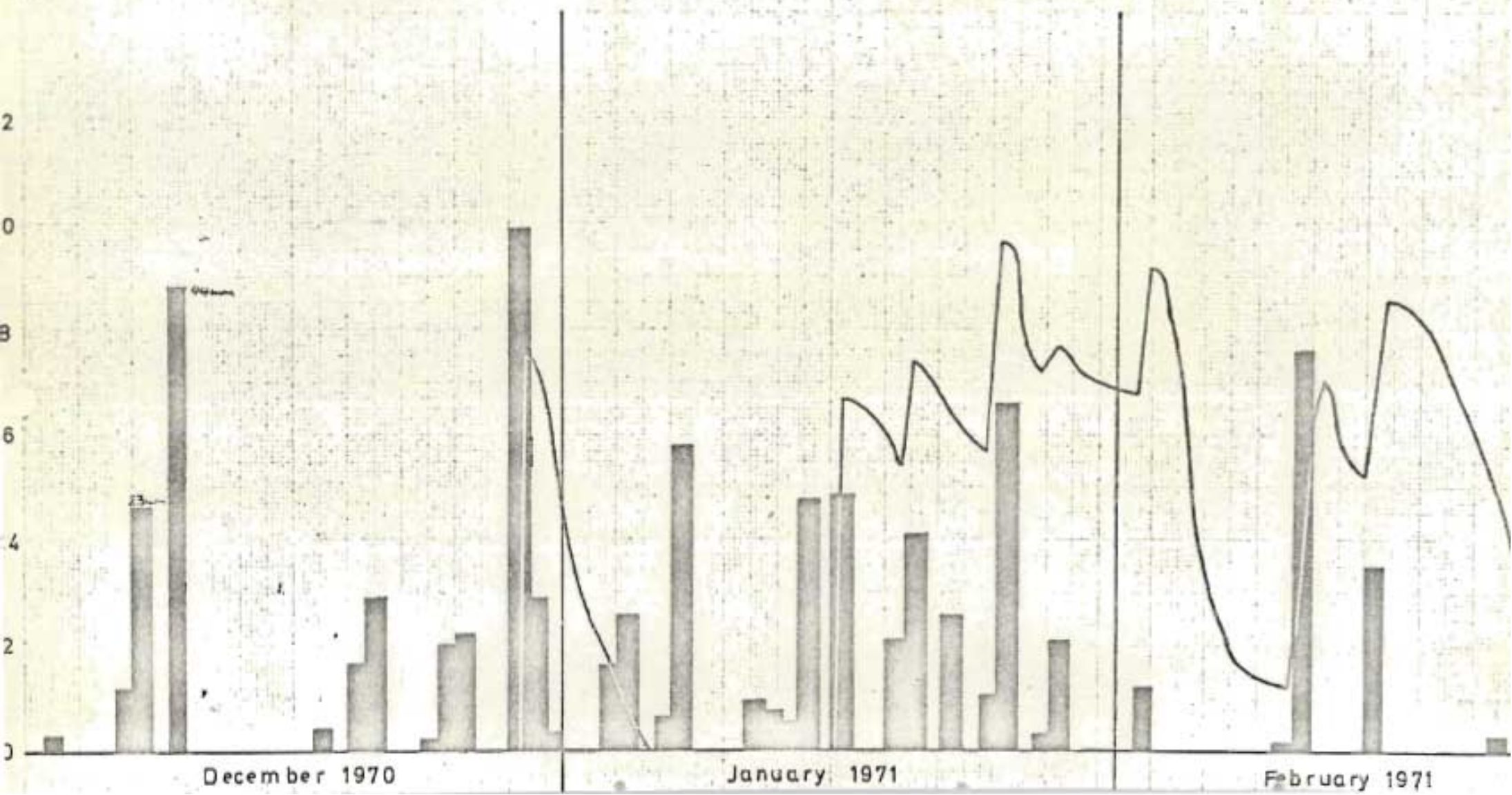


Fig. 33 GAUGED WATER FLOW, RAINFALL AND DETAILED HYDROGRAPHS
BH's 665 AND 952 - LOBATSE WEST BASIN - JAN. - APRIL 1972.

Fig. 34

Discharge - rainfall relationship (After Robins, 1971)

Discharge (thousands of gallons per day)



cold storage store (E), Gulley opposite B.M.C. main gates (F), gulley behind Post Office (H). A further gulley occurs opposite the Lobatse Indian School (I), but drains into the Railway basin, which is separated from the western basin by a low dolomite hill.

The areas of the various catchments were calculated by Jennings (1961) and Robins (1971) with very good agreement. Lamont's gulley catchment was unaccountably ignored by Robins. The areas and calculated discharge for the past two rainy seasons are given in Table 31 .

Summary of Results of Gauging Measurements

During the 1970/71 season a total of 159 873 m³ of rain water was calculated to have run off the hills to the west of the Lobatse western dolomite basin, the major portion of which was considered to have immediately entered the porous fill overlying the dolomite and to have gone directly to recharge the ground-water basin. In 1971/72 this amount was calculated to be 382 121 m³. These figures represent a run-off of 21,9 mm or 3,99 per cent of the mean seasonal rainfall for the 1970/71 season and a run-off of 52,35 mm or 9,55 per cent of the mean seasonal rainfall for the above average 1971/72 rainy season (684 mm). As the rainfall total for the 1970/71 rainy season was slightly above normal (579 mm compared to the long term average of 548 mm), there is thus an excellent agreement between data obtained by using an independent method. i.e. Four per cent recharge calculated from stream gauging for a year with slightly above average rainfall compared with 3,84 per cent recharge calculated from long term water level data and water

TABLE 31

CALCULATED RUN-OFF TO LOB. W. BASIN

CATCHMENT	AREA M ²	RUN-OFF 1970/71* SEASON GALLONS	m ³	WEIGHT OF WATER (SHORT TONS)	RUN-OFF 1971/72 GALLONS	m ³	WEIGHT OF WATER (SHORT TONS)
A	2,645,012	29,042,000	132 009	145,210	69,514,000	315 973	347,570
B	120,490	1,323,000	6 014	6,615	3,141,000	14 272	15,705
HOSPITAL							
C (GAUGED WEIR)	145,700	1,600,000	7 273	8,000	3,830,000	17 409	19,150
D	46,080	506,000	2 300	2,530	1,187,000	5 395	5,935
E	116,900	1,284,000	5 836	6,420	3,064,000	13 927	15,320
F	58,170	639,000	2 905	3,185	1,494,000	6 791	7,470
G	50,100	550,000	2 500	2,750	1,302,000	5 918	6,510
H	20,730	228,000	1 036	1,140	536,000	2 436	2,680
TOTAL(A to H)		35,172,000	159 873	175,850	84,068,000	382 121	420,340
I	2,138,000	23,478,000		117,390	56,186,000		280,930

* NOTE: All totals for the 1970/71 season barring A and H were calculated by Robins. A number of minor arithmetical errors made by Robins have been corrected. All other calculations were made by the writer.

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Some calculations using data from gauging weirUsing observation borehole A6 (Fig. 26).

1. From 1.8.70 to 1.8.71, the water level rose in observation borehole A6 from 25,73 m to 24,78 m. i.e. 0,95 m. During this period, 82 227 m³ (18,09 m.g.) were pumped, while recharge as calculated by extrapolation from the hospital weir gauging was 159 873 m³ (35,17 m.g.) or 13 323 m³ per month (assuming all run-off goes to recharge).

$$\begin{aligned} \therefore \text{Excess of recharge over abstraction} &= 159\,873 - 82\,227\text{m}^3 \\ &= 77\,646\text{m}^3 \end{aligned}$$

$$\therefore \text{Storage capacity for 0,95 m of aquifer} = 77\,646\text{m}^3$$

$$\begin{aligned} \text{Quantity of water stored per unit drop in level} &= 77\,646 \times \frac{100}{95} \\ &= 77\,646\text{m}^3/\text{m} \end{aligned}$$

As rainfall for the season (579 mm) was only slightly above average (548 mm), there is an excellent correspondence between the above recharge of 159 873 m³ and the average recharge rate of 150 000 m³ per year calculated from long term water levels and abstraction figures. This tends therefore to confirm that the above assumption of nearly all run-off contributing to recharge is correct. This is also confirmed by observation of the flood waters. When these reach the toes of the gullies, the water can be seen to infiltrate directly into the permeable scree. None of the flood water thus collected in pools at the surface, where it could be evaporated, while the lack of any significant concentration of vegetation in this area probably means that little transpiration losses can occur. Data from tritium measurements of the ground water, however, shows that there is no

significant rise in tritium levels (which could be expected with recharge water with high tritium mixing with water with about 0,7 TU). This is interpreted by the writer as giving valuable data on the actual mechanism of recharge which is regarded as a downward displacement of moisture in the unsaturated zone to the water table.

2. The static water level rose from 25,15 m on 1st October 1971 to 22,5 m on 1st October 1972 - i.e. by 2,65 m. During this period, gauging on the Hospital gully weir indicated a total recharge to the western basin of 382 127 m³. During this same period 83 773 m³ of water were pumped from boreholes.

$$\begin{aligned} \therefore \text{Excess of replenishment over} \\ \text{abstraction} &= 382\ 127 - 83\ 773\ \text{m}^3 \\ &= 298\ 354\ \text{m}^3 \end{aligned}$$

∴ An increase in storage of 298 354 m³ resulted in a rise in water level of 2,65 m.

$$\begin{aligned} \therefore \text{Quantity of water stored per unit} \\ \text{(metric) drop in level from 22,5} \\ \text{to 25,15 m} &= 112\ 586\ \text{m}^3/\text{m of} \\ &\text{aquifer.} \end{aligned}$$

For this period recharge rate = 9 382 m³ per month.

3. On 1.6.70 and 1.5.71, water levels were the same (Fig. 26). During the same period, 135 409 m³ (29,79 m.g.) were pumped from the western basin. i.e. During this period replenishment may be assumed to equal abstraction because of identical water levels.

During the 1970/71 season, calculated run-off and hence assumed recharge was 159 873 m³ (35,17 m.g.). The difference can be accounted for by a possible time lag in the recharge of the aquifer (corroborated by a rise

in water level in the months following the above period), or could be caused by evapotranspiration or soil zone losses. One thing is clear, however, that a very high percentage of run-off does infiltrate to replenish ground-water storage in the Lobatse area. The assumption of run-off for this particular basin going to recharge of ground-water is thus confirmed.

Artificial Recharge

Artificial replenishment of the Lobatse aquifers (using excess water (overflow) from Nuane Dam) should be seriously considered at some time in the future for Lobatse water supply. This would supply extra water storage in a large, low-cost evaporation-free reservoir. As the ground-water basins are already equipped with boreholes and an efficient reticulation system, the capital costs of such a scheme would be very low.

GROUND-WATER STORAGE CAPACITY

The ground-water storage capacity of all basins in the Lobatse area was calculated using a combination of data from long term pumping (abstraction) figures and water level fluctuations in observation boreholes situated some distance away from existing production boreholes and hence away from cones of depression of pumping boreholes. In addition pumping from all boreholes in the Abattoir area in the vicinity of observation borehole A6, was stopped for at least 24 hours prior to the measurement of the monthly water level in the borehole. The average recharge rate (safe yield) was first calculated

for as long a period as possible, over which water levels at the beginning and end of the period were the same. Hence knowing the amount of water pumped from all boreholes in the basin over the same period, it was then assumed that abstraction over the whole period equalled the recharge.

This assumption could be made because of the lack of springs or any other obvious leakage from the ground-water basins and the fact that evapotranspiration losses would be negligible both because of a lack of large trees and shrubs in the area and also because of the depth of the water table (730 m). The next step was to take two points on the hydrograph as widely separated in time and vertical elevation as possible and, knowing the amount of water pumped during this same period, the difference between the amount abstracted by pumping and the calculated total recharge was assumed to represent the net loss or gain in storage capacity for that depth interval. From this a storage capacity per metre of aquifer was calculated and hence the total storage capacity for the whole aquifer was estimated knowing the thickness of the aquifer from a combination of past fluctuations of water levels in the aquifer, geological logs and geophysical data.

The major possible sources of error in the above calculations are:

- (i) the assumed recharge rate,
- (ii) the assumed saturated thickness of the aquifer,
- (iii) the assumption that there is no decrease in storage with depth.

This latter can be largely eliminated by obtaining an

average storage capacity which is representative of as wide a difference in water levels as possible.

The recharge rate is probably fairly reliable, provided long term periods are taken and provided the period chosen does not end or start in the middle of the rainy season.

The figures taken for the saturated thickness of the aquifer are, in all cases, regarded as conservative. They however, probably represent the major source of error in the calculations of storage capacity.

Estimates of the storage capacity for five Lobatse groundwater basins for which long term data are available, are given in Table 32, while estimates of the total storage capacity of all the Lobatse basins are given in Table 33.

Use of Aquifer Test Data to Calculate Storage Capacity

Debney (1969) used the data (Jennings, 1969a) which indicated a 2 per cent specific yield for the Lobatse western basin dolomite aquifer, which is a water table aquifer. Assuming the same aquifer thickness as used for the earlier storage capacity calculations, he obtained a calculated storage capacity of $872\,727\text{ m}^3$. This compares remarkably well with the mean figure of $869\,988\text{ m}^3$ (Table 32) obtained from long term water level and pumping data.

Storage Capacity and Specific Yield Variations with Depth

Enslin and Kriel (1967) have shown that dolomite aquifers in the Republic of South Africa show a rapid decrease in porosity with depth. Storage capacity calculations (See Table 34) over different depths within the Lobatse western

TABLE 32

STORAGE CAPACITY OF VARIOUS LOBATSE AQUIFERS

Calculated safe yield (table 24) in m ³ /month <i>to be kept safe.</i>	Drop or rise in water level in metres	Period over which drop or rise occurred	No. of months	Abstraction over same period m ³	Recharge over same period m ³	Diff. = storage capacity for drop or rise in column 2, m ³	Storage capacity per metre of aquifer m ³	Estimated aquifer thickness m	Total storage capacity of aquifer m ³
1. <u>LOBATSE RAILWAY SUB-BASIN</u> 1 262	- 2,13 (9,756-11,89)	1.5.68-1.5.70	24	151 027	30 768	120 259	56 400	> 11	> 621 056
2. <u>LOBATSE WESTERN BASIN</u> 11 857 (142 284 n.p.a.)	+ 11,28 (35,06-23,78)	1.12.63-31.8.69	69	225 000	69 x 11 857 = 818 133	593 133	62 583	> 15	> 708 745
11 857	+ 12,00 (35,82-23,82)	31.5.63- 30.6.72	111	504 409	111 x 11 857 = 1 316 127	811 718	63 415	> 10	> 951 232
3. <u>LOBATSE EASTERN BASIN</u> 3 687	- 4,57	1.10.57-30.9.63	71	335 216	71 x 3 687 = 261 777	74 439	16 653	> 18	> 299 754
4. <u>LOBATSE ESTATES SOUTHERN BASIN</u> 3 300	- 22,400	1.5.61-31.10.64	41	158 627	41 x 3 300 = 135 300	23 327	1 041	> 30	> 31 230
3 300 <i>= 4,0 x 10⁴ m³ per year</i>	- 3,567	1.11.60-31.8.72	142	512 409	142 x 3 300 = 468 600	43 809	12 281	> 30	> 368 430
5. <u>LOBATSE ESTATES CENTRAL BASIN</u> 4 748	- 9,146	1.10.62-31.11.64	23	327 273	23 x 4 748 = 109 204	218 069	23 843	> 18	> 435 152

TABLE 33SUMMARY OF STORAGE CAPACITY OF LOBATSE AQUIFERS

	<u>STORAGE CAPACITY m³</u>
Lobatse Railway Sub-basin	621 056
Lobatse Western Basin	951 232
Lobatse Eastern Basin	299 754
Lobatse Estates Southern Basin	368 430
Lobatse Estates Central Basin	436 152
Going Dolomite Basin (Estimated at $\frac{1}{2}$ capacity of Lobatse Western Basin)	237 808
Pitsanyane Dolomite Basin (Estimated at $\frac{1}{2}$ capacity of Lobatse W. Basin)	237 808
Teachers Training College Basin (Estimated 2 x Safe yield)	74 545
Lobatse Estates Northern Basin (Estimated to be similar to Central Basin)	<u>436 152</u>
TOTAL	<u>3 662 937</u> m ³ = 805 846 140 m.g.

basin support this evidence and show a progressive decrease with depth.

TABLE 34

SHOWING DECREASE IN STORAGE CAPACITY(AND SPECIFIC YIELD)
WITH DEPTH*, LOBATSE WESTERN BASIN

<u>Depth m</u>	<u>Storage Capacity m³/m</u>	<u>Specific Yield %</u>
22,5 - 26,15	91 393	3,15
24,78 - 25,73	82 000	2,82
23,78 - 35,06	56 953	1,96

*Calculations based on an aquifer area of $2,9 \times 10^6 \text{ m}^2$
(1,11 sq. miles)

Storage Capacity Calculations using Isotopic Measurements

The use of environmental isotopes in the Lobatse area has been described in greater detail in a separate chapter on isotopes and only a brief summary will be given here.

Using the average value of $11\ 857 \times 12 \text{ m}^3 = 1,4 \times 10^5 \text{ m}^3$ the annual recharge and value of $T = 92 \text{ yrs}$ then

$$\begin{aligned} \text{Storage capacity} &= 92 \times 142\ 284 \text{ m}^3 \\ &= 13\ 090\ 128 \text{ m}^3 \end{aligned}$$

This value is 15 times higher than the calculated storage capacity derived from long term pumping and water level data but probably includes all water present in the unsaturated zone. The volume of water in this zone assuming 8 per cent moisture and a dolomite basin area of $2,9 \times 10^6 \text{ km}^2$ is $7\ 374\ 272 \text{ m}^3$, which together with the calculated storage capacity totals $8\ 244\ 261 \text{ m}^3$, leaving a difference of $4\ 845\ 867 \text{ m}^3$. This difference probably represents a more

realistic value for the storage capacity of the aquifer because it is calculated without the need to estimate the aquifer thickness - the main possible source of error in the earlier storage capacity calculations.

THE USE OF ISOTOPES AS AN ADDITIONAL GEOHYDROLOGICAL TOOL
IN THE LOBATSE AREA

A detailed project to determine the effectiveness of environmental tritium as an additional geohydrological tool was commenced in 1969 in collaboration with the Nuclear Physics Research Unit (N.P.R.U.) of the University of the Witwatersrand. To date more than 1000 water samples have been measured for tritium and over 2100 samples collected. Results have been presented by Verhagen, Sellschop and Jennings (1970, 1970a and 1974) and by Jennings et al (1974). These results are described in more detail in the chapter on Environmental Isotopes.

The main conclusions from this joint research project undertaken by the writer and Professor J.P.F. Sellschop and Dr. B. Verhagen (both of N.P.R.U.) are:-

1. It was found possible to obtain excellent repeatability of measurements on the very low levels of tritium found to be present in ground water in Botswana. This therefore gives confidence in the reliability of measurements at extremely low levels. Colleagues in the northern hemisphere, had previously queried the ability of a laboratory to make reliable and meaningful measurements at these low levels (largely because of the much higher atmosphere tritium levels in the northern hemisphere with a consequent much

higher risk of contamination.) .

2. Differences in tritium levels in the different ground-water basins in general confirmed the distinct hydrogeological characteristics of the basins.
3. Areas of recharge were indicated by higher tritium levels.
4. The mechanism whereby recharge takes place was more clearly defined using a combination of tritium data from both the unsaturated and saturated zones. As a result, a model for the recharge of aquifers in the western basin was postulated and was successfully applied to other basins in the area.
5. Calculations of the storage capacity for the different basins (Verhagen, Sellschop and Jennings, 1970, 1970a) had earlier given consistently higher values (by a factor of about ten) than those obtained from draw-down and pumping figures. However, infiltration measurements through the unsaturated zone have underlined the importance of water stored in this zone. Calculations, using the tritium method, of the total amount of water present in both the unsaturated and saturated zone are thus now in reasonable agreement (but still somewhat higher) than obtained by conventional methods. This difference is regarded by the writer as being due to additional water present in the saturated zone, which had not been taken into account because of the lack of geohydrological data

on the true thickness of the aquifer. The tritium method could thus be a valuable tool in obtaining reliable estimates of ground-water storage in fissured, secondary type aquifers.

6. While tritium measurements have confirmed the overall geohydrological assumption of discrete ground-water basins, they have also showed (e.g. southern part of western and eastern basins) that some leakage probably takes place from one basin to another.
7. Carbon-14 isotopic data has helped show the general pattern of ground water movement in the Lobatse Estates Central Basin, which tritium had failed to do. ^{14}C measurements have furthermore showed that mixing of "old" and "young" waters is taking place in the Railway and Lobatse Estates Southern Basins.

GEOPHYSICS AS AN AID TO BOREHOLE SITING

Geophysics has long been used as an aid to the siting of boreholes in Lobatse. Electrical resistivity, and magnetic surveys were carried out initially by Geophysical Surveys Limited and later by the Geological Survey of Botswana. In addition to the earlier use of the above two methods, gravity, self-potential, constant separation resistivity, Afmag and horizontal loop-inductive electromagnetic traverses have been carried out. The electromagnetic methods proved useful in delineating a major wrench fault on Lobatse Estates and the gravity method proved useful in delineating zones of decomposition in

the Lobatse western basin. However, the method which undoubtedly yielded the best results was the electrical resistivity method which proved useful in locating zones of decomposition in both the dolomite and quartzite aquifers in the Lobatse Western and Lobatse Estates aquifers respectively. A typical example of an electrical resistivity depth probe is given in Fig. 36 .

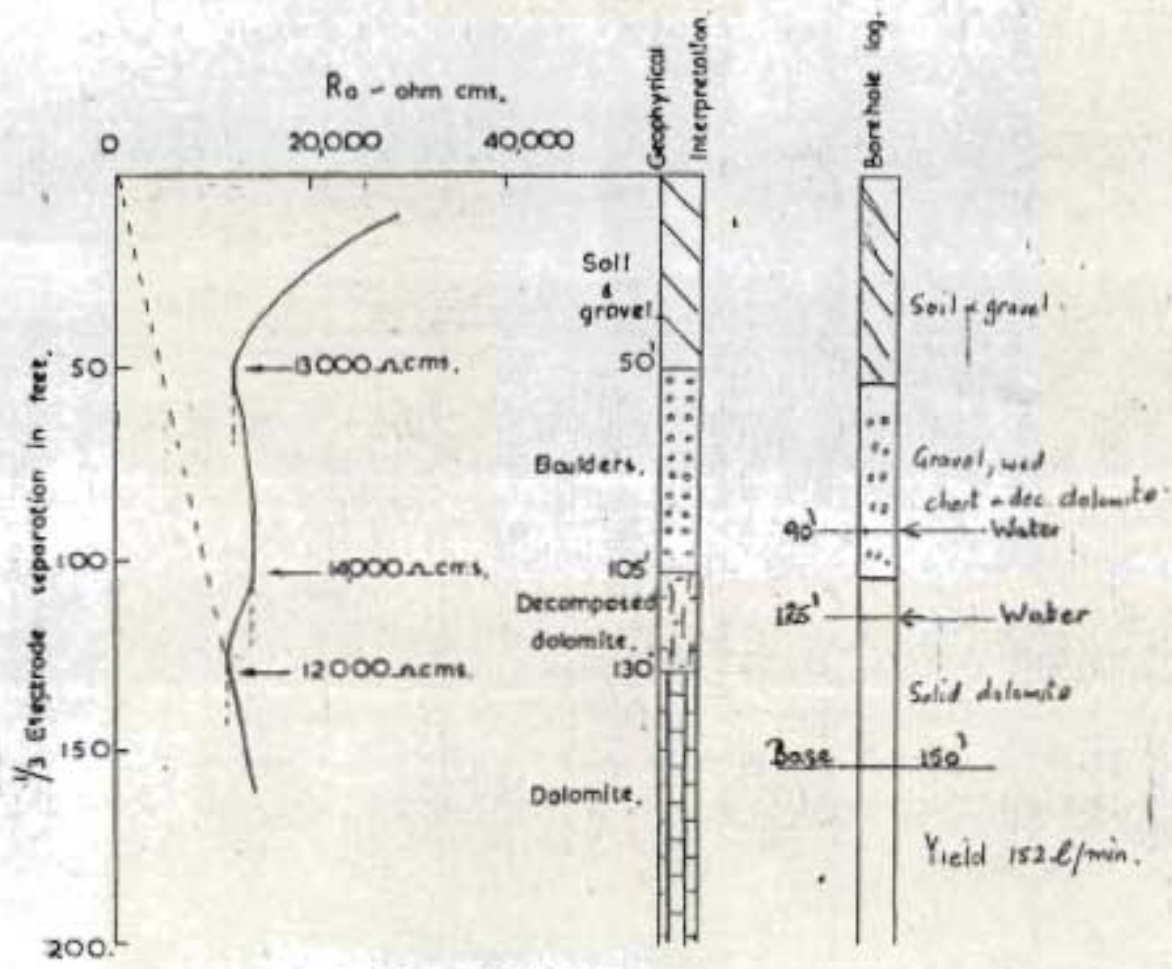
A number of boreholes have been electrically logged while fluid temperature and conductivity logs have been carried out on a number of boreholes. The fluid conductivity log proved useful in one case in giving the exact entry point of water into the borehole.

PUMP TESTS

Carefully controlled aquifer evaluation pump tests have been carried out in both the dolomite and shale/quartzite aquifers. Particularly detailed results were obtained from a pump test carried out at borehole A.2 in the Lobatse Western Sub-Basin, where five observation boreholes were available at distances of 104 to 321 m from the pumped borehole (Jennings, 1969a). The results of this test using the Theis non-equilibrium formula gave values for the coefficient of transmissivity (T) of 248 metres squared per day and a value for the coefficient of storage (S) of 0,20 (2,0 per cent specific yield for a water table aquifer). On Lobatse Estates values for T were as high as 621 metres squared per day. The lack of suitably spaced observation boreholes in this area unfortunately prevented obtaining values for S which could be used to calculate the storage capacity.

Fig. 36
C.D.C. ABATTOIR BOREHOLE SITES.

A typical resistivity curve.



DEPTH PROBE 10.
Site 2.b

Debney (1969) has used the above values for borehole A.2 to calculate the total volume of the western Lobatse basin and has obtained a figure of 872 000 m³ assuming a 15 m saturated thickness and a specific yield of 2 per cent. This figure agrees remarkably well with the figure of 868 000 m³ obtained earlier using pumping figures and water level fluctuations. Debney also showed that even after two years of continuous abstraction, a fully efficient well should be capable of yielding 378 litres per minute for a drawdown of three metres.

HYDROCHEMISTRY

Systematic sampling, on a monthly basis, of borehole water for chemical analysis has been carried out since January 1969 on a large number of boreholes. In addition to pumped samples, depth sampling, using a special sampler was carried out for routine chemical and tritium analyses.

Slight chemical stratification was noted in a number of boreholes with an increase in total dissolved solids (t.d.s.) with depth. Examples of this slight chemical stratification with increasing depth are given in Table 35. Boreholes 629 and 2135 are both situated in the western basin while boreholes 1331 and 1352 are in the Lobatse Estates northern basin. The chemical stratification in the northern basin was noted only during a period when no pumping (December 1969) was taking place in the basin. Boreholes 629 and 1352 are both situated at a considerable distance from pumping boreholes in the western basin. It is concluded therefore that the chemical layering

TABLE 35

SHOWING CHEMICAL STRATIFICATION WITH DEPTH BH 629, 2135 (W. BASIN) 1331, 1352 (LOB EST. C. BASIN)

BH. NO.	629	629	1331	1331	1352	1352	2135	2135
DATE	8.6.'71	8.6.'71	22.9.'69	22.9.'69	8.12.'69	8.12.'69	8.4.'70	8.4.'70
DEPTH	100'	168'	130'	350'	200'	340'	120'	179'
pH	6.80	7.15	7.90	7.55	6.70	7.65	7.55	7.45
CO ₃ ⁻⁻	-	-	13	-	-	-	-	-
HCO ₃ ⁻	116	426	167	240	87	240	212	344
Cl ⁻	7	7	7	7	7	14	7	11
SO ₄ ⁻⁻	5	135	24	430	15	33	8	51
F ⁻	1	1	1	1	1	2	1	1
<u>TOTAL ANIONS</u>	129	569	212	678	110	296	228	407
K ⁺	4	8		1	1	1	4	5
Na ⁺	4	6	10	11	1	-	4	5
Cu ⁺⁺	25	108	4	202	18	44	38	90
Mg ⁺⁺	7	54	22	29	12	38	22	27
<u>TOTAL CATIONS</u>	40	176	81	249	32	85	68	127
<u>SUM TOTAL</u>	169	745	293	927	142	382	296	534
T.d.e.	124	596	228	916	112	344	212	376
THEOR T.d.e.	110	529	208	805	98	264	197	359
K	160	800	400	975	135	360	290	540

in these boreholes has come about as a result of gravitational settling of the slightly heavier water during times of little disturbance of the ground water in the basins by pumping.

In the vicinity of the Meat Commission, there is a marked age (tritium) and chemical stratification, with an increase in t.d.s. from 600 at 27 m to 1570 parts per million at 43 m in borehole A6 (western basin). There was a drop from 16,1 tritium units (TU) at 27 m to 4,5 TU at 43 m. Similar stratification is present in borehole X4 (eastern basin, See Table 36). This marked chemical stratification is undoubtedly due to pollution by effluent from the Botswana Meat Commission which discharges effluent with a very high dissolved solids content through an unlined drain into the nearby Peleng River. Effluent disposal into the river has increased to such an extent that a perennial flow of water now passes down the river past the Lobatse Estates southern and central groundwater basins. As a result of this, boreholes in the southern basin have showed a deterioration in water quality (Table 37). The only borehole in the Lobatse Estates central basin to show this is borehole 112, which is situated on the banks of the Peleng River. Water from this borehole has shown a rise in t.d.s. content of from 402 on 1.8.1962 to 1796 parts per million on 29.9.1969. This has subsequently dropped since effluent brine containing the equivalent of approximately one ton of sodium chloride per day was removed by tanker and dumped elsewhere.

The water in the western dolomite basin is generally of moderate quality with average t.d.s. of 300-400 parts

TABLE 36

CHEMICAL AND TRITIUM STRATIFICATION IN BHS x 4 AND A.6 LOB. W BASIN

BH No.	P772(x4)	P772(x4)	P772(x4)	Z1661(A.6)	Z1661(A.6)	Z1661(A.6)	P.209(A3)
DATE	29.7.'69	29.7.'69	29.7.'69	25.4.'69	25.4.'69	25.4.'69	14.1.'71
DEPTH	50'	95'	145'	85'	125'	140'	PUMPED
pH	7,6	7,60	7,70	7,25	6,95	7,15	7,05
CO ₃ ⁻⁻⁻	-	-	-	-	-	-	-
HC O ₃ ⁻	295	362	457	108	255	261	289
Cl ⁻	358	522	852	207	435	770	851
SO ₄ ⁻	39	60	59	110	44	30	81
F ⁻	1	1	1	1	1	1	1
TOTAL	693	945	1369	426	735	1062	1222
K ⁺	17	7	8	5	7	9	9
Na ⁺	33	41	46	90	148	250	305
Ca ⁺⁺	109	200	300	44	111	164	161
Mg ⁺⁺	100	124	188	46	62	88	111
<u>TOTAL CATIONS</u>	<u>259</u>	<u>372</u>	<u>542</u>	<u>185</u>	<u>328</u>	<u>511</u>	<u>1041</u>
<u>SUM TOTAL</u>	<u>952</u>	<u>1317</u>	<u>1911</u>	<u>611</u>	<u>1063</u>	<u>1573</u>	<u>2263</u>
TRITIUM TU	14,3±1,4	13,6±0,8	12,8±0,8	16,1±1,5	13,3±1,4	4,5±0,6	

TABLE 37

VARIATIONS WITH TIME IN DWS. 023, 1112 (LSD, CRT. S AND C BASINS) DUE TO POLLUTION
BY AMATEUR EFFLUENT

Ch. No.	023	023	023	023	023	023	023	023	023	023	023	023	023	023	1077	1077	1077	1077	1077	1117	1117	1117	1117	1117
DATE	20.1.70	20.4.70	21.2.70	7.7.70	10.9.70	10.11.70	7.1.71	8.3.71	11.6.71	26.7.71	28.10.71	7.2.72	19.5.72	15.11.72	20.1.70	25.2.70	10.4.70	22.5.70	2.7.70	1.0.72	20.2.70	10.4.70	22.5.70	2.7.70
DEPTH	200'	200'	200'	200'	200'	200'	200'	200'	200'	200'	200'	200'	200'	200'	PUMPED	PUMPED	PUMPED	PUMPED	PUMPED	PUMPED	PUMPED	PUMPED	PUMPED	PUMPED
PH	7.30	7.40	7.10	7.40	7.60	7.40	7.30	7.40	7.20	7.05	6.95	7.10	6.90	7.50	7.10	7.15	7.25	7.20	8.10	8.3	7.05	7.15	7.30	7.50
CO ₂	-	-	-	-	33	26	-	-	-	-	-	-	-	-	-	-	-	-	53	-	-	-	-	33
HCO ₃ ⁻	532	509	510	520	451	484	620	572	542	556	550	658	507	625	559	506	509	556	474	266	513	650	641	625
Cl ⁻	39	37	78	39	100	34	50	72	70	67	79	85	77	106	64	60	92	304	497	15	354	419	774	645
SO ₄ ⁻	15	94	31	64	25	69	102	47	58	47	41	59	13	38	38	37	18	18	10	5	20	16	15	51
F ⁻	1	1	1	2	1	1	1	1	1	2	1	2	3	1	1	1	2	2	2	1	1	1	2	2
<u>TOTAL CATIONS</u>																								
	580	701	620	633	608	644	761	692	671	672	679	801	650	770	692	672	681	966	1044	507	888	888	1630	1753
K ⁺	1	4	2	2	2	1	3	1	2	2	1	1	1	1	2	2	2	4	5	4	3	2	3	3
Na ⁺	60	57	58	65	56	74	100	64	30	60	66	67	70	55	60	63	73	133	140	22	48	50	47	48
Ca ⁺⁺	33	70	43	30	66	47	85	52	46	43	38	69	60	171	44	43	47	107	160	38	153	171	252	316
Mg ⁺⁺	74	79	61	78	84	70	79	83	99	85	90	99	67	37	64	78	66	110	125	29	138	129	235	260
<u>TOTAL CATIONS</u>																								
	160	210	184	180	187	200	247	200	155	190	195	206	190	264	190	205	208	354	422	96	313	357	547	627
<u>SUM TOTAL</u>																								
	750	911	804	813	795	844	1028	892	826	870	874	1036	807	1034	882	870	899	1314	1465	602	1201	1338	2221	2383
T.d.s.	620	738	572	476	890	680	640	675	423	620	640	772	856	-	728	648	714	1358	1348	294	1318	1673	2010	2128
THION C.d.s.	435	821	545	553	573	606	713	611	508	597	600	714	560	-	577	590	609	1041	1233	157	640	1059	1504	1577
X	600	9	675	750	950	900	975	950	850	900	950	1100	1000	-	1400	900	1000	1700	1700	440	1400	1000	3000	3200

per million with calcium and magnesium cations and bicarbonate anions dominant. A typical example of this type of water is given in Table 35. The waters in the eastern quartzite basins are generally of better quality except where contaminated by effluent. Four boreholes with excellent quality water containing less than 100 parts per million t.d.s. are situated in the Lobatse Estates central and northern basins. Typical analyses of these pure waters are given in Table 38. These waters, which are slightly acid, are even better quality than the pure waters found in the Okavango Swamps. The excellent quality of the water is probably due to the lack of contaminating salts in the quartzitic sandstone aquifer.

Most of the waters may be classified as Type A (van Straten 1961), i.e. with equivalent $(Ca^{++} + Mg^{++}) > (Na^{+} + K^{+})$ and $(CO_3^{--} + HCO_3^{-}) > (SO_4^{--})$ though boreholes which have been contaminated by effluent are classed as type E. It is interesting to note that N_a^{+} has been eliminated from the effluent by cation exchange in the stream alluvium during infiltration.

WATER LEVELS

Hydraulic Gradients

The collars of a number of boreholes in the Lobatse western and eastern basins and Lobatse Estates basins, were levelled using a dumpy level and all water levels were measured at a time when no pumping was taking place, in order to determine whether any clear hydraulic gradients were

TABLE 38

SHOWING EXCEPTIONALLY PURE GROUND WATER IN BHS 2250, 2265, 2264, 2265 AND 2271 LOB.EST. CENTRAL AND NORTH BASINS

BH NO.	2250	2265	2262	2264	2271
DATE	6.10.'69	2.7.'70	3.3.'71	2.7.'70	16.12'69
DEPTH	140'	PUMPED	PUMPED	PUMPED	PUMPED
pH	6.15	5.90	6.10	6.40	5.75
CO ₃ --	-	-	-	-	-
HCO ₃ -	47	47	34	41	13
Cl -	7	4	11	7	11
SO ₄ --	6	5	5	18	9
F -	1	1	1	1	1
<u>TOTAL ANIONS</u>	61	57	51	67	34
K +	1	1	2	1	1
Na +	3	2	1	2	2
Ca ++	13	7	9	4	4
Mg ++	6	6	5	10	5
<u>TOTAL CATIONS</u>	23	16	17	17	12
<u>SUM TOTAL</u>	84	73	68	84	46
T.d.s.	68	56	56	72	40
THEOR.t.d.s.	60	49	51	64	33
K	85	78	75	72	55

present.

Lobatse Basins

These levels are shown in Fig.37 and show clearly that water levels in the northern (P.212) and southern ends of the western (railway basin Bh 1368) basin have appreciably higher levels than the boreholes in the central part of this basin. Boreholes in the central part of the western basin show very little hydraulic gradient and hence it is concluded that the aquifer has a good transmissivity. It is interesting to note that the two boreholes with the highest water levels are situated near the toes of the largest gullies. There is a steady decrease in water level evaluations northwards from the D.C.'s office boreholes (1368 etc,) and there is also some evidence of a gradient from borehole P.212 southwards (borehole 665 has a higher water level than the other boreholes in the central part of the western basin).

There is a difference of about 5 metres between eastern and western basin boreholes, thus confirming geological evidence that these two basins may be regarded as discrete geohydrological units.

Tritium measurements on boreholes in these basins confirm the postulated recharge areas at the northern and southern ends of the western basin and also that the eastern basin may be regarded as a hydrologically separate basin. (See Chapter on Isotopes).

/Lobatse.....

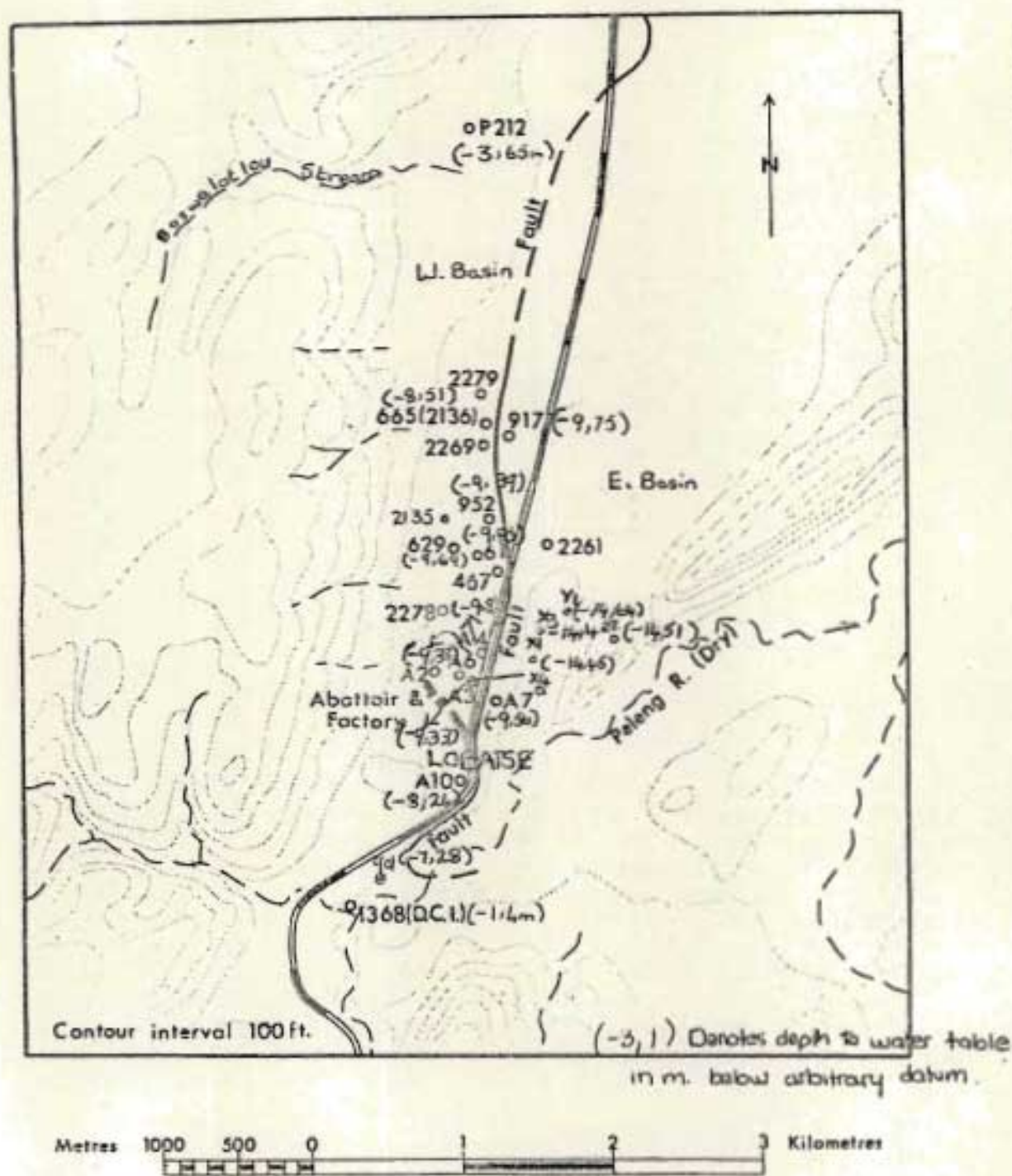


FIG 57 Map: Lobatse western basin, and eastern Basin - water levels

Lobatse Estates Basins

Water levels in boreholes on Lobatse Estates are shown in Fig.38 . Water level gradients in the southern basin are in general higher in a southwesterly direction, indicating flow from this direction.

Boreholes in the central basin have clearly different levels to that of the southern basin (± 17 m difference) indicating hydrological discontinuity between the two basins. This has been confirmed by considerably different tritium levels in the two basins.

In the northern basin water levels indicate an easterly and northerly source of recharge, presumably the dip slope of the Magaliesberg Subgroup quartzites.

Long Term Water Level Fluctuations

Long term water level fluctuations are given for the Lobatse Railway (Figs.39,40) Western (Figs. 26, 41, 42) Eastern (Figs.27,43) Lobatse Estates Southern (Fig.28) and Central Basins (Fig 31).

All show some seasonal response to recharge by rainfall while the other fluctuations are in response to varying pumping rates. Particularly large fluctuations are caused by pumping in the Lobatse Estates southern basin. The sympathetic response by different boreholes in different basins to pumping, is shown in Figs.44, 45, 46, 47.

These long term fluctuations have been used to calculate the average recharge rate and the average percentage of rainfall forming the recharge component. (See earlier

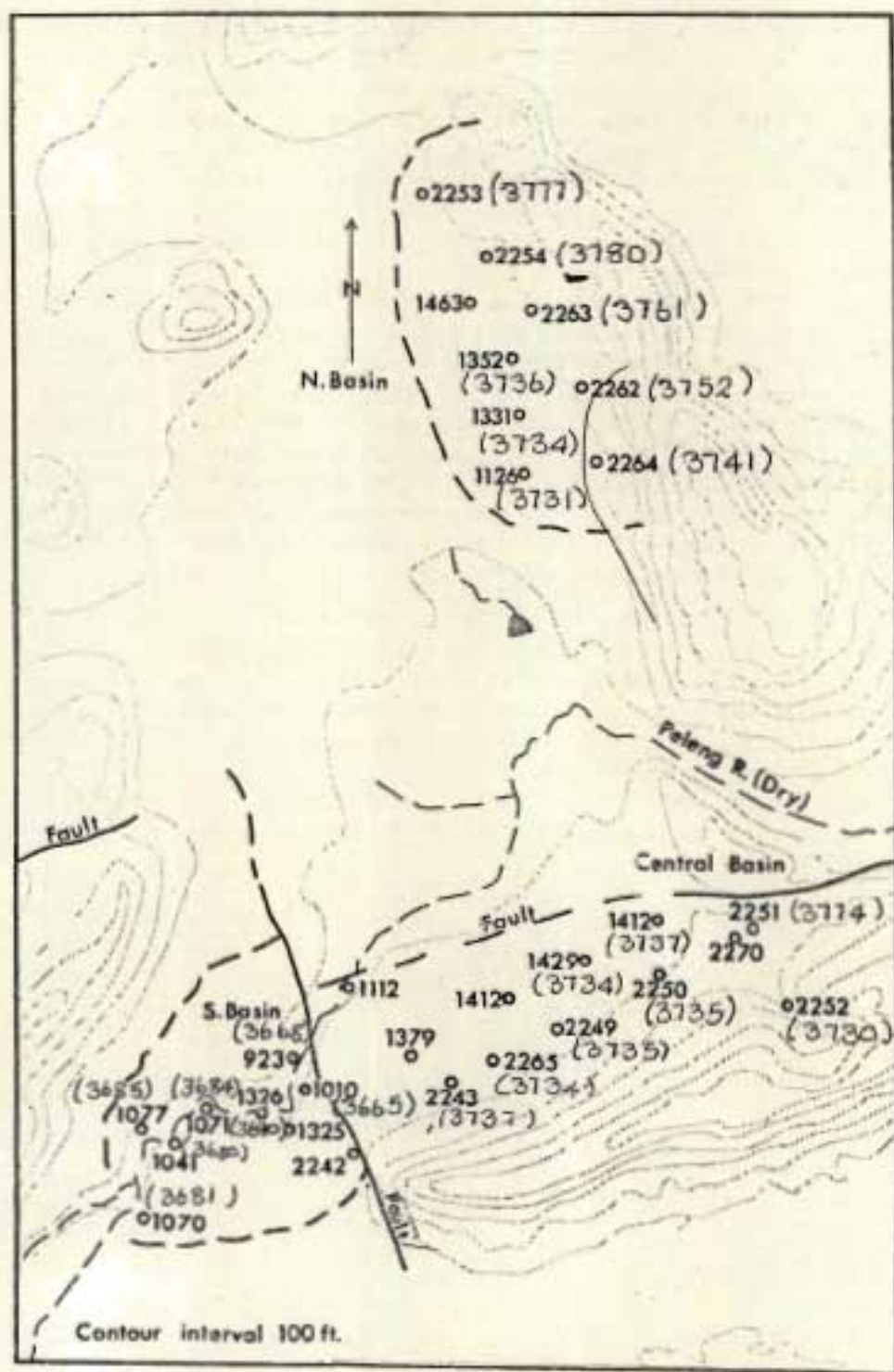


FIG. 38 Map: Lobatse Estates basins - water levels
 Figures in brackets denote water level in feet above sea level.

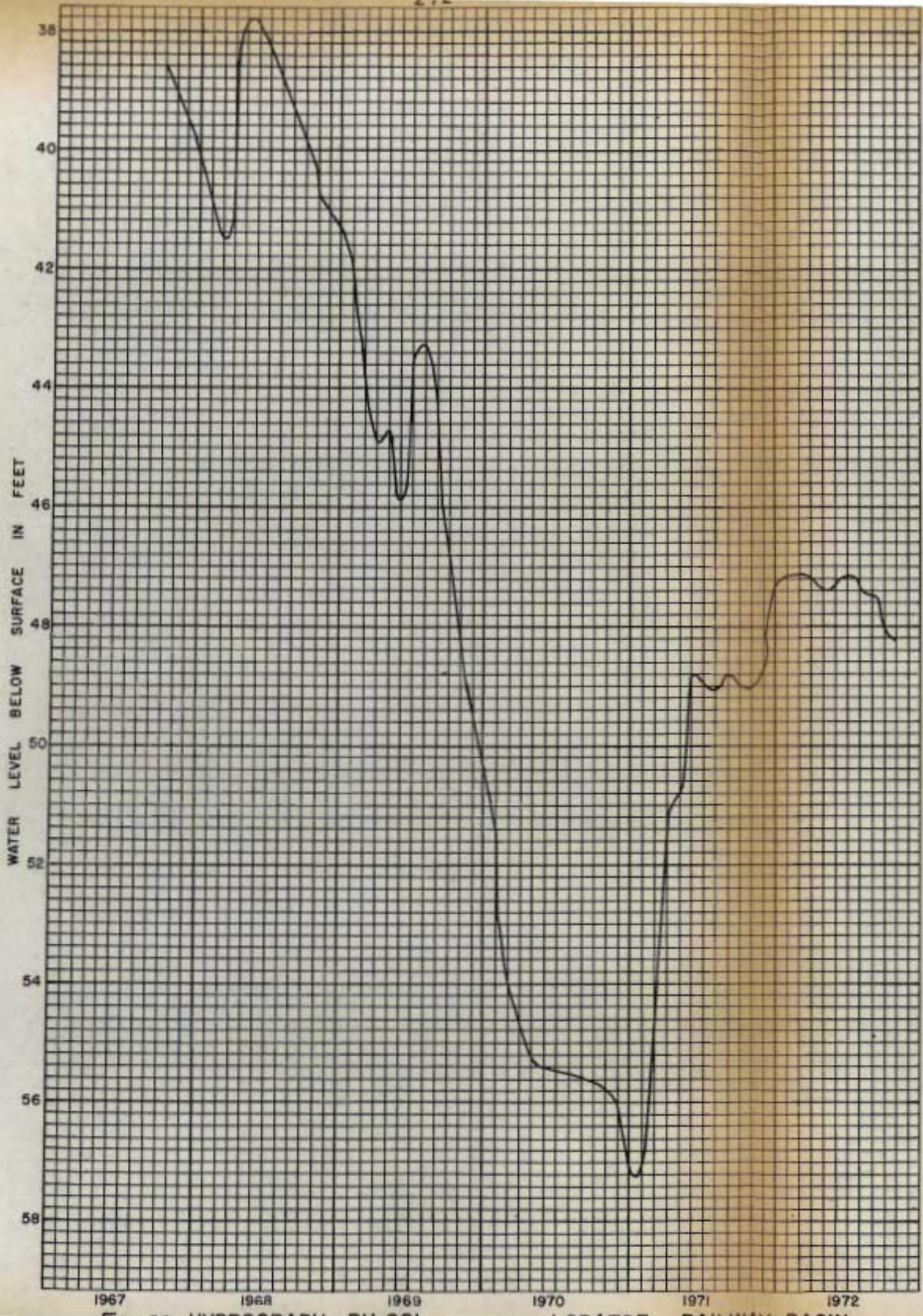
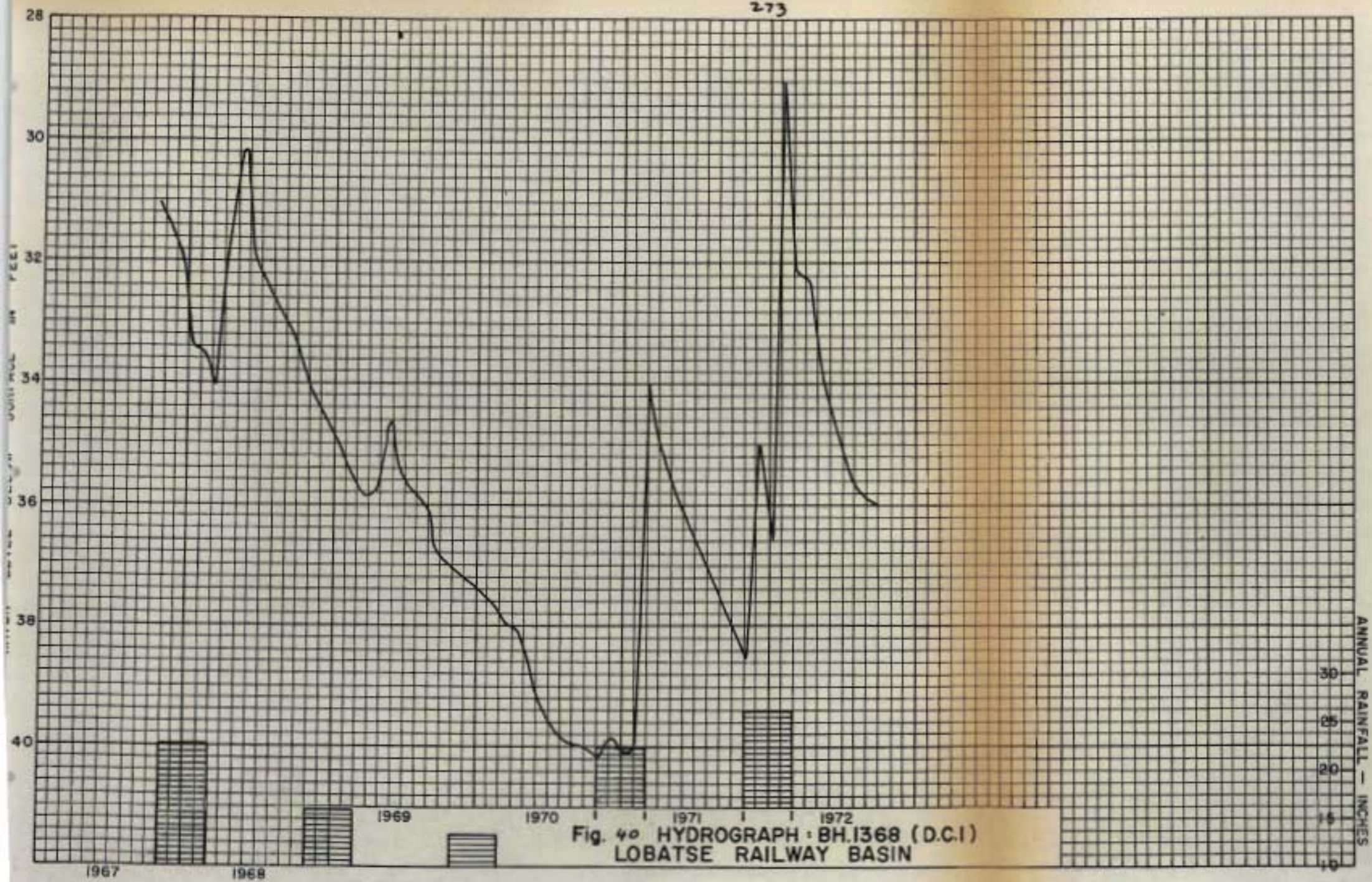


Fig. 21. HYDROGRAPH: BH 901. LOBATSE RAILWAY BASIN



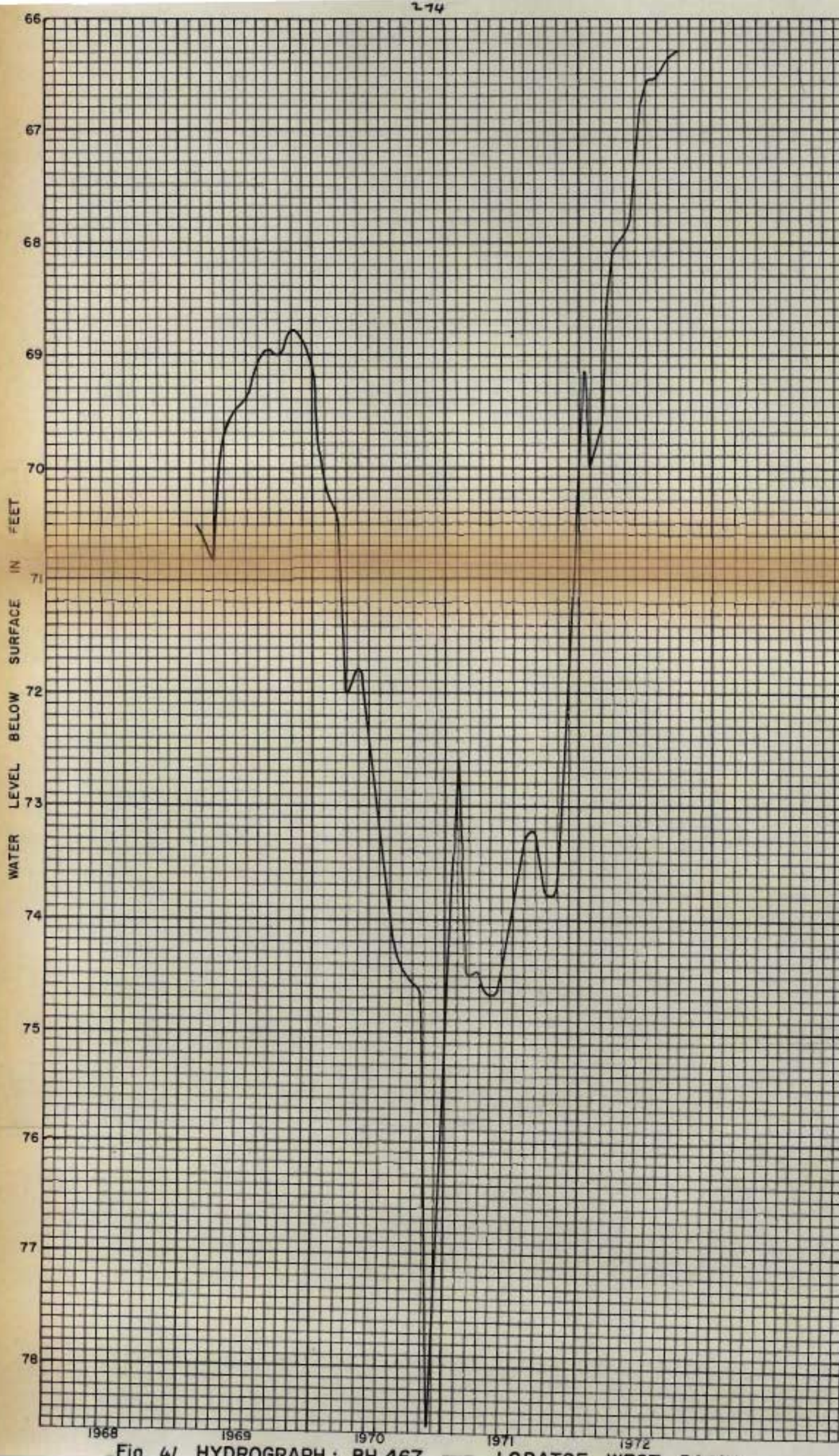


Fig. 4/ HYDROGRAPH : BH.467 — LOBATSE WEST BASIN

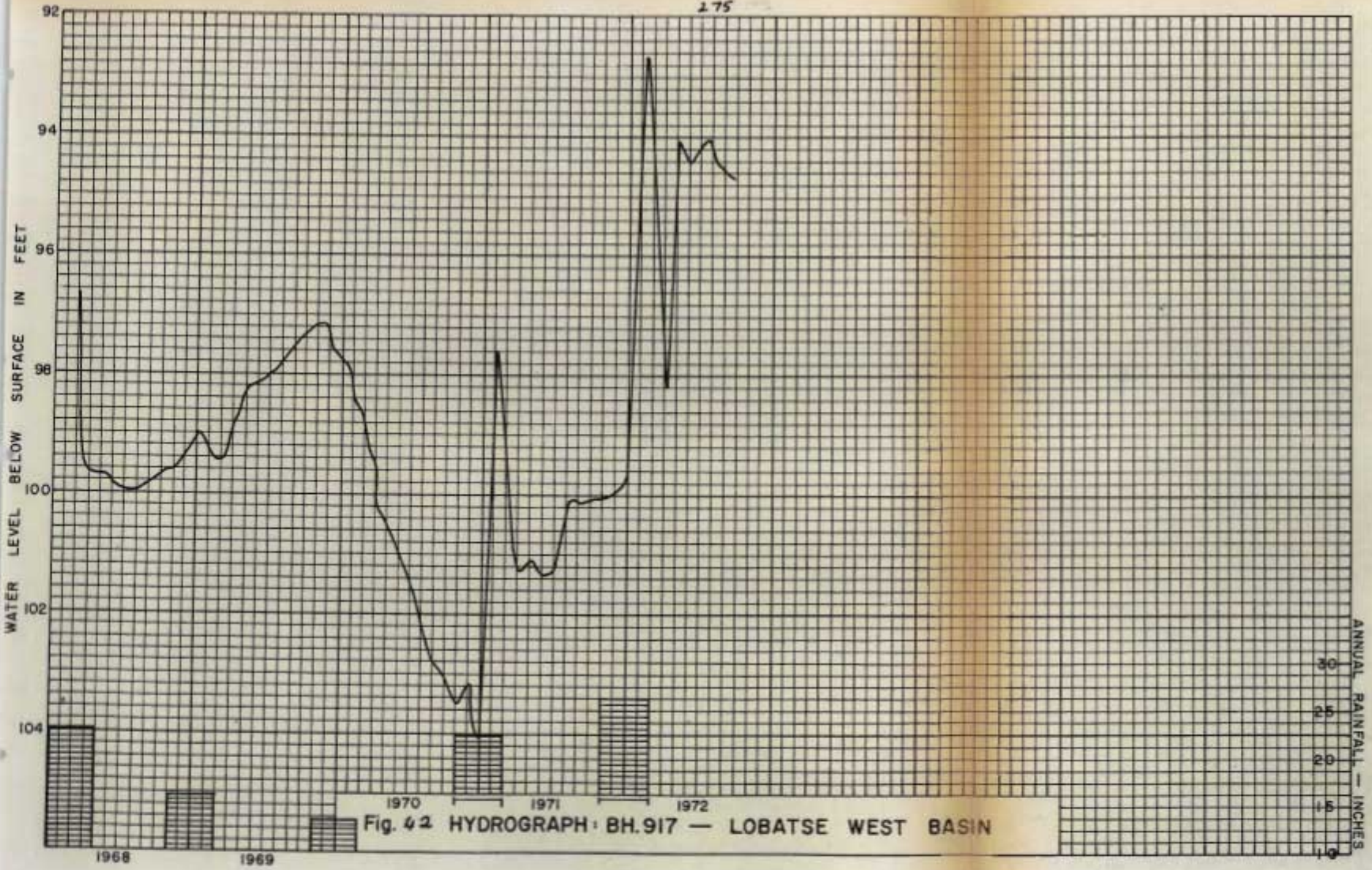


Fig. 42 HYDROGRAPH BH.917 — LOBATSE WEST BASIN

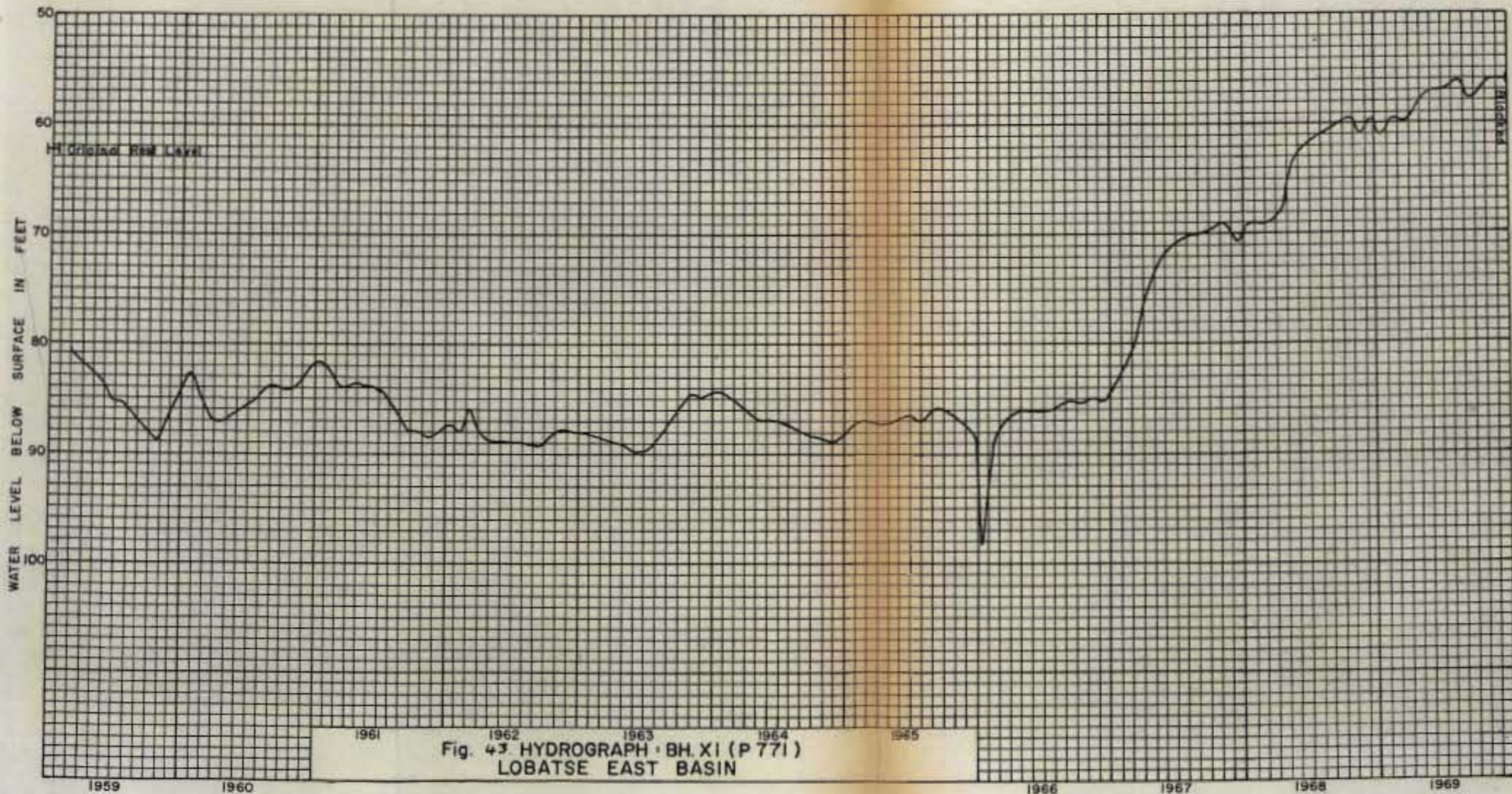


Fig. 43 HYDROGRAPH - BH. XI (P 771)
LOBATSE EAST BASIN

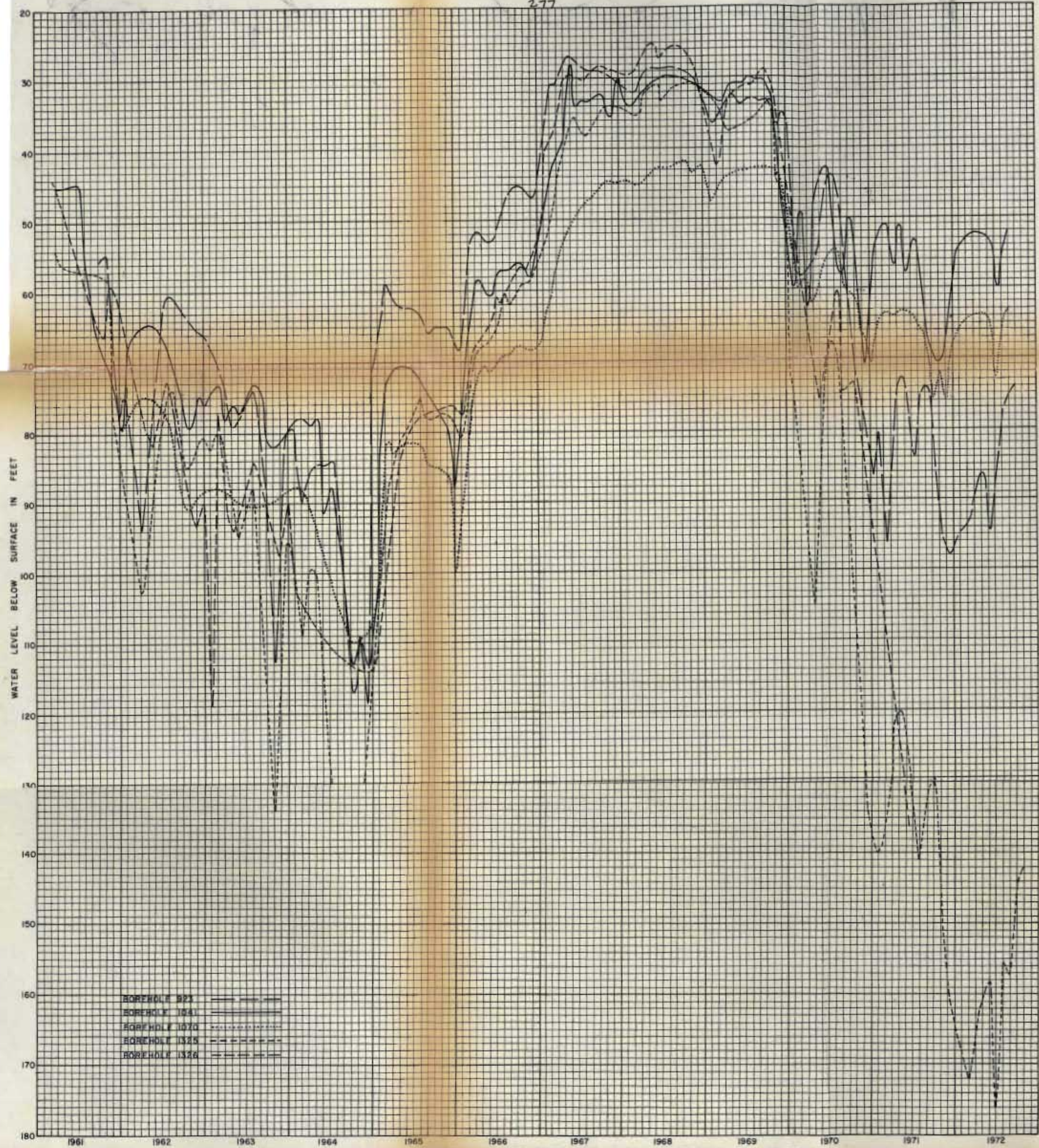


Fig. 44 HYDROGRAPHS - BH's 923, 1041, 1070, 1325, 1326 - LOBATSE ESTATES SOUTH BASIN

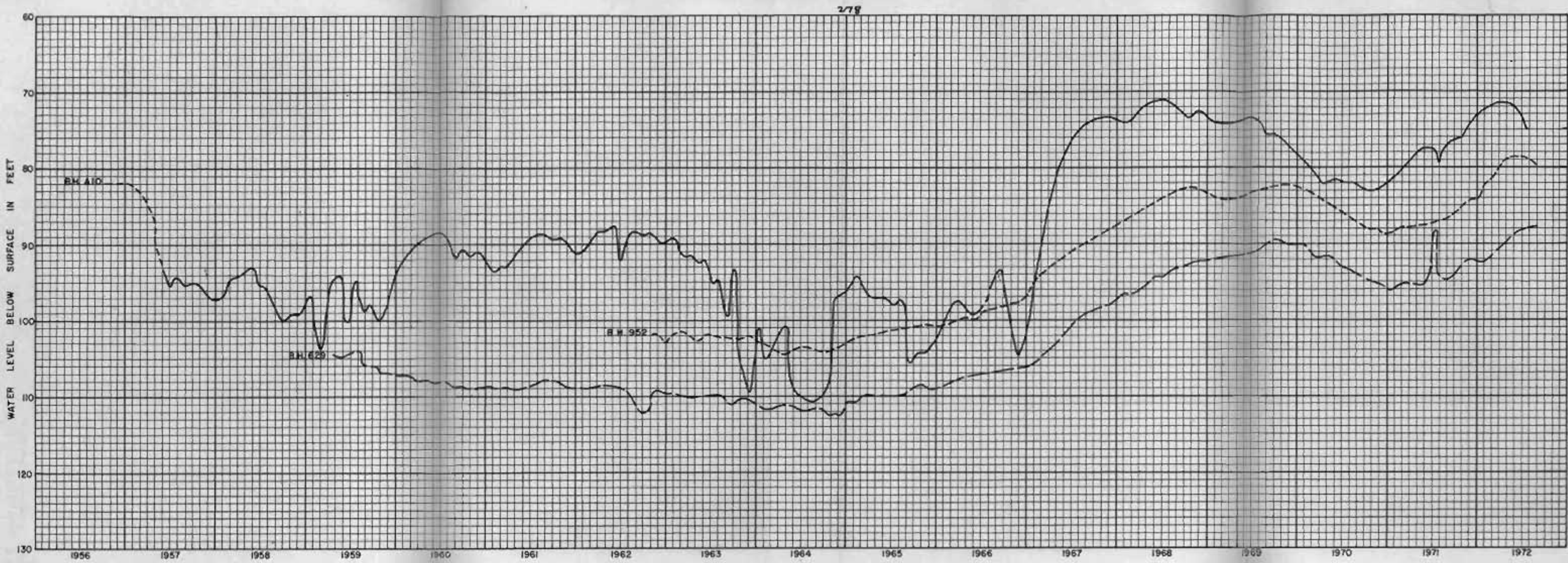


Fig. 45 HYDROGRAPH: BH's 629, 952, AIO (P767) — LOBATSE WEST BASIN

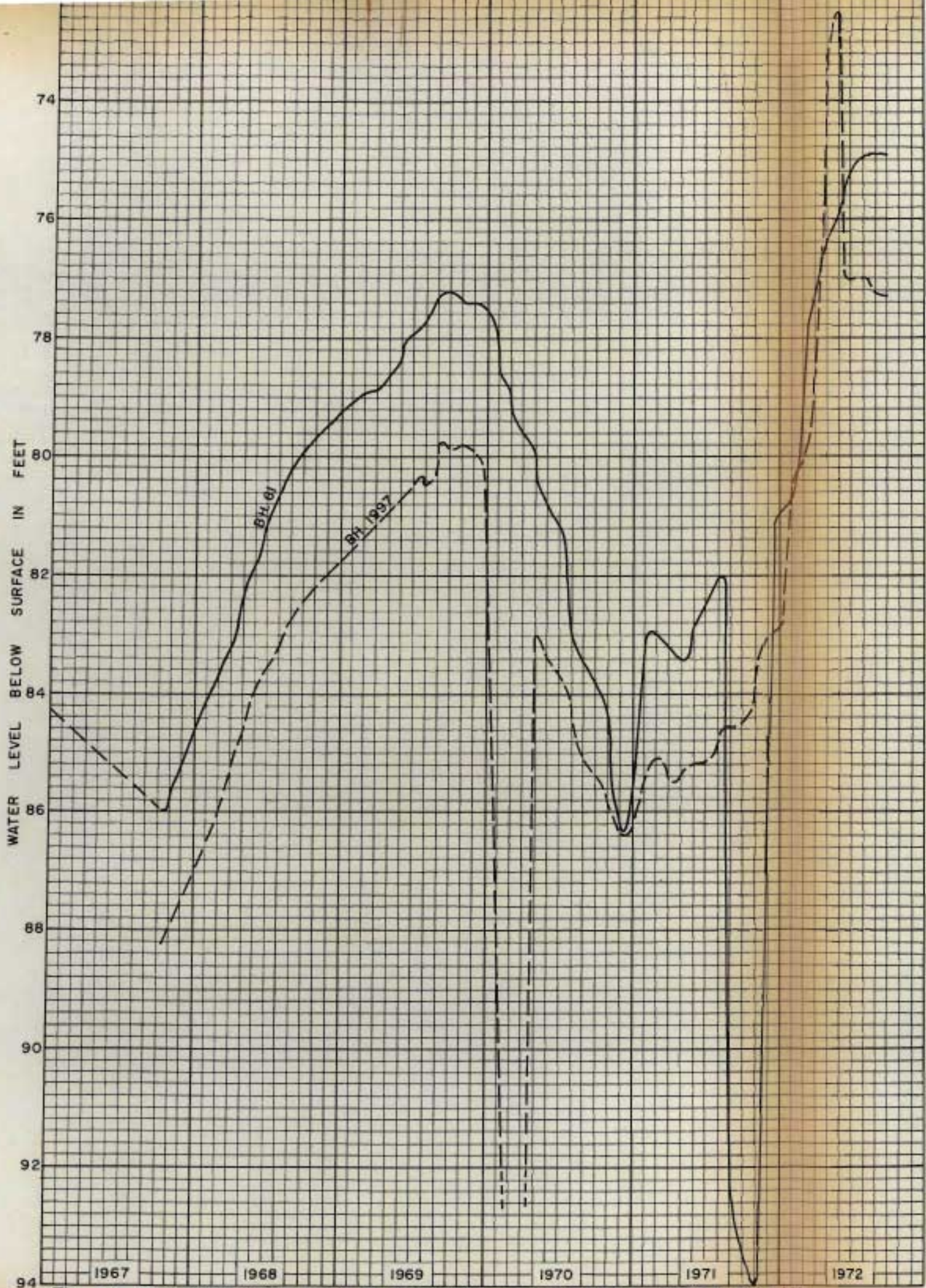


Fig. 46 HYDROGRAPHS: BH's 61 AND 1997 — LOBATSE WEST BASIN

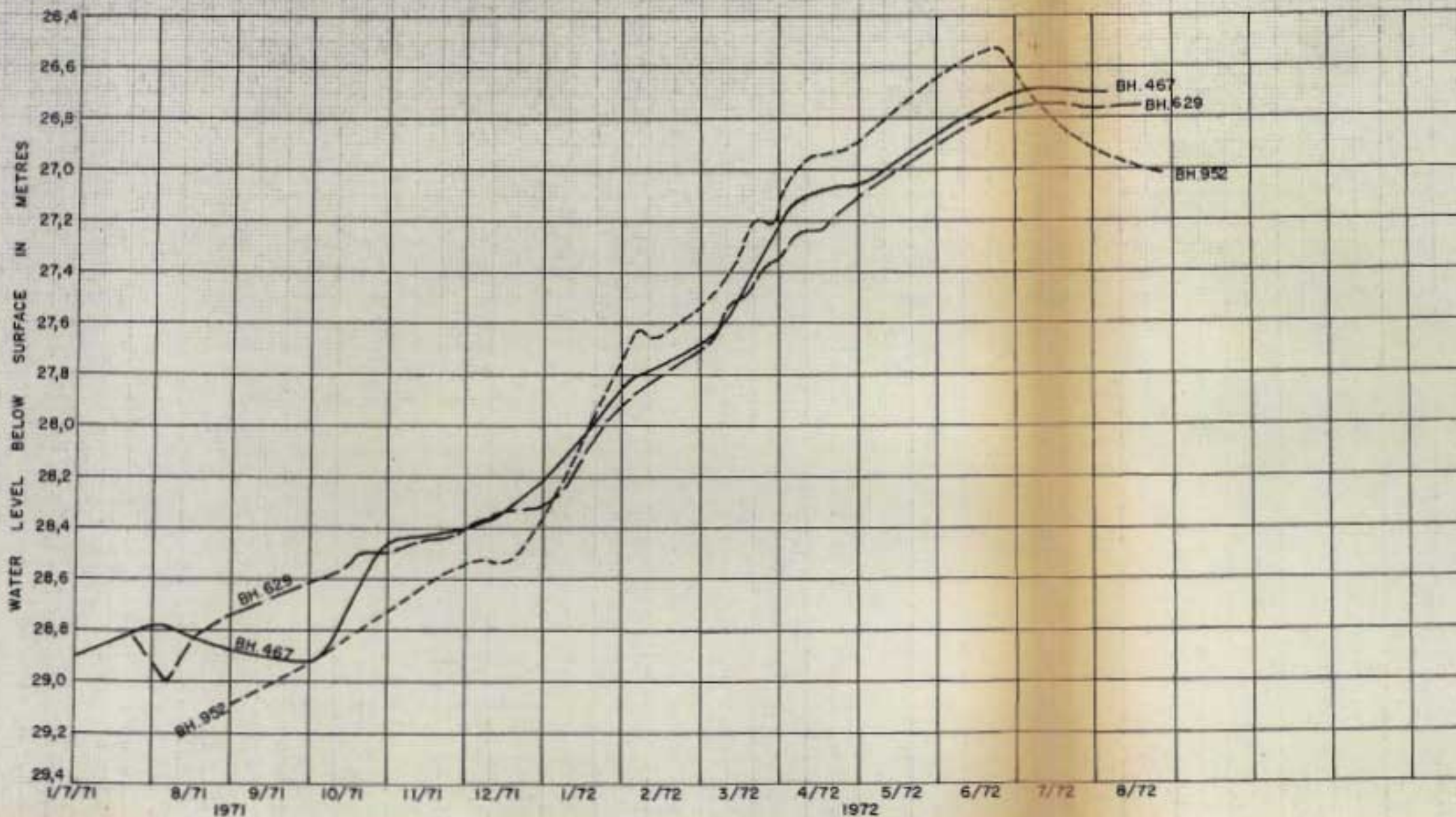


Fig. 47 DETAILED HYDROGRAPHS • BH's 467, 629, 952
LOBATSE - WEST BASIN - JULY 1971 TO AUG. 1972 .

sections on replenishment and safe yield).

Differences in water levels have also, in combination with known pumped abstraction figures, been used to estimate the storage capacity of the different groundwater basins.

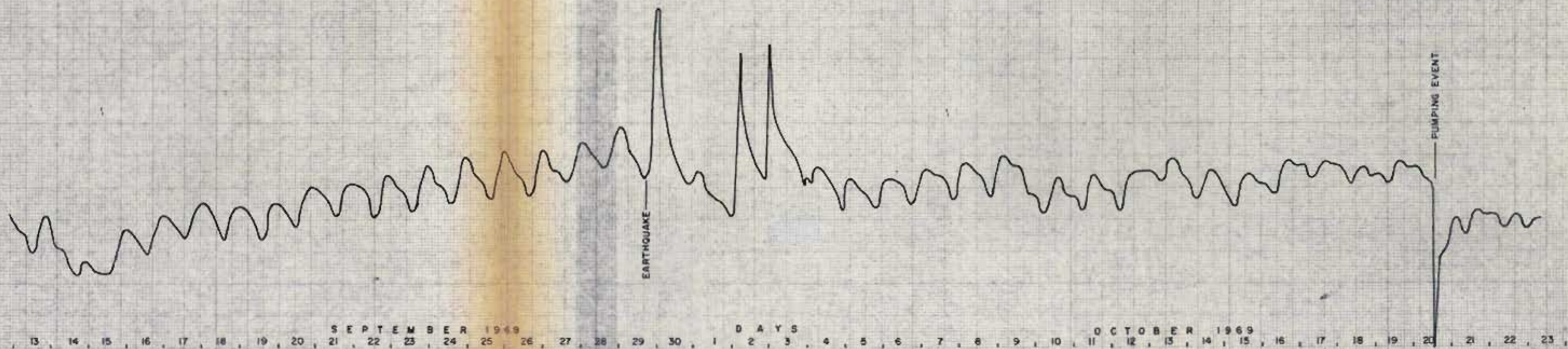
Short Term Fluctuations (See Chapter on Water Levels)

Certain boreholes show diurnal fluctuations caused by pressure variations during the day. Others show regular variations in water level and can be correlated with lunar changes and are thus of tidal origin.

A single borehole showed interesting water level changes in response to the major Boland (Cape Province) earthquake on 29/9/1969 (Fig.48). This has been described in more detail in a separate Chapter on Water Levels.

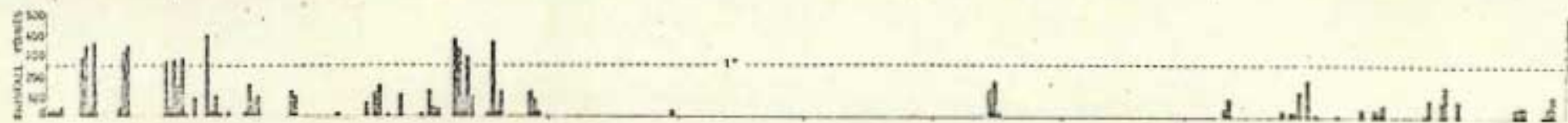
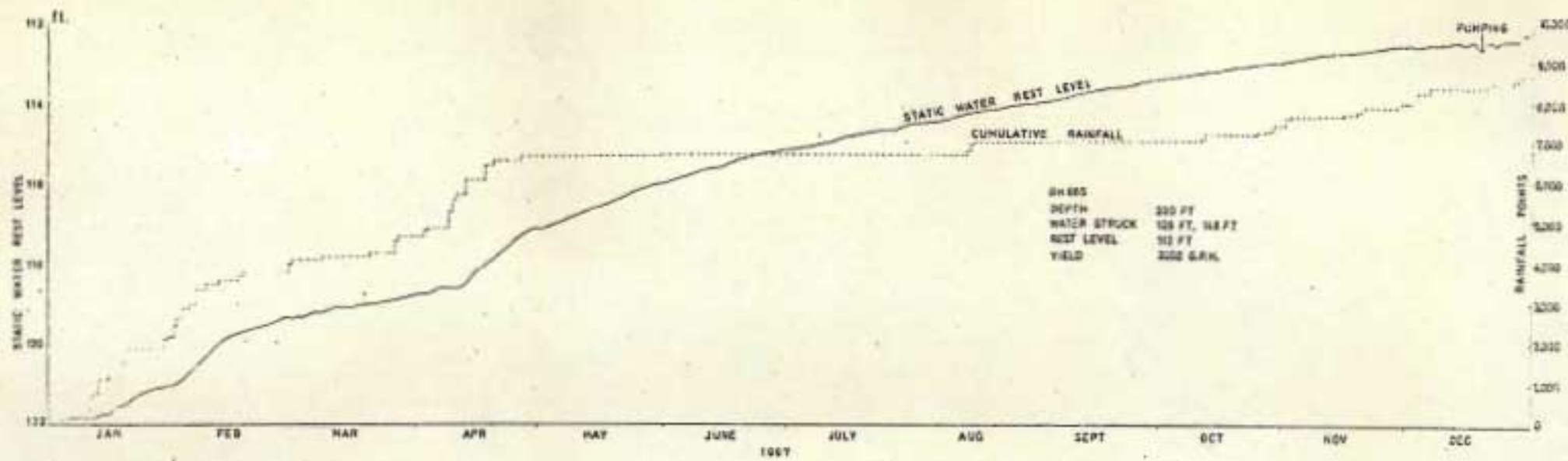
Fluctuations in water levels due to recharge are shown in Figs.49-58. The extremely rapid response in water levels to prolonged heavy rainfall may be due either to rapid direct movement of water, concentrated in the toes of the gullies, to the water table, or it could be a response due to a "displacement" or "piston flow" effect of older water present in the unsaturated zone being displaced downwards to the water table by recent recharge. This latter possibility is supported by tritium measurements which show that there is no rapid rise in tritium content (average 0,8 TU) in the ground water yet rain water infiltrating rapidly into the porous surface zone is known to contain 30 - 50 TU.

Fig. 48 SHOWING FLUCTUATIONS CAUSED BY BOLAND EARTHQUAKE (CAPE) IN BH.1325 -LOBATSE ESTATES SOUTH BASIN - SEPTEMBER 1969.



NOTE— Main shock was felt at Pretoria at 2006 hours on 29th September.
 Magnitude of shock was 6,3 on Richter Scale.
 No significant rain fell during this period.
 21 After quakes occurred between 29th September and 10th October.
 These varied in magnitude between 3,8 and 5,2.

RATIO 1:6



HYDROGRAPH SHES ENGLISH MEDIUM SCHOOL
 FIG 49

283

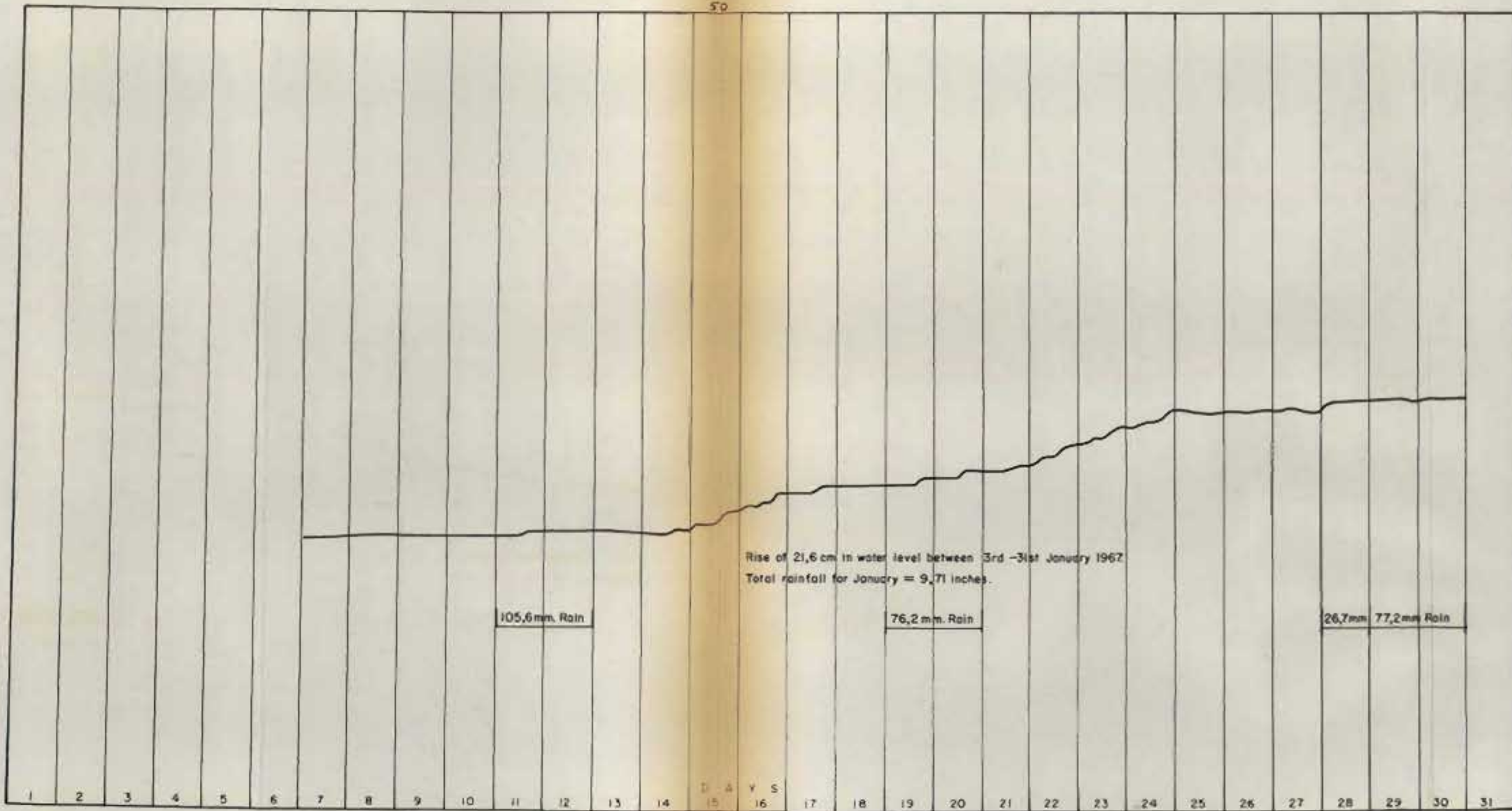


Fig. 8 HYDROGRAPH BH.952 - LOBATSE WEST BASIN - JANUARY 1967
SHOWING RISE IN WATER LEVEL IN RESPONSE TO HEAVY RAINFALL.

RATIO 1:6

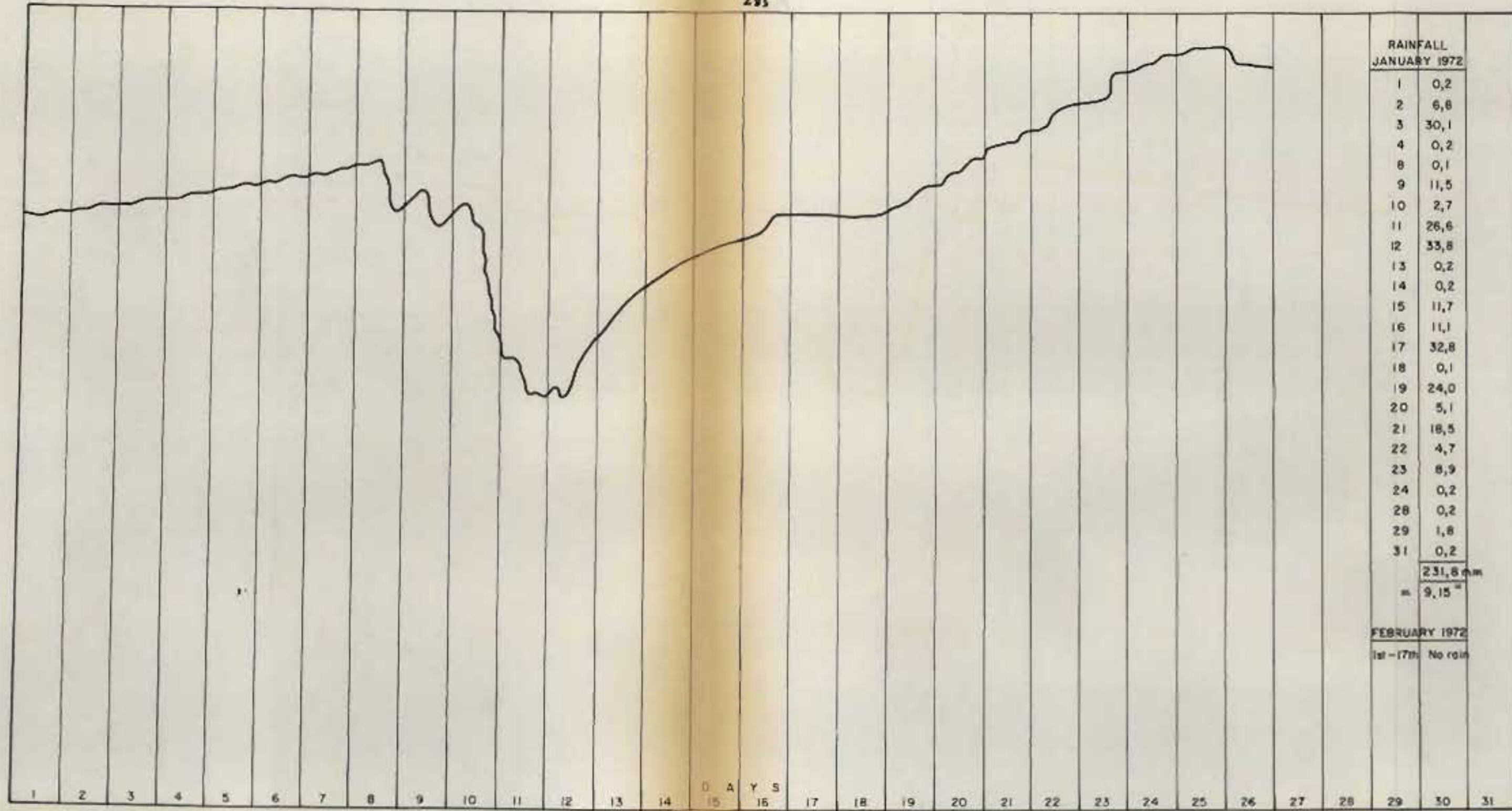


Fig. 51 HYDROGRAPH BH. A6 - LOBATSE WEST BASIN - FEBRUARY 1972
 SHOWING EFFECTS OF HEAVY RAINFALL IN JANUARY 1972. NOTE ALSO DROP
 IN LEVEL DUE TO PUMPING (8th - 12th FEBRUARY 1972)

RATIO 1:6

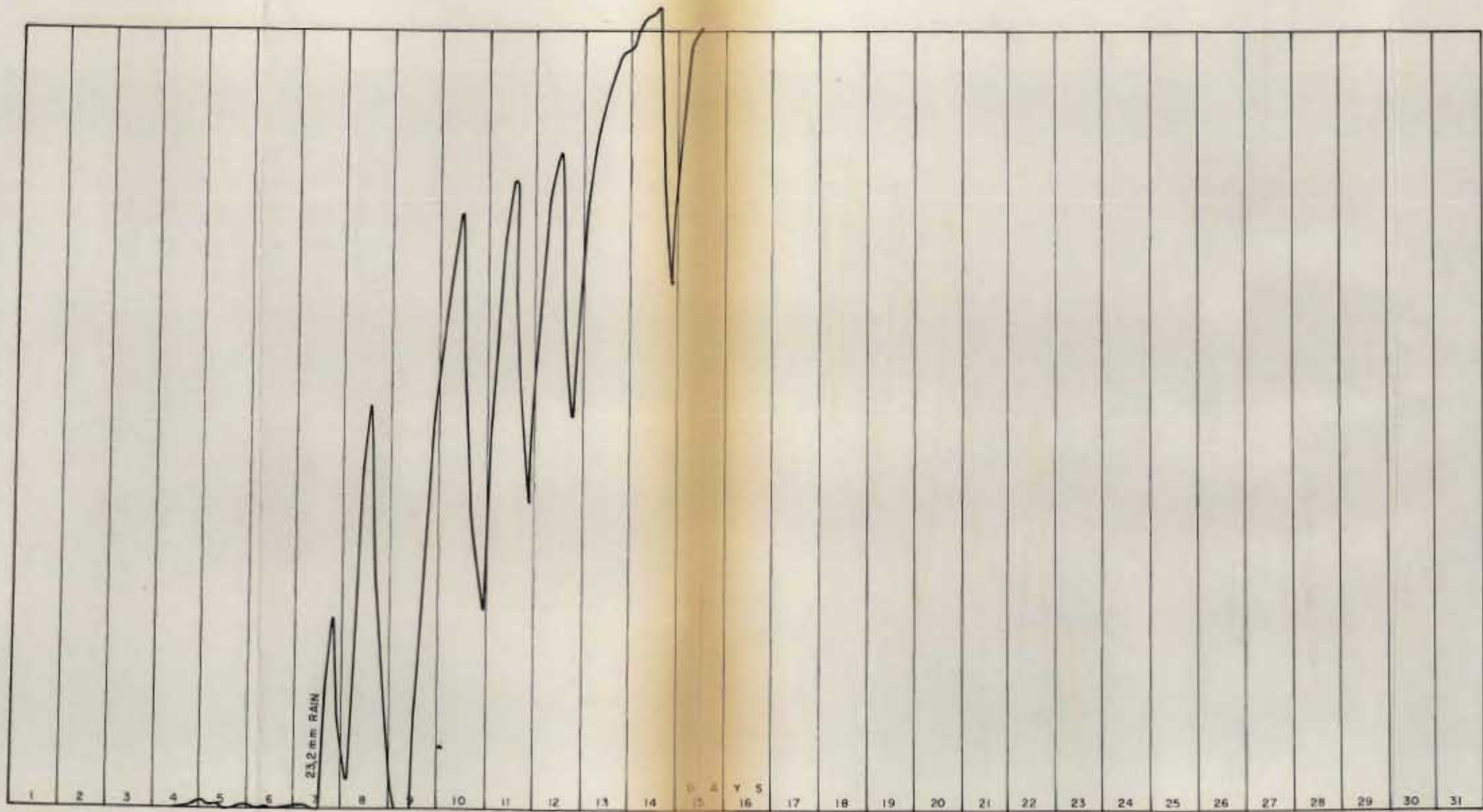


Fig. 52 HYDROGRAPH BH.1071 — LOBATSE ESTATES SOUTH BASIN — JANUARY 1969
SHOWING RESPONSE TO PUMPING IN NEARBY BOREHOLE AND TO RECHARGE FOLLOWING
23,2 mm OF RAIN ON 7th JANUARY. NO OTHER RAIN FELL BETWEEN 10th DECEMBER
AND 27th JANUARY.

RATIO 1:6

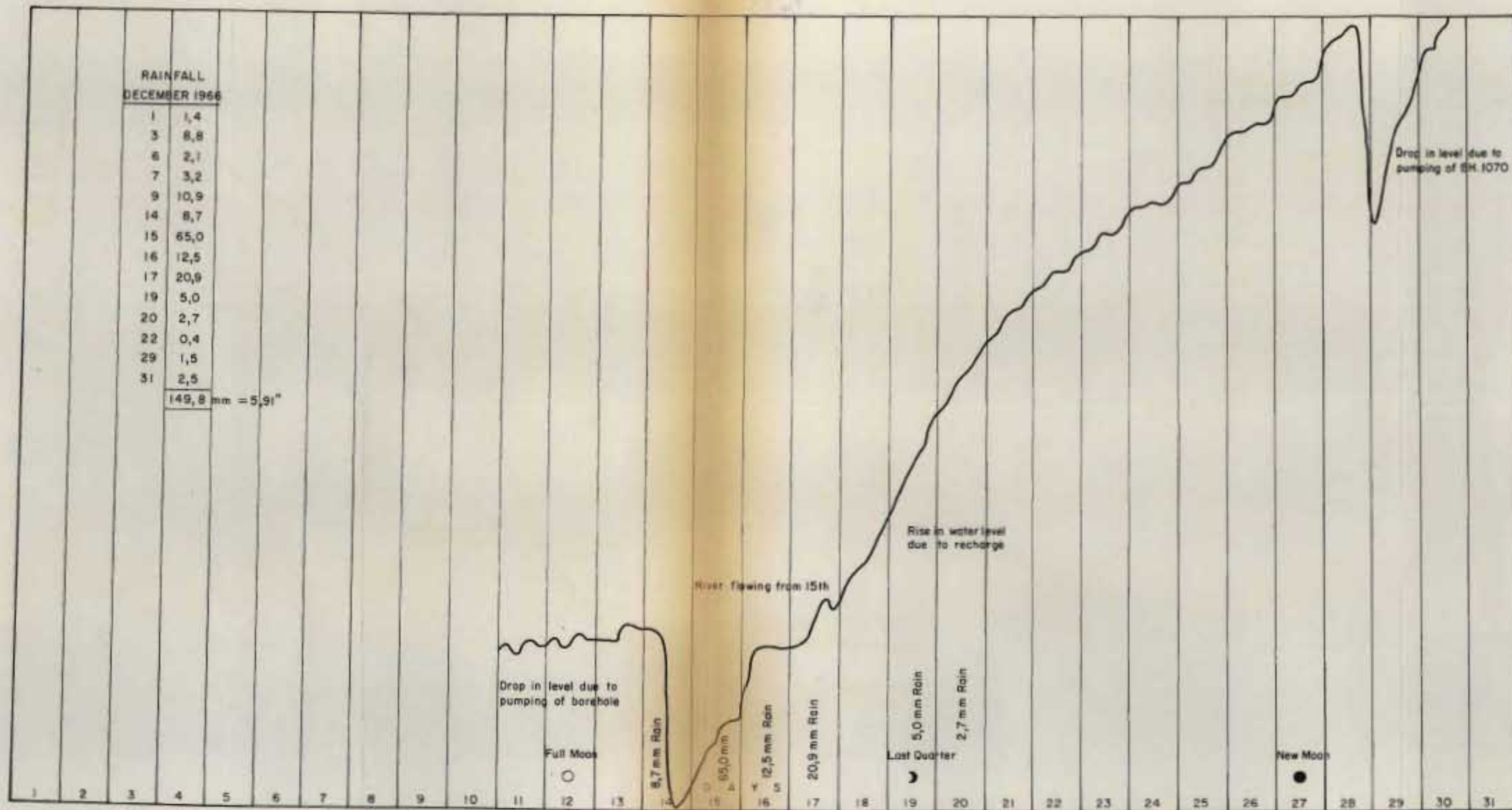


Fig. 53 HYDROGRAPH BH.1071 - LOBATSE ESTATES SOUTH BASIN - DECEMBER 1966
SHOWING FLUCTUATIONS DUE TO PUMPING, TIDAL EFFECTS AND RISE DUE TO RECHARGE
THROUGH BED OF PELENG SPRUIT.

RATIO 1:6

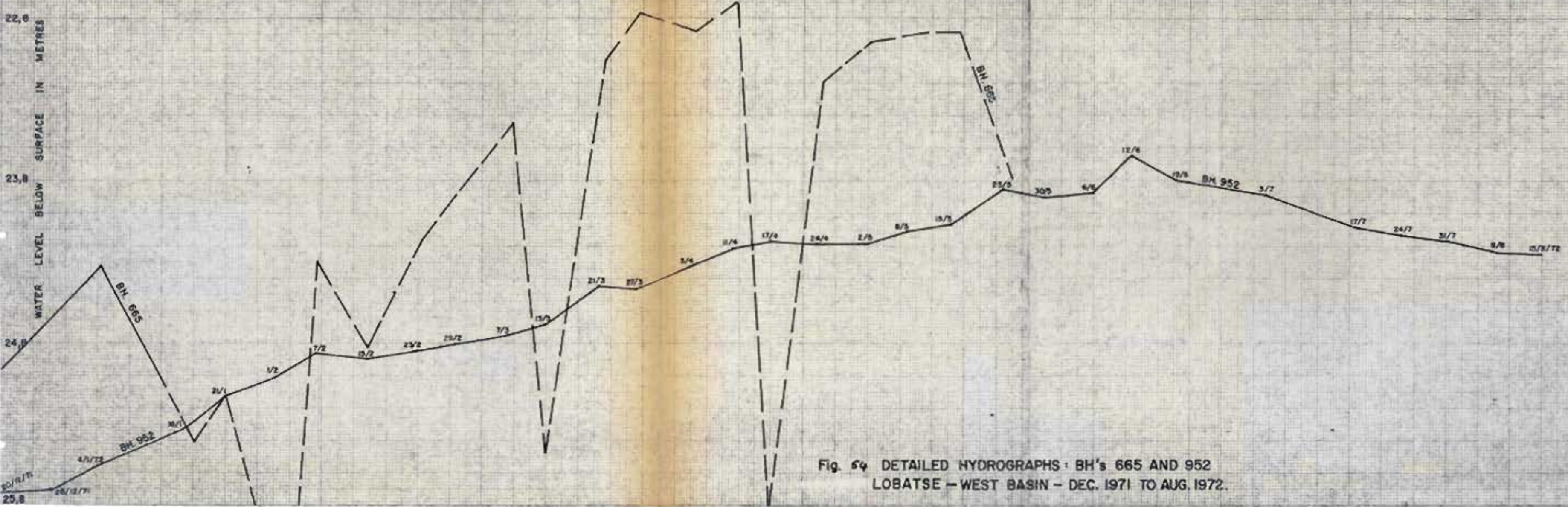


Fig. 64 DETAILED HYDROGRAPHS : BH's 665 AND 952
LOBATSE - WEST BASIN - DEC. 1971 TO AUG. 1972.

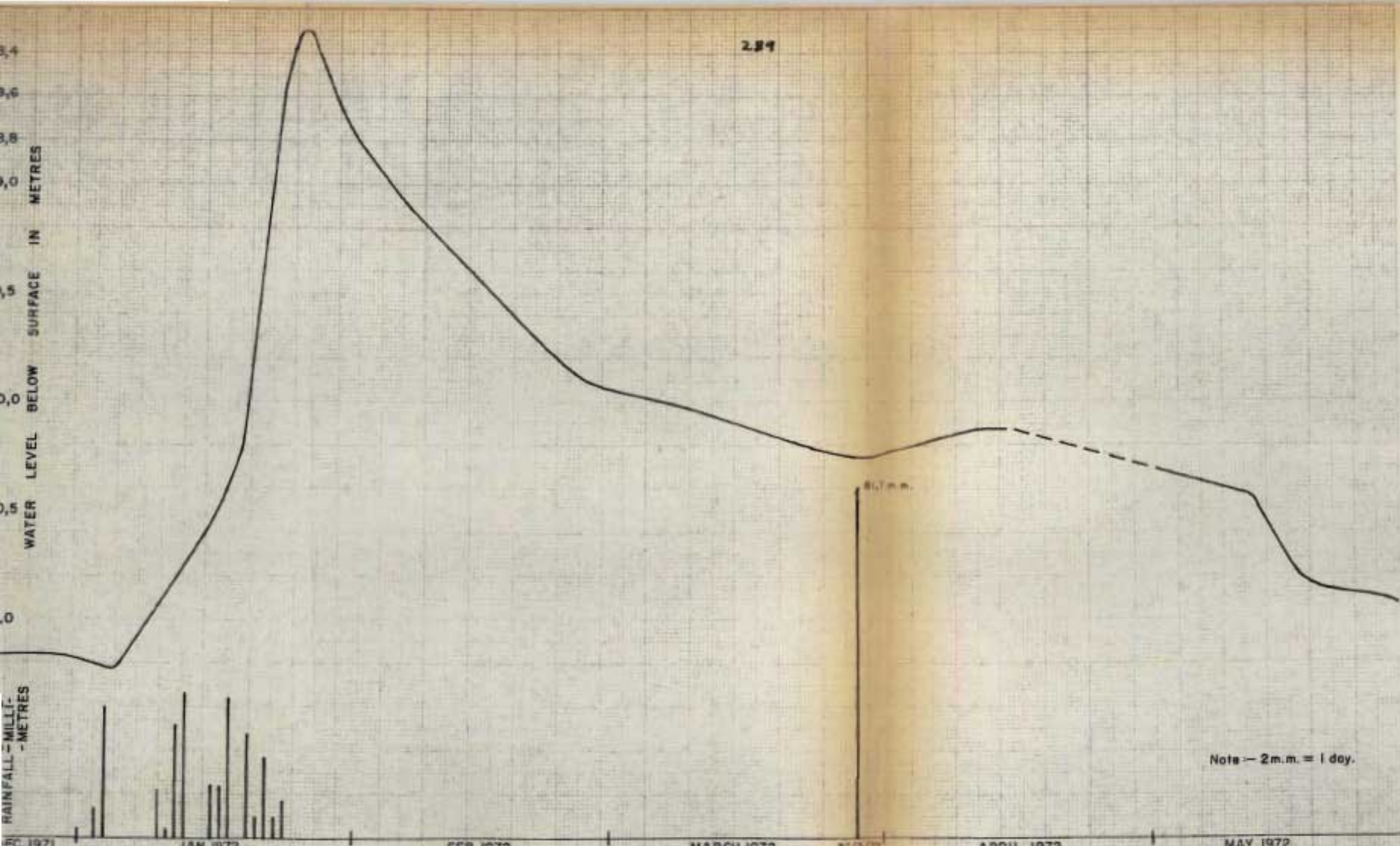


Fig. 55 RAINFALL AND DETAILED HYDROGRAPH BH.1368 (D.C.I.) - LOBATSE RAILWAY BASIN - DEC. 1971 TO MAY 1972.

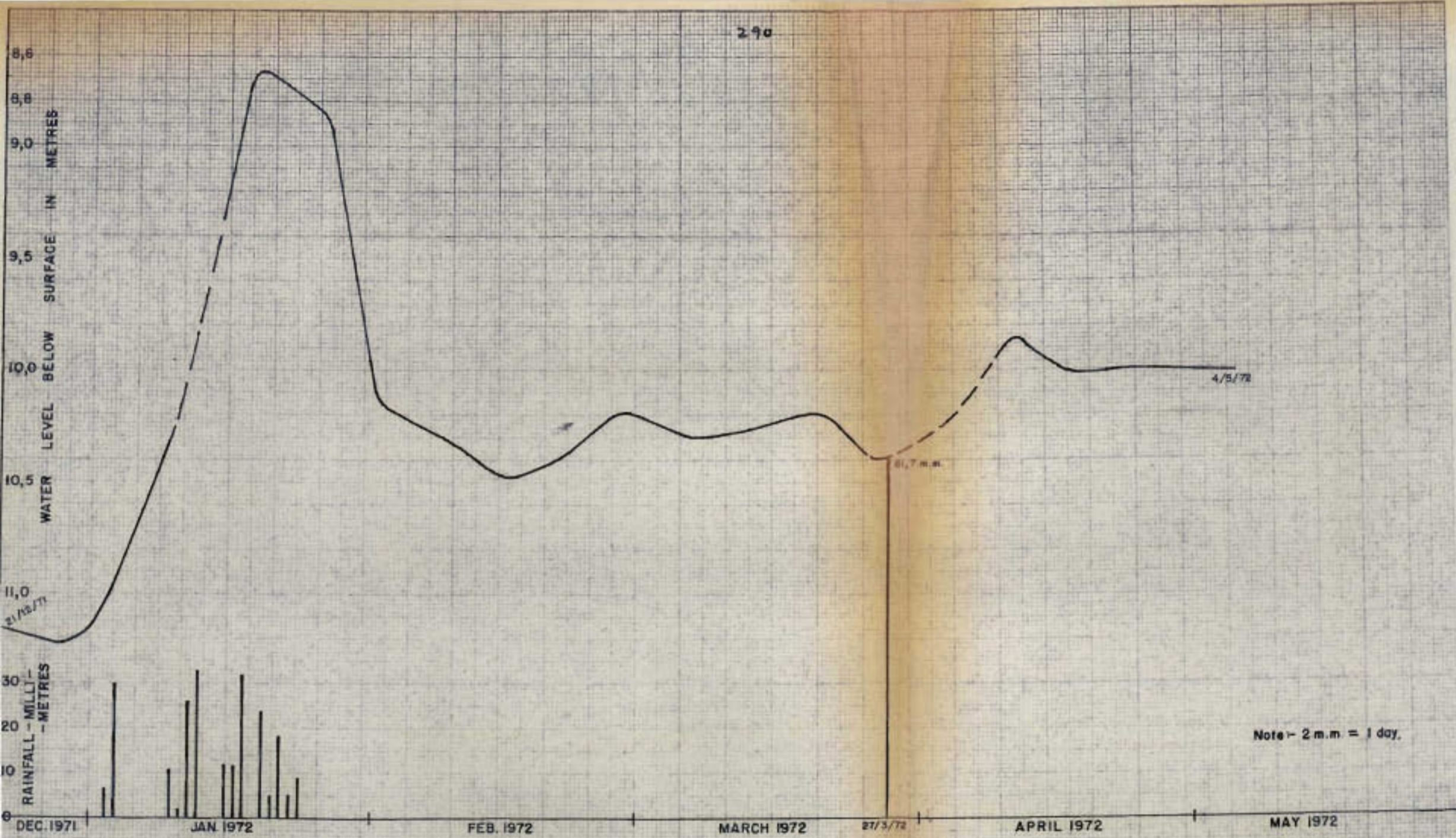


Fig. 56 RAINFALL AND DETAILED HYDROGRAPH: BH.X4 - LOBATSE — EAST BASIN - DEC. 1971 TO MAY 1972.

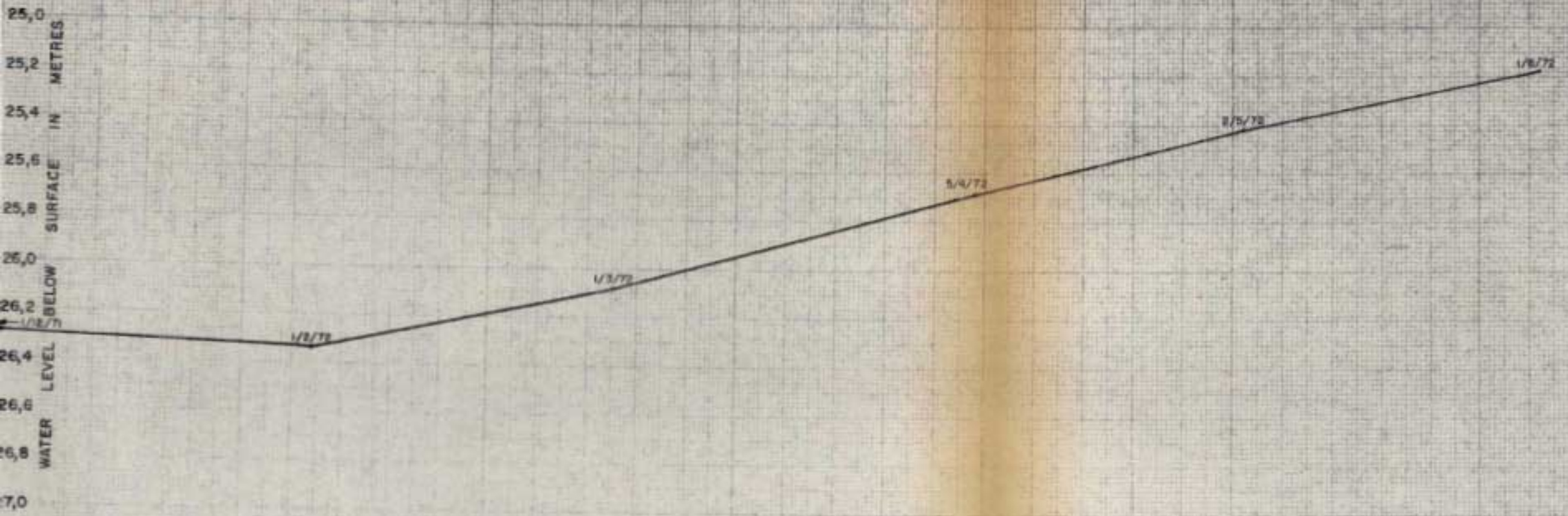


Fig. 57 DETAILED HYDROGRAPH BH.2136 - LOBATSE — WEST BASIN - DEC. 1971 TO JUNE 1972.

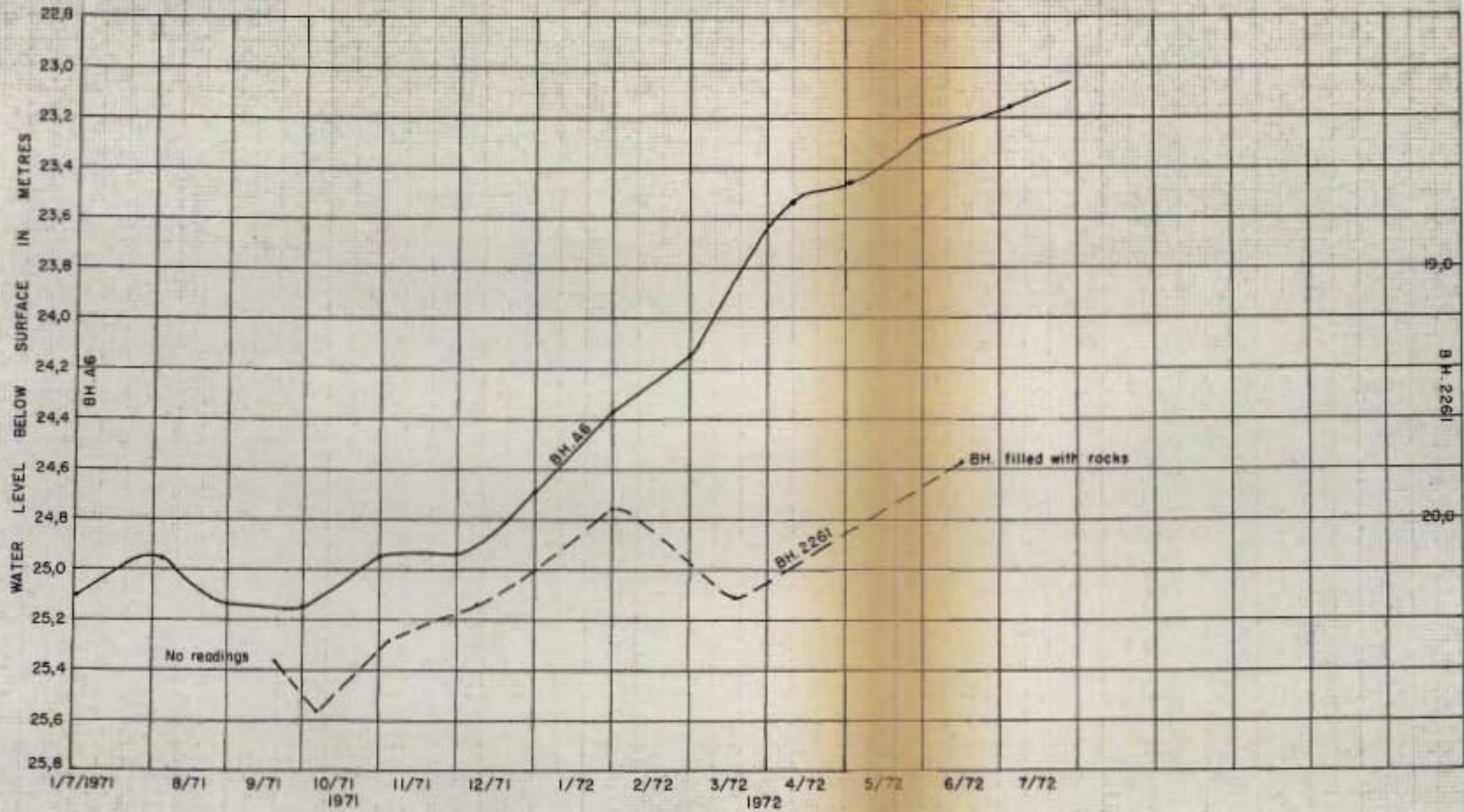


Fig. 58 DETAILED HYDROGRAPHS | BH.A6 (LOBATSE WEST BASIN) AND BH.2261 (LOBATSE EAST BASIN)- JULY 1971 TO JULY 1972.

Notes on Hydrograph for Borehole A6 - Lobatse Western Basin (Fig. 26).

The regular measurement of water levels on observation borehole A6 in the Lobatse western basin, was commenced in mid-1956, while occasional measurements are available before this.

By looking at the hydrograph and cumulative rainfall and pumping departure curves it can be clearly seen that the overall shape of the hydrograph corresponds closely to the cumulative departure curve from the calculated mean monthly safe yield of 2,75 million gallons per month ($12\ 500\ m^3/m$). Fluctuations on the hydrograph correspond very closely to peaks or positive gradients on the cumulative departure curve from the long term monthly rainfall averages. The close correlation of these peaks may therefore be interpreted as rises in water level due to recharge following above average rainfall. There is no time lag between rainfall peaks and water level peaks and hence recharge is assumed to take place extremely rapidly (less than one month) despite the fact that the water level in the borehole varies from 24 to 36 m.

These hydrograph peaks may thus be used to make semi-quantitative estimates of ground-water recharge and the frequency of this discharge. These estimates are given in Table 30.

Notes on Hydrograph for Bh X4 - Lobatse Eastern Basin (Fig. 27).

Pumping commenced from this basin in October 1957 and by the end of 1972 over $622\ 720\ m^3$ (137 m.g.) of water had

been pumped from the basin. Monthly water level measurements have been taken on an observation borehole in this basin since 1957.

The general form of the hydrograph shows a close correlation with the cumulative departure curve from a pumping rate of 0,80 million gallons (3 636 m³) per month between 1959 and the end of 1966. In the first half of 1967 however, the hydrograph shows a marked deviation from the cumulative water abstraction departure curve with a marked rise in water level occurring despite an increase in water pumped from the basin. This corresponds with the large peak in the cumulative rainfall departure curve for the same period. A further rise in water level in 1968 again corresponds to a rainfall surplus. From 1969 on, the hydrograph and cumulative pumping departure curve again show a similar trend, i.e. with total abstraction governing the overall shape of the curve. Minor peaks on the hydrograph often show close correspondence with the rainfall curve. Where sharp peaks occur on the rainfall curve there is often a corresponding sharp peak on the hydrograph. e.g. January 1960, December 1960, November 1963 and January 1971. This indicates that recharge takes place very rapidly in this basin, i.e. less than a month is taken for the rainfall to cause a rise in the groundwater table which lies between 10 and 27 m below ground level.

By studying the peaks on the hydrograph semi-quantitative estimates of ground-water recharge have been made (See Table 30).

Notes on Hydrograph for Bh 1071 - Lobatse Estates South Basin. (Fig. 28).

Large scale pumping of water from the Lobatse Estates southern basin for township water supply, commenced in November 1960. Prior to this, water level fluctuations are due to increments in storage due to recharge during the 1959/1960 season and losses due to natural leakage, with minor pumping from the basin by the farmer for cattle watering. It can be seen that natural losses from the basin are therefore not large.

By looking at the hydrographs between 1961 and 1964 there is a large overall drop in water level caused by pumping exceeding the mean recharge rate. This is clearly shown by comparing the hydrograph with the cumulative departure curve from a mean recharge rate of 0,73 million gallons per month obtained from long term water levels and known water abstractions. Major lows in the water level are clearly related to increased pumping, i.e. end April 1962, end October 1963, end October 1964. By comparing the hydrograph with the cumulative departure curve from the mean monthly rainfall, it can be seen that peaks in the hydrograph correspond roughly with peaks in the cumulative rainfall departure curve, but with hydrograph peaks displaced two to three months, indicating a time lapse between peak rainfall and actual recharge in the observation borehole, whose levels vary from 15 to 35 m below surface. The hydrograph clearly shows that almost no recharge occurred during the 1962/1963 rainy season and again during the 1963/1964 season.

/The.....

The section of the hydrograph from 1965 to 1969 shows large recovery in water level due to a marked reduction in pumping in mid - 1965, with superimposed ground-water peaks, caused by recharge during the 1964/1965, 1965/1966, 1966/1967 rainy seasons. An especially large rise in water level took place following the exceptionally heavy 1966/1967 season. Little recharge apparently took place during the 1967/1968 and 1968/1969 seasons.

The section of the hydrograph between 1970 and mid-1972 shows an overall marked drop in water level due again to overpumping with superimposed peaks due to recharge in the 1970/1971 and 1971/1972 seasons. The peak in July 1970 is probably due largely to a drop in pumping (see cumulative pumping departure curve) during May and June 1970.

From mid-1972 to mid-1973, there was again a rise in water level, due largely to a decrease in pumping. An increase in pumping in the second half of 1973 resulted in a corresponding drop in water level.

Conclusions

Detailed analysis of the hydrograph for borehole 1071 in the Lobatse Estates basin has enabled semi-quantitative estimates of recharge of ground-water. (See Table 30).

Notes on Hydrograph Bh 1412 - Lobatse Estates Central Basin. (Fig.31).

Pumping commenced from this basin in February 1961, while regular measurement of water levels in the basin was commenced in 1964 with some measurements having been taken

early in 1963. By comparing the hydrograph for observation borehole 1412 with the cumulative departure curves for the mean monthly rainfall and the estimated mean recharge of 1,00 million gallons per month (454^5 m^3 per month) it can be seen that the main form of the hydrograph is controlled by deviations from the mean monthly recharge, while minor peaks on the otherwise fairly smooth curve are caused by recharge events. These minor peaks occur during or just after the 1964/1965, 1966/1967, 1968/1969, 1969/1970, 1971/1972 rainfall seasons. It would appear therefore, that this basin, from which over 25^4 million gallons ($1\ 150\ 000 \text{ m}^3$) had been pumped by the end of 1972, has been pumped at a considerably greater rate than that of the recharge and as a result, has shown a decline in water level of more than 23 m. It appears furthermore that recharge occurs more infrequently than in the other Lobatse ground-water basins, because of a greater lack of favourable recharge conditions - either ephemeral rivers or gullies concentrating water in areas favourable for recharge (only one major gully drains the quartzite hill east of the basin while recharge from the Peleng River on the western margin of the basin is probably prevented from reaching the main sandstone/quartzite aquifer by impermeable shale horizons overlying this aquifer). Significant recharge therefore only appears to have taken place during the abovementioned 5 years, out of a total of 9 years (1964-1972).

The fact that no diminution of yield occurred in any of the production boreholes in this basin, despite a drop

in water level of 23 m and despite the fact that recharge only occurred in 1969/1970 and 1971/1972, indicates that the storage capacity of this basin is very large.

CONCLUSIONS

The collection of long term hydrogeological data has enabled accurate calculations of specific yield, safe yield and storage capacity of the various Lobatse ground-water basins to be made, as well as an estimate of the percentage of mean annual rainfall which is likely to recharge the aquifer. The total storage capacity is estimated to be $3,6 \times 10^6 \text{ m}^3$, which is much greater than the Nuane Dam capacity of $2,27 \times 10^6 \text{ m}^3$. The combined safe yield is calculated to be $72\,273 \text{ m}^3/\text{m}$.

The use of tritium has helped delineate recharge areas; the mechanism of recharge, and has been used to calculate the turnover time of water and the storage capacity of the basins. The storage capacity obtained using this method, indicates a larger volume of water present than indicated by the conventional method.

Study of hydrographs has enabled semi-quantitative estimates of seasonal recharge and of the frequency of recharge, to be made.

HYDROGEOLOGY OF THE ORAPA AREAINTRODUCTION

Following the discovery by de Beers (Botswana) Pty. Ltd. of a large kimberlite pipe containing payable quantities of diamonds, the provision of an assured supply of water, initially for prospecting and later for pilot plant testing and plant and township construction, became of vital importance. Fortunately the Cave Sandstone aquifer was able to meet these early needs. However, detailed aquifer evaluation tests indicated that the provision of the large amounts of water required for full scale production (2 to 4 million gallons per day, 9 091 to 18 182 m³/d) could be more economically met by a surface water supply scheme and consequently the Mopipi surface storage dam was completed and filled by mid 1971. This scheme however, has a considerable element of uncertainty, as the Boteti River has been known in the past to have carried no flow downstream of Rakops (Tsienyane) for longer periods than the total storage period of the reservoir and in fact at the time of writing (December, 1973) the Mopipi Dam is completely dry. As a result it was decided by the Geological Survey to commence a limited amount of hydrogeological research in the Orapa area. This research was later expanded when the Diamond Research Laboratory (de Beers) made a grant to the Nuclear Physics Research Unit of the Witwatersrand University, to carry out further research, in collaboration with the Geological Survey. All work conducted by the Geological Survey in this programme was under the writer's direct supervision.

PREVIOUS WORK

Previous descriptions of the area are to be found in the report by the consultant engineers on "Water Supply to AKI (Orapa)" (Anon, 1969) and by Robins (1972 and 1972a). The writer was directly involved with the geohydrological studies at Orapa which included pump tests; logging of boreholes and geophysical work, but gratefully acknowledges the assistance and advice given by Mr. A.G.P. Debney of the Institute of Hydrology, Wallingford, who carried out most of the aquifer tests at Orapa. This work was conducted on behalf of the Consultant Engineers with the assistance of the writer and other staff of the Geological Survey.

PHYSIOGRAPHY

The Orapa area consists of relatively flat, scrub-covered country which slopes gently toward the Makgadikgadi Depression (D.6). A prominent scarp overlooks the southeastern corner of the Makgadikgadi, but elsewhere there is a gradual drop towards the base of the Depression which is situated at an altitude of about 915 m. Most of the area is covered by Kalahari Beds unconsolidated sands, calcrete and silcrete but occasionally the older solid geology is exposed, particularly along the rim of the Makgadikgadi. The near ubiquitous sand cover prevents any effective run-off and consequently no active drainages are present, though the fossil Letlhekane valley can be traced on air photos as a very faint shallowly incised feature (less than 15m deep), for over 100 km. Two other minor fossil drainage valleys are also present in the area.

The main physiographic feature of the area is the enormous flat-floored Makgadikgadi Depression which occupies an area of over 1 280 000 hectares. This Depression is usually underlain by a shallow, brine water table. The only other physiographic feature of any significance is a low scarp extending northwards then westwards from Serowe but which dies out due east of Orapa and marks the eastern limit of the Kalahari region.

Rainfall and Climate

Only 4 years rainfall data (and this incomplete) are available for Orapa. The maximum monthly rainfall recorded during this period was 206,3 mm (January 1972) while monthly rainfall exceeding 100 mm fell on 5 other occasions viz: 183 mm (February 1969); 107,6 mm (March 1969); 104,5 mm (November 1969); 157,8 mm (December 1970) and 106,7 mm (March 1972). The available rainfall data are shown in the table below:-

TABLE 39
RAINFALL AT ORAPA 1968-1973 IN mm

	1968	1969	1970	1971	1972	1973
JANUARY		31,6	24,8	160*	206,3	36,9
FEBRUARY		183,0	48,8	30*	28,7	56,9
MARCH		107,6	10,4	40*	106,7	33,8
APRIL		12,8	22,0*	15*	25,6	0,0
MAY		0,9	0,0	1*	4,2	1,9
JUNE		0,0	5,5	0,0	0,0	0,0
JULY		0,0	0,0	0,0	0,0	0,0
AUGUST		2,1	0,0	0,0	0,0	0,0
SEPTEMBER		0,0	5,3	40,6	8,5	4,6
OCTOBER		15,9	0,0	34,8	?	97,5

continued...	1968	1969	1970	1971	1972	1973
DECEMBER	44,5	49,9	157,8	51,3	34,3	
<u>TOTAL</u>	(67,1)	508,3	290,4	421		

* Estimated from surrounding rainfall gauges at Serowe, Gweta and Totome.

GEOLOGY

TABLE OF GEOLOGICAL FORMATIONS

<u>FORMATION</u>	<u>GROUP</u>	<u>AGE</u>
Sediments of Makgadikgadi Unconformity?		Tertiary and Recent
Sand calcrete ferricrete Unconformity	Kalahari	Mesozoic - Tertiary
Stormberg Lava Ntane (Cave) Sandstone	} Karoo Supergroup	} Late Palaeozoic Early Mesozoic
Mosu Sandstone		
Kautse Beds		
Non-carbonaceous and carbonaceous Beds.)		
Mea arkose Tlapana Mudstone		

INTRUSIVE ROCKS

Kimberlite Pipes	Post-Karoo
Dolerite Sills	Post-Karoo
Dolerite Dykes	Post-Karoo

KAROO SUPERGROUP

Ecce Subgroup

Rocks of this subgroup do not crop out at Orapa itself and are only found to the north and northeast, where they are exposed on the escarpment forming the southern margin of the Makgadikgadi Depression. A deep, diamond core borehole 2125 A/D1 drilled 6 kilometres east of Orapa however has revealed the following lithological succession:-

0 - 99,6 m	Basalt (Stormberg).
99,6 - 152,1 m	Pale grey to pink fine-grained sandstone (Cave) with dark grey siltstone lenses at 99,6 m and a thin, red micaceous mudstone band at 132 m.
152,1 - 152,4 m	Dark brown mudstone.
152,4 - 168,4 m	Pale grey fine-grained (Cave) sandstone.
168,4 - 169,6 m	Maroon, silty sandstone
169,6 - 176,8 m	Pale, grey-brown fine-grained sandstone.
176,8 - 177,4 m	Medium-to coarse-grained sandstone with occasional green clay pellets.
177,4 - 179,4 m	Maroon and pale grey or brown laminated mudstone with thin siltstone intercalations.
184,4 - 184,7 m	Maroon mudstone.
184,7 - 203,3 m	Brown to pale grey medium-grained sandstone with thin bands of maroon, silty sandstone.
203,3 - 204,8 m	Grey shale.
204,8 - 209,1 m	Brown, medium-grained sandstone.
209,1 - 212,1 m	Brown, extremely coarse-grained sandstone with occasional vein quartz pebble bands at \pm 211,9 m. N.B. This rock is extremely porous and is probably a good aquifer.
212,1 - 256 m	Maroon, brown and blue-grey silty mudstone.
256 - 257,9 m	Grey medium-grained slightly micaceous sandstone.
257,9 - 303,5 m	Grey, silty mudstone.

Cave Sandstone

The Cave Sandstone underlies the basalt either with a slight unconformity, or in some areas, the lava flows are inbedded with the uppermost sandstone beds thus indicating contemporaneity between the closing stages of the deposition of the Cave Sandstone and the outpourings of Stormberg lavas.

The Cave Sandstone crops out in a fringe surrounding the lavas from west of Orapa eastwards then southwards past Serowe past Moijabana (E.7) to west of Shoshong (F.6).

The sandstone varies in colour from pink to orange, or may be buff, or even white. It is generally fine-to medium-grained and consists of well-rounded "millet seed" sand grains with some feldspar. It is characteristically poorly cemented, and often soft and friable. Pink marly sandstones are generally developed towards the base of the succession. The sandstone on the contact with the overlying basaltic lava is often hard and better-cemented than the remainder of the sandstone. It is moreover, often well-fissured, commonly with fissures up to 3 cm in diameter. Diamond core-drillers drilling at Orapa, have reported poor core recoveries in this zone, while a cavity of 76 cm was reported on the basalt contact in a borehole drilled in the central Kalahari Game Reserve. (Bh. 1599, E.3). It is therefore likely that the fissures within the indurated zone act as conduits for the passage of water into boreholes penetrating this horizon. This more permeable zone forms the most consistent aquifer in Botswana, with virtually every known borehole penetrating this horizon producing yields varying from 38 to over 450 litres per minute. Pump testing of the Cave Sandstone aquifer has shown however, that the Coefficient of transmissibility of the Cave Sandstone is surprisingly low - an average of only 1 000 g.p.d/ft. ($15 \text{ m}^2/\text{d}$).

This can probably be accounted for by the fact that the fissures on the contact have little lateral extent. Tests in which samples of core from the indurated contact zone were soaked in hydrochloric acid, showed that rapid and complete disintegration of the hard, calcite-cemented sandstone took place. It is probable therefore, that acid treatment of the aquifer would result in increased coefficients of transmissivity.

Stormberg Lava

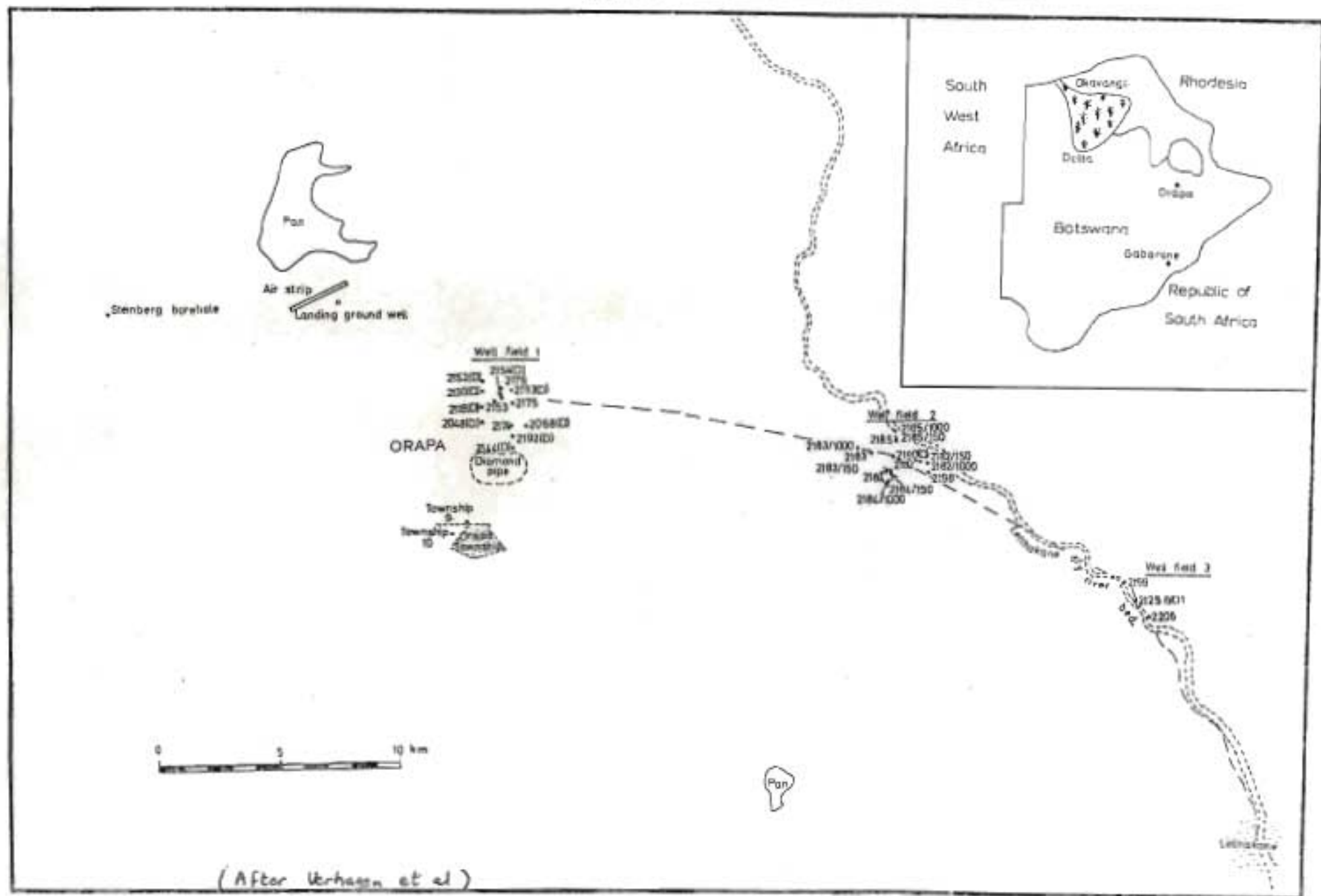
Basaltic lavas of the Drakensberg Lava Subgroup of the Stormberg Group (Karoo Supergroup) crop out over an extensive belt extending from Serowe (E.7) northwestwards to Orapa (D.6). They then run in a southwesterly direction for at least 180 km and then swing southeast towards Kutswe (F.5) and Lephepe (F.6). From here they run north and then northeast back to Serowe. These lavas are overlain unconformably by Kalahari Beds while they are underlain by the Cave Sandstone Stage which forms an irregular fringe around the margin of the lavas.

Boreholes in the area indicate a maximum thickness of basalt of 252 m at Serwe north of Serowe. Several boreholes e.g. 1703, 2065, 2083, encountered less than 30 m of basalt. A number of fairly closely spaced boreholes, e.g. 2065 and 1694, 2199 and 2206 and 2152 and 2183, although at similar elevations, show respective basalt thicknesses of 65 m, 43 m and 77 m, thus indicating possible differences in pre-basalt relief, or more likely, the presence of minor faulting. At Orapa itself, the average depth to the base of the basalt is 110,2 m (12 boreholes) with a maximum thickness of 118,3 m of basalt and a minimum of 100,6m. (See Fig. 59).

At the 8 mile wellfield the average thickness of the basalt in 5 boreholes (2182, 2183, 2184 and 2190) is 86 m while the average thickness of basalt in the 2 boreholes constituting the 12 mile wellfield is 53,7 m.

Elsewhere in the Kalahari region the greatest known depth of basalt is in borehole 1351 near Lephepe (F.6, more than 401 m).

FIG 59 BOREHOLE LOCATIONS - ORAPA



(After Verhagen et al)

In borehole 1578 at Semolale, in the Tuli basalt trough in eastern Botswana (D.9), the basalt attains a thickness of over 249,39 m (borehole stopped in basalt).

A study of the diamond core borehole drilled at Serwe (E.7) as part of the hydrogeological research programme, shows that the borehole penetrated Stormberg basalt lavas from 11,28 m - 252 m (See Appendix). The basalt varies in colour from black to grey or even reddish-brown. It consists of alternating fine-grained massive and amygdaloidal zones and occasionally shows minor fracturing and thin veins of calcite. A study of the amygdaloidal zones shows that 22 individual lava flows make up the total thickness of 240,72 m with an average thickness of 10,94 m. Individual flows vary from 2,74 to 32,92 m in thickness.

The presence of tuff bands up to 23 cm in thickness and of a single thin band of green shale indicate a temporary lull in the volcanic outpourings. Close examination of the lavas indicates that there is no marked interflow weathering of the basalt. As the fine-grained basalts lack intergranular space and also have a general absence of jointing, it is not surprising that in the Serowe - Orapa region, the basalts form an extremely poor aquifer. This is supported by data from numerous boreholes penetrating the basalt in this region in which the driller seldom recorded supplies in excess of 2 l/min being encountered in the basalt. Where large supplies are encountered in the basalt, e.g. Panda ma Tenga (A.6) and Morukuru (D.7) areas, it is probable that water is encountered in basins of decomposition, on weathered flow contacts, or in fracture zones.

A petrographic description of the basaltic lavas was given earlier in the section on the geology of Botswana.

Kalahari Beds

Prior to the drilling of a number of core boreholes for hydrogeological research in both the central and northeastern Kalahari regions, little was known of the true nature of these virtually unknown beds, both because of a paucity of natural sections and because of the difficulty in identifying the true nature of rock types from sludge samples from percussion drilled boreholes. The diamond coreholes have thus provided unique information on these beds.

Only three of the coreholes drilled in the Serowe-Orapa region encountered significant thicknesses of Kalahari Beds - Tshepe, Makoba and Mahata.

Summary logs of the Kalahari Beds section of two of these boreholes are given below:-

TSHEPE

0 - 3'	Sand
3 - 39'	White to mottled siliceous sandstone with some calcareous cement and occasional "root holes" filled by poorly cemented sandstone or sand.
39 - 72'	Mainly white (medium-grained) sometimes ferruginous-stained, calcareous-cemented sandstone with occasional vertical root-holes filled with poorly cemented sandstone.
72' - 90'	Mottled sandstone with appearance of "conglomerate" consisting of round to elongate fine-grained brown calcareous sandstone "pebbles" $\frac{1}{4}$ " to 1" in diameter set in a matrix of coarser-grained dark brown calcareous sandstone. This sandstone contains pebbles of basalt towards the base at $\frac{2}{90}$ '.

MAKOBA

0' - 4'	Sand and grey sandy soil.
---------	---------------------------

- calcareous with occasional pipe-like rootholes.
- 30' - 82½' Pink to mottled pink and white calcareous sandstone with occasional rootholes/pipes of red sandstone.
- 82½' - 89' Red calcareous sandstone "conglomerate" with rounded, white, silty limestone segregations.
- 89' - 182' Mainly fine-grained pink calcareous sandstone with occasional partly infilled "pipe".

Base of Kalahari Beds at 182'.

The main characteristics of the Kalahari Beds in this section are thus the extremely thin cover of unconsolidated Kalahari sand of \pm 1 metre, underlain by 9 - 12 m of partly silicified red sandstone underlain by up to 45 m of fine-grained pink sandstone bearing a startling similarity to the Cave sandstone, but distinguished by occasional thin pipe-like "root-holes". Thin mottled zones in which segregations of the calcareous matrix have taken place are also present and it gives the sandstone a "conglomerate-like" appearance. As noted later in the section on the Stormberg lavas, the presence of identical "conglomerate-like" intercalations within the lavas is regarded as evidence that lower Kalahari Beds are coeval with the lavas and are probably much older than originally thought.

The Kalahari Beds in the Makoba area are of sufficient thickness for water to be encountered within the Kalahari Beds. The poorly cemented nature of the soft friable calcareous sandstones is such as to be reported by percussion drillers as "running sand" when saturated with ground water.

In the Orapa area a thin veneer of Kalahari sands overlies calcrete which in turn overlies decomposed basalt. The maximum recorded thickness of Kalahari Beds in this area is 16 m in borehole 2185/150. These consist mainly of

sand with less than 30 cm of calcrete. No ground water occurs in the Orapa area within the Kalahari Beds except in the shallow hand-dug well near the large pan on the edge of the landing ground (airstrip).

Intrusive Rocks

Dolerite Dykes

A number of west-northwesterly trending post-Karoo intrusive dolerite dykes can be clearly discerned on air photos and can be traced for distances up to 30 km. Similar dykes are presumed to be responsible for similar trending magnetic lineaments present in the sand covered area south of Orapa.

Kimberlite Pipes

A large number of Kimberlite Pipes with surface areas of up to a maximum of 112 hectares intrude the basalt in the Orapa area. Much of the material in the main Orapa pipe is regarded as of secondary kimberlitic origin following the slumping back of kimberlitic material into the original crater. A number of the pipes are known to contain economic quantities of diamonds and production from the 2125AK/1 pipe is in progress and is planned for the 2125DK/1 pipe. Only very minor quantities of water, identical in chemical quality to that of the neighbouring basalt, were encountered during pitting operations to evaluate the pipe. It is concluded therefore, that the kimberlite pipes in the Orapa area do not constitute aquifers of any significance, while boreholes drilled in the basalt in close proximity to the kimberlite intrusion, produced no greater supplies of water than the average for the area.

A log of one of the hydrogeological research boreholes is given in Appendix 3 .

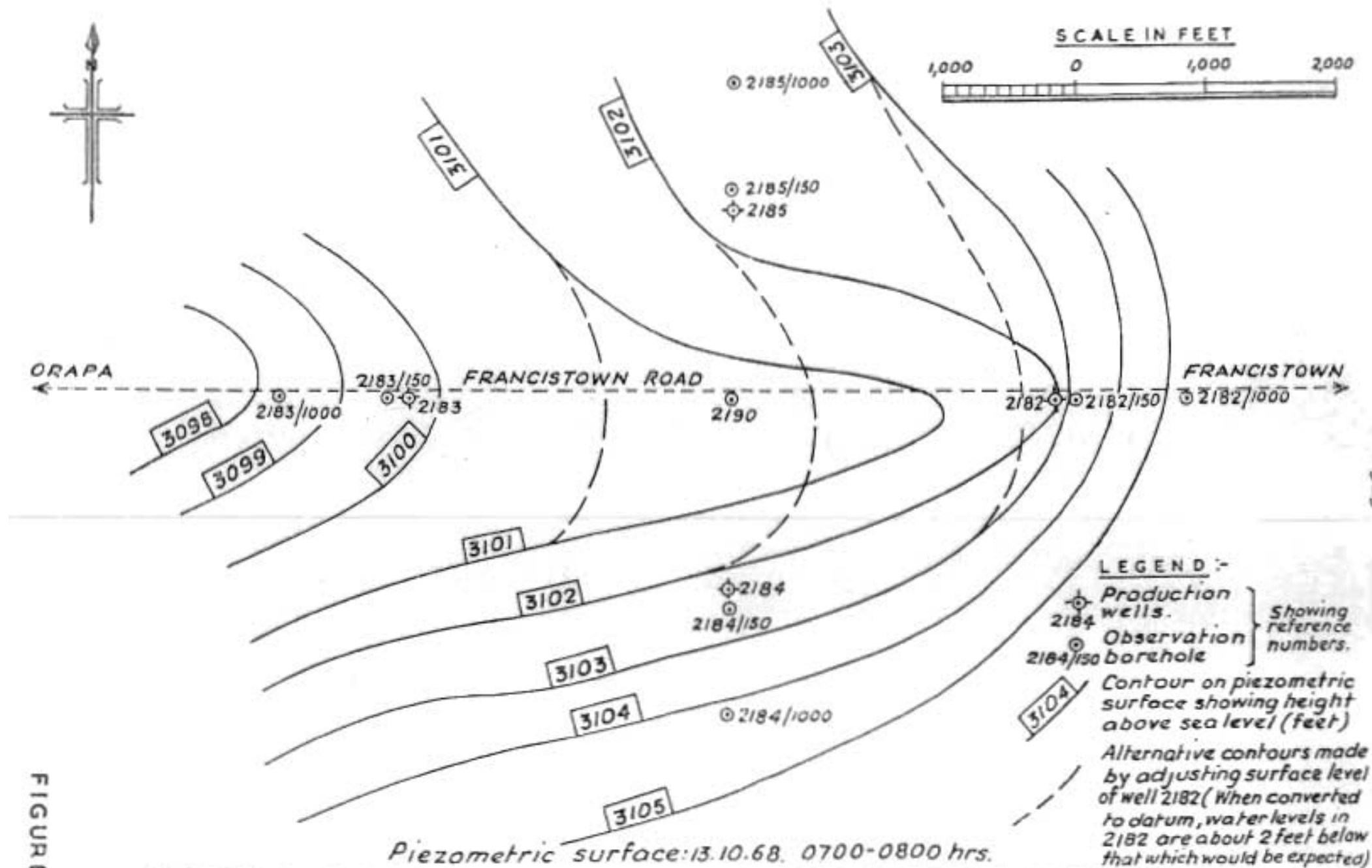
This borehole is of particular interest as it reveals indirect evidence of the age of the Kalahari Beds. The calcareous sandstone conglomerate between 154 and 165 feet is identical in appearance to that of rocks present between 64 and 84 feet above the top of the Stormberg basalt at 90 feet. This could thus provide important evidence that the lowermost beds at least of the Kalahari Group are contemporaneous with the Stormberg lavas and hence the age of these beds could be as old as Liassic. This could have important connotations for kimberlite prospecting in Botswana as the late-Cretaceous kimberlite pipes could thus be of post-Lower Kalahari age.

HYDROGEOLOGICAL RESEARCHIntroduction

The discovery of the world's second largest payable kimberlite pipe at Orapa led to a rapid increase in the demand for water, initially for evaluation of the pipe and later for the pilot plant operations and construction stages of the mine. As a result of this demand, a total of 22 boreholes was drilled between 1967 and 1969 (see Table 40 for details of these boreholes). This extensive drilling programme was preceded by photogeological interpretation and in some cases by geophysical surveys.

Subsequent to the drilling, all borehole collar elevations were accurately levelled, and some of the most detailed aquifer evaluation tests undertaken in South Africa were carried out by Sir Alexander Gibb and Partners in collaboration with the Geological Survey (under the writer's supervision) in order to determine the long term effects of sustained pumping at various projected pumping rates. In order to carry out the aquifer tests properly a wellfield consisting of 4 8 inch production boreholes was drilled by percussion methods in a virgin area 8 miles (12,8 km) from Orapa in a symmetrical pattern with a 6 inch observation borehole drilled at the centre and a total of 8 diamond cored observation boreholes drilled 150 feet (45 m) and 1000 feet (300 m) from each production hole (see Fig. 60). Detailed water level observations have been made subsequently in the area while samples of water have been collected at regular intervals for chemical and tritium analysis. Samples have

..../also



LEGEND :-

- Production wells.
- Observation borehole
- Contour on piezometric surface showing height above sea level (feet)
- Alternative contours made by adjusting surface level of well 2182 (When converted to datum, water levels in 2182 are about 2 feet below that which would be expected)

} Showing reference numbers.

Piezometric surface: 13.10.68. 0700-0800 hrs.
**BOREHOLE LOCATION PLAN AND PIEZOMETRIC SURFACE
 CONTOURS FOR MAIN TEST PUMPING AREA. (After Anon, 1969)**

TABLE 40

BOREHOLES - ORAPA AREA

NO.	LOCALITY	DEPTH	WATER STRUCK	STATIC REST LEVEL	AFTER TEST	YIELD	DEPTH OF BASE OF BASALT	CYLINDER DEPTH	DIAMETER OF BOREHOLES	DRAW DOWN	DURATION OF TEST	DATE DRILLED
2048	Orapa	408'	140', 354'	70'?	52'	+1800 gph	354'	360'	6"	Not to intake	9 hrs	20.6.67-13.7.67
2065	Demoutsa	200'	40', 150'	32'	52'	1600	40'	160'	6"	Intake	9 hrs	19.7.67-3.9.67
2068	Orapa	418'	82', 370'	37'	37'	+1200	370'	380'	6"	Not to intake	24 hrs	9.8.67-12.9.67
2083	Orapa Airstrip	212'	201'	43'	43'	1600	78'	200'	6"	Intake	24 hrs	14.9.67-27.9.67
2118	Orapa	426'	80', 380'	39'	39'	1440	380'	390'	6"	Intake	7 hrs	11.12.67-16.1.68
2130	Orapa	420'	342'	47'	47'	2000	342'	390'	6"	Intake	17 hrs	17.1.68-19.2.68
2152	Orapa	423'	60', 35', 0, 390'	39'	39'	+3600	330'	380'	6"	Intake	3 hrs	8.4.68-25.4.68
2153	Orapa	390'	374'	63'	63'	3600	374'	390'	5"	Intake	2 hrs	2.7.68-2.7.68
2154	Orapa	585'	64', 390', 520', 570'	45'	45'	1000	368'	560'	6"	Intake	2 hrs	25.4.68-17.5.68
2174	Orapa	400'	370'	51'	51'	1000	360'	400'	6 1/2"	Intake	15 hrs	12.8.68-9.10.68
2175	Orapa	412'	382', 390', 408'	50'	50'	2000	376'	400'	6 1/2"	Intake	5 hrs	21.8.68-11.10.68
2179	Orapa	464'	360', 380', 440'	51'	51'	2540	344'	400'	8"	Intake	25.8.68-10.9.68	
2182	E. of Orapa	402'	90', 295'	53'	53'	5000	295'		8"		26.8.68-10.9.68	
2183	E. of Orapa	385'	45' - 285'	42'	42'	3000	280'		8"		12.9.68-26.9.68	
2184	E. of Orapa	335'	225'	34'	34'	3000	280'		8"		18.9.68-?	
2185	E. of Orapa	455'	225'	34'	34'	+3000	275'		6"		7.10.68-16.10.68	
2190	E. of Orapa	304'	90', 200'?	-	-	3000	200' (280?)		5"		17.10.68-4.11.68	
2192	Orapa	430'	60', 379', 420'	48'	48'	2500	380'		6 1/2"	24 hrs	4.11.68-20.11.68	
2193	Orapa	450'	56', 346', 370', 425'	48'	48'	2570	340'		6"		17.10.68-23.10.68	
2198	E. of Orapa in valley	325'	90'	42'	42'	3000	220'		6 1/2"		15.11.68-16.12.68	
2199	E. of Orapa in valley	432'	38', -324'	97.7	97.7	3600	280'		6 1/2"		18.12.68-31.1.69	
2206	E. of Orapa in valley	354'	75', 354'	22.6	22.6	7200	138'		6 1/2"			

also been taken for stable isotope and carbon - 14 analysis. A number of boreholes were logged for fluid and formation resistivity, one downhole S.P. log was undertaken and shot firing tests carried out to observe whether yields could be improved.

Laboratory tests were carried out on certain core samples to determine the porosity and permeability. All boreholes were equipped with water meters but the extremely fine silt pumped with the water from the Cave Sandstone aquifer unfortunately resulted in rapid failure of all the meters. However, because water requirements for the diamond treatment plant were well known, fairly accurate estimates of the total amount of ground water used could be made.

As part of the general policy of carrying out hydrogeological research within Botswana, a line of diamond core boreholes was drilled by the Geological Survey Department extending from Serowe to Letlhakane (D.6). The object of this research was to determine the geology of this sand-covered northeastern section of the Kalahari desert; to determine the nature of the basalt/Cave sandstone contact; and to commence research on long term water level fluctuations both in the vicinity of and away from pumped boreholes. Following the discovery of the Orapa diamond pipe, the Anglo American Corporation of South Africa Limited and the Geological Survey drilled a further series of diamond core observation boreholes at Orapa; between Orapa and the 8 mile wellfield; at the 8 mile wellfield; at the 12 mile wellfield and west of Orapa at Mopipi. As a result of this

drilling a unique opportunity was presented to study the nature of Botswana's most widespread and consistent aquifer (Basalt/Cave Sandstone). A log of the deep borehole 2125A/D1 drilled 6 km east of Orapa was given on page 303. This borehole is interesting in that a considerably thicker succession of sandstone is present in the Cave Sandstone subgroup. An unusually coarse-grained, highly porous sandstone (slightly conglomeratic) is found at the base of the stage. This particularly porous zone has never been tested as an aquifer and could well supply the answer to the present water crisis at the Orapa Mine.

Hydrogeology

Hydrogeological properties of the Kalahari Beds

Apart from shallow hand-dug wells in the Letlhakane area (D.6) southeast of Orapa yielding some water (saline) in calcrete, the Kalahari Beds in the Orapa area are nowhere sufficiently well developed to form an aquifer of any significance.

In the Makoba area 80 km to the southeast, the Kalahari Beds are sufficiently well developed to yield good supplies of water while north of the Makgadikgadi Depression the Kalahari Beds also form a good aquifer. (Nata, Odiakwe area, Fig. 61).

Hydrogeological properties of the Stormberg Basalt

Although the Stormberg basalt forms an important aquifer in the Panda ma Tenga area (A.6) in northern Botswana, and also further southeast (180 km S.E. in the Morukuru area (D.7, Fig.71)), the basalt forms a poor aquifer in the Orapa area and generally

GEOLOGICAL SURVEY

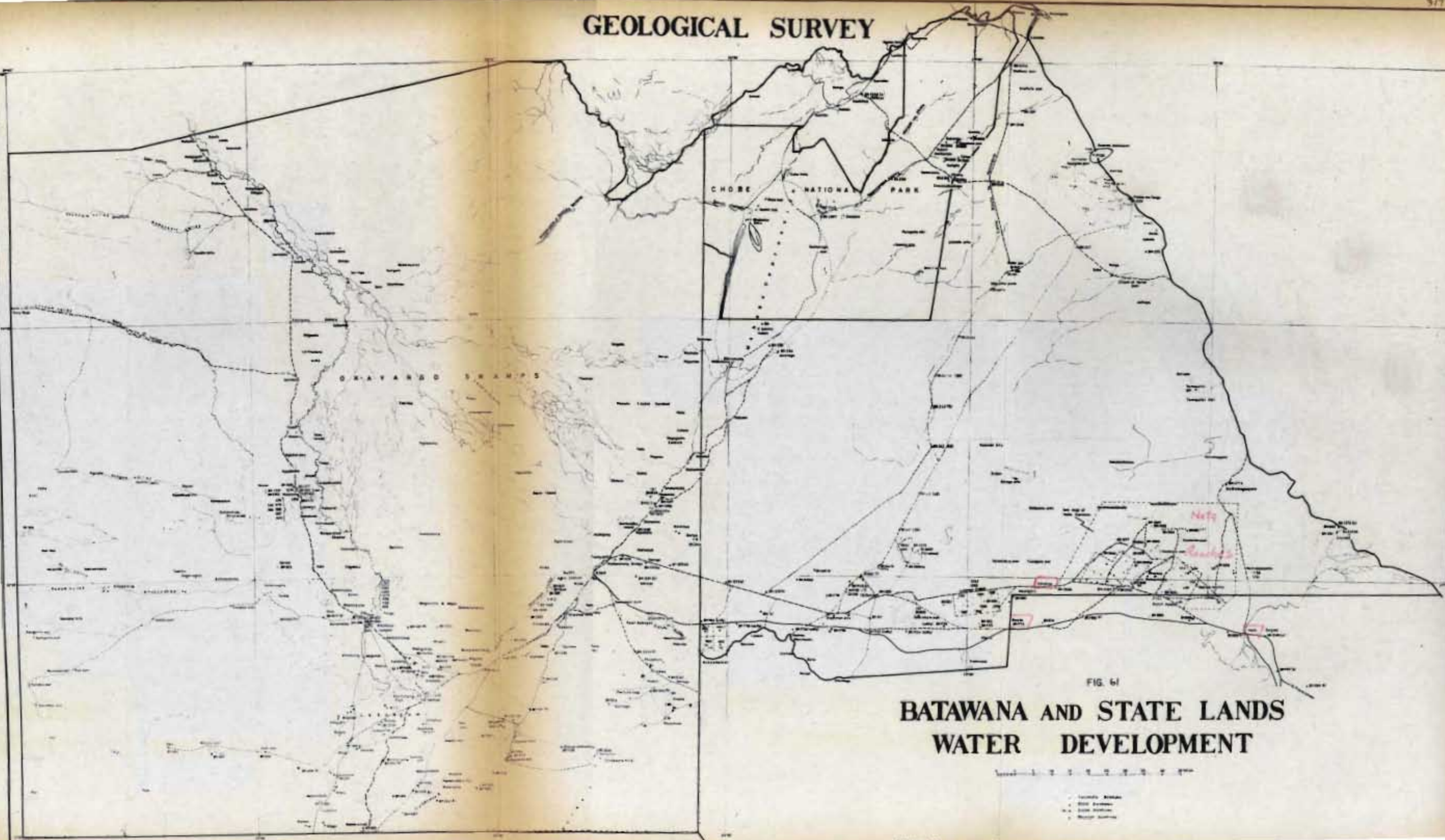


FIG. 61
**BATAWANA AND STATE LANDS
 WATER DEVELOPMENT**

Laboratory investigation of physical properties of the Stormberg basalt

Tests on a core sample from core borehole 2185/1000 at Orapa gave the following results - Table 41 .

TABLE 41

LABORATORY TESTS ON DRILL CORE FROM BASALT - 8 MILE WELL
FIELD - ORAPA

<u>BOREHOLE</u>	<u>SAMPLE DEPTH</u>	<u>DENSITY</u>	<u>POROSITY</u>		<u>(millidarcy's)</u> <u>PERMEABILITY</u>	
			Vert.	Horiz.	Vert.	Horiz.
2185/1000	161'8"	Dry bulk 2,47g/cc	7,8 \pm 0,5%	7,44 \pm 0,5%	1	1
		Saturated bulk 2,55g/cc				
		Grain 2,675				

It can be seen therefore that unweathered basalt has a low porosity and an extremely low permeability. It is expected that the weathered zones between some lava flows will have considerably higher porosities and permeabilities.

Hydrogeological Properties of Cave Sandstone

The contact zone with the overlying basalt forms Etswana's most important and consistent aquifer. Although it had long been known that this "indurated zone" was an important aquifer, very little was known of it's exact nature. The recently drilled diamond coreholes have given important new data on this aquifer. In addition to the indurated zone, the leached, poorly cemented and highly porous zone immediately below the indurated zone also probably provides water to drilled holes. In the indurated zone open fissures are often present while examination of the core logs shows that

core losses of up to two metres occur in this zone. The "indurated" zone referred to in most literature is somewhat of a misnomer as the actual contact metamorphic zone seldom exceeds more than a few centimetres of hard, maroon sandstone. This is usually followed downwards by up to one metre of hard, calcite cemented sandstone occasionally with open fissures up to 2 to 3 cm in diameter. Below this zone a very poorly cemented, porous sandstone generally occurs (approximately 3 m thick). This whole zone is probably the one which yields water to boreholes penetrating it and is probably the zone which shows up as a resistivity low on formation resistivity logs.

A summary log of diamond boreholes penetrating the contact is given below in the Table:-

TABLE 42

SUMMARY OF SELECTED CORE LOGS PENETRATING CAVE SANDSTONE CONTACT

Borehole Number	Description
2182/1000	15 cm Indurated sandstone underlain by 45 cm calcareous sandstone with thin calcite veins. <u>Note</u> 1,82 m lost in 6 m of core containing contact zone.
2183/150	76 cm Indurated calcareous sandstone with thin calcite veins. <u>Note</u> 2,13 m core lost in 10,6 m of core containing contact zone.
2184/150	7,6 cm Indurated sandstone underlain by 63,5 cm of sandstone with calcite filled joints. <u>Note</u> 1,6 m core lost in 2,6 m of core.

2185/150	12,5 cm Calcareous sandstone with horizontal joints (partly open) with calcite filling underlain by 40,6 cm of calcareous sandstone.
2125A/D1	38,1 cm Indurated but cavernous sandstone underlain by 2,97 of leached and highly porous sandstone.
2125A/D	30,48 cm Indurated sandstone underlain by fine-grained well sorted, soft, friable and porous, thin-bedded sandstone.
Serowe recorder borehole	1,14 m Red indurated sandstone with thin white calcite veins intersecting core at 45° angle. An open fissure 7,6 cm from the basalt contact contains calcite crystals.
Bosupswe recorder borehole	1,3 cm Altered sandstone underlain by 95 cm white calcareous sandstone underlain in turn by yellow and pink sandstone.
Mashoro recorder borehole	22,8 cm Pink indurated sandstone underlain by 15,24 cm of calcareous white sandstone.
Tshepe recorder borehole	2m5 cm Altered white sandstone with thin calcite vein underlain by 2,43 m of white calcareous sandstone.
Makoba recorder borehole	0,63 cm Indurated sandstone underlain by 45 cm calcareous sandstone.

Laboratory investigation of physical properties of the Cave Sandstone

Laboratory tests were carried out by the Institute of Geological Sciences on drill core on samples from boreholes 2185/150, 2185/1000 and 2183/150 (Fig. 59). These results are given below in the Table:-

TABLE 43

LABORATORY TESTS ON DRILL CORE FROM CAVE SANDSTONE - 8
MILE WELL FIELD, ORAPA

<u>BORE-</u> <u>HOLE</u>	<u>SAMPLE</u> <u>DEPTH</u>	<u>DENSITY</u>	<u>POROSITY</u>		<u>PERMEABILITY</u> (Millidarcy's)		
			Vert.	Horiz.	Vert.	Horiz.	Strike
					Dip		
2185/ 1000	218'8"	Dry Bulk 1,84 Saturated 2,14 Grain 2,63					
			30', 1%	29', 8%	4101	4099	
2185/ 1000	252'2½"	Dry Bulk 1,95 Saturated 2,21 Grain 2,64					
			25,9%	26,15 (Mean of dip & strike)	1555	3128	
2185/ 1000	221'		-	27,55 (")	-	2650	3627
	224'		-	19,90 (")	-	987	
	229'		-	31,75 (")	-	3943	5310
	230'		31,3	31,4 (")	3016	3418	3607
	280'		28,3	28,0 (")	2300	2425	2187
	300'		28,7	23,8 (")	3949	898	1644
2183/ 150	279'		11,8	15,5 (")	25	330	196
	285'		28,5	27,95 (")	2261	1883	1710
		Mean	26,09%	(26 deter- minations)		Mean 2531 (mean of 5)	

The mean values of 26,01% for the effective porosity and of 2531 millidarcys thus indicate a remarkably high porosity and also a very high permeability for the Cave sandstone.

PUMP TESTING
AQUIFER EVALUATION

Extremely detailed tests were carried out in an undeveloped area 13 km east of Orapa by the Geological Survey in conjunction with the Anglo-American Company of South Africa Limited and Sir Alexander Gibb and Partners.

Four eight inch boreholes were drilled on a diamond pattern with boreholes on the long axis 5000 feet apart and 3000 feet apart on the shorter axis. Diamond core observation boreholes (NX diameter) were then drilled at a distance of 150 and 1000 feet each from the eight inch boreholes and on the extension of each axis (See Fig. 60). A six inch observation hole was drilled in the geometrical centre of the area. Controlled pump tests were then carried out to provide quantitative data relating to the Cave Sandstone aquifer and to give an idea of the performance of the aquifer under pumping conditions. Elsewhere in Botswana, the only area where any extensive exploration of the Cave Sandstone aquifer had taken place was at Serowe and even here little quantitative data was available.

All production boreholes penetrated the Kalahari Beds, Stormberg basalt and the Cave Sandstone aquifer. They were lined with unperforated steel casing to a depth of \pm 30 m and were unlined below that depth. Although small quantities of water were encountered in the basalt, the main supplies of the water were encountered under confined conditions at or below the basalt/sandstone contact with static water levels rising to some 60 m above this interface.

Water level observations were made using electrical depth sounding probes and with four automatic water stage recorders. Barometric readings were taken at frequent intervals and curves corrected for barometric fluctuations where necessary. A single step-drawdown test was carried out to determine borehole performance characteristics while all other tests were conducted by pumping at a constant rate and determining the drawdown in the pumped hole and using all other boreholes for drawdown observation purposes. Each eight inch hole was pumped in turn after allowing sufficient time between tests for water levels to recover. The drawdown in the pumped hole was initially measured at one minute intervals and then with gradually reduced frequency as the test progressed. Water levels in the observation holes at 150 feet and 1 000 feet from the pumped hole were measured initially at five minute intervals and then at greater time intervals as the test proceeded. All other boreholes were carefully monitored during the tests but at less frequent intervals. Initial tests were carried out using a reciprocating pump, but later tests were carried out using a turbine pump capable of delivering a more steady flow and of pumping greater amounts of water than the 304 litres per minute (4 000 g.p.h.) capable of being delivered by the piston pump.

The water level data was then plotted and analysed using conventional non-equilibrium techniques as described in the section on aquifer evaluation.

Results of data from two typical pump tests are given below:-

2183

$$t = 120 \text{ mins}$$

$$r = 8 \text{ in}$$

$$Q = 50 \text{ g.p.m.}$$

$$s = 340' \text{ plus}$$

$$S = 0.000034$$

$$\frac{Q}{s} = \frac{50}{340} = 0.15 \text{ g.p.m./ft}$$

$$\text{Drawdown at 150 ft} = 33 \text{ ft, } r^2 = 22500$$

$$\text{Drawdown at 1000 ft} = 1 \text{ ft, } r^2 = 1,000,000$$

$$T = 280 \text{ g.p.d./ft (3,47 m}^2\text{/day)}.$$

2182

$$Q = 4,300 \text{ g.p.h. for } 7\frac{1}{2} \text{ hours}$$

$$\text{Drawdown at 150 ft} = 20.3 \text{ ft, } r^2 = 22500$$

$$\text{Drawdown at 1000 ft} = 75 \text{ ft, } r^2 = 1,000,000$$

$$t = 450 \text{ mins}$$

$$r = 8 \text{ in}$$

$$Q = 72 \text{ g.p.m.}$$

$$s = 19\frac{1}{2} \text{ ft}$$

$$S = 0.0011$$

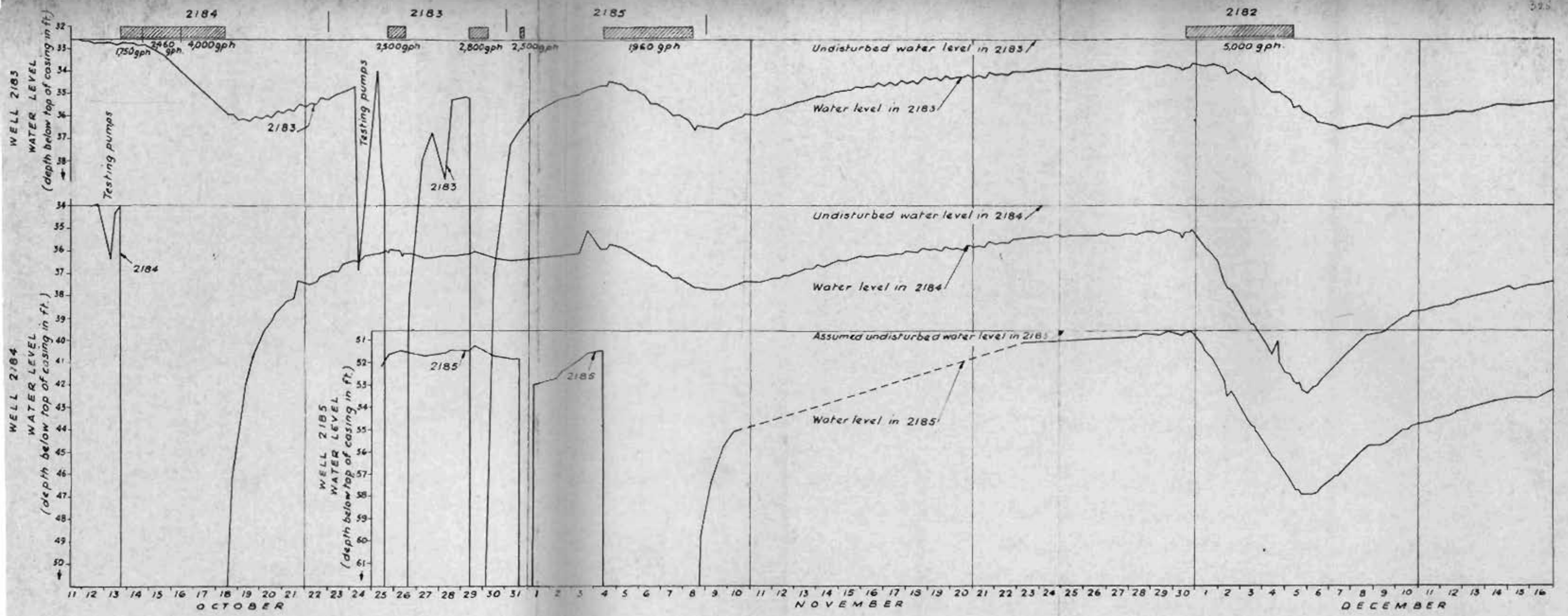
$$\frac{Q}{s} = \frac{72}{19.5} = 3.7 \text{ g.p.m./ft.}$$

$$T = 6000 \text{ g.p.d./ft (74,4 m}^2\text{/day)}$$

Results of the pump tests indicate that the Cave Sandstone aquifer has a calculated coefficient of transmissibility range of 260 to 6 000 gallons per day per foot (3,2-74 m²/day) with an average of about 1 000 gallons per day per foot (15 m²/day) and a coefficient of storage ranging from 0,000018 to 0,000280 and an average of 0,0001 (0,01 per cent). Curve matching indicates that leaky artesian conditions exist.

Typical drawdowns for a pump test are given in Fig. 62.

Having established the range of values for S and T, a series of distance-drawdowns for hypothetical boreholes can be drawn up in order to calculate the long term effect of



WATER LEVEL FLUCTUATIONS IN BOREHOLES
2183, 2184 AND 2185
DURING PUMPING TESTS.

FIGURE 62.

continuous pumping without recharge, and also to establish probable costs and optimum spacing for a large well field. (See Fig. 63).

It can be seen that for a borehole ($T = 500$ gallons per day per foot drawdown ($7,5 \text{ m}^3/\text{d}$) and $S = 0,00006$) a drawdown of 72 feet (21,9m) at a distance of 10 miles (16 km) can be anticipated after 1 000 days pumping at a rate of 3 000 g.p.h. (228 l/min).

It is thus obvious that despite the considerable storage potential of the Cave Sandstone, it is nevertheless a relatively poor aquifer by international standards and its development as a source of major ground water supply will be governed by the high cost necessary for the establishment of widely spaced, low yielding boreholes with large drawdowns and consequent high pumping costs. Determination of whether or not replenishment of the aquifer takes place, and the magnitude and frequency of this recharge, thus becomes of vital importance to the cost of the production and assessment of the long term reliability of the Cave Sandstone aquifer.

Step Drawdown Test Borehole 2184

A three stage step-drawdown test was conducted on borehole 2184 during mid-October 1968 by the writer in conjunction with Sir Alexander Gibb and Partners. The test commenced at a rate of 1750 gallons per hour (133 l/min) on October 13 at 17.30 hours and continued to 16.30 hours on October 14 when the pumping rate was increased to 2460 gallons per hour (186,9 l/min). During the first period the water level dropped from 34,0 feet (10,36 m) below surface to 70,6 feet (21,5 m). During the second period the water level dropped

DISTANCE-DRAWDOWN GRAPH

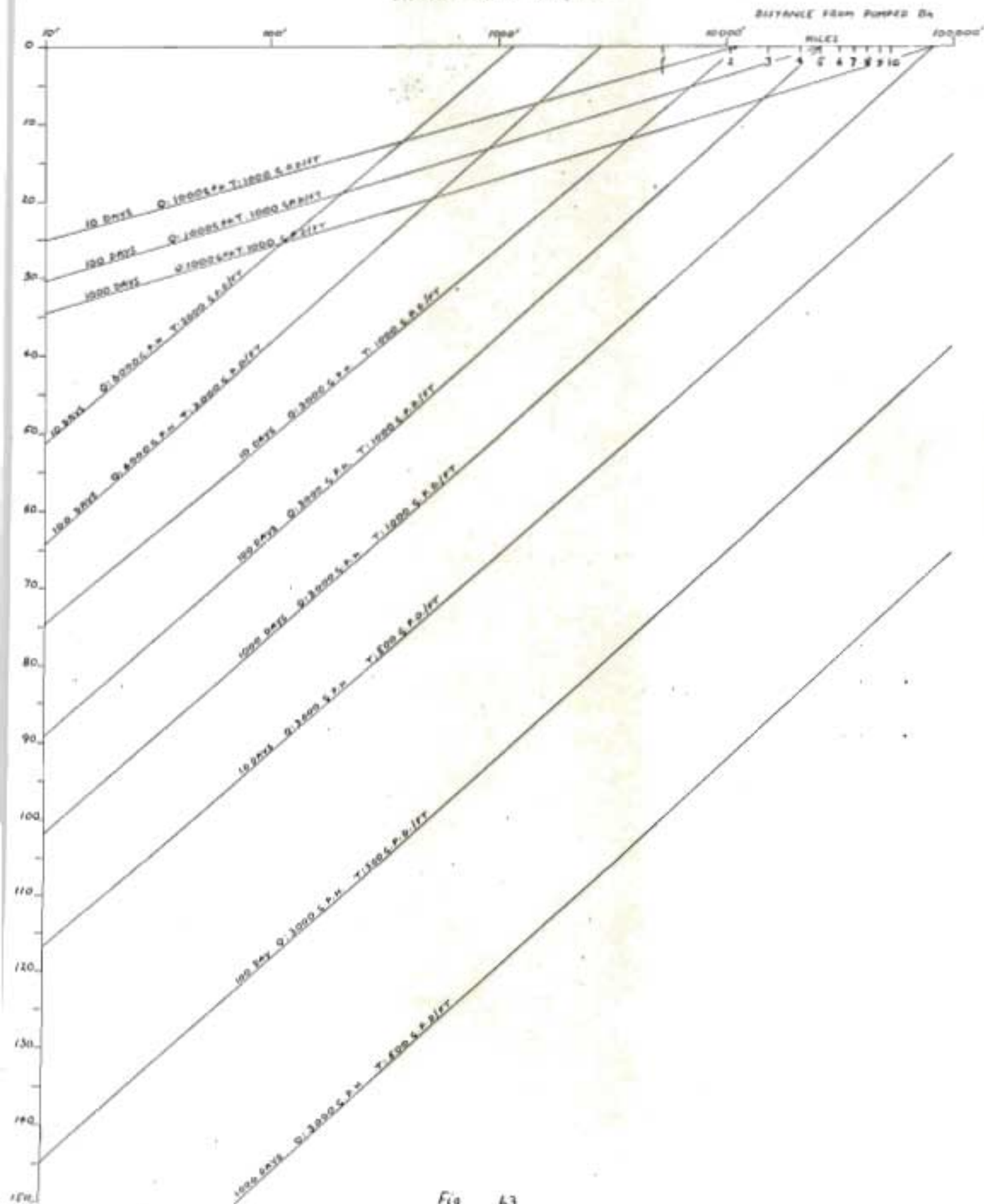


Fig 63

to 91,9 feet (28 m). At 1 000 hours on the 16th the pumping rate was increased to 3 760 gallons per hour (285,7 l/min) resulting in a further drawdown to 120,6 feet (36,76 m) after a further 8 hours.

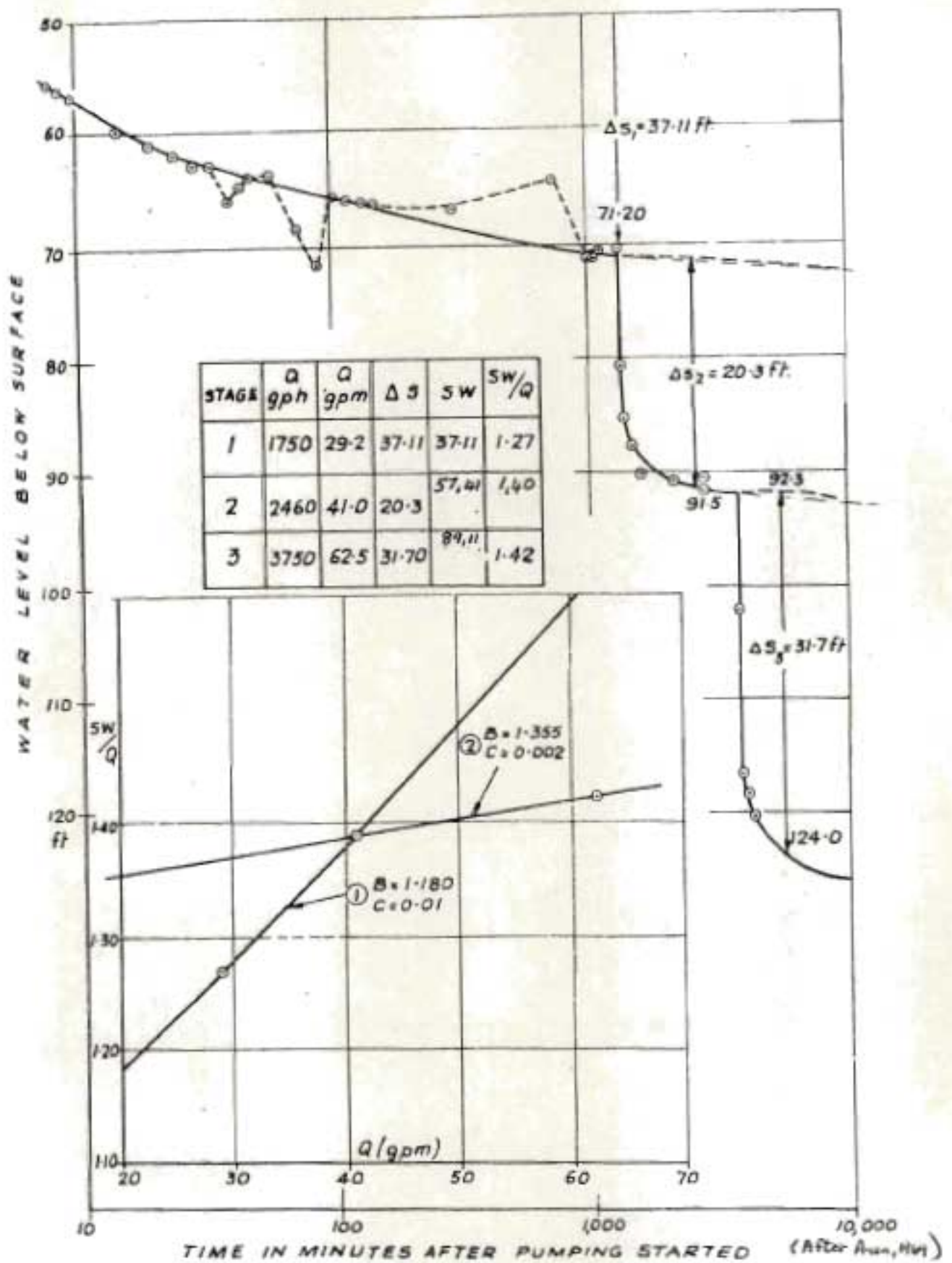
The step-drawdown data were then analysed to determine the "formation" and "well loss" components of drawdown in the pumped well using Jacob's (1946) equation $S_w = BQ + CQ^2$ where S_w is the theoretical drawdown in the pumped well, B is the "formation" constant, C is the "well loss" constant and Q is the discharge. Results are shown in Fig. 64.

Attempts at Improving Aquifer Performance

In an attempt to improve the aquifer performance in borehole 2183 following an earlier test, a 9 kg charge of dynamite was detonated on the basalt/sandstone contact. This explosion resulted in 7,6 m of basalt debris and fine sand accumulating at the bottom of the hole. This was cleaned out and the hole was retested. The effects of shot firing were assessed by comparing the theoretical and actual specific capacities of the borehole. The theoretical value was obtained from the equation:-

$$\frac{Q}{S} = \frac{T}{264 \log (Tt / 2246 rw^2 S - 65,5)}$$

where $T = 600 \text{ g.p.d./ft}$, ($7,4 \text{ m}^2/\text{day}$) $S = 0001$, t is the time after pumping started (1350) and rw^2 is the radius of the well in feet while the "well efficiency" was calculated for each test where "well efficiency" = $\frac{BQ}{S_w}$ and where $S_w = BQ + CQ^2$. S_w is the theoretical drawdown for the pumped borehole, B is the formation constant, C is the well loss constant and Q is the discharge.



STEP DRAWDOWN TEST IN WELL 2184

TABLE 44

RESULTS OF DRAWDOWN TESTS ON BOREHOLE 2183

	<u>Borehole</u>	<u>Walton method</u>		<u>Jacob method</u>		<u>Hantush method</u>	
		<u>T</u>	<u>S</u>	<u>T</u>	<u>S</u>	<u>T</u>	<u>S</u>
1st Test	2183	-	-	300	-	-	-
	2183/ 150	215	0,000053	1390	0,000035	250	0,000084
	2183/ 1000	995	0,000074	1390	0,000054	535	0,000057
After shot- firing	2183	-	-	515	-	-	-
	2183/ 150	235	0,000053	300	0,000041	-	-
	2183/ 1000	1030	0,000075	1900	0,000057	-	-

TABLE

RESULTS OF SHOT-FIRING IN BOREHOLE 2183

	<u>Specific capacity</u> <u>Q (after 700 mins)</u> <u>s g.p.m./ft</u>	<u>Theoretical</u> <u>spec. capa-</u> <u>city g.p.m./ft</u>	<u>Well effi-</u> <u>ciency %</u>
1st test	0,212	0,178	83,9
After shot- firing	0,178	0,178	100

These results indicate that the "efficiency" of the well was improved from 83,9 to 100 per cent, i.e. by 16,1 per cent. The use of explosives to improve borehole pumping efficiency would thus seem to be justified on a routine basis in this kind of aquifer.

Ground Water Storage

Using the mean calculated value of 0,00001 for the coefficient of storage (S) for the Orapa area, the volume of water may be calculated from the equation $V_w = V_r.S$

where V_w = volume of water

V_r = volume of rock through which a change in water level occurs

S = storage coefficient

$$\begin{aligned} \text{therefore } V_w &= 1000. 1000. 100. S \text{ per km}^2 \\ &\quad (\text{assuming a piezometric level} \\ &\quad \text{100 m above the Cave sandstone} \\ &\quad \text{contact}). \\ &= 10^8. 10^{-4} \text{ m}^3 \\ &= 10^4 \text{ m}^3/\text{km}^2 \\ &= 10000 \text{ m}^3/\text{km}^2 \end{aligned}$$

therefore for every km^2 of aquifer confined by basalt a storage of 10^4 m^3 can be assumed. This calculation however represents only water released from the confined aquifer as a result of compression of the aquifer and also because of slight expansion of the water as a result of the decrease in pressure. Thereafter the Cave sandstone would behave as a water-table (unconfined) aquifer with an estimated specific yield of 5-26 per cent, the latter value being obtained from laboratory tests. For a sandstone aquifer of 100 m thickness the water stored in the aquifer would amount to between $10^8. \frac{5}{100} \text{ m}^3/\text{km}^2$ of aquifer and $10^8. \frac{26}{100} \text{ m}^3/\text{km}^2$ of aquifer. i.e. Between 5.10^6 m^3 and $26.10^6 \text{ m}^3/\text{km}^2$ of aquifer. It is thus obvious that, considering the tremendous areal extent of the Cave Sandstone aquifer in Botswana (+51 800 square kilometres), the amount of water in storage is exceedingly large (of the order of 1100.10^6 gallons to 5720.10^6 gallons per square kilometre).

Yields from the Cave sandstone in the Orapa area vary from 1 000 g.p.h. (76 l/min) for a drawdown of 515 feet (157 m) to 6250 g.p.h. (475 l/min) for a drawdown of only 55 feet (16,7 m) with an average of 2700 g.p.h. (205,2 l/min). See Table 40 for details of boreholes drilled at Orapa.

Of 22 boreholes drilled, four boreholes had yields in excess of the capacity of the pumps, i.e. between 1 200 and 3 000 g.p.h. (91-228 l/min), depending on the size of the pump and the head of water in the borehole column.

Specific Capacity (yield divided by drawdown)

The specific capacities of boreholes at Orapa are given in Table 45 below and range from 1,94 to 114 g.p.h./ft.

TABLE 45
SPECIFIC CAPACITY OF ORAPA BOREHOLES

<u>Borehole Number</u>	<u>Depth of intake-ft.</u>	<u>Drawdown ft.</u>	<u>Yield g.p.h.</u>	<u>Specific capacity gallons per ft. drawdown</u>
2048	360	?	+1800	?
2065	160	128	1600	$\left. \begin{array}{l} 12,5 \text{ g.p.h./ft} \\ ? \\ 10,19 \\ 4,1 \\ 5,83 \\ 10,55 \\ 11,0 \\ 1,94 \\ 5,71 \\ 7,27 \end{array} \right\} 7,67 \text{ g.p.h./ft.}$
2068	380	?	+1200	
2083	200	157	1600	
2118	390	351	1440	
2130	390	343	2000	
2152	380	341	+3600	
2153	390	327	3600	
2154	560	515	1000	
2174			1000	
2175	400	350	2000	
2179	400	349	2540	
2182				
2183				
2184				
2185				
2190				
2192				

2198
2199
2206

20 gallons per
hour per foot
of drawdown

These results indicate large drawdowns for moderate yields and hence the need for numerous widely spaced boreholes and high pumping costs for any large scale abstraction scheme.

WATER LEVELS

Long term fluctuations

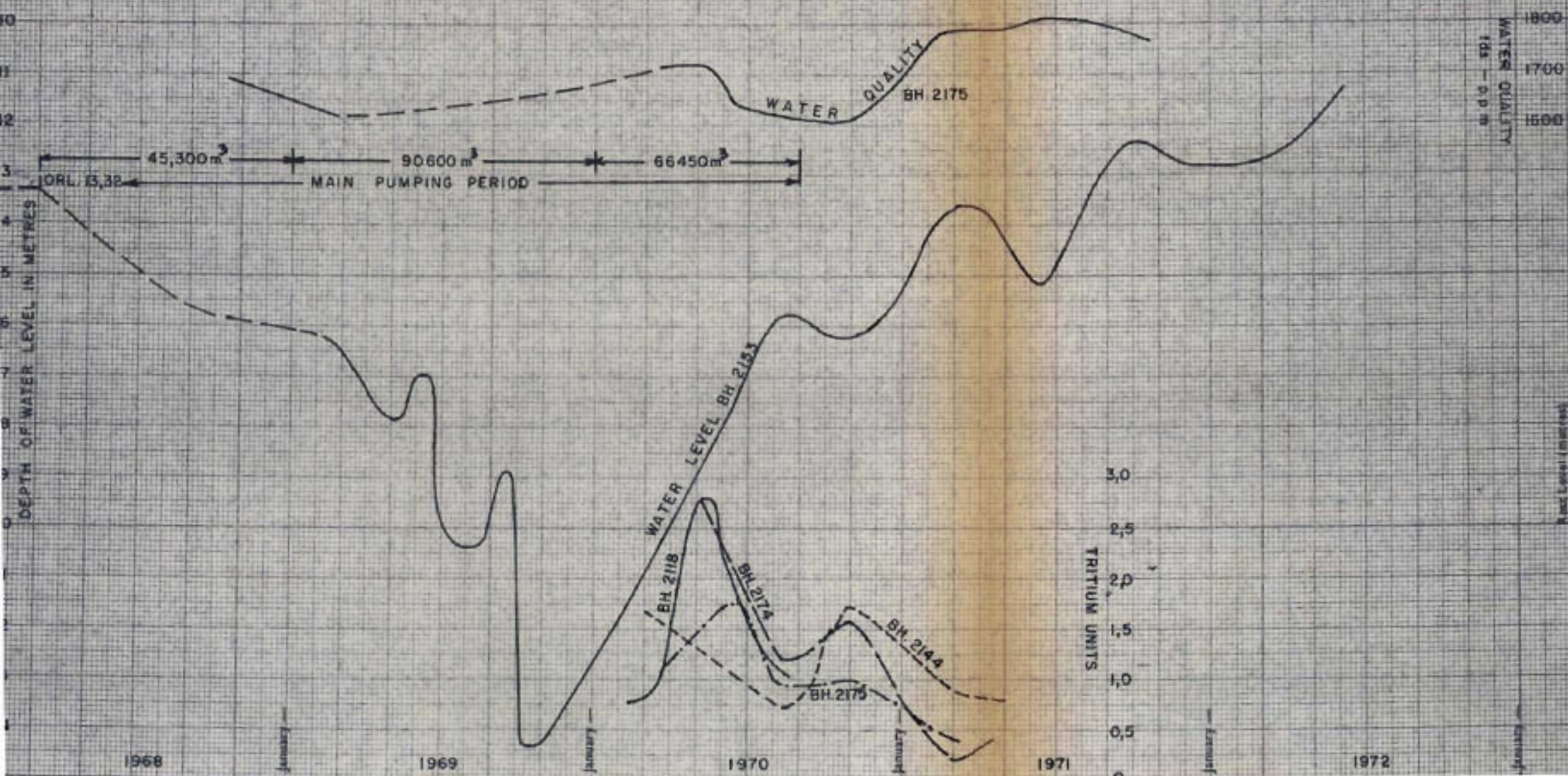
Orapa wellfield (1) (See Fig. 59).

Abstraction of water from the Orapa well field has been estimated as follows:-

1968	45 300 m ³
1969	90 600 m ³
1970	66 450 m ³
1971 on	nil
<u>Total</u>	<u>202 350 m³</u>

This resulted in a maximum drop in water level in observation borehole 2153 of 11 m (see Fig. 65) for a total abstraction of 202 350 m³ during 1968, 1969 and 1970. As water levels recovered to above the original measured level by mid 1971 it can be seen that recharge from 3 seasons (1968-69, 1969-70, 1970-71) more than exceeded the abstraction and hence recharge \geq 202 350 m³, i.e. $>$ 67 450 m³ p.a. or $>$ 5 620 m³ per month (236 400 g.p.m). This figure is regarded as a minimum because if comparison with the hydrograph for borehole 150, Letlhakane (Fig. 66), (which is an area of moderate abstraction compared to that of Orapa) is made, it can be seen that moderate recharge took place in the 1968-1969 and 1970-1971 seasons, virtually no recharge took place in the 1969-1970 season and major recharge took place in the 1971-1972 season.

Fig. 65 HYDROGRAPH (BH.2153), WATER QUALITY (BH.2175)
AND TRITIUM VALUES FOR ORAPA WELLFIELD 1



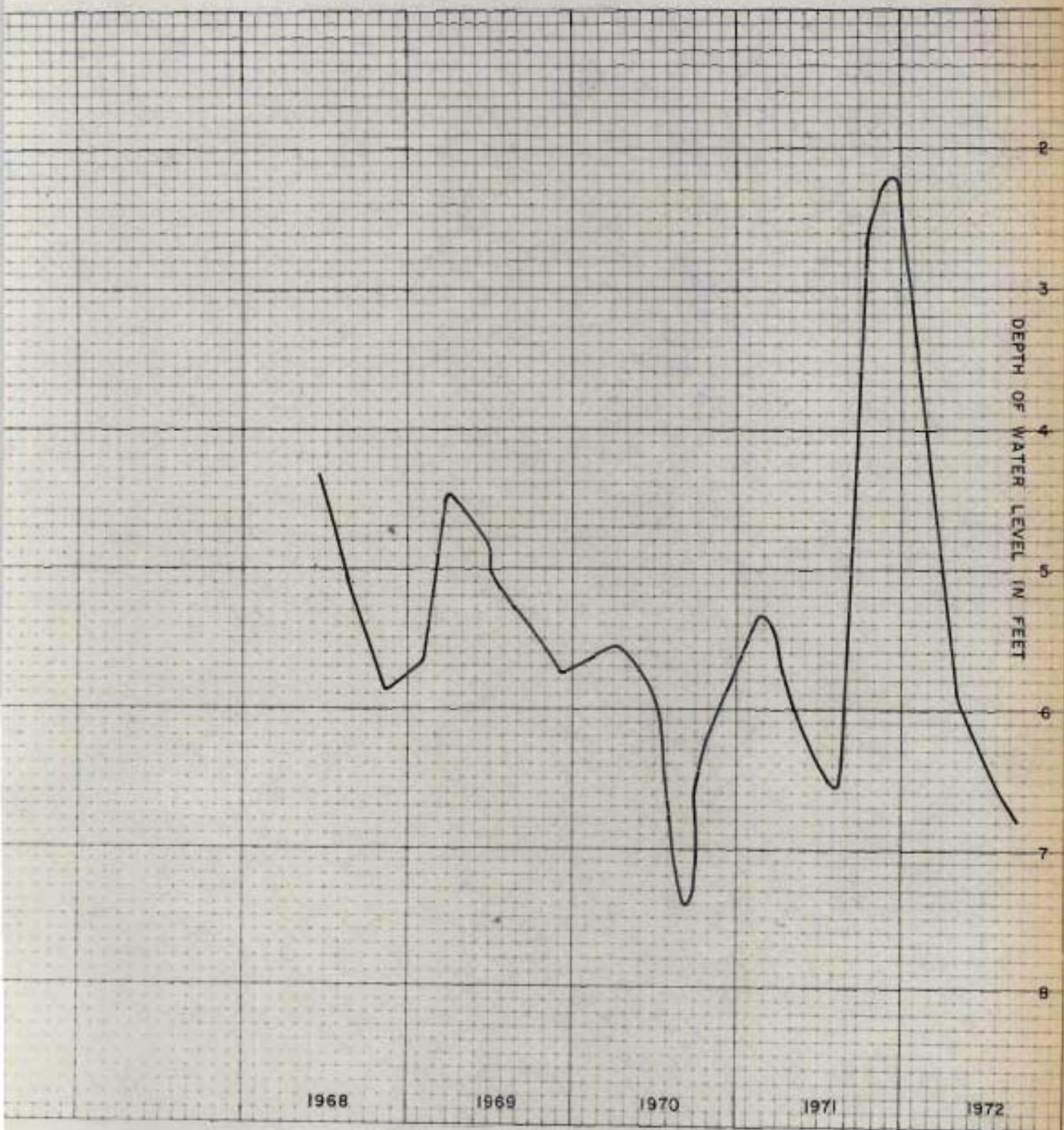


Fig. 66 HYDROGRAPH BH. 150- LETLHAKANE

The three seasons considered above for recharge calculations thus consist of two moderate seasons and one very poor season. Thus the calculations above may be regarded as being very conservative in view of the known conditions prevailing elsewhere in Botswana in which very occasional, abnormally heavy rainfall results in massive replenishment of aquifers. The behaviour of water levels in the different boreholes in this wellfield is shown on Fig. 67.

Orapa Wellfield (2). (8 mile wellfield, see Fig.59, Plate 61, p.240)

Examination of a typical hydrograph for wellfield 2 (see Fig. 68, 69), shows that water levels declined from approximately 12,5 m, as a result of the abstraction of 181 200 m³ water, and recovered to the pre-pumping level (January 1970) by January 1972 after cessation of pumping in July 1971. Thus replenishment of 181 200 m³ took place over 2 seasons (1970-71 and 1971-72) at a rate of 90 600 m³ p.a. or 7 550 m³ per month. This compares remarkably well with the minimum figure of 5 620 m³ per month for wellfield number one (Orapa).

Wellfield 3. (12 mile wellfield)

Examination of the hydrograph for observation borehole 2125/B/D1 (Fig. 70) shows that the water level declined 8 m as a result of the abstraction of 115 050 m³ of water from the aquifer during 1970 and 1971 but had returned to virtually its pre-pumping level by early 1972. (i.e. after 2 rainy seasons - 1970/1971 and 1971/1972). Therefore annual recharge for the 2 season period = 57 525 m³ p.a. or 4 794 m³ per month. This is again in relatively good agreement with recharge figures for wellfields 1 and 2.

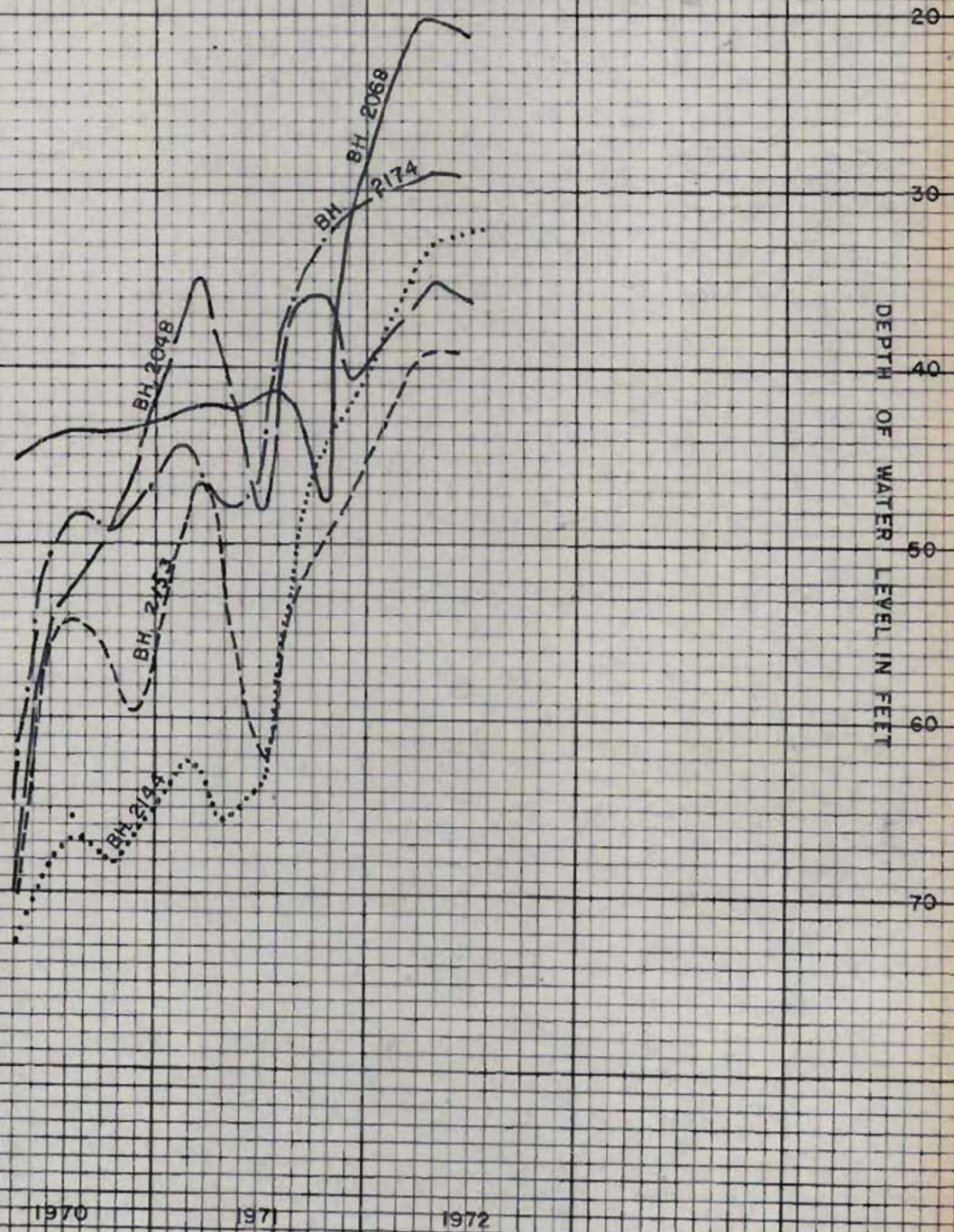


Fig. 67 HYDROGRAPHS WELLFIELD I - ORAPA

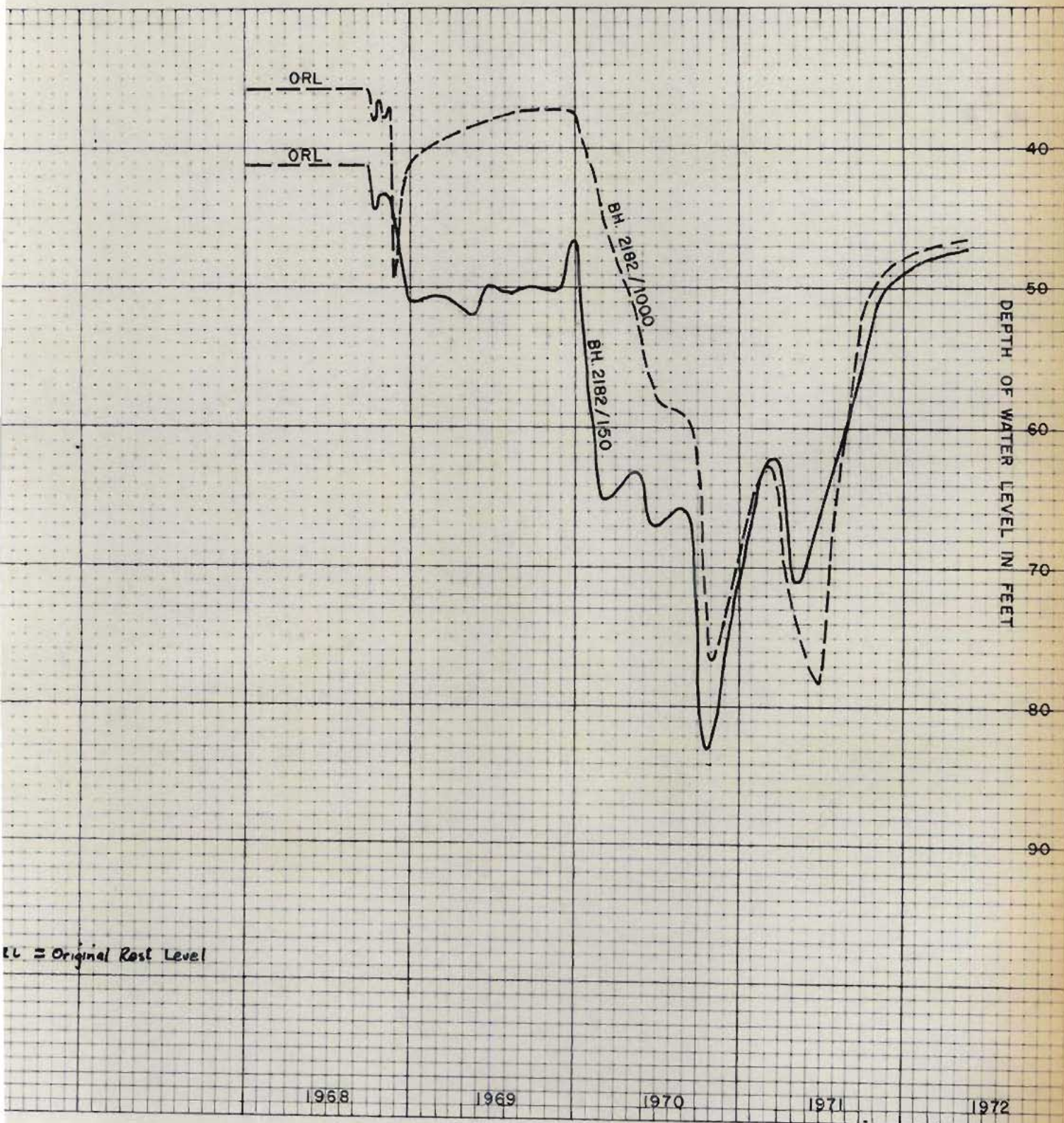
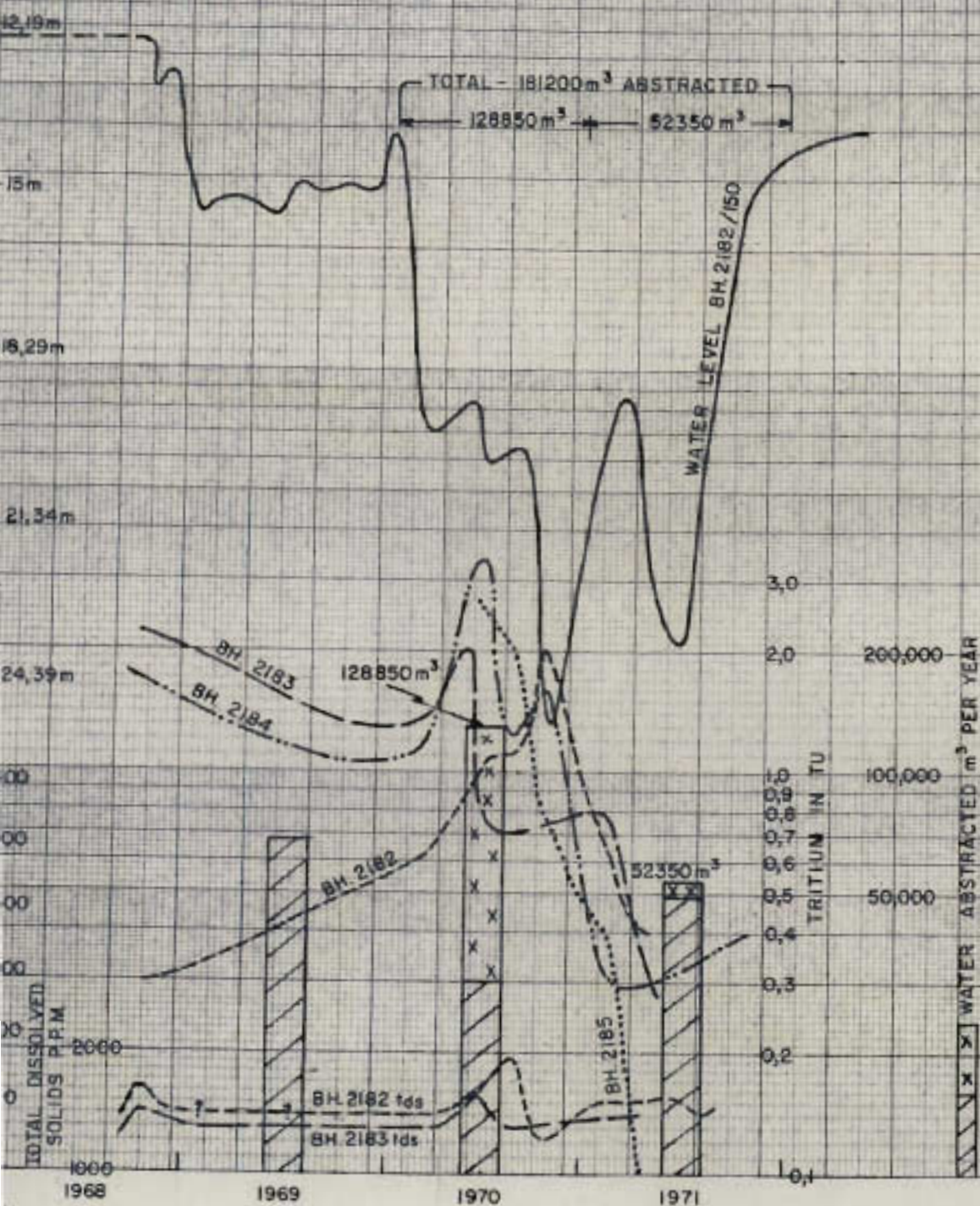


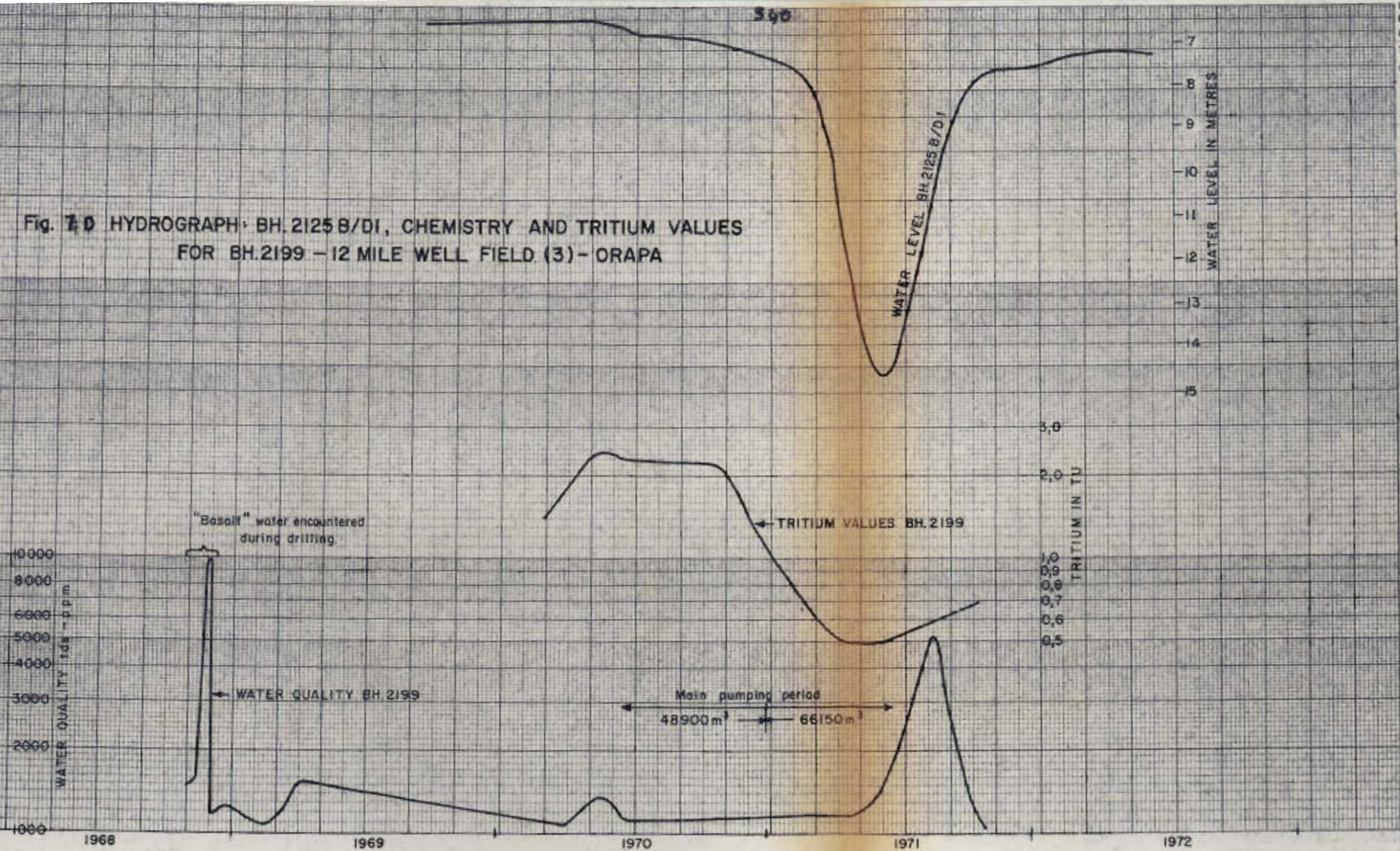
Fig. 68 HYDROGRAPH BHs. 2182/150 AND 2182/1000
ORAPA 8 MILE FIELD



From 1st January 1970 to 1st January 1972 181200m³ water were abstracted.
 During the same period water levels had recovered to the original level on 1st January 1970
 ∴ replenishment of 181200m³ took place over 2 years i.e 7550 m³ (661000 gallons) per month.

Fig. 69 HYDROGRAPH - BH.2182/150 AND TRITIUM VALUES
 8 MILE WELL FIELD (2) - ORAPA

Fig. 7.0 HYDROGRAPH · BH.2125 B/DI, CHEMISTRY AND TRITIUM VALUES FOR BH.2199 - 12 MILE WELL FIELD (3) - ORAPA



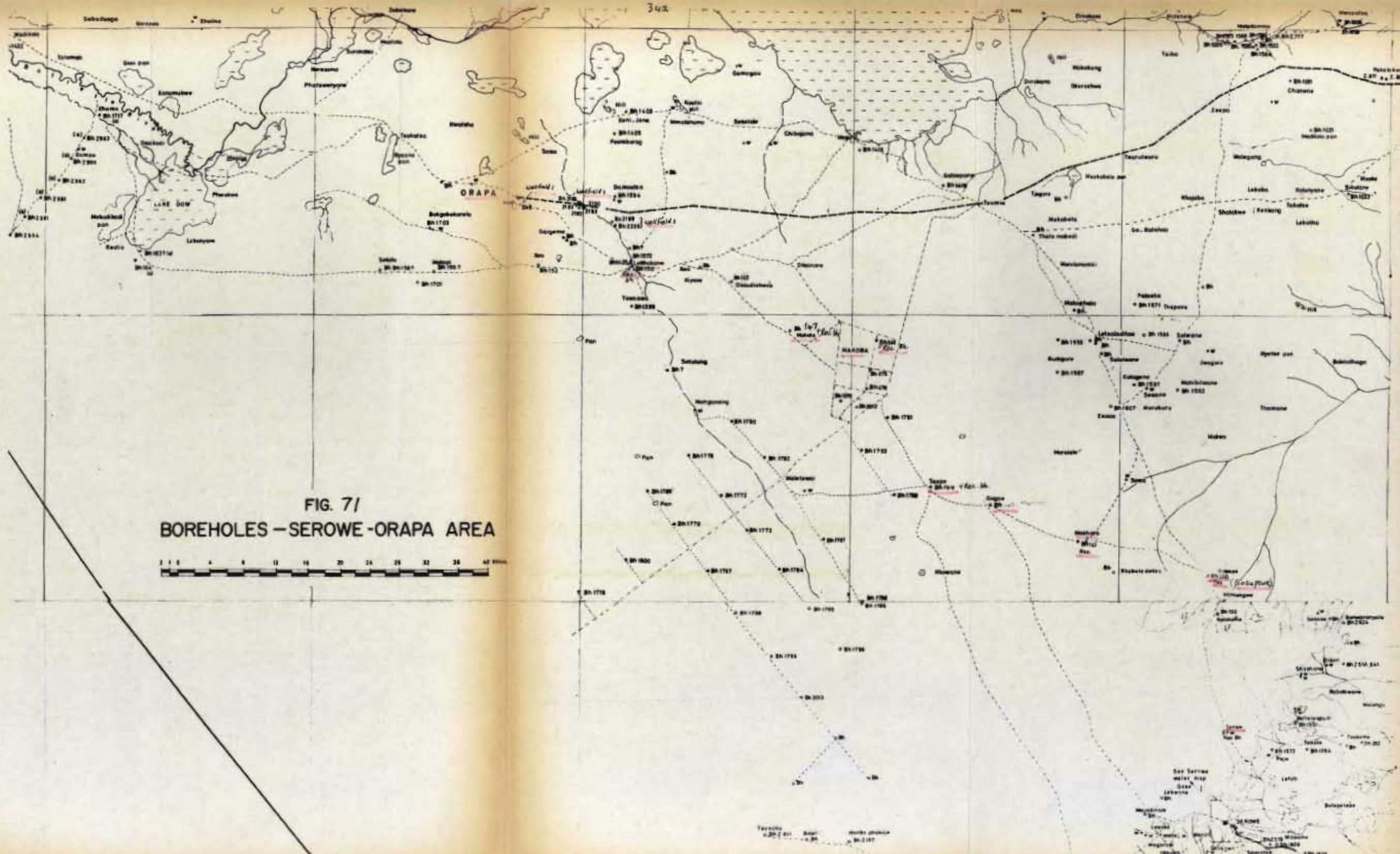


FIG. 71
BOREHOLES - SEROWE-ORAPA AREA



Recorder Boreholes Serowe - Letlhakane

Following the drilling of a line of diamond core boreholes from Serowe to Letlhakane (Fig. 71) measurements of water levels at two monthly intervals was commenced in 1968. Four typical hydrographs are shown in Figs. 72 - 75. All recorder boreholes are situated in close proximity to existing boreholes and show to a varying extent, the influence of pumping on the water levels. All show an overall slight downward trend in water levels due to slight overpumping during the period of the hydrograph. Regular replenishment of the aquifer is shown by the Bosupswe and Makoba boreholes (Figs. 72 and 74).

General recharge considerations

It would appear therefore that recharge at widely separated points in the aquifer amounts to a minimum of 5 988 say 6 000 m³ per month. It would appear therefore, that a ground-water supply scheme for Orapa would not require as many boreholes as originally anticipated (Anon. 1969). This could result in considerable savings in both wellfield drilling, equipping and pumping costs though this would have to be balanced against possible increased piping costs to specially selected borehole sites giving higher transmissibilities.

Conclusions concerning study of water level fluctuations

The Letlhakane hydrograph (borehole 150, Fig. 66) and the hydrographs (67, 69, 70) prove that present day recharge is taking place and thus completely refute the evidence Anon. (1969) that no recharge is taking place at present. Further evidence to support this contention will be provided in the section on Isotopes.

...../undisturbed

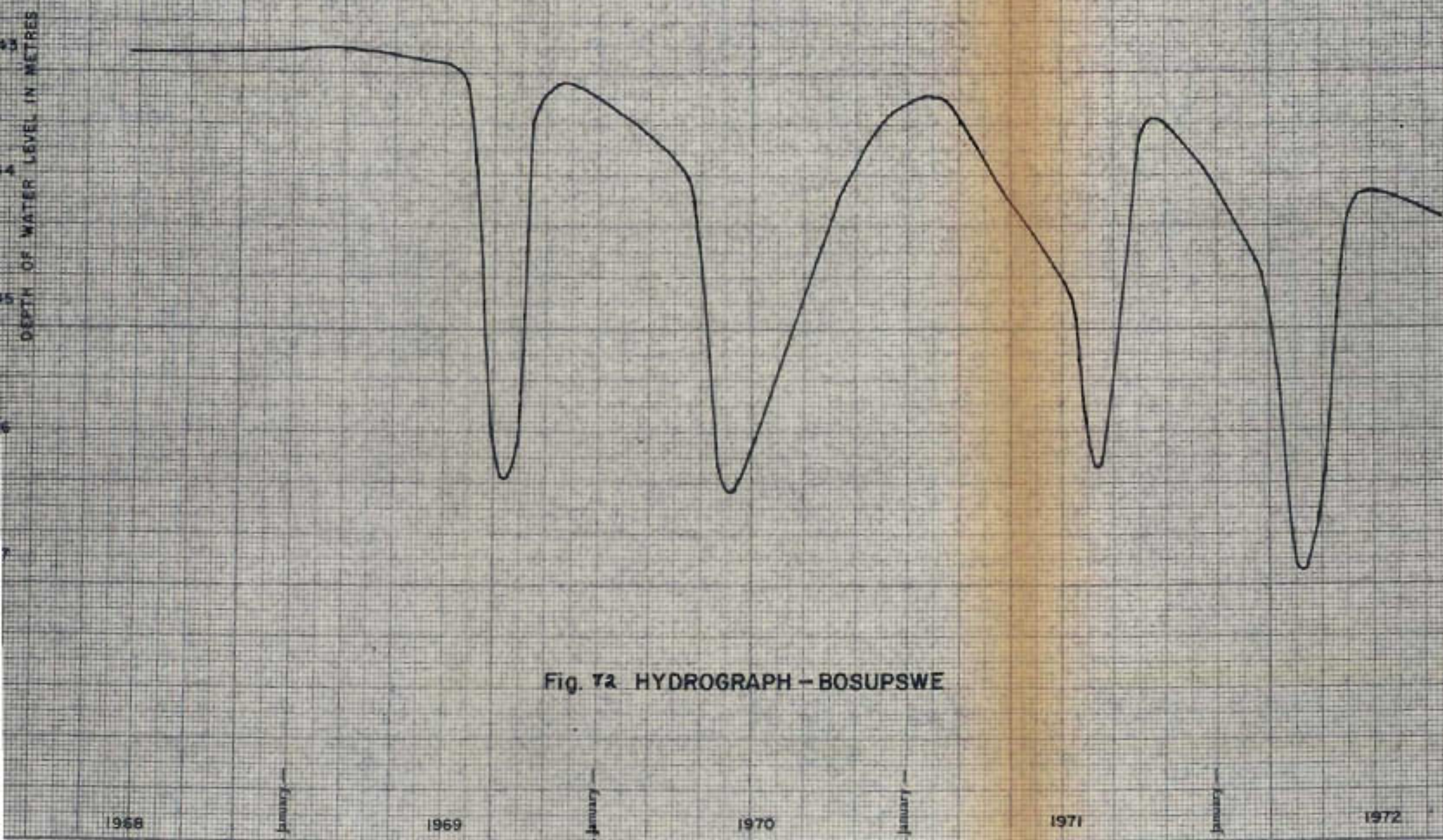


Fig. 72 HYDROGRAPH - BOSUPSWE

Water Level (in metres)

DEPTH OF WATER LEVEL IN METRES

BOREHOLE NEARBY NOT PUMPING
ONLY ON 9-7-1969
26-8-1970
18-8-1971
8-12-1971
22-4-1972
16-5-1972

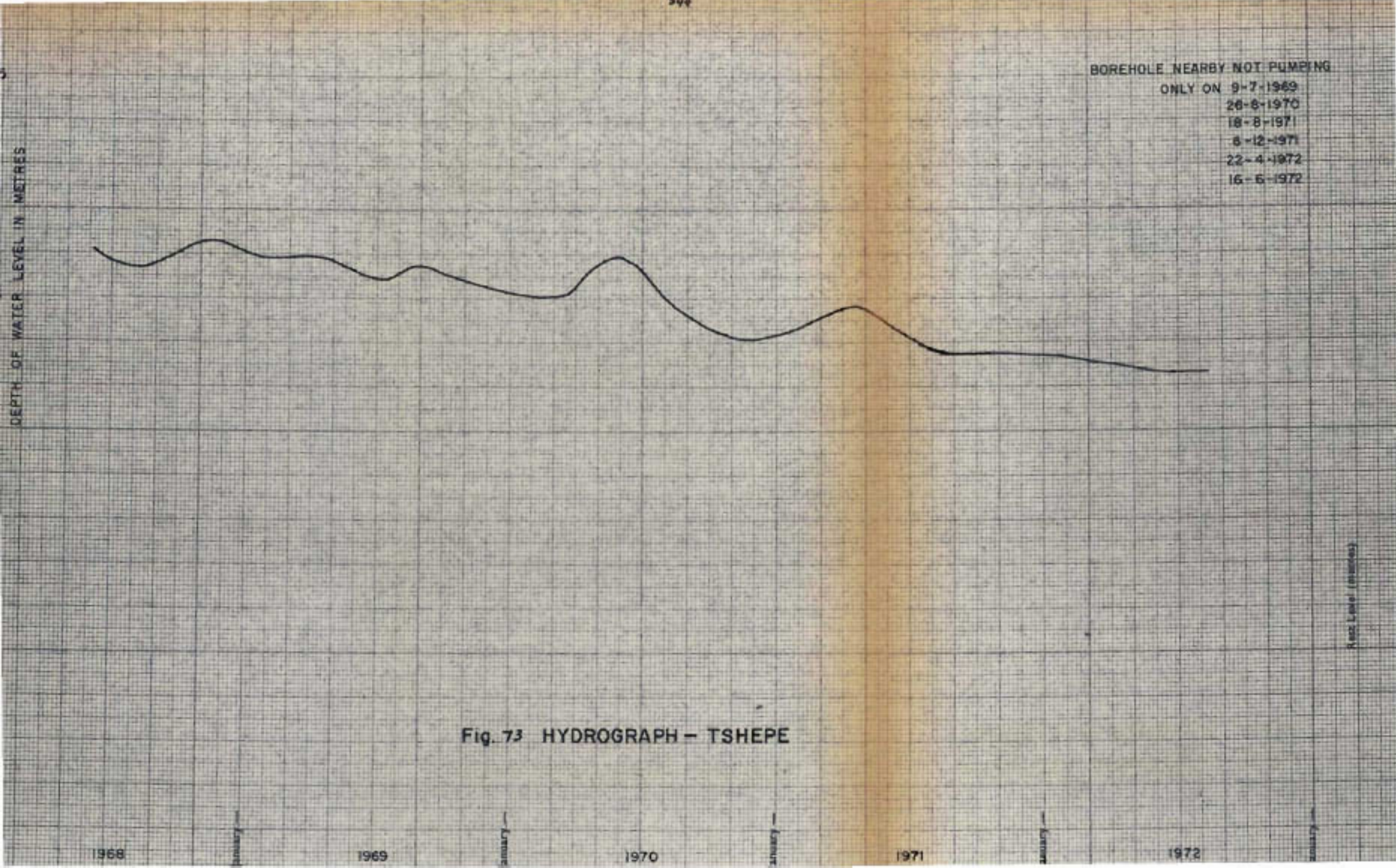


Fig. 73 HYDROGRAPH - TSHEPE

Rest Level (metres)

DEPTH OF WATER LEVEL IN METRES

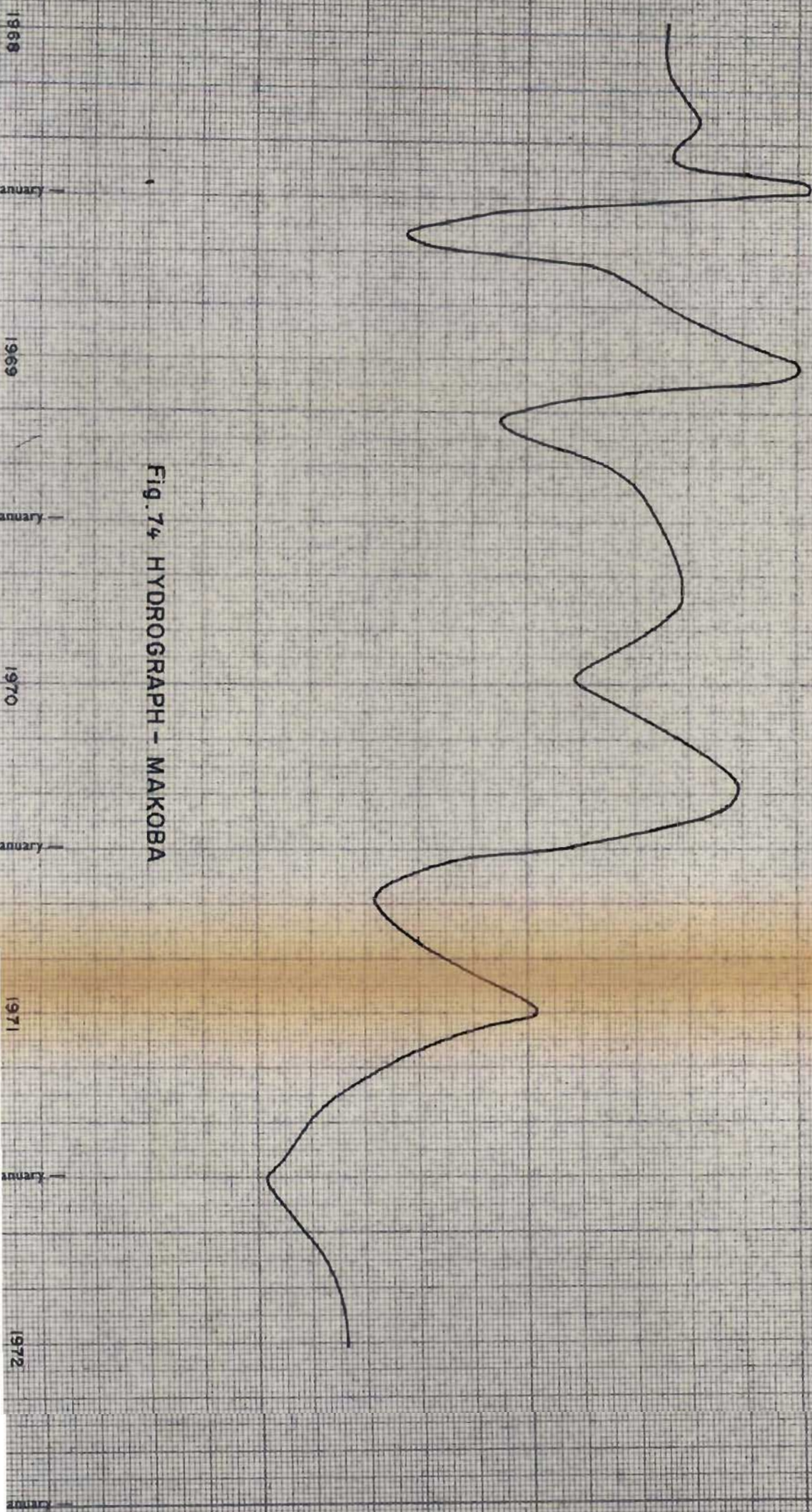


Fig. 74 HYDROGRAPH - MAKOBA

Rest Level (metres)

BOREHOLE NEARBY PUMPING
ONLY ON 23-2-1971
29-4-1971
18-8-1971

DEPTH OF WATER LEVEL IN METRES

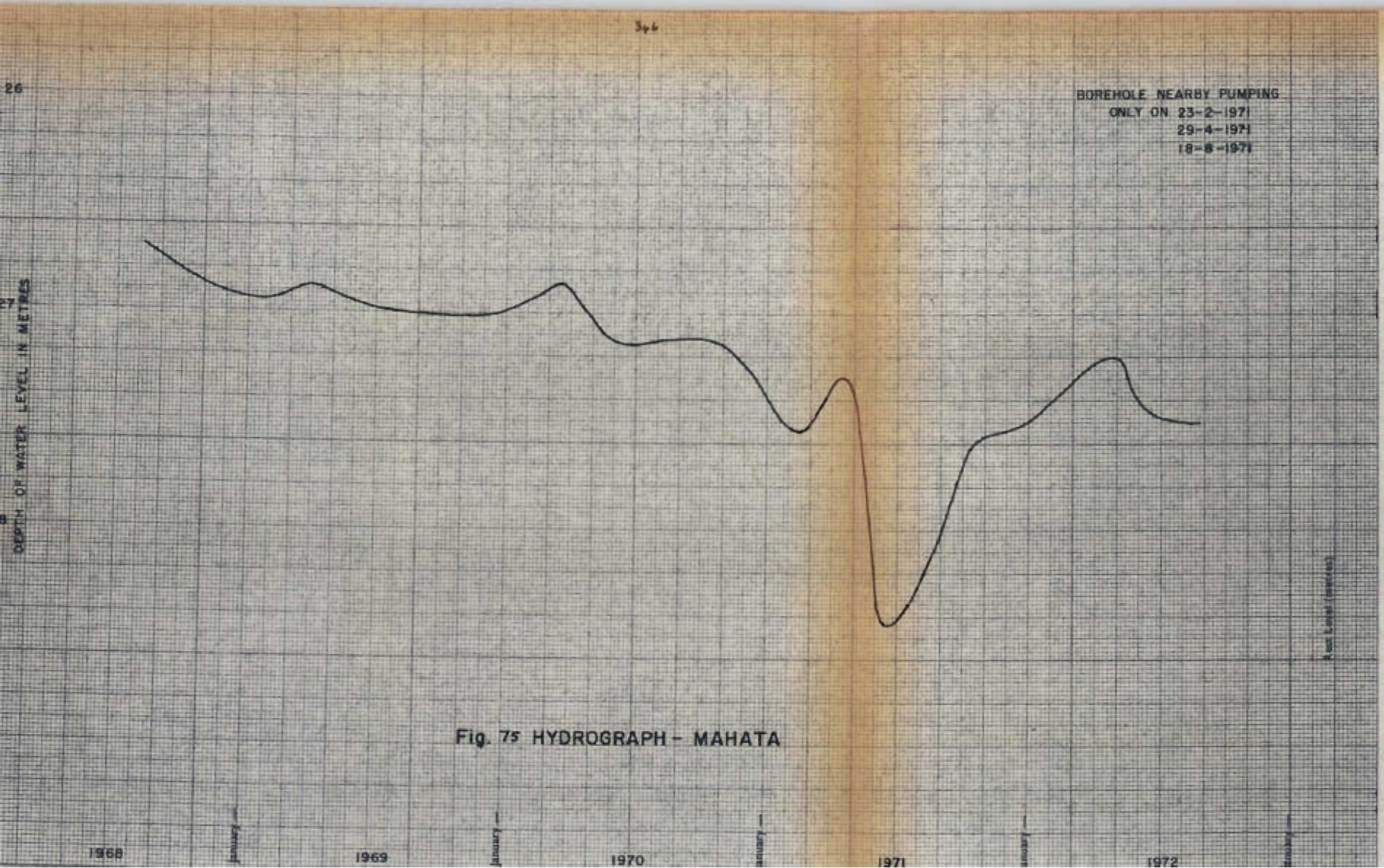
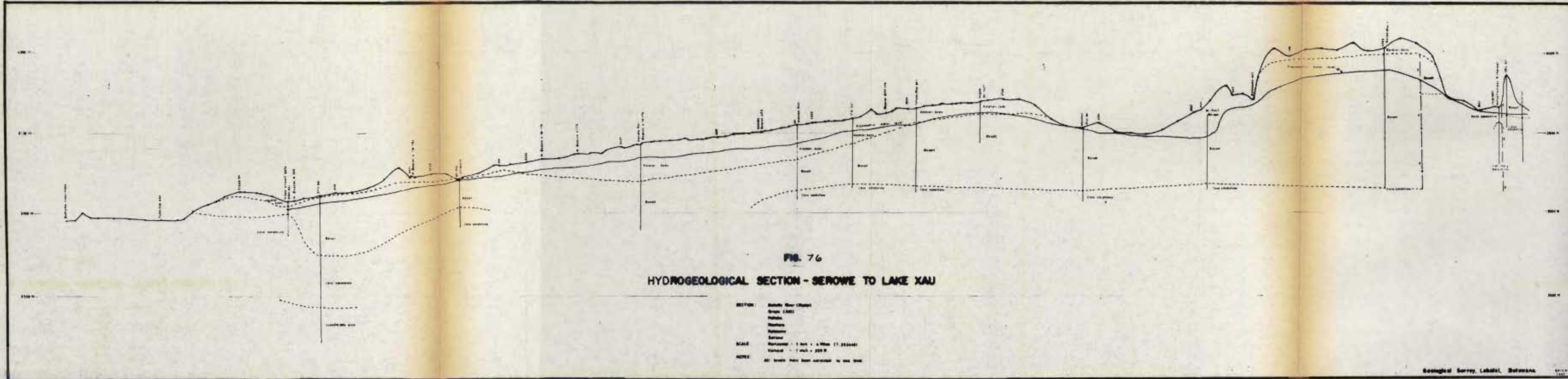


Fig. 75 HYDROGRAPH - MAHATA

Feet Level (inches)

Undisturbed Water LevelsSerowe-Orapa-Lake Xau

In order to determine the source of recharge for the Orapa area, accurate barometric levelling was carried out in 1968 between Serowe and Lake Xau using the recently completed trigonometrical points for control. The results of this survey are plotted in Fig. 76 and show an apparent hydraulic gradient from Serowe to Gugae towards Orapa. However the danger of deducing a ground-water flow direction from a two-dimension model cannot be overemphasized. In order to obtain a better picture of the hydraulic gradient accurate levelling of boreholes drilled for a drought relief programme in the Makoba area was carried out (See Fig. 77). Isopiezometric contours were plotted by the writer, as well as depths to the base of the Kalahari Beds and depths to the base of the basalt (See Figs. 78-81). These show a general north-westerly flow direction. However, in view of the confined conditions present at both Serowe and Gugae the writer feels it is more probable that recharge occurs in the nearest areas of unconfined conditions (i.e. further east in areas with Cave sandstone exposures or sub-outcrops) and not at these two localities as postulated by Robins (1972). Further levelling and plotting of isopiezometric surfaces eastwards, northeastwards and northwards from Orapa may show that recharge takes place in the area of Cave sandstone fringing the basalt (See Geological map, Fig. 7). Should this be the case the previous supposition (Anon., 1969) of no recharge feeding the confined Cave sandstone could be seriously in error.



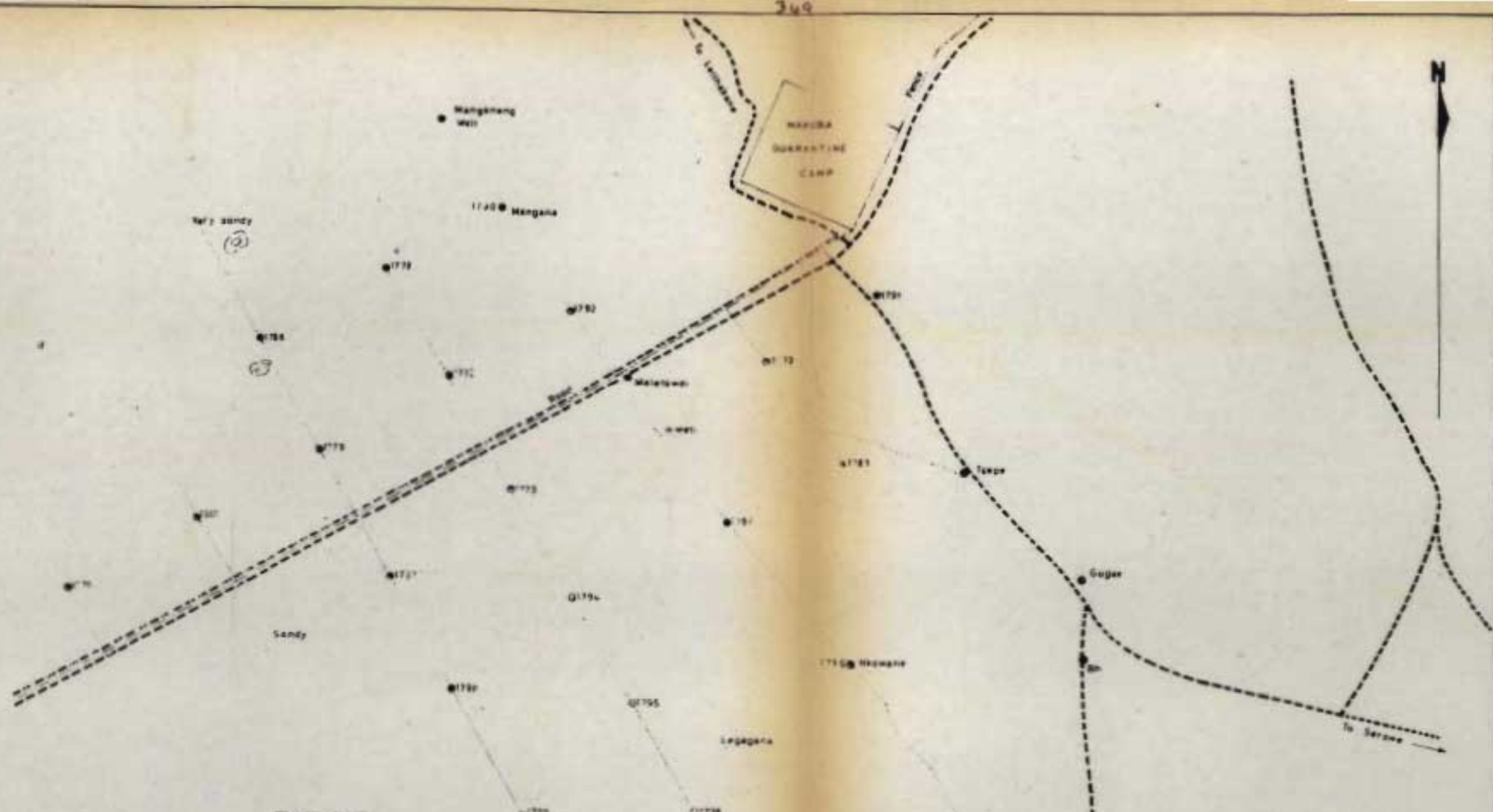


FIG. 77

**DROUGHT RELIEF BOREHOLES
MAKOKA AREA
BAMANGWATO**

BOREHOLE DATA

OFFICIAL No.	DEPTH	W.S.	R.L.	YIELD	OFFICIAL No.	DEPTH	W.S.	R.L.	YIELD
1771	80	200576	150	200	1777	510	197201	16	400
1772	45	197	109	1640	1778	510	19530475	15	1700
1774	515				1779	245	18710	11	1900
1775	45	182114	120	1260	1784	100	125	129	1170
1779	100	200	841	5170	1785	415	457	113	510
1780	245	74	38	1900	1786	400	350	114	210
1781	270	200	28	1140	1787	310	260	180	1100
1784	2-5	192212	117	800	1788	211	320	188	800
1789	310	195070	50	1900	1789	510	190480	127	200
1790	400	120	36	710	1817	400	200735	182	840

BELIDY

OFFICIAL No.	KALAHARI	K.A.S./K.A.U.	OFFICIAL No.	KALAHARI	K.A.S./K.A.U.
164	80	7	1781	100	290-400
1772	130	580	1782	100	480
1773	80	220	1783	100	480
1775	200	7	1784	100	250
1776	80	44	1785	120	250
1778	80	280	1786	100	420
1786	100	300	1787	100	200
1787	104	250-300	1787	80	250
1788	120	242	1788	110	330
1789	110		1789	100	110
1790			1800	120	330



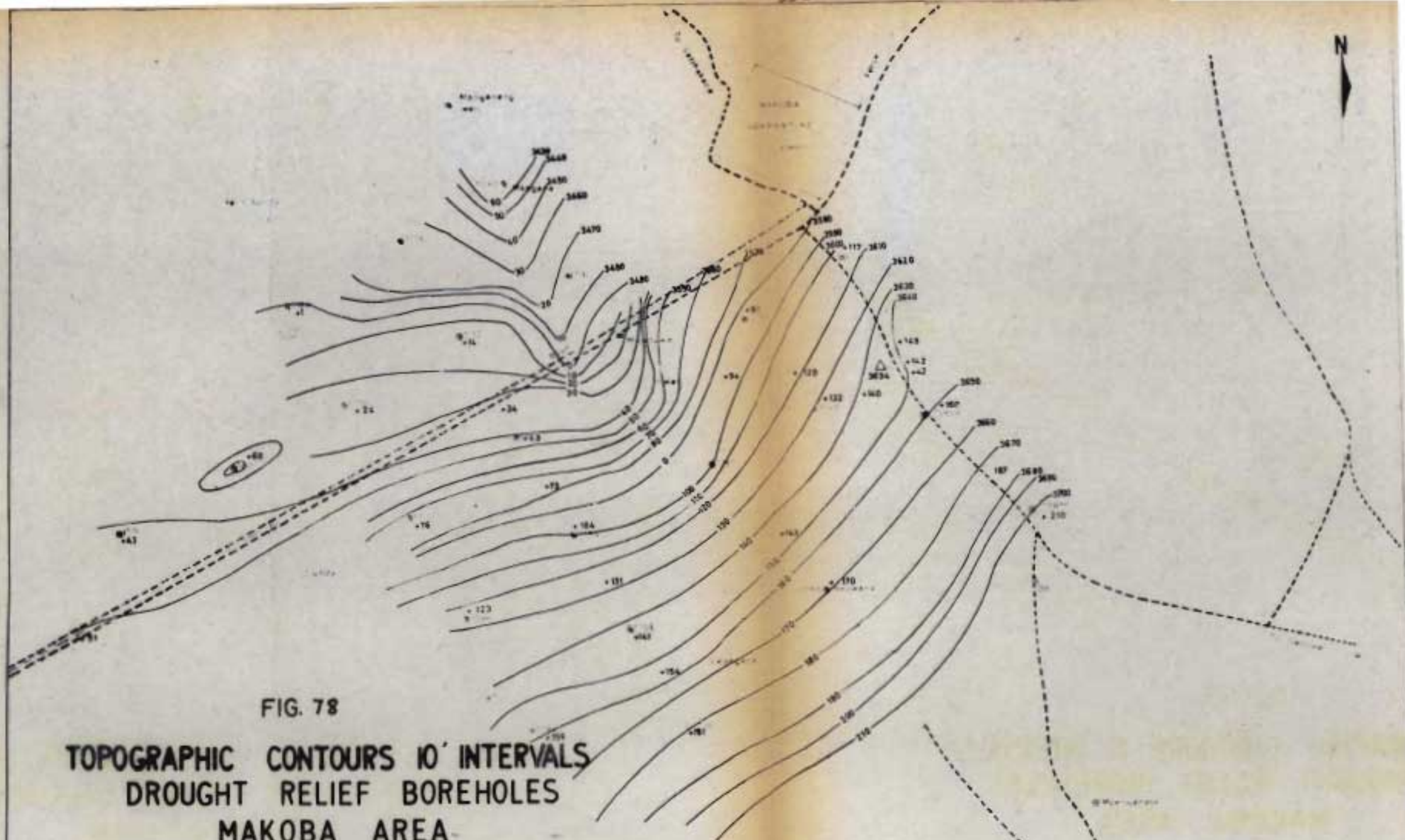
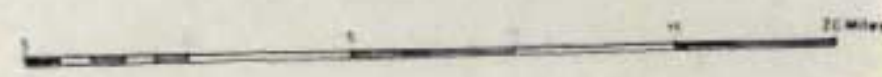


FIG. 78

**TOPOGRAPHIC CONTOURS 10' INTERVALS
DROUGHT RELIEF BOREHOLES
MAKOPA AREA
BAMANGWATO**

BOREHOLE DATA

OFFICIAL No.	DEPTH	W S	N L	YIELD	OFFICIAL No.	DEPTH	W S	N L	YIELD	OFFICIAL No.	BALANCE	P.A.S./K.L.	OFFICIAL No.	BALANCE	YIELD
1772	400	300576	213	230	1777	410	300203	81	430	1784	90	-	1791	100	300400
1773	285	121	-	417	1780	370	452045	14	1710	1779	90	207	1782	100	400
1774	400	-	-	-	1782	150	8720	41	1420	178	200	-	1784	100	-
1775	450	34111	-	1200	1784	410	125	112	1470	179	90	141	1785	100	200
1776	300	-	102	110	1785	470	111	111	110	179	90	90	1786	100	400
1780	270	41	37	1400	1786	410	110	110	110	179	100	300	1787	100	100
1787	370	280	30	1140	1787	310	240	14	110	1787	100	25 120	1788	100	200
1788	240	10012	100	100	1788	370	100	100	400	1788	100	200	1789	100	100
1789	310	8 10000	10	1000	1789	310	330400	227	210	1789	100	-	1790	100	100
1790	450	100	12	700	1790	430	29000	180	800	1790	100	-	1790	100	100



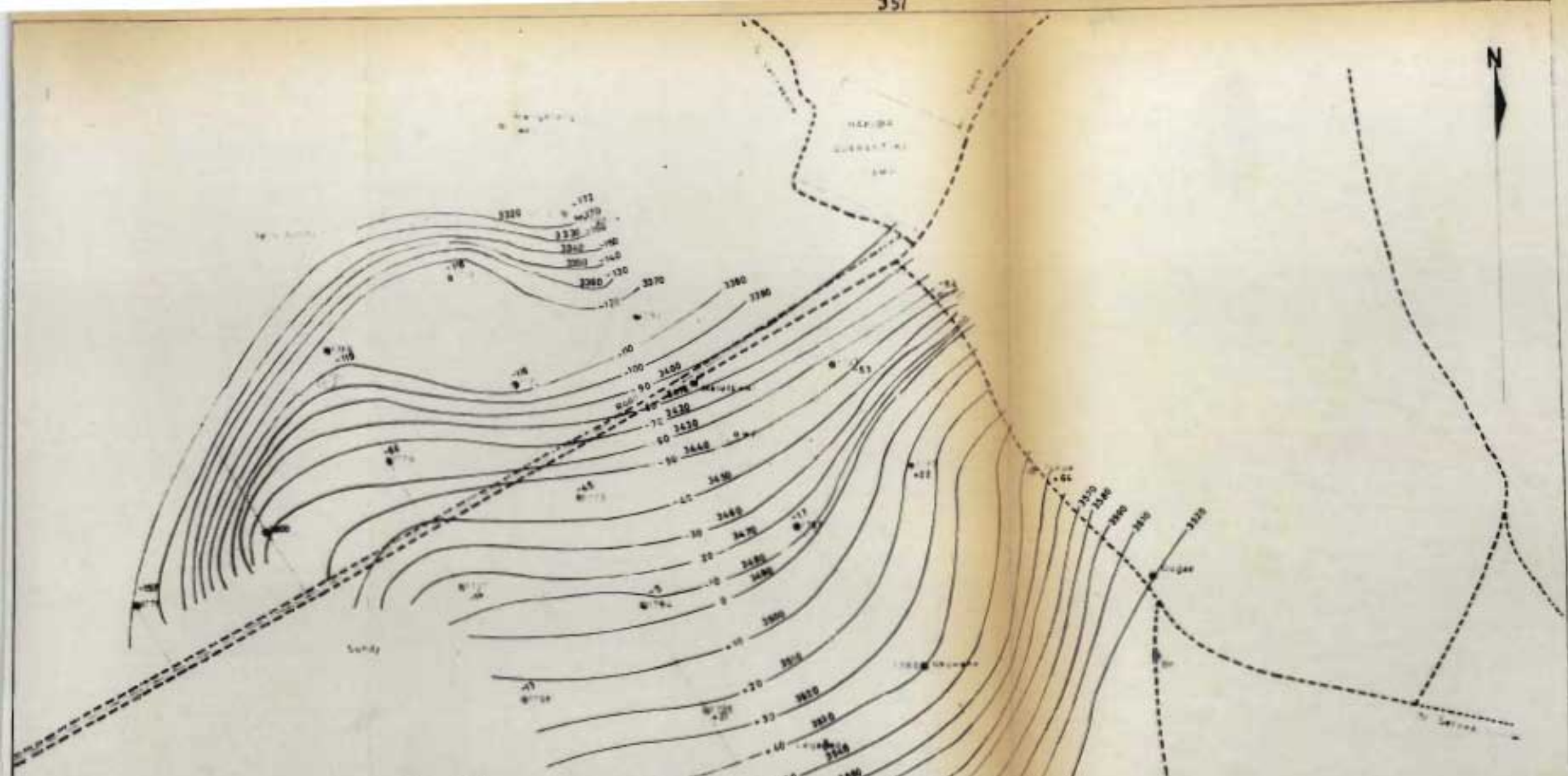


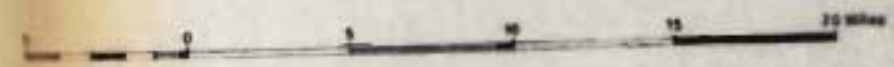
FIG. 79
CONTOURS AT BASE OF KALAHARI BEDS - 10' INTERVALS
DROUGHT RELIEF BOREHOLES
MAKOPA AREA
BAMANGWATO

BOREHOLE DATA

OFFICIAL No.	DEPTH	W S	R L	YIELD
1772	480	248540	213	200
1773	285	225	145	31.2
1774	505			
1775	450	245440	14	1,180
1776	350	420	143	5,177
1777	240	24	50	1,900
1778	310	280	30	1,140
1779	245	130,252	108	500
1780	510	4,150,000	20	1,900
1781	400	120	112	920

DELIVERY

OFFICIAL No.	KALAHARI	KALAFRA V	OFFICIAL No.	KALAHARI	KALAFRA V
1782	90	7	1781	130	260-400
1772	130	580	1782	100	680
1773	90	220	1783	150	
1774	200	1	1784	120.7	250
1775	80	400	1785	120	420
1776	80	280	1786	120	350
1777	130	300	1787	80	250
1778	250	250,320	1788	90	250
1779	120	242	1789	110	310
1780	110		1790	110	140
1790	400		1800	120	330



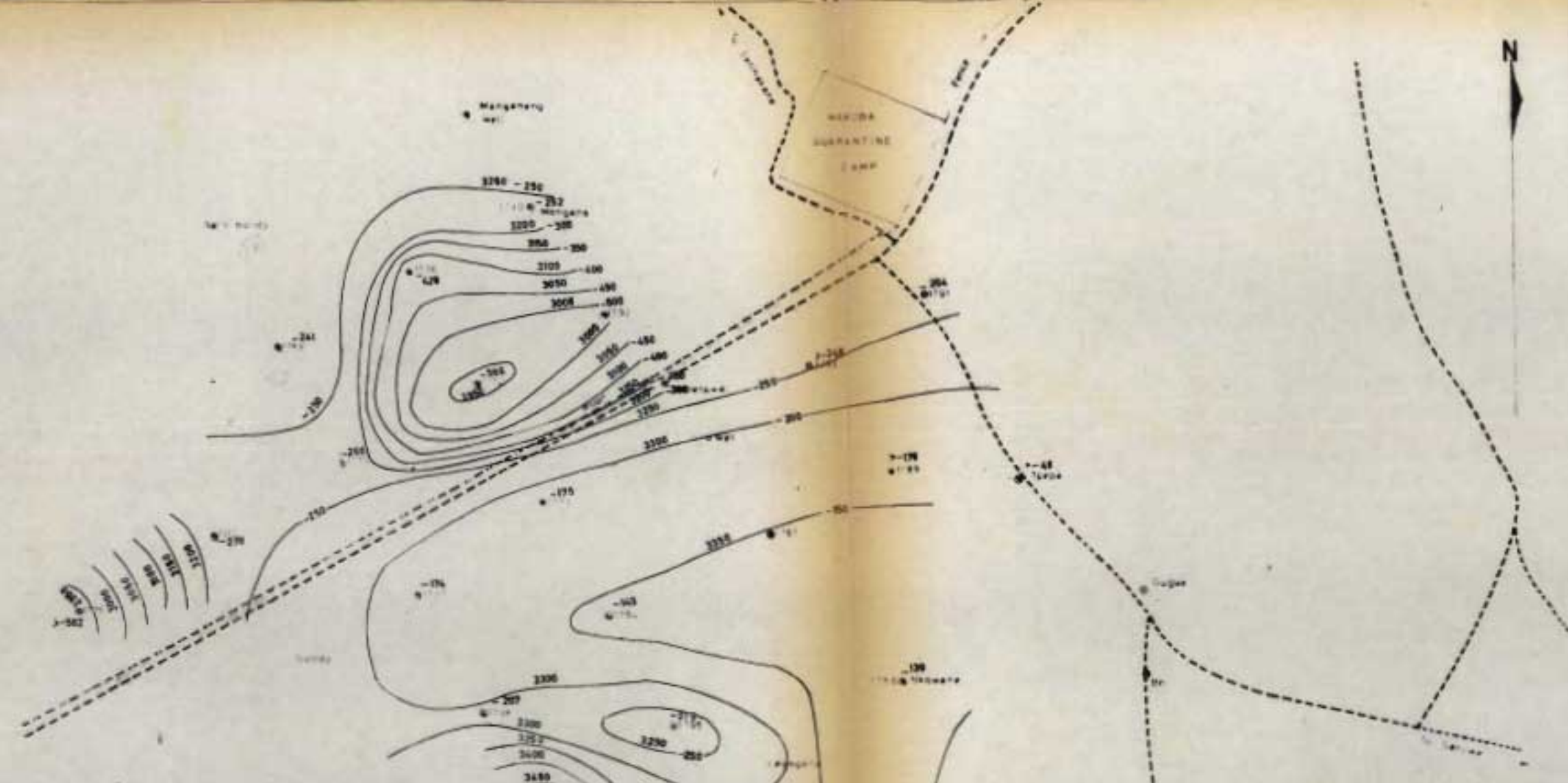


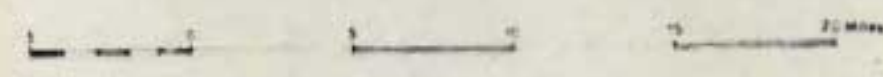
FIG. 80
CONTOURS BASE OF BASALT 50' INTERVALS
DROUGHT RELIEF BOREHOLES
MAKOKA AREA
BAMANGWATO

BOREHOLE DATA

OFFICIAL No.	DEPTH	W. S.	H. S.	YIELD	OFFICIAL No.	DEPTH	W. S.	H. S.	YIELD
1772	630	20000	100	200	1771	410	11200	10	400
1773	100		100	1000	1770	610	10000	5	1200
1774	100				1769	400	8000	10	1000
1775	100		100	1000	1768	100	100	100	1000
1776	100		100	1000	1767	100	100	100	1000
1777	100		100	1000	1766	100	100	100	1000
1778	100		100	1000	1765	100	100	100	1000
1779	100		100	1000	1764	100	100	100	1000
1780	100		100	1000	1763	100	100	100	1000
1781	100		100	1000	1762	100	100	100	1000
1782	100		100	1000	1761	100	100	100	1000
1783	100		100	1000	1760	100	100	100	1000

WELL LOG

OFFICIAL No.	BALANAR	KASTRA U	OFFICIAL No.	BALANAR	ALLIRED
1772	90	100	1761	100	100
1773	90	100	1762	100	100
1774	90	100	1763	100	100
1775	90	100	1764	100	100
1776	90	100	1765	100	100
1777	90	100	1766	100	100
1778	90	100	1767	100	100
1779	90	100	1768	100	100
1780	90	100	1769	100	100
1781	90	100	1770	100	100
1782	90	100	1771	100	100
1783	90	100	1772	100	100



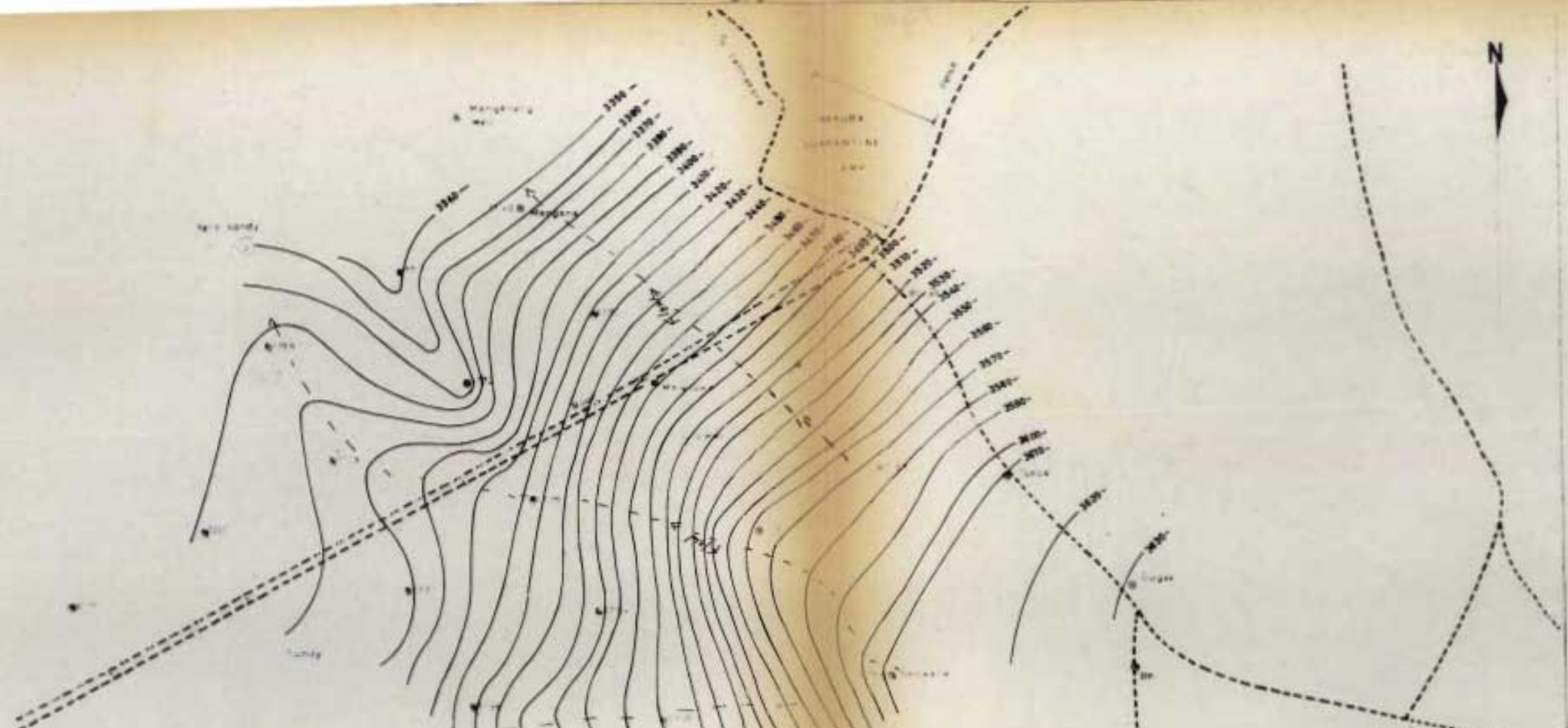


FIG. 81
 10' INTERVAL
 ISO PIEZOMETRIC CONTOURS
 DROUGHT RELIEF BOREHOLES
 MAKOBA AREA
 BAMANGWATO

BOREHOLE DATA

OFFICIAL No.	DEPTH	W.S.	R.L.	YIELD	OFFICIAL No.	DEPTH	W.S.	R.L.	YIELD
1771	80	200574	150	200	1787	450	19280	74	100
1772	140	200575	140	1440	1788	570	1927478	8	1000
1773	400				1789	145	19275	10	1200
1774	450	192576	120	1200	1790	100	19276	120	1000
1775	200	200	120	1100	1791	475	19277	140	1100
1776	200	192577	100	1000	1792	470	19278	140	1000
1777	370	192578	90	1100	1793	350	19279	180	1000
1778	240	192579	110	1000	1794	300	19280	180	1000
1779	240	192580	110	1000	1795	300	19281	180	1000
1780	240	192581	110	1000	1796	300	19282	180	1000
1781	240	192582	110	1000	1797	300	19283	180	1000
1782	240	192583	110	1000	1798	300	19284	180	1000
1783	240	192584	110	1000	1799	300	19285	180	1000
1784	240	192585	110	1000	1800	300	19286	180	1000

DEVELOP

OFFICIAL No.	KALANAR	KASTRAU	OFFICIAL No.	KALANAR	KASTRAU
1785	80	190	1791	100	200
1786	80	220	1792	100	200
1787	80	240	1793	100	200
1788	80	260	1794	100	200
1789	80	280	1795	100	200
1790	80	300	1796	100	200
1791	80	320	1797	100	200
1792	80	340	1798	100	200
1793	80	360	1799	100	200
1794	80	380	1800	100	200



Mashoro Artesian borehole number 141 (See Fig. 76).

One of the two known artesian boreholes in Botswana was sited at Mashoro in basaltic lavas below the main Kalahari escarpment which is present only a short distance to the west. This borehole encountered a weak artesian flow when it penetrated the basaltic lavas at 121 m.

8 Mile Wellfield (2)

Piezometric surface contours were measured on 13th October 1968 prior to the commencement of the detailed pump tests. These contours are shown in Fig. 82 and show a general westward gradient and hence indicate a recharge area somewhere to the east.

Isopiezometric contours in the vicinity of a pumping borehole

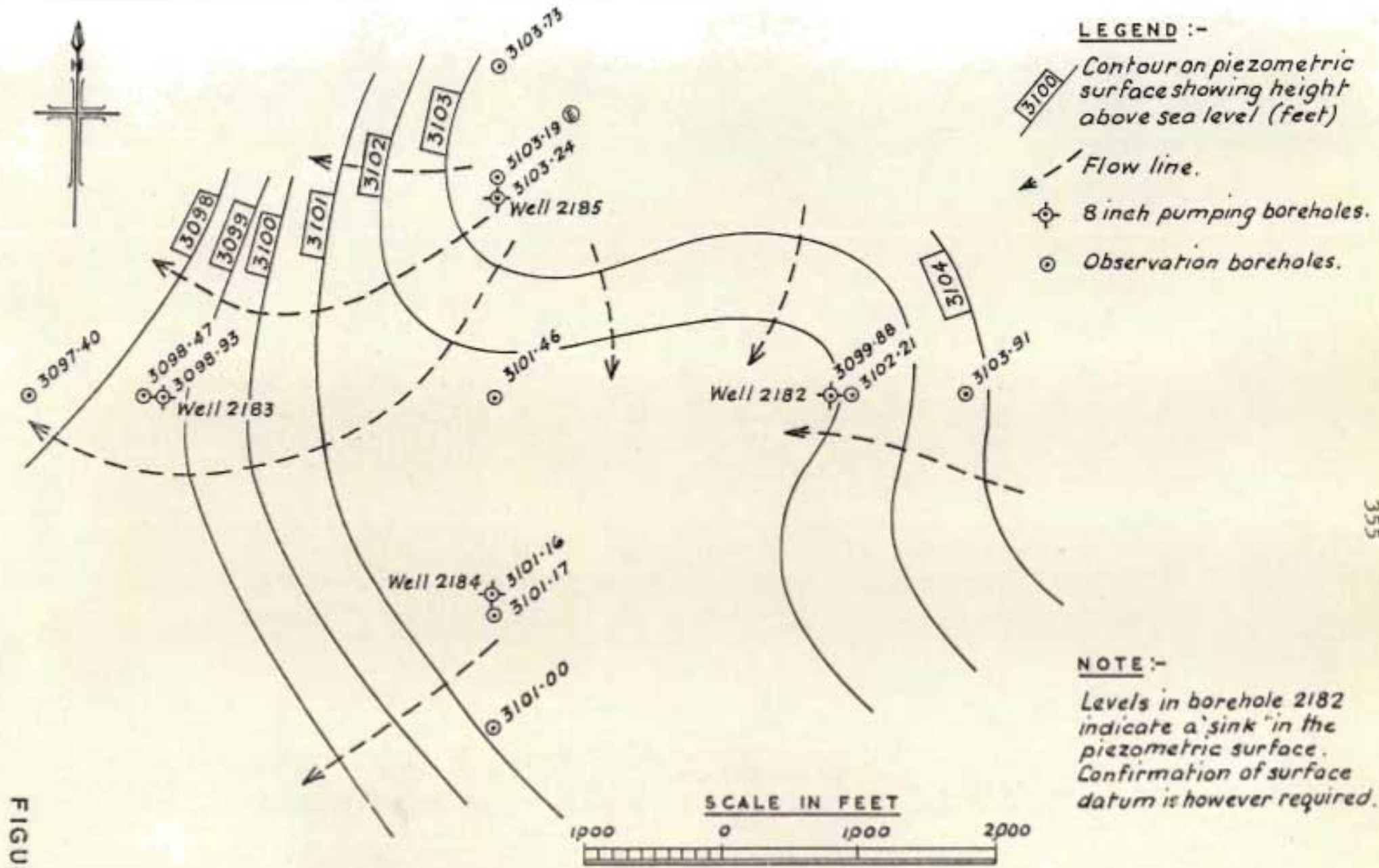
The numerous observation boreholes at wellfield 2 (8 mile) enabled a clear picture of flow conditions to be built up during the pump tests. Fig. 83 shows the isopiezometric contours after 5 days of pumping from borehole 2182.

Short term fluctuations

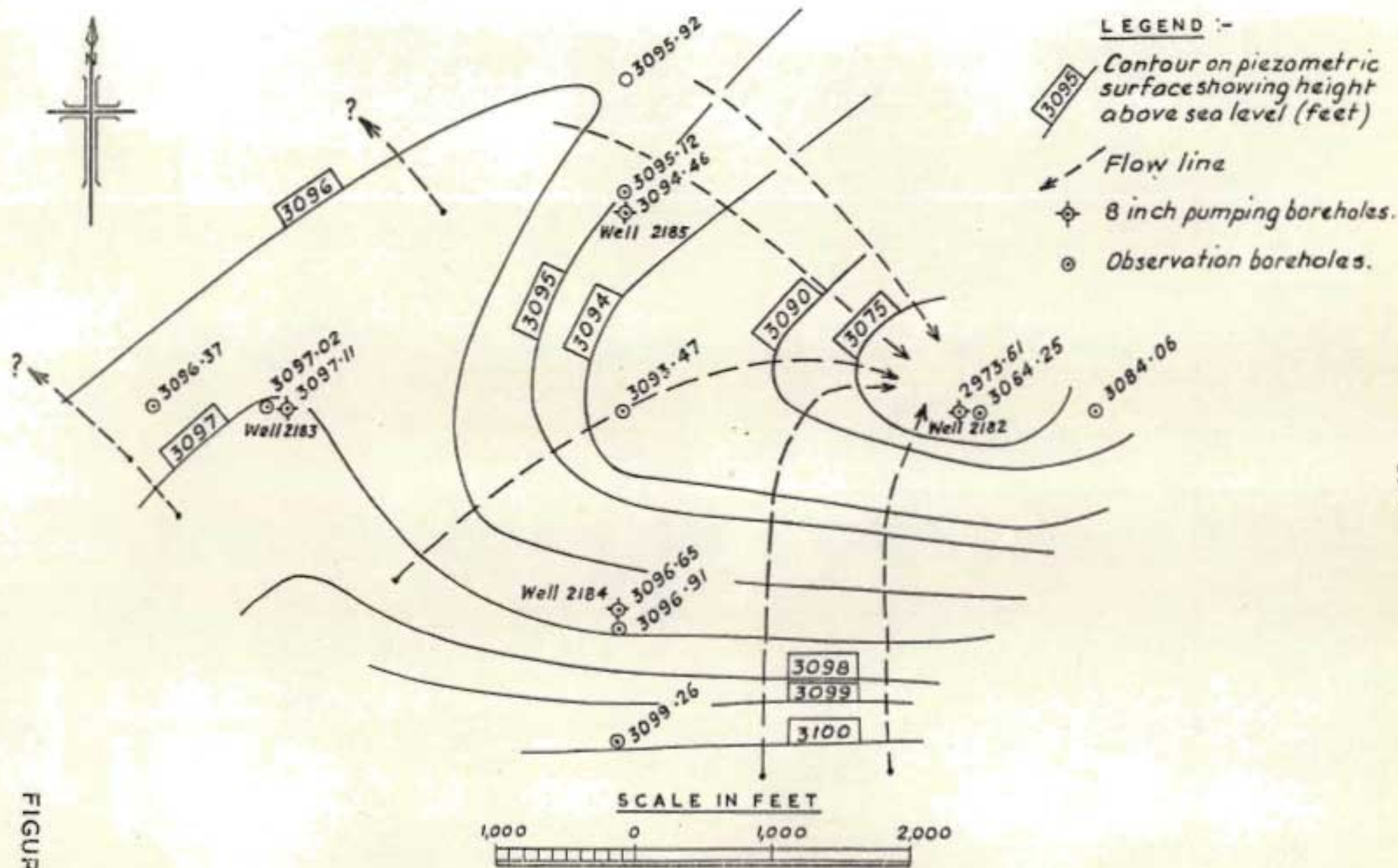
Short term fluctuations during the pumping of production boreholes in the Orapa wellfield (1) are shown in Fig. 84 which is derived from the automatic water level recorder on observation borehole 2153.

Rate of Ground-Water Flow

Using Figure 76 there is a hydraulic gradient of 400 feet over 64 miles from Makoba to borehole 2083 (Orapa) i.e. a hydraulic gradient of $\frac{400}{64.5280} = \frac{400}{337\ 920} = \frac{1}{845}$



Piezometric surface : 29.11.68. 0700-0800 hrs.
PIEZOMETRIC SURFACE PRIOR TO TEST OF WELL 2182



Piezometric surface : 5.12.68. 0800-0900 hrs. (AFTER Anon, 1969)

PIEZOMETRIC SURFACE AFTER 5 DAYS ABSTRACTION FROM WELL 2182

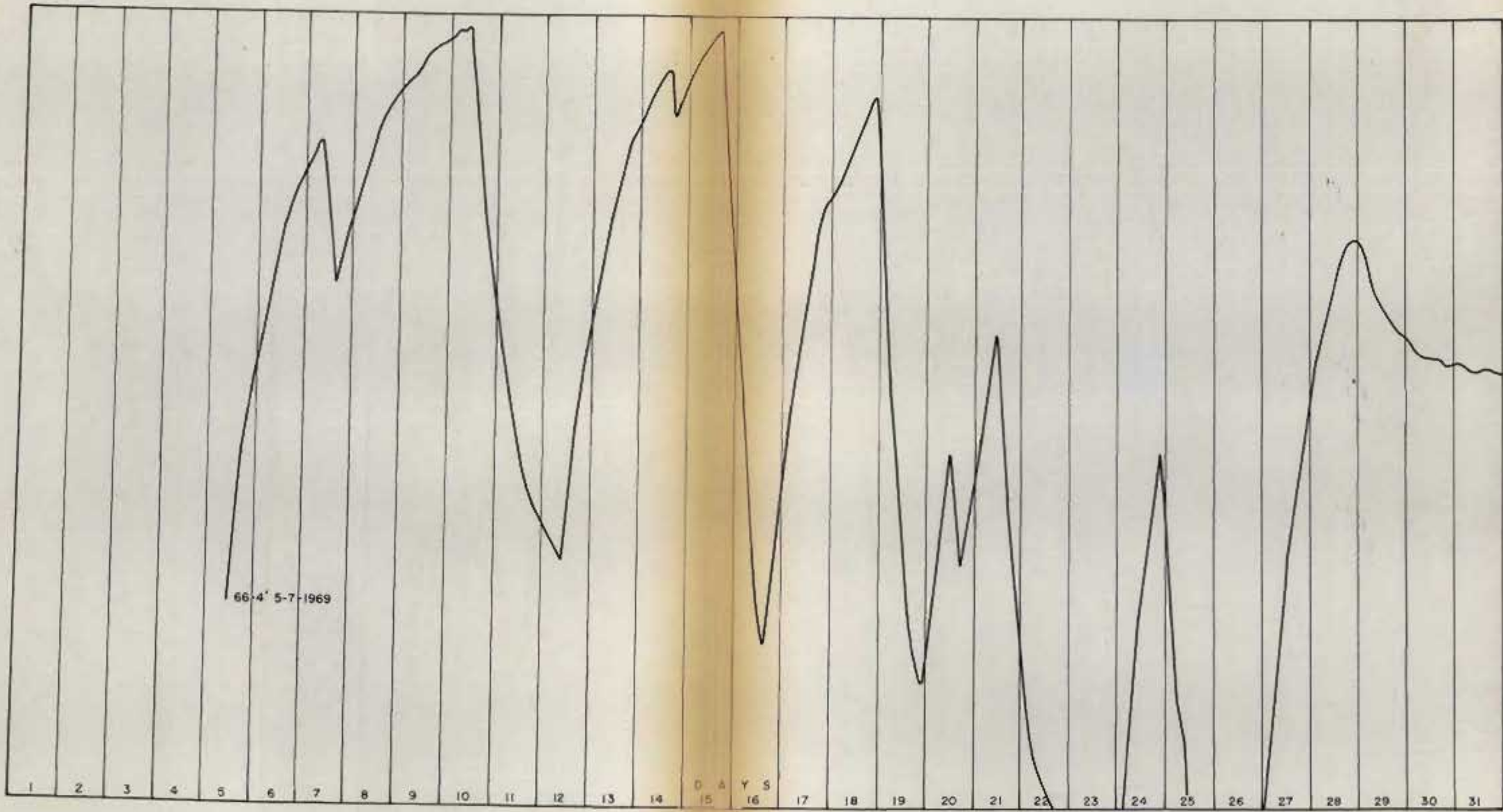


Fig. 84 HYDROGRAPH BH.2153-ORAPA WELLFIELD I
SHOWING LARGE FLUCTUATIONS DUE TO PUMPING OF NEARBY BOREHOLES

The equation for ground-water velocity combines Darcy's Law with the basic velocity equation for hydraulics. (See chapter on aquifer hydraulics).

$$\text{Darcy's law states } Q = K A \frac{dh}{dl}$$

$$\text{while the velocity equation is } \frac{Q}{A} \text{ or } Q = Av$$

$$\text{therefore, by substitution } Av = K A \frac{dh}{dl}$$

$$\text{and } v = \frac{Kdh}{dl} \quad (1)$$

Equation (1) assumes water movement throughout the entire cross-sectional area. However as water can only move through the pore space the actual velocity is proportional to the porosity (a) i.e. $v = \frac{K}{a} \frac{dh}{dl}$. Therefore, using a value of T of 15 m/day for the Cave sandstone aquifer, and assuming an aquifer thickness of 90m (from Core logs), and a porosity of 20%, then $v = \frac{15}{845} \times \frac{100}{20} \times \frac{365}{90}$ m/yr

$$= 0,36 \text{ m/yr.} \quad (a)$$

Using the same figure (76) a hydraulic gradient of $\frac{1}{634}$ is present from Letlhakane borehole to bh. 2083 (Orapa)

$$\begin{aligned} \text{Therefore } v &= \frac{15}{634} \times \frac{100}{20} \times \frac{365}{90} \text{ m/yr} \\ &= 0,48 \text{ m/yr} \quad (b) \end{aligned}$$

Using the same figure (76) above, a hydraulic gradient of $\frac{1}{646}$ is present from Makoba to Gugae.

$$\begin{aligned} v &= \frac{15}{646} \times \frac{100}{20} \times \frac{365}{90} \text{ m/yr} \\ &= 0,47 \text{ m/yr} \quad (c) \end{aligned}$$

All the above gradients were calculated using a single line of levels and not from a flow net and should be viewed with caution.

From the isopiezometric surface map of the Makoba area (Fig. 81) a gradient of $\frac{40}{10\ 000} = \frac{1}{250}$ can be measured.

$$\begin{aligned} \text{Therefore } v &= \frac{15}{250} \times \frac{100}{20} \times \frac{365}{90} \text{ m/yr} \\ &= 1,21 \text{ m/yr} \quad (\text{d}) \end{aligned}$$

For a ground water flow rate of 1,21 m/yr it would therefore take $\frac{180000}{1,21}$ years = 148 760 years for water at Serowe to reach Orapa. For a flow rate of 0,36 m/yr, it would take 500 000 years to reach Orapa.

The presence of both tritium and carbon - 14 (time range 50 and 50 000 years respectively) in the ground water at Orapa indicate that recharge in the Serowe area only is out of the question and hence it may safely be concluded that recharge takes place at some point closer than that postulated by Anon (1969).

The above calculations have been made assuming an aquifer thickness of 90 m which is the total thickness of sandstone present. However if data from formation resistivity borehole logs is taken into account, the thickness in which ground water movement can take place may be as little as 3 m. This 3 m zone, being a fissured and very porous zone immediately below the basalt contact, is known generally as the "indurated zone".

Should the main aquifer be 3 m, as postulated by Anon. (1969), flow rates through the porous medium only would then be:

(a)	10,79	m/yr
(b)	14,4	m/yr
(c)	14,1	m/yr
(d)	36,3	m/yr

For a flow rate of 10,79 m/year it would take 16 682 years for water to reach Orapa from Serowe while at a rate of

...../36.3 m/year

36,3 m/year it would take 4959 years to reach Orapa. These figures are regarded as somewhat too high.

ENVIRONMENTAL ISOTOPE STUDIES AT ORAPAIntroduction and previous work

The earliest samples for tritium analysis from the Orapa area were collected by the writer in 1968 as part of the general research programme on the application of isotopes in hydrogeology in Botswana being carried out in collaboration with the Nuclear Physics Research Unit (N.P.R.U.) of the University of the Witwatersrand. Following the earlier exploratory work, and a realisation by de Beers Prospecting Industrial Diamond Division (Diamond Research Laboratory) that the provision of an assured water supply for the Orapa Mine was of vital importance, and that further research was warranted, a research group was set up to: "study the ground water regime at Orapa, to assess the abstractable quantities of water and to provide recommendations on the optimum ways of further development of the ground water resources, in case of future demands". As a result an extensive series of tritium and carbon - 14 measurements were made in the low-level counting laboratories of the Nuclear Physics Research Unit. Results of this work have been presented by Sellschop et al (1973) and Mazor et al (in press). The assistance of my colleagues in this project, especially of Professor J.P.F. Sellschop, Dr. B. Th. Verhagen and Dr. E. Mazor is gratefully acknowledged. All measurements unless otherwise acknowledged were carried out in the laboratories of the N.P.R.U.

Isotopic Studies

Details on the mode of formation of and application of environmental isotope studies has been given elsewhere in this thesis (Chapter on Isotopes).

Tritium Results - Orapa

Tritium results for Orapa boreholes are given in Table 46 and Figures 69, 70, 84, 85.

T A B L E 46ORAPA, CARBON -14 AND TRITIUM DATA

<u>BOREHOLE DESCRIPTION</u>	<u>DATE OF SAMPLING</u>	<u>TRITIUM T U</u>	<u>CARBON -14 pmc</u>
*2153	October 1968	0,6 +/- 0,3 1,9 +/- 0,5	10,1 +/- 0,3
2175	October 1971	0,0 +/- 0,1 (28/4/71)	9,3 +/- 0,5
2182	"	0,4 +/- 0,2	15,0 +/- 0,4
*2184	October 1968	1,7 +/- 0,4	22,6 +/- 0,3
2198	October 1971	1,8 +/- 0,4	12,9 +/- 0,5
2199	"	0,7 +/- 0,3	9,1 +/- 0,5
2206	"	0,8 +/- 0,2	20,2 +/- 0,8
Steinberg's	"	2,8 +/- 0,3	86,2 +/- 2,0
Mahata	"	3,6 +/- 0,5	69,1 +/- 1,3
Makoba	"	0,0 +/- 0,4 (26/2/71)	78,0 +/- 1,4
Tshepe	"	1,9 +/- 0,4	78,4 +/- 1,3
Mashoro	"	1,3 +/- 0,3	20,6 +/- 0,8
Bosupswe	"	2,9 +/- 0,3 (26/8/70)	4,5 +/- 0,3

* Analyses by Dr. J.C. Vogel

All other analyses by Nuclear Physics Research Unit.

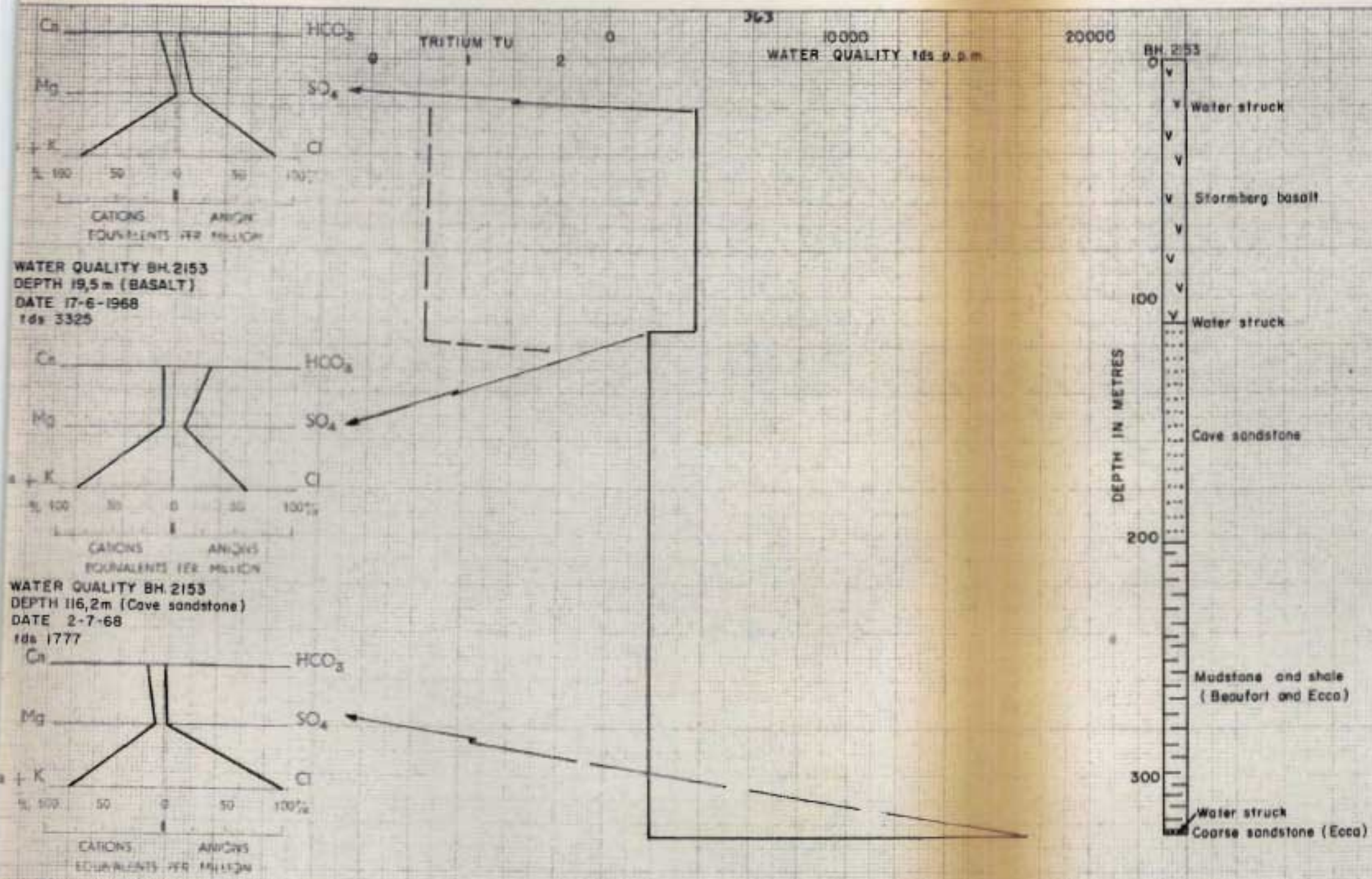


Fig. 44 DIAGRAM SHOWING GEOLOGICAL LOG, DEPTH WATER ENCOUNTERED, TRITIUM VALUES AND CHANGES IN CHEMICAL QUALITY WHILE DRILLING BH. 2153 — ORAPA.

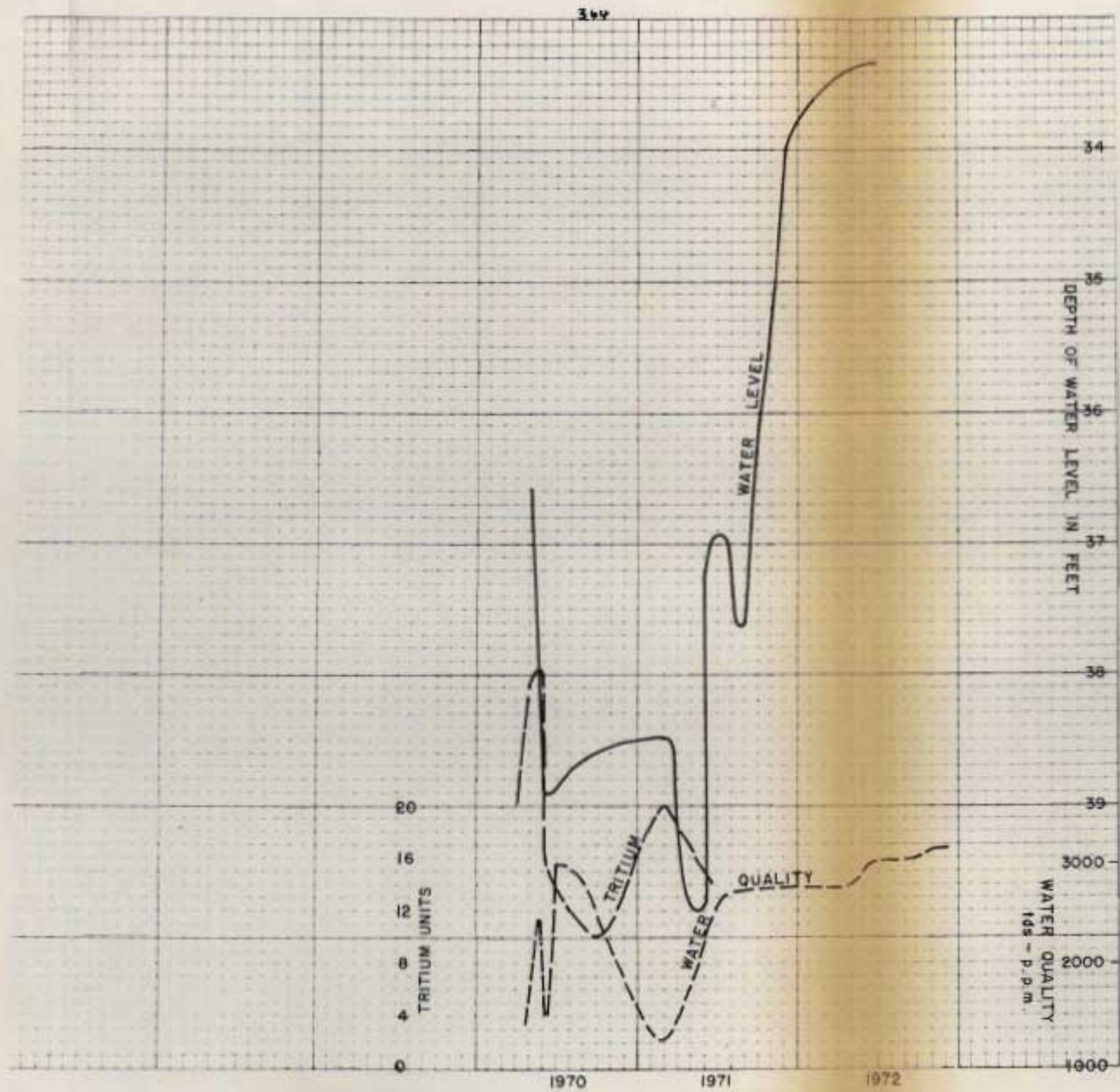


Fig. 85 HYDROGRAPH ORAPA LANDING GROUND WELL,
TRITIUM VALUES AND GROUND WATER CHEMISTRY.

It can be seen that in general the Cave sandstone aquifer has small but definite amounts of tritium (1.17 ± 0 , TU - average of 102 measurements). This could be interpreted as:-

- (i) a ground water body which is more than 20 years old;
- (ii) a body which has been recharged by recent waters (post-bomb) directly through the Kalahari Beds and basalt. (This is considered to be unlikely as the Cave sandstone aquifer is confined,)
- (iii) an aquifer in which the post-bomb (post-1952) recharge in the nearby phreatic Cave sandstone aquifer has moved laterally to the confined areas being studied. This then raises the question of whether permeabilities are sufficiently high to enable this to take place and here we have conflicting evidence from laboratory tests and pump tests. There are also uncertainties as to the nearest areas of Cave sandstone sub-outcrop (because of the paucity of the exposures). Robins (1972) however, mentions the presence of Cave sandstone halfway across the pan at the Orapa airstrip and hence Cave sandstone is present only 8 km from wellfield 1 at Orapa Mine. On theoretical grounds it would seem that under the prevailing hydraulic gradients thought to be present in the area, the flow velocity through a porous medium is unlikely to exceed a maximum of 36 m/yr (see earlier section). However, experience resulting from the drilling of core boreholes both in the Orapa and Kweneng areas, has shown that flow undoubtedly takes place mainly along fissures. These fissures are in all probability

hydraulically interconnected over long distances, and hence it would be feasible for "modern-water" falling on the unconfined Cave sandstone aquifer to move at considerably greater velocities than calculated earlier, provided sufficient head existed. This head would have been considerably increased by the large scale pumping that took place in the Orapa area.

- (iv) a perched Kalahari Beds/basalt aquifer recharging the semi-artesian Cave sandstone aquifer once boreholes have penetrated the confining horizon i.e. mixing of high tritium waters with the effectively zero activity water in the Cave sandstone. This is regarded as unlikely as water encountered in the basalt, e.g. 2153 had no greater tritium content than Cave sandstone water. Most boreholes in the Orapa area show fluctuations in tritium values with time. When these fluctuations are compared with the periods of heavy pumping of the wellfields (Figs.67,69,70) it would appear that tritium levels on the water diminished during pumping in the 8 and 12 mile wellfields (2 and 3) while tritium levels in the Orapa wellfield (1) attained their nadir at a period when water levels were beginning to recover. An adequate explanation for this phenomenon is not immediately obvious. It would seem however, that older waters were drawn into the wellfield areas to replace younger water pumped out. The evidence to date does however, indicate that no large scale replenishment of the aquifer by young water, e.g.

from a perched Kalahari Beds/basalt aquifer, took place. It also indicates the probability that the volume of water in the aquifer is large in comparison with the amount abstracted.

Carbon - 14

As stated in the Chapter on Isotopes, the carbon - 14 content of pre-1952 recent water is around 85% modern carbon, while values greater than 85 pmc indicate a probable post-1952 component. Results of thirteen ^{14}C and I analyses are given in Table 46. These include eight measurements from the Orapa area and five from the line of recorder boreholes drilled between Serowe and Letlhakane (see Figs. 59, 71).

Orapa Wellfield (1)

The two ^{14}C analyses carried out by independent laboratories give excellent agreement at ± 10 pmc.

Eight Mile Wellfield (2)

Three ^{14}C analyses on boreholes 2182, 2184 and 2198 give values of 15,0; 22,6 and 12,9 pmc respectively. Of these the two easternmost boreholes give the oldest values.

Twelve Mile Wellfield (3)

^{14}C values of 9,1 and 20,2 pmc were obtained for boreholes 2199 and 2206 respectively. It is interesting to note that borehole 2206, which produced the highest yield in the Orapa area, has considerably more ^{14}C than borehole 2199. All tritium levels for these boreholes are low and vary between 0,0 and 1,8 TU.

Shallow Orapa Landing Ground Kalahari Beds well and Steinberg's well

Both these shallow hand dug wells, consisting of nodular calcrete (Kalahari Beds) overlying basalt, show considerable amounts of tritium to be present in the ground water. They also both show marked fluctuations in tritium levels with time. (See Fig. 85).

These fluctuations are interpreted as indicating considerable amounts of modern recharge in relation to total storage capacity of the perched Kalahari Beds aquifer. Both boreholes show peak values occurring in May 1970, while a lesser peak occurs at the Landing ground well in March 1971. There is thus a delay of about four months from the peak of the rainy season to the peak values and hence this provides evidence on either the rate of direct infiltration or the rate of lateral movements from the nearby pan in the case of the landing ground well, where recharge probably takes place following the collection of water in the pan after heavy thunderstorms.

Steinberg's Well

This well has water containing 86,2 pmc and thus indicates the recent origin of this water. When the tritium content of this water (up to 4,5 TU) is considered it may be deduced that the water in this well is less than 20 years old.

The fact that the bicarbonate ions in this water contain near atmospheric concentrations of ^{14}C indicates that the bicarbonate in the water must be derived from biogenic sources in the soil horizon and cannot have come from the breakdown of carbonate rocks.

Recorder Boreholes Mahata-Bosupswe

The three boreholes Mahata, Makoba and Tshepe with the deepest Kalahari Beds cover in the northeastern Kalahari have, rather surprisingly relatively large amounts of carbon -14. i.e. 69,1; 78,0 and 78,4 pmc respectively and tritium concentrations of $3,6 \pm 0,5$ TU, $0,0 \pm 0,4$ TU and $1,9 \pm 0,4$ TU. This indicates a post-bomb component in at least two of the boreholes and relatively young waters in the carbon - 14 time scale for all three, i.e. the waters are probably a mixture of recent recharge water with older waters.

Summary logs of these two boreholes are given in Table 47 :-

TABLE 47DETAILS BOREHOLES, MAKOKA AND TSHEPE

<u>Bh 146</u>	<u>Makoba</u>	<u>Bh 144</u>	<u>Tshepe</u>
0 - 55,8 m	Kalahari Beds	0 - 27,4 m	Kalahari Beds
55,8 - 114,9 m	Basalt	27,4 - 143,6 m	Basalt
114,9 - 132,6 m	Cave Sandstone	143,6 - 157 m	Cave Sandstone
Water stuck	35,4 and 54,6 m	Water stuck	19,2 and 56,7 m
Rest level	22,6 m	Rest level	12,8 m
Yield	228 l/min.	Yield	76 l/min.

These boreholes all encounter water in Kalahari Beds under semi-confined conditions and hence, although water obviously cannot be replenished by direct infiltration in this area, it is considered likely that replenishment of this aquifer is likely to occur within a relatively short distance of these boreholes.

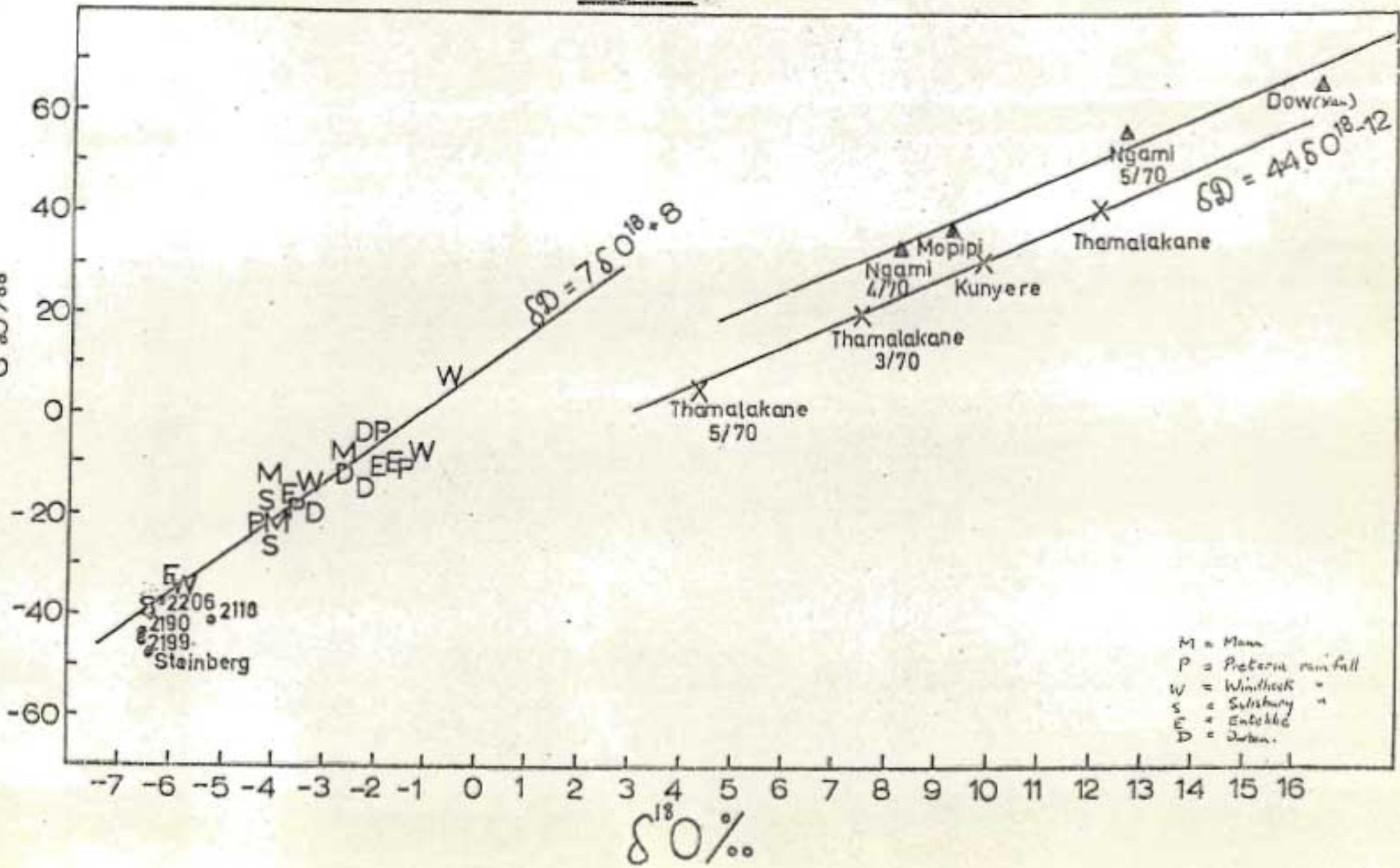
Interpretation of Combined Tritium and Carbon - 14 Data

Consideration of both the tritium and carbon - 14 values in water from the Cave sandstone aquifer was used by Mazor et al (in press), to determine the time origin of this water. If the small amounts of water, 0,4 to 1,8 TU, present in the Cave sandstone waters be assumed to be due to a small element of post-bomb recharge, then the corresponding overall ^{14}C values in the water could be expected to be 2 - 10 pmc. Should recent recharge have occurred in pre-bomb times, the tritium would now have decayed to values of less than 2 TU from an original value of at least double this amount, but the carbon -14, because of its much greater half-life, would not have decayed to appreciably less, and hence the corresponding ^{14}C values would be higher by a factor of two i.e. 4-20 pmc. As ^{14}C values range from 9,3 to 22,6 pmc, it appears likely that all the ^{14}C in the water can be explained by the addition of small quantities of recent water, either recharged from the Kalahari Beds/basalt aquifer as postulated by Mazor et al (in press) or by recharge into the Cave sandstone unconfined aquifer and subsequent flow beneath the confining layer accompanied by mixing with older waters with zero radioactivity levels. The latter view is preferred as the confined nature of the Cave sandstone aquifer cannot permit recharge as postulated by Mazor et al (in press) and furthermore the scanty evidence from samples taken while drilling provides evidence that the basalt waters are of similar age to the Cave sandstone waters. Drilling evidence from the Orapa area furthermore indicates no water as being contributed to the borehole in the shallow Kalahari Beds horizons.

Stable Isotopes

Detailed comments on stable isotope measurement have been made in the chapter on environmental isotopes. The marked difference between the stable isotope data plotted on Fig. 86 shows clearly that the isotopically light ground waters in all wells and boreholes in the Orapa area cannot be derived by recharge from isotopically enriched surface waters of the Thamalakane-Kunyere-Lake Ngami-Boteti River-Lake Xau-Mopipi Pan system. Furthermore, stable isotope data also shows that recharge probably takes place under conditions of heavy rainfall and low evaporation.

FIG 86



GEOPHYSICSSub-surface Geophysical MethodsFormation Resistivity Logs

All boreholes at the 8 mile wellfield were logged using a formation resistivity logger manufactured in Johannesburg by F.G. Slack and Company. This logger has a surface electrode and three downhole electrodes whose spacing can be varied in three stages from two to four or eight feet to give a normal resistivity log. All boreholes logged followed a similar pattern which consists of high resistivity values in the basalt with much lower values in the Cave sandstone. The contact zone is characterised by very low resistivity values separated from a smaller resistivity low (6m lower down in the hole) by a zone of higher than average resistivity for the sandstone. A number of zones of relatively lower resistivity are present in the basalt but the lowest of these are all of much higher resistivity than the Cave sandstone.

The very low resistivity values just at the base of the basalt or immediately on the sandstone contact probably indicate the main zone in which ground-water flow into the borehole takes place.

A typical resistivity log is given in Fig.87.

Self-potential Log

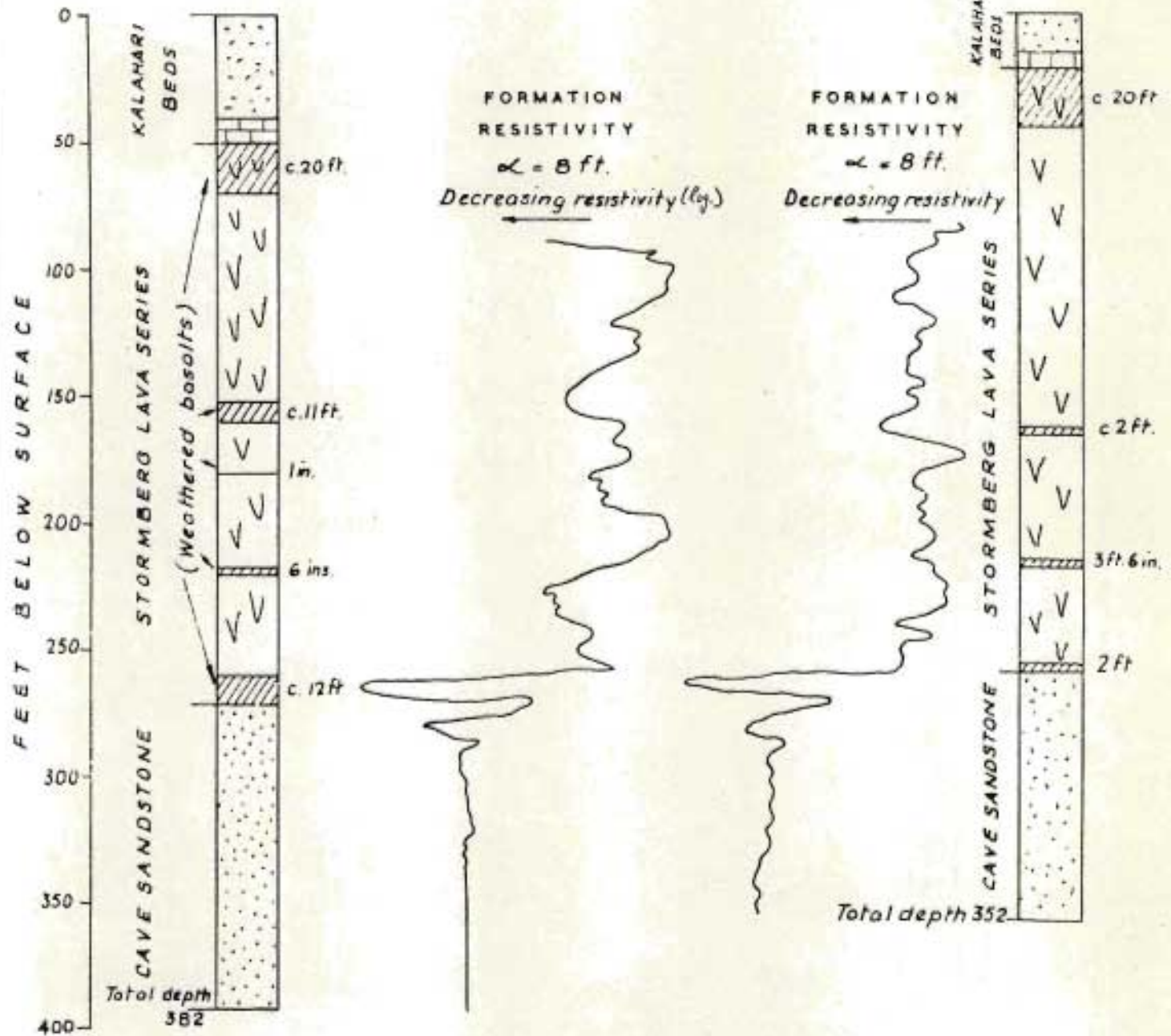
A single self-potential log using a "home-made" unit consisting of a potentiometer and silver-silver chloride electrodes was made in borehole 2153 at the Orapa wellfield. This log is shown in Fig. 88. The main features of this log are two very low self-potential zones, one 6 m above the

BOREHOLE 2185 /150

BOREHOLE 2184 /150

STRATA LOG

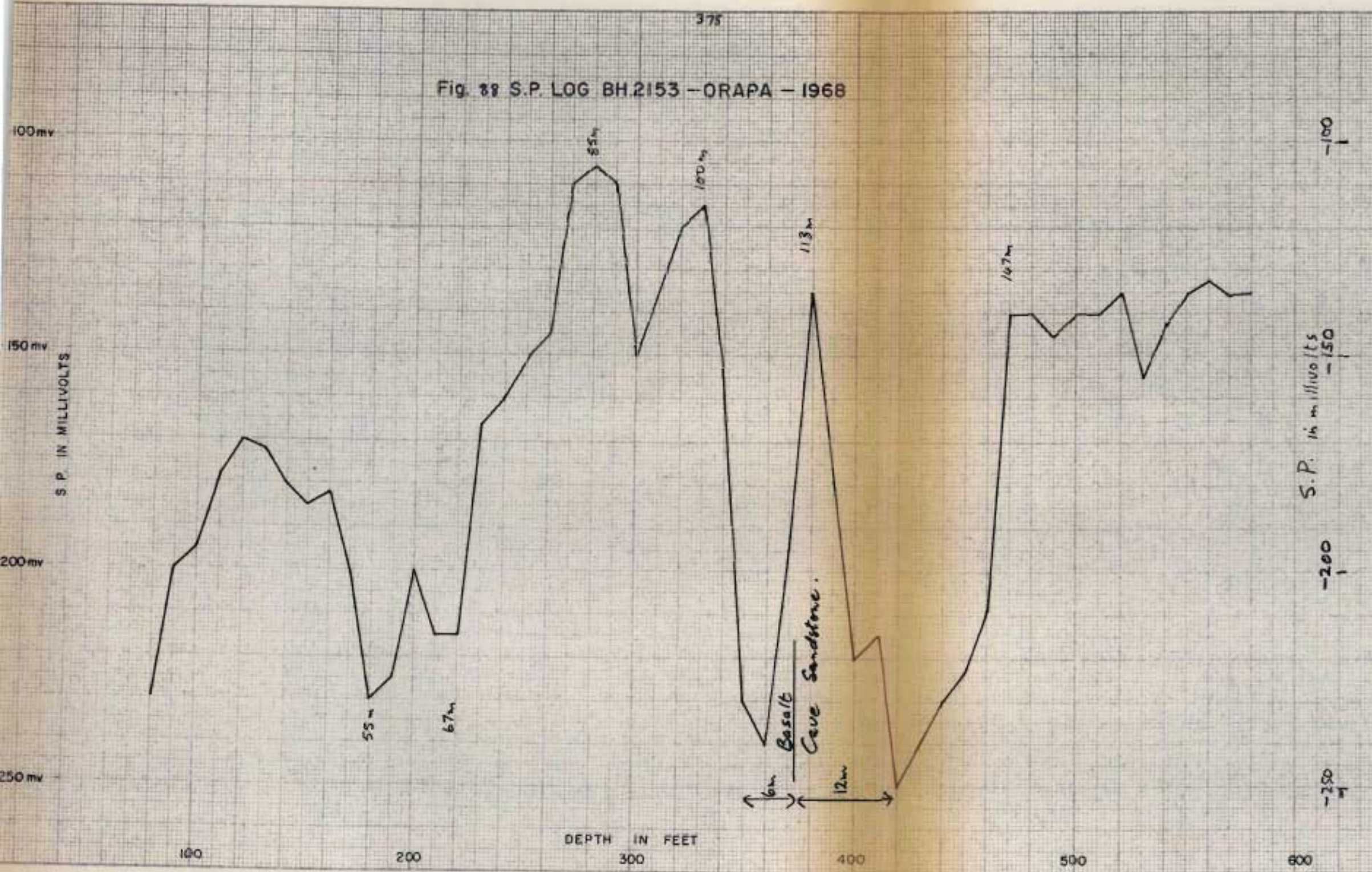
STRATA LOG



RELATIONSHIP BETWEEN STRATA AND FORMATION RESISTIVITY (After Anon, 1924)

FIGURE 87

Fig. 88 S.P. LOG BH.2153 - ORAPA - 1968



basalt/sandstone content and the other 12 m below the contact. An additional zone with low self-potential values is present from 55 to 67 m in the basalt. High SP zones are present at 85 m, 100 m, 113 m and below 146 m. These zones are interpreted as porous and permeable sections in which ground-water flow is able to take place. According to Todd (1959) positive values occur with flow from the formation into the well while negative values occur in zones of reverse flow. Davis and de Wiest (1966) have cautioned that beds with permeabilities far too low to be of interest as aquifers may give rise to large potentials. An alternative interpretation of the low SP zones in the basalt is that these may represent highly mineralised zones differing considerably in quality from that in the borehole. (Walton, 1970).

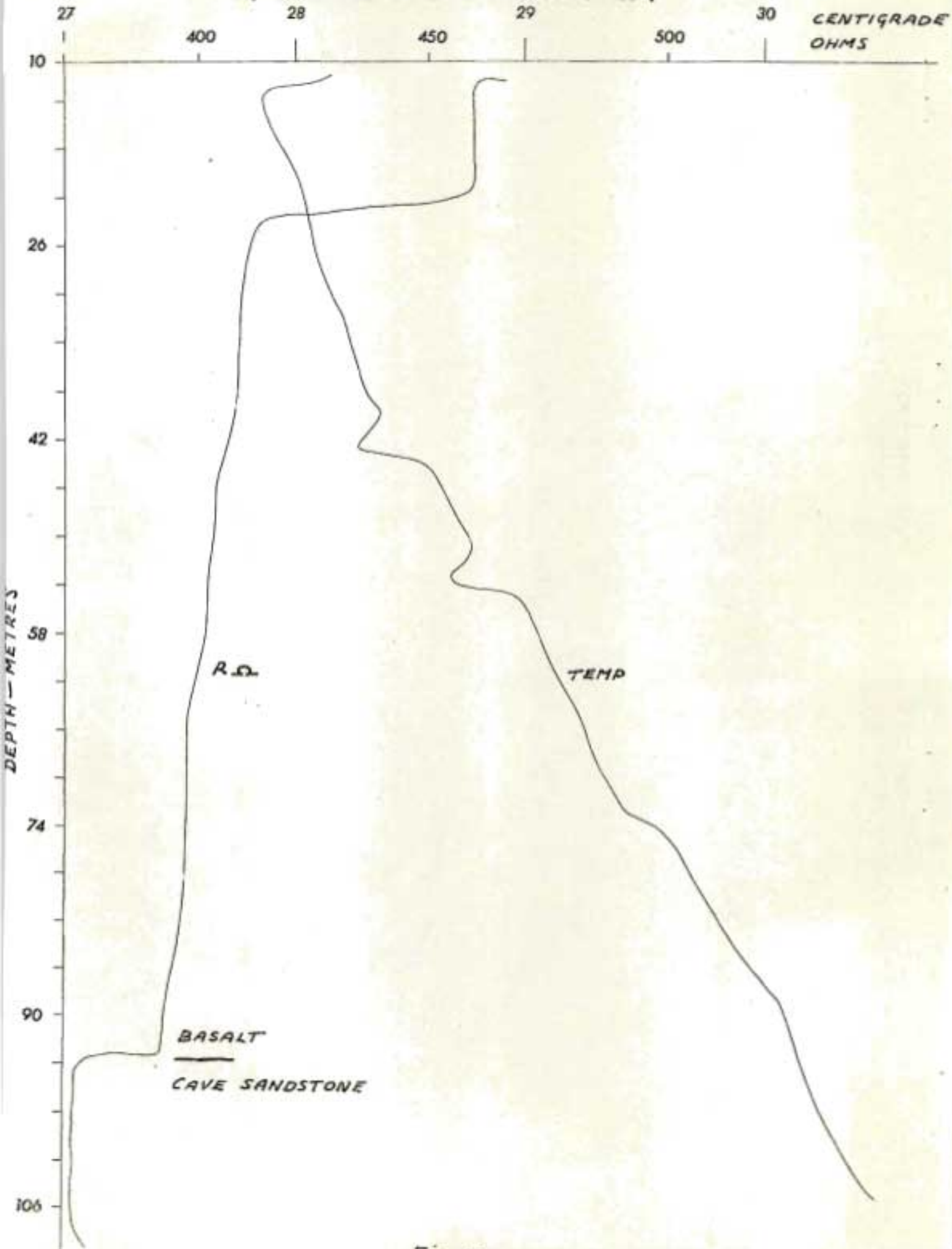
Fluid Conductivity, Resistivity and Temperature Logs

In addition to the formation logs carried out at the Eight Mile Wellfield (No. 2) at Orapa, fluid conductivity, resistivity and temperature logs were conducted using a Tamron instrument in order to provide additional information in the Orapa aquifers. The instrument used was made in Israel and does not have a continuous recording device as with the formation logger. Readings were generally taken at 1 meter intervals but can be taken at 1 cm intervals if desired. Typical logs obtained are shown in Figs. 89 and 90.

These logs show that there is a general temperature increase with depth in all boreholes. This increase is attributed to the normal geothermal gradient.

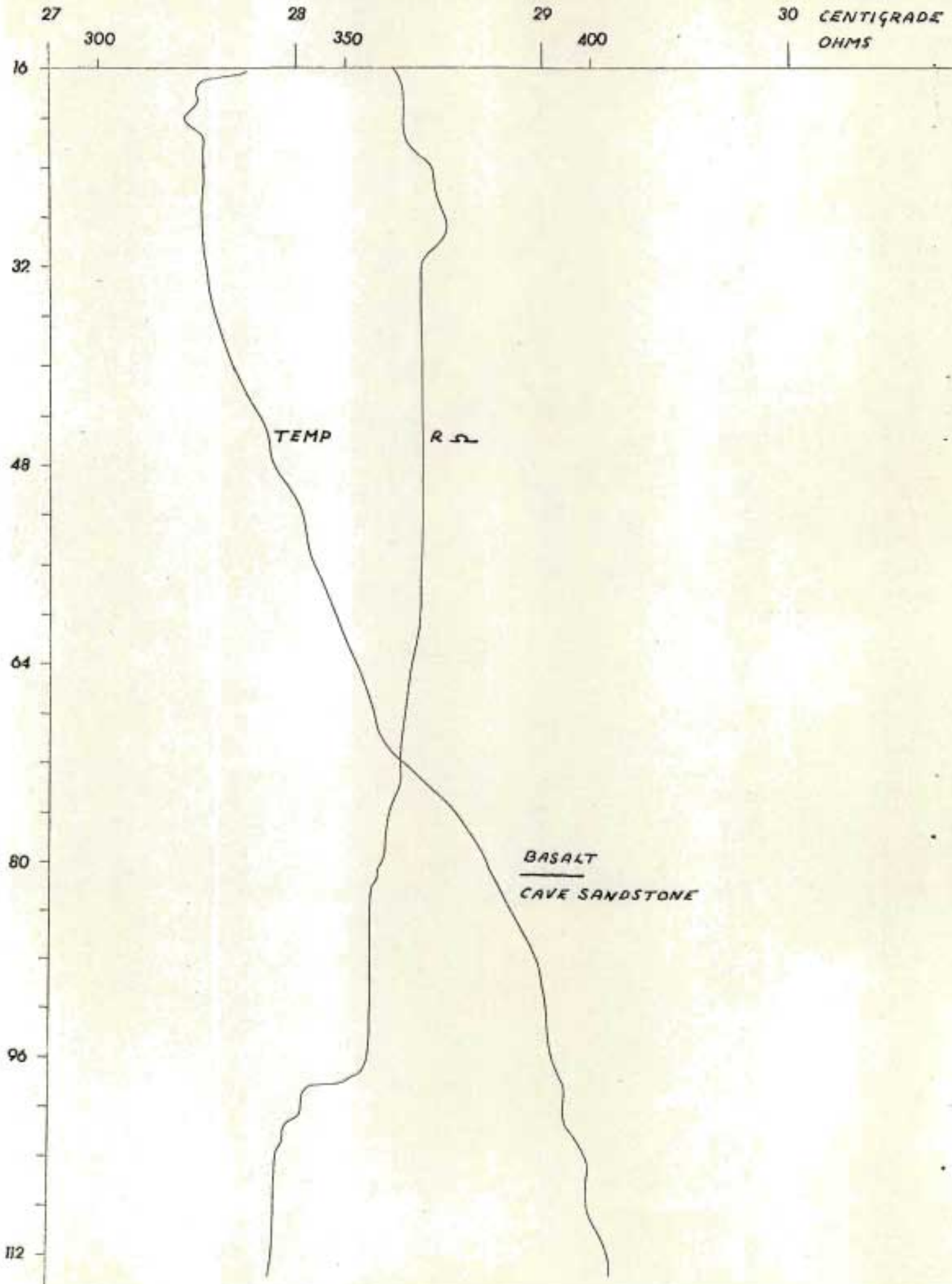
Occasional deviations from the smooth curve could be due to water of a different temperature entering the borehole.

TEMPERATURE & CONDUCTIVITY LOG



378
Bh 2185/150 - ORAPA

TEMPERATURE & CONDUCTIVITY LOG



Marked changes in fluid resistivity were encountered and could be pin-pointed to within one centimeter. These points are interpreted as entry points of water into the borehole column. Most logs show this marked change in fluid resistivity to occur at the sandstone contact but it is interesting to note that the change in boreholes 2185, 2185/150 and 2185/1000 occurred at 97,25 m, below the contact at 82,6 m, indicating that the main water supply was encountered at this depth and not on the contact. Unfortunately the data concerning points at which water was encountered while drilling is unreliable as the hole was drilled by a private contractor who maintained little control over his drillers.

Surface Methods

Because of the known simple "layer-cake" type geology in the Orapa area, most boreholes were sited on geological grounds alone without the use of geophysical aids. However, it was considered that data from airborne geophysical surveys could be used to detect conductive fault zones, and the data from a Barringer INPUT survey was scrutinised, and a linear conductor of considerable strike length detected by the survey was selected for trial drilling. The conductive zone was pinpointed on the ground by Afmag and a reconnaissance electromagnetic instrument (McPhar REM) and self-potential methods and two boreholes, 2199 and 2206, were drilled. These boreholes gave yields of 5 000 (380 l/min) and 7 000 g.p.h. (532 l/min) respectively. These yields are approximately 200 to 400 per cent higher than the average yield for the area and hence future siting of boreholes should utilise integrated geophysical techniques to delineate zones of higher than average permeability.

HYDROCHEMISTRYIntroduction

Systematic sampling of water from more than twenty-two boreholes and wells in the Orapa area was commenced on a two monthly basis in 1970. All boreholes were also sampled during and at the completion of drilling and during the detailed pump tests at the end of 1968. In addition to pumped samples, a depth sampler as described in the chapter on isotopes was used to sample unused boreholes at various selected depths.

The Orapa AreaCompositional Types (See Table 50)

Four distinct types of water are present in the Orapa area each of which can be directly related to the host rock type, i.e. Stormberg basalt, Cave sandstone, Eccca sandstone and Kalahari Beds. Water encountered in shallow Kalahari Bed wells, bears a fairly close compositional relationship to the water encountered in the Cave sandstone, but the latter contains less bicarbonate and more chloride ions than that of the Kalahari Beds type of water.

Kalahari Beds Type

A diagrammatic representation (Stiff diagram) of a typical Kalahari Bed water type is given for borehole 2199, Orapa, in Fig.91 for the sample taken at 11,6 m. This water type is characterised by dominant Na^+ and HCO_3^{--} ions with low Ca^{++} , Mg^{++} , SO_4^{--} and Cl^- ions. The source of the sodium

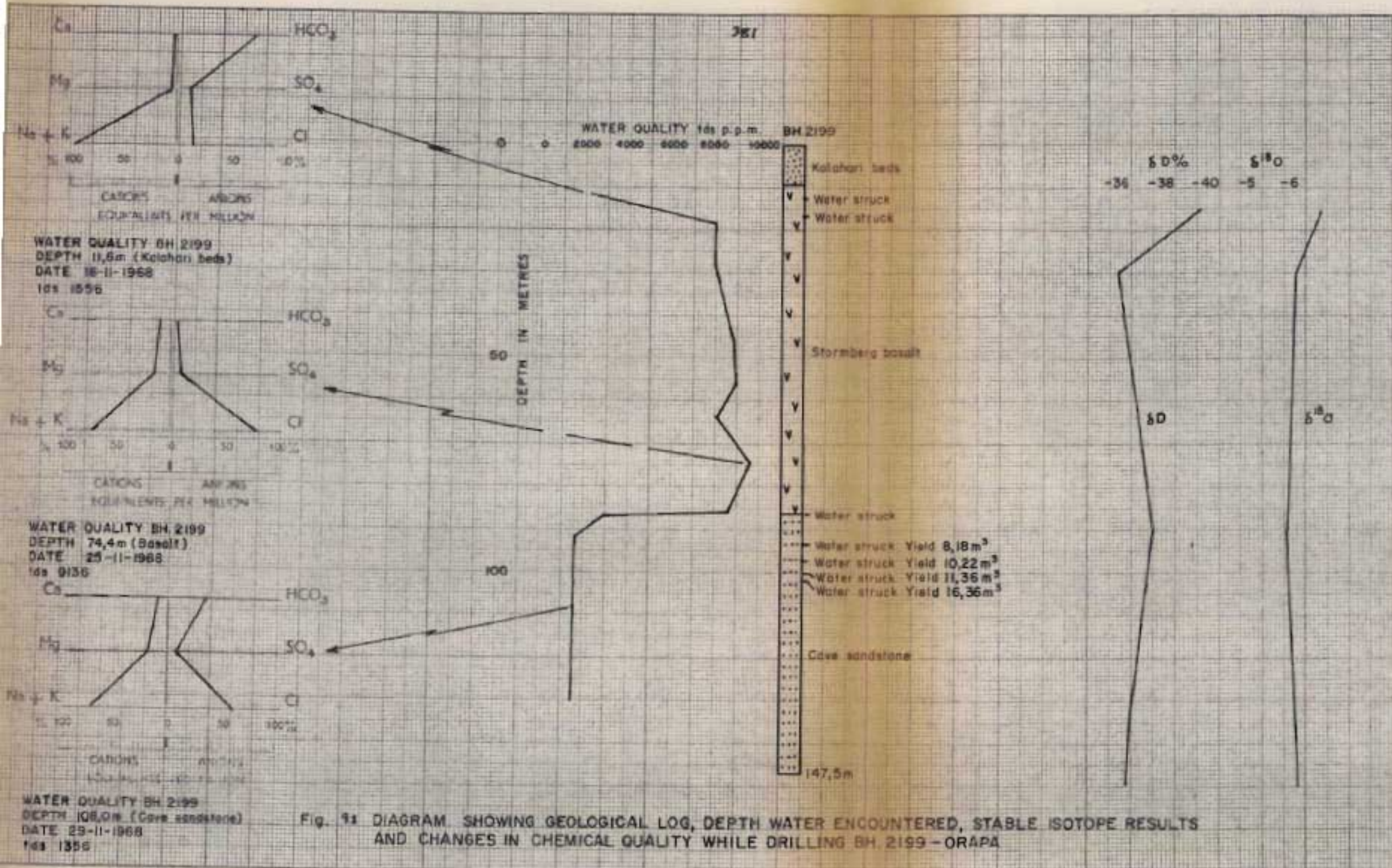


Fig. 91. DIAGRAM SHOWING GEOLOGICAL LOG, DEPTH WATER ENCOUNTERED, STABLE ISOTOPE RESULTS AND CHANGES IN CHEMICAL QUALITY WHILE DRILLING BH 2199 - ORAPA

is probably from breakdown of feldspars while the majority of bicarbonate is obtained from the biologically active soil zone where biogenic carbon dioxide is converted to bicarbonate. (See section on carbon -14).

Stormberg Basalt type water

In the Orapa area, ground waters encountered in the basaltic lavas are generally characterised by a moderately high total dissolved solids content and are represented diagrammatically in Fig. 91, where it can be clearly seen from the sample taken at 74,4 m that sodium and chlorine ions are dominant with much less magnesium, calcium and bicarbonate ions present. i.e. $\text{Na}^+ + \text{K}^+ \text{Mg}^{++} \text{Ca}^{++}$ and $\text{Cl}^- \text{HCO}_3^- \text{SO}_4^-$. In addition to the high Na^+, Cl^- type water comparatively fresher water is occasionally encountered in the basalt, particularly near the top of the basalt, e.g. sample from 11,6 m (Fig.91). This water is characterised by high Na^+ and high HCO_3^- ions.

Cave sandstone type water

Cave sandstone type waters are characterised by their relatively fresher quality with an average tds of approximately 1 500 ppm total dissolved solids. The dominant cation is Na^+ with lesser Mg^{++} and even less Ca^{++} while the dominant anion is Cl^- ($\pm 60\%$ epm) and slightly less HCO_3^- ($\pm 30\%$ epm) and about 10% epm SO_4^{--} . The Cave sandstone type water appears to be a mixture of Kalahari Beds and basalt type waters and hence replenishment of the Cave sandstone aquifer could come by recharge from Kalahari Beds and from basalt waters. It should also be borne in mind that water recharged

directly into the Cave sandstone through a shallow soil cover would have a similar chemical composition to that of the Kalahari Beds.

An unusual Cave sandstone water

Water of exceptionally poor quality, the poorest in the Orapa area, was encountered in borehole 2083 on the edge of the large pan adjacent to the Orapa airstrip. An analysis of this water is shown in Table 48. This water has a tds of 41916 ppm and consists predominantly of the cation Na^+ with predominant Cl^- anion and moderately high SO_4^{--} content. This unusual quality water was encountered at a depth of 61 m in the borehole and is one of the few boreholes known where water was not encountered on the basalt contact at 23,78m. As the basalt cover wedges out over the pan the poor quality water is probably related to the solution of evaporite deposits in the pan by rainwater which has infiltrated through the pan floor.

Ecce sandstone aquifer

This water type was encountered at a depth of 325 m in only one borehole, viz bh 2153 at Orapa (Fig. 84). This was encountered in coarse-grained, feldspathic sandstone which is probably continuous with the brine-bearing sandstone aquifer underlying the eastern Sua section of the Makgadikgadi Depression. This water contains over 17 708 ppm total dissolved solids and is a predominantly Na^+ , Cl^- type water. This water type is depicted graphically in a Stiff diagram in Fig. 84. This saline water was cut off by backfilling the borehole to prevent contamination of the higher Cave sandstone aquifer. This quality water is not typical of the Ecce aquifer elsewhere in Botswana, but is obviously

TABLE 48CHEMICAL COMPOSITION OF BOREHOLE 2083 (AIRSTRIP) - ORAPA

ph	7,45
CO ₃ ⁻⁻	313
HCO ₃ ⁻	789
Cl ⁻	25060
SO ₄ ⁻⁻	4580
F ⁻	2
Total anions	30744
K ⁺	107
Na ⁺	16400
Ca ⁺⁺	302
Mg ⁺⁺	365
Total cations	17174
Sum total	47918
tds	41916
Theor.tds	47530
K	> 20000

related to the nearby internal drainage centre (Makgadikgadi Depression). (See Table 50)

Variations in chemical quality with time

Most boreholes in the Orapa area showed very little time variation during pump tests lasting up to 6 days (Table 49) or even over much longer periods (Figs. 65, 70). Apart from boreholes 2199 and 2206 which show some variation in chemical composition with time, the only other sampling point showing variations with time is the Landing Ground well. This well shows marked water level, tritium and chemical fluctuations. (Fig. 85). The fluctuations occur mainly in Cl^- , SO_4^{--} and Na^+ ions.

TABLE 49

WATER QUALITY FLUCTUATIONS DURING PUMP TEST ON BH. 2182, 8 MILE WELLFIELD, ORAPA.

	ph	HCO_3	Cl	SO_4	F	K	Na	Ca	Mg	tds
30/11/68	7,2	405	481	136	1	9	325	93	52	1480
1/12/68	7,8	405	485	125	1	9	325	95	49	1460
3/12/68	7,9	405	481	149	1	9	330	93	52	1472
5/12/68	7,5	405	483	196	1	9	330	93	52	1472
Pumping rate for 6 day test = 5 000 g.p.h. (22,72 m ³ /hr)										
Total pumped = ± 600 000 gallons.										

The Mopipi Water Scheme

The Orapa Diamond Mine is currently Botswana's second largest revenue producer and contributes over R5 million per annum by way of taxation to the Botswana Government. The mine is at present drawing all its water from the Mopipi Storage Dam which creates off-river storage for Orapa and requires

TABLE 50

CHEMICAL COMPOSITION OF WATER ENCOUNTERED DURING DRILLING IN BHS. 2153 AND 2199 DRAPA IN P.P.M.

BH. 2153:		GEOLOGY OR REMARKS	pH	CO ₃	HCO ₃	Cl	SO ₄	F	K	Na	Ca	Mg	tde SUM	tde	THEOR tde	k	TEM
DATE	DEPTH																
17.6.68	?	Basalt	7,70	-	55	1673	290	2	8	1000	177	15	3510	3492	3483	5000	
17.6.68	19,5	"	7,20	14	28	1673	290	2	8	1050	177	13	3325	3564	3311	5200	84
2.7.68	116,16	Cave Sand- stone	7,25	20	443	605	110	2	15	500	51	31	1777	1764	1559	2500	84
2.7.68	?	"	7,70	20	436	608	105	2	15	500	51	32	1769	1764	1555	2600	
3.10.68	?	"	7,90	14	406	587	165	2	13	510	43	34	1774	1716	1575	2700	
4.12.68	121,95	"	8,10	48	345	625	110	2	13	513	48	26	1730	1720	1555	2600	86
27.1.69	325,0	Ecca Mud- stone shale	7,10	172	172	10586	222	1	50	5625	824	228	17708	19720	17621	720000	
28.1.69	170,73	& sandstone (after back- filling)	8,05	27	378	757	238	1	9	713	19	9	1913	1972	1721	3160	86
BH. 2199:		Water struck	8,25	41	1037	136	147	2	4	550	9	9	1935	1556	1408	2100	
18.11.68	11,58		7,40	62	662	3750	550	5	10	2480	47	179	7845	7828	7519	11000	
25.11.68	18,29		7,30	28	577	3715	750	4	12	2350	234	199	7866	7696	7582	11000	
26.11.68	28,66		7,50	28	690	3930	950	5	11	2600	243	215	8672	8388	8333	12000	
27.11.68	46,95		7,60	28	606	4145	825	5	11	2650	230	217	8717	8684	8419	11000	
27.11.68	56,1		7,60	28	606	3750	750	5	10	2400	238	191	7978	7796	7680	11000	
28.11.68	65,2m		7,90	21	408	401	185	2	7	375	39	54	1498	1348	1297	2000 -	
29.11.68	65,2m		7,40	28	563	4680	775	4	15	2750	305	260	9400	9136	9123	13500 -	
29.11.68	74,39		7,30	21	479	4467	523	2	19	2375	386	272	8544	9972	8301	12500	
29.11.68	83,53	Basalt 282'	7,75	21	394	1179	207	2	9	775	84	79	2750	2776	2550	4250	
29.11.68	86,58	Cave sd/st.	8,00	42	373	500	73	2	7	388	52	44	1481	1448	1291	2250	
29.11.68	92,68	1800 g.p.h.	7,95	48	366	800	73	2	7	388	50	48	1482	1460	1296	2250	
29.11.68	95,73	2250 g.p.h.	8,00	21	394	493	73	2	7	375	43	50	1458	1436	1258	2220	
29.11.68	98,74	2500	7,90	42	366	461	81	2	7	363	52	43	1417	1360	1231	2150	
29.11.68	101,82	+3600	8,00	35	380	461	81	2	7	363	43	48	1420	1356	1227	2100 -	
29.11.68	107,92	+3600	7,70	-	491	352	87	2	7	315	51	40	1345	1172	1096	1700	
16.12.68	126,22		8,05	20	389	410	130	2	7	365	34	42	1397	1212	1200	1900	
17.12.68	131,70																

pumping at the rate of 8,5 cumecs for a period of 2 months a year to replenish storage in the pan. The pan is 1 900 ha in extent and has a capacity of approximately $100 \times 10^6 \text{ m}^3$ which is capable of supplying Orapa's needs for 2 to 3 years without any replenishment. The source of supply is the Boteti River which has, in the past, been known to run dry for long periods. A synthetic record devised by Sir Alexander Gibb and Partners (Anon. 1969) showed that for the period 1929 - 1960, there was no flow at Tsienyane (Rakops) during the period 1929 to 1937, from 1941 to 1943 and again from 1945 - 1947, a total of 15 years out of 30 years. Consequently there is likely to be insufficient flow once every two years to fill the Mopipi Dam. At the time of writing (December 1973) and following two seasons of poor flow in the Boteti River a full scale crisis is impending with sufficient water left in the Dam for only a few weeks production. As a result a crash drilling programme is now in progress to supply the necessary ground water to keep the mine and township supplied with water (estimated at 1,2 million gallons per day ($5\,455 \text{ m}^3$)) and once again ground water will have to be used to prevent a disastrous blow to the national economy.

Recommendations for the temporary solution of the present crisis were made by Jennings (1973) and are based on the exploitation of the deep (saline) Middle Ecca sandstone aquifer present in the Orapa area and high transmissibility zones in the Cave sandstone aquifer as determined by photo-geological studies and airborne electromagnetic and magnetic surveys.

CONCLUSIONS

Hydrogeological studies in the Orapa area have enabled coefficients of storage and transmissivity for the important Cave sandstone aquifer to be calculated; estimates of the storage capacity per square kilometre have been made; water level observations have indicated that regular recharge of the aquifer takes place (supported by isotopic evidence); an estimate of the rates of flow in the aquifer has been made, while diamond core boreholes have given valuable information on the exact nature of the Kalahari Beds and the important aquifer at the top of the Cave sandstone.

APPENDIX 3SERWE BOREHOLE - SUMMARY LOG OF BASALT ZONE

0	-	37	Kalahari Beds sand
37	-	70	Decomposed basalt
70	-	87'9"	Basalt with numerous zeolites Base of flow
87'9"	-	105	Grey basalt
105	-	107	Basalt with scattered amygdales Base of flow?
107	-	15	Grey basalt
115	-	123	Highly amygdaloidal basalt Base of flow?
123	-	160	Slightly amygdaloidal grey basalt with amygdales of calcite and zeolite
160	-	193'5"	Dolerite (post-basalt, transgressive)
193'5"	-	200	Reddish amygdaloidal basalt with thin irr- regular tuff bands less than 25 mm thick.
200	-	219	Massive basalt (non-amygdaloidal) with thin black dolerite dyke at 212' - 213½'.
219	-	264	Reddish basalt with irregular vesicles cavities filled with green mineral (chlorite?)
264	-	264'4"	Amygdaloidal basalt
264'4"	-	299	Massive basalt Base of flow
299	-	302'5½"	Slightly amygdaloidal basalt
302	-	324	Black, fine-grained basalt (dolerite?)
324	-	325	Grey lava with 4" amygdaloidal lava at base
325	-	329	Black dolerite
329	-	334	Massive basalt
334	-	337	Amygdaloidal Basalt
337	-	349	Dolerite?
349	-	363'3"	Slightly amygdaloidal basalt becoming more so for 2'3" at base
363'¼"	-	392'¾"	Fine-grained black dolerite?
392	-	405	Massive basalt
405	-	408	Amygdaloidal basalt

408'	- 414'10"	Massive basalt
414'10"	- 420	Amygdaloidal reddish basalt
414'10"	- 431'6"	Slightly amygdaloidal basalt
431'6"	- 454'2"	Massive basalt
	- 467'	Highly amygdaloidal basalt
	- 490'	Massive basalt
490'	- 493'7"	Highly amygdaloidal basalt
	- 499'	
499'	- 506'10"	Amygdaloidal basalt
506'10"	- 524'6"	Massive basalt
	- 530'	Slightly amygdaloidal basalt
	- 536'	Highly amygdaloidal basalt
	- 554'	Massive basalt
	- 560'	Highly amygdaloidal basalt with two tuff bands 5'9" thick
	- 582'	Amygdaloidal basalt
	- 662'	Massive basalt
662'	- 669'	Amygdaloidal basalt
	- 717'	Massive basalt
	- 722'	Amygdaloidal basalt
	- 749'	Massive basalt
	- 782'4"	Amygdaloidal basalt with tuff band and green shale
	- 789'9"	Massive basalt
	- 791'8"	Amygdaloidal basalt
	- 826'5"	Massive basalt Base of basalt
	- 830'	Red indurated sandstone with thin calcite veins and fissure 3" from contact.

APPENDIX 4

TSHEPE DIAMOND CORE BOREHOLE (4) - HYDROGEOLOGICAL RESEARCH PROGRAMME

Depth of nearby pumping borehole 206 ft (62,8 m). Water struck 63 (19,2 m) and 186 ft (56,7 m). Rest level 42 ft (12,8 m). Base of Kalahari Beds at 96 ft (29,2 m). Yield 1 000 g.p.h. (76 l/min).

<u>0' - 15'</u>	12' ca. of core, 3' lost.
1'0"	Siliceous sdst., locally calcareous
0'5"	Calc. rubbly sdst., Fragmentary core
3'0"	Siliceous sdst., occasional horizontal parting of calc. cement
1'6"	Siliceous sdst., irregular calc. cement with cavities present
5'6"	Siliceous sdst., locally "pipes" infilled with red sand or cavernous
0'6"	"Breccia" of siliceous sdst with calc cement
<u>15' - 25'</u>	5' core 5' lost
0'6"	Siliceous sdst., locally calcareous
0'6"	as above with local ferruginous discolouration
4'0"	White siliceous sdst., locally calc.
<u>25' - 37'</u>	10 $\frac{1}{2}$ " core 11'1 $\frac{1}{2}$ " lost
10 $\frac{1}{2}$ "	Calc. sdst., with ferruginous discolouration
<u>37' - 44'</u>	6'9" core 3" lost
0'11"	Mottled siliceous sdst., local ferruginous staining with calc. cement
1'5"	White siliceous sdst., occasional rootholes infilled by poorly cemented (calc) sdst
1'4"	Ferruginous mottled sdst., slightly calc.
1'8 $\frac{1}{2}$ "	White sdst., slightly calc.,
0'2 $\frac{1}{2}$ "	Ferruginous stained sdst., slightly calc.
0'4 $\frac{1}{2}$ "	White calc. sdst
0'5"	Mottled (ferruginous stained) sdst., locally calc.
0'2 $\frac{1}{2}$ "	White sdst
<u>44' - 54'</u>	9'10" core 2" lost
3'6"	Mottled (ferruginous, calc) white sdst
1'7 $\frac{1}{2}$ "	White calc. sdst., vertical root holes infilled with poorly cemented sdst., irregular vertical joint
1'10"	Mottled calc, sdst
2'3 $\frac{1}{2}$ "	White(calc) sdst, slight mottling
0'1"	Calc sdst.
0'6"	Brown mottled (calc) sdsi

<u>54' - 64'</u>	10' Core
10'	White calc. sdst. with irregular ferruginous mottling
<u>64' - 84'</u>	20' Core
7'8"	as above
7'	"Conglomeratic" calc. sdst., round to elongate calc. sdst. ("pebbles" $\frac{1}{4}$ " to 1" diam.), light brown colour, in matrix of coarser grained calc. sdst., darker in colour
5'4"	calc. sdst., round to sub-angular "pebbles" ($\frac{1}{4}$ " to 1 $\frac{1}{2}$ " diam), dark brown to pink colour. Larger pebbles cut by calc. veins
<u>84' - 93'</u>	9' Core
0'5"	Calc. sdst. "conglomerate" sub-vertical slicken-sided joints with some silicification along joints; small angular sdst. pebbles and dark brown basaltic pebbles in sandy calc. matrix
0'6"	Light brown sdst., with siliceous and minor calc veining
0'11"	"Cgl" of dark brown basaltic pebbles in sandy matrix, fine siliceous veining of pebbles
3'0"	"Breccia" of basaltic pebbles with calc, veining $\frac{1}{2}$ " thick horiz. and fine vert
0'8"	White to pale brown calc. graphitic sdst.
0'4 $\frac{1}{2}$ "	as above but locally silicified
<hr/> ca.90' Base of Kalahari Beds <hr/>	
2'11"	Breccia of basalt, calcite veining, locally calc. sdst. infilling, basalt slightly amyg. (Base of flow)
2 $\frac{1}{2}$ "	Calc. sdst. with small basaltic pebbles
<u>93' - 101'</u>	6'4" Core 1'8" lost
0'5 $\frac{1}{2}$ "	Fine grained amyg. basalt, horiz. calc. veining
5'3 $\frac{1}{2}$ "	Amyg. basalt., horiz. calc. veins, locally fine vert. veins
0'7"	Basalt with calc. veining
<u>101' - 111'</u>	5'3 $\frac{1}{2}$ " core 4'8 $\frac{1}{2}$ " lost
3"	as above

3'9"	Fresh basalt, occasional calc. veins
0'2½"	Altered basalt
0'11"	Rubble of amyg. basalt (Top of flow)
0'2"	Calc. sdst. breccia, angular basalt fragments
0'2"	Amyg. basalt
<u>111'-120'</u>	1'2½" Core 7'9½" lost
0'5"	Amyg. basalt
0'½"	Calc. vein
0'9"	Fine-grained amyg. basalt (Base of flow)
<u>120'-126'</u>	1'10" Core 4'2" lost
0'2"	Rubble of above
0'4"	Basalt rubble
0'10"	Calc. clayey weathered amyg. basalt
0'1"	Fine grained amyg. basalt
0'5"	Sandy calc. rubble
<u>126'-132'</u>	3'0½" Core 2'11½" lost
1'6"	Fine grained amyg. basalt rubble
1'6½"	Amyg. basalt, calcite veining
<u>132'-137'</u>	5'2" Core
0'3½"	Amyg. basalt
0'0½"	Calc. sdst.
3'1"	Amyg. basalt, calc, veining, fine vertical veins
0'11"	Basalt, locally amyg. fine calc. veins predominant
0'1½"	Calc. sdst.
0'8½"	Basalt, fine calc. veins
<u>137'-144'</u>	6'4" Core 0'8" lost
0'4"	Calcareous sdst.
1'5"	Slightly amyg. basalt, calc veins
0'2½"	Calcareous sdst.
0'7½"	Slightly amyg. basalt
0'1"	Calcareous sdst.
3'8"	Basalt, vert. veins of calcite along joints
<u>144'-154'</u>	5'3" Core, 4'9" lost
4'4"	as above
0'11"	Fragmentary core of basalt
<u>154'-165'</u>	6'9" Core 4'3" lost
0'10"	Calcareous sdst. "Conglomerate" of Kalahari type
0'5"	As above with basalt fragments
0'4"	Calc. sdst. "Conglomerate" (Kalahari type)
0'9"	Calc veined decomposed basalt
1'6"	calc. sdst. "Conglomerate" same basaltic material
2'9½"	Calc. veined "Conglomerate", predominantly basaltic
0'1½"	Calc. sdst.

<u>165'-175'</u>	6'1" Core 3'11" lost
5'1"	Calc. sandy "Conglomerate", some basaltic material
0'6"	Calc. basaltic "Conglomerate"
0'6"	Calc. veined clay (? decomposed basalt)
<u>175'-182'</u>	2'4" Core 4'8" lost
1'10"	Clayey rubble
0'6"	Silty limestone
<u>182'-192'</u>	5'5" Core 4'7" lost
0'1"	limestone
1'5"	Fragmentary core of decomposed calc.basalt
3'11"	Decomposed basalt, clayey
<u>192'-200'</u>	6'9" Core 1'3" lost
1'4"	as above (rubble)
3'9"	Decomposed basalt
0'11½"	Fragmentary core of above
0'1½"	Drusy calcite
0'7"	Decomposed basalt
<u>200'-215'</u>	8'2" Core 8'10" lost
5'6½"	Basalt, sub-vert.veins (joints) of calcite
6'5½"	Altered basalt, sub-vert.joints
2'2"	As above, but locally calc.infilled joints
<u>215'-225'</u>	9'8" Core 0'4" lost
5'2"	Altered basalt, some calc.veins
4'6"	Alt.basalt.Vert.vein(1" diam.) of calcite with ? epidote
<u>225'-245'</u>	15'2" Core 4'10" lost
6'7"	Alt.basalt, some sub-vert.calc.veins
1'7½"	Friable alt.basalt,some calc.veins & calcification of basalt
0'9½"	Fragmentary core of limestone breccia,basaltic material
0'7"	Limestone
0'3"	Clay (decomposed base of flow?)
2'3'	Calcified alt.basalt, some calcite veins
3'1"	Alt.basalt,calcite veins
<u>245'-252'</u>	5'1" Core 1'11" lost
2'5"	Alt. basalt
2'8"	Fragmentary core of alt basalt
<u>252'-258'</u>	3'4" Core
3'0"	Alt.basalt.vert.calc.veins (along joints)
0'4"	Basalt
<u>258'-278'</u>	20' Core

0'2"	Slightly alt. basalt calc.veins
1' 2"	Basalt
0'2"	Alt. basalt
2'9"	Basalt
0'1"	Calcite druses
2'9"	Basalt
<u>278'-288'</u>	10' Core
10'	as above
<u>288'-295'</u>	7'10 $\frac{1}{2}$ " Core
7'5 $\frac{1}{2}$ "	as above
0'5"	Fine grained basalt (Base of flow?)
<u>295'-303'</u>	1'2" Core 6'10" lost
1'2"	Basalt
<u>303'-322'</u>	18'7" Core 0'5" lost
18'7"	as above
<u>322'-331'</u>	7'10" Core 1'2" lost
4'10"	as above
3'0"	Jointed basalt (fractured core)
<u>331'-340'</u>	8'4" Core 0'8" lost
8'4"	Basalt
<u>340'-350'</u>	10' Core
10'	as above
<u>350'-370'</u>	19'10" Core
6'11"	Basalt, calc.veins at 2 $\frac{1}{2}$ ", 6 $\frac{1}{2}$ ". 2'4" and between 4'-5'2"
0'7 $\frac{1}{2}$ "	Amyg. basalt. Calc.veins
0'4 $\frac{1}{2}$ "	Alt.amyg.basalt, calcified, calcite veined (Base of flow)
2'0"	Rubbly core of friable calc.sdst.
0'6 $\frac{1}{2}$ "	Amyg. basalt (off shoot of flow)
0'6"	Calc. sdst.
0'7"	Amyg, calcified basalt, calc.veins(Top of flow)
0'6 $\frac{1}{2}$ "	Amyg. basalt.calc. veins
0'3"	Alt. calcified basalt, calc.veins
7'3"	Amyg. basalt
0'3"	Basalt
<u>370'-380'</u>	9'8" Core
5'7"	as above
4'1"	Amyg. basalt
<u>380'-390'</u>	10' Core
3'4"	as above
4'2"	Basalt. few vesicles

0'4½"	Fine grained amyg. basalt (?Base of flow)
2'1½"	Amyg. basalt
<u>390'-409'</u>	19' Core
19'	as above
<u>409'-444'</u>	36'9" Core
5'2"	as above 1" band of calcified basalt at 5'
21'	Basalt, calcified band at 5'½", occasional zeolite and calc.vein
0'6"	Fine grained amyg. (calcified) basalt, Base of flow, contact oblique at 30° to core
0'6"	Green sdst. with apophyse of basalt
3'0"	Red fine grained calc. sdst.(Cave sdst.type)
0'6½"	Ferruginous red sdst.
0'3½"	Amyg. alt. basalt (Top of flow)
0'4"	as above with sdst. xenolith
0'8"	Amyg. basalt
0'4½"	Fine grained amyg. basalt with sdst. xenolith
2'7"	Amyg. basalt
0'3"	Sdst. Indurated
1'6½"	Basalt
<u>444'-448'</u>	5' Core
2'6"	as above
0'5"	Sdst. xenolith, indurated
2'1"	Amyg. basalt
<u>448'-457'</u>	8'4" core
8'4"	Basalt
<u>457'-467'</u>	9'4" Core
0'7½"	Amyg. basalt
0'0½"	Indurated sdst. xenolith
4'11"	Amyg. basalt
0'7"	Basalt, with slickensides jointing and calc.veins
1'11"	Basalt
0'0½"	Calc.vein, basalt locally amyg.
1'2"	Basalt
<u>467'-475'</u>	7'7½"Core
2'6"	Red basalt (alt.)
1'9"	Amyg. fine grained basalt, calc,veins (Base of flow)

 STORMBERG LAVA/CAVE SDST. junction at 471'3"

0'1"	Alt. sdst. with calc. vein
3'3½"	White calc.sdst.
<u>475'-485'</u>	4'9½" Core 5'2½" lost
4'9½"	Calc. sdst.
<u>485'-495'</u>	6'1" Core 3'11" lost
6'1"	Sdst. locally calcareous
<u>495'-505'</u>	8'8½" Core 1'3½" lost
8'8½"	as above
<u>505'-515'</u>	8'9" Core 1'3" lost
8'9"	as above

End of Hole