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GEOLOGIESE OPNAME

GROUND-WATER STUDIES IN NORTHERN NATAL, ZULULAND AND SURROUNDING AREAS

MEMOIR 52

by

W. L. van Wyk, Ph. D.

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EN AANGRENSENDE GEBIEDE

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P.O. Box 40
PRETORIA.

March,

PREFACE

To the Republic of South Africa, in common with most other territories in Southern Africa, underground water is of vital importance to the domestic economy inasmuch as it was and always will be a decisive factor in the settlement of large parts of it.

Fully aware of this, the Geological Survey concentrated over the past 25 years much of its efforts on the study of this subject in many parts of the country and collected a large volume of data bearing on the vast subject of geohydrology. On account of an incessant shortage of staff much of this could, however, never be analysed and, until now, even less processed for publication.

This memoir is the most ambitious publication on underground water ever undertaken in the Republic of South Africa, and its importance can be gauged from the fact that, although it deals only with Northern Natal and Zululand, many of the conclusions reached and certain principles established by the author in regard to the replenishment of underground water and the water-yielding properties of certain rock-types are so fundamental that they are bound to find application much farther afield.

The subject-matter covers a wide field and embraces such matters as the temperature and quality of ground-water and fluctuation of the water-level in bore-holes caused by earth-tides and moving trains. The publication should therefore prove to be a useful reference book to anyone who is interested in and does research on underground water.

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March, 1963.

This memoir is published by kind arrangement with, and with grateful acknowledgment to the University of Cape Town where the original text was accepted as a thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the Faculty of Science of that University.

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GROUND-WATER STUDIES IN NORTHERN NATAL, ZULULAND AND SURROUNDING AREAS

ABSTRACT

The area is bounded by lines of latitude 27° and 29° south, longitude 30° east and the Indian Ocean. It is approximately 19,500 square miles in extent and falls in no less than five physiographic regions.

The climate is warm subtropic, the precipitation occurs mainly in the summer months and the average rainfall varies from less than 800 mm to 1,800 mm per annum.

The Karroo System occupies approximately 70 per cent of the area and is for the purpose of this report the most important geological formation. The oldest rocks in the area belong to the Archaean Complex. Other Pre-Karroo rocks present belong to the Insuzi, Mozaan and Ntingwe Formations and the Table Mountain Series of the Cape System. These rocks mainly occupy the mountainous regions in the Nkandla and Eshowe Districts in the south and the Piet Retief and Ngotshe Districts in the north. The Cretaceous System occurs in the Coastal Belt but is almost everywhere covered by Tertiary and Recent sand.

All the rocks in the area, except the Tertiary and Recent deposits, are inherently impervious and none of them can yield more than about 100 g.p.h. in a conventional six-inch bore-hole. The storage, movement and occurrence of ground-water in these rocks are controlled by their secondary or epigenetic hydrological properties.

The secondary hydrological properties developed as a result of openings produced by jointing, faulting, the intrusion of the dolerite, physical weathering and the modification of these openings by the ensuing actions of weathering and percolating water.

The porosity of rocks increases in all the stages of jointing and weathering. The permeability and effective porosity reach a maximum in the initial stages and decrease again in the more advanced stages of weathering. The average effective porosity of decomposed basalt as calculated for a number of basins of weathering is 7·7 per cent.

In the Lowveld 85 per cent of the bore-hole supplies were struck at depths of less than 40 ft. below the water-table; in Northern Natal 78 per cent of the supplies were struck shallower than 70 ft. below the water-table, while in the Piet Retief area supplies were struck at depths of up to 250 ft. below the water-table. It is proposed that the average maximum depth at which water is struck in bore-holes is a function of the depth of weathering and the physiographic history of an area.

Rainfall has no linear relationship to the yield and percentage successful bore-holes that can be drilled in a particular formation. It, however, affects recharge and has a substantial influence on the depth of the water-table and the occurrence of springs.

The water-table in the area, except in the Tertiary and Recent deposits, is limited to joints, fissures and other permeable zones. Certain evidence suggests that most bore-holes tap " confined " water. The water-levels measured in bore-holes are thus strictly speaking, pressure or piezometric surfaces and not the water-table. It was, however, found that the water-levels measured in bore-holes can for all practical purposes be regarded as indicative of the depth of the water-table unless there is definite evidence to the contrary.

Water-levels in bore-holes fluctuate as a result of pumping, recharge, earth-tides, changes in barometric pressure and moving trains. Fluctuations caused by earth-tides were observed in all the bore-holes investigated. The average fluctuation during spring tides, i.e. during full and new moon, amounted to 0·075 ft. The largest fluctuation amounting to 0·8 ft., was observed in a bore-hole near Vryheid. Fluctuations caused by changes in atmospheric pressure were observed in most bore-holes drilled in basins of weathering in igneous rocks. Fluctuations caused by moving trains were observed in a bore-hole situated on the edge of a shallow-dipping dolerite sheet about 382 ft. from the railway line. Fluctuations of up to 0·05 ft. were registered in the bore-hole each time a train weighing more than 400 tons passed over the edge of the dolerite sheet.

In the Karroo sediments recharge takes place via joints, fissures and other permeable zones and once the soil is saturated to field-capacity rain-water percolates to the water-table not many hours after a downpour. In lava much more water is required to bring the soil and mantle of decomposed lava to field-capacity and leave an appreciable fraction available for ground-water increment. Recharge in the Karroo sediments in Northern Natal took place during every rainy season since 1952. The percentage rainfall that became available as ground-water in an old mine near Hlobane, Vryheid District, was 14·5. In the Stormberg lava in the Lowveld of Zululand, no recharge took place since 1943 and as a result 76·5 per cent of the bore-holes dried up. Recharge took place for the first time during September and October 1957 when 350 mm of rain fell in 21 days.

The temperature of water from approximately 180 bore-holes was measured. It varies from 15·2°C on the Highveld to 24·8°C in the Lowveld and coastal areas and was generally much the same as the mean summer air temperatures of the various regions. The temperature of water from bore-holes which were not over-pumped remained more or less constant. In the case of depleted ground-water reservoirs marked changes in the temperature were recorded after recharge had taken place. There is generally no difference between the temperatures of water from deep and shallow bore-holes. This has been explained by the fact that water in most deep bore-holes is supplied by the zone of weathering which generally does not extend to depths of more than 70 ft. below the water-table.

Based on chemical analyses the ground-water of the area was divided into 4 groups. The distribution of these groups is shown on a water-quality map. Groups A and B are confined to the Lowveld and coastal areas. The concentration of salts is usually higher than 750 parts per million and the water is in most cases unfit for human consumption. Groups C and D generally contain less than 500 parts per million and the water is highly suitable for domestic, live-stock and also for irrigation purposes.

The memoir is accompanied by a geological map of the area in colour on a scale of 1:500,000 and 53 illustrations.

I. INTRODUCTION

A. OBJECTS AND SCOPE OF STUDY

Most of the water obtained in bore-holes in Natal and Zululand, and for that matter in most of South Africa, is supplied by rocks which are inherently impervious. The occurrence, storage and movement of ground-water in these rocks are controlled by their secondary or epigenetic hydrological properties which developed as a result of numerous interrelated geological, physical, chemical, climatic and topographic conditions that affected the rocks at different times after their formation.

Very little has been published on this subject. In most publications dealing with ground-water, the emphasis falls mainly on location and little attention is paid to the basic aspects of the ground-water problem. The current theories regarding the water-table, movement of ground-water in and the hydrological properties of these rocks are not based on comprehensive investigations of natural conditions. They are merely generalisations which have been deduced from the well-known behaviour of ground-water in pervious material.

With the ever-increasing demand for ground-water it is obvious that a better understanding of the geological, physical and other processes that produced the secondary hydrological properties and how these properties control the storage and movement of ground-water, is of primary importance, not only in the successful selection of bore-hole sites but also, inevitably so, in any quantitative ground-water study of an area.

The main objects of this memoir are:—

(i) To differentiate between the primary and secondary hydrological properties of the more important geological formations in the area;

(ii) to describe the more important processes that produced the secondary hydrological properties, with special reference to the important role played by weathering and percolating water; and

(iii) to present qualitative and quantitative data on the hydrological properties produced by the above processes and to examine to what extent these properties control the occurrence, storage and movement of ground-water in the rocks of the area.

In addition, this memoir embodies the results of investigations on the following aspects of ground-water:—

(i) Recharge,
(ii) the water-table,
(iii) water-level fluctuations in bore-holes,
(iv) temperature and
(v) quality.

B. PERIOD OF STUDY

This study is based on geohydrological data collected during the period 1946 to 1958. During this period the author, as a member of the Underground Water and Geophysics Branch of the Geological Survey, was engaged in the selection of bore-hole sites and ground-water research in Natal and Zululand. Over 1,500 bore-hole sites were selected with geological and geophysical methods. Most of these sites were revisited after they had been drilled for a scrutiny of the results and electrical logging of the bore-holes. In addition, an almost complete set of records of all existing bore-holes in the area was collected and listed for study.

The methods and time of investigation of other aspects of the study, which took place within more restricted periods, are given, where appropriate, in the respective chapters.

C. IMPORTANCE OF GROUND-WATER IN THE AREA

Generally, ground-water supplies permit the spread of population in the area, while the concentration of population, and all that goes with it, is dependent on water from rivers. Only a few of the smaller villages, e.g. Ubombo, Magudu and Melmoth, are still dependent on bore-holes for their water-supply. All the bigger towns obtain their water from rivers.

Bantu areas, lying mainly within the rugged, mountainous districts of Nongoma, Hlabisa, Mahlabatini, Nqutu and Msinga, comprise approximately 8,000 square miles which is a little more than 40 per cent of the whole of the study area. These areas are generally well supplied with streams and springs and the usage of water from bore-holes plays but a very subordinate role. The total number of water-yielding bore-holes in these areas amounts to less than one hundred.

In the rest of the area, however, which is comparatively speaking less well supplied with streams and springs, water from bore-holes has become of utmost importance to the farming community during the last 12 years. Prior to 1946 there were less than 300 bore-holes in the area, but the number had increased to approximately 3,300 by the end of 1958.

This tremendous increase in the importance of water from bore-holes was necessitated by the following developments:—

1. (1) Due to an increasing population, many farms were subdivided and bore-holes were required to supply water on the subdivisions for stock and domestic purposes.
2. (2) The early settler in South Africa utilised his farm mainly according to the water resources naturally available on the farm. In most provinces, and especially in Natal, this injudicious practice of land utilisation was one of the main contributory causes of extensive soil erosion in the country. The Soil Conservation Act No. 45 " to make better provision for the combating and prevention of soil erosion, and for the conservation, protection and improvement of the veld, the soil, the surface of the land, the vegetation and the sources and resources of the water supplies in the Union ", was passed in 1946. Under this act an increasing number of farms are annually scientifically planned, subdivided into camps (large paddocks) and fenced in. A great number of bore-holes have been drilled to provide water for stock in these camps.
3. (3) The planting of large wattle plantations, especially in the Vryheid District, caused a lowering of the water-table and consequently a great number of springs have dried up. Landowners resorted to bore-holes for water.
4. (4) Prior to 1946 the cattle disease Nagana, which is carried by the Tsetse fly, precluded stock ranching in the Lowveld and coastal regions. More recently with the use of insecticides such as D.D.T. and B.H.C., the area has virtually been cleared of this dreaded cattle disease, and today the Lowveld is almost exclusively utilised

> for cattle ranching. Except for the Mkuze and Pongola Rivers, there are no other perennial streams or springs in these areas, and an estimated 80 per cent of the cattle are dependent on water from bore-holes. Over 400 bore-holes have already been drilled in this now prosperous area.

The distribution of the total number of successful and unsuccessful bore-holes in the area is given in figure 1.

The number of bore-holes, wells and springs in the 13 more important farming districts of the area is given in table 1. Most of the data have been obtained from the Agricultural Census (1950). The number of water-yielding and non-water-yielding bore-holes in the districts obtained from a comprehensive set of bore-hole records, is given for the period ending 31st December, 1958. As a matter of passing interest it may be added that the 1950 census figures as regards the water-yielding bore-holes are fairly accurate, but the figures given for non-water-yielding bore-holes are invariably too low and thus totally unreliable. This is probably due to the fact that farms often change hands and new owners are usually not informed, and thus not aware of all the dry bore-holes on the farms.

The importance of ground-water in these districts is shown by the percentages of persons and small and large stock dependent on it. In some districts like Babanango, only 2 per cent of the large stock is dependent on water from bore-holes while in other districts, for example Ubombo, almost 75 per cent of the cattle are dependent on bore-hole supplies.

A perusal of table 1 further shows that very little ground-water is used for irrigation purposes. The average yields of bore-holes in the area are from 800 to 1,000 g.p.h. and are seldom sufficient to irrigate with. The " brack " waters of the coastal areas on the other hand, are unsuitable for irrigation purposes.

D. ACKNOWLEDGMENTS

The author wishes to record his indebtedness and sincere appreciation to the following:—

All his colleagues, and especially Mr. J. C. Kruger, Mr. G. J. Ellis and Mr. P. S. Meyer, for their assistance with the field-work. Various members of the Department of Water Affairs who drilled most of the bore-holes and for their co-operation in carrying out certain observations; Sgt. J. Badenhorst of the South African Police for measuring the flow of water from the old mine near Hlobane and Dr. J. F. Enslin of the Hydrological Research Division of the Department of Water Affairs for his supervision and advice during the investigations.

II. DESCRIPTION OF AREA

A. LOCATION

Excluding the portion of Swaziland, the area selected for study coincides with the Vryheid Sheet SE 29/30 of the Topographical Series of South Africa 1: 500,000. It lies on the eastern coast of South Africa between 27° and 29° south latitude, 30° east longitude and the Indian Ocean. The total area is about 19,500 square miles and it forms a portion of the hills and plateaux which descend from the Drakensberg to the Indian Ocean.

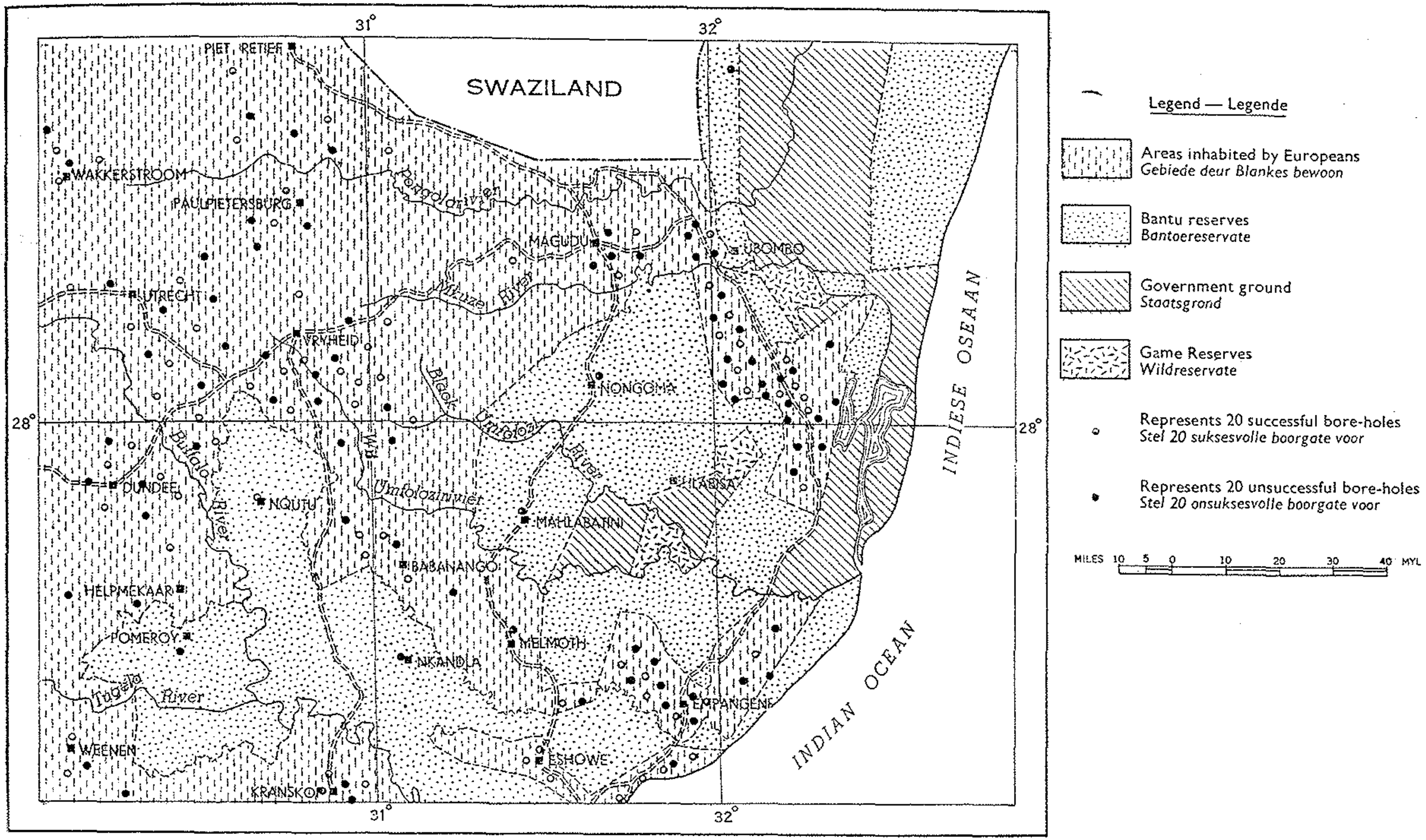

FIG. 1.—Plan showing the distribution of bore-holes in the area.

TABLE 1.—THE NUMBER OF BORE-HOLES, WELLS AND SPRINGS AND THE NUMBER OF PERSONS, LARGE AND SMALL STOCK DEPENDENT ON GROUND-WATER IN THE 13 MORE IMPORTANT DISTRICTS IN 1950 AND 1958*

District	Baba-	Dundee	Eshowe	Help-		Lower		Paul-	Piet	Ubom-			Wakker-		Per-

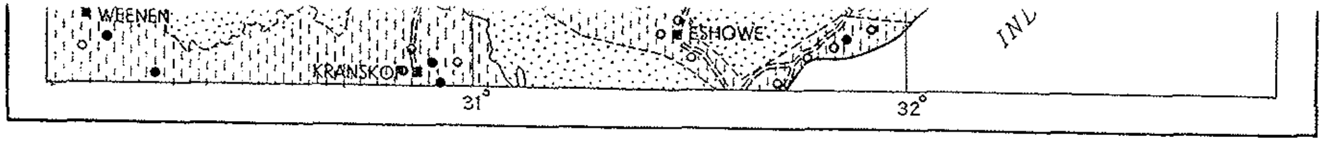

FIG. 1.—Plan showing the distribution of bore-holes in the area.

TABLE 1.—THE NUMBER OF BORE-HOLES, WELLS AND SPRINGS AND THE NUMBER OF PERSONS, LARGE AND SMALL STOCK DEPENDENT ON GROUND-WATER IN THE 13 MORE IMPORTANT DISTRICTS IN 1950 AND 1958*

District	Babanango	Dundee	Eshowe	Helpmekaar	Hlabisa	Lower Umfolozi	Ngotshe	Paulpietersburg	Piet Retief	Ubombo	Utrecht	Vryheid	Wakkerstroom	Total		Percentage of total
Number of farms and holdings 1 morgen and bigger................	183	336	143	137	96	205	275	182	430	35	507	591	285	3,405		—
Area occupied by farms of 1 morgen and bigger....	176,332	166,419	37,123	100,514	95,865	106,351	344,447	127,666	360,600	59,915	408,452	407,535	210,743	2,601,962		—
Number of water-yielding (31st December, 1958)* bore-holes, i.e. yield more than 100 g.p.h.........	43	198	23	33	162	134	85	10	104	26	184	196	89	1,287	2,916	44·13
Number of dry bore-holes (31st December, 1958)*, i.e. yield less than 100 g.p.h.................	42	192	25	51	196	148	126	6	65	165	287	206	120	1,629		55·86
Number of flowing bore-holes on 31st December, 1956*................	nil	3	nil	nil	1	nil	1	1	nil	nil	1	4	1	12		—
Number of permanent springs on farms on 31st August, 1950..........	536	896	254	568	31	214	585	870	1,646	2	1,710	1,190	1,496	9,998	13,903	71·91
Number of non-permanent springs on farms on 31st August, 1950..........	119	559	94	230	26	108	120	261	442	9	823	688	426	3,905		—
Persons who were mainly dependent for water from bore-holes and wells during 12 months ended 31st August, 1950......	419	4,289	435	1,197	1,608	7,206	990	292	8,173	477	3,611	2,353	948	31,998	135,109	23·68
Persons who were mainly dependent for water from other sources during 12 months ended 31st August, 1950..........	6,585	8,988	6,282	4,011	2,195	10,788	8,235	8,500	11,732	321	10,100	20,319	5,055	103,111		76·32

NOTE.—A bore-hole usually has a diameter of six inches and is drilled by a boring machine. A well is dug by hand, usually has a diameter of 3 to 6 ft. and is seldom deeper than 50 ft.

*Figure supplied by the author up to 1958.

Based on Agricultural Census, 1950.

TABLE 1.—THE NUMBER OF BORE-HOLES, WELLS AND SPRINGS AND THE NUMBER OF PERSONS, LARGE AND SMALL STOCK DEPENDENT ON GROUND-WATER IN THE 13 MORE IMPORTANT DISTRICTS IN 1950 AND 1958*(*continued*)

District	Babanango	Dundee	Eshowe	Helpmekaar	Hlabisa	Lower Umfolozi	Ngotshe	Paulpietersburg	Piet Retief	Ubombo	Utrecht	Vryheid	Wakkerstroom	Total		Percentage of total
Number of large stock mainly dependent for water from bore-holes and wells during 12 months ended 31st August, 1958..........	1,227	6,949	2,550*	2,715	16,553*	35,003*	43,535*	4	3,613	17,195	7,493	3,375	2,338	142,550	623,103	22·88
Number of large stock mainly dependent for water from other sources during 12 months ended 31st August, 1950......	43,895	43,738	6,423*	19,961	10,244*	29,003*	58,256*	29,466	45,299	5,688	75,086	84,519	28,975	480,553		77·12
Number of small stock mainly dependent on water from bore-holes and wells during 12 months ended 31st August, 1950.........	1,606	18,649	82	2,900	1,197	695	860	nil	3,964	1,061	13,466	4,158	11,332	59,970	692,487	8·66
Number of small stock mainly dependent on water from other sources during 12 months ended 31st August, 1950.................	42,658	49,100	1,080	37,880	1,751	1,174	33,068	36,683	43,349	47	184,498	86,615	114,614	632,517		91·34
Land in morgen actually irrigated during 12 months ended 31st August, 1950, from bore-holes and wells........	11	35	—	2	—	—	28	3	57	2	52	24	3	217	2,457	8·83
Land in morgen actually irrigated during 12 months ended 31st August, 1950, from other sources...............	114	322	3,037	113	57	1,010	980	521	3,656	236	811	784	599	2,240		91·17
Number of water-yielding wells at 31st December, 1950*................	7	105	17	7	19	42	4	nil	22	5	49	54	14	345		—

NOTE.—A bore-hole usually has a diameter of six inches and is drilled by a boring machine. A well is dug by hand, usually has a diameter of 3 to 6 ft. and is seldom deeper than 50ft.

***Figure supplied by the author up to 1958.**

Based on Agricultural Census, 1950.

B. Physiographic Regions

Based mainly on the work of the Geological Survey (1955) and King (1951) the area under consideration falls into five regions each of relatively uniform physiography (fig. 2).

1. COASTAL BELT

In the north this region forms a 40-mile-wide sandy plain between the Lebombo Mountain and the Indian Ocean. It seldom exceeds 250 feet above mean sea-level and it gradually narrows southwards and is approximately 15 to 20 miles wide at the latitude of Eshowe. In the south the belt is more undulating than in the north, and is underlain mostly by Pre-Cretaceous rocks which are not covered by Tertiary and Recent sand except along the coast.

2. LOWVELD

The Lowveld is an undulating bush-clad strip of country separating the Coastal Belt and the Lebombo from the Middleveld. It generally lies between 500 and 2,000 feet above sea-level.

In the north the Lowveld occupies the only semi-arid region in Natal (Schulze, 1947).

3. LEBOMBO

The narrow north–south trending Lebombo Mountain range, which dies out at the latitude of Ingweni Station, rises abruptly from the Coastal Belt on the east and the Lowveld on the west and reaches an elevation of 2,300 feet.

King (1951) classifies the Lebombo Mountain as Lowveld while the Geological Survey (1955) includes both this mountain range and the Lowveld in what is called the Lebombo Region. There is a marked difference between the climate (fig. 3), the vegetation and the quality and occurrence of ground-water on the Lebombo Mountain range and on the Lowveld and Coastal Belt on either side. For this reason, the author classifies the Lebombo as a separate entity.

4. EASTERN MIDLANDS OR MIDDLEVELD

Most of the area under consideration falls in this region. It extends inland from the Lowveld and includes the elevated areas like Ceza and Qudeni. North of these elevated and highly dissected areas the altitude falls to the undulating flats of Northern Natal which lie from 3,500 to 4,000 feet above sea-level. This country is studded with isolated mountains such as Zuinguin, Hlobane and Thabankulu in the east, and Doringberg and Biggarsberg in the west.

5. HIGHVELD

This region starts just northwest of Vryheid and is a highly dissected plateau lying at an altitude of 5,000 to 6,000 feet above sea-level. It represents a spur of the Drakensberg which ends in a series of outliers of high ground at its eastern extremity.

C. Drainage

Comparatively speaking, the area is well supplied with numerous rivers of which the largest are the Pongola, Mkuze, Black and White Umfolozi, Umhlatuzi, Blood and Tugela.

Except for the Pongola and Mkuze which flow through flatter country, all the rivers have steep gradients. The velocity of water flow is high; there are few large still pools, and the rivers generally consist of a series of rapids.

1950*.........	7	105	17	7	19	42	4	nil	22	5	49	54	14	345	—

Note.—A bore-hole usually has a diameter of six inches and is drilled by a boring machine. A well is dug by hand, usually has a diameter of 3 to 6 ft. and is seldom deeper than 50ft.

*Figure supplied by the author up to 1958. Based on Agricultural Census, 1950.

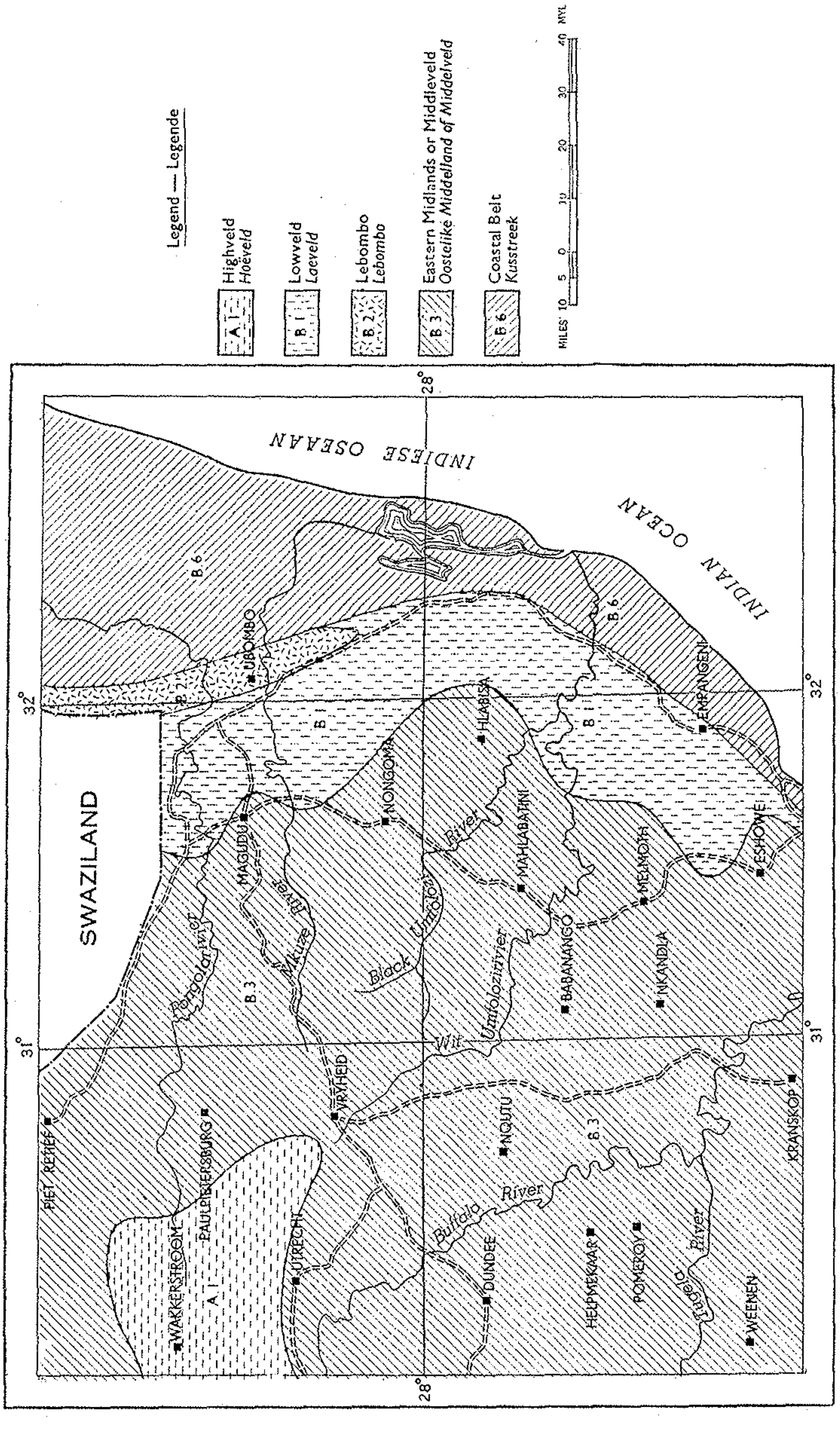

FIG. 2.—Physiographic regions of the area.

The larger rivers are all perennial, but during the dry winter season their flows are considerably reduced, and in years of drought even large rivers such as the Mkuze and the Black and White Umfolozi may dwindle to mere trickles, and occasionally have been known to dry up almost completely, especially along their lower reaches.

In addition to the large rivers there are numerous streams and rivulets, and in the rainy season almost every valley has a stream of running water. Along the coastal belt these streams are perennial. In the Middleveld, however, chiefly owing to the highly dissected topography and the comparatively high intensity of thunderstorms, the flow of the smaller streams is most erratic. All are subject to sudden floods in summer, while they frequently dry up completely after a short spell of dry weather. Some of the larger tributaries, being fed by springs, are perennial, but most of them also dry up during winter.

FIG. 2.—Physiographic regions of the area.

D. CLIMATE

1. GENERAL CHARACTERISTICS

In the area topographical features and climate are closely associated, a fact which is clearly evident when relief maps are compared with maps showing isohyets. The undulating nature of the country, however, results in the formation of local climates varying within such short distances that the available climate classification maps are not detailed enough to show these isolated micro-climates.

According to a broad classification by Schulze (1947), based on the deficit of precipitation in relation to evapo-transpiration, using the index described by Thornthwaite (1948), the area falls within a warm humid to sub-humid climate except for the areas immediately east and west of the Lebombo Mountain range which stand out conspicuously as warm semi-arid regions (fig. 3).

2. RAINFALL

Precipitation occurs mainly in the summer months, i.e. November to March, and most of it falls in heavy showers during thunderstorms. Except for the Coastal Belt the area is subject to prolonged droughts in the spring and early summer. The Coastal Belt has two rainfall maxima, in January and in March; the inland part has a single maximum in January.

Along the southern Coastal Belt the annual precipitation exceeds 1,000 mm, and in places is as high as 1,500 to 1,800 mm. In the Midlands the annual precipitation seldom exceeds 1,000 mm; in the low country to the east and west of the Lebombo, and in all the larger river-valleys it is below 800 mm. In the uplands precipitation is again higher, and on the Qudeni and Ceza Escarpments exceeds 1,800 mm per annum. The rainfall map (fold. 1) demonstrates very clearly how the general topography influences the rainfall. By intercepting the moist southeast and southwest rain-bearing winds, the Lebombo Mountains are responsible for the dry belt in the Pongola, Mkuze and Umzunduzi flats; the Qudeni and Helpmekaar Mountains are similarly responsible for the arid conditions of the Buffalo, Tugela and Sundays River valleys. Aspect also has a pronounced effect upon rainfall, and this is especially the case at higher altitudes where the fall on the southeastern faces of the mountains is much increased since they face the chief rain-bearing winds.

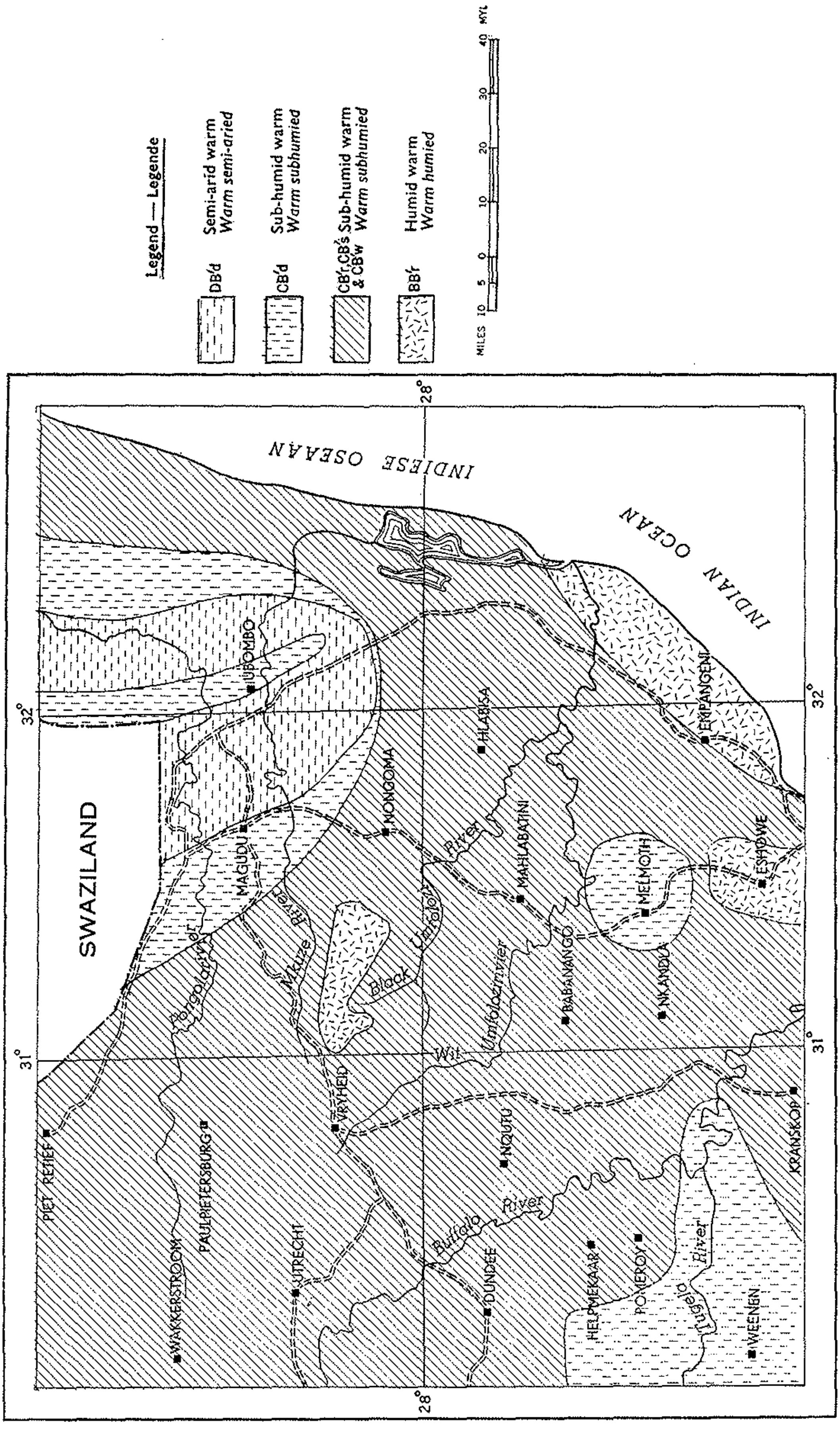

FIG. 3.—Climates of the area according to Thornthwaite's Classification (after Schulze, 1947).

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3. TEMPERATURE AND HUMIDITY

Unfortunately very few temperature and humidity stations have been established in the area and in several of these the results are not sufficiently complete to be of real value. Few records are available for the uplands of Qudeni, Ngome and Ceza of high rainfall and for the larger river-valleys of low rainfall.

The mean temperatures (mean maximum+mean minimum÷2) for a number of stations are given in table 2 (Climate Statistics, 1954 and Beater, 1949).

The differences in summer and winter temperatures increase from the coast to the inland areas where hot summers are followed by cold to very cold winters. January is the hottest month and July the coldest. Frosts are practically unknown on the Coastal Belt, though light frosts occur in some of the valleys. In the Midlands and Northern Natal frosts are more frequent, and may be severe in certain deeper valleys. On the uplands of Qudeni and the Drakensberg Escarpment severe frosts are common and falls of snow are not unusual in winter.

TABLE 2.—AIR TEMPERATURES

Station	Mean temperature in °C		
	Summer (October–March)	Winter (April–September)	Mean annual
Empangeni	24·05	18·8	21·4
St. Lucia	23·4	19·5	21·5
Mkuze	24·3	19·4	21·8
Pongola	24·2	19·8	22·0
Nkwaleni	23·8	18·3	20·6
Eshowe	21·3	17·8	19·6
Melmoth	21·1	17·3	19·2
Hlabisa	21·9	18·1	19·9
Weenen	22·1	14·5	18·4
Dundee	20·1	13·9	17·0
Vryheid	20·1	14·8	17·6
Paulpietersburg	19·9	14·7	17·3
Piet Retief	19·8	14·0	16·6
Wakkerstroom	16·3	10·1	13·2

E. SOILS

With the exception of certain small areas which include parts of the Coastal Sugar Belt (Beater, 1957) no detailed survey of the soils in the area has yet been carried out. Except for work done by Summer (1957) on the physical and chemical properties of the Tall Grass Veld soils (see fig. 5), nothing has been published on the hydrological characteristics of the various soil types.

According to a broad classification (Van der Merwe, 1940) into soil-groups according to their characteristic morphology as influenced by climate, parent material, vegetation and other factors, the soils of the area fall into four main types, viz. 1. podsolic, 2. lateritic, 3. subtropical and 4. miscellaneous (fig. 4).

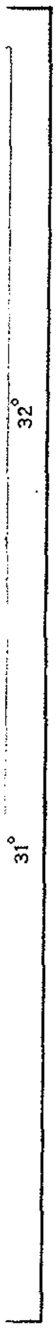

FIG. 3.—Climates of the area according to Thornthwaite's Classification (after Schulze, 1947).

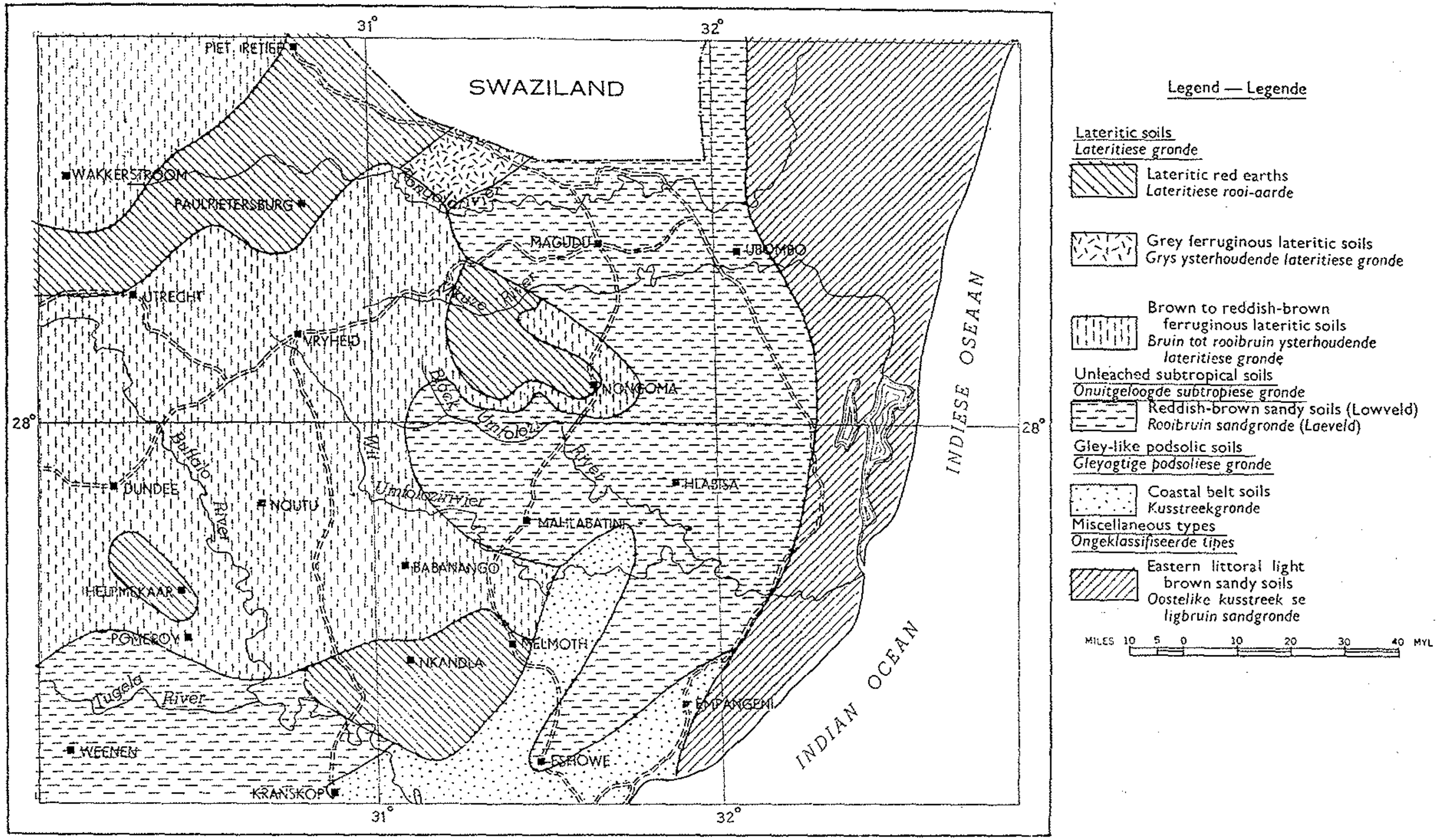

FIG. 4.—The distribution of soil types (after Van der Merwe, 1940).

1. PODSOLIC TYPES

(*a*) *Coastal Belt Soils*

These soils are of residual-colluvial origin and consist of light to dark-greyish brown, sandy loam, to a sandy clay loam with a crumbly structure.

This subgroup is confined to a comparatively narrow strip of the Coastal Belt. It extends from beyond Mtunzini in the south to Empangeni where it sweeps inland through Eshowe along a narrow strip terminating at Hlabisa in the north.

2. LATERITIC TYPES

(*a*) *Lateritic Red Earths*

The soils constituting this group are, due to the surface-relief, of residual and colluvial origin. They are characteristically deep red in colour and are clayey but possess a good structure.

Their main occurrence is in the north of the area where they form a narrow band 10 to 20 miles wide which runs through Utrecht, Paulpietersburg and the wattle growing areas of Piet Retief. The soils of the Helpmekaar, Nkandla and Ngome highlands represent outliers.

(*b*) *Brown to Reddish Brown Ferruginous Lateritic Soils*

The normal soils, which have developed under good surface-drainage consist of a greyish brown sandy loam to sandy clay loam, slightly dense, breaking into crumbs. Then soils rest on light-brown gravelly sandy loam which is fairly dense but not cemented. The gravel consists of iron-oxide concretions mixed with soil material.

They occupy the bulk of the area and cover most of Northern Natal and Northern Zululand.

(*c*) *Grey Ferruginous Lateritic Soils*

This subgroup consists of a grey sand with a slightly coherent, friable structure and is underlain by a brown, ferruginous concretionary layer of well-cemented hardpan called " ouklip ". The water-absorbing capacity of the soils is good but their water-retaining capacity is extremely poor owing to their shallowness and sandy nature.

The soils occupy a small area extending from north of Louwsburg into Swaziland.

3. UNLEACHED SUBTROPICAL TYPES

(*a*) *Reddish Brown Sandy Soils* (*Lowveld*)

These are typical Lowveld soils and although classified as sandy soils the group also includes the dark clay soils derived from the Stormberg basalt.

The soils are residual and as a rule rather shallow. A marked characteristic is the absence of any apparent horizons and of any secondary deposits like iron-oxide concretions or nodules of carbonate of lime in the soil sections.

They occur from Eshowe northwards and occupy the bush-clad Lowveld areas west of and including the Lebombo Mountain range.

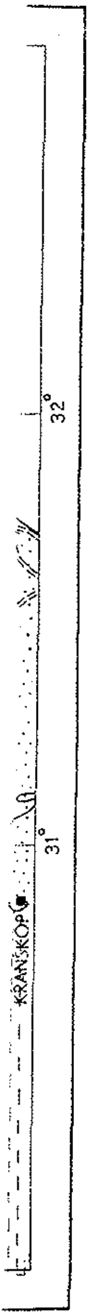

FIG. 4.—The distribution of soil types (after Van der Merwe, 1940).

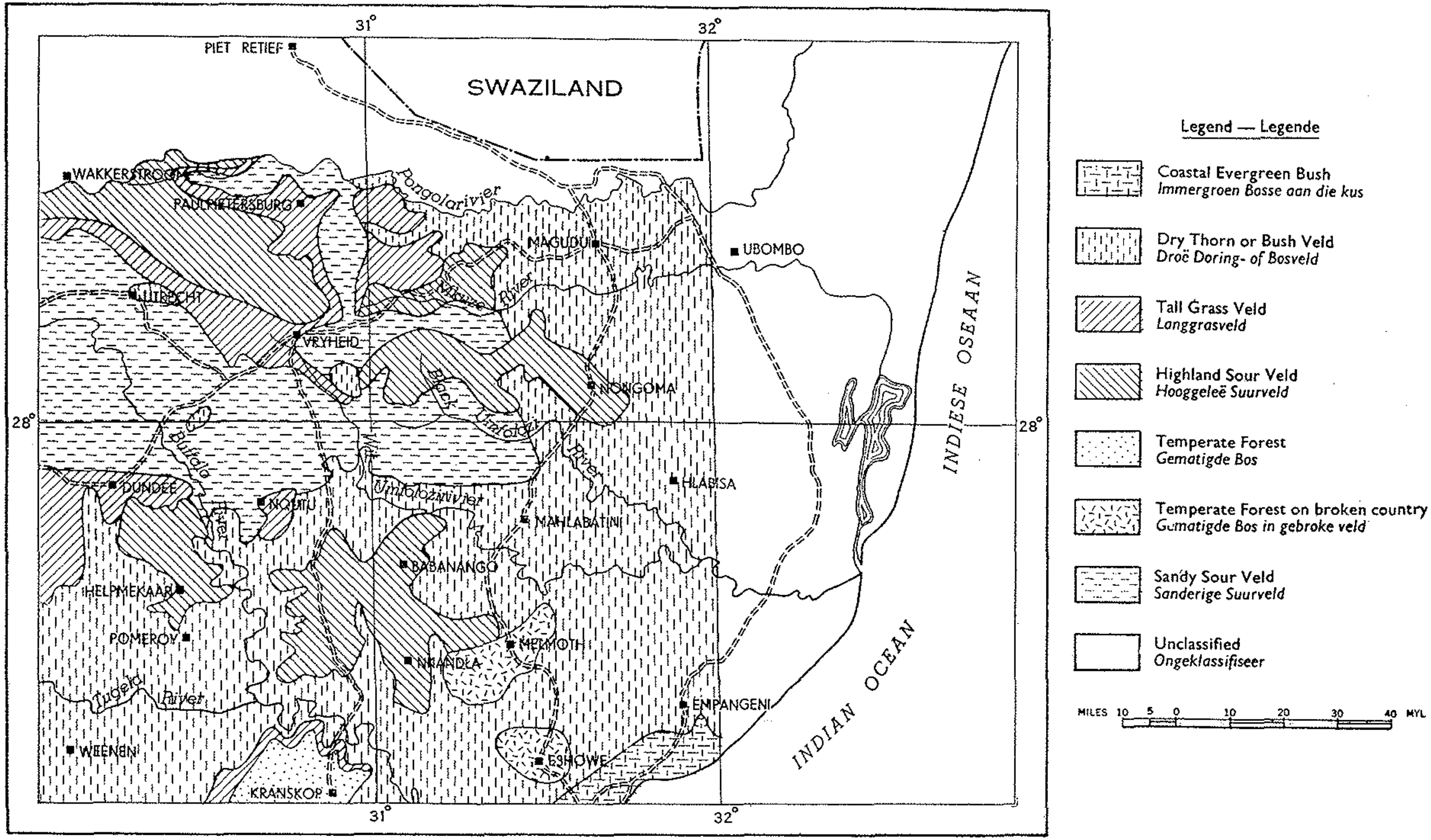

FIG. 5.—The distribution of vegetation types (after Pentz, 1950).

4. MISCELLANEOUS TYPES

(a) *Eastern Littoral Light-brown Sandy Soils*

These soils are classed as a light-brown, sandy soil and the material from which they are developed consists of a ubiquitous mantle of sand, with no other exposures except along banks of creeks and lagoons. They occupy an area 20 to 50 miles wide extending from Richard's Bay along the coast into Portuguese territory in the north.

F. VEGETATION

The broad consideration of ecology with its manifold aspects has, as regards Natal and Zululand, been treated by Bayer (1938) and Pentz (1950).

As has already been shown, climate in the area varies more with changes in altitude than with any other factor, and thus it is found that vegetation can, to a large extent, be correlated with altitude. The validity of this statement is well illustrated by the following classification of vegetation types in the study area by Pentz (1950).

1. COASTAL EVERGREEN BUSH

This vegetation type extends from the coast to an altitude of approximately 1,500 feet above sea-level (fig. 5). The vegetation changes to thornveld where it is intersected by river-valleys. On the whole the coastal bush consists of low forest and scrub of which the following species are common: *Millettia caffra*, *Celtis kraussiana* and *Canthium* spp.

Taller bush and forest occur in some valleys and farther inland on hill-slopes. Characteristic examples are *Celtis kraussiana*, *Alberta magna*, *Combretum* spp. and *Ficus* spp.

Amongst the grasses are *Aristida junciformis*, *Bothriochloa* spp. and *Chloris gayana*.

2. DRY THORN OR BUSH VELD

The Dry Thorn Veld extends up most of the river-valleys from the coast to altitudes of just over 3,000 feet. It extends over the greater part of the basins of such rivers as the Tugela, the Umfolozi and the Pongola.

The most important tree species are *Acacia arabica*, *Acacia karroo* and various other *Acacia* spp.

The main grasses of the area are *Chloris gayana*, *Digitaria* spp. and *Eragrostis superba*.

3. TEMPERATE FOREST ON BROKEN COUNTRY

This vegetation type occurs at an altitude of 3,400 to 4,000 feet on the Melmoth and Eshowe hills. The country is broken and the soils are mostly red, deep, continuous and not easily erodible.

The main tree species are *Podocarpus* spp., *Scolopia mundtii* and *Cussonia spicata*.

4. SANDY SOUR VELD

The Sour Veld occurs between 3,000 and 4,000 feet and occupies a large area in the districts of Newcastle, Dundee, Utrecht and Vryheid.

This area is fairly flat, the soils are poor, shallow and sandy and the rainfall is erratic and ranges from 600 to 900 mm per annum.

The vegetation consists of poor grassveld of which the typical species are *Andropogon eucomus*, *Eragrostis* spp. *Digitaria tricholaenoides*.

FIG. 5.—The distribution of vegetation types (after Pentz, 1950).

5. TALL GRASS VELD

This veld type occurs at an altitude of 3,500 to 4,500 feet, and extends from Dundee along a narrow strip below the foothills of the Drakensberg to Utrecht and Vryheid.

The country is undulating and the soils on the whole are shallow. The rainfall averages about 750 mm per annum, but is poorly distributed.

The only trees are *Acacia lasiopetalu* and *Acacia caffra* occurring as isolated trees or in small clumps.

The main grasses are *Hyparrhenia* spp., *Sporobolus indicus* and *Setaria ingrirostri.*

6. HIGHLAND SOUR VELD

The Sour Veld occurs at an altitude of 4,500 to 6,000 feet. It extends in a narrow belt from below the Drakensberg through Utrecht to Vryheid. There are also a few isolated high-lying areas with this type of veld in the districts of Helpmekaar, Louwsburg, Nongoma, Babanango and Qudeni.

The country is undulating, the soils, though poor, are deep and continuous, are mainly of a sandy nature, and are not easily erodible.

The veld carries a very dense sward of fairly short grass of which the following species are typical: *Tristachya hispida, Themeda triandra* and *Monocymbium cerisaeforme.*

G. HUMAN ACTIVITIES

Human activities in the area are largely devoted to a variety of farming and mining enterprises. Live-stock farming, and particularly cattle farming, overshadows crop production by far and constitutes more than 70 per cent of the cash income derived from farming. In 1957 the total number of cattle in the area amounted to no less than $1\frac{3}{4}$ million. (Unpublished figures obtained from the Department of Agriculture.)

The main lines of farming on the different veld types are given in table 3.

TABLE 3.—AGRO-ECONOMIC CLASSIFICATION (AFTER PENTZ, 1950)

Veld type	Main line of farming	Subsidiary and supporting lines
Coastal Evergreen	Sugar	Dairy cattle, tropical fruits
Dry Thorn or Bush Veld	Beef ranching	—
Tall Grass Veld	Beef ranching	Fodder crops; hay
Highland Sour Veld	Dairying	Potatoes, fodder crops
Temperate Forest	Wattle and timber	Dairying
Sandy Sour Veld	Beef ranching	Wattle and timber

More than 90 per cent of the coal in Natal is produced in the area. The average monthly output of the collieries in the Vryheid, Dundee, Utrecht and Newcastle Districts amounts to approximately 490,000 tons. All aspects of the coal resources have been comprehensively described by Blignaut and Furter (1940, 1952).

Other minerals such as gold, asbestos and fluor-spar are also sporadically mined in Zululand. Most occurrences are described in Mineral Resources of the Republic of South Africa (1959).

III. GEOLOGY

A. General Geology

A detailed account of the geology of the area does not lie within the scope of this report and only a short description of each formation will be given.

In 1904 Anderson published a geological sketch map of the area. Subsequently about two-thirds of the area were geologically mapped and described by Blignaut and Furter (1940, 1952), Botha (1939), Du Toit (1931), Genis (1960, 1961), Humphrey and Krige (1931, 1932), Matthews (1959), Rossouw *et al.* (1950) and Visser (1959). The author made a reconnaissance survey of portions of the area.

The accompanying geological map has been compiled from the available information (see fold. 3 in pocket). It should be noted that as large areas have not yet been mapped, especially in Zululand, the map is not everywhere reliable. Although the ubiquitous Karroo dolerite dykes and sills play a very important role in the occurrence of ground-water, they are not shown on the map, firstly because it would be unpracticable to show all the intrusions on the map and secondly because they would have to be omitted anyway from the unsurveyed portions.

The principal geological formations represented in the area are summarised in table 4.

Table 4.—GEOLOGICAL FORMATIONS

Tertiary to Recent			Sand, " fossil soil ", ferricrete and other superficial deposits
Cretaceous System		Upper Division	Sandstone, shale, limestone
		Lower Division	Conglomerate, sandstone, shale
Karroo dolerite			Dykes and sheets
Karroo System	Stormberg Series	Bumbeni Stage	Conglomerate, basalt, various tuffs, agglomerate, trachyte, syenite
		Lebombo Stage	Rhyolite, pyroclasts, breccia
		Drakensberg Stage	Basalt
		Cave Sandstone Stage	Sandstone
		Red Beds Stage	Mudstone
	Beaufort Series	Upper Beaufort Stage	Mudstone, sandstone
		Middle Beaufort Stage	Mudstone, sandstone
		Lower Beaufort Stage	Sandstone, mudstone
	Ecca Series	Upper Ecca Stage	Shale
		Middle Ecca Stage	Shale, sandstone, coal
		Lower Ecca Stage	Shale
	Dwyka Series		Tillite, sandstone, shale
Cape System	Table Mountain Series		Sandstone, shale
Transvaal System	Ntingwe Formation		Limestone, shale, conglomerate
Pongola granite			Porphyritic and equigranular granite

Witwatersrand System	Mozaan Formation	Shale, quartzite, lava
Basic intrusives		Gabbro, ultrabasic rocks
Dominion Reef System	Insuzi Formation	Quartzite, lava, phyllite
Archaean Complex	Archaean granite	Several ages and types of granite, granitic gneiss, migmatites
	Jamestown Igneous Complex	Ultrabasic and basic rocks and their metamorphosed derivatives
	Mfongosi Formation	Schist, banded ironstone

1. THE ARCHAEAN COMPLEX

This complex consists of several suites of granite, basic intrusives and intensely metamorphosed rocks, not yet satisfactorily correlated throughout the area. Du Toit (1931) states that the different formations are very difficult of interpretation because of their highly folded and recrystallised condition and the fact that they occur as narrow strips set within a granitic complex.

The formations mainly occupy mountainous regions which are generally well supplied with springs and except for the granite, no bore-holes have been drilled in them.

(*a*) *The Mfongosi Formation*

This formation occurs mainly in the Tugela River valley where it was mapped and described by Matthews (1959). It consists of a complex assemblage of schist.

(*b*) *The Basic Intrusives*

Several comparatively small outcrops of basic and ultrabasic rocks and their metamorphosed derivatives occur in the Tugela Valley and in the Piet Retief District. The correlation of these rocks with the Jamestown Igneous Complex is still somewhat speculative.

Outcrops of gabbro and ultrabasic rocks of Post-Insuzi age also occur in the Piet Retief and Paulpietersburg Districts.

(*c*) *The Archaean Granite*

Except for the Pongola granite, the different exposures of granite, granitic gneiss and migmatites in the area are, for the purpose of this report, all classified as Archaean granite.

The granite occupies a considerable area near the coast extending from northeast of Empangeni to Eshowe, from where it extends inland along the valley of the Tugela River to beyond its junction with the Buffalo River. Further north it occurs in the valley of the White Umfolozi River, from near Vryheid to within 30 miles of the coast. It appears again in the Pongola River valley and at Piet Retief in the north.

A great number of bore-holes, mainly in the Vryheid, Piet Retief and Lower Umfolozi Districts, has been drilled in the granite.

2. THE INSUZI FORMATION

This formation lies unconformably upon the Archaean Complex and consists chiefly of quartzite, lava and phyllite. In the north these strata occupy a considerable area in the Piet Retief, Paulpietersburg and Vryheid Districts. Further south the strata occur as comparatively small inliers or outliers, chiefly along the Black and White Umfolozi, Buffalo and Tugela River valleys.

Comparatively few bore-holes have been drilled in this formation.

3. THE MOZAAN FORMATION

The quartzite, shale and lava belonging to this formation occupy considerable areas in the Piet Retief, Paulpietersburg, Ngotshe and Vryheid Districts.

A number of bore-holes, mainly in the Piet Retief District, has been drilled in this formation.

4. THE PONGOLA GRANITE

The granite occupies a comparatively small area in the Ngotshe and Piet Retief Districts and extends from northeast of Louwsburg through the Pongola River valley into Swaziland.

The area is well supplied with springs and as far as is known not a single bore-hole has been drilled in this granite.

5. THE NTINGWE FORMATION

The formation comprises a basal conglomerate passing upwards through passage beds of alternating grit and shale into a zone of blue mudstone, which is overlain by red and white limestone. Matthews (1959) correlates these rocks with the Transvaal System.

The rocks occupy a narrow east–west belt in the mountainous area of the Nkandla District lying immediately north of the Tugela River.

The area is well supplied with springs and no bore-holes have been drilled in this formation.

6. THE TABLE MOUNTAIN SERIES

Following a great hiatus in the geological succession, the Table Mountain Series was laid down upon the denuded surface of ancient formations. It consists almost wholly of reddish or purplish, medium to coarse-grained sandstone with occasional pebble bands and maroon coloured shale. It builds the grass-clad, rolling hills of Eshowe, Melmoth and Ntonjaneni. Further north it is found in the White Umfolozi River valley south of Mahlabatini.

A considerable number of bore-holes in the Eshowe and Ntonjaneni Districts has been drilled in the sandstone.

7. THE KARROO SYSTEM

For the purpose of this report, the Karroo rocks are the most important geological formations in the area. They occupy more than 70 per cent of the total area, and approximately 80 per cent of the bore-holes have been drilled in them.

(*a*) *The Dwyka Series*

The basal member of the system rests everywhere unconformably upon an uneven surface formed by the older rocks. It is composed of tillite with subsidiary thin intercalations of sandstone and shale. The thicker beds of tillite are fairly uniform in character, consisting of a somewhat sandy, unstratified matrix in which are embedded boulders and pebbles of a great variety of rocks. It differs from its intensely hard Cape representative in that the matrix is somewhat soft and friable (Blignaut and Furter, 1940).

The thickness of the tillite varies considerably, on account of having been deposited on an uneven surface of the older rocks. In the Vryheid District, for instance, bore-holes have proved the thickness in certain areas to be less than a 100 feet, while according to Blignaut and Furter (1940) it attains a thickness of up to 500 ft. in other parts of the district.

The series occupies considerable areas in the Ngotshe, Vryheid, Babanango, Nkandla and Mahlabatini Districts and occurs as isolated outliers in the most unexpected places on the older rocks.

(*b*) *The Ecca Series*

All three stages are present and well developed in the area.

(i) *The Lower Ecca Stage.*—The Lower Ecca shale is everywhere present below the Middle Ecca Stage, resting conformably on the Dwyka Series and non-conformably on the granite in the absence of the former. The shale maintains its lithological characters throughout the area and consists of typical argillaceous, thinly bedded, dark-blue rocks.

The thickness of the shale, which is 800 feet at Tugela Ferry, diminishes steadily in a northerly direction (Du Toit, 1931). Near Vryheid the thickness is only 150 feet (Blignaut and Furter, 1940). Borings in the Ngotshe District, however, proved the thickness to be 300 to 400 feet.

The more important occurrences are in the Vryheid, Babanango and Ngotshe Districts where a great number of bore-holes has been drilled in them.

(ii) *The Middle Ecca Stage or Coal-measures.*—This zone following conformably upon the Lower Ecca shale, consists of a mass of sediments over 1,200 feet thick, composed mainly of coarse greyish white sandstone and grits very markedly false-bedded and interbedded with lenticular sandy, micaceous and sometimes carbonaceous shale. Blignaut and Furter (1940) estimate that the succession in Northern Natal contains 45 per cent shale. The main coal-seams are situated in the central portion of the succession.

The strata occupy the bulk of the area and are for the purpose of this report the most important geological formation. It occupies most of Northern Natal, i.e. the Helpmekaar, Dundee, Utrecht, Vryheid and Paulpietersburg Districts. From Vryheid it extends eastwards through Mount Ngwibi and Nongoma to within 40 miles of the coast. From Nongoma it stretches northwards through Magudu into Swaziland and southwards through Hlabisa to be terminated 10 miles north of Eshowe by a large fault.

(iii) *The Upper Ecca Stage.*—Like the Lower Ecca, this stage consists mainly of shale. The shale is blue-grey throughout, fine-grained and not as well-bedded as the Lower Ecca shale.

The stage occurs chiefly in the Weenen District where borings proved the thickness to be well over 400 feet, and on the foothills of the Belalasberg north of Utrecht where it attains a thickness of 460 feet (Blignaut and Furter, 1952). In the east if forms a narrow and indented outcrop that follows the Lebombo Monocline from the Swaziland border in the north to beyond Heatonville in the south.

(*c*) *The Beaufort Series*

The beds of this series form a contrast to the dominantly shaly beds of the Upper Ecca Stage below in having bands of fine- to medium-grained, yellowish and felspathic sandstone, alternating with thick bodies of blue, green or occasionally red and purple mudstone and shale, sometimes with calcareous nodules.

The beds occur in the Weenen District and on Belalasberg and Utrecht Mountains. Nearer the coast they dip eastward and crop out along a narrow zone following the Lebombo Monocline.

(*d*) *The Stormberg Series*

(i) *The Red Beds and Cave Sandstone Stages.*—These two subdivisions consist of thin, purple and red mudstone and massive fine-grained sandstone respectively. Their total thickness is probably less than 200 feet. Like the Upper Ecca Stage and the Beaufort Series in the east, they dip to the east and form a narrow outcrop that follows the north–south trending Lebombo Monocline.

(ii) *The Drakensberg Stage.*—This subdivision consists of basalt. The basalt occupies the flats and rolling hills immediately west of the Lebombo Mountain in the north and extends as far south as Empangeni, where it ends against Archaean granite at a major fault. The basalt is almost everywhere weathered to a depth of 20 to 40 feet and forms very few outcrops. A large number of dyke-like bodies of rhyolitic and trachytic breccia and granitic rocks associated with the Bumbeni Stage occurs in the basalt west of Mhlosinga. Most of these rocks are more resistant to weathering than the basalt and give rise to prominent hills and bush-clad ridges.

(iii) *The Lebombo Stage.*—The basalt is overlain by a thick succession of rhyolite and pyroclastic material. These rocks build the Lebombo Mountain and extend southwards as far as Hluhluwe Station.

Thick layers of pyroclastic material interbedded with the rhyolite are especially abundant between the Umsunduzi and Mkuze Rivers but are confined to the upper half of the succession north of this area. The numerous north trending dyke-like bodies of rhyolitic breccia are regarded as the feeders along which the lava escaped to the surface. The rhyolite in contact with these so-called " breccia dykes " usually displays distorted flow-lines and is highly resistant to weathering. The westward facing, vertical escarpment of the Lebombo is defended by the resistant contact-zones of a dense swarm of these " breccia dykes ". The " breccia dykes " both in the basalt and in the rhyolite play a very important role in the occurrence of ground-water, for a large number of successful bore-holes was drilled in and next to them.

(iv) *The Bumbeni Stage and Intrusive Syenite.*—While mapping the southern Lebombo region members of the Geological Survey recently discovered a hitherto unknown assemblage of rocks on the eastern flanks of the Lebombo Mountain. This stage was provisionally called the Bumbeni Beds after the farm on which it was first discovered.

North of the Umsunduzi River the base of the beds consists of conglomerate in which fossil wood was found. This is followed by vesicular basalt which is overlain by a thick succession of trachytic lava, agglomerate and various kinds of welded tuff which cap the Empileni Hill. South of the Umsunduzi River the conglomerate and basalt disappear and agglomerate with trachytic lava and welded tuff rests directly on rhyolite.

The beds dip 5 to 10 degrees northeast and rest unconformably on rhyolite which dips 30 to 35 degrees east.

The beds have received only superficial examination but although there are local unconformities, there seems little doubt that they belong to the Karroo System.

The rocks are intruded by at least three irregular bodies of syenite. A large number of conspicuous trachyte necks and associated dykes occur in the beds and also in the underlying rhyolite.

The light-coloured agglomerate resting on basalt which occurs in the Umsunduzi River west of the Lebombo Mountain and the large number of dyke-like bodies of rhyolitic and trachytic breccia west of Mhlosinga Station also belong to the Bumbeni Stage.

8. THE KARROO DOLERITE

The ubiquitous dolerite intrusions in the Karroo and older formations consist of a complex network of dykes and sheets, which play a very important role in the occurrence of ground-water in the area.

Sills are relatively scarce in the more massive Dwyka tillite and older formations. However, they occur abundantly higher up in the succession where they assume the form of domes, basins, troughs and arches and even a vertical dyke-like form. The thickness, composition and characteristics of each individual intrusion are remarkably constant over areas running into hundreds of square miles, a fact which enabled Blignaut and Furter (1940, 1952) to map separately and allocate distinctive names to the various intrusions encountered in the Northern Natal coal-field.

Sills vary in thickness from a few to several hundreds of feet. Except for the Lebombo, virtually all the principal mountains, flat-topped spurs and plateaux in the area are capped by dolerite sills.

Dykes are numerous throughout the formations they invaded. They are not always visible at the surface in flat country, but are well exposed in great numbers in deeply eroded dongas and stream-beds. Except for those dykes that were erupted from a remarkable swarm of north–south trending fissures associated with the Lebombo monoclinal flexure, there appear to be no preferred directions in the rest of the area.

9. THE CRETACEOUS SYSTEM

Lying unconformably upon lava of the Karroo System in the north and upon granite near Empangeni in the south, the Cretaceous rocks appear very seldom from beneath a cover of Tertiary and Recent sand. The dip is always gently seaward and the sandstone, mudstone and shale have yielded abundant fossils representing all stages of the Cretaceous.

Borings have proved that these strata underlie the Tertiary and Recent sand everywhere on the coastal plain from Richard's Bay northwards into Portuguese territory.

10. TERTIARY AND RECENT FORMATIONS

The red and grey sand with an occasional sandstone layer is confined to the coastal areas. The sand gives rise to bush-covered dunes, rising from sea-level to as much as 400 ft. in some instances on the otherwise featureless coastal plain.

Further inland deposits of the same general geological age are represented by:—

(a) "*Fossil Subsoil*"

This soil, occurring extensively in Northern Natal and the interior of Zululand, has largely been overlooked by previous workers in the area. According to Summer (1957) it is of Quaternary age.

The deposits consist of yellow to pale-brown loam, from 10 to 40 ft. in thickness and containing numerous fine fossil root-holes at depths out of reach of present-day vegetation roots. According to Summer (1957, p. 26) the soil readily slakes in water and is thus highly erodible (pls. I and II). A survey undertaken by the writer disclosed the fact that over 60 per cent of the extensive donga-type of soil erosion in the area occurs on places where this subsoil is present.

(b) *Laterite*

This surface-deposit, nowhere more than 5 ft. in thickness, occurs mainly in Northern Natal in the areas covered by the lateritic types of soil.

For all practical purposes there are no recent alluvium or talus deposits of notable thickness in the area. In this respect Fair (1947, p. 118) concluded that:—

> " In the interior of Natal, and this applies to much of South Africa, structural control is the primary factor keeping slopes steep. Under these conditions sheetwash is able to remove debris from the foot of the hills at a rate not out of proportion to the supply of weathered waste. On weaker rocks slopes flatten almost as soon as they are generated, but as sheetwash is superior to soilcreep concave slopes are dominant over convex ".

B. STRUCTURAL GEOLOGY

Most of the Pre-Karroo rocks are intensely folded and faulted, except for the Table Mountain sandstone which lies virtually flat.

The Karroo System which occupies more than 70 per cent of the area, is near-horizontal with an imperceptible dip to the south. On the monoclinal flexure of the Lebombo, near the coast, however, the entire system, including the basaltic and rhyolitic lavas, has an easterly tilt of 15 to 25 degrees. There is no evidence of Post-Karroo folding apart from that associated with the intrusion of the dolerite.

The north–south trending faults associated with the Lebombo Monocline and the later movements of Middle Cretaceous age (Du Toit, 1931), which are in general diagonal to the former, are mainly confined to the area near the coast. In the interior there are a few small faults, but the great majority of displacements is due to dolerite intrusions.

The mode of intrusion and tectonic disturbances caused by the dolerite intrusions, have been expressed by Du Toit (1920) in what he states as the Law of Minimum Lateral Thrust. The application and validity of this law in the Northern Natal coal-fields have fully been described by Blignaut and Furter (1940) and Blignaut (1952), and need not be discussed in detail.

Suffice to remark that when any sedimentary beds are found invaded by a dolerite sill, the beds above are lifted vertically through a distance equal to the vertical thickness of the intrusion (fig. 6). This fact also holds true for inclined sheets and dykes, whatever the angle of inclination. When an already emplaced dolerite body is cut by a younger intrusion, it is uplifted in the same way and it may happen that the amount of dislocation in a sedimentary bed is the sum of thickness of the two intrusions (Blignaut, 1952).

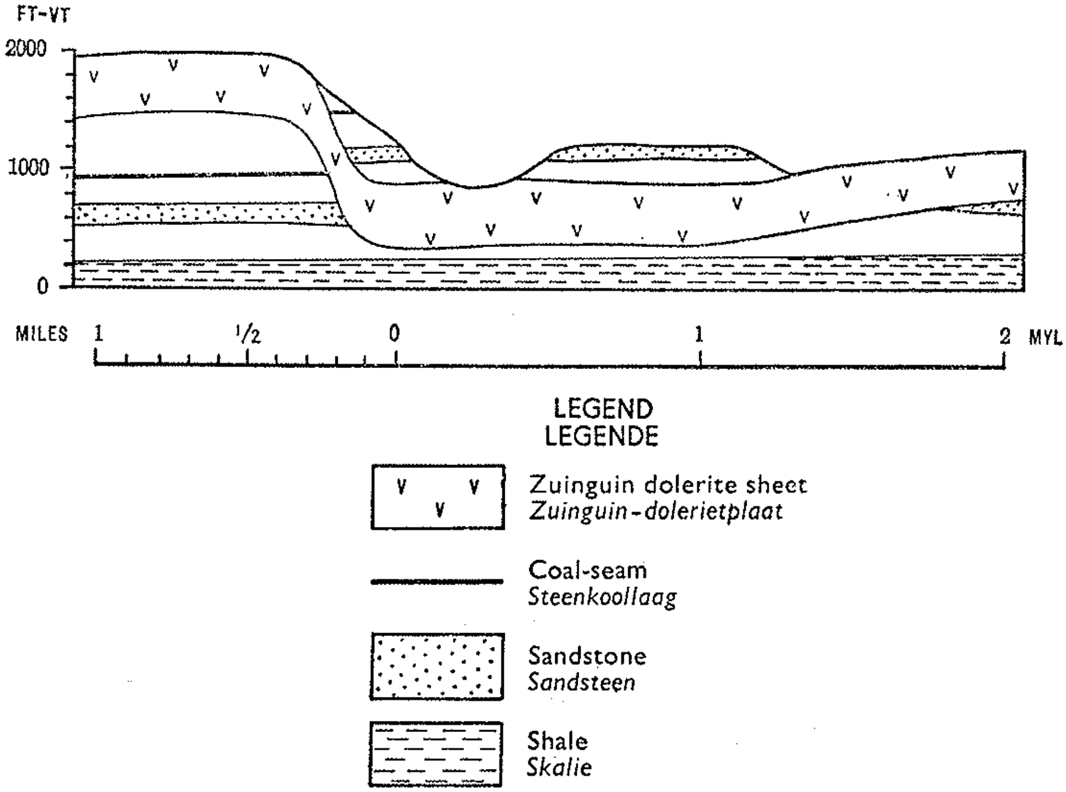

FIG. 6.—Diagrammatic section showing the dislocation of strata by a dolerite sheet. Kambula, Vryheid District (after Blignaut and Furter, 1940).

The horizontal disposition of the uplifted beds is not disturbed except for mild tilting near the contact.

IV. THE HYDROLOGICAL PROPERTIES OF THE MORE IMPORTANT GEOLOGICAL FORMATIONS

The only publication on this subject which includes the rocks of Natal and Zululand is by Frommurze (1937). His work is based on a statistical analysis of bore-hole data regarding the average percentage successes, average daily yield and average depth at which water had been struck in the various geological formations under different climatic conditions. He reached the conclusion that structures and rainfall are the most important controlling factors.

A great number of porosity determinations, mainly on Karroo sandstone, has been made by Du Toit (1915) and Wybergh (1932). Both authors remarked on the low degree of porosity as compared with sandstone in other countries.

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Most other papers relating to ground-water are mainly concerned with location and very little quantitative data on the basic hydrological properties of the rocks are given. (For a comprehensive list of references see Frommurze, 1953.)

A. METHODS OF INVESTIGATION

1. BORE-HOLE DATA

Frommurze expressed the water-bearing properties of the different geological formations in terms of the average percentage of successful* bore-holes drilled in them. The author maintains that this method is misleading. For, as will be shown later, the percentage of successful bore-holes drilled in a particular formation is more dependent on the absence or presence of structures which are conducive to the development of high permeability and on the extent to which the bore-holes were sited advantageously to these structures than on its inherent water-bearing properties as a lithological unit. In this study a similar analysis of bore-hole data is used, but the percentage of successful bore-holes is correlated and expressed in relation to structures or to the electrical resistivity of the formations.

2. GEOPHYSICAL METHODS

Geophysical methods were not only used in the routine selection of bore-hole sites but their conscientious application proved to be a valuable aid in this ground-water study. The electrical resistivity apparatus and the vertical-force magnetometer were used.

(*a*) *The Resistivity Method*

The Gane-Enslin instrument (Enslin, 1944, p. 19–28) based on the Gish-Rooney type was used and the Wenner electrode configuration was employed throughout (Jakosky, 1940).

The field-technique consisted generally of taking a series of depth-probes along one or more traverses. The electrode line was kept as far as possible parallel to the strike of the formations or the structure to be investigated. This eliminates all variations in resistivity near the electrodes and avoids unnecessary irregular and complicated curves which are difficult to interpret. The constant-separation method was only used occasionally to determine, for instance, the positions of non-magnetic dolerite dykes and narrow conductive zones.

The empirical method of interpretation, based on the " potential bowl " theory (Heiland, 1940), was used in all the investigations, supplemented by correlation of depth-probe curves with bore-hole data. The various aspects of application and the usefulness of this method under South African conditions have been described comprehensively by Enslin (1944, 1948) and Vegter (1953).

Electrical logging (Jakosky, 1940, p. 669–712) was also carried out in all bore-holes where possible. By this method the vertical variations in the electrical characteristics of the geologic section traversed by bore-holes are measured. Its value for estimating ground-water supplies and the quality of ground-water has been described by Barnes and Livingstone (1947). For the purpose of this study the method in many cases proved to be more useful than the driller's log for correlating certain structures with the depth at which water was struck in a bore-hole.

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*" Successful " or " water-yielding " bore-holes are bore-holes that maintained a yield of more than 100 imperial gallons per hour during a nine-hour pumping test.

The resistivity of a formation is a function of the following factors (Heiland, 1940 and Vegter, 1953):—

(i) The porosity (or open space due to fracturing).

(ii) The disposition of the pores or openings.

(iii) The resistivity of the water contained in the formation.

(iv) The degree of saturation.

(v) The resistivity of the mineral grains.

According to Heiland (1940, p. 636) the resistivity of the mineral grains may be disregarded in determining the resistivity of virtually all porous rocks. The resistivity of a saturated formation is therefore generally a linear function of its porosity and the resistivity of the water contained in its pores or other openings.

The resistivities of different geological formations vary within a wide range, but it has been found that if the degree of saturation and the salinity of the water of any particular formation in a particular area are the same, lower resistivities indicate higher porosities and more advanced state of fracturing or decomposition, while higher resistivities indicate lower porosities and also induration.

Permeability is a function of porosity, grain arrangement or packing, the disposition of other openings and the size of the pores or openings, and is therefore only partly related to resistivity (Enslin, 1952).

From the foregoing it is evident that the resistivity of any particular formation in an area varies according to its total porosity and indirectly to its permeability and therein lies the diagnostic value of this method as regards water-bearing properties of rocks (Vegter, 1953).

(*b*) *The Magnetic Method*

This method was used extensively to trace concealed dolerite intrusions. Its application and the technique for tracing and determining the contacts of dolerite dykes under a cover of soil have fully been described by Enslin (1950) and Snyman (1954).

3. FIELD-TESTS

The author carried out a large number of field-permeability or water-absorption tests in deep and shallow bore-holes. (For full details see Enslin, 1956 and Earth Manual, 1957.) The technique employed was to do the tests while drilling operations were in progress. The first absorption test was usually made when the bore-hole had reached a depth of 10 to 20 feet and thereafter every 10 to 20 feet during drilling operations until the bore-hole was completed. Water was on each occasion poured into the bore-hole and the drop in level noted at short intervals. The rate of recession per foot pressure of water above the static water-level gives an indication of the permeabilities of the formations traversed by the bore-hole. Due to anomalous results obtained (a discussion of which is beyond the scope of this memoir), however, no quantitative calculations have been made and the data were used for comparative purposes only.

The pumping (dewatering) method (Clark, 1917) has been employed for determining specific yield. It consists in observing the lowering of the water-level and hence the volume of material drained by pumping a measured volume of water. The specific yield is the ratio of the volume of water pumped to the volume of material drained. The equation for calculating specific yield is as follows:—

$$y = 100\left(\frac{Y}{V}\right)$$

where y is the specific yield;
Y the volume of water pumped; and
V the volume of material drained.

Although this field-method has the great advantage of avoiding all artificial conditions involved in laboratory determinations, it has the disadvantages of requiring heavy pumping operations, a number of observation bore-holes and the not always possible task of really delimiting the extent of the ground-water reservoir, especially in sedimentary rocks. A number of tests has been carried out, mainly in the Stormberg lava where ground-water occurs in isolated basins of decomposition, the extent of which can be determined accurately by geophysical methods.

4. LABORATORY TESTS

The porosities of most rocks in the area have been determined both in their fresh or solid state and at different stages of weathering.

The specimens experimented upon consisted for the most part of sections of bore-hole core. The specimens varying in weight from 50 to 100 grams, were soaked in water until no further absorption took place. The saturated specimens were then weighed in water and in air, then oven-dried and weighed again. The formula for calculating porosity is:—

$$P = \frac{y - x}{y - z} \times 100\%$$

in which P is the porosity,
x the weight of the dry specimen,
y the weight of the saturated specimen, and
z the weight of the saturated specimen in water.

B. PRIMARY HYDROLOGICAL PROPERTIES

The primary or syngenetic hydrological properties of rocks are inherent characteristics unaltered by secondary processes, agents and forces such as weathering, folding, faulting and jointing.

Except for the Pre-Karroo rocks, which are in places intensely folded and faulted, the formations in the area lie virtually flat and, except for the intrusion of the dolerite, there are comparatively few structures that could be conducive to changes in their hydrological properties. This statement, corroborated by an analysis of bore-hole records and electrical resistivity surveys which show very little variation in the resistivity of the rocks over large areas, suggests that the formations still possess their primary hydrological properties over far the greater part of the area. This naturally does not apply to the near-surface layers where most rocks are weathered to some extent.

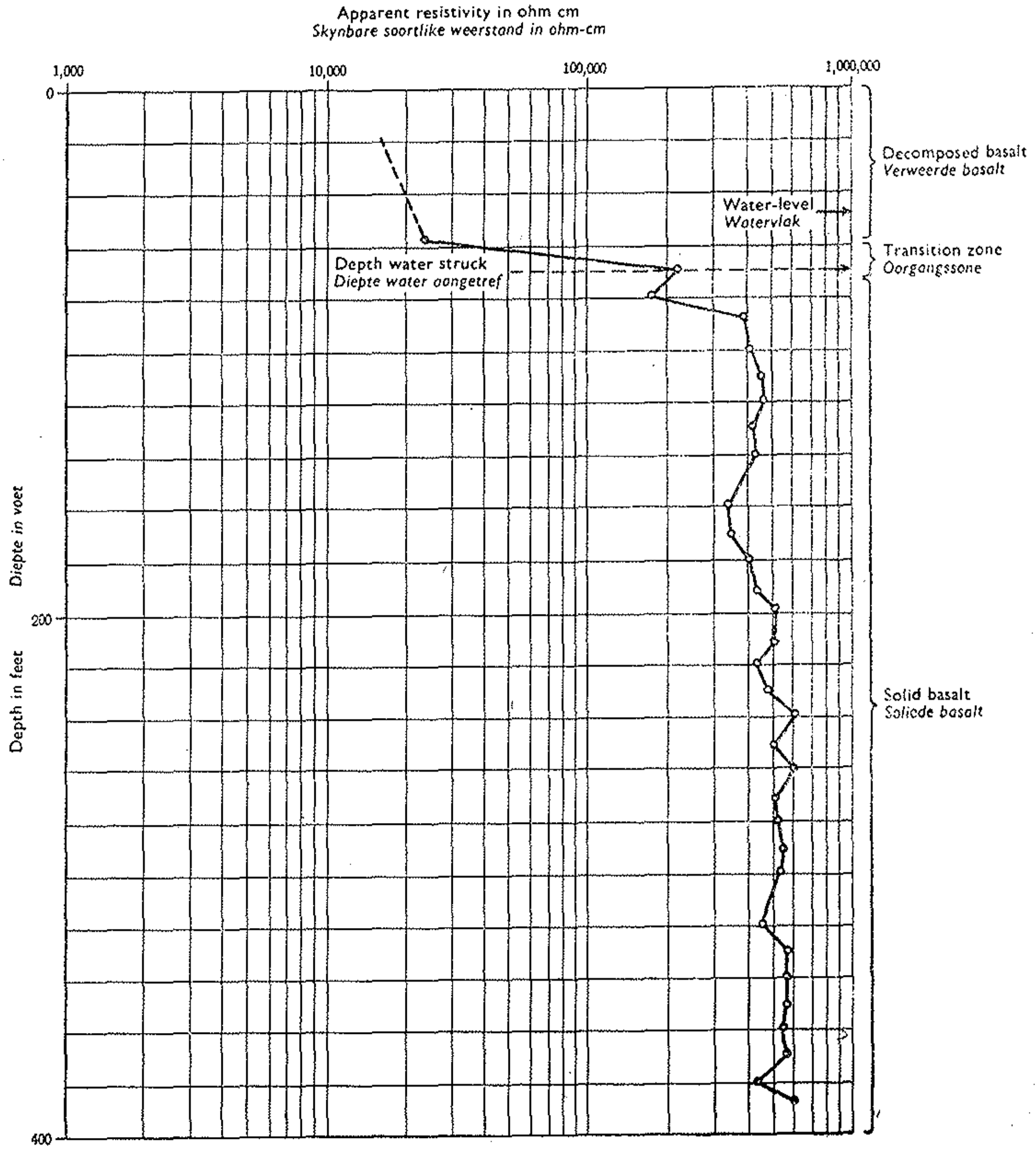

FIG. 7.—Resistivity and geological log of a typical bore-hole in basalt. H.80, Hlabisa District.

The primary hydrological properties of the rocks in the area are of such a nature that they are unimportant in the occurrence of ground-water. It is, however, considered desirable to discuss them briefly in order to compare them with the secondary hydrological properties which will be discussed later in this chapter.

1. IGNEOUS ROCKS

Several kinds of interstices are developed in igneous rocks during the process of solidification. They comprise small cavities or inclusions in some of the crystals, small intercrystal spaces, vesicles produced by steam or other gaseous material escaping from extruded lava and cavities produced in lava-flows by the movement of the lava while it is congealing (Meinzer, 1923).

Some igneous rocks, like basalt, rank among the important water-bearing formations in many parts of the world (Meinzer, 1923). In South Africa, however, Du Toit (1913), Enslin (1943) and Frommurze (1937) showed that no water is obtained in any of the igneous rocks unless they are fractured or weathered.

The more important igneous rocks in the area are the Archaean and Pongola granites, the Karroo dolerite and the Stormberg basalt and rhyolite.

The author made a few porosity determinations on basalt, granite and dolerite and the values in every case were less than one half per cent. These low porosities corroborated by the fact that none of the bore-holes drilled in unfractured rock yield water, prove that all the primary openings in these rocks are very minute or communicate with one another only very imperfectly and are therefore unimportant with respect to water-supply.

Some 28 bore-holes have been drilled in the Stormberg lava to depths of more than 300 feet and in no case was water obtained in the solid rock Figure 7 represents a typical example of a deep bore-hole in basalt. In this case a little water was obtained only in the fractured transition zone immediately below the weathered rock.

2. SEDIMENTARY ROCKS

Some of the highest yielding aquifers in the world consist of sandstone (Bennison, 1947). The artesian supplies of the Rehoboth, Gibeon and Gobabis Districts in South West Africa are obtained in thick sandstone belonging to the Ecca Series (Frommurze, 1931). The aquifer in the Uitenhage artesian area is a porous, pebbly sandstone of the Cretaceous System (Du Toit, 1946).

Mudstone and shale are nowhere reported to be satisfactory aquifers.

As already shown, approximately 70 per cent of the area under consideration is covered by a great variety of sedimentary rocks comprising sandstone, shale, mudstone and tillite. Although no primary aquifers exist in these rocks, nevertheless by far the largest volume of ground-water utilized in the area is obtained from them. Some data regarding the primary hydrological properties of these rocks have been obtained and are discussed below.

(*a*) *Porosity*

The author made a large number of porosity determinations on most of the sedimentary beds in the area. The method employed has been described on a previous page. Most of the specimens experimented upon consisted of bore-hole core obtained from depths where electrical logging suggested that no weathering has taken place. The values are given in table 5.

TABLE 5.—AVERAGE POROSITY RANGES OF SEDIMENTARY ROCKS IN NATAL AND ZULULAND

Type of rock	Geological Formation	Number of determinations	Average porosity range in per cent
Mudstone............	Beaufort Series	33	25·4–26·9
Sandstone............	Beaufort Series	23	5·4– 6·8
Shale................	Upper Ecca Stage	5	2·5– 2·7
Shale...............	Middle Ecca Stage	17	1·8– 2·5
Sandstone...........		11	4·0–12·9
Shale................	Lower Ecca Stage	19	1·5– 3·1
Tillite................	Dwyka Series	7	0·5– 1·3
Sandstone............	Table Mountain Series	4	9·0–16·9

These values show that the porosities of all the sediments are of low order, except those of the mudstone. The low porosity of the sandstone, even of the coarser varieties, is probably due to the cementing material which fills the original pore-space between the individual grains. According to Wybergh (1932) the more important cementing materials in the Karroo sandstone are silica, sericite and kaolinite.

In general, relatively little cementation occurs in shale and the decrease in porosity accompanying conversion of a clay to a shale is the result of compaction caused by the pressure of the superincumbent beds. Athy (1930) has shown that the porosity of shale is a negative exponential function of its depth of burial. He has further computed the porosity of a shale from its depth of burial from the formula:—

$$P = p(e^{-bx})$$

where P is the porosity,

p the average porosity of surface clays,

b a constant, and

x the depth of burial.

The author could establish no definite trend in the porosity–depth relations of the different shale horizons in the area. This is possibly due to complications caused by texture and a certain amount of cementation. Athy's porosity–depth curve, however, suggests that the shale belonging to the Middle Ecca Stage of Northern Natal had been buried to a depth of 5,000 to 7,000 feet.

No determinations have been made on mudstone in the area under consideration. The values quoted are for mudstone belonging to the Upper Beaufort Stage obtained from Ntabamhlope, Estcourt District. There is, however, very little difference in the electrical resistivity of the mudstone on Ntabamhlope and Beaufort mudstone in the area studied. This suggests that there is not much difference in their hydrological properties and that the values quoted are representative of both areas. It is possible that the values given are somewhat too high because the mudstone invariably disintegrates on being exposed to the air or on being dried out, and porosity determinations on this type of rock with the method employed, yielded some anomalous results.

Despite their high porosity, the mudstone is one of the poorest water-yielding rocks in the whole area and also in the Estcourt District. As in clays, this is undoubtedly due to their low specific yield and low permeability.

(*b*) *Specific Yield*

Smitter (1958) remarked on the low specific yield of the Karroo rocks in Controlled Area Number Three, situated on the Highveld of Transvaal. He gave the specific yield of a porous coherent Karroo sandstone, tested by the United States Bureau of Standards, as 2·8 per cent.

In practice laboratory determinations of specific yield on rocks with a high specific retention, as with all the rocks found in the area, usually involve the use of somewhat elaborate and costly testing equipment. Furthermore, the fact that the formations yield no, or very little water in bore-holes, makes it virtually impossible to determine specific yield with any of the recognised field-methods. Consequently no quantitative values have been determined for rocks in the area. However, judging from the relatively low porosities of the rocks and the fact that none of the bore-holes drilled in them have been successful, one can only reach the conclusion that the values must be of a rather low order.

(*c*) *Permeability*

In order to gain a more precise understanding of the permeabilities of Karroo rocks, Smitter (1958) determined permeabilities of rock specimens obtained from deep bore-holes. His tests indicate the following:—

(i) The greater proportion of the Karroo materials are permeable but only slightly so.

(ii) Within limits the materials manifest a considerable range of permeabilities varying often abruptly over very short vertical distances.

(iii) At no point are coefficients of transmissibility (the product of a permeability coefficient and the thickness of a water-bearing stratum) of sufficient order to give, in a hypothetical six-inch bore-hole, yields even approaching a minimum limit of success.

No laboratory tests have been made but boring results, corroborated by field permeability tests carried out in bore-holes, conclusively proved that none of the rocks in the area are permeable enough to yield, in a six-inch bore-hole, an amount even approaching 100 g.p.h.

The resistivity and geological log of a deep bore-hole in Middle Ecca sediments is given in figure 8. The bore-hole intersected a great variety of sandstone and shale beds and was frequently bailer-tested at different depths while drilling operations were in progress. These tests showed that the only supply of water was obtained in a fracture in sandstone at a depth of 63 feet and that the unfractured sediments brought about little, if any, augmentation in the yield.

Borings have also proved that primary structures in sedimentary rocks, such as bedding or stratification-planes and the contacts between layers of sandstone and shale, have very little effect on the permeability. This is proved by the fact that deep bore-holes yield no more water than shallow ones when drilled in the same type of succession (see fig. 8).

3. RESISTIVITIES

At this stage it is considered desirable to discuss briefly the " original " resistivities of the rocks, which to some extent reflect certain physical properties that are used to evaluate hydrological properties.

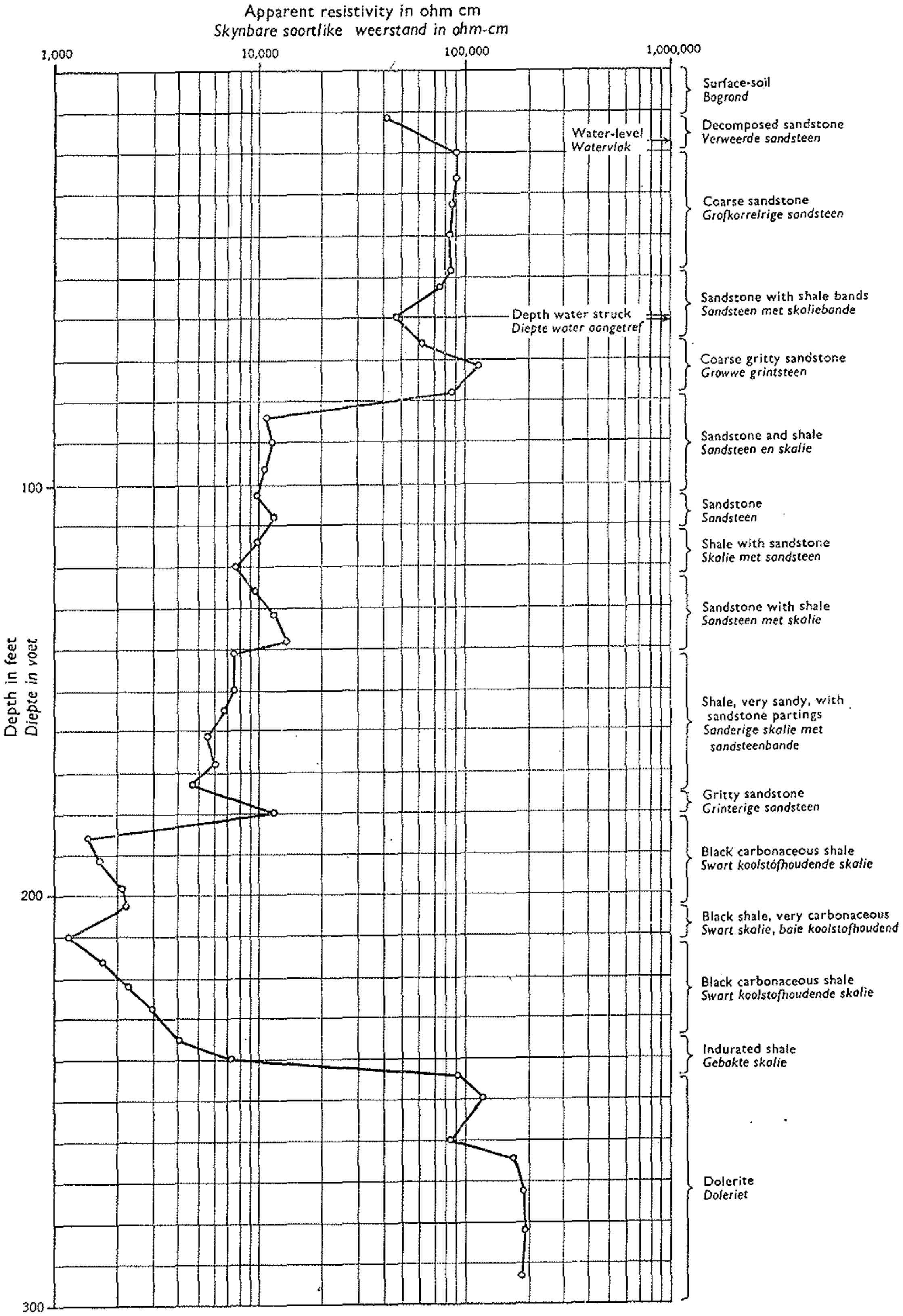

FIG. 8.—Resistivity and geological log of a typical deep bore-hole in Middle Ecca sediments. Waterhoek, Vryheid District.

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(*a*) *Igneous Rocks*

The resistivities of all the igneous rocks in the area are invariably high, usually greater than 50,000 ohm cm (fig. 7). The granite and dolerite have the highest resistivities, invariably greater than 100,000 ohm cm.

The resistivities of the Stormberg basalt and rhyolite are somewhat lower, usually ranging from 50,000 to 500,000 ohm cm. This is probably due to the fact that these rocks occur in an area where the ground-water contains from 1,000 to 3,000 p.p.m. total solids, the conductivity of the water thus being responsible for the lower resistivities.

(*b*) *Sedimentary Rocks*

The different types of sedimentary rocks exhibit a marked difference in resistivities, but in the great majority of cases a variation in resistivity is accompanied by a discernible variation in lithology. It follows that if there is no change in the lithology and the quality of the water remains the same, the resistivity of a saturated homogeneous sedimentary zone will remain the same over large areas.

The resistivities of all the homogeneous sedimentary strata in the area, e.g. the Table Mountain sandstone, Lower Ecca shale, Upper Ecca shale and Beaufort mudstone vary within narrow limits and indicate that there is very little lateral change in the lithology of these rocks over most of the area, especially Northern Natal.

The resistivities of the Middle Ecca sediments, which consist of a succession of lenticular alternating shale and sandstone, are somewhat variable from place to place.

The resistivity ranges of the different geological formations in the area are given in table 6. The values have been obtained from electrical logs in conventional six-inch bore-holes. All the values for sedimentary rocks, except the Cretaceous beds, are given for inland areas where the quality of the water is generally good and its influence on the measured resistivities negligible. The resistivities given for basalt, rhyolite and Cretaceous rocks are for the coastal and Lowveld areas where the water is invariably brackish and contains a high percentage of total solids.

TABLE 6.—RESISTIVITY RANGES OF THE MORE IMPORTANT GEOLOGICAL FORMATIONS IN THEIR FRESH STATE

Rock-type	Geological Formation	Apparent resistivity range in ohm cm	Average resistivity of water in ohm cm
Granite	Archaean	500,000	3,000
Sandstone	Table Mountain Series	20,000– 40,000	1,500
Tillite	Dwyka Series	40,000–100,000	3,000
Shale	Lower Ecca Stage	6,000– 10,000	3,000
Sandstone with intercalations of shale	Middle Ecca Stage	20,000–100,000	3,000
Shale with intercalations of sandstone		5,000– 30,000	
Shale	Upper Ecca Stage	6,000– 10,000	3,000
Mudstone	Beaufort Series	2,000– 5,000	3,000
Sandstone		20,000–100,000	
Basalt and rhyolite	Stormberg Series	100,000	500
Shale and mudstone	Cretaceous System	300– 1,500	100

C. SECONDARY HYDROLOGICAL PROPERTIES

The secondary or epigenetic hydrological properties were formed by events subsequent to the formation of the rock. The importance of these properties can hardly be over-estimated for, as it will be shown, they control the occurrence, storage and movement of ground-water in most rocks of the area.

The principal hydrological properties of rocks are porosity, specific yield and permeability. These properties control (1) the entrance of water into any formation and (2) the capacity to hold, transmit and deliver water. Krumbein (1942) showed that these properties are extremely sensitive and strongly affected by all diagenetic changes in sediments. Tolman (1937) pointed out that they are equally sensitive to all changes in the constitution of a rock irrespective of by whatever forces, agents and processes they may be caused. The properties as determined may have either larger or smaller values than those of the original or unaltered rock.

Van Hise (1904) in his classic discussion of ground-water calls any change in the constitution of a rock " metamorphism ". He showed that at any given time and place, under any given set of conditions, changes take place and minerals tend to form which remain permanent under those conditions; a tendency toward adaptation to existing conditions. He further pointed out that all the different kinds of " metamorphism " are related in the most intricate manner and that certain metamorphic results which have been attributed to one of these forces, agents or processes could equally well be attributed to another.

From the above it follows that the epigenetic hydrological properties developed as a result of numerous interrelated and complex geological, physical, chemical, climatic and topographical conditions that affected the rocks at different times after their formation. A full discussion of all these conditions would be an impossible task and is beyond the scope of this report. The problem can be simplified by stating that hydrological properties develop in two stages, namely, (1) the formation of openings by the more important geological and physical processes, and (2) the modification of these openings by the ensuing actions of circulating water and weathering processes.

The effect of these processes that produce secondary openings, on the yield of bore-holes and how boring sites can be located by geological and geophysical methods have been described by Enslin (1943, 1950), Vegter (1953) and others. None of these workers, however, approached the problem from a quantitative point of view.

The more important processes that affected the hydrological properties of the rocks in the area are discussed below.

1. NEAR-SURFACE PHYSICAL PROCESSES

Although these processes are for the most part only operative near the surface and have no direct influence on the immediate yields of bore-holes, they are nevertheless of great importance. This is because they are mainly responsible for the maze of joints and fissures usually found near the surface, which not only accelerate chemical weathering and soil formation, but also influence the infiltration capacity of the rocks.

(*a*) *Unloading*

The expansion of rock masses when the confining pressures are lessened by uplift and erosion, finds relief in the development of cracks and joints. They are mostly low-angle joints that formed roughly parallel to the ground-surface and their spacing increases with depth (Reiche, 1950).

(*b*) *Thermal Expansion and Contraction*

Rocks exposed to the surface absorb heat from the sun during the day and expand, but on cooling during the night they do not contract to their original volume. In this way pore-space is developed. Rocks may also form joints and break apart on rapid cooling.

(*c*) *Frost Action*

This process is widely operative in the middle and high altitudes where frost occurs and is responsible for widening of existing joints, and in places a tremendous amount of rock disintegration.

(*d*) *Organic Activity*

The direct and indirect value of organic activity in hydrology can hardly be over-estimated. Tree and other roots widen cracks and joints and accelerate the weathering of rocks by exchanging H-ions from the roots for metal (Ca, Mg, K, etc.) ions in the rocks (Keller and Fredrickson, 1952).

These actions are known to be operative to considerable depths. At least four cases have been encountered in Northern Natal where the roots of *Eucalyptus sideroxylon* entered bore-holes in shale at depths of 70 to 90 feet below ground-surface. In Zululand the roots of certain Lowveld trees, e.g. *Ficus sycomorus*, *Acacia robusta* and *Acacia karroo*, have been fished out of a large number of bore-holes at depths of 50 to 80 feet below ground-level (see pl. III).

Apart from the above actions, the openings left by the rotting of dead roots form important channels or conduits that facilitate the infiltration and circulation of ground-water.

Of importance also is the work of mixing performed by various animals within the zone of weathering and particularly in the soil. Earthworms, ants, rodents, etc. perform incredible service in this way. Materials mixed in this way, may not only be more subject to chemical weathering but the organic matter may also increase the infiltration capacity of the soils and the underlying material.

2. DEEP-SEATED GEOLOGICAL PROCESSES

For the purpose of this study the more important geological changes in the rocks of the area are jointing, faulting and the effects of the intrusion of the dolerite. The effects of these changes on the hydrological properties are essentially the same as those of the near-surface physical changes described above. From a water-supply point of view they are, however, of primary importance because they extend to depths below the water-table where the extent, pattern, size, openness, continuity and interconnection of the openings produced by the processes (modified by weathering) largely govern the storage capacity of the rocks and the yield of bore-holes.

(*a*) *Jointing*

Nearly all consolidated rock formations are broken by joints that have been described by a large number of authors as being amongst the most important water-bearing openings.

Joints which are not associated with faults or the intrusion of the dolerite, may have been formed by compression, tension or torsion. Lahee (1952) pointed out that a distinction between them is not always possible. For the purpose of this report they may be divided into two classes:—

(i) *Minor Joints.*—They are especially abundant near the surface, but are also found at depths greater than those caused by the physical processes which have already been described. These joints are mainly responsible for the formation of basins of decomposition in igneous rocks as will be shown later.

(ii) *Diastrophic or Master Joints.*—They are defined as fracture-planes along which there has been little or no displacement. Many of them are near-vertical and extend to great depths as open fissures. They cannot be located by the geophysical methods employed and are usually responsible for the unexpected successful bore-holes remote from dolerite intrusions or other structures.

Owing to a well-developed soil cover throughout the area, joints are very seldom conspicuous features and although they play an important role in the hydrological properties of the rocks, they are of little value in the selection of bore-hole sites. Most of the bore-hole sites that were selected on joints were failures. This paradox arises presumably from the fact that joints are only prominent in areas where rock crops out and where the processes of weathering have had little opportunity of opening them to depths below the water-table.

An analysis of the bore-hole records shows that there are comparatively few water-yielding joints in the Karroo rocks. Only about 17 per cent of the bore-holes in Northern Natal obtain their yields from joints not associated with dolerite intrusions or faults. Less than 5 per cent of the bore-holes drilled in lava obtain their yields in such structures but in the Pre-Karroo rocks the figures are somewhat higher. Approximately 60 per cent of the supplies in Table Mountain sandstone and about 50 per cent in the Archaean granite were struck in joints.

(*b*) *Faulting*

Faults and their influence on ground-water have been discussed comprehensively by Meinzer (1923). He showed that faults do not only affect the distribution and position of aquifers, but they may also act as subterranean dams impounding the ground-water, or as conduits some of which may reach to great depths and allow the escape to the surface of deep-seated water, often in large quantities and at high temperatures.

Apart from the faults associated with dolerite intrusions (fig. 6) there are very few true faults in the area and comparatively few bore-holes have been drilled in them, most of them being successful. An exception is the Ngotshe District where only two out of the eleven bore-holes drilled in faults yielded more than 100 g.p.h. The failure of these holes was mainly due to the presence of impermeable clayey gouge along the fault-planes.

No exceptionally high yields have been obtained in faults. For instance, the highest yield obtained in faults in the Nkwaleni Valley is 1,250 g.p.h., while other bore-holes drilled alongside dykes in the same area yielded over 3,000 g.p.h. As far as could be ascertained no large springs owe their existence to faults, except probably one or perhaps two of the three thermal springs that occur in the area.

(*c*) *Intrusion of the Dolerite*

According to Blignaut (1952) the metamorphic effects of dolerite intrusions on the coal-measures of the Karroo System have been a major tragedy from an economic point of view. Coal-seams over hundreds of square miles have been affected by the heat of the intrusions and rendered almost valueless for present-day purposes.

From a ground-water point of view, however, the effects of the intrusions on the hydrologic properties of most sedimentary rocks in the area can be regarded as a blessing. The yields of more than 80 per cent of the successful bore-holes drilled in sedimentary rocks are directly or indirectly the result of the effects produced by these intrusions on the otherwise non-water-yielding rocks of the area. The study of ground-water is therefore intimately concerned with the dolerite.

The ubiquitous dolerite intrusions in the Karroo and Pre-Karroo rocks are represented by a complex network of dykes and sheets. The rocks in contact with them invariably exhibit a certain amount of alteration. According to Blignaut (1952, p. 23) the alteration in Northern Natal is confined to the effects of " baking " and discoloration and there is little evidence of pneumatolytic action. " Baking " refers to the hardening or toughening of the rocks. Sandstone and grit are converted into quartzite and arkosic rocks, while the most noticeable effect on shale and mudstone is hardening and a change in colour to buff or white.

Another feature in connection with the dolerite intrusions is the very slight disturbance of the rocks surrounding them; in both large and small intrusions there is a general absence of tilting of the sediments. A study of bore-hole core and a comparison of the tilting and folding observed alongside the same dolerite intrusion on the surface and in nearby coal-mines, suggest that it is in most cases a near-surface phenomenon produced by the differential volume increase of the dolerite and sediments as a result of weathering.

There is furthermore little brecciation or fracturing of the country-rock and masses of sedimentary material included or caught up between two parallel or convergent but inclined sills show little evidence of inclination.

Faulting produced by the intrusion of dolerite has already been discussed in chapter III.

The yields of approximately 80 per cent of the successful bore-holes drilled in Karroo sediments were obtained in the " baked " or contact-zone adjacent to dolerite intrusions. This fact proves that the " baked " zones have higher permeabilities than the unaffected sediments. Paradoxically the porosity of the sediments in these zones is lower than that of the unaffected rocks further away from the intrusions where bore-holes do not yield water.

The author made a number of porosity determinations on specimens of the same rock-type obtained at different distances from dolerite intrusions. The results (table 7) show that the metamorphism produced by the dolerite affected the porosity of the sediments adversely; rocks in the contact-zone invariably have lower porosities than the unaffected rocks away from the intrusions. This phenomenon can be explained by the fact that " baking " is a process of cementation, i.e. rearrangement and crystallisation of substances already in the country-rock, and the infiltration and crystallisation of some magmatic silica, etc. (Lahee, 1952). In general the decrease in porosity appears to be proportional to the extent of metamorphism or " baking " and the distance away from the intrusion.

TABLE 7.—DECREASE IN POROSITY DUE TO BAKING BY DOLERITE

Type of rock	Intrusion	Distance from intrusion in feet	Percentage porosity
Middle Ecca sandstone...........	Dyke (25 ft. wide)	25*	8·65
		10	7·37
		3	1·16
		0	0·362
Lower Ecca shale................	Dyke (12 ft. wide)	15*	2·51
		5	1·12
		1	0·468
Middle Ecca sandstone...........	Sill (80–100 ft. thick)	25	0·945
		6	0·391
		2	0·055

* Unaffected.

The *decrease* in porosity is furthermore also accompanied by an *increase* in the electrical resistivity of the sediments in the contact-zone. Figure 9 shows the resistivity logs of two bore-holes drilled at different distances from a near-vertical, 30-feet-wide dolerite dyke in Upper Beaufort mudstone and sandstone on Ntabamhlope, Estcourt District. Bore-hole 15 N was situated 12 feet from the dyke and intersected it at a depth of 100 feet. Its yield was 1,000 g.p.h. Bore-hole 15 L was situated 35 feet from the same dyke and yielded less than 50 g.p.h. The porosities of specimens obtained from the same layers in the two bore-holes are given in table 8.

TABLE 8.—COMPARISON OF POROSITIES OF THE SAME LAYERS AT DIFFERENT DISTANCES AWAY FROM A DOLERITE DYKE. NTABAMHLOPE, ESTCOURT DISTRICT

Rock-type	Depth of specimen in feet	Distance from dyke in feet		Percentage Porosity	
		Bore-hole N	Bore-hole L	Bore-hole N	Bore-hole L
Mudstone.................	30	8·5	31	9·7	20·3
Sandstone................	55	5·5	28	6·45	7·75
Sandstone................	70	3·5	26	4·85	7·20
Sandstone................	80	2·5	25	3·57	7·07
Sandstone................	86	1·5	23·5	5·35	—
Sandstone................	90	1·0	23·0	2·7	7·22
Sandstone................	99	0·5	22·5	1·79	5·94

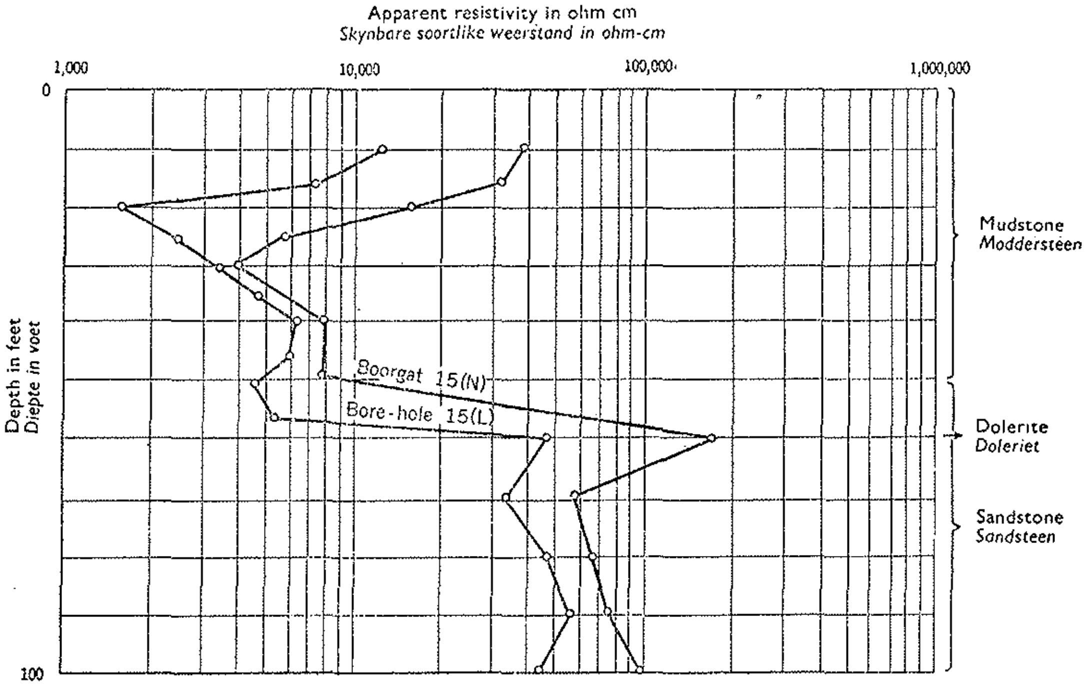

FIG. 9.—Electrical logs comparing the resistivity in two bore-holes situated at different distances from a dolerite dyke. Ntabamhlope, Estcourt District.

The high permeability of the contact-zone has been explained by Enslin (1950, p. 195) as follows: " The effect of the induration and crushing of the sedimentary rock is that the permeability has been increased and the contact zone has been changed into an aquifer lying between the solid dyke and the saturated, low permeability country rock. The sedimentary rock along this narrow zone has been changed from one with a resistivity falling within Range A to one with a resistivity in Range B. If the dyke intrudes a sediment with a resistivity falling within Range B, the effect may be that the resistivity is increased so as to fall within Range C, the formation has become impervious and the contact zone as well as the dyke can now act as a barrier to ground-water motion and not as an aquifer ". Range A refers to mudstone and shale with a resistivity of less than 3,500 ohm cm wherein the chance of striking a supply is extremely small. The percentage successful bore-holes in sediments falling within Range B (3,500 to 12,000 ohm cm) is high and gradually decreases with increasing resistivity in Range C (more than 12,000 ohm cm).

The following, however, suggests that Enslin's explanation for the high permeability of the contact-zone does not hold true in Northern Natal and Zululand:—

(i) Most bore-holes which intersected contact-zones with a resistivity falling in Range C (i.e. >12,000 ohm cm) yield strong supplies of water. (See figs. 9 and 10.) This proves that contact-zones with a high resistivity are also aquifers and not impermeable ground-water barriers as contended by Enslin.

(ii) In the area the percentage of successful bore-holes in sediments with resistivity in Range B is also high, but as will be shown later, it is only high in places where these sediments crop out. When they are covered by dolerite or sediments with resistivity in Range A or C, the chances of striking water in them are extremely small. This suggests that the high permeability is also of secondary origin and not an inherent characteristic of these sediments.

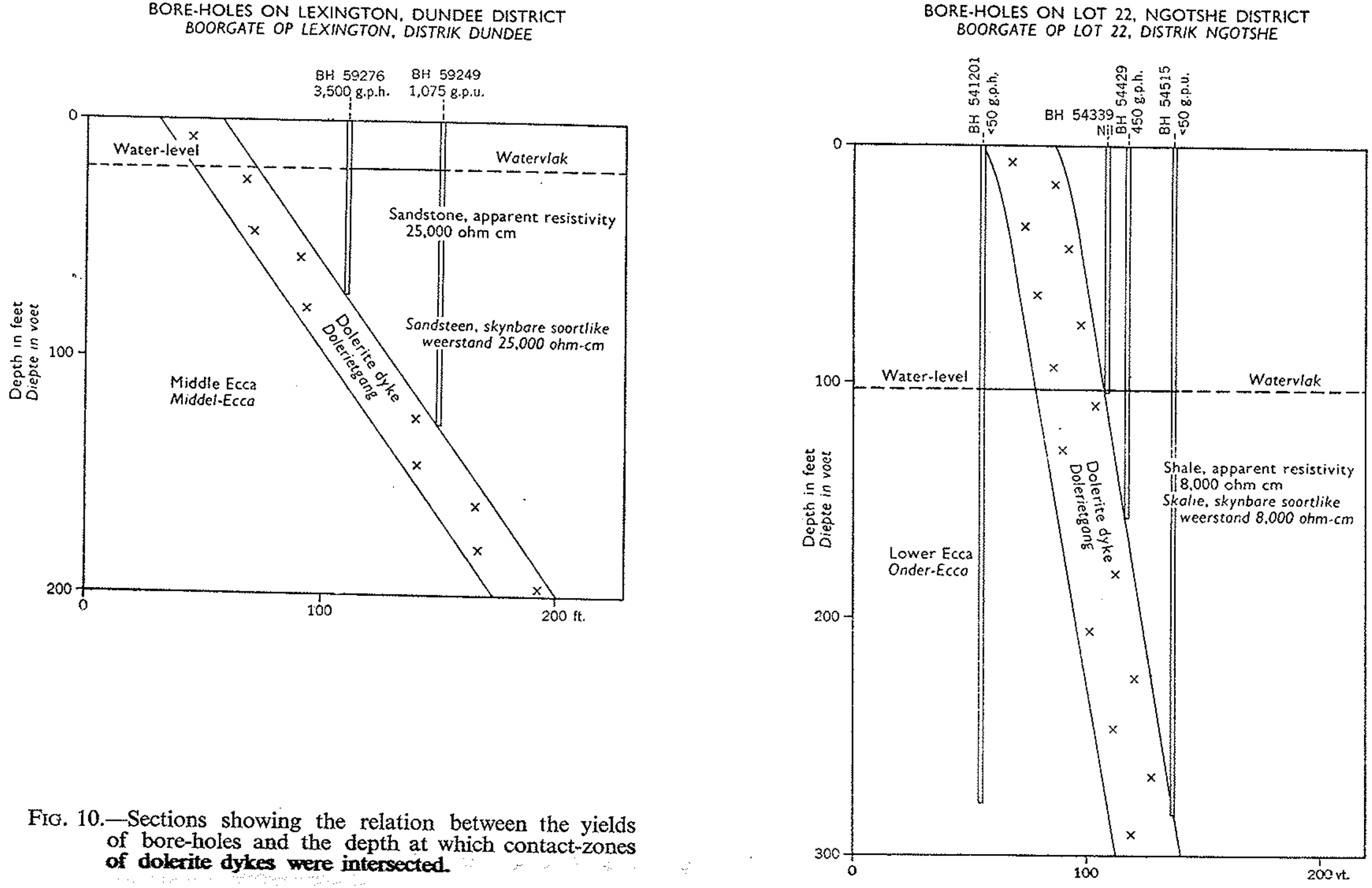

FIG. 10.—Sections showing the relation between the yields of bore-holes and the depth at which contact-zones **of dolerite dykes were intersected.**

The author is of the opinion that the high permeability of the contact-zone is due to joints that developed in the zone during cooling. Amongst other evidence this contention is supported by a study of the occurrence of ground-water in 5 coal-mines in the Vryheid and Dundee Districts. This showed that all flows associated with dolerite intrusions issue from isolated joints in the " baked " zone.

Two sets of tension-joints developed in the dolerite and in the adjoining contact-zone during cooling, viz. (1) columnar joints in three directions, each 120 degrees to the other and (2) joints parallel to the contact. In the area columnar jointing is usually best developed in the dolerite (pl. IV), but it is by no means a constant feature. Joints parallel to the contact are best developed in the " baked " zone.

Observations showed that both types of jointing, whether in the dolerite or in the " baked " zone, are best developed and have the closest spacing nearest the contact. Away from it their regularity decreases, their spacing increases, and they actually fade away and disappear outside the " baked " zone. For this reason it is commonly found that bore-holes intersecting the contact have the highest yields. This fact is also well illustrated by Enslin (1950, p. 198), who showed that the yield of a bore-hole is a function of the distance away from a dyke.

Another interesting feature about these joints is that although they may be prominent on the surface, a study of them in coal-mines showed that at depth they are hardly, if ever, visible and very few exist as open fractures. This is further corroborated by the fact that bore-holes which intersected the contact-zone at depths of more than 70 feet below the water-table were either failures or yielded small supplies of water, while holes intersecting the same zones at lesser depths yielded strong supplies (fig. 10). The implication is that the joints exist as lines of weakness only and that it is imperative that they be opened by the processes of weathering to render the contact-zones permeable.

The width of the contact-zone, and consequently the distance away from dolerite intrusions at which bore-holes yield water, varies a great deal. It is commonly held among mining men in Natal that the width of the " baked " zone produced by a dolerite intrusion is roughly equal to the thickness of the intrusion. Although this general rule is applicable for all practial purposes, bore-holes have shown that the width varies, not only with the different intrusions, but also with the same intrusion in the different types of rock. In the Beaufort mudstone the " baked " zone is invariably very narrow. Even for dykes up to 30 feet wide, it is generally only a few inches and seldom as much as one foot wide. Contact-zones appear to be the widest in the Dwyka tillite and Lower Ecca shales. Most bore-holes drilled in the Magudu and Gluckstad areas at distances of 3 to 4 times the width of dolerite dykes from the dykes, yielded strong supplies of water and their cores still showed definite signs of discoloration of the shale or tillite.

It should be noted that where the surrounding rock is granite, Stormberg lava or any other igneous rock, high permeability in the contact-zone does not develop to the same extent as in sedimentary rocks. Only 4 of the 37 bore-holes that have been drilled in dolerite–granite or dolerite–lava contact-zones were successful. The reason for this is as yet not fully understood but in the case of the basalt it may be due to the fact that the basalt and the intrusive dolerite have more or less the same composition and very little metamorphism of the contact took place (Lahee, 1952, p. 150).

FIG. 10.—Sections showing the relation between the yields of bore-holes and the depth at which contact-zones of dolerite dykes were intersected.

3. PROCESSES OF WEATHERING AND CIRCULATING WATER

The ever-present joint action of weathering and circulating water represents the second and most important stage in the development of the secondary hydrological properties of rocks. Water inevitably attacks and modifies all the openings produced by the physical and geological processes described above.

In general, weathering is a selective and self-intensifying process which constantly tends to accentuate the degree and depth of decomposition along joints, or zones, which permit the optimum circulation of water. Where the joints are close together, weathering begins by incipient alteration along the joints or fractures, progressing by stages to residual boulders and " jointed ribs " of relatively fresh rock, separated by " seams " of granular material (pls. V and VI). In this way the deep basins of decomposition, which are the most important source of ground-water in igneous rocks, are formed. In rocks less susceptible to weathering, like most sedimentary rocks, or where the joints are further apart, the process is confined to chemical decomposition along the joints, and the solution and subsequent removal of the soluble parts by circulating water. Between these two extremes, there are many intergradations depending on the type of rock and the distribution and arrangement of the joints.

(*a*) *Depth of Weathering*

An analysis of bore-hole data shows that ground-water in the area is obtained in permeable material which exists only to a certain depth below the water-table and that very few bore-holes yield water below that depth. Evidence will be represented to show that the average maximum depth to which the material is permeable in the different regions, is related to the depth of weathering and the physiographic history of the area. Depth of weathering, as used here, thus not only refers to the depth of chemical decomposition, but also to the depth to which the openings produced by the physical and geological processes described above have been opened by weathering and percolating water to render them valuable as a source of water-supply.

Effective weathering extends approximately to the water-table, although ground-water circulation permits alteration to greater depths in formations or rock-zones of high permeability (Reiche, 1950, p. 84). The fact that there is no difference in the temperatures of ground-water obtained from springs and deep or shallow bore-holes in different regions of Natal and Zululand, proves that little circulation occurs at great depths and suggests that most movement occurs in a zone which does not extend far below the water-table. For, if in the average deep bore-hole a substantial part of the water comes from the lower part of the hole, its temperature and the average temperature of all the water from the hole would be higher than that from springs or shallow holes, which is not the case. (For a full discussion on ground-water temperatures see chapter VII.)

Evidence that most of the openings produced by the processes already described exist only to a certain depth, is found in the following facts:—

(i) Although numerous dykes were intersected and plotted on the colliery plans of most coal-mines in Northern Natal, they are all comparatively dry. A study to establish the relation between ground-water occurrences in the mines and the dolerite intrusions showed that in those mines having roof-beds of several hundred feet thick, e.g. Hlobane and Northfields, only a very small percentage of the flows occur near or have any relation to the intrusions. In shallow mines and shallow sections of the above mines, where the roof-beds are less than 200 feet thick, however, there is every evidence that substantial flows came from the contact-zones of dolerite dykes.

(ii) A great number of cases can be listed where a bore-hole that intersected a fault or the contact-zone of an inclined dyke at a depth of more than 200 feet below the water-table was weak or even unsuccessful, but a second bore-hole which intersected the same structure at a shallower depth yielded a strong supply of water (see fig. 10).

The above evidence is supplemented by an analysis of bore-hole data which shows that, except in the Piet Retief area, ground-water is obtained in permeable zones which exist only to a certain depth below the water-table and that a very small percentage of the bore-holes yield water below that depth (see figs. 11 and 12). The diagrams of figure 11 have been obtained by plotting the yields of bore-holes in different regions against the maximum depths below the water-level* at which water entered the bore-hole, i.e. WS—WL, where WS is the maximum depth at which water enters the bore-hole and WL the depth to the water-level.

The curves of figure 12 have been obtained by plotting the percentages of the total number of water-yielding bore-holes in the different areas against the maximum depths below the water-level that water entered them.

It should be noted that in most cases only the depth at which the main supply of water was struck† is recorded on the bore-hole log, although water may have been struck at several deeper levels in the bore-hole. The author, however, had the opportunity of visiting a large number of the bore-holes while drilling or testing operations were in progress and where possible bailer or water absorption tests were carried out and some holes were pump-tested at different levels to ascertain as accurately as possible the lowest level at which water entered the bore-hole (fig. 13).

Figures 11C and 12C show maximum depth below the water-table at which water enters most bore-holes in the Lowveld, i.e. in the Ngotshe, Hlabisa and Ubombo Districts. Most of the bore-holes that have been included in the calculations were drilled in basalt and rhyolite. Water in these formations usually occurs in deep basins of decomposition and the aquifer is the comparatively thin transition zone between the decomposed and solid lava. This is an excellent example to illustrate that the zone in which water is struck below the water-table extends to the limit of weathering. It may be added that the bore-hole data regarding the depth of weathering are fully corroborated by no less than 20,000 electrical depth-probes that have been taken on the lava in the routine selection of bore-hole sites. Figures 11B and 12B represent data obtained from 485 bore-holes drilled in granite and rocks of the Karroo System in Northern Natal. Figures 11A and 12A have been constructed from data obtained from 37 bore-holes in granite in the Piet Retief District and the northern portion of Paulpietersburg District. This area adjoins the Northern Natal area.

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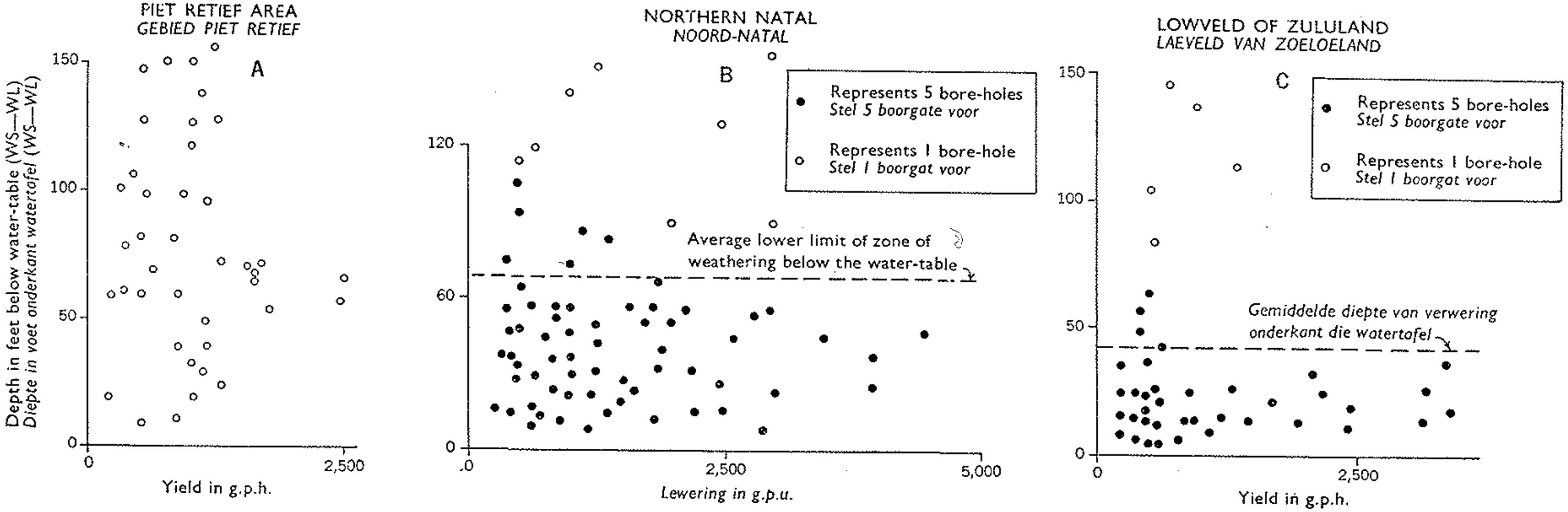
*The water-table is the upper surface of the zone of saturation and is in the area mostly confined to joints, fissures and permeable weathered rock. The term water-level refers to the level of water measured in bore-holes. In many cases this level represents a pressure surface which may or may not coincide with the water-table in nearby permeable zones. For full discussion see chapter on " Water-level and water-table studies ".

†Due to the lack of permeable strata the water enters bore-holes through joints and other comparatively thin permeable zones. During drilling operations sudden increases in the yield of the bore-hole are experienced whenever one or more of these structures are intersected. The depths of these sudden increases in yield are recorded on the driller's log and hence the terms " water struck " " water obtained " and " water enters bore-hole ".



WS = Maximum depth at which water enters bore-hole
Maksimale diepte waarop water by boorgat inkom

WL = Depth to water-level
Diepte van watervlak

FIG. 11.—The thickness of the zone of weathering below the water-table in different areas expressed as a function of the depth below the water-table at which bore-holes yield water.

WS = Maximum depth at which water enters bore-hole
Maksimale diepte waarop water by boorgat inkom

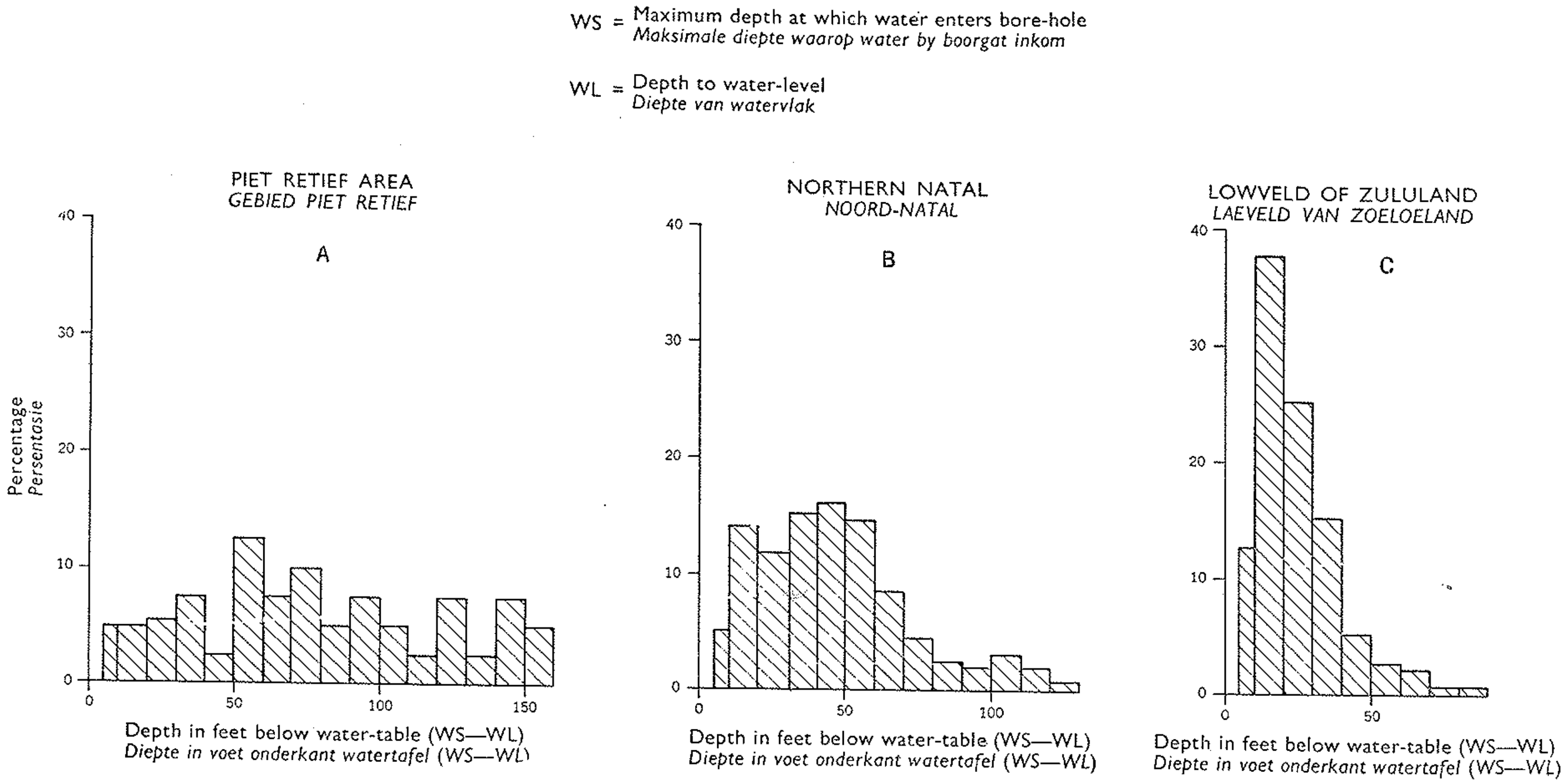


FIG. 12.—The relation between percentages of successful bore-holes and the depths below the water-table at which they yield water in the different areas.

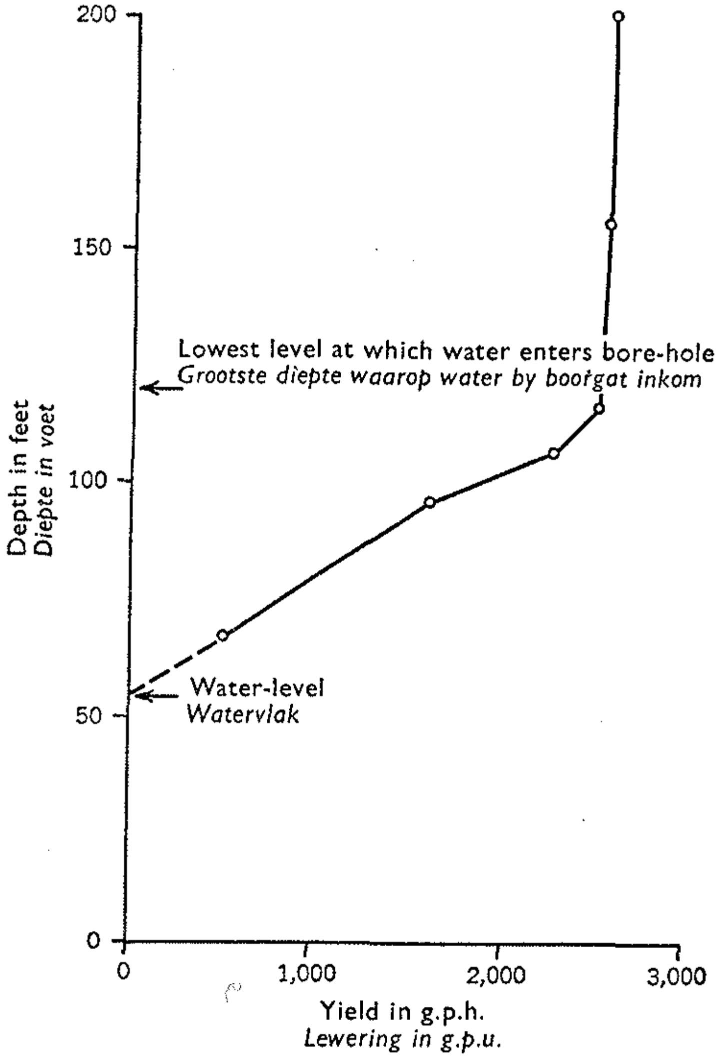


FIG. 13.—The yield of a bore-hole tested at different depths to determine the lowest level at which water enters a bore-hole. Lubeck, Vryheid District.

The following may be deduced from figures 11 and 12:—

(i) In the Lowveld areas the depth of weathering extends to 40 ft. below the present water-table, and 85 per cent of the bore-hole supplies have been struck in this zone, while only 15 per cent of the bore-holes yield water at greater depths.

(ii) In Northern Natal joints and fissures, mainly produced by dolerite intrusions, are permeable to a depth of 70 ft. below the present water-table. More than 78 per cent of the bore-hole supplies have been obtained in this zone. Basins of weathering in the granite and dolerite also very seldom extend to depths of more than 50 to 60 ft. below the water-table.

(iii) In the Piet Retief area the weathered zone extends to depths of more than 150 ft. below the water-table. Bore-hole data show that the granite is in places intensely weathered to depths of 200 to 250 ft. below ground-level. This great depth of weathering, but a shallow water-table, suggests an earlier time when the water-table stood low, much lower than in the adjoining Northern Natal and in the Lowveld or coastal areas.

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Although it is outside the scope of this study, the following might throw some light on the problem of the greater depth of weathering in the Piet Retief area than in the adjoining Northern Natal.

Twenhofel (1932, p. 17–18) showed that a consideration of the depth of weathering below the present water-table may afford a valuable clue to the determination of the sequence of the geological events in a region, as both depth and rate of weathering are related to the position of the water-table.

An attempt has been made to correlate the depth of weathering with the erosion-surfaces suggested by Fair and King (1954). The results, however, show that there is no correlation. Their " African Surface ", for instance, includes both Northern Natal where the Archaean granite is seldom weathered deeper than 70 ft. below the water-table, and the Piet Retief area where the same granite is intensely weathered to depths of more than 150 ft. below the water-table. In the rest of the area the rocks in their suggested " Post-Gondwana ", " African " and " Pliocene " surfaces are, for all practical purposes, weathered to the same depth below the water-table.

These facts may indicate:—

(i) That if the erosion-surfaces suggested by the above authors do exist, the sequence of geological events that gave rise to an almost constant depth of weathering below the water-table in Northern Natal and Lowveld areas is of a much later date than the land-surfaces. The author suggests that the events date back to the Early and Middle Pleistocene, during which period the entire area was subjected to intensive erosion (see chapter III).

The deep dongas and valleys caused a lowering of the water-table and deeper weathering ensued. The thickness of the " fossil soils " in the Vryheid and Babanango Districts suggests that some of the dongas and valleys were 40 to 50 ft. deep. The water-table rose again to probably near its present position during and after deposition of the colluvial " fossil soils " in the eroded areas.

(ii) That the physiographic history of the area that extends from Paulpietersburg through Piet Retief northwards is entirely different from that of the adjoining Northern Natal. The presence of thick deposits of " fossil soils " indicates that the events just described also affected the Piet Retief area. The exceptional great depth of decay with approximately the same water-table as in Northern Natal, however, suggests an earlier time when the water-table stood much lower and definitely lower than in Northern Natal.

(*b*) *Lateral Extent of Weathering*

Although weathering generally proceeds downward, it also attacks and changes the hydrological properties of the rocks laterally away from the openings produced by the physical and geological processes already described. It will be shown that this action explains why in some formations water is obtained at some distance away from a given structure while in other formations the same structure must be intersected in order to obtain water.

Near the surface where there is an abundance of interconnecting joints, weathering proceeds laterally with comparative facility giving rise to a continuous mantle of decomposed rock. The rolling topography of Natal and Zululand, with few outcrops and a generally well-developed soil-cover, is a typical example.

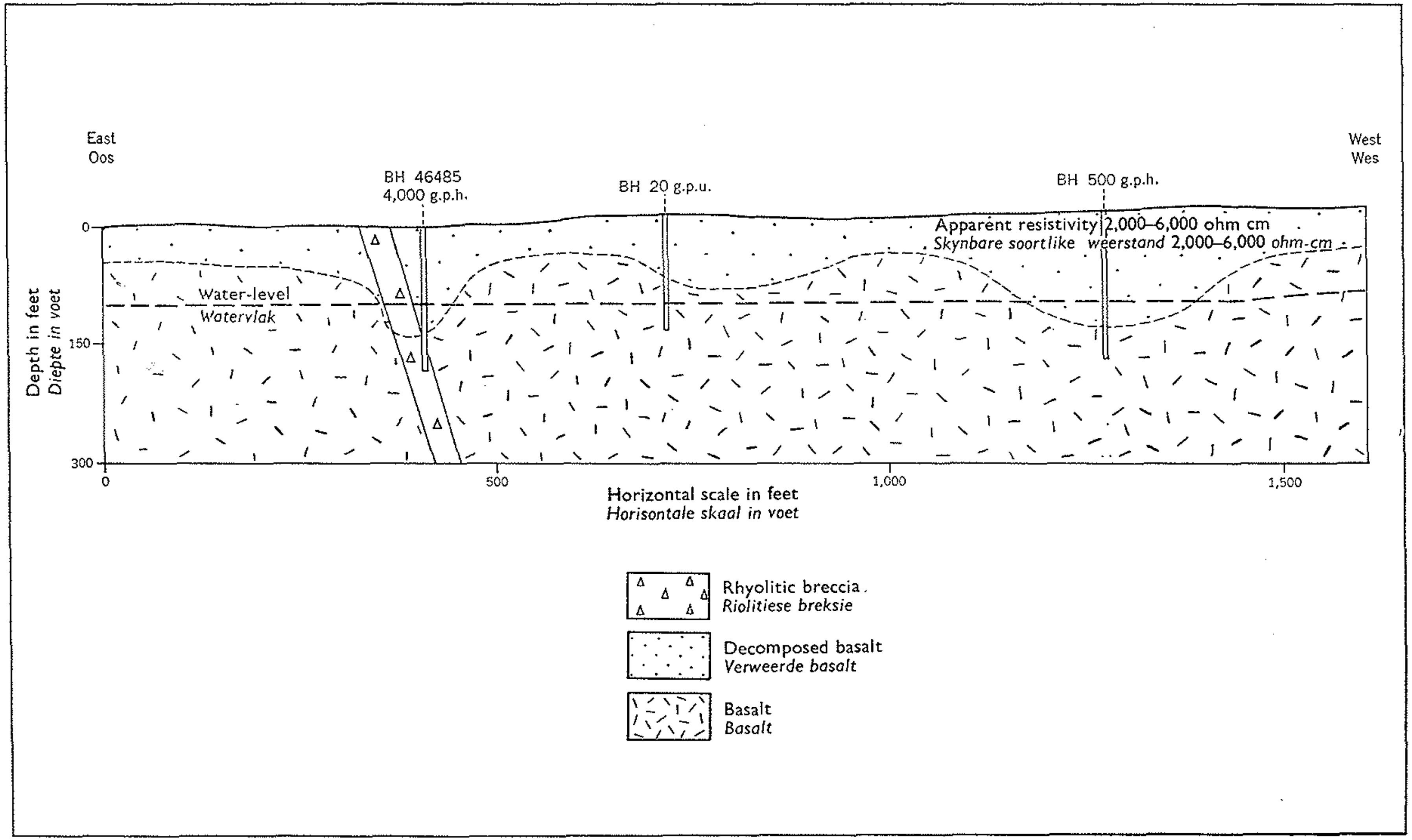

FIG. 14.—Section across typical basins of weathering in basalt. Nkurali, Hlabisa District.

At greater depths where joints or " attacking points " are less abundant, the lateral extent of weathering is largely controlled by the susceptibility of the rocks and by ground-water conditions:—

(i) *In Igneous Rocks.*—Igneous rocks are more susceptible to weathering than sedimentary rocks (Merrill, 1906) and consequently weathering plays a greater role in their epigenetic water-bearing properties. The granite in the Piet Retief District is weathered everywhere to depths of 80 to 250 ft. below surface, while lava in the Lowveld is generally weathered to depths of 25 to 50 ft. (fig. 14) and consequently the geohydrology of both these areas is largely dominated by the hydrological properties of the thick mantle of decomposed rock. The hydrological properties of igneous rocks at different stages of weathering will be described on a subsequent page.

More than 83 per cent of the successful bore-holes drilled in igneous rocks are situated in so-called basins of decomposition. The importance of these basins as underground water reservoirs and their location by the electrical resistivity method have been described by Enslin (1943). More than 20,000 depth-probes, taken in the Lowveld areas to locate such basins in basalt for the selection of bore-hole sites for water, revealed that they generally show no surface-indication, and occur at the most unexpected places in almost any topographic situation. They are usually saucer-shaped when formed at the intersection of two or more sets of joints, but may also be extended troughs when formed along fault-zones, dolerite dykes or any linear structure (see fig. 14).

(ii) *In Sedimentary Rocks.*—Sedimentary rocks are generally less susceptible to weathering than igneous rocks and as far as could be ascertained no deep basins of decomposition exist in any of the sedimentary rocks encountered in the area.

Although sandstone and shale may be highly weathered near the surface, electrical loggings in bore-holes have shown that weathering at depth is in most cases confined to alterations along joints and fractures and that very little decomposition of the blocks separating the joints ever takes place (pl. VII). This also explains why most of the high permeability zones found along dolerite dykes, or inclined dolerite sheets, seldom extend laterally beyond the " baked " zone in which the joints had been formed (see fig. 10).

The contact-zones of sedimentary rock with horizontal dolerite sheets, in contrast to the contact-zones along dykes, are usually unproductive. Approximately 179 of the bore-holes in the area intersected horizontal dolerite sheets and in only 35 of them supplies of more than 100 g.p.h. were obtained. In a number of cases where no water was obtained in the upper contact-zone, the bore-holes were deepened to penetrate the dolerite sheet in an effort to strike water in the lower contact-zone, with equally little success.

However, where the lower contact of a horizontal dolerite sheet intersects the surface and the water-table is sufficiently near the surface, bore-holes that penetrate the zone at depths below the water-table invariably yield a good supply of water. Figure 15 shows the distribution of successful and unsuccessful bore-holes which penetrated the contact-zones of horizontal or near-horizontal dolerite sheets.

FIG. 14.—Section across typical basins of weathering in basalt. Nkurali, Hlabisa Distric

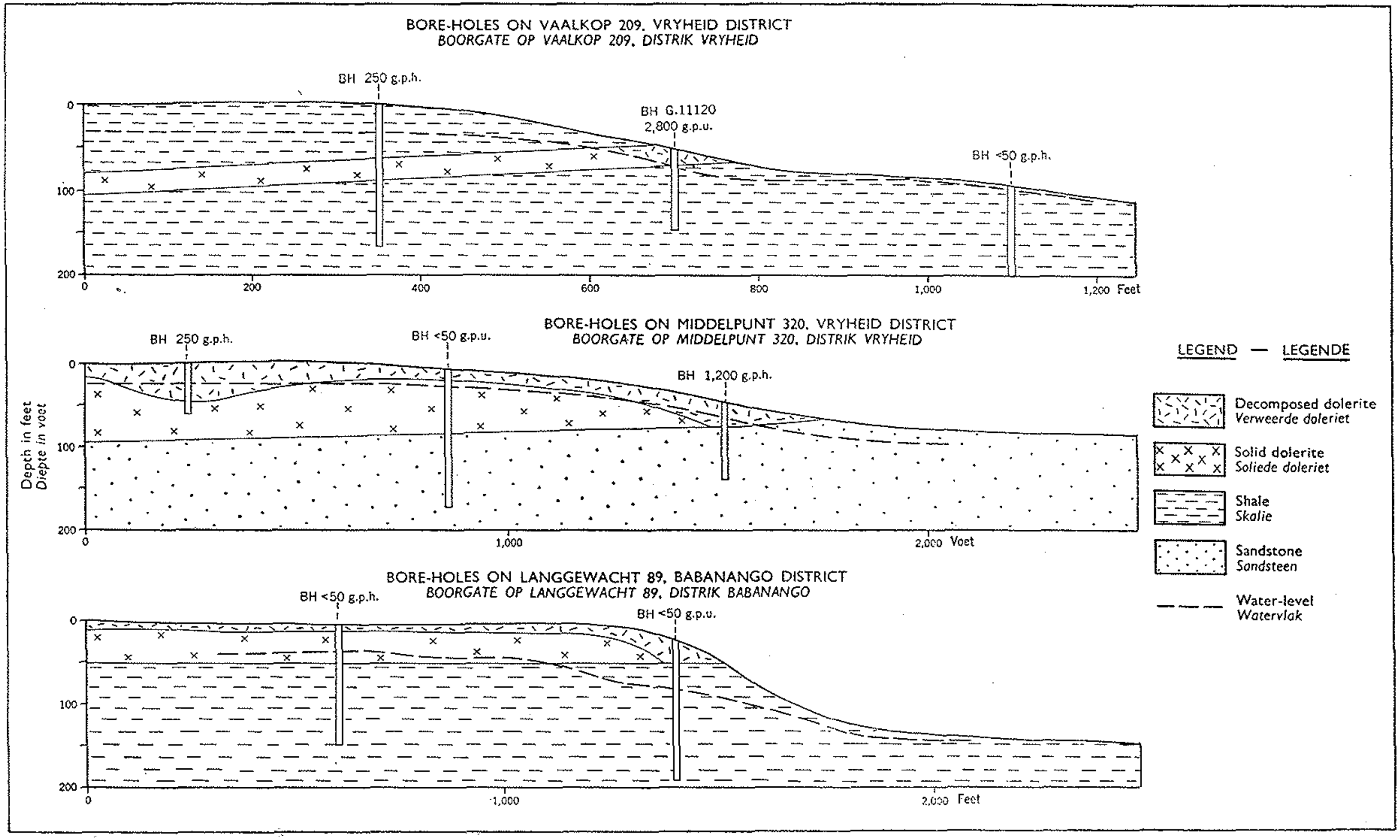

FIG. 15.—Sections showing the influence of contact-zones of horizontal dolerite sheets on the yields of bore-holes.

This observation, namely that the contact-zone of an intrusion acts as a high-yielding aquifer under certain conditions while it is impervious, not many scores of feet away, indicates that:—

(i) The contact-zone as a whole has not been changed into an aquifer lying between the solid dolerite intrusion and the saturated, low permeability country-rock as suggested by Enslin (1950, p. 195). It rather supports the author's contention that contact-zones are permeable by virtue of joints that developed during the cooling of the dolerite magma and which had subsequently been opened or widened by weathering and circulating waters.

(ii) The contact-zone has a high permeability near the surface under a cover of decomposed or fractured rock which permits circulation of ground-water. It is, however, impermeable under a cover of impermeable rock. The impervious cover allows no downward movement of water and protects the zone from weathering. The horizontal disposition of the zone on the other hand does not allow sufficient movement of ground-water laterally to open the joints and render the zone permeable.

Another interesting example which illustrates the lateral extent of weathering in sediments is the following:—

The author constructed a curve showing the correlation between the electrical resistivity and percentage of successful bore-holes (Enslin, 1950, p. 195) for the sedimentary rocks in Natal and Zululand (fig. 16). The curve shows that the chance of striking a supply in sediments with resistivity in Range A (less than 3,500 ohm cm) is extremely small. The percentage successful bore-holes in sediments with a resistivity falling within Range B (3,500–20,000 ohm cm) is high and rapidly decreases with increasing resistivity to Range C (more than 20,000 ohm cm). The resistivity ranges of the different sedimentary rocks are given in table 6.

Interesting, however, is the fact that the percentage successful bore-holes in sediments with resistivity in Range B is only high in places where these sediments crop out. In places where they are covered by some thickness of sediments falling within Range A or C and where they are remote from dolerite intrusions, no water is obtained in them. For example:—

(i) Lower Ecca shale, which falls in Range B, covers large areas in the Vryheid and Babanango Districts. None of the 73 bore-holes drilled almost at random in them were failures, while none of the holes remote from dolerite intrusions yielded supplies exceeding 100 g.p.h. where the shales are covered by Middle Ecca sediments.

(ii) On De Jagersdrift, Dundee District, the three bore-holes that were drilled at random in Middle Ecca sediments with resistivity in Range B all yielded more than 800 g.p.h. Only one of the seven bore-holes that intersected the above beds under a cover of massive sandstone with a resistivity of 120,000 ohm cm, however, yielded more than 100 g.p.h. (fig. 17).

FIG. 15.—Sections showing the influence of contact-zones of horizontal dolerite sheets on the yields of bore-holes.

From the foregoing it is evident that the high permeability of sediments with resistivity falling within Range B is not an inherent characteristic but of epigenetic origin. Two questions that need further discussion are (1) what explanation can be offered for the fact that sediments with resistivity in Range B develop a high permeability over wide areas, while the development of permeability in other sediments under the same topographical and climatic conditions, is confined to openings produced by geological processes and (2) why are the sediments with resistivity in Range B only permeable where they crop out? The following explanation is offered:—

> It has been established that a much higher percentage of bore-holes yielded water in the thinly bedded sediments than in the more massive ones which also fall within Range B. All the bore-holes drilled from the surface into the thinly bedded Lower Ecca shale were successful while only 20 to 30 per cent of the holes drilled in the more massive Middle and Upper Ecca shale yielded more than 100 g.p.h.

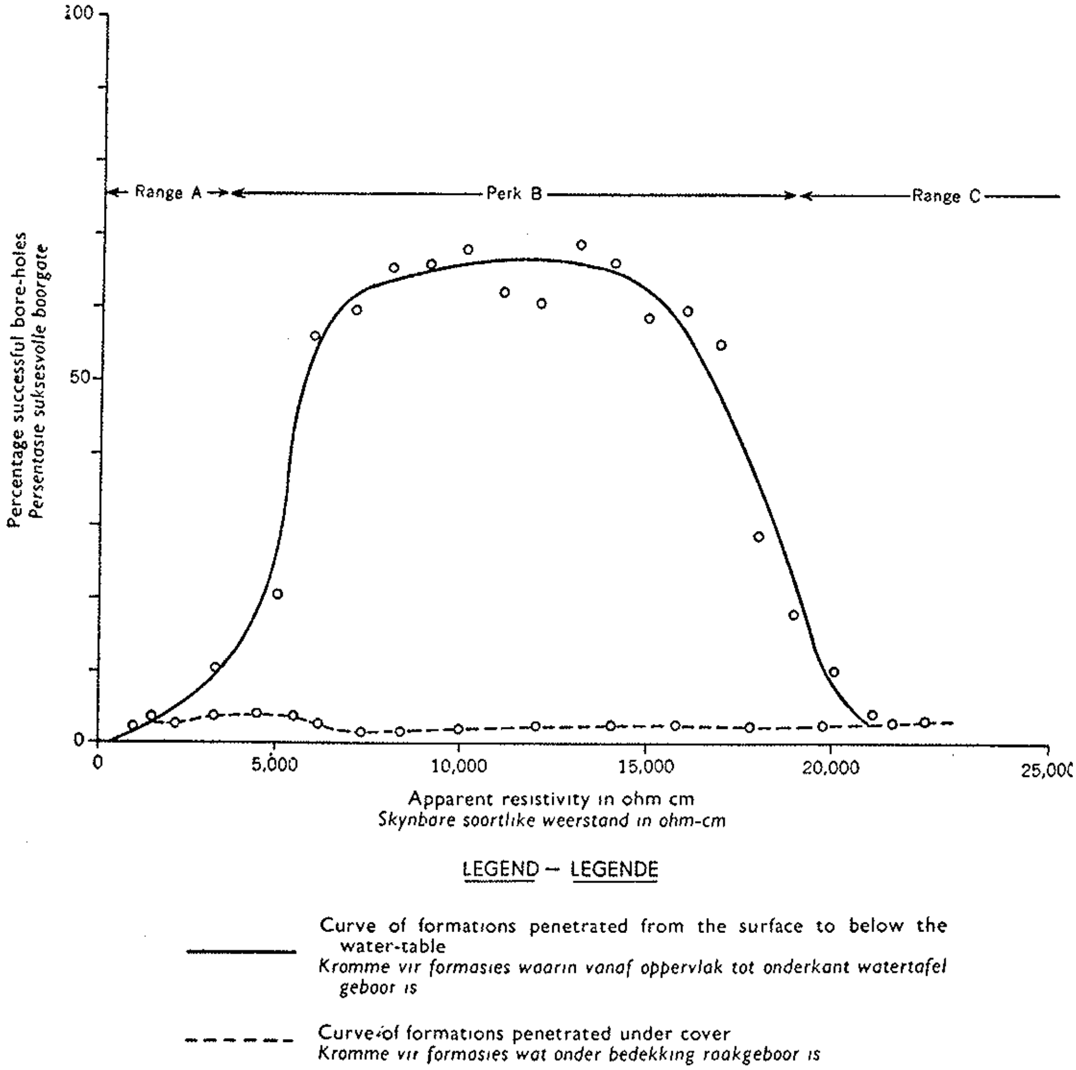

FIG. 16.—Curves showing the correlation between the apparent resistivity of Karroo sediments and the percentage of successful bore-holes in them.

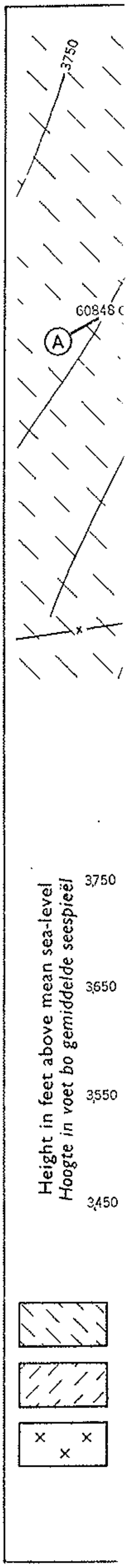

FIG. 17.-

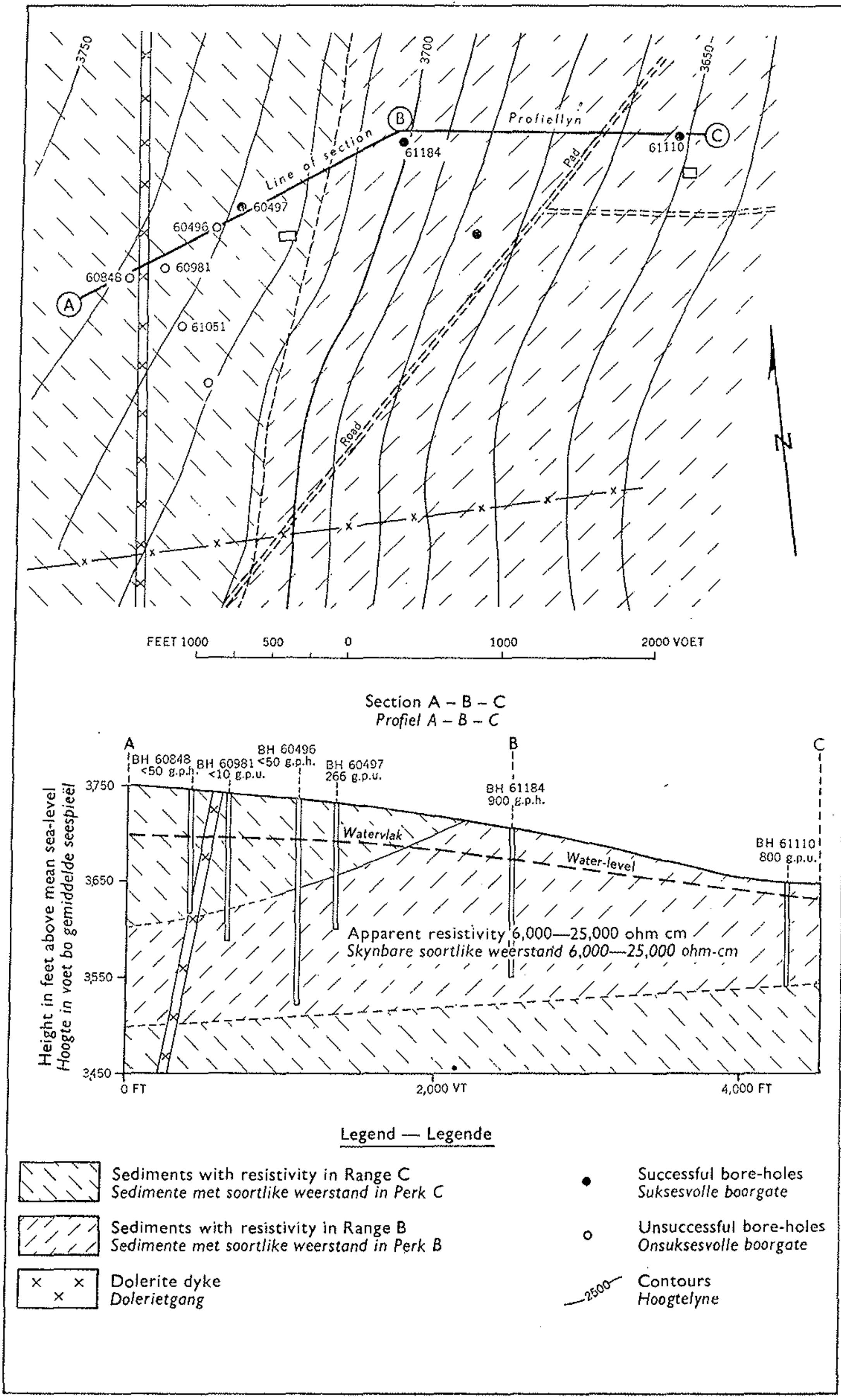

FIG. 17.—The occurrence of ground-water in sediments falling within resistivity Range B. De Jagersdrift, Dundee District.

Not all rocks exhibit the same joint frequency. According to Price (1959, p. 167) the frequency is determined by the amount of strain energy stored in rock prior to the onset of the jointing. For instance, he shows that joints (cleats) in coal occur very much more frequently than in a nearby sandstone (several cleats to the inch as opposed to one joint every few feet or so in sandstone). Owing to a generally well-developed soil-cover no comprehensive study of joint frequencies could be carried out. However, a feasible explanation to the above problem can be given by assuming that the joint frequency in the thinly bedded sediments falling in Range B is much higher than in the sediments with resistivity in Ranges A and C. The large number of joints and bedding-planes permits circulation of ground and rain-water which open and interconnect them to render the formation permeable over wide areas. The smaller number of joints and fewer bedding-planes in sediments with resistivity in Ranges A and C do not permit sufficient circulation to render the formations permeable over large areas, and permeable zones are confined to isolated joints. The mechanism envisaged is shown in figure 18.

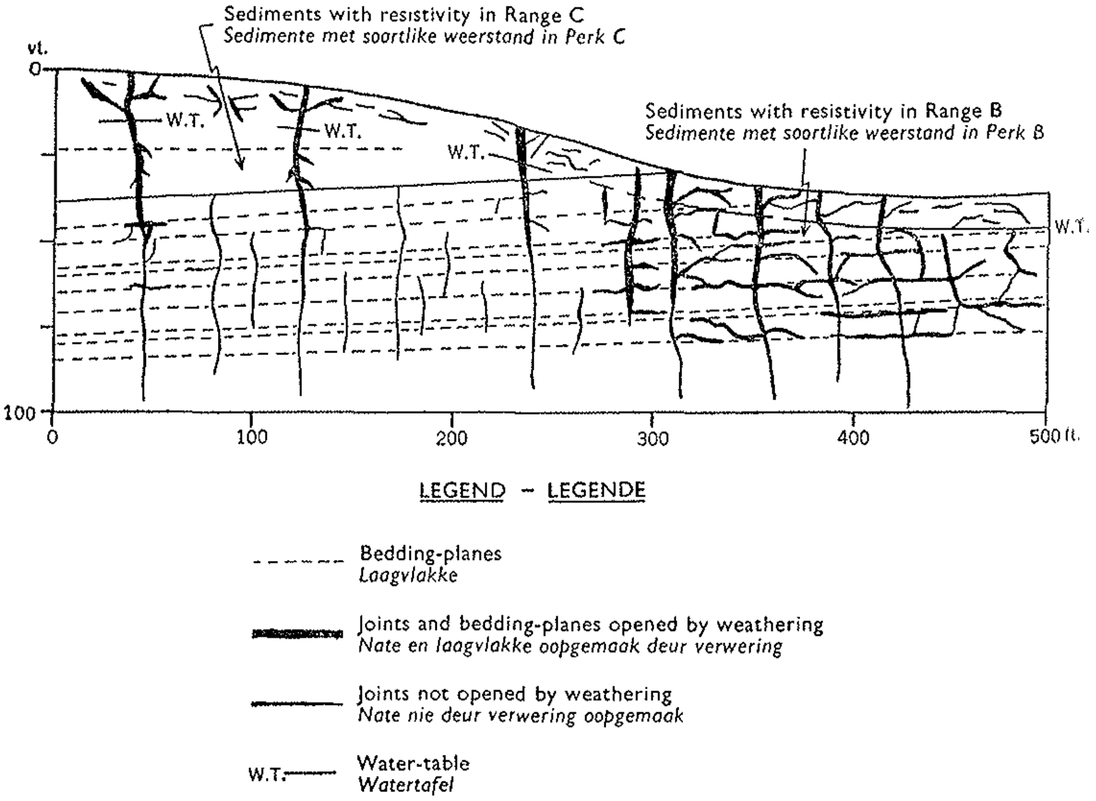

FIG. 18.—The development of high permeability in sediments falling within resistivity Range B when exposed to the surface.

Most of the joints are probably poorly developed when formed and exist as lines of weakness only. It is thus imperative that they have to be opened by weathering and circulating water before they can be of value as conduits for ground-water. In places where the sediments in Range B are covered by impervious rock with few joints there is apparently, as is the case with contact-zones of horizontal dolerite sheets described above, not sufficient circulation of rain or ground-water to attack and open the joints, and consequently the sediments remain impermeable under these conditions.

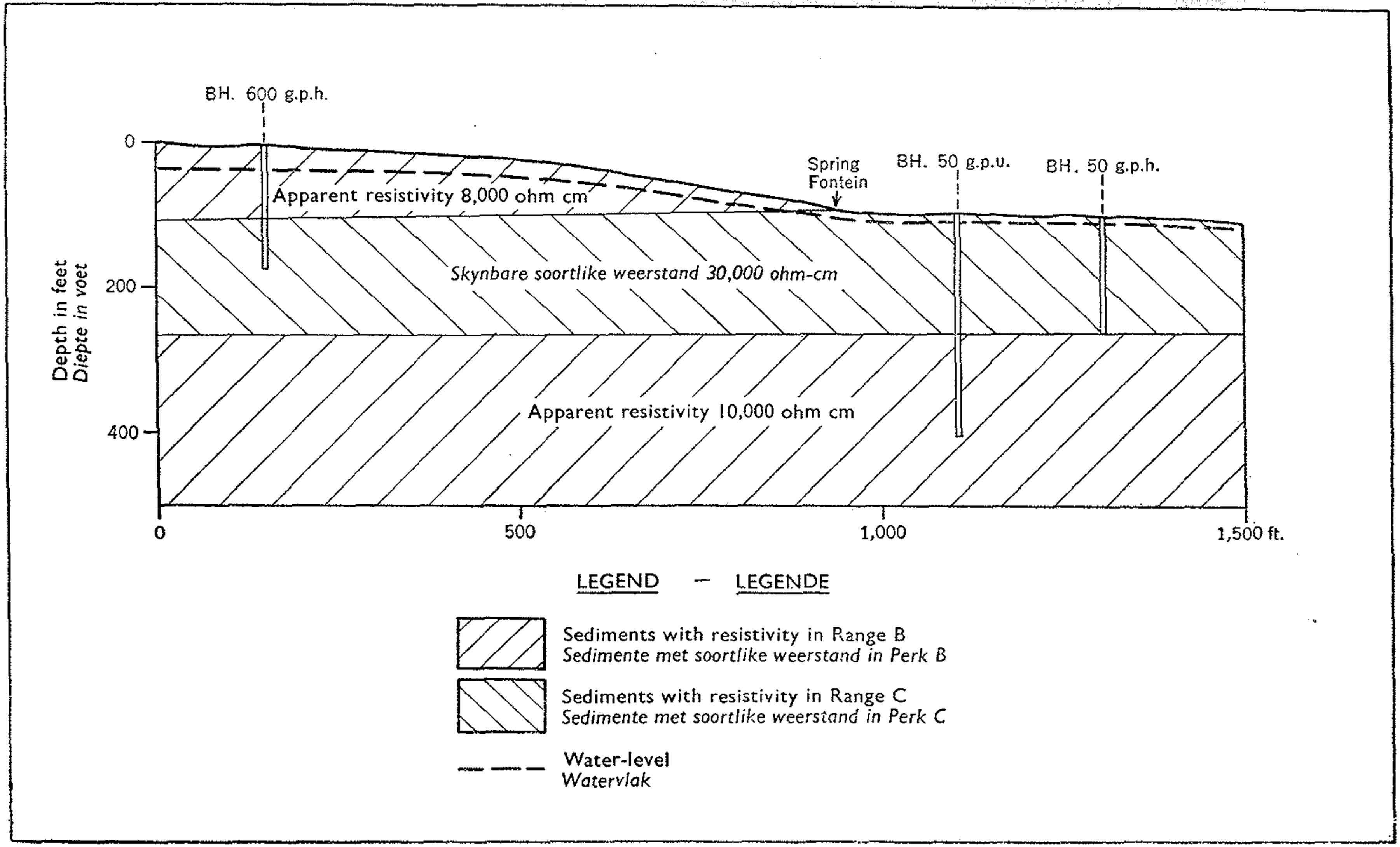

FIG. 19.—Section showing successful bore-hole on high ground and unsuccessful bore-holes on low ground. Klipspruit, Utrecht District.

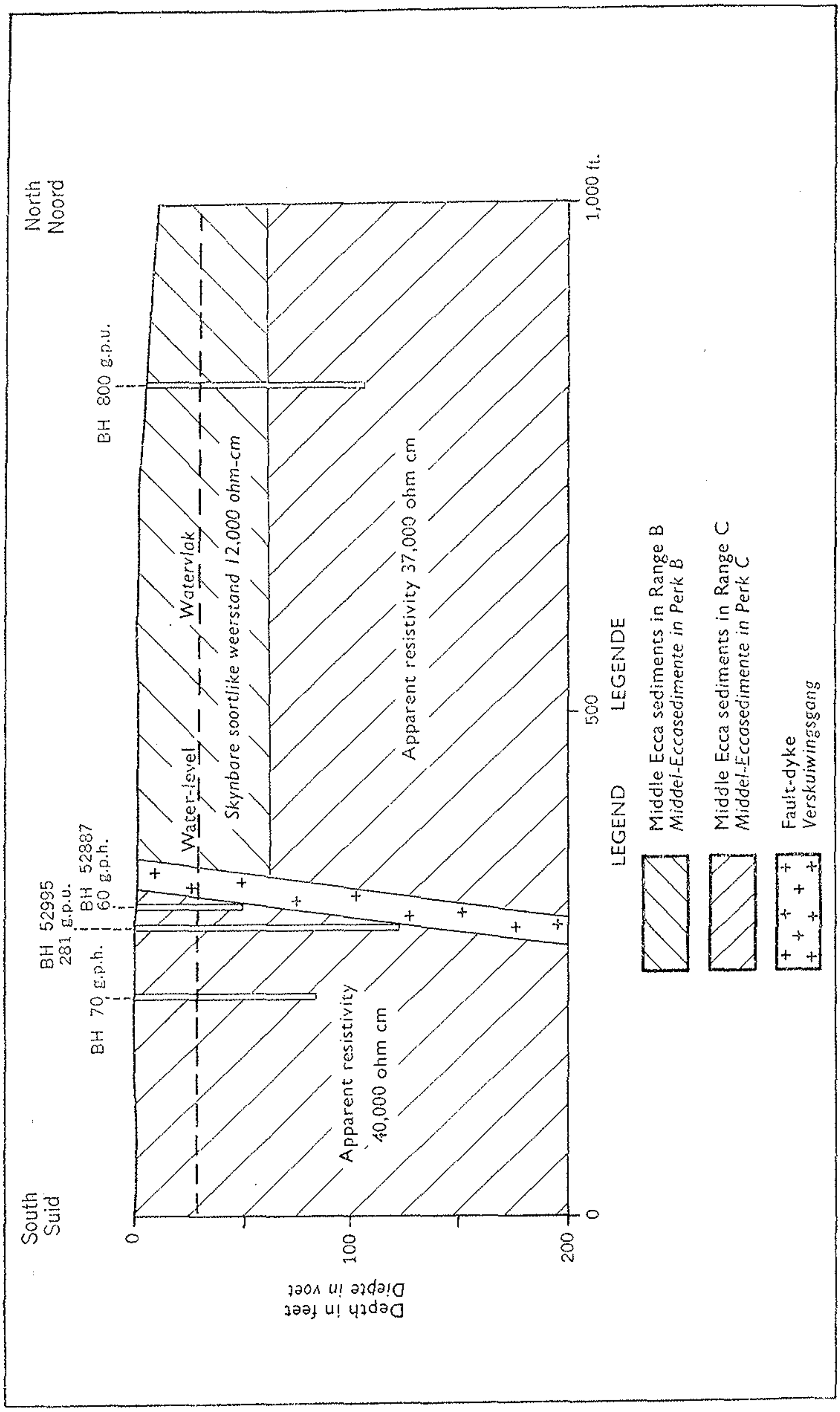

FIG. 20.—Section showing fault-dyke and the yields of bore-holes on both sides of it. Bloemendal, Vryheid District.

Incidentally, the occurrence of ground-water in these sediments, which cannot easily be distinguished from sediments with resistivity in Ranges A and B in the field, explains two controversial problems which have always baffled drilling men in Natal:—

(i) It is often found that a high percentage of successful bore-holes are drilled on high ground while most of the bore-holes in adjoining valleys are failures. Electrical resistivity surveys showed that in all these cases the hills are composed of sediments with resistivity in Range B, while the valleys which had cut through these sediments are underlain by unproductive sediments in Range C (fig. 19).

(ii) Many cases can be listed where a high percentage of successful bore-holes has been drilled on one side of a dolerite dyke, while all the holes on the other side are failures. Frommurze (1937), Snyman (1954) and others have described the same phenomenon occurring in other parts of South Africa. Their explanation is that the dolerite dykes act as underground barriers (aquifuges) that intercept the natural ground-water flow, with the result that only the bore-holes drilled behind or above such barriers yield water.

A study of the reactions of water-levels in bore-holes drilled on opposite sides of a dolerite dyke, while one of the holes was being pumped, however, showed that very few dykes in Natal, if any, act as aquifuges, especially where the water-levels are within 50 ft. of the surface. (For hydrographs and a full discussion see chapter V.) This fact rules out, as far as Natal is concerned, the theory put forward by the above-mentioned authors.

Electrical loggings carried out in bore-holes suggest that displacement had taken place along all these dykes (fig. 20). For in each case it has been found that sediments falling within resistivity Range B exist in juxtaposition with unproductive high resistivity sediments on the opposite side of the dyke.

(c) *Effects of Weathering on the Hydrological Properties*

It has been shown that most openings produced by physical and geological processes are modified by weathering and circulating water; that the maximum depth at which most bore-holes yield water also coincides with the depth of weathering and that most ground-water in igneous rocks occurs in basins of decomposition. It is thus evident that the degree and the lateral and vertical extent of weathering control, not only the yield of bore-holes, but also the movement and storage of ground-water.

The influence of weathering on igneous rocks, which are more susceptible than sedimentary rocks, is probably easier to understand and to evaluate. However, its influence on sedimentary rocks, although in most cases confined to the opening up and interconnecting of joints, is of equally great importance.

Adequate data for a comprehensive discussion of this important aspect are lacking. The author, however, has made a number of laboratory and field-determinations which are given below.

(i) *Effects on Porosity.*—The porosity of a rock is extremely sensitive to the effects of weathering (Fraser, 1935). Du Toit (1915), for instance, pointed out that a substantial increase in the porosity of Karroo sandstone has been brought about by weathering within the surface-zone.

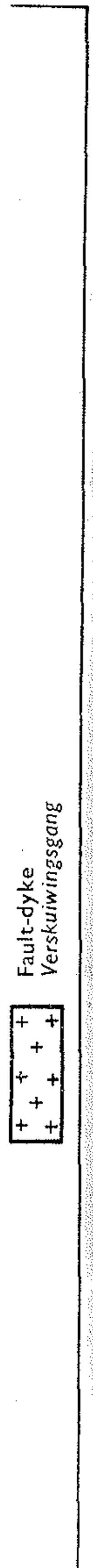

FIG. 20.—Section showing fault-dyke and the yields of bore-holes on both sides of it. [illegible], Vryheid District.

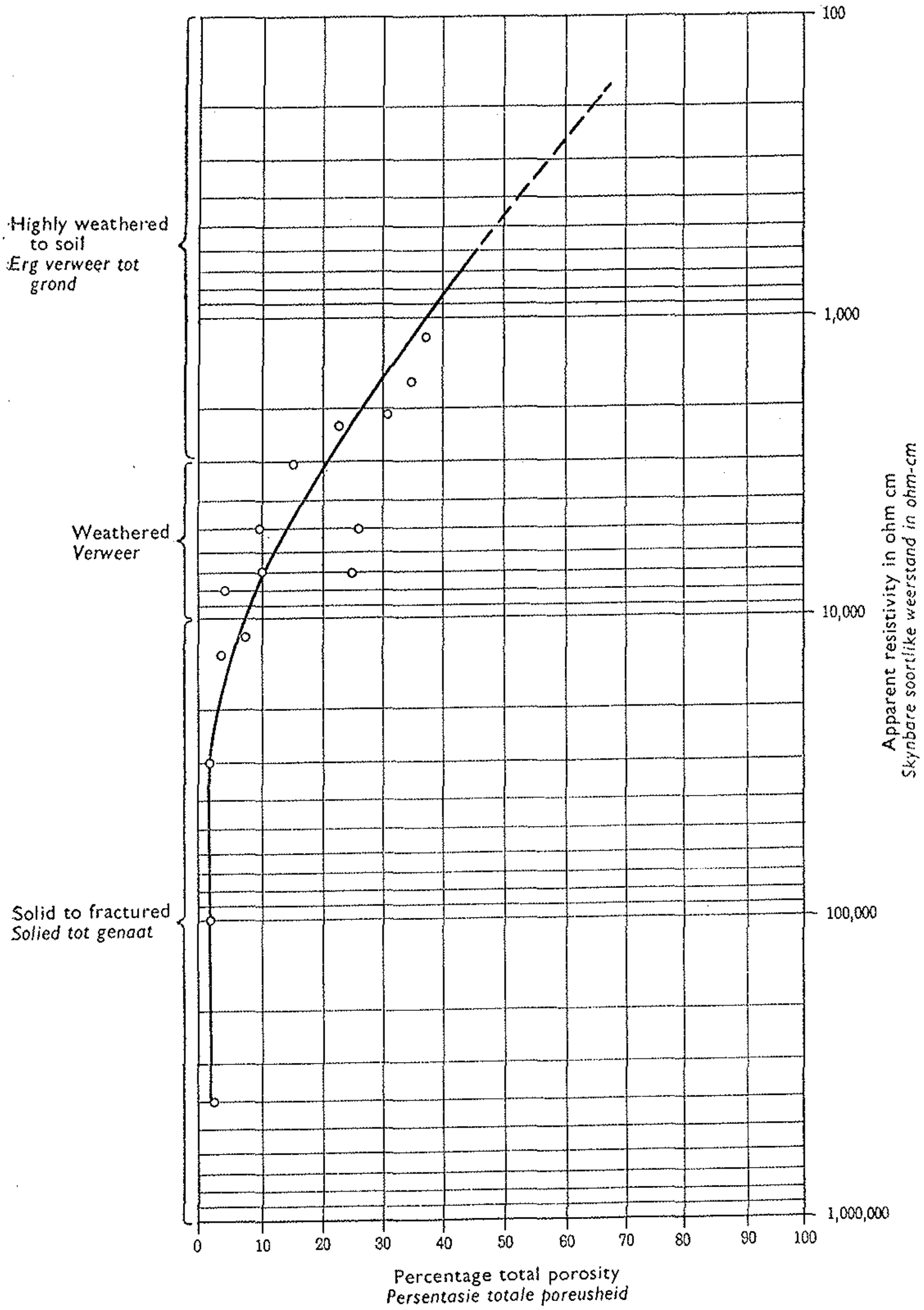

FIG. 21 —Curve showing relation between porosity and degree of weathering in basalt.

The author made a number of porosity determinations on specimens of different rock-types exhibiting different stages of weathering.

The porosities of basalt on Broxburn, Ubombo District, at different stages of weathering are given in figure 21. The determinations were carried out on specimens taken from quarries and sections of bore-holes falling within the resistivity ranges shown on the curve. The resistivity of the basalt was taken as a criterion of the degree of weathering.

It is significant to note that the curve shows no increase in porosity in the fractured zone, although there is a marked variation in the resistivity. The lower resistivity is the result of the fractures filled with water or decomposed material that have a high conductivity. It is obvious, however, that by virtue of the fractures and decomposed material in them, the zone as a whole has a much higher porosity than solid rock.

The condition just described is typical of the circumstances that prevail in sedimentary rocks where weathering is confined to joints and joint-systems with very little alteration of the blocks between them, and where laboratory determinations of porosity can have some academic, but almost no practical value, because the zones of weathering are not included in small samples.

A few porosity determinations have been carried out on decomposed sandstone, shale and mudstone for comparative purposes. The porosity of sandstone also shows a sharp increase in the weathered stages and values as high as 15 to 27 per cent have been obtained. Shale and mudstone revert to clay on weathering which naturally causes a large increase in their porosities. Values ranging from 10 to 47 per cent have been obtained.

(ii) *Effects on Specific Yield.*—Owing to the almost insuperable task of determining areally the reservoir extent in sedimentary rocks, all efforts to do specific yield determinations had to be abandoned.

Very little quantitative data are available, but an analysis of bore-hole data and electrical loggings in the bore-holes suggest that the specific yield of all the rocks in the area is low when fresh, slightly higher when fractured, probably reaches a maximum in the semi- to weathered stages and declines sharply when the rocks reach a highly weathered stage.

The specific yield as determined for decomposed basalt is given in table 9. As already shown, ground-water in basalt occurs in isolated basins of decomposition. The size of all four basins tabulated in the table was determined as accurately as possible with the electrical resistivity method. For the calculations it was assumed that there is no leakage of water from or to adjoining basins. A section across the basin of decomposition on Broxburn, Ubombo District, is shown in figure 22.

The determinations and calculations were made in the manner described on a previous page. In cases 3 and 4, however, no continuous pumping tests were carried out. The lowering of the water-levels was observed over a period of months in which no rain fell and an accurate record was kept of the amount of water that was pumped from time to time during the period.

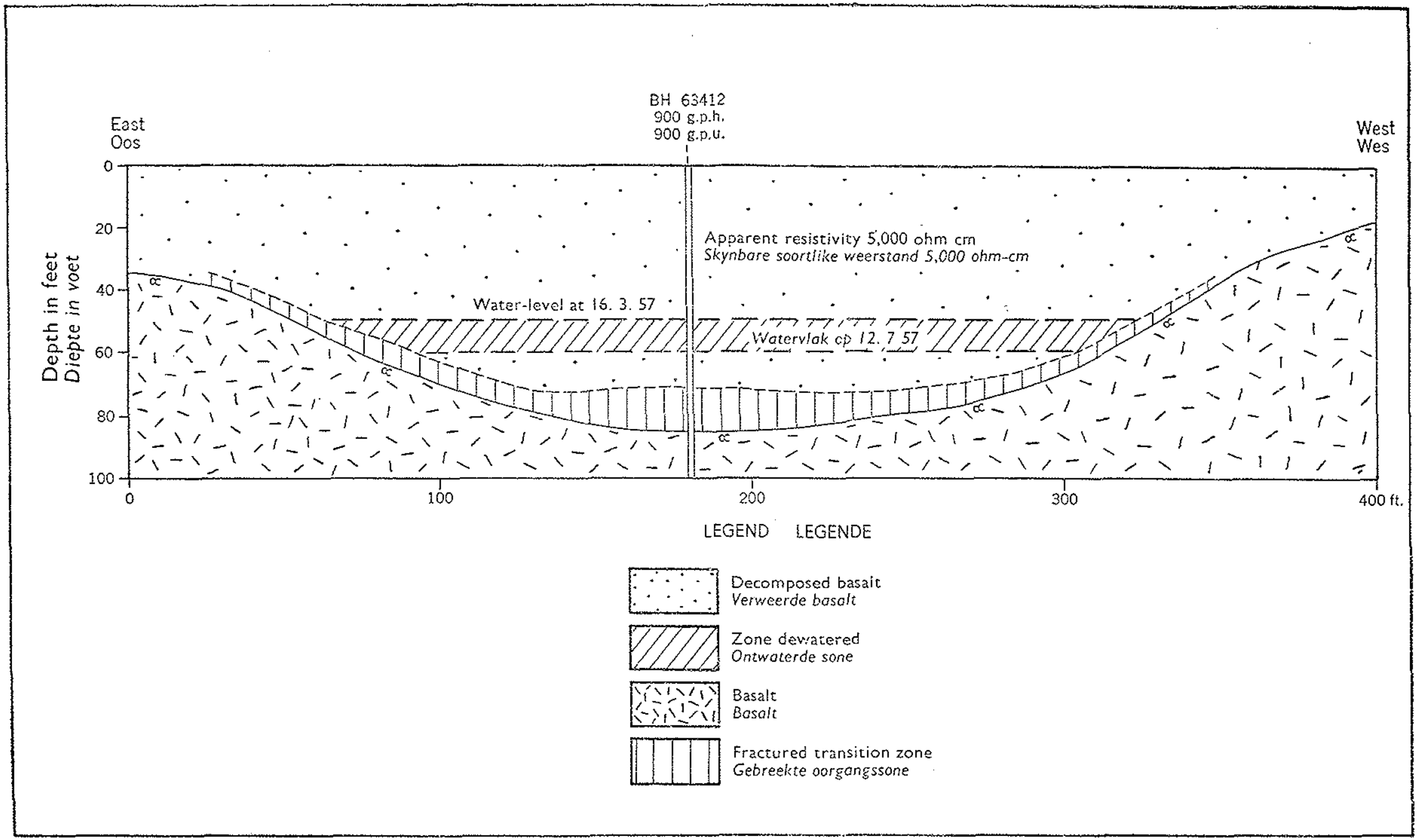

FIG. 22.—Illustrating the determination of effective porosity in basalt. Broxburn, Ubombo District.

TABLE 9.—SPECIFIC YIELD OF DECOMPOSED BASALT

Location	Volume of rock dewatered in cubic ft.	Total amount of water pumped in gallons	Specific yield (Percentage)	Resistivity in ohm cm
Cavin Baine, Hlabisa District..........	100,090	60,000	9·6	5,000
Carstairs, Hlabisa District.............	117,761	45,000	6·13	3,000
Elgin, Ubombo District...............	271,000	125,000	7·4	5,000
Broxburn, Ubombo District...........	175,000	95,000	8·7	5,000

(iii) *Effects on Permeability.*—It is common knowledge among drillers that no water is obtained in igneous rocks that are in a very advanced stage of decomposition. In this respect Frommurze (1937, p. 21) states that 30 per cent of the bore-holes in crystalline rocks in the Barberton District are failures; their logs report decomposed rock—running sand—running mud, etc., indicating that the texture and cohesion of the rocks have been destroyed by decomposition.

Vegter (1953) constructed resistivity—percentage successes and resistivity–yield correlation curves for bore-holes drilled in granite in Northern Transvaal and the Kenhardt area. According to the curves for Northern Transvaal the highest percentage of successful bore-holes (nearly 100 per cent) and also the highest yields are obtained in decomposed granite with a resistivity of 10,000 to 30,000 ohm cm.

The author constructed similar curves for bore-holes drilled in basalt and dolerite in Natal. However, when electrical logging of bore-holes was introduced at a later stage, the curves were discarded because the logging of more than 135 bore-holes in basalt and dolerite showed that the water is invariably obtained, not in the decomposed material, but in high resistivity fracture-zones (see figs. 7 and 23). In most cases these zones represent the transition zone lying between the decomposed and solid rock, but may also occur as layers surrounded by decomposed material some distance above the transition zone. For corroboration, the author carried out water-absorption tests and kept a careful check of the depths at which water was struck in a number of bore-holes while drilling operations were in progress. In all the cases the holes remained dry while drilling progressed through the decomposed material until the much harder transition zone was intersected. Water then flowed into the bore-hole and rose to a level above the transition zone in which the water was struck (see fig. 22).

As already shown, the resistivity of the fractured transition zone varies from 10,000 to 100,000 ohm cm depending on the number of fractures and the resistivity of the decomposed material filling them. The thickness, which may be anything from a few to scores of feet, is seldom constant and may vary within short distances—a fact which accounts for the anomalous yields sometimes obtained in bore-holes situated in the same basin of decomposition. The permeability of the transition zones, according to the yields of the bore-holes intersecting them, depends mainly on the openness of the fractures and to a lesser extent on the thickness of the zone (fig. 24).

FIG. 22.—Illustrating the determination of effective porosity in basalt. Broxburn, Ubombo District.

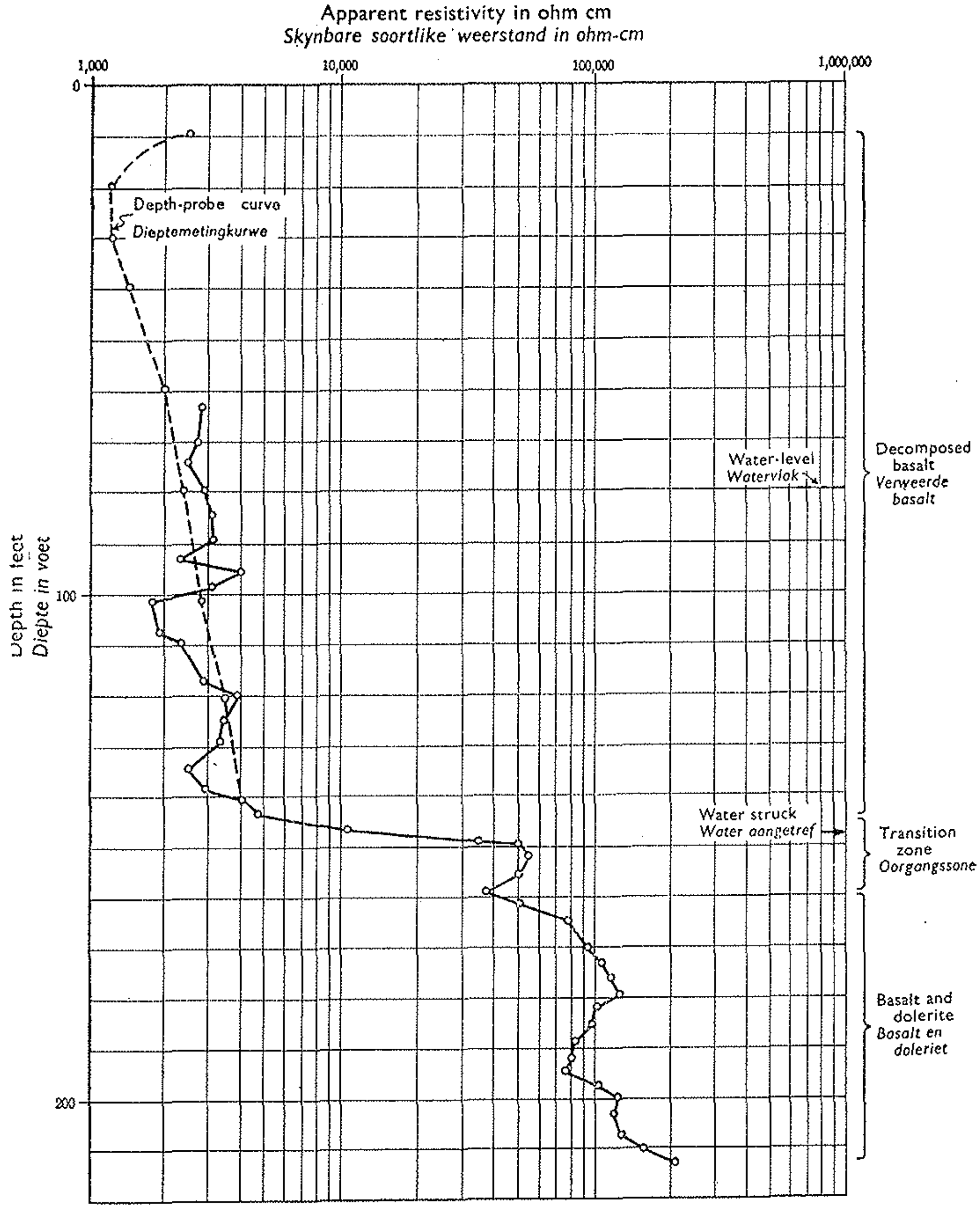

FIG. 23.—Electrical log showing transition zone in decomposed basalt. H.49, Hlabisa District.

A hypothetical curve that shows the relation between the water-yielding capacity of basalt in the different stages of weathering, is given in figure 25. The curve is based on data obtained from electrical loggings and the yields of bore-holes. It shows that basalt, and for that matter most other rocks, has an optimum permeability when fractured and in the initial stages of weathering which rapidly decreases in the weathered and highly weathered stages.

In conclusion it may be added that the permeable zones which form the conduits along which water can move at a high rate into the bore-hole, are invariably comparatively narrow. Their capacity to store water is consequently small and if pumped at a high rate, the water stored in them will be depleted in a very short time. It is thus imperative that they be linked hydraulically with other sources of water in the low permeability solid or decomposed rock surrounding them. The yield of a bore-hole is thus a function of a number of interrelated permeabilities, namely:—

(i) The permeability of the conduit intersected by the bore-hole.

(ii) The permeability of joints and fissures linking the conduit to the surrounding low permeability reservoir rocks.

(iii) The permeability of the reservoir rocks in which the bulk of the water is stored.

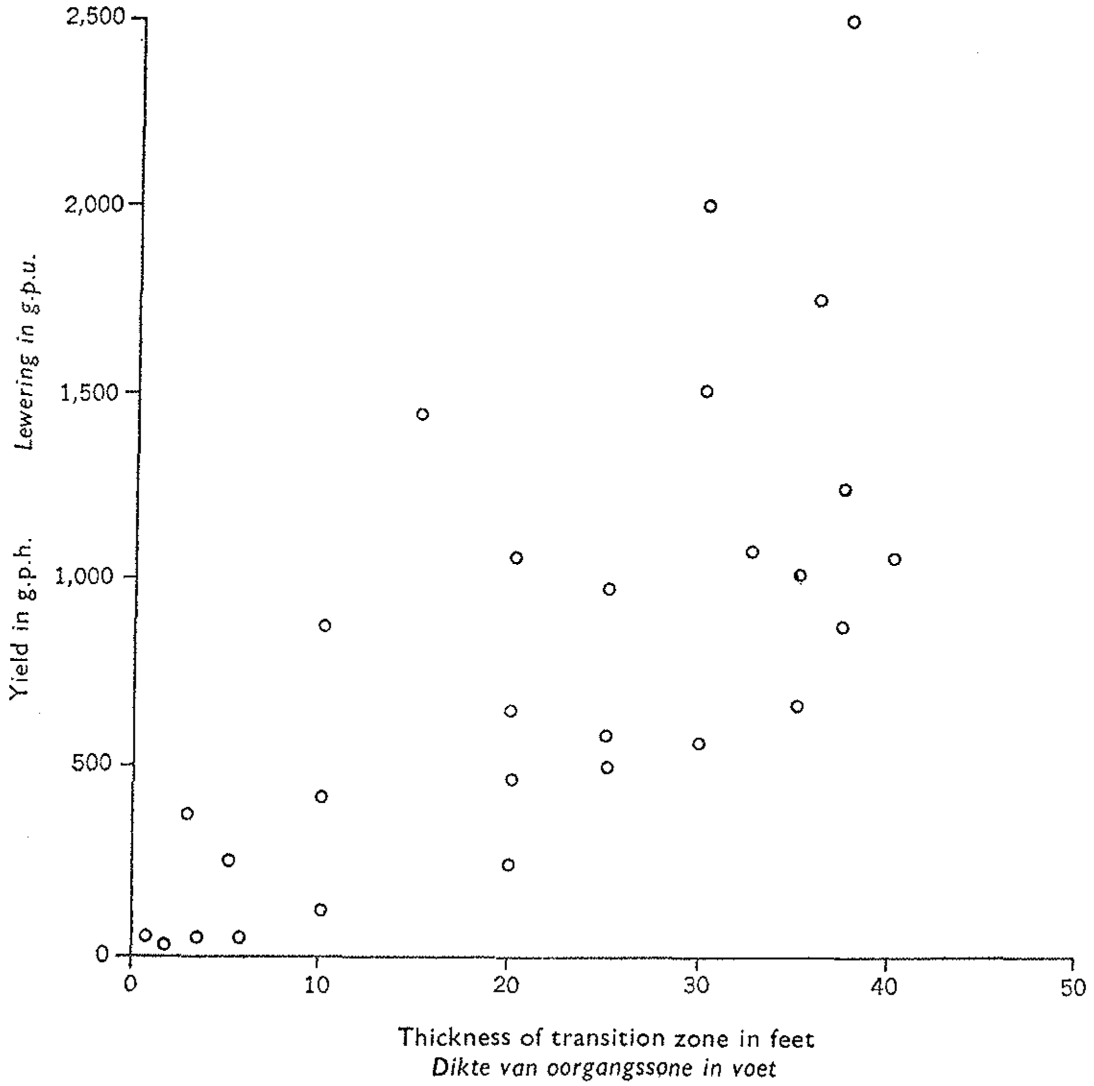

FIG. 24.—Diagram showing the relation between the thickness of the transition zone and the yield of bore-holes in basalt.

D. INFLUENCE OF CLIMATE ON THE HYDROLOGICAL PROPERTIES

Frommurze (1937) stated that the quantity of ground-water available in any rock formation increases in amount as the average annual rainfall gets higher, though after the rainfall exceeds a certain figure, the percentage of dry holes increases too, owing to a greater degree of weathering within the rock. Du Toit (1928, p. 86) on the other hand, is of the opinion that the magnitude of rainfall is a much overrated factor in ground-water supplies, for there is less trouble in obtaining good supplies in the Karroo rocks around Laingsburg and Prince Albert in the Cape, a region with a rainfall of about 175 mm per annum, than from the same formation in the Umfolozi Settlement in Zululand where the rainfall is over 750 mm per annum.

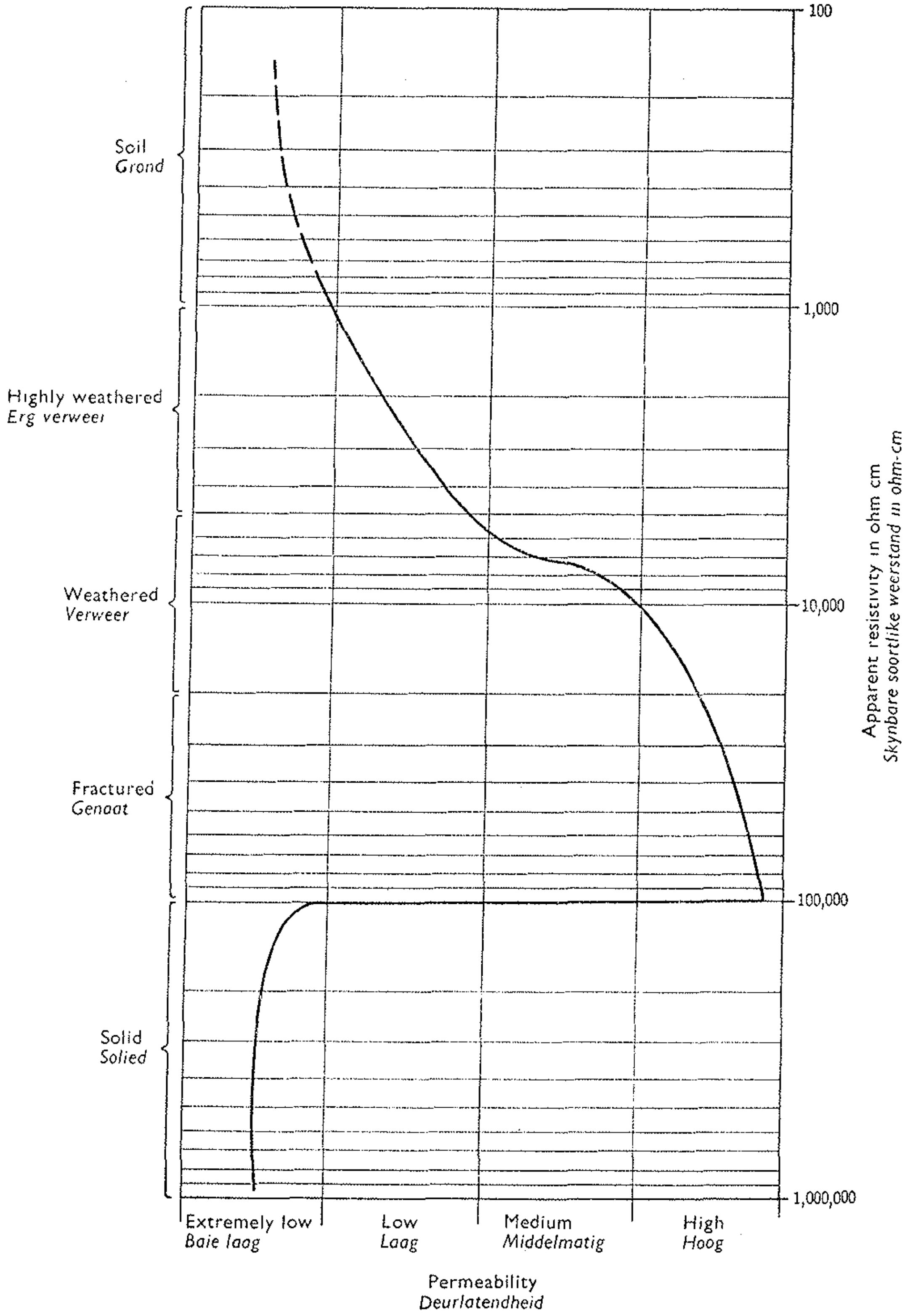

FIG. 25.—Hypothetical curve showing the relation between state of weathering and the permeability of basalt.

The area under consideration, with its large variety of geological formations and varying climate ranging from semi-arid, with an average rainfall of 500 mm per annum, to humid, with an annual rainfall of over 1,500 mm (fig. 3), offers ideal conditions to compare the validity of the divergent opinions held by the above authors.

A comparison between the yields of bore-holes drilled in the same geological formations under different climatic and rainfall conditions showed that there is no direct relation between the yield of bore-holes and rainfall (table 10). For example, it is easier to obtain a successful bore-hole with a high yield in the Archaean granite in the Vryheid and Babanango Districts where the annual rainfall is from 600–750 mm, than in the same formation in the Eshowe and Empangeni Districts where the rainfall is 1,000 to 1,800 mm per annum.

TABLE 10.—RELATION BETWEEN RAINFALL AND YIELD OF BORE-HOLES

Area	Rainfall in mm	Geological Formation	Percentage of successful bore-holes	Median yield of bore-holes in g.p.h.	Average highest yields in g.p.h.
Eshowe and Empangeni Districts	1,000–1,250	Archaean granite	37	900	2,500
Babanango and Vryheid Districts	500–750	Archaean granite	49	1,000	4,000
Mtunzini District..........	1,000–1,250	Dwyka tillite and Lower Ecca shale	73	800	3,000
Babanango and Vryheid Districts	500–750	Dwyka tillite and Lower Ecca shale	53	850	3,000

The obvious explanation for the fact that rainfall has no linear relationship to the yield and percentage successful bore-holes that can be drilled in a particular formation is that the rocks are inherently impervious and that the frequency at which water is struck and the yield of bore-holes are largely dependent on secondary hydrological properties produced by structures such as joints, fissures, faults and dolerite intrusions. The absence or presence of such structures in a particular formation is naturally not controlled by climatic conditions. Furthermore, the depth of weathering, which plays such an important role in the hydrological properties of rocks, is the result of the past climatic and physiographic history of an area; the present climatic conditions appear to have no noticeable effect. For instance, in the Piet Retief area the Archaean granite is everywhere intensely weathered to depths of 200 to 250 feet, while in the adjoining Vryheid District it is seldom weathered deeper than 90 feet, yet the annual rainfall in both areas is the same (fold. 1). The depths of weathering quoted above have been established from bore-hole records and electrical resistivity surveys conducted in the routine selection of bore-hole sites.

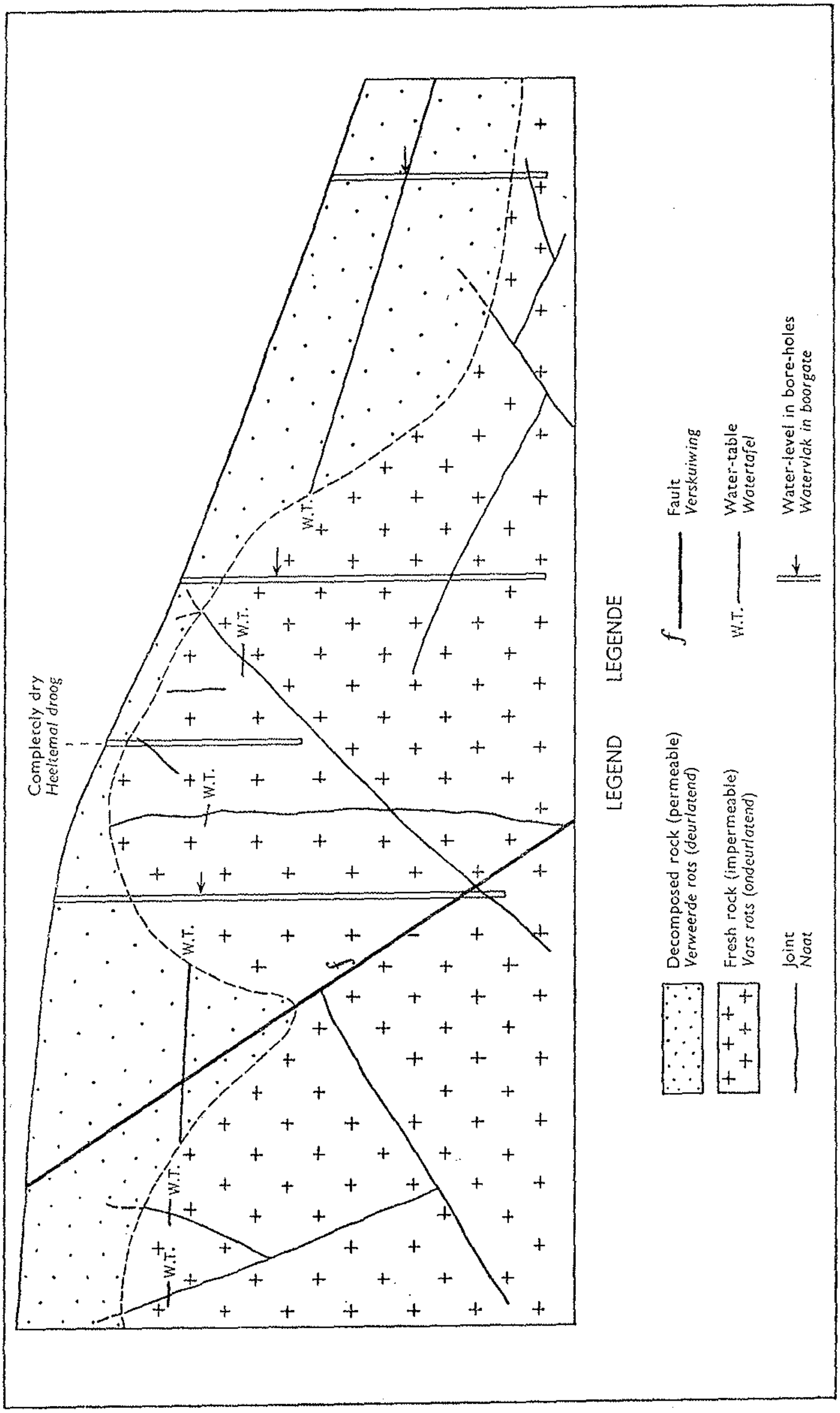

FIG. 26.—Schematic diagram illustrating the concept of water-table and water-level in bore-holes in fresh, jointed and weathered rock.

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The present rainfall conditions, however, have a substantial effect on recharge, the depth to the water-table and the occurrence of springs. Water-level fluctuations in bore-holes in the lava south of Hluhluwe Station suggest that recharge takes place during every rainy season. The rainfall of this region varies from 900–1,000 mm per annum. In the lava north of Hluhluwe Station, which occupies the only semi-arid region in Natal (fig. 3), however, recharge took place only once since 1943. The average water-level in the latter region prior to recharge in 1957, was 69 feet but it rose to 39 feet from surface after the recharge. The average water-level south of Hluhluwe Station remained more or less at a constant depth of 25 feet from surface during the period 1943 to 1957.

Mostly due to the frequent recharge and a comparatively high water-table, there are more springs in the high rainfall regions such as Eshowe, Qudeni and Ngome, than in the lower rainfall areas such as Magudu, Nongoma and the Tugela Basin.

V. WATER-LEVEL AND WATER-TABLE STUDIES

The water-table in granular pervious material has been described in detail by Tolman (1937). The fundamental laws governing the interpretation of water-table slopes have been described by Meinzer and Wenzel (1940), while accounts of studies on the various aspects of the water-table are found in most United States Geological Survey Water-Supply Papers dealing with ground-water.

Du Toit (1956), Frommurze (1937) and others came to the conclusion that in South Africa, owing to lack of pervious strata, there is generally no water-table. However, as far as the author is aware, no detailed studies on any aspect of the water-table or water-levels in bore-holes have been made in this country.

A. General Water-table Conditions in the Area

1. GENERAL CONSIDERATIONS

The water-table in pervious soil or rock is the upper surface of the zone of saturation. In impervious rock the water-table is absent (Meinzer, 1923, p. 30). The water-table in fractured impermeable rock as defined by Tolman (1937, p. 291) is " the surface at the contact between the water body in the fractures and the overlying ground air ".

It has been shown in the previous chapter that all varieties of rock in the area, except the Tertiary and Recent sand, are inherently impermeable and that ground-water moves and is stored in secondary openings in the formations.

According to the above definition a water-table is present in these formations. It is, however, confined to the secondary openings and is interrupted by fresh rock separating them (fig. 26). This is probably the case in the Karroo sediments in Northern Natal. In places again, where the rocks are highly fractured or deeply weathered over large areas, such as the granite in the Piet Retief District and the lava in the Lowveld, an uninterrupted water-table may be present over comparatively large areas. In these areas the water-table lies in the mantle of decomposed material and is only interrupted by solid rock in places where weathering has not proceeded to a depth below the water-table.

Joint
Naat

Water-level in bore-holes
Watervlak in boorgate

Fig. 26.—Schematic diagram illustrating the concept of water-table and water-level in bore-holes in fresh, jointed and weathered rock.

2. THE WATER-TABLE IN RELATION TO WATER-LEVELS OBSERVED IN BORE-HOLES

The author investigated ground-water and water-table conditions in a great number of bore-holes. The results in each case, except in the Tertiary and Recent sand, suggested that the holes tapped confined water. This has been established as follows:—

(*a*) A large number of bore-holes was visited while drilling operations were in progress. In each case the hole remained dry or comparatively dry until a fissure or any other permeable zone was intersected. Water then flowed into the bore-hole and rose to some point above the level at which it was struck.

(*b*) The hydrographs of all 59 bore-holes investigated show fluctuations of their water-levels caused by earth-tides and changes in atmospheric pressure. (See " Minor fluctuations " further on.) These fluctuations are characteristic of bore-holes tapping artesian or confined water and are usually absent in water-table wells (Meinzer, 1932).

The water-levels observed in the above holes, and for that matter probably in most bore-holes in the area, are therefore strictly speaking pressure or piezometric surfaces and not a water-table. The author, however, found sufficient evidence to prove that in most cases the water-levels observed in bore-holes coincide very closely with the general water-table in the secondary openings. There is also evidence that in most areas each joint or joint-system does not have its own individual water-table but that they are interconnected to such an extent that there is an apparent continuity of the water-table over large areas. The evidence is substantiated by the following arguments:—

It has been shown on a previous page that the capacity of most of the permeable zones or conduits to store water is generally small and, if pumped at a high rate, the water stored in them will be depleted in a very short time. The fact that they produce large quantities of water, proves that they are linked hydraulically with other sources of water in the semi-confining, low-permeability fractured or decomposed rock surrounding them. The "confined water conditions" observed in the area are thus the result of the heterogeneous permeabilities of the strata traversed by a bore-hole and are usually merely a reflection of the imperviousness of the enclosing beds relative to a particular conduit or aquifer under consideration. This also explains the low pressure and consequently the paucity of artesian or flowing bore-holes in the area. For it stands to reason that any high pressure that may develop in an aquifer or conduit due possibly to infiltration of rain-water where the aquifer intersects the ground-surface, can easily be dissipated by forcing the excess water laterally and vertically upwards into the confining* beds until a new equilibrium is reached. An instance occurred in Southern Natal where a road-embankment constructed on a permeable layer from which springs were issuing, was saturated in this way and caused incipient failure of the road (Van Wyk and Forbes, 1959).

---

*Confining beds as used here refer to the rock surrounding or enclosing a conduit or aquifer and which are in places slightly permeable by virtue of weathering or interconnecting small joints and fissures.

It follows that there is probably always an adjustable equilibrium between the hydrostatic pressure in the conduits and the water-table in the openings of the confining beds. When the pressure in the conduits is lowered by pumping, water flows from the confining beds into the aquifer and, vice versa, when the pressure in the aquifer is raised by addition of water, the excess water is forced under pressure from the aquifer into the confining beds until a new equilibrium is reached. The mechanism envisaged by the author is explained in folder 2.

The ultimate fountain-head (Tolman, 1937, p. 559) of an aquifer or conduit after recharge has taken place, will be determined by the following circumstances:—

(*a*) If the confining beds become impermeable laterally or vertically upwards some of the excess water will remain in the aquifer and true artesian conditions may develop. The fact that there are only 25 flowing bore-holes is evidence that this is generally not the case in the area. Even bore-holes intersecting steep aquifers like faults, or the contact-zones of dolerite dykes on a mountain side, are very seldom artesian.

(*b*) If the confining beds are relatively permeable throughout, all excess water will be forced into them and consequently the fountain-head in the aquifer will be lowered gradually until it stands at the same level as the water-table in the confining beds (fold. 2). This is generally the condition in the area. It is verified by the following observations:—

  (i) It is almost invariably found that the water-level in successful bore-holes, which represents the pressure-surface of a high water-yielding aquifer and the water-levels in nearby unsuccessful bore-holes, which represent the water-table or pressure-surface of minor openings, stands at the same level relative to the ground-surface (see figs. 10 and 15).

  (ii) The configuration of the surface projected through the water-levels in both successful and unsuccessful bore-holes is generally, like the water-table in pervious granular material, a subdued replica of the surface-topography (fig. 27).

  (iii) The water-level in bore-holes usually stands close to the surface in areas where springs or marshy conditions occur. These are water-table springs. Observations showed that they dry up during the winter when the water-levels in bore-holes also stand at a lower level.

(*c*) Where water is withdrawn from the aquifer by effluent seepage or leakage into an interconnecting fissure at a rate faster than it can be supplied from the confining beds, a negative pressure may develop. The water-level in a bore-hole intersecting the aquifer would then stand at a lower level than the water-table in the openings of the confining beds. On the farm Umveloosdrift 172, Vryheid District, for instance, a bore-hole was drilled in decomposed granite to a depth of 80 feet. Its yield then was 50 g.p.h., and the water-level was 50 feet from the surface. Later the hole was deepened to 150 feet. A fracture yielding 1,700 g.p.h. was intersected at 120 feet and the water-level immediately dropped to 65 feet. The water-levels in two deep bore-holes in the vicinity remained at a depth of approximately 50 feet from the surface.

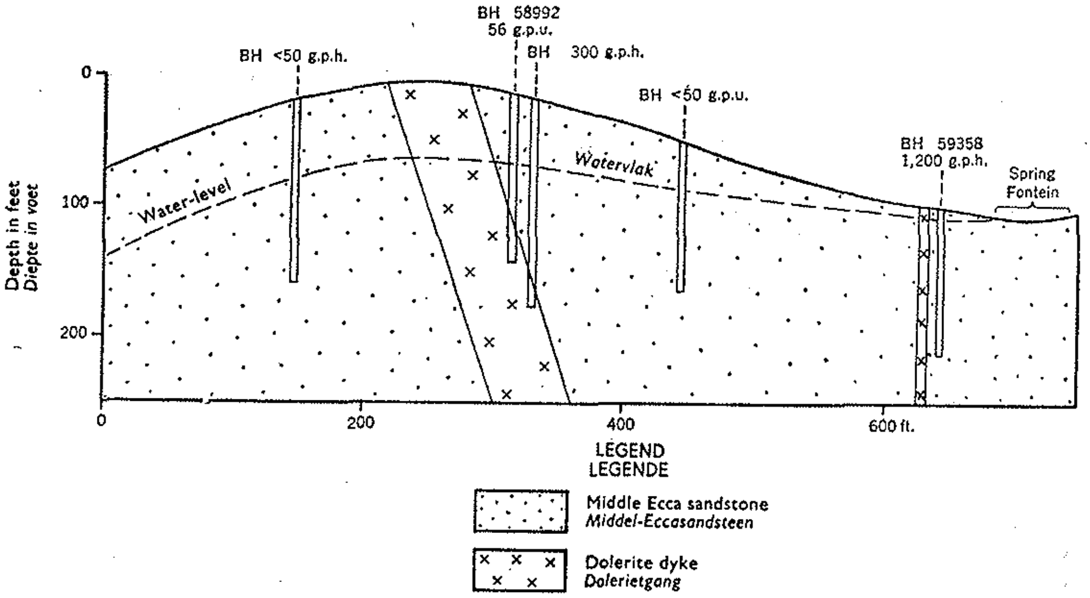

FIG. 27.—Section showing the configuration of the surface projected through the water-levels in bore-holes. Susanna, Ngotshe District.

3. THE WATER-TABLE IN SEDIMENTARY ROCKS

It has already been shown that most bore-holes tap " confined " water which is supplied by the relatively less permeable confining beds. Thus there generally is a complicated combination of water-table and confined water conditions with the distinction between the two not always definite. The water-level measured in bore-holes is strictly speaking a pressure-surface and not the water-table. However, as already shown, the water-level in bore-holes can, for practical purposes, also be regarded as indicative of the depth to the water-table, unless there is evidence to the contrary.

It has also been shown that the surface projected through the water-levels in bore-holes, which is now assumed to represent the water-table, is generally a subdued replica of the surface-topography. There are many local irregularities, such as temporary ground-water mounds formed by differential infiltration of rain-water and also depressions along dykes and other linear permeable zones, which act as drains along which the ground-water can escape to lower lying areas (see chapter VI).

In low lying areas the water-table generally intersects the ground-surface and gives rise to water-table springs and marshy conditions. In the gentle undulating flats of Northern Natal and on the Highveld in the Wakkerstroom area, its average depth is 37 feet from the surface.

In the mountainous and highly dissected areas it varies in depth from 50 to 150 feet below ground-surface depending on the topography of the land, the transmissibility of the openings through which the ground-water moves and the relative rates of discharge by water-table springs in the nearby valleys. These interrelated factors differ from place to place, and no average depth to water-table can be given for any particular area.

Shallow, perched water-tables are a common occurrence in the sedimentary rocks and they usually give rise to numerous small non-permanent seeps and springs on hill-sides.

4. THE WATER-TABLE IN IGNEOUS ROCKS

The water-table conditions in fractured or decomposed igneous rocks are similar to those in sedimentary rocks and there is usually very little difference between the water-level in bore-holes in igneous and nearby sedimentary rocks occurring on the same topographical situation.

In the extensively weathered granite in the Piet Retief area the water-table is in many places uninterrupted by solid rock for many square miles. Its average depth from ground-surface in this area is 34 feet.

Prior to 1957 the average depth to the water-table in the Stormberg lava in the Lowveld was 76 feet. It was often interrupted by solid lava and stood at a different level in each basin of decomposition. On Boyne, Hlabisa District, for instance, the water-table in a basin stood at 59 feet, while in an adjoining basin, situated 300 yards downstream, it was 110 feet from the surface.

Replenishment took place during September and October 1957, and the water-table rose on an average to a level above the divides between most of the basins of decomposition. It is now uninterrupted over comparatively large areas and stands more or less at the same level in adjoining basins, but with a gentle slope in the direction of the topographically lower ones. The average depth of the water-table at the end of 1958 was 39 feet.

B. FLUCTUATIONS OF WATER-LEVELS

Water-level observations have been made with 8 automatic water-stage recorders and manual depth-to-water measurements in bore-holes with a steel tape or an electrical water-stage meter. The data collected show several types of water-level fluctuations pertaining to conditions or forces at work in the ground-water bodies as follows: recharge from rain, pumping, earth-tides, atmospheric pressure and moving trains. The first two types may be cyclic and commonly produce a yearly or seasonal effect. The latter three operate momentarily and have no large or lasting effects.

1. FLUCTUATIONS CAUSED BY RECHARGE FROM RAIN

Hydrographs obtained from all bore-holes, expect those in the Stormberg lava, generally show a rise in the water-level during the summer months due to recharge by rain-water. The magnitude of the fluctuations, which is dependent on the amount of recharge and the relative effective porosities of the formations, differs widely in different bore-holes. In some holes the water-levels rise after each downpour, while in others there is a gradual rise during the rainy season.

Examples and a full discussion are given more appropriately in the chapter on " Recharge Studies ".

2. FLUCTUATIONS INDUCED BY PUMPING

The pumping of ground-water causes considerable fluctuations of water-levels in bore-holes.

(*a*) *Diurnal Fluctuations*

Most bore-holes in the area are pumped daily and diurnal fluctuations refer to the fluctuations of the water-level in the pumped bore-holes and other bore-holes in their vicinity during pumping.

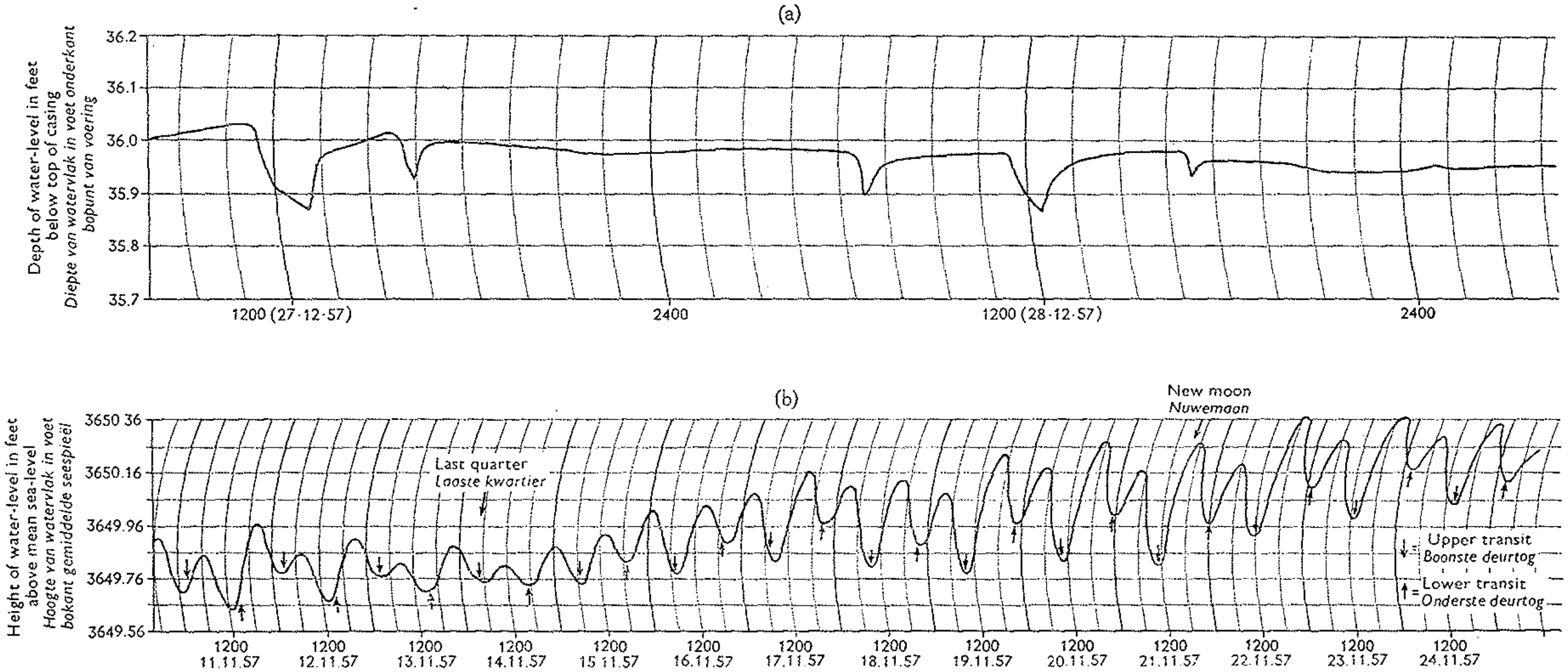

FIG. 28 (*a*)—Hydrograph showing fluctuations of the water-level in bore-hole No. 63759 caused by the pumping of a distant bore-hole. Buena Vista, Vryheid District.

(*b*)—Hydrograph showing the phases of the moon and its upper and lower transits in relation to water-level fluctuations in bore-hole No. 62711. Mooiplaas, Vryheid District.

Due to the difficulty of measuring the water-level in a bore-hole equipped with a pump, only a few measurements were made in holes while they were being pumped. They invariably showed a decline of the water-level, the magnitude of which was dependent on the yield of the bore-hole, the rate at which it was being pumped, and the duration of the pumping. In bore-holes that were over-pumped, the water-levels dropped to the intake of the pump-cylinder, while in stronger holes where only a moderate supply was pumped, the decline of the water-level was comparatively small. On Rietvlei, Utrecht District, for instance, bore-hole No. 56386 which yielded 400 g.p.h., was pumped at a rate of 600 g.p.h. Measurements in the bore-hole showed that the water-level dropped within 35 minutes from 31 feet to the intake of the pump-cylinder at 120 feet, after which the output of the pump decreased to 400 g.p.h. On Lot 7, Ngotshe District, again, the water-level in bore-hole No. 62059 which yielded 4,000 g.p.h. and was pumped at a rate of 1,200 g.p.h., dropped only 5 feet during a period of 9 hours pumping. In both the above cases the water-levels rose to almost their original levels within a few hours after the pumps had been stopped.

A large number of observations was made in bore-holes while a bore-hole some distance away was being pumped. Figure 28 (*a*) shows the water-level fluctuations in bore-hole No. 63759, Buena Vista, Vryheid District, due to the pumping of bore-hole No. 63879 situated 200 yards away. Both bore-holes were drilled in Lower Ecca shale and were situated on opposite sides of a 6-feet-wide northwest–southeast trending dolerite dyke. The yield of the pumping hole was 2,029 g.p.h. and that of bore-hole No. 63759, 950 g.p.h.

The pump was operated 5 times in 48 hours for periods varying from 1 hour 45 minutes to 15 minutes. The rate of pumping on each occasion was 1,000 g.p.h. The hydrograph shows an immediate drop in the water-level every time the pump on bore-hole No. 63879 was started. The decline during the first 15 minutes was fast and gradually became less as time of pumping increased. Likewise, the rise in water-level was steep immediately after pumping was stopped and then became less and levelled off some distance below the level it stood prior to pumping.

These immediate fluctuations in response to pumping of a distant bore-hole are due primarily to changes in hydrostatic pressure in the " confined " aquifer consisting, in this case, of interconnecting joints. When the pressure is reduced at the start of the pumping operations the loss of head throughout the interconnected joints is rapid and water-levels drop. When pumping is stopped just the reverse takes place. The small difference in water-level before and some hours after pumping represents the amount of water extracted.

The water-level in shallow bore-holes (see fold. 2), and also deep bore-holes where there is an imperfect hydraulic connection with the aquifer tapped by the pumping hole, does not show these immediate reactions. Instead there may be a gradual decline if the hole is situated in the area of influence of the cone of pressure-relief caused by the pumping hole. The decline represents the amount of water extracted.

This is best illustrated by a comparison of the hydrographs for three bore-holes on Driefontein, Vryheid District (fig. 29). They were obtained while a fourth bore-hole (No. 57702) was pump-tested for 9 hours. The hydrograph of unsuccessful bore-hole No. 57515, situated only 12 feet away from the pumping hole, shows a steady decline of the water-level

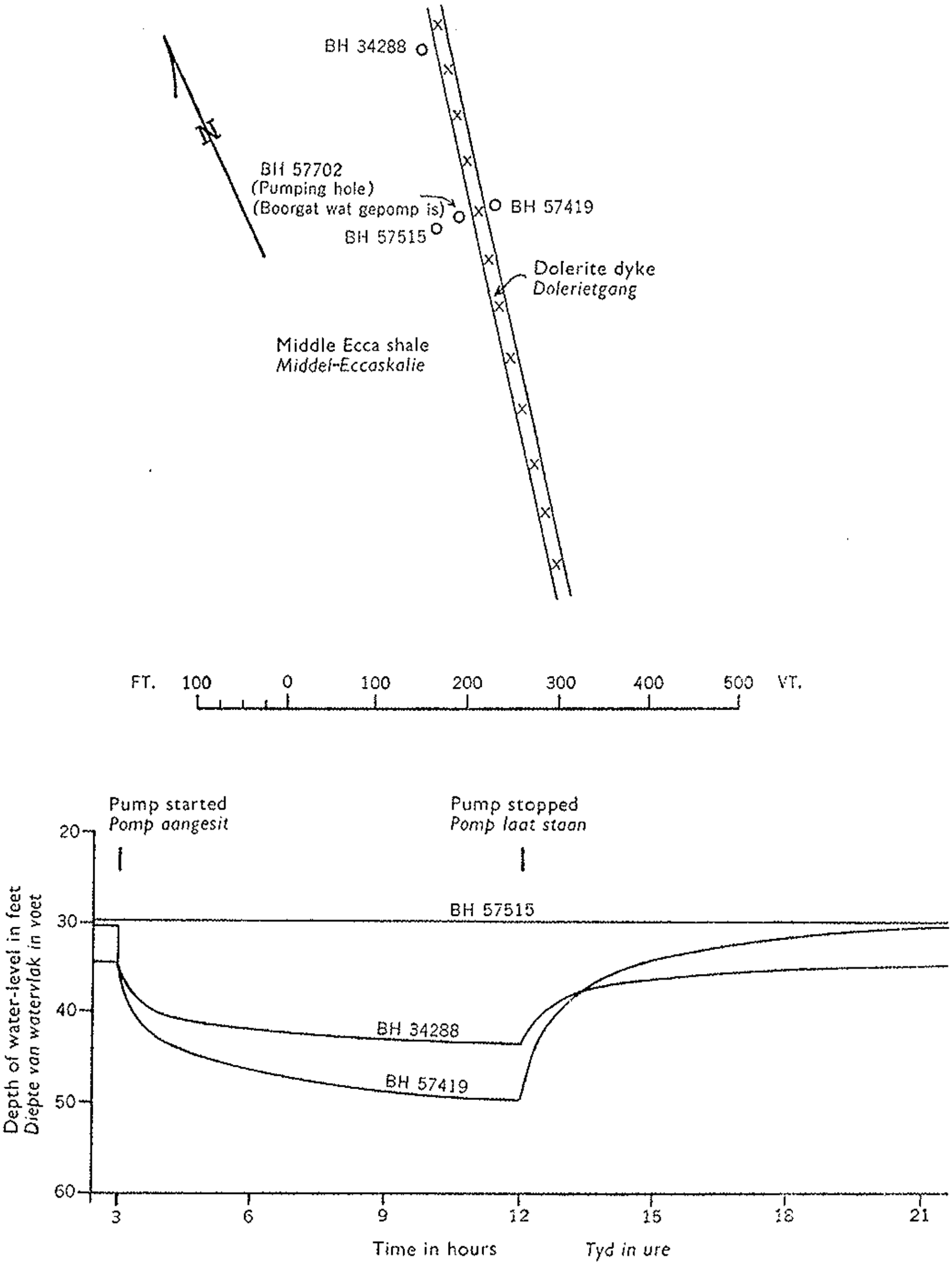

FIG. 29.—Hydrographs of bore-holes showing fluctuations of the water-level while a distant bore-hole was being pumped. Driefontein 125, Vryheid District.

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that amounted to 3 inches at the end of the test. The hydrographs of bore-holes Nos. 34288 and 57419 which, like the pumping hole, intersected the high-permeability contact-zone of the dolerite dyke, show large fluctuations due to pressure-relief in the narrow aquifer parallel to the dyke.

(*b*) *Seasonal Fluctuations*

In contrast to a general rise of water-levels in bore-holes due to recharge each year, there is a corresponding decline due to discharge by pumpage and natural discharge by springs during the winter months. In dissected areas where there are many springs, the combined discharge by pumping bore-holes and springs causes a comparatively larger decline than in flat country where there are few natural discharge points. For instance, the water-level in bore-hole No. 63403, Afgesny, Vryheid District, dropped only 3 feet during April to December 1957, while the water-level in bore-hole No. 49567, Grootgewacht, Vryheid District, which is situated in more dissected country, declined 25 feet during the same period. The quantities of water pumped from these holes were more or less the same.

The decline of water-levels in bore-holes in the lava of the Lowveld owing to pumping is not seasonal, for replenishment does not take place each year. Records show that there was a steady decline of water-levels in the area from 1930 owing to pumpage and transpiration by phreatophytes. By 1957 they had dropped to such a low level that 76·5 per cent of the bore-holes dried up. However, water-levels rose again when replenishment took place in September and October 1957. (See chapter on " Recharge Studies ".)

3. MINOR FLUCTUATIONS

Minor fluctuations of the water-level in bore-holes are those caused by earth-tides, atmospheric pressure and less commonly by moving trains.

These phenomena, which commonly occur in artesian aquifers, have been described by Jacob (1939), Parker and Stringfield (1950), Robinson (1939), Young (1913) and others.

The author observed similar fluctuations of the water-level in bore-holes tapping a number of non-artesian aquifers that are quite diverse in geological and hydrological properties. In order to study the phenomena more comprehensively, a total of 69 bore-holes was equipped with automatic water-stage recorders for periods varying from a few days to several years. The holes were selected at random in the different geological formations, regardless of depth or yield. Most of the fluctuations were small, usually less than 0·075 feet, and the recorders had to be adjusted in such a way that they could register the smallest fluctuations. In many cases it was necessary to readjust the weights and positions of the float and counter-weight in the bore-holes several times before the desired sensitivity was obtained.

(*a*) *Fluctuations Caused by Earth-tides*

Semi-diurnal fluctuations of the water-level, ranging from 0·05 to 0·80 feet were observed in all 69 bore-holes investigated. The bore-holes were situated at altitudes ranging from 4,000 feet to 250 feet above mean sea-level. They also included bore-holes drilled in most of the geological formations present in the area, except the Tertiary and Recent sand. Their yields ranged from 4,000 g.p.h. to less than 50 g.p.h., and their depths from over 400 feet to less than 50 feet. They tapped almost every conceivable type of aquifer found in the rocks of the area, e.g. contact-zones of dolerite sills

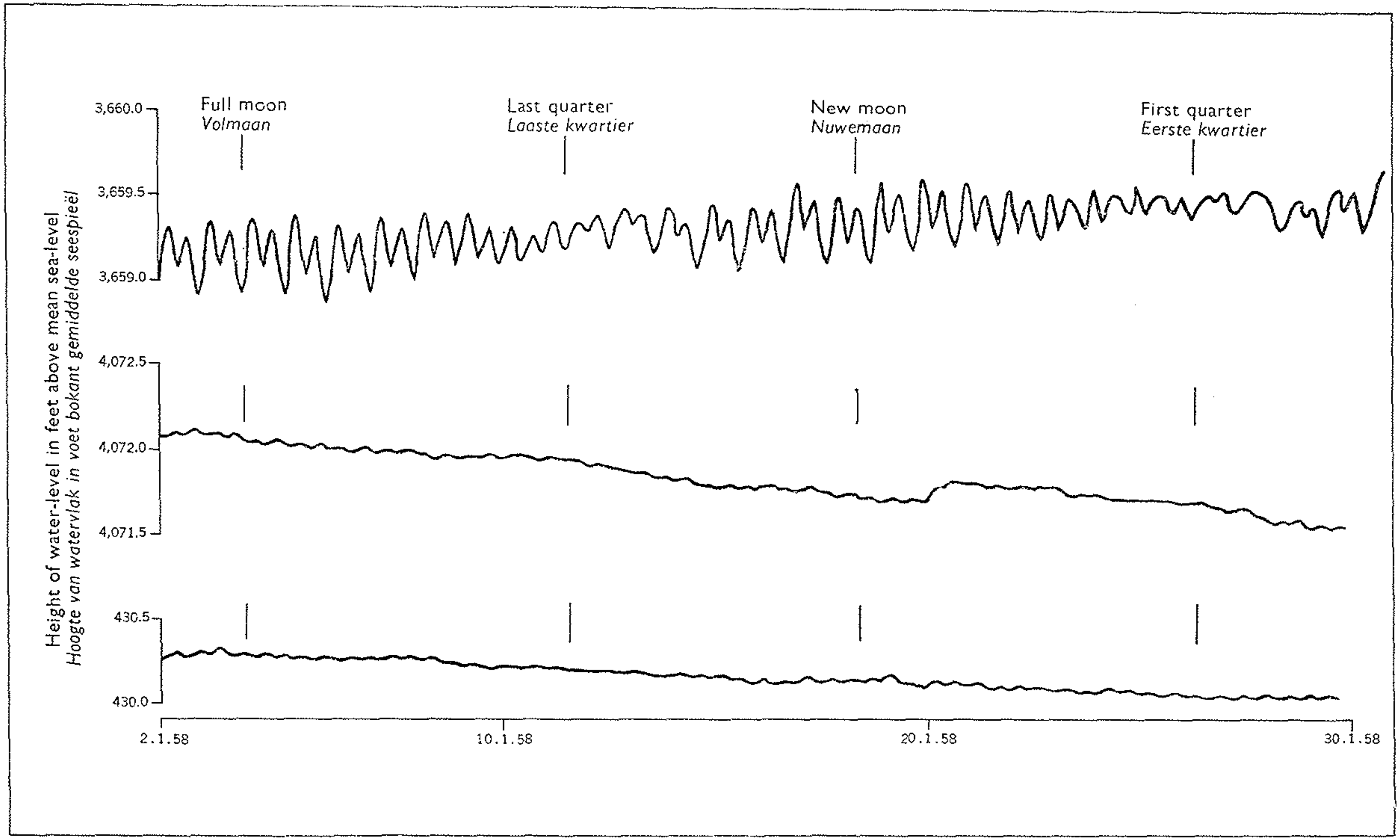

FIG. 30.—Hydrographs of bore-holes drilled in different geological formations at different altitudes showing fluctuations of the water-level caused by earth-tides.

and dykes, faults, transition zones between, and weathered rocks in basins of decomposition, isolated joints and joint-systems. The hydrographs of 3 bore-holes are shown in figure 30, and their hydrological and geological data are given in table 11.

TABLE 11.—HYDROLOGICAL, GEOLOGICAL AND TOPOGRAPHICAL DATA OF THREE BORE-HOLES SHOWING SEMI-DIURNAL FLUCTUATIONS OF THEIR WATER-LEVELS CAUSED BY EARTH-TIDES

	Hydrograph 1	Hydrograph 2	Hydrograph 3
Bore-hole number..................	62711	63403	Private
Farm..........................	Mooiplaas	Afgesny	Broxburn
District..........................	Vryheid	Vryheid	Hlabisa
Altitude above mean sea-level in feet	3,707	4,100	493
Geological formation..............	Middle Ecca shale	Lower Ecca and Dwyka tillite	Lava
Aquifer..........................	Contact-zone of dolerite dyke	Fault	Transition zone in basin of decomposition
Depth in feet.....................	167	184	300
Yield in g.p.h....................	4,000	563	80
Depth to water-level from surface in feet	48	28	63

Long-term records show that these semi-diurnal fluctuations are present the whole year round and are not dependent on some seasonal or hydrological condition. That they are the result of earth-tides produced by the attraction of the moon and the sun has been established as follows:—

(i) On April 18, 19 and 20, 1958, during new moon, gravity measurements were made with a gravity meter at a bore-hole on Eensgevonden 2 miles west of Vryheid, which showed large semi-diurnal fluctuations of its water-level. The gravity measurements were made at hourly intervals. The observed gravity values were then plotted on the hydrograph of the bore-hole and also on that of a second bore-hole on Mooiplaas situated 5 miles south of Vryheid obtained during the same period. This showed that the variations in the earth's gravity caused by the attraction of the moon are in phase with fluctuations of the water-levels in the bore-holes (fig. 31).

(ii) The times of the moon at transit (Nautical Almanac, 1957) have also been plotted on a number of hydrographs showing large semi-diurnal fluctuations [fig. 28 (*b*)]. In each case it was found that:—

  (*a*) The periods of new and full moon coincided with the periods when the semi-diurnal fluctuations occurred most regularly and were of the largest amplitude.

  (*b*) The periods of the first and last quarters of the moon coincided with the smallest and most irregular fluctuations.

  (*c*) The upper and lower transit of the moon corresponded closely with the lowest water-level. During the early periods of new and full moon, however, the tendency appeared to be for the lowest water-levels to precede the transit of the moon. In some cases low water-levels in the bore-holes preceded the moon's transit by periods of up to two hours. But in each case

FIG. 30.—Hydrographs of bore-holes drilled in different geological formations at different altitudes showing fluctuations of the water-level caused by earth-tides.

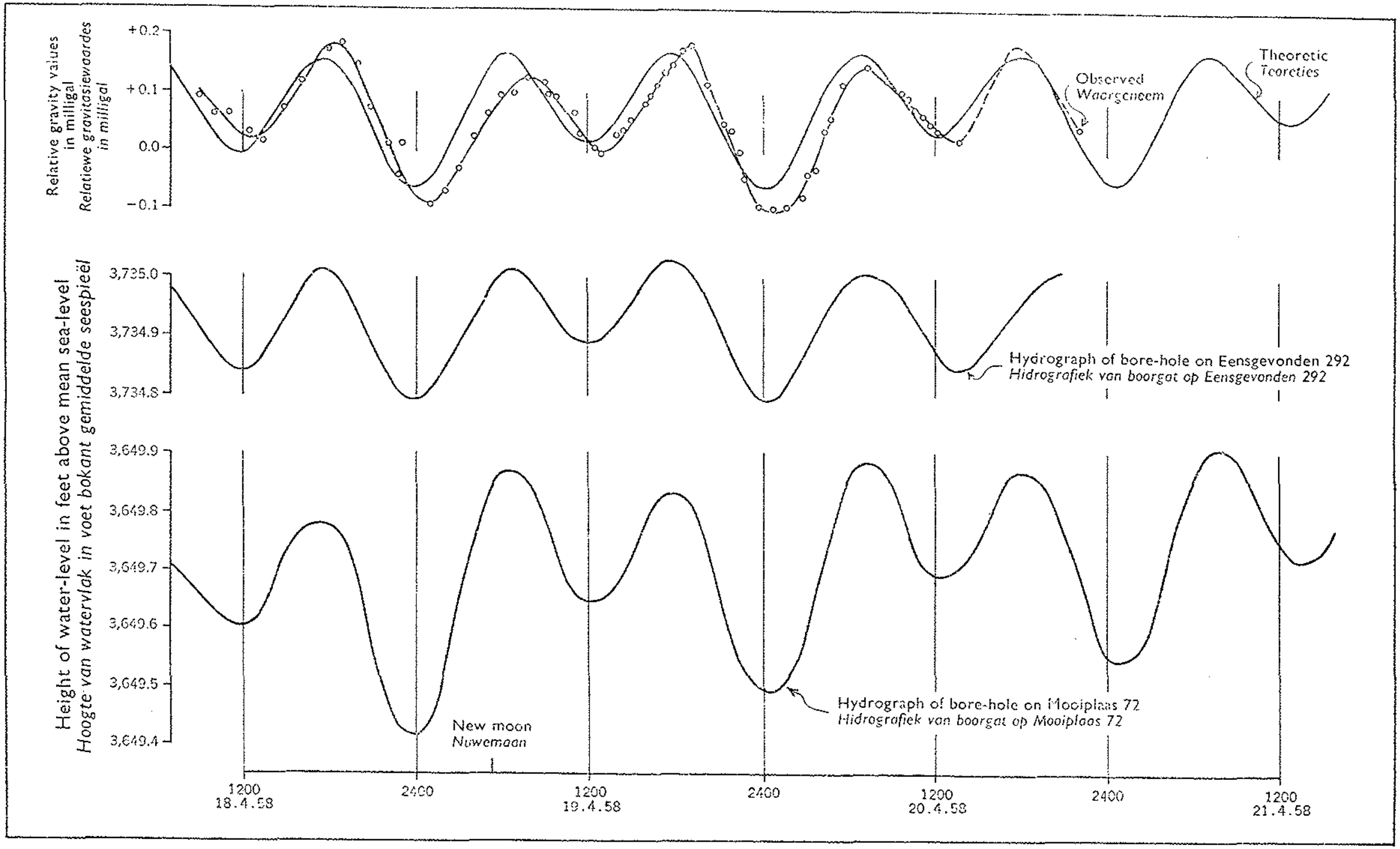

FIG. 31.—Curves showing the relation between gravity anomalies caused by attraction of the moon and semi-diurnal fluctuations in bore-holes, Vryheid District.

it was found that as the lunar periods progressed the low water caught up on the moon's transit and the two usually corresponded at periods of full and new moon and during the quarters.

Theiss (1939) also found that in the Carlsbad Well, the lowest water-level appeared to precede the moon's transit, while Robinson (1939) found that in wells in New Mexico and Iowa there was a tendency for the moon's transit to occur a little before the lowest water-level in the bore-holes. They however, gave no explanation for the phenomena. In the bore-holes of the area under discussion the periods with which the lowest water-level in the bore-holes preceded the moon's transit differed from bore-hole to bore-hole. They did not even remain constant for a particular bore-hole during two successive months. The author is of the opinion that it can be linked with the declination of the moon and the sun in relation to the strike and dip of the aquifer. The reason, however, is as yet not fully understood and it is still being investigated by him.

It is noteworthy that the times of low water in the bore-holes, in contrast to ocean tides, occurred at about the time of the moon's transit. The explanation given by Theiss (1939) is that the crust of the earth in any given area rises and falls with the deformation of the earth caused by the tidal forces. The crust is most probably alternatively expanded when the earth bulges up and compressed when it subsides. The water in the confined aquifers shares in this deformation. Hence with the expansion of the aquifers incident to the tidal bulge the hydrostatic pressure falls, causing the water-level in the bore-holes to drop, and with its compression incident to tidal depression the hydrostatic pressure rises and consequently the water-level in the bore-holes also rises.

In general no two bore-holes responded in exactly the same way to the tidal forces. It was found that even with holes tapping the same confined aquifer there were in many cases some differences in the magnitude of the fluctuations caused by these forces during the same period. Two bore-holes on Eensgevonden, Vryheid District, for instance, were situated 121 yards apart. They were drilled in Lower Ecca shale and pumping operations had proved that they tapped the same confined aquifer consisting of an interconnected system of joints. Yet the tidal fluctuations in one of the holes amounted to 0·3 feet during times of full and new moon and only to 0·08 feet in the other during the same period. This was probably due to lateral changes in the rigidity of the aquifer, or in the hydrological properties of the confining beds which caused different degrees of confinement.

The water-level in bore-holes drilled in sedimentary rocks is generally unaffected by changes in atmospheric pressure and they show the largest tidal fluctuations, amounting in some cases to 0·8 feet. The average fluctuation, however, amounts to 0·075 feet which is somewhat greater than most tidal fluctuations described in the literature. Hydrographs of bore-holes drilled in basins of decomposition in igneous rocks generally also exhibit fluctuations caused by changes in atmospheric pressure. Their tidal fluctuations are comparatively small and difficult to analyse.

As these fluctuations have been observed in bore-holes tapping non-artesian aquifers that are quite diverse in hydrological properties, it would seem possible that they occur more generally than is commonly believed. The author is of the opinion that they occur in most, if not all, bore-holes drilled in decomposed or fractured impervious rocks.

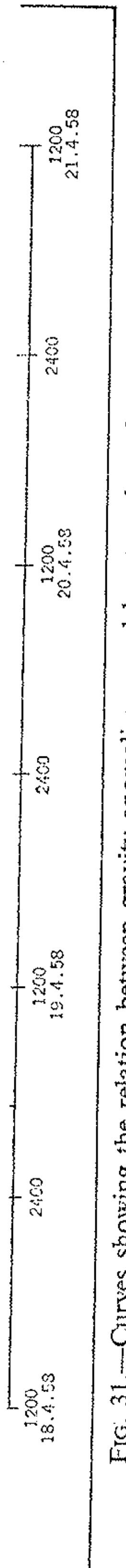

FIG. 31.—Curves showing the relation between gravity anomalies caused by attraction of the moon and semi-diurnal fluctuations in bore-holes, Vryheid District.

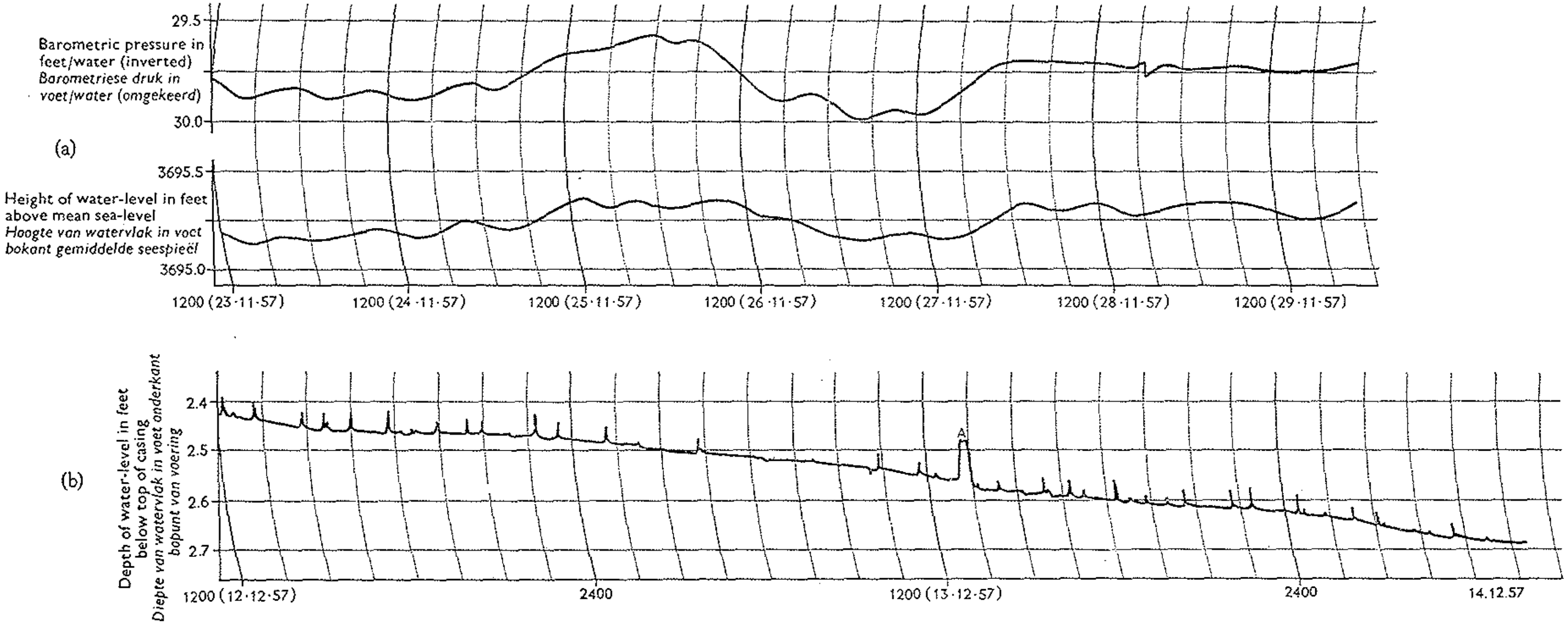

FIG. 32 (*a*)—Graph showing water-level fluctuations produced by changes in atmospheric pressure. Arcadia 660, Vryheid District.

(*b*)—Hydrograph showing fluctuations of the water-level in bore-hole No. G. 11199 caused by a passing train. Eensgevonden 408, Vryheid District.

(*b*) *Fluctuations Caused by Changes in Atmospheric Pressure*

This phenomenon has been described by Tolman (1937, p. 332) and others. It was observed in most bore-holes drilled in decomposed basins in igneous rocks but appears to occur less commonly in bore-holes drilled in sedimentary and fractured igneous rocks. The fluctuations are generally small and are in most cases masked by tidal and other fluctuations to such an extent that they are difficult to analyse.

An example of this type of fluctuation observed in a bore-hole on Arcadia, Vryheid District, is shown in figure 32 (*a*). The atmospheric pressure fluctuations in feet of water for the same period are also shown. The barometric curve, obtained with a microbarograph at the bore-hole, is inverted to show more clearly the relation between the changes in atmospheric pressure and the water-level fluctuations in the bore-hole.

It will be noted that the barometric efficiency of the above aquifer is about 50 per cent, that is, the water-level in the bore-hole rises 0·5 feet in response to a drop in atmospheric pressure equivalent to a head of one foot. The author attempted to calculate an average barometric efficiency for particular types of aquifers occurring in the same types of rock. It was, however, found that, as with the tidal fluctuations, no two bore-holes respond in the same way to changes in atmospheric pressure and the conclusion was reached that the magnitude of these fluctuations is more dependent on local confinement conditions than on the characteristics of a particular type of aquifer as a whole.

(*c*) *Fluctuations Caused by Passing Trains*

While studying tidal effects in bore-holes momentary rises and declines of the water-level of 0·01 to 0·05 feet produced by passing trains were discovered in a bore-hole situated on the farm Eensgevonden 3 miles west of Vryheid. As far as is known it is the first time this phenomenon has been observed in South Africa.

A geological and geophysical investigation showed that the bore-hole (No. G. 11199) is situated in Lower Ecca shale on the contact of a shallow northeasterly dipping dolerite sheet (fig. 33). The total depth of the hole is 112 feet and the yield is 2,500 g.p.h. The water was struck in the semi-baked contact-zone of the shale and the dolerite intrusion. According to the driller's log, the hole remained comparatively dry until the water was struck at 68 feet. The water then rose to 13 feet from the surface. This, corroborated by the fact that the water-level fluctuates as a result of earth-tides and passing trains, is evidence that the bore-hole tapped a "confined" aquifer.

The top of the bore-hole is 10 feet higher and, at the nearest point, 382 feet distant from the railway line. The effect of train loading on the aquifer is shown on the hydrograph of the bore-hole [fig. 32 (*b*)]. The westbound trains from Vryheid travel on the dolerite sheet for about 1,100 yards. Careful observations show that the water-level in the bore-hole begins to rise when the locomotive has reached a point some 250 feet from the edge of the dolerite sheet. As the train moves on, the water-level continues to rise until the last truck has passed a spot about 50 to 100 feet from the edge of the dolerite, and then drops again to its normal level within 2 to 5 minutes.

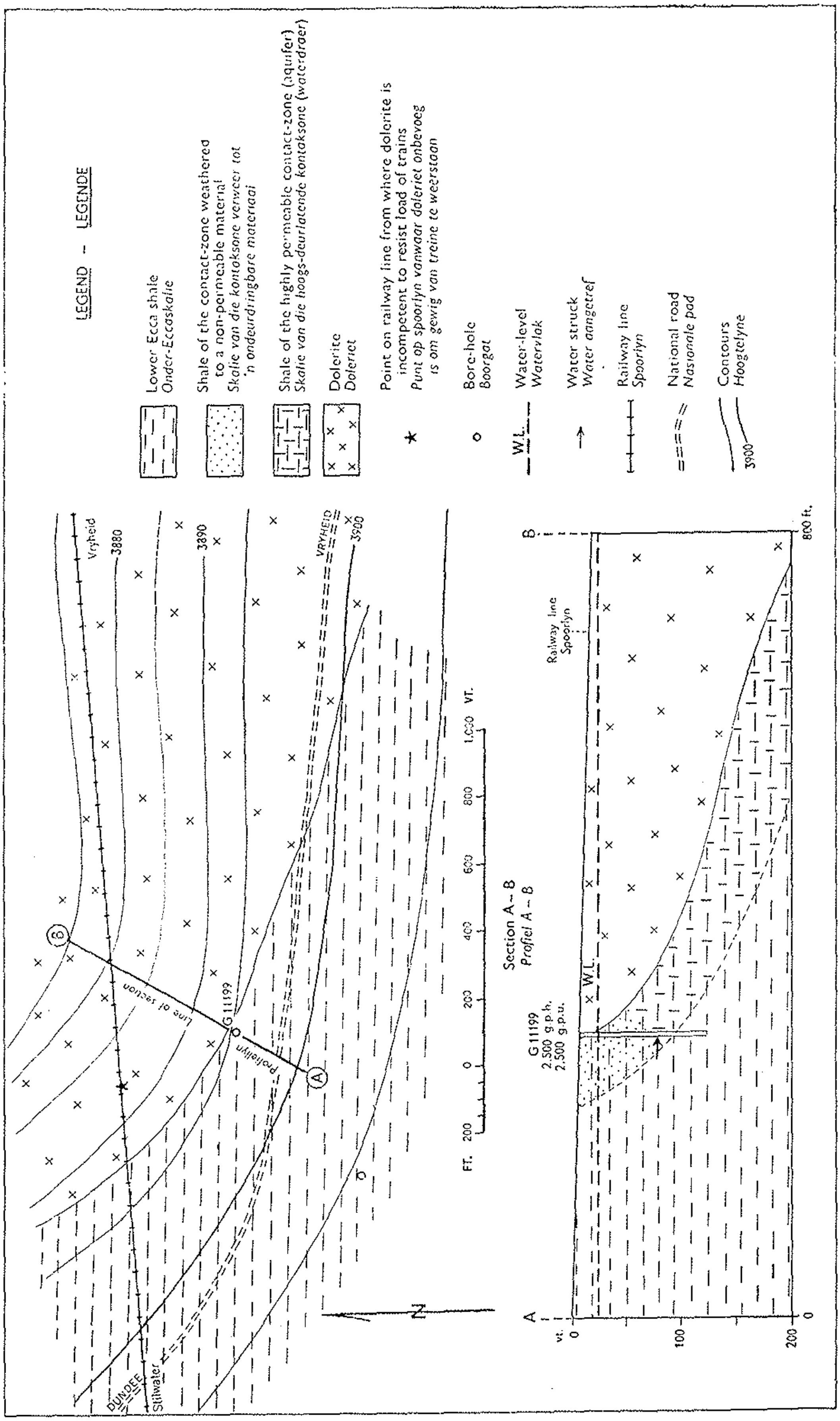

FIG. 33.—Plan and section showing the geology at bore-hole No. G. 11199. Eensgevonden 408, Vryheid District.

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The eastbound trains to Vryheid travel on shale from Stilwater Station. The water-level in the bore-hole begins to rise when the locomotive moves onto the dolerite. It then continues to rise until the last truck has passed a point about 200 feet from the dolerite–shale contact and then declines to the level observed before the train approached the area.

The trains from Vryheid are generally heavily loaded with coal. They all travel at more or less 9 to 12 feet per second and the magnitude of the water-level fluctuation produced by each train is directly proportional to its weight (fig. 34). Trains with a total weight of less than 200 tons generally cause no discernible fluctuation. The trains travelling towards Vryheid are usually empty, travel much faster and the water-level fluctuations they cause are comparatively smaller.

In order to examine the phenomenon further, arrangements were made with the South African Railways and a train from Vryheid was stopped opposite the bore-hole for a period of 20 minutes. The train consisted of two locomotives and 22 trucks loaded with coal. Its total weight amounted to approximately 1,650 tons. The front locomotive stopped on the dolerite–shale contact with the rest of the train standing on the dolerite. As the moving train approached the edge of the dolerite, it caused the usual rise of the water-level. After it had stopped the level continued to rise but at a slightly lower decreased rate and reached its maximum after 4 minutes. It then remained at the high level for the whole period the train was stationary, and started to decline only after the train had moved off and the last truck had passed the point about 100 feet from the contact of the dolerite referred to above [see fluctuation A, fig. 32 (*b*)].

Water-level fluctuations of all the bore-holes in the vicinity, one of which was located only 200 feet from the railway line, were also investigated. They were all situated in shale remote from the dolerite intrusion. Their hydrographs all show tidal fluctuations but none of them exhibit fluctuations due to passing trains.

It has already been shown that bore-hole No. G. 11199 (fig. 33) taps a " confined " aquifer consisting of the jointed contact-zone between the shale and the dolerite intrusion. The zone is probably present everywhere beneath the shallow dipping sill. The conditions that give rise to the fluctuations of the water-level in this bore-hole can be explained as follows: The trains travelling from Vryheid reach a point where the dolerite becomes too thin and thus incompetent to resist the load, and by yielding it compresses the underlying aquifer. As a result the hydrostatic pressure in the aquifer rises and causes the water-level in the bore-hole to rise accordingly. As the last truck approaches the edge of the dolerite most of the load has been removed and the pressure in the aquifer recovers to its initial value and the water-level in the bore-hole drops to its original position. Likewise the trains travelling to Vryheid cause a rise of hydrostatic pressure when they move onto the dolerite. The pressure returns to normal again only after the last truck has reached the point where the dolerite is sufficiently competent to resist the load. The aquifer can be assumed to be perfectly elastic for it was compressed an average of 30 times every 24 hours by passing trains and each time it returned to its original shape after the load had been removed.

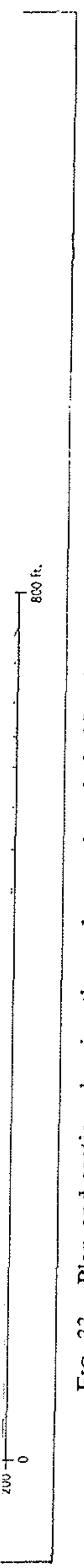

FIG. 33.—Plan and section showing the geology at bore-hole No. G. 11199. Eensgevonden 408, Vryheid District.

An attempt was made to determine the actual depression of the ground by passing trains. The method used was to set up three theodolites on shale at distances of 100 to 500 feet from the railway line. They were sighted at stadia rods placed at different positions next to the railway line. The moving trains, however, caused so much vibration of the ground that no positive values could be obtained. However, the depression of the ground even by trains with load intensities of 2·5 tons per foot of track, appeared to be very small.

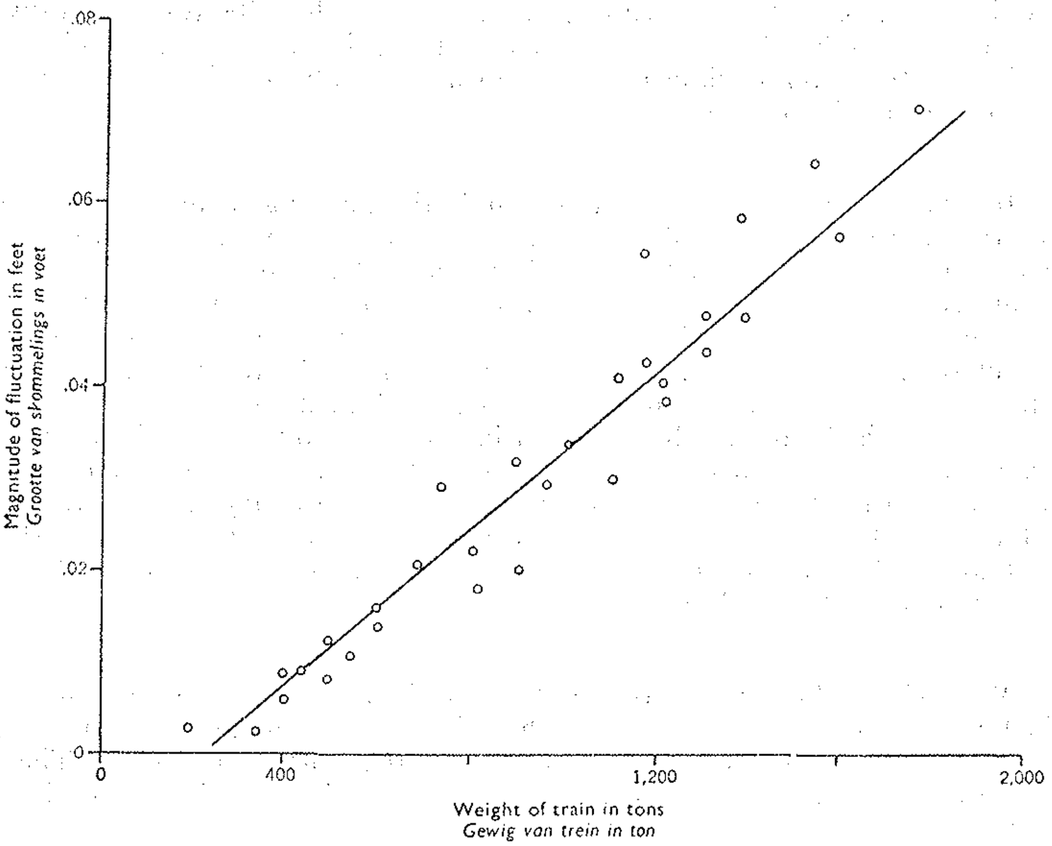

FIG. 34.—The relation between the magnitude of the water-level fluctuation and the weight of a train.

Another factor that was studied was the magnitude of the fluctuations in relation to the depth of water-level below ground-surface. The size of the fluctuations caused by trains with the same load intensities per foot track was compared on hydrographs of the bore-hole obtained in August 1957, when the water-level stood at 20 feet and again in December 1957, when it was only 2 feet from the surface. There was very little difference, if any, and it thus appears as if the depth to water-level below ground-surface plays an insignificant role.

VI. RECHARGE STUDIES

The quantity of ground-water available for long-term extraction is dependent on recharge (replenishment) by rainfall and also from streams and surface-irrigation. Very little work has been done in connection with this important aspect of ground-water and the only experimental data available were produced by Theron (1949) and Smitter (1958) who published the results of observations made with lysimeters in the neighbourhood of Pretoria and on the Highveld of Transvaal. The low average figure of 2 to 4 per cent and less was obtained. Van Warmelo (1924), estimated infiltration over the catchment of the Steenkoppies Spring by equating its annual flow with the annual ground-water increment derived from rainfall. He reached the conclusion that the average infiltration over the catchment area underlain by shale, quartzite and dolomite was 9·56 per cent of the annual rainfall. Enslin (1949), basing his figures on the minimum flow of 13 rivers in the Eastern Transvaal and Northeastern Natal gave figures that vary from 2·3 to 19·8 per cent of the annual average rainfall, with an average of 4·5 per cent.

A. Recharge in Karroo Rocks in Northern Natal

According to Summer (1957) the infiltration capacity of soils in Natal, derived from different geological formations under different climatic and topographical conditions, differs widely. He, for instance, found that the infiltration rates on dolerite soil are far higher (from 5 to 22 times) than those for soil derived from the Beaufort Series while soil derived from felspathic sandstone of the Ecca Series is intermediate between that of dolerite and Beaufort soil

Most of Northern Natal and Zululand is characterised by numerous springs and seeps which occur in all topographical situations during the summer months but most of them are temporary and disappear during dry spells. Observations showed that they occur at higher altitudes than the water-levels in nearby bore-holes and that they issue from perched water-bodies formed in places where the infiltration capacity of the soil and near-surface formations exceeds that of the underlying strata.

A number of water-level studies have been made in bore-holes since 1952. They invariably showed a rise in the water-levels during the summer months, which suggests that recharge takes place regularly each year.

Noteworthy, however, are the different ways in which the water-level responds to the infiltration of rain-water in the same geological formation. In some bore-holes the water-level fluctuates widely after each downpour while in others it rises steadily during the rainy season. This is best illustrated by comparing the hydrographs of two bore-holes A and B in figure 35. The holes are situated 350 feet apart in Lower Ecca shale. The initial water-levels in both were approximately 25 feet from surface. Pumping tests proved that they are situated in the same ground-water compartment. Both yielded about 700 g.p.h. and according to electrical logging there is very little difference in the resistivity of the shale. It can thus be safely assumed that there is very little difference in the hydrological properties of the shale in the vicinity of the bore-holes. Nevertheless, the water-level in bore-hole A responded almost immediately after each downpour and fluctuated widely as the rainfall varied, while in bore-hole B it remained relatively stable during the early part of the record and rose steadily during the latter part. The latter fluctuations covered only a small vertical range, but the rise, though retarded, continued over a long period.

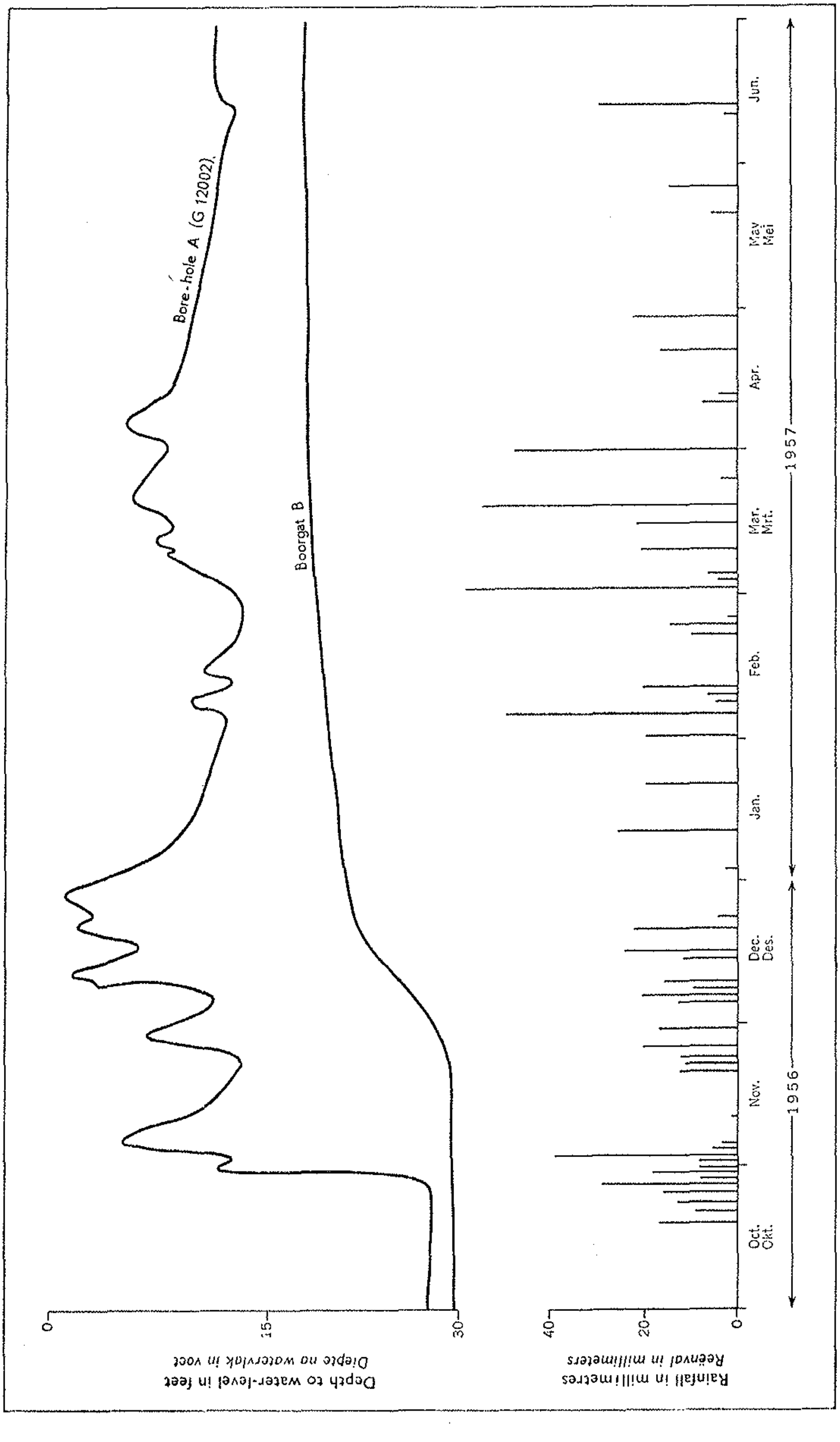

FIG. 35.—Hydrographs showing differential recharge in Karroo sediments. Eensgevonden 408, Vryheid District.

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This phenomenon is of great importance for it gives an indication of the manner in which rain-water percolates down to the water-table in impermeable rocks. It can be explained as follows:—

(1) It has been shown in chapter 3 that all Karroo rocks are inherently impervious and that they are only permeable in places and along zones where conditions permitted the development of high permeability. The implication then is that very little, if any, rain-water can percolate through fresh rock, and that recharge takes place only via permeable zones in the zone of aeration.

(2) After percolating downward by film flow through the soil and underlying decomposed rock as a relatively continuous body or sheet (Meinzer, 1942), further downward movement is then restricted to joints and other permeable zones connected to the soil layer. On reaching the water-table, ground-water mounds are formed, which cause the large fluctuation in water-levels of bore-holes intersecting the permeable zones. The fact that the water-level starts to decline soon after it has reached the highest points (bore-hole A, fig. 35), shows that the mounds are temporary and disappear soon (*a*) by spreading in a horizontal direction by way of interconnected permeable zones not connected to the soil, or (*b*) by a readjustment of the general water-table through interconnected permeable zones below the water-table.

It will be noted that there is very little time lag in the response of the water-level to the rainfall, which suggests that rain-water reaches the water-table not many hours after a downpour. Hydrographs obtained from several other bore-holes show that once the soil has been saturated to field-capacity, rain-water percolates to the water-table at depths of 40 to 60 feet within 48 hours after a heavy rain. A considerable time lag, however, is suggested by the hydrograph of bore-hole B. This bore-hole is apparently situated where no fractures or other openings are connected to the saturated soil in such a manner as to receive the rain-water directly. The rise in water-level in this case is dependent on the proximity and the rate of spreading of the ground-water mounds.

The above is further corroborated by observations in shallow coal-mines in the Vryheid District that lie above the water-table. They invariably showed that rain-water enters the mines through fractures only and that the intervening fresh rock remains comparatively dry right through the rainy season. Little water usually enters the mines during the early part of the rainy season, but once the soil has been saturated to field-capacity, water enters the mines not many hours after a downpour.

1. A QUANTITATIVE DETERMINATION OF RECHARGE IN MIDDLE ECCA ROCKS IN NORTHERN NATAL

The percentage of rainfall that infiltrates and becomes available as ground-water in an old mine near Hlobane in the Vryheid District, has been determined. The old mine which was abandoned in 1937 is 1,948,800 square feet in extent (fig. 36). The area vertically above the mine represents a typical Northern Natal landscape; it is a flattish grass-clad hill with some wattle trees, a farmhouse surrounded by a small orchard and a mealie land. The soil varies in thickness from a few inches near the northern boundary of the area to 2 to 3 feet in the vicinity of the farmhouse.

FIG. 35.—Hydrographs showing differential recharge in Karroo sediments. Leeugevonden 400, Vryheid District.

The roof-beds, consisting of Middle Ecca sandstone with intercalations of sandy shale, vary in thickness from 5 feet near the adit to 60 feet near the northern and northwestern boundary (see fig. 6). The beds are intruded by a dolerite dyke. The Alfred Seam, that was worked, is 3 feet 6 inches thick and dips slightly (1:46) in a southerly direction, i.e. towards the adit where the measurements were made.

A series of wide cracks formed along the northern boundary of the mined area when the mine collapsed. These cracks were blocked or isolated from the rest of the area by deep trenches to prevent run-off water from entering the mine. The rain that fell on the cracks entered directly into the mine, but this factor being so small, was ignored in the calculations.

The adit was partly blocked by a wall consisting of clay and loose stones to avoid possible sudden flood peaks and ensure an even flow of water from the mine over longer periods. A 90 degree V-notch was installed 50 feet from the adit. Regular measurements were made once a week during the winter months and more often during the rainy seasons (fig. 37). The rainfall was measured at the Hlobane Mine less than half a mile away. The average rainfall of the area over the last 35 years was 720 mm per annum.

An arbitrary low flow (Cf) of 12,000 gallons per day was taken as a constant reference, and measurements were made through periods of high flow until the low flow was again reached.

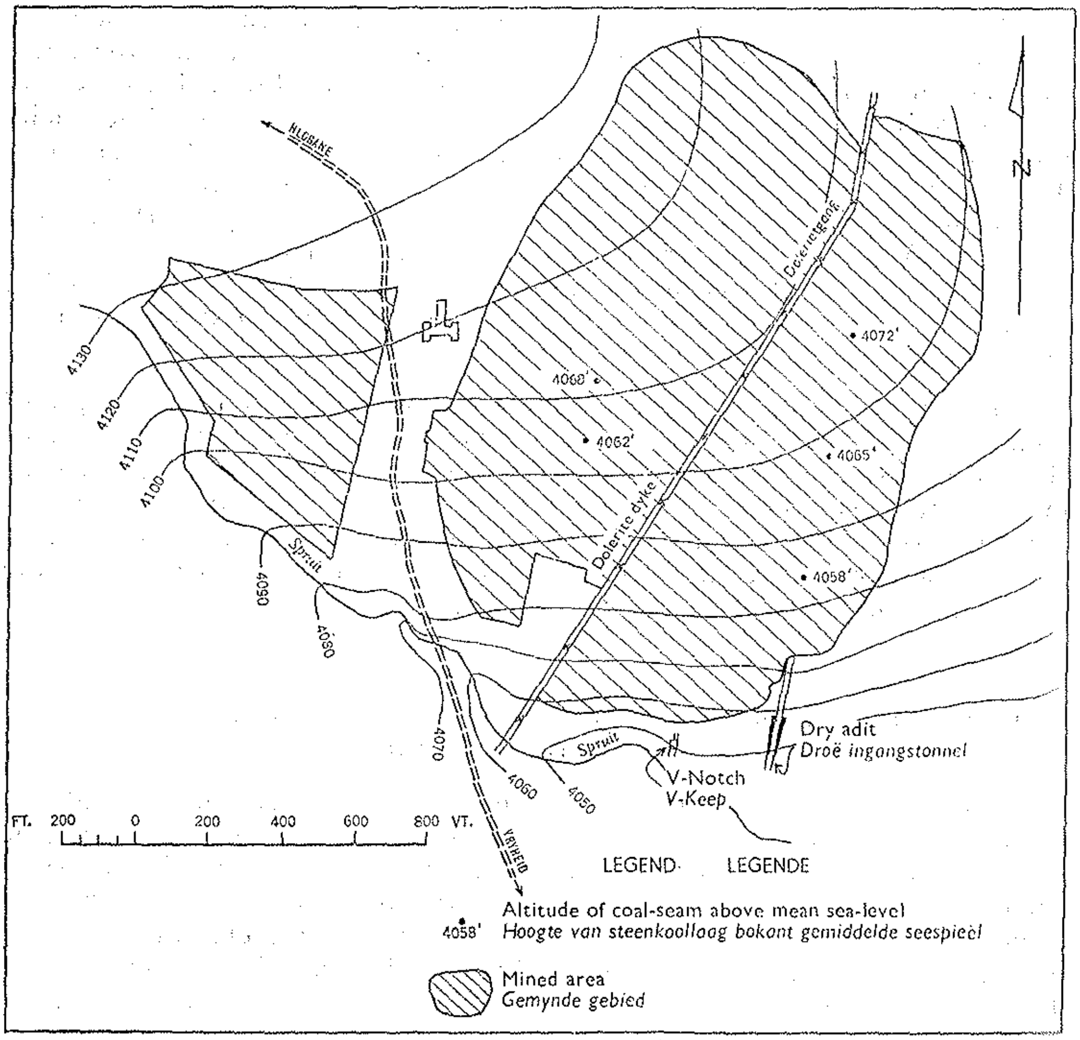

FIG. 36.—Plan showing old mine near Hlobane, Vryheid District.

The formula for calculating the recharge expressed as a percentage of the rainfall is:—

$$I = \frac{Tf - Cf}{Rv} \times 100\%$$

where I is the infiltration,

Tf is the total flow (volume) in gallons
Cf is the constant flow (volume) in gallons
Rv is the volume of rain-water that fell on the mining area.

The results obtained are summarized in table 12.

TABLE 12.—INFILTRATION AS A PERCENTAGE OF RAINFALL IN MIDDLE ECCA ROCKS. HLOBANE, VRYHEID DISTRICT

Period	Rainfall in millimetres	Percentage infiltration
1/9/56 to 24/5/57	995	14·7
4/7/57 to 12/9/57	108	10·1
15/9/57 to 22/4/58	884	18·9

The permanent flow during winter months suggests that ground-water enters the mine from outside areas. There may be slow leakage from the rest of the ground-water compartment in which the mine is situated, or from neighbouring flooded mined areas. The amount of water measured is thus in excess of the percentage recharge by rainfall that fell directly on the mined area. This factor, however, is largely compensated for in the calculations by subtracting the low flow (Cf) from the total flow (Tf) measured.

The percentage recharge figures obtained are much higher than the lysimeter-values quoted by Smitter (1958) and Theron (1949). They, however, compare favourably with the values calculated from field-observations obtained by Van Warmelo (1924) and Enslin (1949).

In corroboration of the high recharge figures it may be added that as far as the author is aware there is no general decline of the water-table in Northern Natal. It has already been shown that recharge takes place each year and no bore-holes have dried up.

B. RECHARGE IN STORMBERG LAVA

Ground-water recharge differs from place to place and from time to time—not only because of differing intake facilities, but also because with the same intake facilities, the ratio of recharge to precipitation differs greatly with the amount, intensity, duration and distribution of rainfall. The recharge studies that were conducted on the Stormberg lava, show how these interrelated factors influence the proportion of rain that reaches the ground-water reservoirs, and are, therefore, discussed in detail.

1. GENERAL GROUND-WATER CONDITIONS

The lava occupies a bush-clad strip of country 10 to 15 miles wide lying at an altitude of 500 to 2,000 feet above mean sea-level. It extends from Mcemane Station in the south into Swaziland to the north.

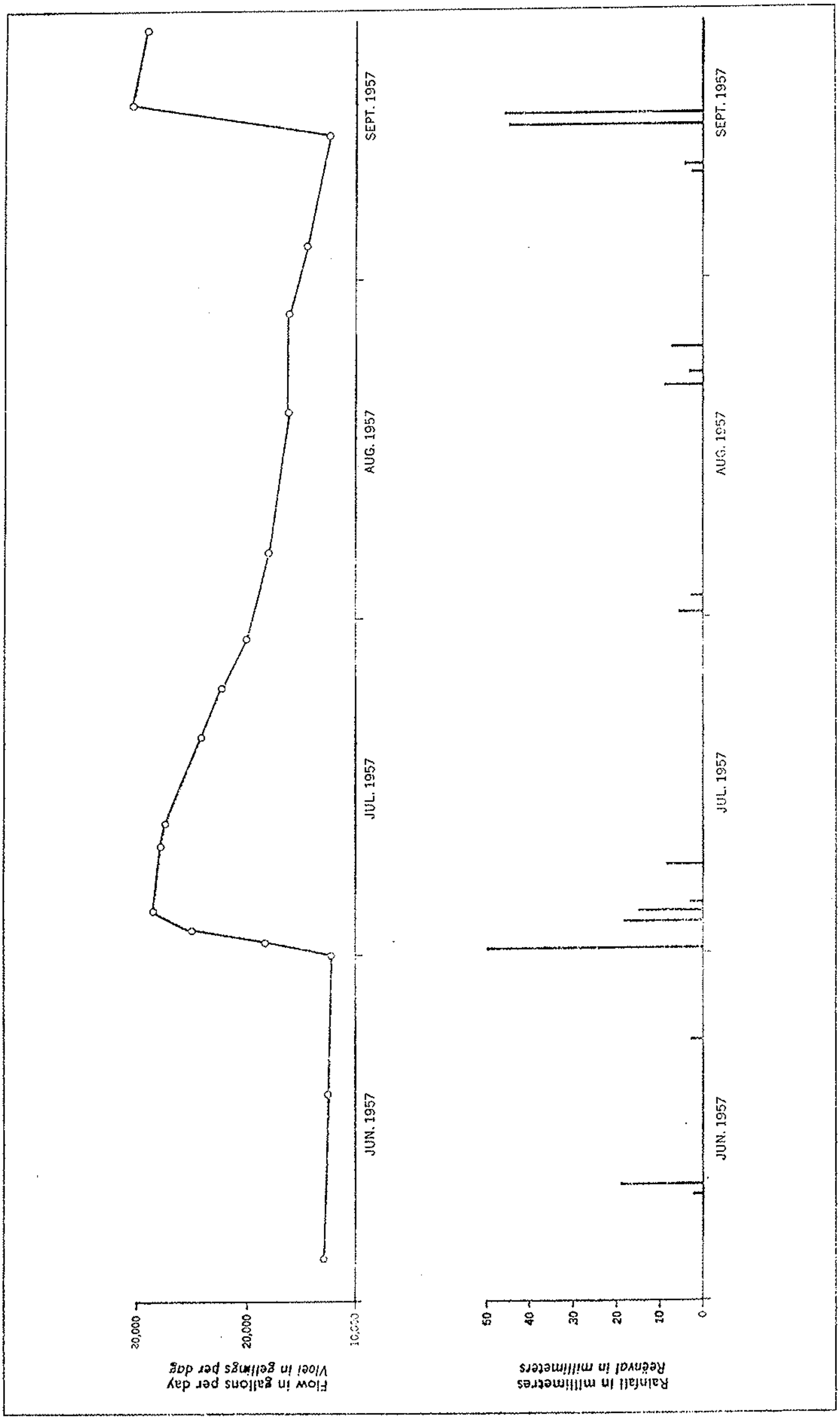

FIG. 37.—Diagram showing rainfall and fluctuations in flow from mine near Hlobane, Vryheid District.

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There are not springs in the area. Apart from the Mkuze and Pongola Rivers in the north, there is no other surface-water and farming communities are entirely dependent on bore-holes and a few small earth dams for their water-supply (see table 1). A total number of 533 bore-holes, of which 251 were successful, has been drilled in the lavas. Their median yield is 850 g.p.h.

Ground-water occurs in isolated basins of decomposition in the lava. There are very few rock outcrops and the 20,000 electrical depth-probes that have been taken to locate basins of decomposition for the selection of bore-hole sites for water, show that the lava is almost everywhere intensely weathered to depths of 15 to 50 feet below ground-surface (see fig. 14).

2. DRYING UP OF BORE-HOLES

Investigation of ground-water conditions in the lava was commenced by the author in 1946 but regular water-level measurements in bore-holes have only been made since 1949.

In 1943 bore-hole supplies showed signs of weakening and the position became worse in years to follow. By the beginning of 1957 the water-table in the area had declined on an average from 39 feet (calculated from records of bore-holes drilled prior to 1943) to 69 feet below ground-level. A total of 192 bore-holes, i.e. 76·5 per cent, dried up during this period (pl. VIII), and most of the water-yielding bore-holes were confined to deep basins of decomposition. Most bore-holes situated in shallow basins dried up completely. Furthermore, the percentage of successful bore-holes drilled by the 5 boring machines which operated in the area in an effort to alleviate the desperate water position, dwindled down to less than 10 per cent in 1957. Bore-hole sites selected by geophysical methods were more successful, although on some farms it was necessary to do up to 500 electrical depth-probes in order to locate a suitable deep basin of decomposition.

The ground-water conditions prior to and after 1943 are summarised in table 13.

TABLE 13.—GROUND-WATER CONDITIONS IN THE LAVA PRIOR TO AND AFTER 1943

	Prior to 1943	After 1943
Number of bore-holes drilled........................	304	176
Percentage successful...............................	63	19
Average depth to water-table in feet................	39	69
Average depth at which water was struck in feet......	62	78

3. CAUSES FOR THE LOWERING OF THE WATER-TABLE

The water-table did not only decline as a result of pumping, for even bore-holes situated many miles from pumping holes dried up. On Mussolini, Hlabisa District, for instance, bore-hole No. 15467 drilled in 1930 yielded 1,700 g.p.h. and the water-level at the time was 24 feet from surface. Its total depth was 63 feet and the water was struck at a depth of 40 feet. In 1950 it was for the first time equipped with a pump and it was then found that the water-level had dropped to 49 feet and the yield was less than 50 g.p.h. Similarly, on Cavin Baine a bore-hole drilled in 1929 yielded 960 g.p.h. and the water-level was 50 feet below ground-level. The hole was never used but in 1956 the water-level had dropped to 86 feet.

FIG. 37.—Diagram showing rainfall and fluctuations in flow from mine near Hlobane, Vryheid District.

This lowering of ground-water levels, even in areas where there was no artificial discharge by pumping, can be attributed to the following causes:—

(*a*) Possible slow leakage of ground-water to a deep-seated water-table. There is, however, no evidence to support this for if the general fresh and unfractured nature of the lava is considered it appears very unlikely that large amounts of ground-water can percolate beyond the zone of weathering.

(*b*) Transpiration of the ground-water by Lowveld trees appears to be the more feasible explanation and for the following reasons:—

  (i) No bore-holes dried up in the Palm Veld immediately south of Hluhluwe Station where trees are less abundant and thus wider spaced than in the rest of the area.

  (ii) Roots of trees have been found in a great number of bore-holes at depths of up to 80 feet below surface (pl. IX).

Plants that habitually send their roots to the water-table in order to obtain a perennial and secure supply of water are termed phreatophytes by Meinzer (1927).

Unfortunately botanists are at present unable to identify the roots that were taken from the bore-holes and no complete list of Lowveld phreatophytes can be given. The author is, however, conducting an experiment in which growth regulating weed-killers (2, 4-D and 2, 4, 5-T) are poured into bore-holes in which roots occur. It is expected that all trees feeding on ground-water in the vicinity of the treated bore-holes will be killed and in this way a comprehensive list of phreatophytes can be established. A preliminary and very tentative list of phreatophytes in the area is as follows: *Acacia karroo, Acacia robusta, Acacia xanthophloea, Zizyphus mucronata, Ficus sycamorus, Ficus ingens* and *Palmae* spp.

The transpiration of different plant associations in the Karroo, Pretoria and Drakensberg areas has experimentally been determined by Henrici (1940, 1946, 1947). Nothing, however, has been published on the transpiration ratios of the Lowveld trees, but the following illustrates that they make heavy demands on ground-water and are capable of keeping the water-table at a low level:—

A number of wells, up to 40 feet in depth, had been dug in the Tertiary sand in the adjoining False Bay area. Most of the wells were completely dry, the rest yielded some water during the summer months but dried up shortly after the cessation of the rainy season. Some years later in 1955, during the pineapple-boom, however, when the trees and bush had been cleared to cultivate pineapples, the water-table rose to within a few feet of the surface during the first rainy season. The result was that even the shallow wells then yielded supplies of water all the year round. In fact, the water-table in places then stood so near to the surface that some pineapple-lands had to be drained to save the crops.

4. RECHARGE

Very little, if any, recharge of the ground-water reservoirs took place from 1943 to 1956 (fig. 38). During September to October 1957, however, 350 mm of rain fell in 21 days and recharge took place on an extensive scale. The average water-table over the whole of the area rose to a level higher than it had been prior to 1943, and all the bore-holes that had dried up, again yielded strong supplies of water (fig. 38).

The percentage of the September–October rainfall that percolated to the water-table in a basin of decomposition on Insepe, Hlabisa District, was calculated. The size of the basin was determined geophysically and it was assumed that only rain-water that fell directly on the basin percolated to the water-table and that there was no leakage from nearby reservoirs. The result and method of calculation are summarized in table 14. The specific yield of the decomposed lava was taken to be 7·7 per cent as calculated on a previous page.

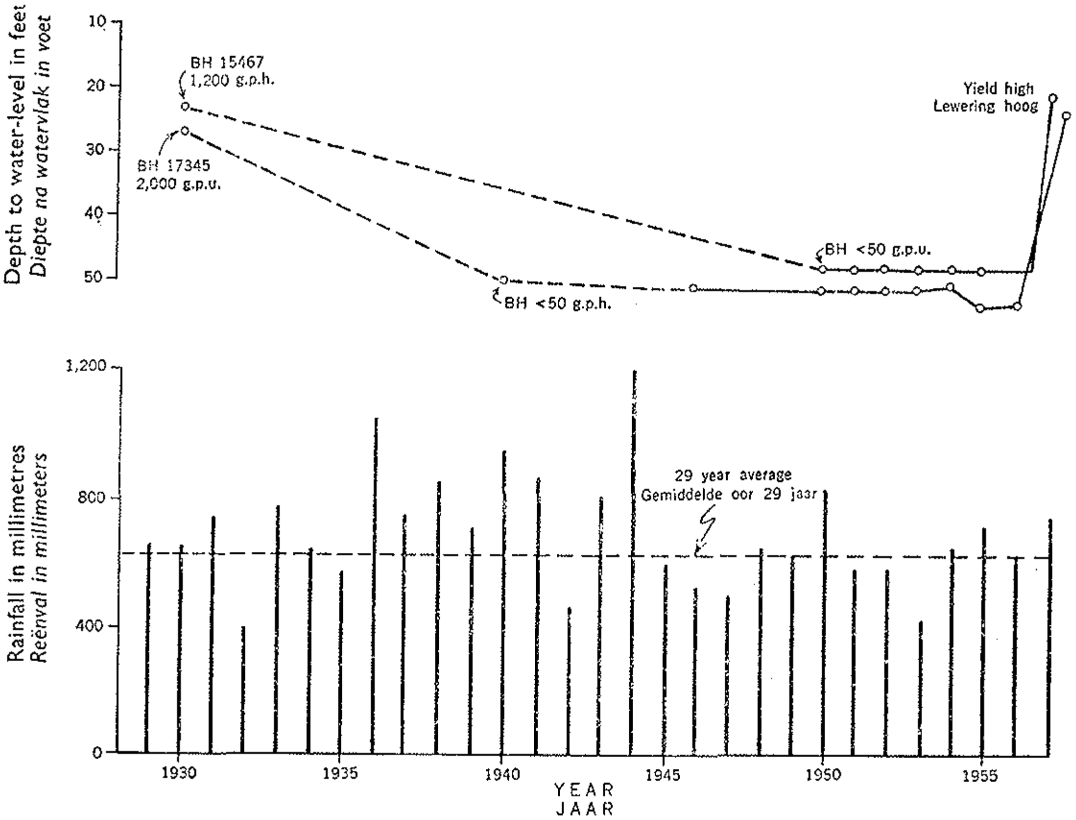

FIG. 38.—Fluctuations of water-levels in bore-holes Nos. 15467 and 17345 in relation to the average annual rainfall at Harrogate, Hlabisa District.

TABLE 14.—PERCENTAGE RECHARGE TO BASIN OF DECOMPOSITION DURING SEPTEMBER–OCTOBER 1957. INSEPE, HLABISA DISTRICT

Water-level below top of casing		Total increment in gallons	Percentage recharge	
Prior to recharge	After recharge	$Y = \frac{y \times V}{100} \times 6\cdot25$	September–October 1957 $\left(\frac{Y}{X} \times \frac{100}{1}\right)$	Whole of 1957 $\left(\frac{Y}{Z} \times \frac{100}{1}\right)$
65′	49′ 7″	81,570	7·34	3·23

Y = Total increment.
y = Specific yield (7·7).
X = Amount of rain in gallons that fell on the basin during September–October 1957.
Z = Amount of rain in gallons that fell on the basin during the whole of 1957.
V = Total volume of decomposed lava recharged.

Although 76·5 per cent of the bore-holes in lava dried up, none of the 81 bore-holes drilled in sedimentary rocks in the adjoining Magudu area showed signs of weakening. The vegetation, topography and rainfall in the two areas are, for all practical purposes, the same.

This significant fact can be explained by the different ways in which percolation of rain-water to the zone of saturation is accomplished in the two rock-types:

(*a*) It has been shown earlier in this chapter that in the Karroo sediments rain-water percolates to the water-table by way of joints and other permeable zones and that once the soil has been saturated to field-capacity, rain-water percolates to the water-table not many hours after a downpour.

(*b*) In the lava, on the other hand, the zone of aeration consists almost everywhere of a 20 to 50-feet-thick mantle of structureless highly weathered lava, which generally has a low permeability. Rain-water percolates down to the water-table through this formation by film-flow as suggested by Meinzer (1942). Much more water is required to bring the moisture content of the soil and total thickness of decomposed lava to field-capacity and leave an appreciable fraction available for ground-water increment.

During the period 1943 to 1956 the rainfall was somewhat lower than in previous years (fig. 38). The rainfall during 1943, 1947, 1949, 1953 and 1954 was higher than the 29-year average for the area, yet regular water-level measurements showed that no recharge took place. Owing to the transpiration of the dense cover of Lowveld trees the deficit of moisture in the soil and zone of aeration is large at most times and recharge to the ground-water reservoirs can only occur after moisture has accumulated from a series of rains. It is obvious that during 1943 to 1956 the amount and frequency of the downpours never synchronised to such an extent to allow rain-water to percolate down to the water-table. Conditions were probably always such that evapo-transpiration had sufficient time to dissipate the moisture of a downpour before the next downpour occurred.

During September to October 1957, a time of the year when transpiration losses of moisture are still at a very low ebb, all the factors controlling recharge synchronised for the first time and recharge took place on a grand scale. The total rainfall for 1957 was nothing spectacular and was only 96·5 mm above the 29-year average (fig. 39). When the monthly figures are compared it is apparent that the rainfall during September and October was far higher than the monthly averages over the period of 29 years. The monthly rainfall for the rest of 1957 was far below average (fig. 39). Recharge took place in early October after the exceptionally good rains in August and September brought the soil and mantle of decomposed lava up to field-capacity and paved the way for percolation directly to the ground-water reservoirs.

Unfortunately four automatic water-stage recorders installed on bore-holes were washed away by heavy floods, and valuable data regarding the exact date rain-water first reached the water-table and the period through which recharge took place, were lost.

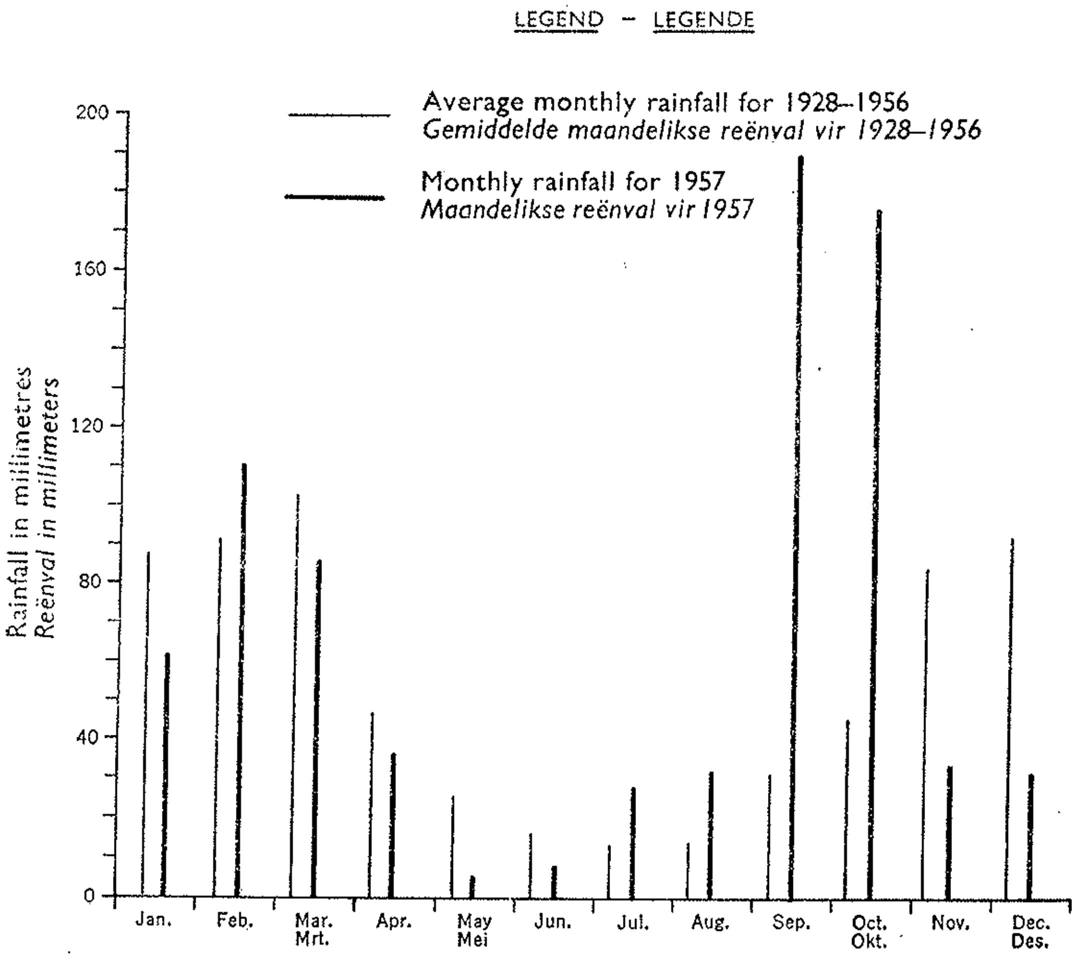

FIG. 39.—Comparison of the monthly rainfall during 1957 with the average monthly rainfall for the period 1928—1956. Harrogate, Hlabisa District.

VII. GROUND-WATER TEMPERATURES

Temperatures in deep bore-holes have been measured and published by Bouwer (1952), Krige (1939) and Weiss (1938). Apart from the temperatures of thermal waters (Kent, 1949) nothing has been published on the temperature of ground-water in South Africa.

During the period September 1956 to December 1958 the temperatures of water from about 180 bore-holes were observed in the area. Observations were made with 6 mercury thermometers calibrated in single degrees Fahrenheit and their accuracy was regularly checked against one another. As far as possible, temperatures were only measured at bore-holes where the discharge points were less than 15 feet away, and after they had been pumped at as high rates as possible for 20 to 30 minutes.

Some of the values obtained and the approximate ground-water isotherms are given in figure 40.

The temperature of water in the ground at any place is in general about the same as the mean annual air temperature (Collins, 1925). Near the surface the temperature of the water follows the changes in air temperature. At greater depths the water has a higher temperature corresponding to the increase of the earth temperature with increasing depth.

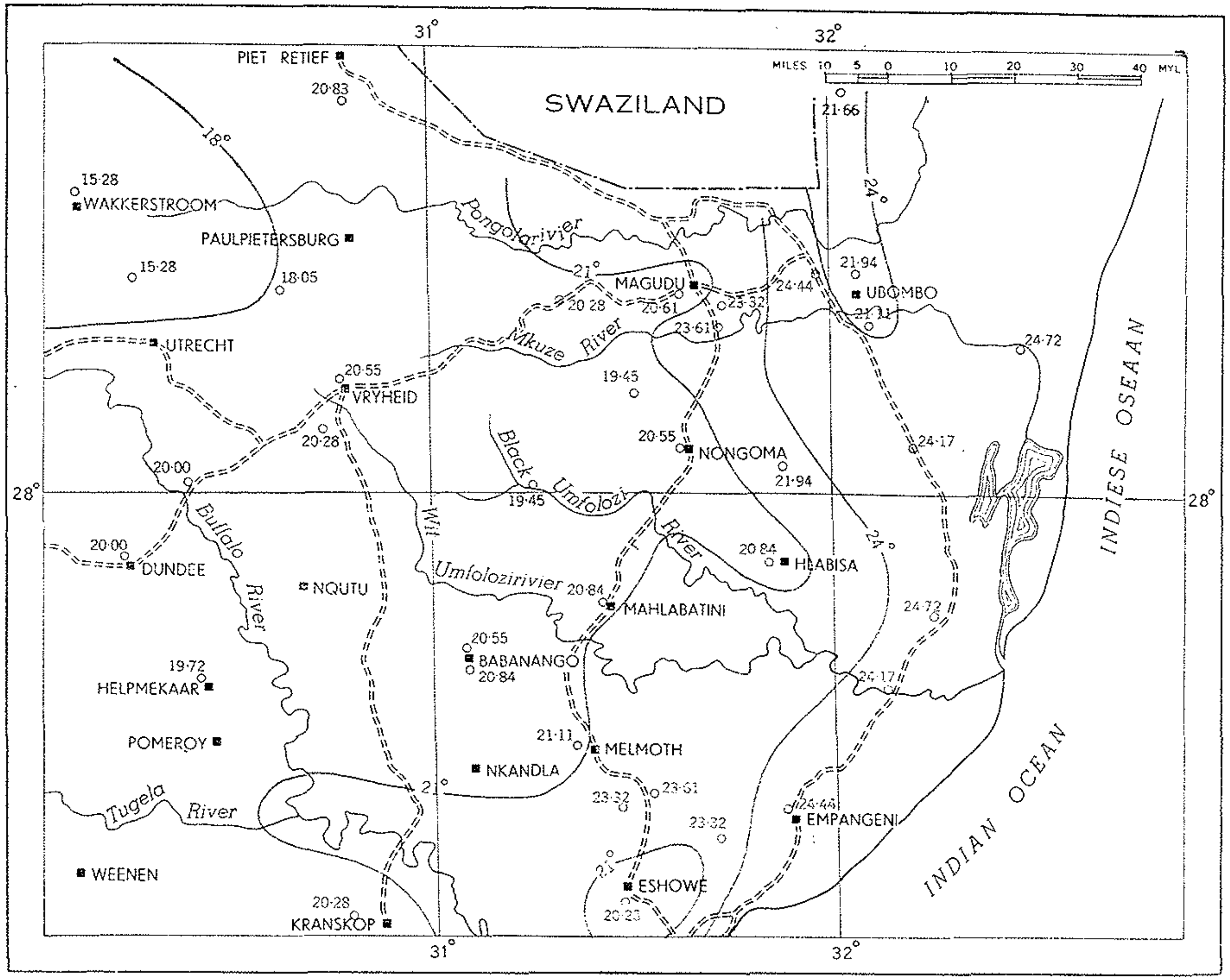

FIG. 40.—Isotherms of bore-hole water in degrees Centigrade for the period September 1956—December 1958.

The temperature of ground-water in the area is everywhere from 1 to 3·5° C higher than the mean annual air temperature. The values, however, compare favourably with mean summer air temperatures, i.e. October to March (table 15).

TABLE 15.—COMPARISON OF GROUND-WATER TEMPERATURES WITH THE MEAN ANNUAL AIR AND MEAN SUMMER AIR TEMPERATURES

Station	Average ground-water temperature in ° C	Mean summer air temperature in ° C (October–March)	Mean annual air temperature ° C
Empangeni	24·44	24·05	21·10
Eshowe	20·55	21·32	19·72
Mkuze	24·44	24·27	21·82
Pongola	23·33	24·17	22·00
Nkwaleni	23·61	23·79	20·60
Melmoth	21·11	21·06	19·17
Dundee	20·00	20·10	17·00
Vryheid	20·29	20·10	17·55
Piet Retief	20·00	19·90	16·60
Wakkerstroom	15·29	16·33	13·50

Air temperatures according to Climate Statistics (1954) and Beater (1949).

A possible explanation for the similarity between the ground-water temperatures and the mean summer air temperature lies in the fact that recharge of ground-water reservoirs takes place during the summer months. It has already been shown that there is generally no time lag and rain-water reaches the water-table within 48 hours. As a result of the general low diffusivity of rocks, thermal changes are extremely slow (Weiss, 1938), and it follows that the temperature of ground-water is to a large extent dependent on the temperature and volume of rain-water that reaches the water-table from time to time. Byers, Moses and Harney (1948) described a technique for measuring the temperature of rain at the ground and concluded that significant differences between the rain and the ambient air temperature usually occur for a short period in the first portion of the thunderstorm rain period and that differences in temperature between the ambient air and the rain falling during the latter portion of the storm are small. The temperature of rain-water is thus much higher than is generally accepted.

The temperatures of water from 7 bore-holes in Northern Natal were measured at least once per month during the period September 1956 to December 1958. The depths of the bore-holes vary from 60 to 200 feet and their yields from 500 to 1,000 g.p.h. None of the holes were over-pumped and no appreciable lowering of the water-levels occurred during the winter months. Although recharge took place during the summer months no descernible changes in the temperatures of the ground-water were recorded.

However, in the case of depleted ground-water reservoirs where there is storage for large additions of infiltrating rain-water, marked changes in the temperature of ground-water may occur. This is well illustrated by the following two cases, where in the first case a rise but in the second one a decrease in temperature occurred depending on the temperatures of the rain-water that reached the ground-water reservoirs.

(1) In the Lowveld of Zululand no recharge took place during 1946 to 1956. During this period ground-water levels dropped on the average from 39 feet to 69 feet and 76·5 per cent of the bore-holes

FIG. 40.—Isotherms of bore-hole water in degrees Centigrade for the period September 1956—December 1958.

dried up. During September and October 1957, 380 mm of rain fell within 7 days, recharge took place on a grand scale and the water-levels rose on an average to within 35 feet from the surface. Temperature measurements of ground-water then showed an increase varying from 0·5 to 1·7° C. Observations were continued in the same bore-holes during 1958 and 1959, but no appreciable change in temperature took place.

(2) During 1958 under-drainage by means of horizontal bore-holes was affected in the 100-feet-high embankment at Chestnut Grove on the national road between Pietermaritzburg and Durban (this is outside the area under consideration). More than 2¼ million gallons of water was drained from the site during the period August 1958 to February 1959. Recharge took place during March 1959, the flow from the horizontal bore-holes increased and the temperature of the water decreased from 18·1 to 17·3° C.

According to Bouwer (1952) the geothermic step (i.e. the increase in depth per unit rise in temperature) in Karroo rocks in the Orange Free State is 130 feet/1° C or 73 feet/1° F. However, in all the cases studied no apparent relation exists between the depth of bore-holes and the temperature of ground-water in the area. Temperatures of water from bore-holes over 300 feet in depth are the same as shallow bore-holes in the same areas.

The obvious reason for this phenomenon is that although the high permeability conduits occur at great depths, they are connected to shallow stored water or reservoirs in the zone of weathering that supply the bulk of the water when the bore-hole is pumped. If a substantial part of the water in the average deep bore-hole, came from the lower part of the hole, its temperature and the average temperature of all the water from the bore-hole would be higher than that from shallower holes, which is not the case. In this connection Bouwer (1952, p. 101) also found that due to circulation of ground-water, the geothermic steps in dolomite were abnormal immediately below the water-table; on an average this " zone of disturbance " was found to extend to 400 feet below the water-table, for temperatures obtained at 200 feet showed no appreciable difference from those at 400 feet.

VIII. QUALITY OF THE GROUND-WATER

Bond (1946) classified the various types of ground-water occurring in the principal geological formations in South Africa into 5 main groups. He showed that certain formations yield very characteristic water, owing to their mineralogical composition or past geological history.

A geochemical survey of the ground-water carried out by the author, showed that Bond's classification of the water in the area under consideration is not only unreliable for most places, but also too generalised to be of much academic or practical value. This is mainly due to the fact that his classification is based on insufficient data obtained from bore-holes and other sources which are not representative of a particular formation or area.

A. Methods of Investigation

Approximately 150 samples of water obtained from bore-holes and springs in various parts of the area were collected for analysis. The specific resistance of all these samples, which is a measure of their total dissolved solids, was determined with a resistivity apparatus and a standardised Siemens Bridge resistivity cell and the total dissolved solids read off on a standard curve. The pH-values, chloride and total hardness of 35 of the samples were determined with a " Dearborn Water Testing Set ".

In addition 146 chemical analyses of ground-water from various parts of the area, made by the Soils Research Institute (formerly Division of Chemical Services), the Chemical Branch of the South African Railways and Harbours and by private analysts were collected and studied. Many of these analyses, especially those by the South African Railways and Harbours, however, are concerned mainly with the potability of water and are thus incomplete, but proved valuable in calculating the averages of some of the more important constituents of the water.

B. CLASSIFICATION

By using the same basis of classification as Bond (1946), the author compiled a water-quality map to illustrate the distribution of the various types of water in the area (fig. 41). There is naturally a certain amount of mingling of types, but the contacts between the groups have been drawn as accurately as possible.

In the discussion that follows, a table showing one or more typical analyses in each group is given. In addition all the important constituents have been expressed as a percentage of the total dissolved solids at 105° C in order to facilitate comparison.

1. GROUP A. HIGHLY MINERALISED CHLORIDE WATER

The chief characteristics of this group are as follows:—

(i) It usually contains more than 3,500 parts of dissolved salts per million and is thus unsuitable for domestic or stock watering purposes.

(ii) The chloride content is high and usually exceeds 30 per cent of the total dissolved solids (see table 16).

(iii) Soda alkalinity (Na_2CO_3 or $NaHCO_3$) is never present (Bond, 1946).

This high salinity water is confined to the Cretaceous beds on the Zululand Coast. The author found great difficulty in obtaining samples of ground-water from this formation, since relatively little boring has been carried out in it, and most bore-holes were abandoned soon after they had been drilled on account of the high salinity.

2. GROUP B. MINERALISED CHLORIDE WATER

Water from this group occurs in the fairly flat and bush-clad Lowveld areas. It also extends far inland along flats and up the main river-valleys.

There is very little difference in percentage composition between the water in this group and the Group A water. The concentration of salts, however, is much lower and varies between 750 and 2,500 parts per million.

The water is extensively used for stock drinking but the salinity is, however, in most cases still too high for human consumption and it is very seldom used for domestic purposes.

As there are some differences in the composition of water from the Stormberg lava and Karroo sediments, the analyses are given separately (table 17). The main differences are:—

(i) The pH-values of water in the sediments averaging 8·1, are higher than in the basalt (7·1).

(ii) The soda alkalinity (Na_2CO_3 or $NaHCO_3$) of water from the sediments is extremely low, while in the basalt it averages more than 9 per cent and can be as high as 50 per cent of the total dissolved solids.

The relatively high chloride content, averaging 40 per cent of the total solids, is no doubt evidence that the salinity of the water is due to cyclic salts carried from the Indian Ocean inland by prevailing winds. Further

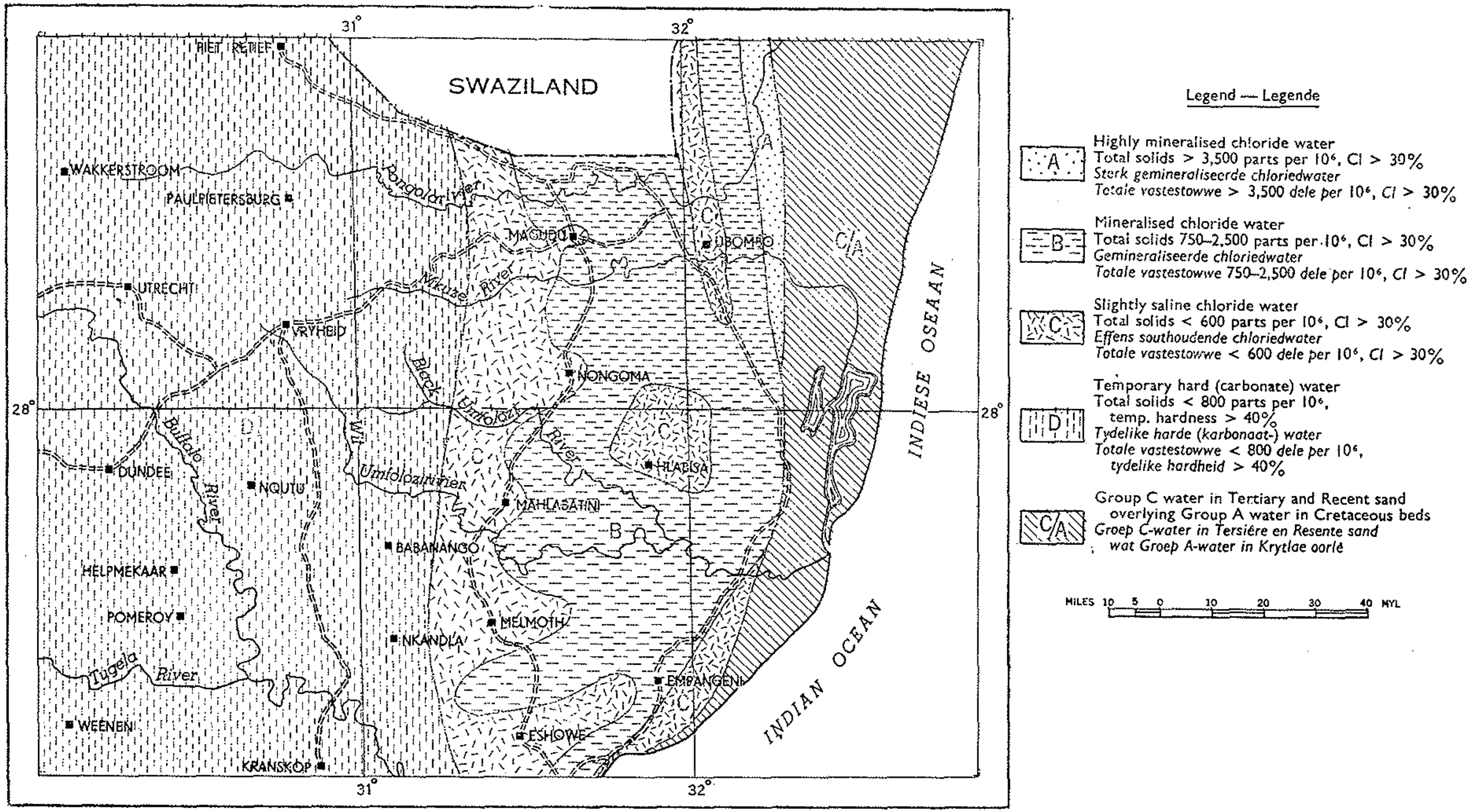

FIG. 41.—Water-quality map.

evidence is the occurrence of stunted or deformed trees (pl. X) in the area in which this type of water occurs. These trees are usually bent over at a height of 5 to 8 feet and grow horizontally in the direction away from the prevailing moist-laden sea-winds. A great number of these trees, mostly the *Ficus sycamorus*, occur north of Empangeni at distances up to 20 miles from the sea. According to Bayer (1938) the deformities are due, not to the direct mechanical effect of the wind, but to the fact that winds carry with them salt spray from the sea which kills off the young shoots and the exposed side and encourages growth on the leeward side.

TABLE 16.—A TYPICAL CHEMICAL ANALYSIS AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP A

Locality	Ronaldshay, Ubombo District. Bore-hole 80 ft. deep	Average of 5 analyses
Formation	Cretaceous rocks	Cretaceous rocks
Dionic conductivity at 20° C (mho cm × 10^6)	7,750·0	—
Total dissolved solids at 105° C (parts per 10^6)	5,000·0	5,000·0
pH at 20° C	7·6	7·5
Ions	Parts per million	
$Na^{\cdot}$	1,156·0	—
$Mg^{\cdot\cdot}$	438·0	—
$Ca^{\cdot\cdot}$	200·0	—
Sum of cations	1,794·0	—
F'	0·6	—
Cl'	2,556·0	2,750·0
NO_3'	nil	—
SO_4''	288·0	—
HCO_3'	1,092·0	—
CO_3''	nil	—
Sum of anions	3,936·6	—
$NaHCO_3$	nil	—
Na_2CO_3	nil	—
Temporary hardness as $CaCO_3$	22·0	—
Permanent hardness as $CaCO_3$	895·0	—
Total hardness as $CaCO_3$	n.d.	1,680·0
Expressed as a percentage of total dissolved solids		
$Na^{\cdot}$	23·12	—
$Mg^{\cdot\cdot}$	8·7	—
$Ca^{\cdot\cdot}$	4·0	—
F'	0·012	—
Cl'	51·1	43·1
NO_3'	nil	—
SO_4''	5·76	—
Temporary hardness as $CaCO_3$	0·44	—
Permanent hardness as $CaCO_3$	17·90	—
$NaHCO_3$	nil	—
Na_2CO_3	nil	—

Analyses by Soils Research Institute, Pretoria.

3. GROUP C. SLIGHTLY SALINE CHLORIDE WATER

The salts in this type of water are also cyclic and again there is very little difference in percentage composition between the water in this group and the water in Groups A and B (table 17). In the concentration there is, however, a large difference for in this group the total salts are usually less than 600 parts per million. The water is highly suitable for domestic, livestock and also for irrigation purposes.

The group occurs in three distinctly different areas and a typical analysis of water from each of these areas is given in table 18. The areas are the following:

(*a*) *Coastal Area*

The group is here confined to the Tertiary and Recent sand. This sand rests mostly on Cretaceous beds which, as already shown, yield water belonging to Group A. Over most of the coastal area Group C water thus overlies the water belonging to Group A. In the vicinity of False Bay, where the sand is comparatively thin, all the shallow wells and bore-holes yield water belonging to Group C, while deep bore-holes, which penetrate the underlying Cretaceous beds, yield highly mineralised water belonging to Group A.

North of the Mkuze River the sand gives rise to numerous freshwater springs, pans, swamps and a number of lakes. Striking examples are the Mosi Swamp and Lake Sibayi. Between the Mkuze River and Mtubatuba the sand is either absent or comparatively thin and potable water is confined to a number of small pans and shallow bore-holes and wells. South of Mtubatuba, in the vicinity of Kwambonambi and Mposa, the sand attains a thickness of well over 200 feet and rests directly on granite and Karroo rocks. In this area there is no highly mineralised water underneath the sand and even bore-holes that were drilled to depths of 300 feet into the underlying Pre-Cretaceous rocks yield water belonging to Group C.

(*b*) *The Lebombo Mountain*

Apart from a number of bore-holes in the Ubombo and Ingwavuma villages, there are many springs, especially on the eastern slopes, from which the natives draw their water. The low percentage of salts in the water is undoubtedly due to continual leaching of the cyclic salts. Rain-water charged with salts percolates down to the water-table but is again discharged through springs at a lower level, and little concentration of salts can take place. In contrast the rhyolite in the flat, low-lying regions in the vicinity of Ingweni and Hluhluwe Station, where there are no springs and no leaching can take place, yields water belonging to Group B.

(*c*) *The Escarpment Separating the Lowveld from the Middleveld*

This indented and elevated escarpment runs from Eshowe in the south through Melmoth, Mahlabatini, Nongoma and Magudu in the north. It represents the furthest areas to which cyclic salts are carried inland by the prevailing winds blowing from the Indian Ocean. The area is generally well supplied with numerous springs and the low percentage of salts can also be accounted for by effective leaching through the springs.

TABLE 17.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP B

Karroo Sediments	Stormberg Basalt and Rhyolite

TABLE 17.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP B

Locality	Karroo Sediments			Stormberg Basalt and Rhyolite		
	Gingindhlovu Township, Mtunzini District. Bore-hole 150 ft. deep	Nxogwane Store, Nongoma District. Bore-hole 120 ft. deep	Average of 18 analyses	Banghoek, Ubombo District. Bore-hole 165 ft. deep	S.A. Police Hluhluwe, Hlabisa District. Bore-hole 200 ft. deep	Average of 29 analyses
Formation	Dwyka tillite	Middle Ecca sandstone	—	basalt	rhyolite	—
Dionic conductivity at 20 ° C (mho cm × 10^6)	2,200·0	3,100·0	—	1,220·0	2,050·0	—
Total dissolved solids at 105° C (parts per 10^6)	1,419·0	2,000·0	1,257·1	999·0	1,322·0	1,359·0
pH at 20° C	8·0	8·5	8·1	8·5	7·1	7·3
Ions	Parts per million					
$Na^{\cdot}$	330·0	400·0	—	305·0	368·0	—
$Mg^{\cdot\cdot}$	50·0	125·0	—	27·0	54·0	—
$Ca^{\cdot\cdot}$	nil	110·0	—	11·0	54·0	—
Sum of cations	380·0	638·0	—	343·0	476·0	—
F'	0·013	0·15	—	0·80	nil	—
Cl'	632·0	955·0	—	356·0	454·0	—
NO_3'	6·0	nil	—	nil	nil	—
SO_4''	19·0	24·0	—	41·0	24·0	—
CO_3''	nil	18·0	—	78·0	nil	—
HCO_3'	317·0	372·0	—	561·0	598·0	—
Sum of anions	974·0	1,369·0	—	1,036·8	1,076·0	—

Analyses by Soils Research Institute, Pretoria.

TABLE 17.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP B *(continued)*

Locality	Karroo Sediments			Stormberg Basalt and Rhyolite		
	Gingindhlovu Township, Mtunzini District. Bore-hole 150 ft. deep	Nxogwane Store, Nongoma District. Bore-hole 120 ft. deep	Average of 18 analyses	Banghoek, Ubombo District. Bore-hole 165 ft. deep	S.A. Police Hluhluwe, Hlabisa District. Bore-hole 200 ft. deep	Average of 29 analyses
Formation	Dwyka tillite	Middle Ecca sandstone	—	basalt	rhyolite	—
$NaHCO_3$	nil	nil	—	538·0	227·0	—
Na_2CO_3	nil	nil	—	85·0	nil	—
Temporary hardness as $CaCO_3$	260·0	305·0	—	140·0	355·0	—
Permanent hardness as $CaCO_3$	55·0	485·0	—	nil	nil	—
Expressed as a percentage of total dissolved solids						
$Na^{\cdot}$	23·26	20·0	21·56	30·53	27·83	23·0
$Mg^{\cdot\cdot}$	3·52	6·27	4·22	2·72	4·08	4·65
$Ca^{\cdot\cdot}$	nil	5·5	4·47	1·10	4·08	5·29
F'	0·001	0·007	0·007	0·08	nil	0·147
Cl'	44·53	47·7	49·80	25·62	34·34	43·21
NO_3'	0·42	nil	0·007	nil	nil	0·15
SO_4''	1·33	1·20	0·16	4·10	1·81	2·1
$NaHCO_3$	nil	nil	0·733	53·85	17·17	9·17
Na_2CO_3	nil	nil	0·008	8·51	nil	1·07
Temporary hardness as $CaCO_3$	18·32	15·75	13·59	14·01	26·85	23·3
Permanent hardness as $CaCO_3$	3·87	24·25	7·29	nil	nil	8·98

Analyses by Soils Research Institute, Pretoria.

TABLE 18.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP C

	Karroo and Pre-Karroo Rocks	Tertiary Sand

Analyses by Soils Research Institute, Pretoria.

TABLE 18.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP C

Locality	Karroo and Pre-Karroo Rocks			Tertiary Sand		
	Escarpment	Lebombo Mountain	Average of 26 analyses	Coastal Area		Average of 17 analyses
	Nongoma Township, Bore-hole 180 ft. deep	Ubombo Township, Bore-hole 135 ft. deep		Kwambonambi, Lower Umfolozi District. Bore-hole 200 ft. deep	Dukuduku Forest, Lower Umfolozi District. Bore-hole 300 ft. deep	
Formation	Middle Ecca sandstone	Stormberg rhyolite	—	Tertiary sand	Tertiary sand	—
Dionic conductivity at 20° C (mho cm × 10^6).......	160·0	320·0	—	700·0	n.d.	—
Total dissolved solids at 105° C (parts per 10^6)......	103·0	206·0	203·0	366·0	640·0	450·0
pH at 20° C..................................	7·8	6·6	6·8	8·15	7·5	7·1
Ions	Parts per million					
$Na^{\cdot}$..................................	21·0	48·0	—	206·0	145·0	—
$Mg^{\cdot\cdot}$..................................	6·0	1·0	—	17·0	27·0	—
$Ca^{\cdot\cdot}$..................................	8·0	10·0	—	16·0	24·0	—
Sum of cations..........................	35·0	59·0	—	239·0	196·0	—
F'..................................	nil	1·5	—	nil	0·30	—
Cl'..................................	37·0	62·0	—	241·0	256·0	—
NO_3'..................................	nil	nil	—	nil	67·0	—
SO_4''..................................	7·0	nil	—	nil	58·0	—
CO_3''..................................	nil	nil	—	27·0	nil	—
HCO_3'..................................	58·0	98·0	—	232·0	12·0	—
Sum of anions..........................	102·0	161·5	—	500·0	393·3	—

Analyses by Soils Research Institute, Pretoria.

TABLE 18.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP C (*continued*)

Locality	Karroo and Pre-Karroo Rocks			Tertiary Sand		
	Escarpment	Lebombo Mountain	Average of 26 analyses	Coastal Area		Average of 17 analyses
	Nongoma Township, Bore-hole 180 ft. deep	Ubombo Township, Bore-hole 135 ft. deep		Kwambonambi, Lower Umfolozi District. Bore-hole 200 ft. deep	Dukuduku Forest, Lower Umfolozi District. Bore-hole 300 ft. deep	
Formation	Middle Ecca sandstone	Stormberg rhyolite	—	Tertiary sand	Tertiary sand	—
$NaHCO_3$	8·0	nil	—	134·0	nil	—
Na_2CO_3	nil	38·0	—	nil	nil	—
Temporary hardness as $CaCO_3$	42·0	58·0	—	110·0	10·0	—
Permanent hardness as $CaCO_3$	nil	nil	—	nil	160·0	—
Expressed as a percentage of total dissolved solids						
$Na^{\cdot}$	20·0	23·3	17·24	56·28	22·65	31·17
$Mg^{\cdot\cdot}$	2·85	4·85	11·84	4·64	4·21	3·77
$Ca^{\cdot\cdot}$	7·6	2·91	2·4	4·37	3·75	3·80
F'	nil	0·728	0·51	ni	0·046	0·66
Cl'	35·23	30·0	31·0	65·84	40·00	35·2
NO_3'	nil	nil	14·3	nil	10·46	0·485
SO_4''	6·85	nil	6·1	nil	9·06	0·385
$NaHCO_3$	7·8	nil	9·36	36·61	nil	31·7
Na_2CO_3	nil	18·44	19·2	nil	nil	2·68
Temporary hardness as $CaCO_3$	40·0	28·1	49·2	30·05	1·56	16·80
Permanent hardness as $CaCO_3$	nil	nil	4·08	nil	25·0	7·13

Analyses by Soils Research Institute, Pretoria.

Analyses by Soils Research Institute, Pretoria.

TABEL 19.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP D

Locality	Talana Hill, Dundee District. Bore-hole 200 ft. deep	Kingsley Police Station, Utrecht District. Bore-hole 175 ft. deep	Piet Retief Hospital, Piet Retief District. Bore-hole 135 ft. deep	Babanango Residency, Babanango District. Bore-hole 125 ft. deep	Pomeroy Gaol, Msinga District. Bore-hole 250 ft. deep	Average of 43 analyses
Formation	Middle Ecca sandstone	Middle Ecca sandstone	Dwyka tillite	Lower Ecca shales	Middle Ecca sandstone	
Diouic conductivity at 20° C (mho cm × 10^6)	200·0	n.d.	160·0	115·0	450·0	—
Total dissolved solids at 105° C (parts per 10^6)	194·0	358·0	152·0	115·0	313·0	276·9
pH at 20° C	7·05	7·5	7·3	7·5	7·6	7·36
Ions	Parts per million					
$Na^{\cdot}$	33·0	53·0	17·0	23·0	63·0	—
$Mg^{\cdot\cdot}$	7·0	29·0	7·0	4·0	37·0	—
$Ca^{\cdot\cdot}$	22·0	44·0	19·0	15·0	22·0	—
Sum jo cations	62·0	126·0	43·0	42·0	122·0	—
F'	0·70	1·40	0·60	0·10	0·50	—
Cl'	11·0	25·0	7·0	11·0	28·0	—
NO_3'	nil	6·00	nil	nil	nil	—
SO_4''	30·0	8·0	6·0	4·0	4·0	—
CO_3''	nil	nil	nil	nil	nil	—
HCO_3'	360·0	360·0	116·0	104·0	336·0	—
Sum of anions	401·70	400·4	129·60	119·0	368·50	—

Analyses by Soils Research Institute, Pretoria.

TABLE 19.—SELECTED ANALYSES AND AVERAGE PERCENTAGE CONSTITUENTS OF WATER IN GROUP D (*continued*)

Locality	Talana Hill, Dundee District. Bore-hole 200 ft. deep	Kingsley Police Station, Utrecht District. Bore-hole 175 ft. deep	Piet Retief Hospital, Piet Retief District. Bore-hole 135 ft. deep	Babanango Residency, Babanango District. Bore-hole 125 ft. deep	Pomeroy Gaol, Msinga District. Bore-hole 250 ft. deep	Average of 43 analyses
Formation	Middle Ecca sandstone	Middle Ecca sandstone	Dwyka tillite	Lower Ecca shales	Middle Ecca sandstone	
$NaHCO_3$	44·0	111·0	34·0	51·0	156·0	—
Na_2CO_3	nil	nil	nil	nil	nil	—
Temporary hardness as $CaCO_3$	84·0	229·0	74·0	55·0	182·0	—
Permanent hardness as $CaCO_3$	nil	nil	nil	nil	nil	—
Expressed as a percentage of total dissolved solids						
$Na^{\cdot}$	17·0	14·80	11·18	20·0	20·13	12·8
$Mg^{\cdot\cdot}$	3·60	8·10	4·60	3·47	11·82	4·19
$Ca^{\cdot\cdot}$	11·3	12·29	12·50	13·04	7·03	7·76
F'	0·36	0·391	0·394	0·086	1·60	0·19
Cl'	5·7	6·98	4·60	9·57	8·95	4·44
NO_3'	nil	1·67	nil	nil	nil	0·035
SO_4''	15·5	2·23	3·94	3·48	1·28	3·72
$NaHCO_3$	22·6	31·0	22·36	44·34	49·84	18·72
Na_2CO_3	nil	nil	nil	nil	nil	0·023
Temporary hardness as $CaCO_3$	43·3	63·96	48·68	47·82	58·15	41·71
Permanent hardness as $CaCO_3$	nil	nil	nil	nil	nil	6·52

Analyses by Soils Research Institute, Pretoria.

4. GROUP D. TEMPORARY HARD (CARBONATE) WATER

This group is found inland from the Group C water. Bond (1946) classified the water of Northern Natal and Northern Zululand as " Pure Waters " (total dissolved solids 150 parts per million). He, however, admitted (p. 161) that the Ecca water in Northern Natal does not conform to any particular type. Instead, all types of water (except the highly mineralised chloride type) are found.

TABLE 20.—SELECTED ANALYSES OF " ACID MINE WATER " IN NORTHERN NATAL

Locality	Water from Inyati Mine, Vryheid District	Elandslaagte Police Post, Kliprivier District. Borehole 150 ft. deep.
Dionic conductivity at 20° C (mho cm × 10^6)	3,000·0	2,200·0
Total dissolved solids at 105° C (parts per 10^6)	2,212·0	1,630·0
pH at 20° C	3·15	3·16
Ions	Parts per million	
$Na^{\cdot}$	177·0	520·0
$Mg^{\cdot\cdot}$	66·0	17·0
$Ca^{\cdot\cdot}$	188·0	20·0
Sum of cations	431·0	557·0
F'	0·80	0·80
Cl'	7·0	7·0
NO_3'	nil	nil
SO_4''	1,415·0	1,018·0
CO_3''	nil	18·0
HCO_3'	nil	183·0
Sum of anions	1,422·8	1,226·80
$NaHCO_3$	nil	50·0
Na_2CO_3	nil	nil
Temporary hardness as $CaCO_3$	nil	nil
Permanent hardness as $CaCO_3$	1,100·0	—
Expressed as a percentage of total dissolved solids		
$Na^{\cdot}$	8·00	31·9
$Mg^{\cdot\cdot}$	2·98	1·04
$Ca^{\cdot\cdot}$	8·45	1·22
F'	0·036	0·049
Cl'	0·316	0·43
NO_3'	nil	nil
SO_4''	63·96	62·45
$NaHCO_3$	nil	3·06
Na_2CO_3	nil	nil
Temporary hardness as $CaCO_3$	nil	nil
Permanent hardness as $CaCO_3$	49·72	—

Analyses by Soils Research Institute, Pretoria.

The author obtained 56 analyses of bore-hole water from these areas and, save for a few exceptions, they invariably have more than 150 parts per million, with an average of 276 parts, as total dissolved solids (table 19). He thus classifies this water as temporary hard (carbonate) water. The main characteristics are:—

(i) There is very little permanent hardness.
(ii) The chlorides are low, usually 10 per cent of the total dissolved solids.
(iii) High soda alkalinity; an average of 50 per cent of the total solids and which is due to $NaHCO_3$ rather than Na_2CO_3.
(iv) There is generally more Ca than Mg.

Another interesting feature of the water in Northern Natal is the occurrence of " acid mine water " in the coal-mines and some of the bore-holes situated close to mining areas (table 20). According to Braley (1956, p. 314), " Drainage of acid mine water into surface streams of coal mining areas is one of the most serious problems of stream pollution, since there is no known method that completely prevents its forming and no economically feasible treatment after it has formed. The mine acid problem differs from other pollution hazards because acid production does not end with cessation of mining but actually becomes more evident when pumping is stopped ".

This water is unpotable and is characterized by:—

(i) A low pH-value, usually smaller than 4·0.
(ii) High concentration of salts, sometimes more than 4,000 parts per million.
(iii) The SO_4 content is invariably high, in most cases greater than 60 per cent of the total solids.

The bacteriological oxidation of pyritic disseminations, associated with the coal-measures when they become exposed to the atmosphere in the mines, explains the origin of this water (Ashmead, 1956).

The reactions produce H_2SO_4, Fe_2O_3, $Fe(OH)_3$ and various ferrous sulphates.

GRONDWATERSTUDIES IN NOORD-NATAL, ZOELOELAND EN AANGRENSENDE GEBIEDE

OPSOMMING IN AFRIKAANS

INLEIDING

Die doel van die ondersoek wat in hierdie publikasie behandel word, is die volgende:—

(i) Om te onderskei tussen die primêre (inherente) en sekondêre hidrologiese eienskappe van die vernaamste geologiese formasies in die gebied,

(ii) om die vernaamste prosesse te beskryf wat verantwoordelik was vir die ontstaan van die sekondêre hidrologiese eienskappe, met spesiale verwysing na die belangrike rol wat deur verwering gespeel word, en

(iii) om 'n aantal kwalitatiewe en kwantitatiewe waardes van die sekondêre eienskappe te gee en te bespreek hoe hierdie eienskappe die voorkoms, beweging en ondergrondse bewaring van water beheer.

Die resultate van ondersoeke na die volgende aspekte i.v.m. ondergrondse water word ook gegee en bespreek:—

(i) Aanvulling,
(ii) die grondwatervlak,
(iii) skommelinge van die watervlak in boorgate,
(iv) kwaliteit en
(v) temperatuur.

Die gegewens in die publikasie vervat, is ingesamel gedurende 1946 tot 1958. Gedurende hierdie tydperk was die skrywer verantwoordelik vir die aanwys van boorplekke in Natal met behulp van geologiese en geofisiese metodes. Daar is altesaam sowat 1,500 boorplekke aangewys.

Meeste dorpe se watervoorrade is afkomstig van damme en riviere. Bantoereservate beslaan sowat 8,000 vierkante myl en hulle is grotendeels afhanklik van water verkry uit riviere, spruite, fonteine en tot 'n mindere mate boorgate.

Meeste plase wat deur Blankes bewoon word, is vir hulle watervoorraad van boorgate en putte afhanklik. Die toenemende belangrikheid van ondergrondse water word weerspieël deur die feit dat daar voor 1946 maar sowat 300 boorgate was en dat die getal na meer as 3,300 in 1958 aangegroei het. Boorgatwater word hoofsaaklik vir veesuiping en huishoudelike gebruik aangewend; daar word selde uit boorgate besproei.

BESKRYWING VAN DIE GEBIED

Die gebied beslaan ongeveer 19,500 vierkante myl en word begrens deur breedtegraadlyne 27° en 29° suid, die lengtegraadlyn 30° oos en die Indiese Oseaan.

Dit val in vyf fisiografiese streke, nl. Kusstreek, Laeveld, Lebombo, Oostelike Middelveld en Hoëveld (kyk fig. 2).

Die groot riviere is almal standhoudend terwyl meeste van die groot aantal spruite net gedurende die somermaande vloei.

Die klimaat is warm-subhumied buiten vir die gebiede onmiddellik ten ooste en weste van die Lebomboberge waar die klimaat warm-halfdroog is (kyk fig. 3).

Reën val gewoonlik in die somermaande in die vorm van donderbuie. Die gemiddelde jaarlikse reënval langs die kus wissel van 1,200 mm in die suide tot sowat 900 mm in die noorde. Verder binnelands word die reënval tot 'n groter mate beheer deur die topografie, want dit wissel van 500 mm per jaar in die laagliggende gebiede tot sowat 1,500 mm per jaar op die hoogliggende dele soos Eshowe, Qudeni en Ceza.

Die Kusvlakte en Laeveld is dig begroei met 'n groot verskeidenheid van tipiese laeveldse bome en bosse. Die binnelandse gebiede is met verskillende soorte gras begroei, maar langs die waterlope en klowe kom op plekke digte bos voor.

Boerdery met beeste, skape, wattel en suiker is die vernaamste landboubedrywe. Sowat 90 persent van die Natalse steenkoolproduksie is van steenkoolmyne in die gebied afkomstig.

ALGEMENE GEOLOGIE

Die oudste gesteentes in die gebied behoort tot die Argeïese Kompleks. Dit sluit in skis en gestreepte ysterklip van die Formasie Mfongosi en ultrabasiese en basiese gesteentes van die Stollingskompleks Jamestown en hulle gemetamorfoseerde derivate. Hierdie gesteentes kom hoofsaaklik in die Tugelariviervallei en in die Distrik Piet Retief voor. Baie min boorgate is in hulle geboor.

Die kompleks sluit ook in die Argeïese graniet wat groot gebiede beslaan in die Tugela- en Umfoloziriviervallei, asook in die Distrikte Vryheid, Babanango en Piet Retief. 'n Groot aantal boorgate is in die graniet geboor.

Die Formasie Insuzi, bestaande uit kwartsiet, lawa, skis en filliet, rus diskordant op gesteentes van die Argeïese Kompleks. Dit kom hoofsaaklik voor in die Distrikte Piet Retief, Paulpietersburg en Vryheid, asook as relatiewe klein binne- en buiteleêrs in die Umfolozi-, Buffels- en Tugelariviervallei.

Kwartsiet, skalie en lawa van die Formasie Mozaan beslaan groot gebiede in die Distrikte Piet Retief, Paulpietersburg en Ngotshe.

Die Pongolagraniet beslaan betreklike klein gebiede in die Distrikte Piet Retief en Ngotshe; dit strek vanaf noordoos van Louwsburg, deur die Pongolarivier, tot in Swaziland.

Die Formasie Ntingwe wat beskou word as die ekwivalent van die Sisteem Transvaal in Natal, bestaan uit 'n dun opeenvolging van grintsteen, skalie en kalksteen (Matthews, 1959). Dit kom in 'n smal strokie benoorde die Tugelarivier in die Distrik Nkandla voor.

Die Serie Tafelberg bou die platogebiede in die omgewing van Eshowe en Melmoth. Die serie rus diskordant op al bogenoemde gesteentes en bestaan uit kenmerkende ligrooi, growwe tot middelmatig growwe sandsteen waarin daar dun lense van skalie voorkom.

Die hele Sisteem Karoo, behalwe die Moltenolae, is verteenwoordig en beslaan sowat 70 persent van die gebied terwyl sowat 80 persent van die boorgate daarin geboor is.

Die Serie Dwyka is oral aan die basis van die sisteem teenwoordig en dit rus diskordant op 'n baie ongelyke vloer van ouer gesteentes. Die serie bestaan uit tilliet met lae en lense van sandsteen en skalie. As gevolg van die ongelyke vloer waarop dit rus, varieer die dikte van die serie van minder as 100 voet tot meer as 600 voet op plekke.

Die Serie Ecca volg konkordant op die Dwykatilliet. Die goedgelaagde blouswart skalie van die Étage Onder-Ecca varieer in dikte van sowat 150 voet in die Distrik Vryheid tot sowat 800 voet in die omgewing van Tugela Ferry.

Die Étage Middel-Ecca bestaan uit afwisselende sandsteen en skalielae. Die gesteentes is gemiddeld sowat 1,200 voet dik en beslaan verreweg die grootste gedeelte van die gebied. Steenkoollae kom ongeveer in die middel van die étage voor.

Die Étage Bo-Ecca bestaan uit 'n swakgelaagde blougrys skalie en is van 300 tot 400 voet dik.

Die Serie Beaufort is swak verteenwoordig in Noord-Natal, maar is goedontwikkel in die ooste waar dit op die Lebombomonoklien voorkom en van 15 tot 25 grade oos hel. Dit bestaan uit afwisselende lae sandsteen, skalie en veelkleurige moddersteen.

Die Serie Stormberg kom net in die ooste op die Lebombomonoklien voor waar dit van 15 tot 25 grade oos hel. Die Holkranssandsteen en Rooilae is saam sowat 200 voet dik. Die basalt vorm baie min dagsome en beslaan die vlakte onmiddellik wes van die Lebomboberge. 'n Aantal prominente riolitiese breksiegange kom in die basalt wes van Mhlosinga voor. Die rioliet met ingelaagde piroklaste bou die Lebomboberge. 'n Groot aantal riolitiese breksiegange wat vermoedelik die voerkanale van die lawa was, kom in die rioliet voor.

'n Groep gesteentes wat voorlopig die Bumbenilae genoem is, is onlangs deur lede van die Geologiese Opname naby die suidelike punt van die Lebomboberge ontdek. Die lae bestaan uit konglomeraat, basalt, tragitiese lawa agglomeraat en verskillende soorte tuf. Ten minste drie oneweredige liggame van siëniet wat intrusief is in die gesteentes, is waargeneem. 'n Groot aantal vulkaniese suile en geassosieerde gange bestaande uit tragitiese materiaal kom in die gesteentes en ook in die onderliggende rioliet voor. Versteende hout kom in die basale konglomeraat voor en die groep gesteentes behoort tot die Bo-Karoo.

'n Netwerk van dolerietgange en plate kom in al die gesteentes voor, maar is veral volop in die Karoosedimente.

Die Sisteem Kryt bou die Kusstreek maar is selde of ooit sigbaar onder die bedekking van Tersiêre en Resente sand.

" Fossielgrond " kom taamlik wydverspreid in Noord-Natal voor. Meeste diep dongas is in hierdie grond gekerf. Laterietafsettings, selde meer as 4 voet dik, bedek ook groot dele in Noord-Natal.

STRUKTUURGEOLOGIE

Meeste van die Voor-Karooformasies, behalwe die Serie Tafelberg, is intensief geplooi. Die Serie Tafelberg en die Sisteem Karoo lê min of meer horisontaal, behalwe in die ooste waar die formasies as gevolg van die monoklinale plooiing 'n helling van 15 tot 25 grade oos het.

Verskuiwings kom baie algemeen in die Voor-Karooformasies voor. Behalwe die aantal verskuiwings in die ooste wat met die Lebombomonoklien geassosieer word, word daar relatief min ware verskuiwings in die Sisteem Karoo aangetref. Die meeste verplasings is veroorsaak deur die dolerietintrusies.

Die Sisteem Kryt hel onder 'n lae hoek na die ooste. Daar is geen bekende verskuiwings in hierdie formasie nie.

HIDROLOGIESE EIENSKAPPE VAN DIE VERNAAMSTE GEOLOGIESE FORMASIES

Die primêre of inherente hidrologiese eienskappe van al die gesteentes in die gebied, behalwe dié van sekere Tersiêre en Resente afsettings, is van so 'n aard dat geeneen meer as 100 g.p.u. in 'n gewone sesduim-boorgat kan lewer nie. Die voorkoms, beweging en die bewaring van ondergrondse water is grotendeels afhanklik van die sekondêre hidrologiese eienskappe wat ontwikkel het as gevolg van verskeie geologiese prosesse en magte wat die gesteentes op verskillende tye na hulle ontstaan beinvloed het. Die vernaamste een hiervan is naatvorming deur die indringing van doleriet, rekspanning, verskuiwings en fisiese verwering. In die Karoosedimente is eersgenoemde die heel vernaamste aangesien die lewerings van sowat 80 persent van die suksesvolle boorgate direk of indirek aan die gevolge van die intrusie van die doleriet op andersins nie-deurlatende rotse, toegeskryf kan word.

Meeste nate wat op bogenoemde maniere gevorm word, is toe en word oop of deurlatend gemaak deur skeikundige verwering en die beweging van ondergrondse water deur die nate. Een van die bewyse hiervoor is die feit dat meeste boorgate waar dolerietgange of verskuiwings dieper as ongeveer 200 voet raakgeboor is, geen of baie min water gelewer het, terwyl ander gate wat dieselfde strukture vlakker geraak het, groot hoeveelhede water gelewer het (kyk fig. 10).

Verwering vind in die algemeen net tot op die watertafel plaas en daar is dan ook gevind dat meeste boorgate net tot op 'n sekere diepte onderkant die watertafel water lewer. Hierdie diepte onderkant die watertafel skyn 'n funksie van die fisiografiese geskiedenis van die betrokke gebied te wees. In Noord-Natal is sowat 78 persent van die lewering in beide sedimentêre en stollingsgesteentes tot 'n diepte van sowat 70 voet onder die watertafel aangetref terwyl net 22 persent op groter dieptes aangetref is. In die Laeveld is 85 persent van die lewering op dieptes vlakker as 40 voet onderkant die watertafel aangetref. In die Distrik Piet Retief is die graniet, waarskynlik as gevolg van sy vroeëre fisiografiese geskiedenis, tot dieptes van 200 tot 250 voet verweer en boorgate lewer gevolglik tot daardie dieptes onderkant die watertafel nog water.

In sedimentêre gesteentes is verwering op diepte meestal beperk tot die oopmaak en vergroting van bestaande nate, maar in stollingsgesteentes word verweringskommé gevorm waarin sowat 80 persent van die water gekry is.

Naatvorming en verwering gaan gepaard met 'n aansienlike toename in die poreusheid van die rotse. Die spesifieke lewering en deurlatendheid van die rotse bereik 'n maksimum in die beginstadiums waarna dit weer geleidelik afneem in die meer gevorderde stadiums van verwering. Die gemiddelde spesifieke lewering van verweerde basalt soos bereken vir 'n aantal verweringskomme, is 7·7 persent.

Oor die algemeen skyn daar geen lineêre verwantskap te wees tussen reënval en die lewerings en persentasie suksesvolle boorgate wat in 'n sekere formasie geboor kan word nie. 'n Hoër reënval het egter groot invloed op faktore soos aanvulling, diepte van watertafel en die voorkoms van fonteine.

WATERVLAKSTUDIES

Meeste gesteentes in die gebied is inherent ondeurlatend en daar kan dus streng gesproke nie 'n aaneenlopende watertafel in die gesteentes voorkom nie. Die watertafel in hierdie gesteentes is beperk tot nate en deurlatende verweerde sones.

'n Aantal waarnemings, o.a. die omstandigheid dat die watervlak in boorgate skommel as gevolg van getyeffekte en veranderings in atmosferiese druk, suggereer dat die water onder inperkingstoestande voorkom. Die watervlak wat in boorgate gemeet word, is dus streng gesproke 'n druk- of piesometriese oppervlak en nie noodwendig die watertafel nie. Bewyse is egter gevind dat behalwe in uitsonderlike gevalle, die watervlak soos gemeet in boorgate tog ooreenstem met die watertafel in nabygeleë nate en deurlatende sones en dus vir meeste praktiese doeleindes as die watertafel beskou kan word.

Skommelings van die watervlak as gevolg van verskeie oorsake is met behulp van outomatiese watervlakregistreerders in boorgate waargeneem. Die interessantste hiervan is dié wat veroorsaak word deur getyeffekte, veranderings in atmosferiese druk en bewegende treine.

Skommelings wat veroorsaak word deur getyeffekte is in sowat 69 boorgate waargeneem. Die skommelings is grootste gedurende springtye, d.w.s. gedurende vol- en nuwemaan. Hulle gemiddelde grootte is sowat 0·075 voet en die grootste wat waargeneem is, het sowat 0·8 voet beloop.

Skommelings wat veroorsaak word deur veranderinge in atmosferiese druk is in 'n aantal boorgate waargeneem, maar kom veral in boorgate voor wat in verweringskomme in stollingsgesteentes geboor is.

Skommelings wat veroorsaak word deur bewegende treine is in 'n boorgat in die Distrik Vryheid waargeneem. Die betrokke boorgat is sowat 382 voet van die spoorlyn op die kant van 'n vlakhellende dolerietplaat geleë (kyk fig. 33). Skommelings tot so groot soos 0·05 voet is in die boorgat waargeneem elke keer as daar 'n trein met 'n gewig van meer as 400 ton oor die kant van die dolerietplaat beweeg het.

AANVULLINGSTUDIES

In die Karoosedimente vind meeste aanvulling langs nate plaas. Die watervlak in boorgate wat in of naby nate geleë is wat met die oppervlak verbind is, styg sonder veel vertaging na byna elke neerslag terwyl die styging in boorgate wat weg van nate geleë is baie vertraag en geleidelik is.

In Noord-Natal het aanvulling gereeld elke reënseisoen sedert 1952 plaasgevind. Die gemiddelde aanvulling in 'n ou myn naby Hlobane, Distrik Vryheid, het gedurende 1956 tot 1958 sowat 14·6 persent van die reënval beloop.

In dié gedeelte van die Laeveld wat deur lawa van die Serie Stormberg beslaan word, het daar sedert 1943 geen aanvulling plaasgevind nie ten spyte daarvan dat die reënval in sekere jare heelwat bo die gemiddelde was.

Die gemiddelde watervlak in boorgate het gedaal van 39 voet na 69 voet in 1957 en sowat 76·5 persent van die boorgate het opgedroog. Die vernaamste oorsake vir hierdie daling was transpirasie deur freatofiete en die pomp van boorgate. Gedurende September en Oktober 1957 het daar 350 mm reën binne 21 dae geval en grootskaalse aanvulling het plaasgevind. Die gemiddelde watervlak het gestyg na 38 voet en meeste boorgate wat opgedroog het, het weer water gelewer.

TEMPERATUUR VAN ONDERGRONDSE WATER

Die temperatuur van die water uit sowat 180 boorgate is gemeet. Dit varieer van 15·2° C op die Hoëveld tot 24·8° C in die Laeveld en Kusstreek en is gewoonlik baie na aan die gemiddelde somerlugtemperatuur van die verskillende streke.

Die temperatuur van die water van boorgate wat matig gepomp is, het konstant gebly. In gebiede waar groot hoeveelhede grondwater onttrek is, is daar veranderinge in die temperatuur van die water waargeneem nadat aanvulling plaasgevind het.

Geen direkte verband kon gevind word tussen die temperatuur van die water en die diepte waarop dit in die boorgate aangetref is nie. Water wat op dieptes van 50 voet en meer as 300 voet respektiewelik in boorgate van dieselfde omgewing aangetref is, het min of meer dieselfde temperatuur gehad. Die verklaring hiervoor is die feit dat alhoewel die water vanaf 'n groot diepte gepomp word, dit vanuit 'n baie vlakker diepte voorsien word en het dan gevolglik dieselfde temperatuur as die water uit vlak boorgate in dieselfde omgewing.

KWALITEIT VAN DIE WATER

Volgens die skeikundige ontledings is die grondwater in die gebied in die volgende vier groepe verdeel:—

GROEP A: *Sterk gemineraliseerde chloriedwater.*—Dié groep kom hoofsaaklik in die gesteentes van die Sisteem Kryt voor. Die water word gekenmerk deur 'n hoë chloriedinhoud, gewoonlik meer as 30 persent van die totale opgeloste soute. Die totale vastestowwe is meer as 3,500 dele per miljoen en die water is ongeskik vir gebruik deur mens of dier.

GROEP B: *Gemineraliseerde chloriedwater.*—Dié tipe water kom hoofsaaklik in die Laeveld voor. Die chloriedinhoud is ook meer as 30 persent van die totaal aan vastestowwe. Die totale vastestowwe wissel van 750 tot 2,500 dele per miljoen en die water is geskik vir diere maar nog veels te brak vir huishoudelike gebruik.

GROEP C: *Effens southoudende chloriedwater.*—Hierdie tipe water kom voor in die Tersiêre en Resente sand op die Kusvlakte, op die Lebomboberge en op die platorand wat die Middelveld van die Laeveld skei. Daar is baie min verskil in die persentasie-samestelling van hierdie groep en Groepe A en B. Die soute is dus ook van sikliese oorsprong. Die konsentrasie soute is egter laag, gewoonlik minder as 600 dele per miljoen en die water is hoogs geskik vir huishoudelike gebruik en ook vir besproeiing.

GROEP D: *Tydelike harde (karbonaat-) water.*—Hierdie water is tot die binneland beperk. Die totaal aan vastestowwe is selde minder as 150 dele per miljoen met 'n gemiddelde van 276 dele per miljoen. Die permanente hardheid, asook die chloriedinhoud, is laag.

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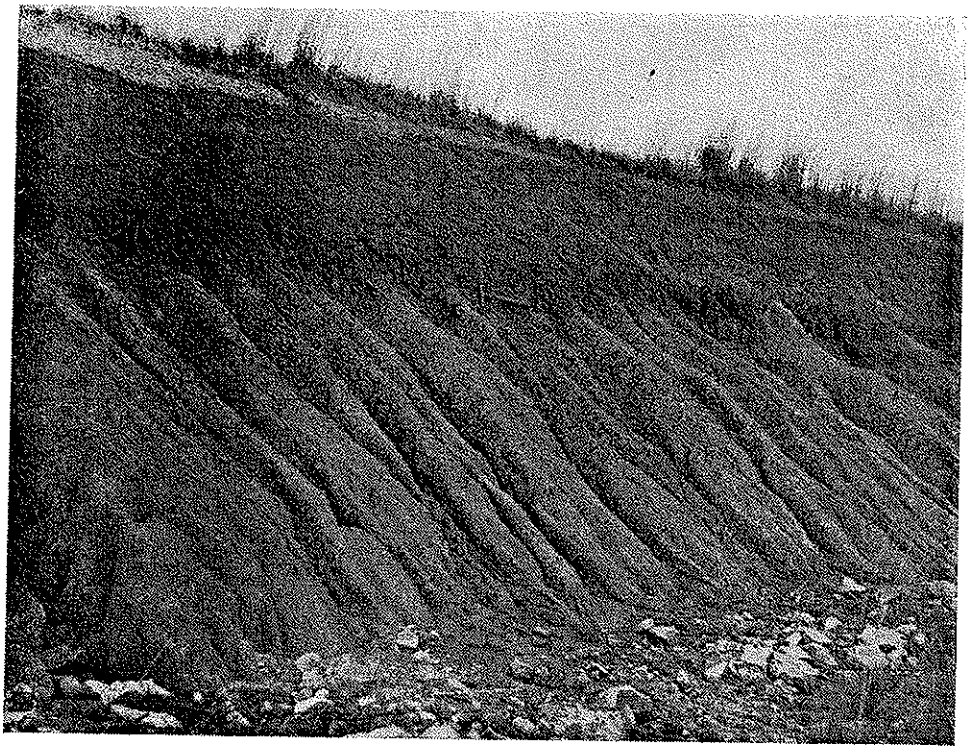


Plate I.—" Fossil subsoil " over Middle Ecca sandstone. Cotswold, Dundee District.

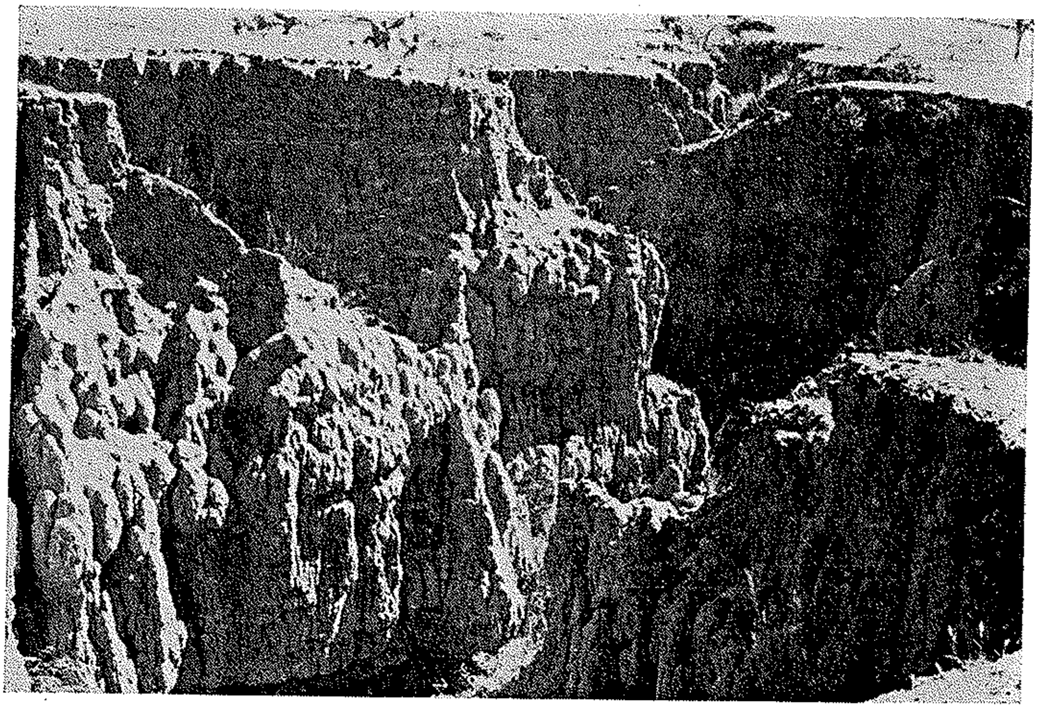


Plate II.—Typical donga-like soil erosion in " fossil subsoil ". Vaalbank 450, Vryheid District.

PLATE III.—Near-surface horizontal jointing in dolerite due to the effects of unloading. Langverwacht, Ngotshe District.

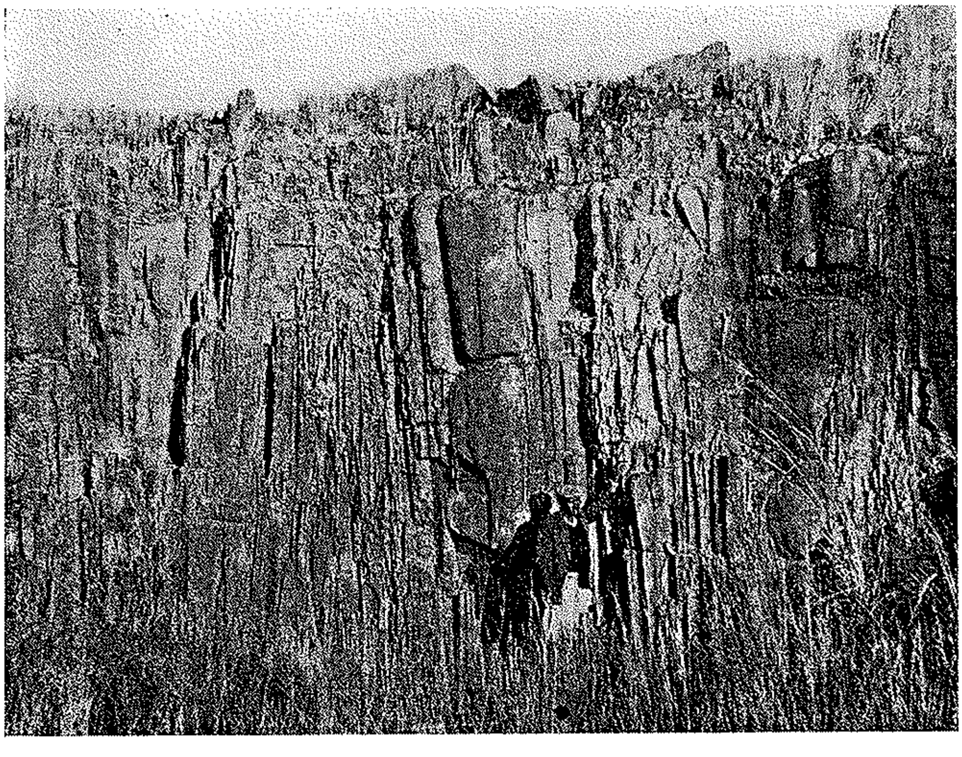


PLATE IV.—Columnar jointing in dolerite. Langverwacht, Ngotshe District.

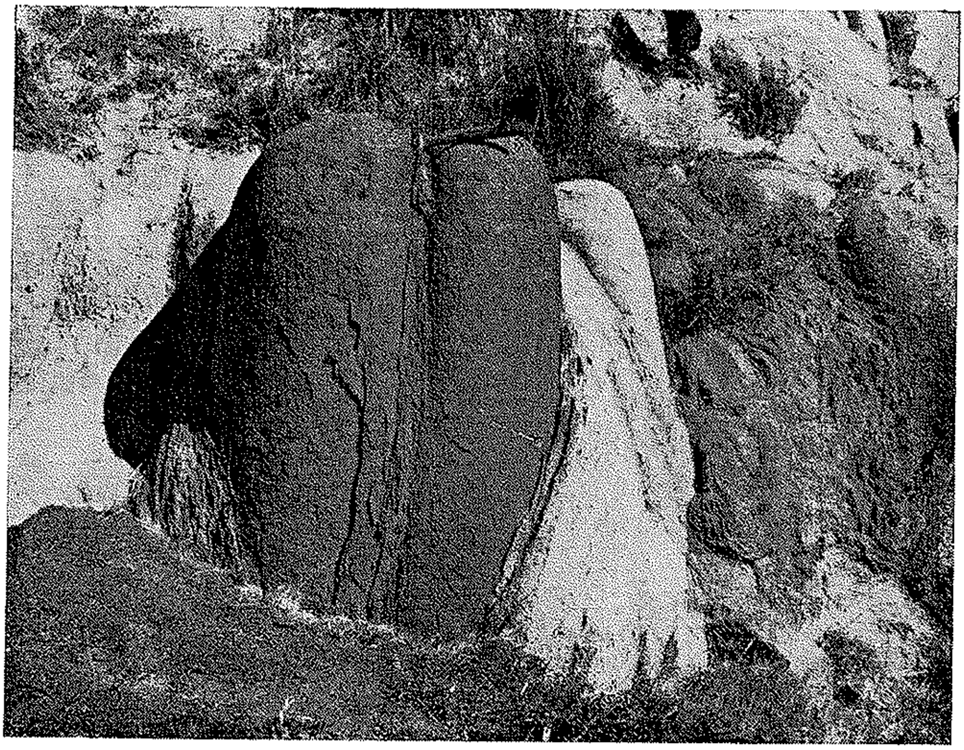


PLATE V.—Spheroidal weathering in dolerite. Bergvliet, Estcourt District. Note weathering along fracture cutting through boulder in foreground.

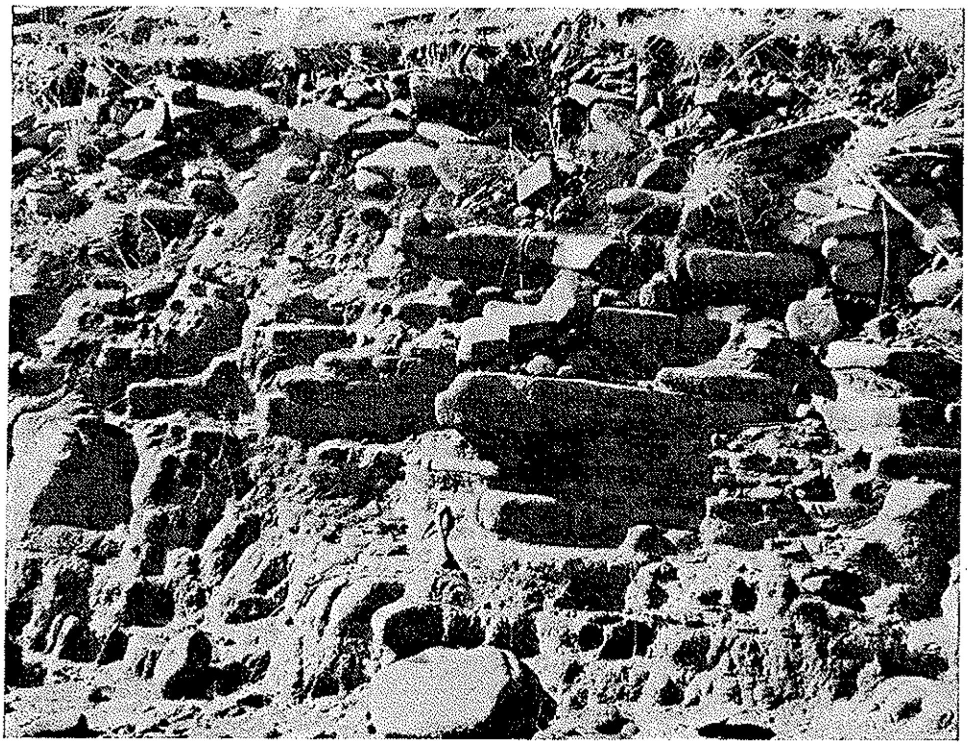


PLATE VI.—Weathering in stratified dolerite. Express, Vryheid District. Note the horizontal position of the boulders, due to weathering along the bedding-planes, as compared with the boulders in plate V.

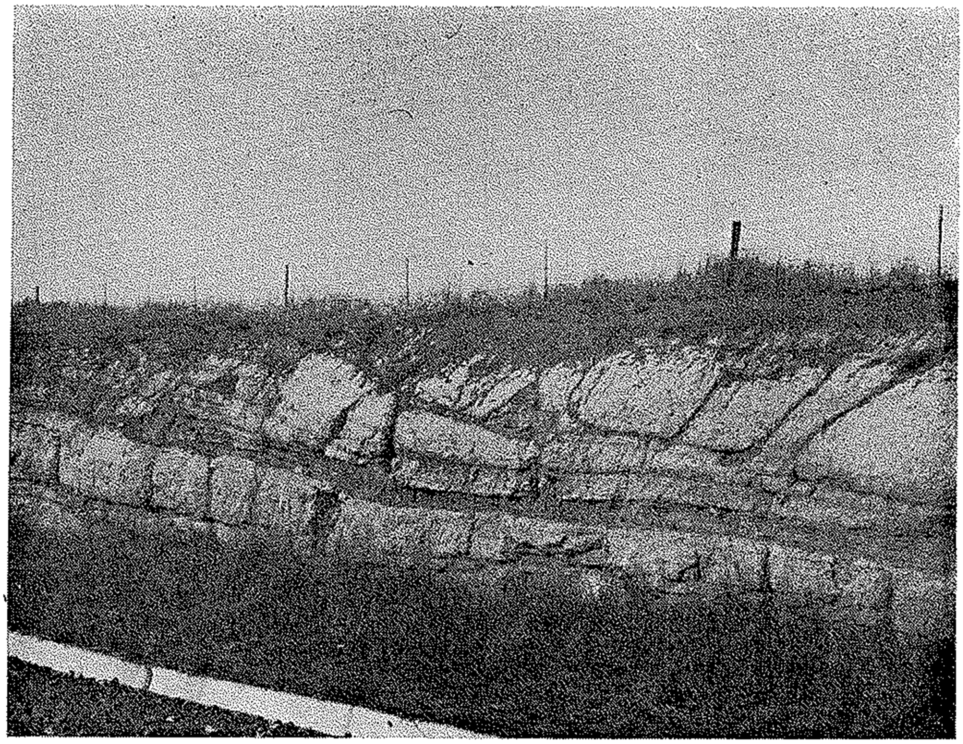


Plate VII.—Weathering in sandstone. Note the pronounced weathering along the bedding-planes and joints, while the rest of the sandstone is virtually fresh. Road cutting, Dundee District.

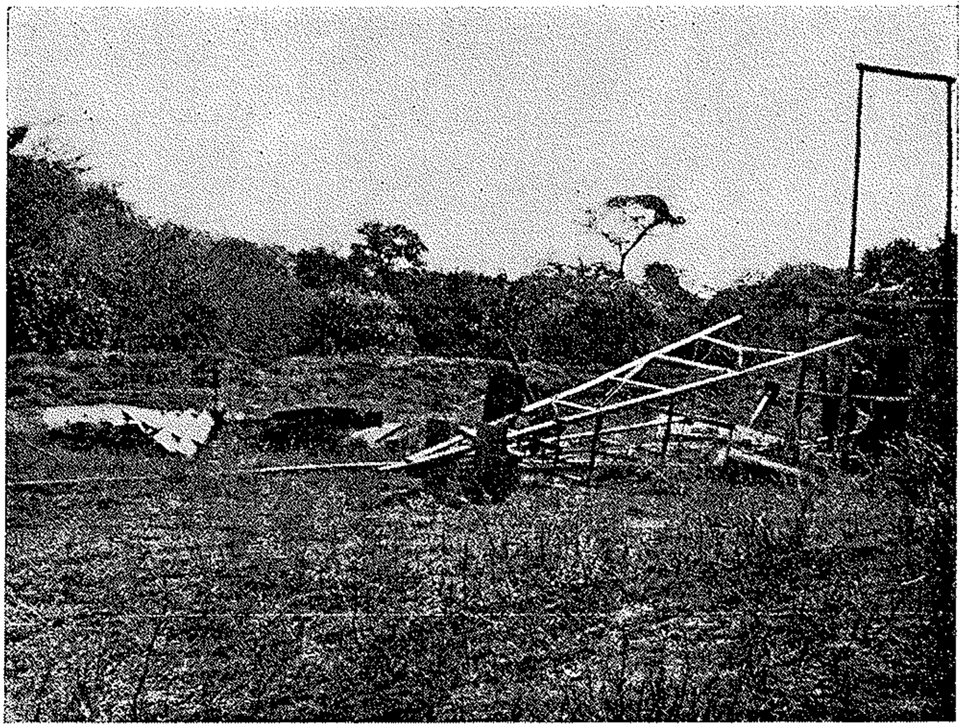


Plate VIII.—A common scene in the Lowveld during 1956—a dismantled windmill after bore-hole had dried up.

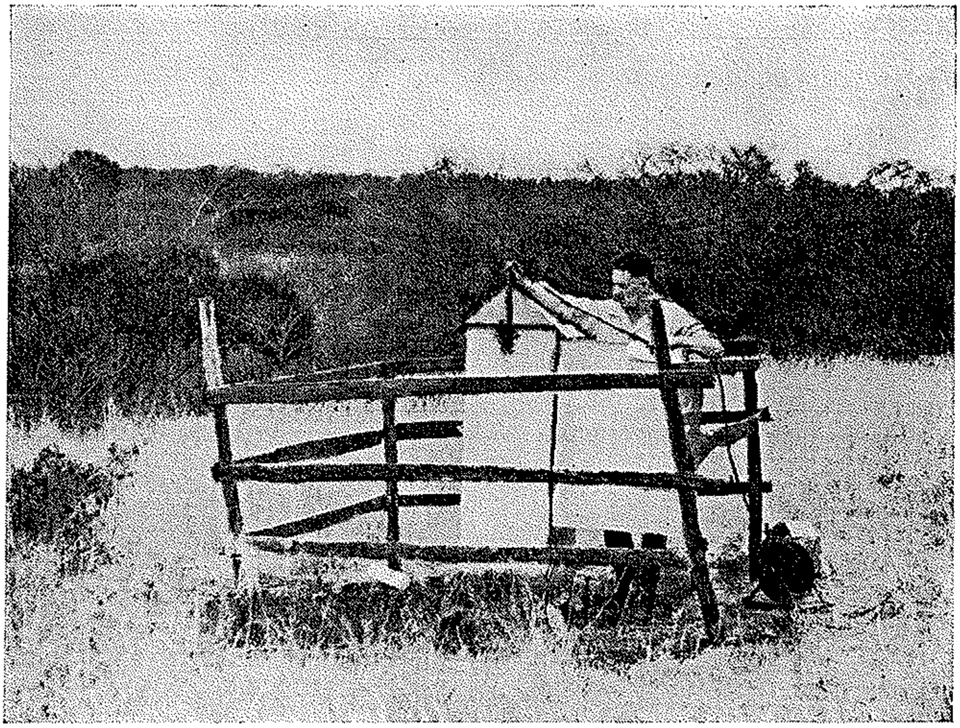


PLATE IX.—Fishing roots from a bore-hole equipped with an automatic water-stage recorder on Broxburn, Ubombo District.

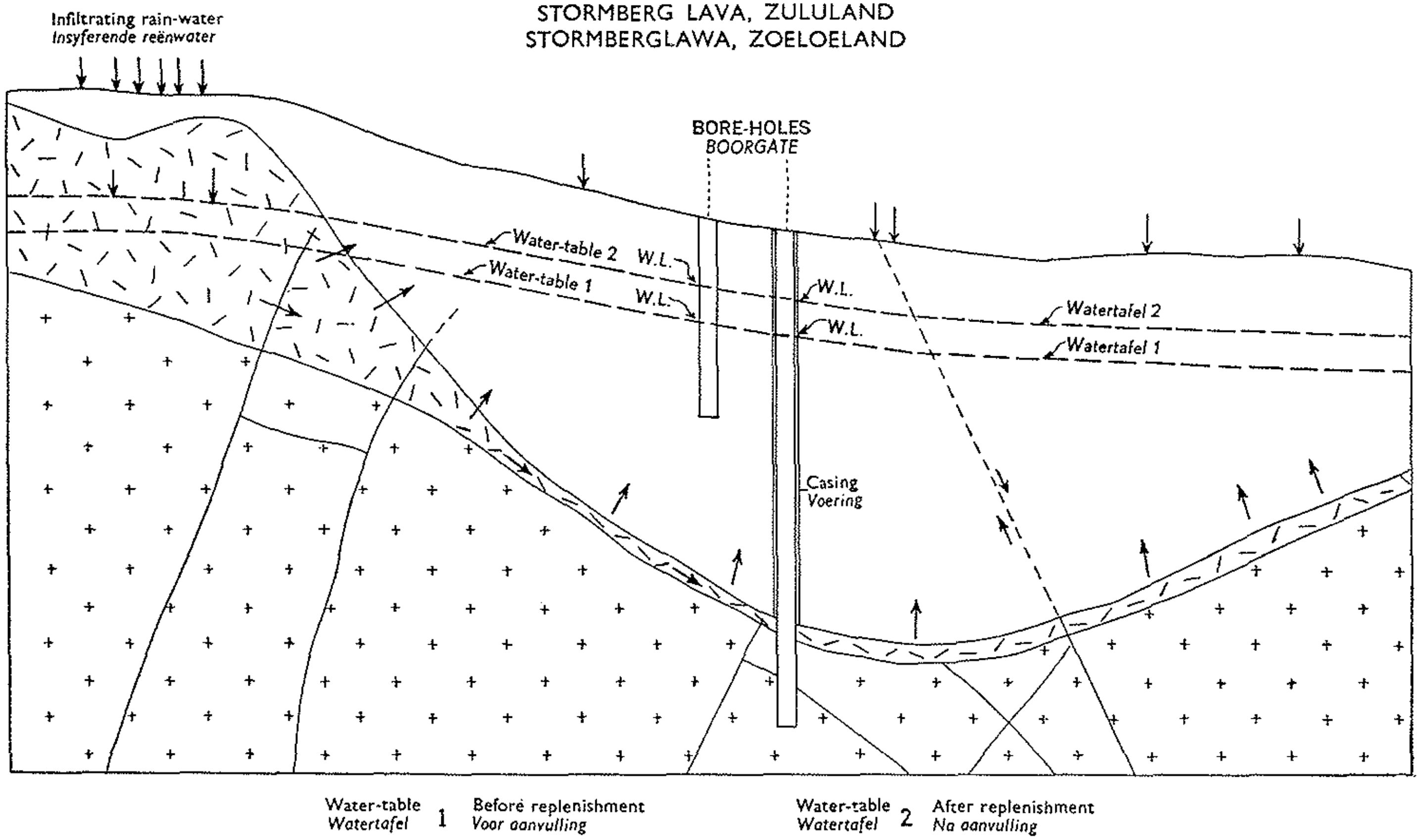
PLATE X.—A deformed *Ficus sycamorus* in Native Reserve No. 3, Lower Umfolozi District.

INDEX

THE FLOW OF WATER INTO THE CONFINING BEDS AND THE ADJUSTED WATER-TABLE AFTER REPLENISHMENT

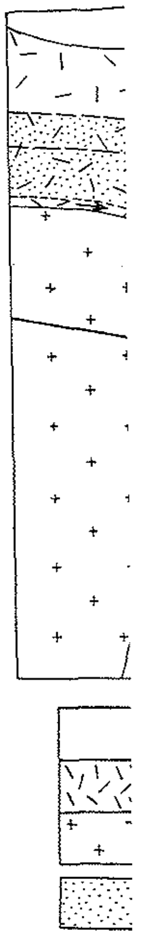
DIE VLOEI VAN WATER NA DIE INPERKINGSLAE EN DIE AANGEPASTE WATERTAFEL NA AANVULLING

STORMBERG LAVA, ZULULAND
STORMBERGLAWA, ZOELOELAND



Water-table / Watertafel 1 Before replenishment / Voor aanvulling

Water-table / Watertafel 2 After replenishment / Na aanvulling



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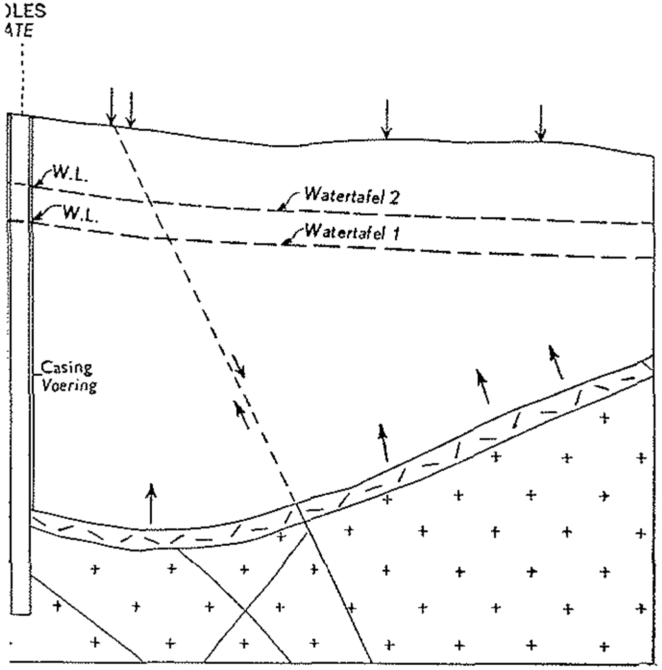
FOLDER
VOUBLAD 2

E ADJUSTED WATER-TABLE AFTER REPLENISHMENT
E AANGEPASTE WATERTAFEL NA AANVULLING

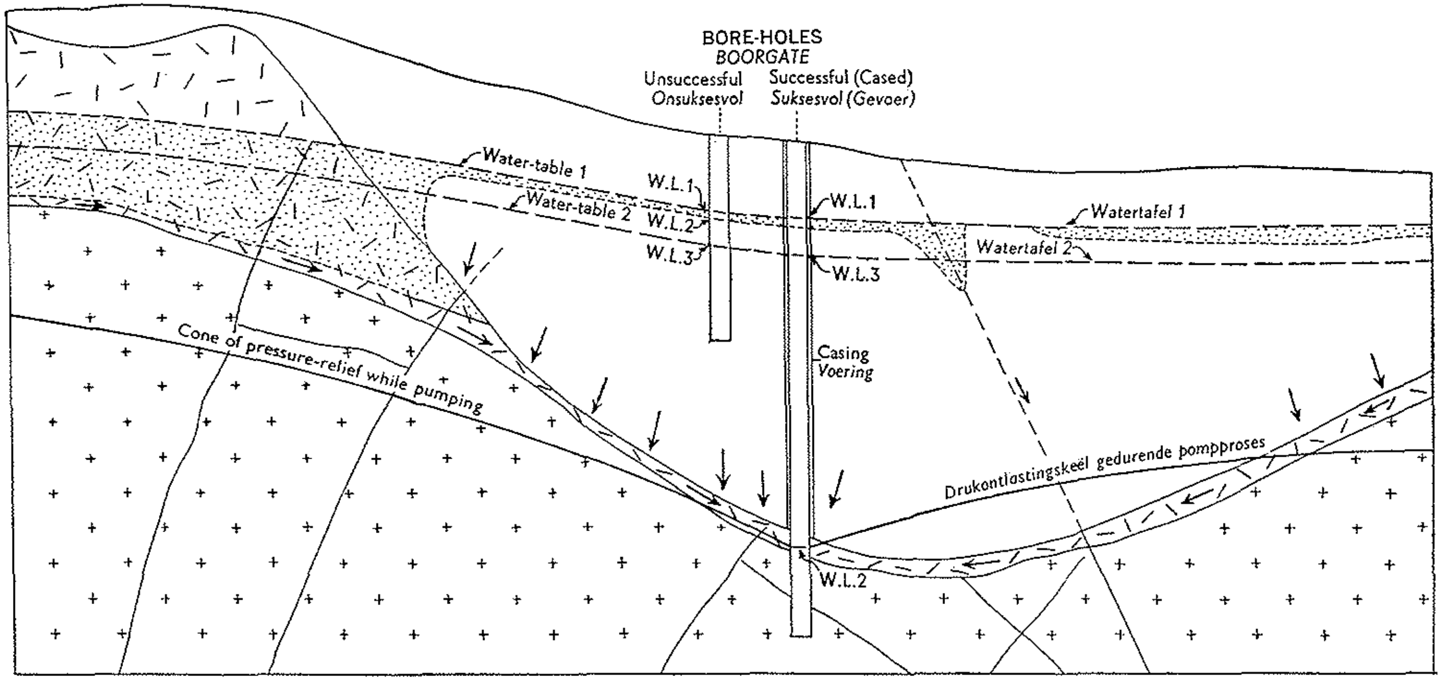
ZULULAND
OELOELAND



Water-table 2 After replenishment
Watertafel 2 *Na aanvulling*

THE FLOW OF WATER FROM CONFINING BEDS INTO THE AQUIFER DURING PUMPING
DIE VLOEI VAN WATER UIT DIE INPERKINGSLAE NA DIE WATERDRAER GEDURENDE 'N POMPPROSES

STORMBERG LAVA, ZULULAND
STORMBERGLAWA, ZOELOELAND



- ☐ Slightly permeable weathered rock (confining beds) / *Effens deurlatende verweerde rots (insluitende laag)*
- ▨ Highly permeable fractured rock (aquifer) / *Hoogs deurlatende gebreekte rots (waterdraer)*
- + Fresh rock / *Vars rots*
- ░ Material dewatered during pumping / *Materiaal ontwater gedurende pompproses*

- - - - Fissure / *Spleet*
- → Flow of water / *Vloei van water*

Water-table 1 Water-table before pumping
Watertafel 1 *Watertafel voor pompproses*

Water-table 2 Water-table after pumping
Watertafel 2 *Watertafel na pompproses*

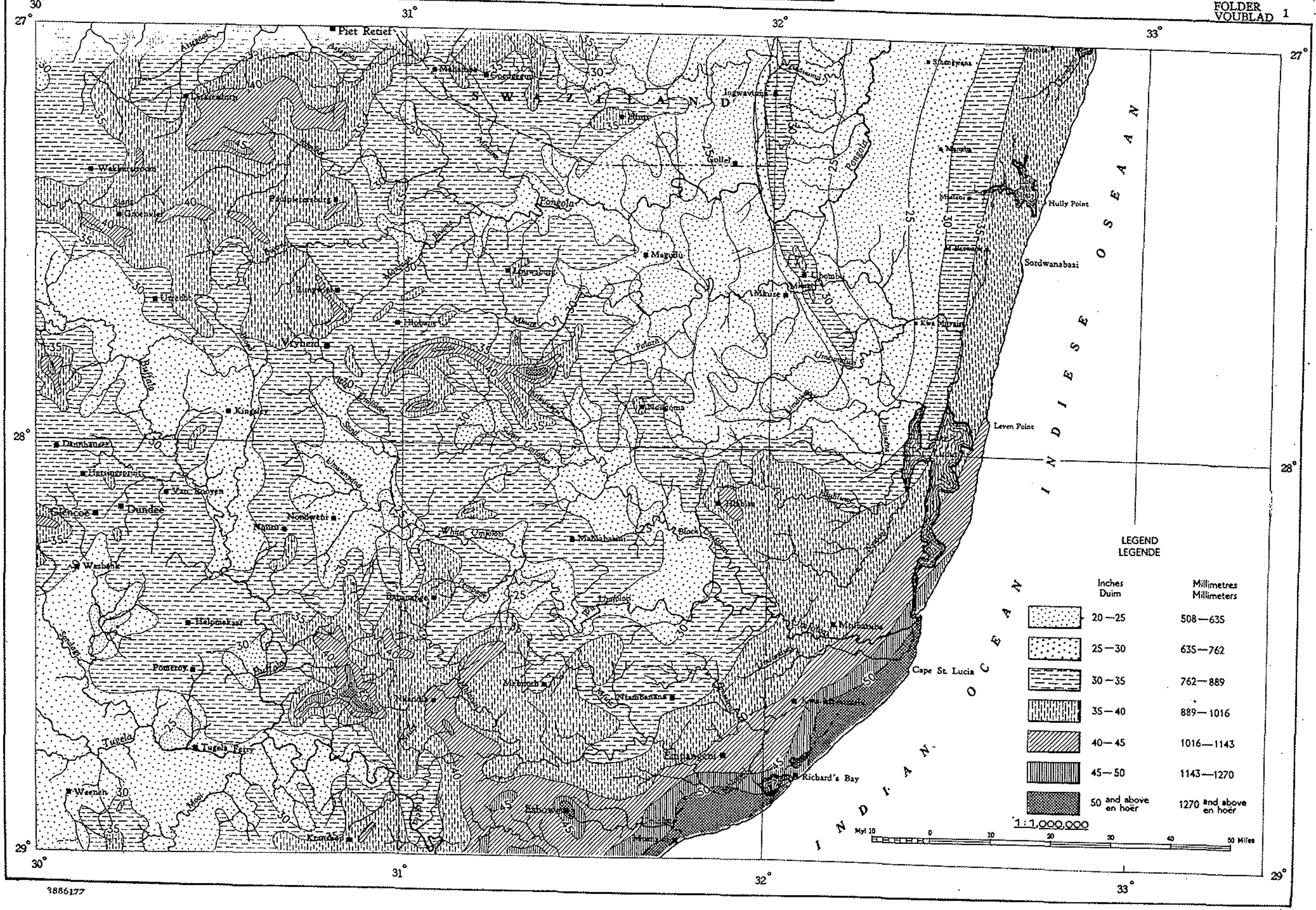
W.L.1 Water-level in bore-holes before pumping
Watervlak in boorgate voor pompproses

W.L.2 Water-level in bore-holes during pumping
Watervlak in boorgate gedurende pompproses

W.L.3 Water-level in bore-holes after pumping
Watervlak in boorgate na pompproses

RAINFALL MAP REËNVALKAART

FOLDER
VOUBLAD 1



	Inches Duim	Millimetres Millimeters
▨	20—25	508—635
▨	25—30	635—762
▨	30—35	762—889
▨	35—40	889—1016
▨	40—45	1016—1143
▨	45—50	1143—1270
▨	50 and above en hoër	1270 and above en hoër

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