TANGANYIKA

UNDERGROUND WATER IN TANGANYIKA

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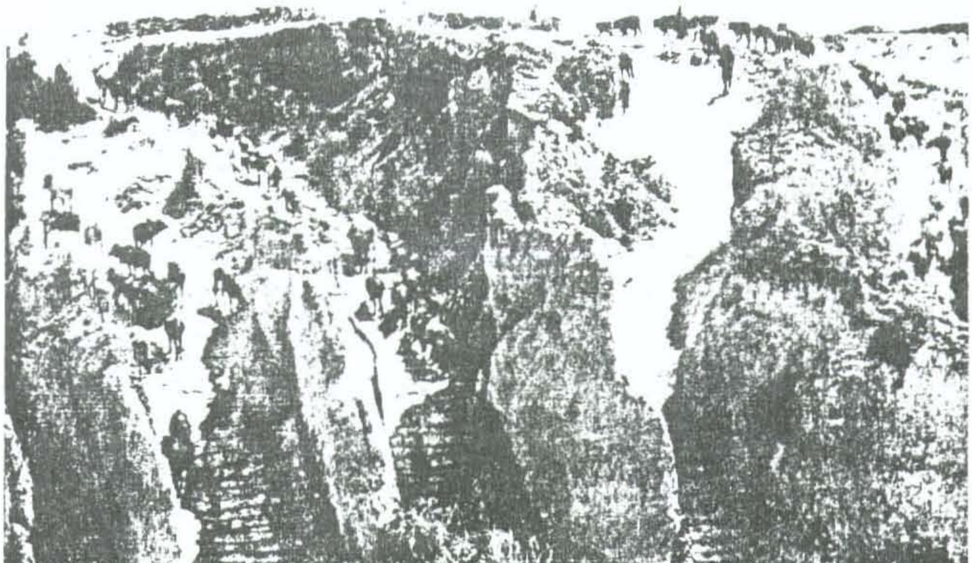

Engasumet Wells *Photo. F. M. Coster*

FOREWORD

Mr. Coster first came to Tanganyika in 1927, where, except for short breaks while working in neighbouring Territories and one year in Canada, he spent his working life before retiring in 1958. For the last twenty years he was employed by the Tanganyika Government as an Engineering Geologist.

It was recognized by Government that Mr. Coster's knowledge of the underground waters of Tanganyika was unique and should be recorded in permanent form for the benefit of all those interested in the Territory's water supplies. He was accordingly asked as his last official task before retirement to place on record the wealth of his unrivalled knowledge and experience in a form suitable for publication.

This book is the result. It is an important contribution which will be of the greatest value to those concerned, both now and in the future, with the development of Tanganyika's water resources.

A. E. TROTMAN,
Minister for Natural Resources,
Dar es Salaam

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TANGANYIKA

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CHAPTER ONE

INTRODUCTION

Tanganyika occupies some 341,000 square miles of land area, and with its rapidly increasing population and consequent expansion of agriculture and livestock husbandry, commerce and industry, the demand for more and better water supplies has become increasingly urgent. To meet such a demand and to plan for future expansion a general reassessment of all water resources, including underground water, is required.

The aim of this work is to give an outline of the present knowledge of the occurrence and distribution of underground water in relationship to the hydrology and geology of the territory, and to summarise the writer's experience gained during nearly eighteen years of work in charge of underground water development as Engineering Geologist to the Tanganyika Government. The quality and the quantity of the water obtained so far in all known boring operations and from other groundwater sources and the methods at present used by the Water Development and Irrigation Department in the search for water are also surveyed and evaluated. The facts presented are based on the results of the investigations, surveys and successes and failures in the field to find and develop underground water. These results have mainly been achieved by the various Government departments, individual officers, private persons, companies and corporations concerned with the development of water supplies.

It is not possible to enumerate or mention in the text, or here, even by name, all the individuals who, in one way or another, have contributed to the accumulated knowledge of underground water in Tanganyika, and therefore only those who have made outstanding contribution are named below.

The former Directors of the Tanganyika Geological Survey, Sir E. O. Teale, G. M. Stockley and C. Bissett; the former Chief Geologists, F. B. Wade, the founder of the Water Boring Section, and D. R. Grantham; the late C. Gillman, the well-known Geographer and Engineer and at one time Water Consultant to the Government of Tanganyika; A. Cawley, Director of Geological Survey, Uganda, formerly Engineering Geologist of the Water Boring Section, Tanganyika, and D. Orr, formerly Geologist, Geological Survey, Tanganyika. Of the German geologists working in Tanganyika before the 1914-1918 War, Koert and Tornau should be named.

Much valuable information has also been collected by the geologists, surveyors and Laboratory staff, past and present, of the Geological Survey and by the geologists and engineers of the Water Development and Irrigation Department, particularly H. Liddle, K. Klimacki and M. T. Avery.

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The Government Chemist, W. E. Calton and staff.

The Secretary of the Sisal Grower's Association, A. L. Le Maitre.

The following officers of the Geological Survey have frequently given advice on technical matters; D. A. Harkin, Deputy Director; H. G. Burks, Chief Research Officer; A. W. Aitken, Paleontologist; J. R. Harpum, Petrologist; T. C. James, Geologist; J. S. Dunbar, Chief Draughtsman and H. W. Hale, Records Officer.

CHAPTER TWO

HYDROLOGICAL CONCEPTS

The occurrence and distribution of underground water cannot be readily understood unless the fundamental processes by which water reaches the soils, rocks and other deposits in which it is generally found are briefly explained. Such an explanation is attempted in this chapter.

Water is classified by geologists as a mineral and, as such, it is in an exceptional position in so far as it is renewable while all other minerals are wasting assets.

Underground water, as found in geological deposits and rocks in Tanganyika, is derived from two main sources, and is classified according to its source:

(a) Groundwater or Meteoric Water.

(b) Juvenile Water or Magmatic Water.

Groundwater is by far the more important of these two, and the majority of the facts dealt with in this work refer to groundwater.

(a) GROUNDWATER

The general process of water circulation, including groundwater renewal or recharge, is often referred to as the hydrological cycle. This cycle is divided into a number of stages, one of which is the groundwater stage.

For the present purpose GROUNDWATER IS DEFINED AS WATER DERIVED FROM PERCOLATION, irrespective of the depth at which it may be encountered. Under this definition the perennial flow or base flow of rivers, streams and seepages would be groundwater, but the scope of this work is limited and does not permit the inclusion of this category of groundwater. The hydrological cycle encompasses the whole process of water circulation from the evaporation of water from the oceans, condensing to form clouds from which water in the form of snow, rain, hail or mist may be precipitated, until its return to the sea by many and varied routes. The groundwater phase is only one integral part of this larger cycle and can be regarded as starting at the stage when precipitation reaches vegetation or the ground and continues until the water again issues on the ground surface or finally reaches the sea.

This process of renewal or recharge which takes place during the groundwater cycle can be expressed by the simple equation:

$$Precipitation = Run\text{-}off + Evapotranspiration + Recharge.$$

Evapotranspiration and recharge, which both depend on percolation of precipitation into the ground, and its delivery to the groundwater zone, are treated under the sub-heading, (iii) Percolation.

(i) *Precipitation.*—The annual amount and distribution of precipitation in the form of rain is the only factor in the equation which is reasonably well investigated in the territory. Intensity of rainfall is, however, little known, and long period records from intensity gauges are probably available from only a few localities. Records of snow, mist and dew appear to be lacking at present.

There are two main distribution belts of rainfall in the territory; the Northern, similar to the Kenya rainfall, with the so-called "short rains" in November-December and the "long rains" from March to May, and the Southern belt, where the rain starts in November-December and ends in April-May, similar to the Northern Rhodesian rainfall. Between these two zones is an intermediate belt, covering most of the Central Province, in which a break in the rains occurs, varying in duration from a fortnight to over three weeks. This break may fall at any time between early January and mid March. The break is often disastrous from an agricultural point of view. Large variations in rainfall distribution and total rainfall over the years are common. Many localities, such as Bukoba District west of Lake Victoria, and Rungwe District north of Lake Nyasa, have local rainfall conditions. The lowest rainfall areas, 10 inches to 20 inches, are situated in the centre of the territory. Precipitation increases towards the coast and inland towards the three great lakes. The highest annual precipitations are recorded from the northern end of Lake Nyasa in Rungwe District, with over 100 inches a year, and over the southern part of Lake Victoria with a similar amount. Many high ranges, amongst them the eastern parts of the Uluguru and Usambara mountains, also show rainfalls up to 100 inches a year or perhaps more.

Twenty-four-hourly maximums are kept by the Meteorological Department. Eight-inch falls are rare but occur in many districts. Seventeen inches fell within twenty-four hours in April, 1955, over a limited area in Rungwe District, causing landslides, washaways and loss of human life.(1) An intensity gauge record of 6 inches in just under three hours was obtained in 1935 in Dodoma in the Central Province. For reliability maps of rainfall see the Royal Commission's Report on East Africa, 1953-1955.

(ii) *Run-off.*—The terms run-off, direct run-off or surface run-off and overland run-off are here used exclusively for the part of the rain which flows on the surface of the ground, i.e. does not infiltrate. Very little is known about direct run-off in the territory. The main streams and river systems that have been gauged give the combined total of groundwater flow and run-off and thus these figures cannot be applied to direct run-off, as defined above. Some run-off statistics have been obtained by the Geological Survey Department, Dodoma, the Veterinary Department at Mpwapwa and the Water Development and Irrigation Department. Most of the figures come from the dry Central Province, but were obtained under varying conditions. Dodoma run-off figures were collected during the years 1930 to 1939(2) from the catchment of the "old" dam, approximately one square mile in extent. The catchment contains bare granite rocks, sandy soils and badly eroded loamy soils covered by low bush vegetation and the grade of the slopes is approximately 4 per cent. The highest annual run-off was 7·7 per cent, the lowest 4·45 per cent. The average rainfall for nine years was 20·19 inches. The average effective rainfalls, i.e. rainfall which produces a run-off, was 14·61 inches and the average run-off for nine years 5·3 per cent. Run-off for individual showers was also recorded from February, 1935, to January, 1936, (a complete rainfall year). The highest run-off recorded was just over 20 per cent for a 2·5 inches storm of an intensity of 0·30 mm. per minute. Short sharp showers of 0·79 inches gave only 1·86 per cent run-off and showers of 1 inch an hour intensity are known to have produced no run-off at all.

Mpwapwa: Run-off experiments were carried out by R. Staples(3), formerly Pasture Research Officer, Veterinary Department, during the years 1933 to 1937. The experiments were made on field plots of 6 ft. by 90¾ ft., 1/80th of an acre with the longest side of the plot down a slope of 6·6 per cent. Water was collected in tanks of from 300 to 600 gallon capacity. The results showed that seasonal run-off rates for a 26 inch rainfall were as high as 50 per cent on bare, hard uncultivated ground. On cultivated soils they reached 30 per cent but under East African grass cover the run-off dropped to 2·8 per cent and below.

Run-off figures collected during the rainfall season 1956-1957 (total 26 inches), from a recently constructed dam at Ikowa, between Dodoma and Mpwapwa, with a catchment of 180 square miles showed the low run-off figure of 1·35 per cent.(4) Scanty as these run-off figures are, and obtained from a relatively small semi-arid area, it is considered that they give some indication as to the actual process and order of run-off rates. The Mpwapwa experiments indicate what takes place on small plots under varying conditions of cover, and the Dodoma and Ikowa figures show what occurs in large areas, both with bush cover and, in the case of Ikowa *mbuga*, cultivated ground and over-grazed pasture and hills.

(1)HALDEMANN, E. G. 1956. *Tanganyika Notes and Records*, No. 45.
COSTER, F. M. 1955. Unpublished preliminary report.

(2)Annu. Rep. geol. Surv. Tanganyika, 1930-1939.

(3)STAPLES, R. 1933-1938. Annu. Rep. Dept. Vet. Scien. and Animal Husbandry.

(4)MACWILLIAM, R., Water Development and Irrigation Dept. Verbal communication.

The main regulator of run-off is the rainfall intensity, and as there are very few intensity gauges in operation, this vital information is not generally available. The second most important factor is vegetation, which varies according to the season. High run-off rates occur mainly before the grass cover has been re-established by the precipitation, and run-off rates, therefore, in general, decrease as the wet season progresses. Slope and soils exercise contributory influence on run-off, largely as a function of rainfall intensity.

(iii) *Percolation.*—Hydrologists recognise three main divisions in the process of groundwater recharge by the precipitation percolation into the ground. Part of this process is little known in its details and requires further investigation and research. The three main divisions are, from the surface downwards:

BELT OF SOIL WATER.

INTERMEDIATE BELT.

ZONE OF SATURATION OR GROUNDWATER ZONE.

Between the two latter there is a sub-belt called the *capillary fringe*. The two first-named belts and the capillary fringe are often grouped together under the *zone of aeration*. Briefly, the type of water movements which take place in the zones can be summarised as follows.

In the soil water belt infiltration and evapotranspiration occur. In the intermediate belt water moves downwards mainly under the force of gravity. In the capillary fringe water moves mainly towards the surface under the influence of capillary forces, due to surface tension, which is opposed to the force of gravity. In the zone of saturation water movements are governed by hydrostatic pressure.

BELT OF SOIL WATER.

Infiltration. The uppermost part of the belt of soil water, the top soil itself and a small part of the subsoil collect and store the precipitation. Soils in general have a large water storage capacity. An average 6 ft. soil profile at Kongwa in the Central Province will store about 22 surface inches of water before becoming saturated.(1) The top soil at Kongwa can probably absorb about one-third of its volume, soils in other areas probably up to 40 per cent or more.

The rate of infiltration is, however, an important factor and varies with the type of soil. Sandy soils absorb water at a far quicker rate than clayey soils. On the other hand, the total storage capacity of a clayey soil may be much higher than that of the sandy one. Investigations into the process of infiltration which have been carried out recently in Europe with the help of certain dyes, show that the soil sections into which water infiltrates are very unevenly distributed. Root, ant and animal holes, as well as size of pore space, all contribute to the random way in which water infiltrates. The total amount of infiltration during a rainfall season, other factors being equal, depends on the intensity of the rainfall and is directly complementary to run-off. Infiltration is also largely dependent on whether the rain water remains clear or contains matter in suspension or in colloidal form. High intensity of rainfall and "dirty" water from cultivated and bare soils slows down infiltration rates. See under Run-off, field plots. When water has infiltrated, part of it is permanently retained and held round the mineral grains of the soil; the holding force may be large but is at any rate higher than the force of gravity. How much is retained depends on the type of soil and soil profile itself. It is estimated that in a Kongwa soil about 7 surface inches of water can be added or accumulated from one rainy season to the next by keeping a clean fallow for one rainy season and a dry season. The depth of the soil profile holding the 7 ins. of water would probably be approximately 6 ft(1).

(1)BROZTOVSKI, Kongwa Research Station. Verbal communication.

Water which is not being retained in the upper soil profile moves downwards into the ground and eventually reaches the zone of saturation and becomes groundwater. The roots of the vegetation, however, take a heavy toll of both the water which has been absorbed and held by the soil, and the part that moves downwards until the latter water has penetrated beyond root level. There is, in addition, in the rainy season and the early dry season also a considerable evaporation from the soil surface. These two water losses are often combined into one term called Evapotranspiration or ET.

Evapotranspiration. As stated above, ET. equals the combined water losses caused by the evaporation from the soil surface and the transpiration from the vegetation until the wilting point is reached. It presumably also includes the amount of water which is necessary to build up all the new leaf and greenery of the vegetation. Water losses caused by Evapotranspiration constitute the major factor governing groundwater replenishment and recharge from the moment the precipitation has reached the ground. The magnitude of ET. can perhaps best be judged by quoting the estimated figures for the U.S.A. which are given as 21½ ins. per year or 72 per cent of the total rainfall.(1) Great difficulties have been encountered in the scientific determination of the ET. rates or factor and a vast amount of literature exists on the subject. The most helpful approach appears to be to determine what is known as the potential Evapotranspiration, the PE. The PE. is the maximum amount of water lost under natural climatic conditions when water in surplus is available to the root system of the plants. This subject has been treated in detail by Thornthwaites in a most interesting and, in many ways, revolutionary paper.(2) According to this paper the PE. factor reaches a relative maximum at a temperature of approximately 26·5°C. when the PE becomes 13·5 cm. a month and this maximum appears to be biologically controlled by the whole process of assimilation. As far as large parts of Tanganyika are concerned it is clear that the ET. rates must fall well below the PE. rates, in other words, the vegetation could consume far larger quantities of water were it available. This leads to the conclusion that for certain types of vegetation in Tanganyika the plant association and the species thereof indicate the minimum ET. under which such associations can exist. There are in Tanganyika two types of vegetation in the drier areas which are of interest in this respect. The first (No. 1) is a deciduous and semi-deciduous and occasionally evergreen thorn or scrub vegetation which covers large areas of Masailand, the Central Province, the Wembere Depression and the Ruaha Basin. In these areas the average precipitation is less than 20 ins. and fluctuates between 8 ins. and perhaps 30 ins.

The second (No. 2) is the Brachystegia open woodland which is deciduous and covers a large tract of country in the Southern Province and from the Central Province westward to Northern Rhodesia and Angola. The average rainfall in this type of woodland varies in Tanganyika between 30 ins. and 40 ins.

It should be mentioned that some of the deciduous vegetation of the type mentioned above, particularly of the Brachystegia species, show that the wilting point is not dependent on the amount of water available in the ground. The power of the root system to extract water from the soil varies as the dry season progresses. Soon after the rains cease most of the vegetation dries up and loses its foliage. The soil, at this period of the season, must still contain appreciable quantities of water available to the roots. The vegetation, in general, remains leafless until just before the rains when many trees come out in new green leaf. These trees must, therefore, be capable of extracting the last residue of water from the parched soils. The exact scientific explanation of this phenomenon is not known to the writer, but the overall effect on the recharge of groundwater must be appreciable, adding as it does perhaps several weeks of water depletion of the soils by transpiration.

As regards type No. 1 it is considered that about 12 ins. to 15 ins. a year is available for ET. and that the vegetation reflects this type of moisture condition.

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(1) THOMAS, HAROLD E. 1951. The Conservation of Groundwater. MACGRAW HILL. p. 21.

(2) THORNTHWAITE, C. W. 1948. Geogr. Review. June. An approach towards a rational classification of climate. pp. 54-94.

For type No. 2, the Brachystegia woodland, the ET. figure lies somewhere near 25 ins. a year. This type of woodland does not thrive in areas with less than 20 ins. a year rainfall under temperature conditions prevailing in the territory. In Tanganyika an investigation(1) was made regarding percolation and moisture conditions which has a distinct bearing on the ET. rates. Soil moisture conditions were investigated all through the year by auger holes to a depth of 24 ft. in the three types of vegetation; deciduous thicket and grassland, altitude 3,500 ft. and evergreen forest woodland and grassland at 5,800 ft. The annual rainfall for the lower altitude was approximately 776 mm. and for the higher, 939 mm.

The deciduous thicket showed little or no moisture at any time beyond 4 ft. depth, i.e. no percolation, but the root system is stated to reach 15 ft depth and some moisture must, therefore, reach to this level. Natural grassland at the same height showed moisture to 12 ft. and a root system to about 10 ft. There was moisture depletion during the dry period to 12 ft. The evergreen forest at 5,800 ft. altitude, showed no moisture below 14 ft. at any time, the roots penetrating to about 18 ft. There were periods of complete moisture depletion to the full depth of the holes, 24 ft.

In mountain grassland (indigenous vegetation) it would appear that the soil below 9 ft. remains permanently moist. Above this level the soil dries out considerably during the dry season, when little moisture is available for grass growth.

The woodland (Brachystegia Spiciformis and Dombeya Mupangae) showed moisture to 24 ft. depth at all times, with depletion zones during the dry season to approximately 14 ft., which is also the depth of the root system.

The results obtained from the deciduous thicket are borne out by drilling in similar areas, boreholes having been unsuccessful, but the result in the evergreen forest, where no moisture appears to have penetrated below 14 ft., does not agree with the fact that many perennial streams start in the evergreen forest. The failure to find moisture can, however, easily be accounted for by the very uneven distribution of surface infiltration.

The Intermediate Belt. The intermediate belt is encountered from below the general depth to which the roots of vegetation penetrate to the upper surface of the next lower belt, the capillary fringe, with which the intermediate belt integrates and co-exists. In high water-table areas the capillary fringe and the belt of soil water meet and the intermediate belt disappears. Water movements in the intermediate belt are, in general, controlled by gravity The exact routes taken by the water and the devious ways in which it can reach the zone of saturation are little known in detail, but will be referred to in the chapter on Hydrologic Properties of Rocks.

The Capillary Fringe. Water movements in the capillary fringe are supported by forces opposed to gravity, and therefore the study of capillary action is a specialised subject which is of great importance to irrigation engineers and agriculturists in general. As far as groundwater is concerned capillary action under avid conditions *decreases* recharge by vast amounts of water and also greatly *increases* the salinity of groundwater. The circumstances under which this takes place are connected with a high groundwater table and hence a high upper capillary fringe surface. The capillary forces, which are considerable, are smallest in coarse alluvium. In the Central Province water will rise 2 ft. to 2 ft. 6 ins. above the water table in sandy river beds. In silts derived from Basement rocks, such as in the Mkomasi valley, the capillary rise is about 6 ft. to 8 ft. Higher figures are known from fine clayey material (the finer the material the greater the rise), but in very fine sediments or soils it may take years before the maximum capillary rise is established. The effect of a capillary water surface rising to near the soil surface, is mainly increased evaporation, the rate of which in dry areas largely depends on how much water can be supplied by the capillaries. The evaporation is accompanied by concentrations of groundwater salts in the upper soil profile. If these salt concentrations are not removed during the rainy season which particularly is the case in areas of sluggish drainage or no drainage at all, salts in the groundwater may soon reach brine concentrations.

(1)Staples, R. 1933-1938. Annu. Rep. Dept. Vet. Scien. and Animal Husbandry.

The process of salt concentration is rapid as evidenced by the destruction by salt of growing sisal, maximum age five to six years, in the Mkomasi Valley, Tanga Province. The rise of the groundwater table in the Mkomasi Valley has been attributed to the removal of the natural vegetation and its replacement by sisal (Coster), combined with the silting up of the valley by the Mombo River (Milne). Other examples can be found in the mbugas and swamps of the Central Province which have a high water-table during the rainy, and part of the dry season. A continuous build-up of salts takes place here and concentrations of from 5,000 to 10,000 p.p.m. of total dissolved salts in the shallow groundwaters from such areas is known. It is possible that such saline shallow groundwater may prove an obstacle to irrigation in the Central Province and elsewhere, as inevitably some of the salt will find its way into reservoir water impounded by dams.

Zone of Saturation or Groundwater Zone. Groundwater available and suitable for human consumption is always on the move, the movements being controlled mainly by hydrostatic pressure. The laws governing such movements have been summarised by Darcy in the general fundamental equation:

$$V = \frac{P \times H}{L}$$

V = Velocity of water.

P = Constant dependent on the character of the material through which the water moves.

H = Difference of head at the ends of the column of material.

L = Length of the same column.

RECHARGE. From the small amount of information existing for run-off and Evapotranspiration the *general* conditions for recharge can be summarised as follows, using the equation:

Precipitation = Run-off + Evapotranspiration + Recharge.

Precipitation = 100 per cent.

Run-off = 4 per cent to 6 per cent.

ET. = Minimum 72 per cent, Average 85 per cent, Maximum possibly 90 per cent, which would give a maximum for recharge of 24 per cent and a minimum of 4 per cent.

From boreholes sunk on a fault line in the Dodoma area, the catchment of which can be estimated with some degree of certainty, and other facts in relationship to vegetation catchment and yield of boreholes, it is estimated that a 10 per cent groundwater recharge in many areas is the maximum that can be expected, but that in other localities the percentage recharge many well fall to 4 per cent or even below.

Before leaving the subject of the groundwater cycle it should be made clear that the amount of groundwater which is available for recharge is, apart from the rainfall conditions, to a very large extent dependent on human activities. Clearing of the natural vegetation on the lower altitudes, particularly in areas of flat topography will undoubtedly increase the amount of water available both for run-off and groundwater recharge. The primitive agriculture and livestock husbandry which is wide-spread in the territory, however, soon destroys the capacity of the soil to absorb the rainfall. Accelerated soil erosion follows, which may altogether remove the top soils which further reduces infiltration rates. The final result is that rain water which should have gone into the ground flows uselessly away. It has been noted that in recent years even large perennial rivers and streams, such as the Ruaha and Ngerengere, have dried out for the first time in their history. For the same reason wells and water-holes in the semi-arid Central Province have become more and more unreliable and some have dried up altogether. Flooding during the rainy season is another result which has become more and more noticeable (in recent years).

An example of the effect of dense vegetation causing depletion of water supplies should also be mentioned. Some years ago a water survey of certain rubber plantations in the Tanga area was undertaken. These plantations were started by the Germans before 1914 and abandoned in the first World War. The second World War created a demand for rubber and the plantations were again cultivated. During the survey, German wells were discovered with remains of pumps near small disused rubber factories and European houses, but none of these wells would yield sufficient water in the 1940s to supply such installations. During the intervening years the rubber trees had grown tall and the foliage had become dense. The rainfall in this area is approximately 50 ins. a year and temperatures high. ET. rates had apparently increased to such an extent that groundwater replenishment had become almost negligible.

Not all groundwater is available for human consumption for several reasons. Some is unpotable, some is locked up in fine silts and clays which will not yield their surplus water, and certain quantities must be absorbed in the natural process of weathering or be lost by deep percolation beyond economic extraction depth.

The total amount of groundwater in existence in Tanganyika is, however, very large, and in the following chapters a description of its distribution and quality and the search for water will be given in relationship to the geology and hydrology of the territory as a whole.

(b) Juvenile Water

A short summary of the occurrence of juvenile water will be found in the chapter devoted to Springs. The total amount of water derived from this source cannot even be estimated, but in comparison with groundwater it is very small. The main effect of juvenile water is the wide-spread contamination of groundwater by the introduction of fluorine, and, to a lesser degree, of sodium carbonate and bicarbonate.

CHAPTER THREE

GEOLOGICAL FORMATIONS IN TANGANYIKA

A very brief description of the main geological formations found within the boundaries of the territory is presented below. For practical reasons connected with the occurrence of groundwater these formations have been classified under the following main headings. Each heading may encompass several geological systems or a multitude of rock types. Space, however, does not permit detailed description of each system or even of the main rock types[1].

Class No. I. Non-metamorphic sedimentary rocks and unconsolidated sediments.

A. Sedimentary rocks in general and unconsolidated sediments of the coastal region in particular.

This sub-class includes all geological systems from the beginning of the Bukoban period to the Recent epoch. The age of the Bukoban is at present considered late Precambrian for lack of fossil evidence. Fossils may, however, be found in the Bukoban rocks and so determine the age of this system.

B. Lake sediments, *Mbuga* deposits (see Page 16) and alluvium. The age of these deposits ranges from Pleistocene to Recent. Pliocene has so far not been recorded with certainty.

Class No. II. Metamorphic sediments of the Karagwe-Ankolean formation and of the Karagwe-Ankolean type, Precambrian.

Class No. III. Older supracrustal rocks belonging to the Nyanzian, Kavirondian and other formations of the same type and origin. Exact age unknown but Precambrian.

Class No. IV. All rocks which can be grouped within the granite clan including some gneissose granites, palingenetic and migmatitic granites of the granitoid shield, mobilized or anatectic granites. As far as is known, the granites are all Precambrian, but the exact age of most is still unknown.

Class No. V. The Basement System (often referred to as the Basement). This system is made up of highly metamorphic para- and ortho-gneisses of mixed and uncertain origin, graphite schists, crystalline limestones and dolomites and quartzites; some gneissose granites amphibolites and charnockites. Included in the Basement System is the Konse Series consisting of quartzites, limestones, etc. This series is known to over-thrust other Basement rocks which appear to be older. The Basement System is Precambrian and some of its components are among the oldest rocks found on earth.

Class No. VI. Intrusive rocks of many kinds including acidic and basic types, forming dykes, sills, and ultrabasic intrusions.

Class No. VII. Younger extrusive rocks, mainly lavas and pyroclastics.

If a *geological map* of the territory be examined it will be seen that the rocks and geological deposits classified above, broadly speaking, have the following distribution:—

[1]Some of the views put forward, particularly regarding the formation of the granitoid shield and supracrustal rocks in Tanganyika, are the writer's own. For detailed information regarding the stratigraphy of Tanganyika the reader is referred to Quennell A. M., A. C. M. McKinlay and W. G. Aitken, "Summary of the Geology of Tanganyika, Part I, Introduction and Stratigraphy; *Mem. Geol. Surv. Tanganyika*, 1, Pt. 1". Information regarding petrology and structures will be found in the many publications and unpublished reports of the Geological Survey of Tanganyika.

The non-metamorphic sedimentary rocks and unconsolidated deposits (Class I A) occur in two main belts, the Eastern and the Western. The two belts converge in the south-west corner of the territory. Between these sedimentary belts lie the large areas of granite and Basement rocks. The granites (including the granitoid shield) are concentrated in the centre of the territory and in the Lake Victoria region and, in general, are surrounded by Basement rocks. The younger volcanics occur in two main areas, to the north of Lake Nyasa in the Rungwe and Mbeya districts, approximately 1,200 square miles in extent, and on the Kenya border. The centre of the latter area lies about half way between the eastern shores of Lake Victoria and the Indian Ocean and the volcanics extend over about 10,300 square miles. The Karagwe-Ankolean rocks occur exclusively to the west of the non-metamorphic sediments in the Lake Victoria—Lake Tanganyika—Lake Nyasa region, and to the south and west in the Lake Nyasa region.

Finally, the main lake beds are situated in the Rukwa depression, covering about 5,600 square miles, and the Wembere depression, west of Lake Eyasi, approximately 4,800 square miles in extent.

(a) Class No. I A—Non-metamorphic Sediments

In greater detail the rocks classified in I A have the following distribution.

(i) *The Eastern Belt.*—The eastern belt is bounded by the Indian Ocean and stretches from the Kenya border in the north to the Ruvuma River in the south. This river is also the boundary between the territory and Portuguese East Africa. In the south the belt is divided by a corridor occupied by older metamorphic rocks of the Basement. These rocks, as far as is known, also underlie the older sedimentary rocks found in the eastern belt. The Basement corridor and, to the north, the Rufiji alluvium, separate a more or less crescent-shaped coastal strip of sedimentary rocks and unconsolidated sediments from the large interior sedimentary areas of the eastern belt. At its broadest part between Dar es Salaam and the Uluguru Mountains the crescent is about 100 miles wide. The deposits found in this strip range in age from Karroo (Permo-Carboniferous) to Recent.

The Karroo rocks of the strip are exclusively of continental origin, the Jurassic marine and estuarine and the Cretaceous, both marine and continental. The conventional geological classification of the sedimentary rocks of Class I has been adhered to in this paper. There are, however, great practical difficulties entailed in distinguishing between the younger Tertiary and the Pleistocene and Recent formations along the coast and in the inland lake areas. From the Miocene upwards, therefore, these formations have been classified as Neogene (after Morley Davies and Neaverson) unless otherwise specified. This conforms with the nomenclature adopted by the Geological Survey of Tanganyika.

The Coastal Strip.—In the most northerly part of the crescent-shaped coastal strip Karroo sediments outcrop resting on the rocks of the Basement System. The basal conglomerates and conglomeratic sandstones[1] are followed, as far as is known from *borehole* records, by black, possibly indurated, shales in the Mjesani-Gombelo area of the Tanga hinterland. The middle Karroo beds (sub-division used for Tanga and Mombasa) are shales and flaggy sandstones. The higher Karroo beds, medium to coarse sandstones which outcrop in the Kilulu Hills and which have been struck in boreholes near Kilulu and towards the coast at Moa, are directly overlain by the Neogene clays to the east. The shore deposits in the Moa area are sandy. A small faulted area of presumed Karroo rocks also occurs at the Pangani Falls. The western boundary of the Karroo in the Tanga area appears mainly to be due to unconformity, but faults occur within the Karroo in the Kilulu area and north to the Kenya boundary.

To the south of the Sigi River a large area of partly oolitic limestone of Jurassic age occurs. This is unevenly developed and has perhaps a maximum thickness of 650 to 700 feet. In places, such as Pongwe, it is interbedded with a grey calcareous shale or mudstone, which is an aquiclude. In the Kwamkembe area this calcareous mudstone, underlying

[1] Halligan, R. In the press. The geology of the Tanga area. *Rec. geol. Surv. Tanganyika*, **Vol. VI.**

white Neogene clays, replaces the limestone and has proved to be dry to more than 700 feet in boreholes. The northern boundary between the oolitic limestone and the Karroo is, as far as is known, a fault. The Jurassic formation has not so far been found definitely resting on the Karroo. To the south of the Ngomeni area, borehole data indicates that the boundary between the Basement rock and the Jurassic limestones is either an overlap, which is the more likely, or a fault with a throw of not more than 150 feet. In general, the development of the Jurassic limestone formation in the Tanga area is irregular, and great changes in development can be expected over short distances. The north Tanga Township area is not directly underlain by limestone, but by silty shales and calcareous sandstone, younger than the oolitic limestones. The south Tanga Township area is interesting from a groundwater point of view. Narrow sand and pebbly beds are found in an old river bed system between 100 feet and 200 feet from the present surface. These deposits are Neogene. Other Neogene deposits explored south of Tanga and in the Pangani District indicate that in addition to the Recent coral reefs at least two transgressions or regressions of the sea have taken place, marked by coral reefs underlain by sands. The depth to these reefs is nowhere very great and their inland extent is not known. The oolitic Jurassic limestones of the Tanga area are not exposed as far south as the Pangani River, where sandy and clayey estuarine beds occupy a large area in which sea-water penetration in places goes far inland. Downstream from the Pangani Falls, and below the small Karroo area mentioned above, Jurassic rocks outcrop for a limited distance. South of the Pangani, Neogene sands and gravels appear to extend from the coast to the Basement boundary as far south as the Handeni-Sadani road. To the south of these, however, a belt of Jurassic and Cretaceous beds occur, stretching to the Ruvu River between the Basement and the Neogene deposits of the coast-line.

The detailed geology of the Dar es Salaam area is still imperfectly known, but, as far as groundwater is concerned, it is characterised by a system of old river beds and estuaries which are today mostly covered by clay deposits and interbedded with coral reefs. North of Dar es Salaam, at Kunduchi, the raised coral and chalk-like reef, which is about 50 feet thick, is underlain by fine sands and sandy clays, the grain size of the material decreasing with depth to at least 257 feet. In the Temeke-Ubongo area coral reefs are to be found at 90 to 100 feet depth, below clays and sandy material. It is, at present, not known how far inland these coral reefs are to be found. Buried, sand-filled river channels are found at the Tanganyika Packers' factory and in the Gerezani Creek area. Inland from Dar es Salaam many sandy deposits contain kaolin, possibly derived from the kaolin sandstones of the Pugu Hills. Wells and boreholes at Ukonga struck running sands mixed with kaolin.

The Pugu kaolin sandstone appears to have been formed by the deposition of quartz and kaolin and is not, therefore, a weathered arkose, although decomposed feldspar is to be found in this sandstone. The content of kaolin varies, however, considerably. There is at about Km. 25 on the Railway a change of the dip in the sandstone from easterly to westerly, probably due to a fault or a flexure at this point.(1) The kaolin sandstone is now considered to be of Miocene age. Some of the valleys of the Eastern Pugu Hills contain good brick clay.

On the western slopes of the Pugu Hills in the Soga area, clays and unconsolidated deposits and running sands prevail to at least 480 feet depth. The solid sandstone outcrop at Ngeta is apparently only a thin surface occurrence, and does not persist in depth, where it is replaced by kaolin and clay-bound soft sandstone. The unconsolidated deposits at Soga are considered younger than the Pugu sandstone.

In the neighbourhood of the Ruvu River alluvium takes the place of the unconsolidated deposits, but to the west of the river flats, formations apparently similar to those at Soga occur again as far as Msua. At Msua sandy clays and clays, some yellow, some green, were encounted in a borehole to approximately 600 feet depth. Scattered over the surface of the flat country to the west of the Ruvu River, and reaching as far as 4 to 5 miles west of

(1)Stockley, G. M. 1928. Diagramatic Cross Section of cuttings along Railway from Morogoro to Pugu. Water Supply Map 28.

the Nhese-Chalinze road, are pebbles of quartz and Basement rocks and some substantial deposits of gravels and large pebbles have been found near the old Ruvu-Ngerengere road. The exact nature of these pebble deposits is not known. The presence of unconsolidated deposits, including deep sandy-clay beds, however, over a large flat area from the new Dar es Salaam-Morogoro road to the old Ruvu River-Ngerengere road, and reaching approximately as far as to the eastern boundary of the Jurassic formation, will make it difficult to find groundwater in this area.

About 4 miles west of Msua on the Central Railway line the Jurassic is encountered. The rocks exposed are largely siltstones with thin irregular limestone and calcareous sandstone bands showing a low easterly dip approximately 5 degrees east. A borehole sunk at Magindu station to over 700 feet encountered only siltstones and one narrow limestone bed.

In the neighbourhood of Kidugallo the lithology of the Jurassic has changed and a thick, shallow-water, oolitic limestone is encountered dipping more steeply 15 to 20 degrees east. The beds immediately underlying the oolitic limestone near the Railway are coarse, calcareous, sometimes pebbly, sandstones containing muscovite and graphite derived from poorly weathered Basement rocks. Still further west, finer clastic sediments occur with thin oolitic bands with a massive arkosic sandstone beneath them. Close to the faulted junction with the Basement at Ngerengere the dip is westward(1) near the Railway line, but further north between Ngerengere and Kizuka, outcrops of a thin marine limestone occur, dipping 40 to 42 degrees east. The structural relations are here obscure, but the thin limestone bed evidently marks an earlier marine transgression than that in which the oolite at Kidugallo was found. West of Ngerengere the Basement rocks prevail, but to the east of the Uluguru Mountains down-faulted areas of Karroo rock occur which, at one time, were unsuccessfully explored for coal.

Between Dar es Salaam and the Rufiji River the geology of the coastal belt or strip is still imperfectly known. The delta deposits and alluvium of the Rufiji River cover a large part of this region. Elsewhere, except in the Maneromango area, there appears to be few outcrops of older rocks below the extensive Neogene sands.

Between the Rufiji and Mbemkuru rivers large areas are covered by Jurassic and Cretaceous rocks. In the Matumbi highlands marine Jurassic beds have been raised to a height of 1,600 to 1,700 feet above sea level, the highest position of any marine beds within the territory.

In the Kilwa area, Paleogene marine deposits occur extending in a narrow belt to the south. The Paleogene does not appear on the coast line to the north of Kilwa. To the east of the marine deposits and in places over-stepping them, is a belt of Neogene to which the sand-hills near Kilwa and on the Kilwa Peninsular belong. To the west of the Neogene there is a narrow belt of essentially argillaceous Cretaceous rocks, followed westward by the "coastal plateau", consisting of lower Cretaceous limestone and terrestial Cretaceous "Makonde beds." Jurassic rocks occur at lower elevations in the vicinity of the coastal plateau, especially in the south near the Mbemkuru River, but also in the two anticlinal structures flanking the eastern and western sides of the Ngarava plateau to the north of this. Only one borehole sunk for water is known in the area between the Rufiji and Mbemkuru rivers. Its approximate position was 24 miles south of Kilwa on the old military Kilwa-Lindi road. The borehole was successful and supplied the military forces during the 1914-18 War. The southern part of Kilwa District has recently been surveyed in detail by W. G. Aitken, and the results will be published shortly.

South of the Mbemkuru River there is an arrangement of formations rather similar to that which occurs to the north. A narrow strip of Neogene consisting of coral limestone and sandy limestone follows the coast line, backed by a belt of Paleogene marls and clays capped by limestone. These formations make up the coastal ridge which stretches from the lower

(1)WADE, F. B. 1934. Unpublished report.

Mbemkuru valley to Lindi Bay. To the west of this ridge marine Cretaceous rocks occu the valleys and the lower ground and at least the eastern edge of the Likonde plate. Jurassic is known from the lower levels in the Mbemkuru River depression, and probal also occurs in the Wangawe valley.

At Lindi itself the Paleogene limestones and clays have been subjected to folding (faulting, possibly both, and some layers of limestone and clays here have shoreward dip. On the fringe of the sea in Lindi town, sands have replaced Recent coral limestone deposits Limestones are, however, found at depth in boreholes there. South of Lindi Bay in the Kitunda area, Oligocene limestones and sandstones have been down-faulted in relation to the Eocene by a fault along the line of Lindi Creek. Miocene deposits, clays and limestones cap the Kitunda headland and to the south overlap the Paleogene. In the inland parts of the Lindi Creek marine Cretaceous(1) clays occur, in places covered by sandy surface deposits, and in the Lukuledi estuary salt water penetrates far inland.

Drilling in the area north of Sudi Bay indicates a flexure or "cliff" stretching in a north-westerly direction. The "cliff" consists of calcareous sandstones and mudstones overlain to the east by younger limestones, sandy in parts, and clays. The younger deposits seem to reach 245 feet above sea level, the older rocks are to be found at 300 feet. Thick deposits of limestone, presumably of Neogene age, continue southwards from Sudi Bay to near Mikindani Bay, where estuarine deposits occur containing gravel beds, clays and at least one coral limestone. Inland estuarine deposits give place to Mikindani beds, largely fluviatile sands. In the Mtwara region, the Mitisu creek is occupied by sandy and clayey deposits with some limestone layers followed by the younger coral reefs of the Mtwara lagoon area. The age of the sandy and clayey surface deposits is not known with certainty, but the strata encountered in boreholes probably belong to the older Neogene. South of Mtwara, Mikindani beds reappear, except in the valleys, the deposits of which may belong to the Ruvuma estuary beds and are older.

The Makonde plateau, which forms the hinterland of the coastal sedimentary strip to the south-west of Mikindani, has been explored by drilling. The borehole samples show that the Makonde sandstone is thickest at the south and south-western edge of the plateau, and either dips or thins out towards the centre. In the boreholes at the centre of the plateau, clays and sandy clays, some red, were penetrated and only one borehole reached the sandstone at a depth of 500 feet below surface at Matopwa. The Makonde sandstone is considered to be of Cretaceous age and terrestial in nature, but no fossils have been found so far, except silicified fossil wood. The Rondo plateau to the north is of similar formation to the Makonde.

The inland non-metamorphic Sediments of the eastern Belt.—The extensive inland region of sedimentary rocks (the "inland plateau"), stretching from the Tunduru and east Songea area in the south to the southern part of the Morogoro and Kilosa districts in the north, is separated from the coastal sedimentary strip by a corridor of Basement rocks in the south and by the Rufiji alluvium in the north. Over large areas the age of these rocks is not definitely known, though elsewhere fossils have been found and a Karroo age is established.

North of the Great Ruaha River the Karroo is partly marine.(2) In the Rufiji basin, further known Karroo beds occur, reported to be folded in the east.(3) The margins of the Karroo outcrops are determined by faults in many cases, down-faulted blocks of this formation having thus been protected from erosion. The marine Karroo is found to a height of approximately 1,300 feet above sea level. The rocks of the area west of Liwali,

(1)STOCKLEY, G. M. 1937. Unpublished report; Hennig and Spath, 1937. Der sedimentstreifen des Lindi-Kilwa Hinterlands. *Palaeontographica*, Suppl. VII.

(2)STOCKLEY, G. M. A further contribution on the Karroo rocks of Tanganyika Territory. *Quart. J. geol. Soc. Lond.*, Vol. XCII. pp. 1-31.

(3)SPENCE, J. 1957. The geology of part of the Eastern Province, Tanganyika. *Bull. geol. Surv. Tanganyika*, 28.

as far south as the Tunduru District, are of uncertain age, but are presumed to be late Karroo. Further south in Tunduru and Songea districts, known Karroo rocks occur in the inland eastern belt. The sedimentary rocks of the inland eastern belt are of importance as far as groundwater is concerned. The sandstones (some of which contain kaolin) and marly strata and the overlying soils are pervious, so that many perennial streams occur in this large area which, at present, is uninhabited or very thinly populated. The soils in general are probably poor. When these perennial streams reach the corridor of Basement rocks they usually dry out.

(ii) *The Western Belt.*—The non-metamorphic sedimentary rocks of the western belt belong, in general, to the following formations; the BUKOBAN, the KARROO and the CRETACEOUS.

The most widespread, and also the oldest, of these formations is the BUKOBAN which occurs in two main areas. The larger area, like the coastal sedimentary rocks, presents a crescent-shaped outline on the map. The northerly tip of the crescent reaches the Uganda border near the Karema River at the western shores of Lake Victoria. The most southerly point lies approximately 25 miles west-north-west of Njombe in the Southern Highlands Province. The centre of this crescent is bounded in the west by Lake Tanganyika, and in this region the formation reaches its greatest development with a width of outcrop of approximately 100 miles in an east-west direction from Lake Tanganyika to south of the Usinge Swamp. The second main area in which the Bukoban rocks occur is to the east of Lake Victoria in the Musoma and east Maswa districts, and possibly also in the western parts of Loliondo District. A relatively small area of rocks suspected to be of Bukoban age has also been located in the Kisigo River basin of the Central Province.

The Bukoban rocks of Tanganyika have mainly been explored by Sir Edmund Teale, G. M. Stockley and the late A. D. Combe. Work is still in progress by officers of the Geological Survey.

In the Mpanda-Kigoma-Kasulu area of the Western Province the sequence of the Bukoban rocks at present is considered to be as follows:—

UHA SERIES.

MALAGARASI SANDSTONE FORMATION.—The Malagarasi sandstone formation is about 3,000 feet thick and comprises alternating, thick, pure sandstone and shale beds. A basal conglomerate is sometimes present. Vertical jointing is conspicuous in the upper members. The shales often contain sandy and slaty bands and the colour ranges from red to brown and yellow.

Overlying the Malagarasi sandstones is the Uha Series, which is threefold, viz.,
Manyovu Red Beds
Dolomitic Limestone
Amygdaloidal Lavas (Uha Volcanic Series).

As yet, the lavas have not been seen in contact with the sandstones, but an unconformity is very likely.

The lavas (total thickness about 2,000 feet[1]) which extend from south of Ilagala, near the mouth of the Malagarasi River, to beyond Kibondo in the north, are fine-grained, dark-green or greenish-grey, frequently amygdaloid basalts.

The Dolomitic Limestone is also a widespread formation, extending from north of Kibondo to south of Ilagala. It lies with unconformity upon the lavas.

The Manyovu Red Beds are best developed south of the Malagarasi River, but extend northwards through Manyovu into Ruanda Urundi. The rocks consist of fine-grained red, grey-wacke sandstone, and are several thousand feet thick.

[1]TEALE, E. O. 1928. *Short Pap. geol. Surv. Tanganyika*, 4.

In general the Bukoban is flat-lying in this area, with only low regional dips. Towards the south-west, however, the Malagarasi series is closely folded into a syncline, and unconformably overlain by the Red Beds. In the southern part of the Bukoban area, in Njombe District, andesitic lavas take the place of the basaltic. The Bukoban rests on the old metamorphic Basement rocks, on the granites and on rocks of the Nyanzian system. In Ukinga rocks of presumed Karagwe-Ankolean type underlie the Bukoban.(1) The boundaries of the Bukoban in certain localities in north Kigoma and west Bukoba districts are outlined by faults, but in other areas, particulary between Uvinza and the Luika River in Chunya District, the boundaries are positioned by erosion and in many places show cliff-like outlines. This indicates that the old pre-Bukoban land surface is now being exposed by erosion and removal of the Bukoban sediments. It would seem, therefore, that in the drainage systems of the Lake Tanganyika and Rukwa depressions the present erosion is about to complete the full circle and has in places reached the same depth as in pre-Bukoban times. If this conjecture is correct, one consequence would be that the high residual hills in the southern part of the granitoid shield and the old Basement rock areas are remnants left behind on the pre-Bukoban land surface.

Another consequence would be that in Tanganyika the presumably Pleistocene(2) land surface of the Nile basin and the pre-Bukoban surface in the Congo drainage region are now in juxtaposition.

It should be added that the nature and weathering conditions of land surfaces have a profound influence on the possibility of striking groundwater in the hard rock formations of the Congo and Nile drainage basins respectively.

Economically, the most important system of the western belt of sediments is the KARROO which contains all the coal deposits of the territory.

The distribution of the Karroo rocks is, to a large extent, governed by systems of block faulting; and, as in the eastern belt, the Karroo has been protected from erosion by downfaulting. Overlap of the Karroo rocks on the Basement, however, occurs in the Songea District and in other southern areas, and gives rise to contact boundaries which are not faults but conditioned by present day erosion. The main outcrops of the Karroo rocks and the major coalfields are situated in Njombe and Songea districts. Other scattered outcrops are found along the Western Rift escarpment from the Nyasaland border in Rungwe District, along the western escarpment of the Lake Rukwa depression, to the Karema gap in the neighbourhood of Lake Tanganyika. An outcrop of rocks, possibly of Karroo age, also occurs on the eastern shore of Lake Tanganyika at Kipili. The Karroo rocks consist mainly of conglomerates, shales, marly beds, coal shales, coal seams and sandstones.

The third sedimentary rock formation in the western belt is the CRETACEOUS, which occurs to the east of the Karroo on the Nyasaland border and in the Songwe River area of Mbeya District. It is also possible that the sandstones underlying the lake deposits of Rukwa and found in boreholes in Ivuna salt pans belong to the Cretaceous. The extent of these sandstones is at present not known.

(b) CLASS I B

Lake Deposits, Mbuga Deposits and Alluvium.—These non-metamorphic sediments are so widely scattered throughout the territory that only some of the major occurrences can be mentioned. The largest tracts of country covered by known lake beds are the Rukwa and Wembere depressions, the basins of Lake Manyara and Natron and the Buhoro flats. Whether lake deposits are to be found in the large Upper Malagarasi Basin is not known.

(1)HARPUM, J. R. 1955. Some problems of pre-karroo geology in Tanganyika. Reunion de Nairobi, Sept., 1954.

(2)The dating as Pleistocene is based on the fact that 110 feet of so-called terrestial oxidised gravels of the land surface overlie 380 feet of limestone, sandstones and clays which, in all probability, belong to the Wembere lake beds (Pleistocene); locality, Isaka, Shinyanga District.

Smaller lake deposit areas of 150 square miles or less are to be found in the East Serengeti Plains, in south-east Masailand and in the Kikuletwa and Upper Ruvu basins in Moshi and Same districts. The total area occupied by lake beds within the territory is probably 12,000 to 15,000 square miles.

The lithology of the lake beds varies considerably from clays, marls and limestones to sandy deposits, ash beds and water-lain tuffs. The marls and limestones are usually to be found in lake basins which lacked drainage or overflow during their development. Such lake basins were the Wembere and Bahi depressions and, in a later stage, the Lake Manyara Basin.

THE WEMBERE LAKE DEPOSITS have a minimum total thickness of 400 feet and include large quantities of marls, limestones, calcareous sandstone and at least one strongly oxidised series of clays. A similar series of oxidised clays occurs in the Bahi lake beds which also contain large quantities of lime. THE BAHI LAKE DEPOSITS reach a minimum thickness of 150 feet in the south of the depression. The maximum lake stage is indicated by sandy beach deposits at no great height above the present level of the swamp and lake.

THE MANYARA DEPRESSION. The lake beds found in the Manyara depression vary considerably according to the position in the basin. Large areas of calcareous deposits are to be found to the east of the present lake, but at the north-east end of the depression, tuffs, sandstones and ash were deposited, and at the northern end, 500 feet of pyroclastics and thick clay beds were encountered in a borehole. The lake may have reached 300 feet above its present level at its maximum extension. The total thickness of lake deposit is not known, but may be over 1,200 feet. At present Lake Manyara is a soda lake.

LAKE NATRON. Little is known of the lake deposits in the Natron area. Ashes, evaporites and impure diatomites do occur.

THE RUKWA DEPRESSION. The lake bed deposits in the Rukwa basin can be divided into two types. The older were deposited in the basin itself and, as far as is known, consist of clays, some of which are green, and sandy clays and diatomite clays. These deposits are connected with a long period of stable lake conditions, when drainage of the lake was adequate. The later deposits were formed when the lake rose some 500 ft. to 600 ft above the present flats and are to be found at the mouth of the gorges of the Lupa-Sira rivers, the Songwe, Rungwa and other rivers. The Lupa-Sira and Songwe lake beds contain sand and ash beds. The Rungwa deposits(1) are sandy on top and contain clay shales and diatomaceous clays at the base. The maximum lake stage, at approximately the 3,300 ft. level, was relatively shortlived and drainage took place to Lake Tanganyika through the Karema gap after the sand bar at Ilinde had been breached.(2) The middle Songwe valley lake beds cannot be considered part of the true Lake Rukwa beds unless they have been uplifted by block-faulting. The older lake beds below Saza Falls have an estimated minimum thickness of 400 ft. The younger lake beds in the Lupa-Sira valley could reach a thickness of 600 ft. if fully developed. The Rungwa deposits (Pleistocene) are estimated to be at least 180 ft. thick.(1)

OTHER AREAS. Amongst the smaller areas of lake deposits is the Makami pan in south-east Masailand, approximately 140 square miles in extent. As far as is known these deposits are entirely calcareous and of a total minimum depth of 100 ft., probably much more. The Ruvu-Kikuletwa beds are often calcareous and appear in places to overlie some of the Kilimanjaro pyroclastic deposits. (Parsons E.). Diamond drilling has penetrated 50 ft. of calcareous lake beds without reaching Basement rocks. The full extent of the Ruvu-

(1)STOCKLEY, G. M. 1938. The geology of the country around Mwanza Gulf. *Short Pap. geol. Surv. Tanganyika*, 29.

(2)TEMPERLEY, B. H. Unpublished reports.

Kikuletwa lake beds is not known. The Buhoro flats are partly unexplored, but remains of old lake deposits are found to approximately 3,800 ft. elevation. These beds are known to contain waterlain tuffs (Guest). Lacustrine beds also occur in the Rungwe District north of Lake Nyasa[1].

Mbuga Deposits. In the following chapters such deposits will frequently be referred to and an explanation of the term *Mbuga* is, therefore, necessary. *Mbuga* is a name used by the African population of the territory to describe an open or sparsely tree-covered flat stretch of country. If trees are to be found they are usually thorn trees. The soils of the *Mbugas* are commonly found to be of the black, clayey variety, often *misnamed* black cotton soil, with which latter soil there is no connection. The *Mbugas* are, in general, but not always, situated within drainage lines, and during the rains large quantities of water move on the surface through these *Mbugas*, usually as slow moving sheets. Actual drainage channels are uncommon and often die out when a true *Mbuga* is reached. During the rains, pools and swamps are commonly formed and lush grass and other vegetation springs up. During the dry season the *Mbugas* offer excellent grazing, but they cannot be so used during the rains. The clayey soils at the end of the dry season contain a network of often large and deep cracks which close up during the first showers of rain. The black clays are often as much as 20 to 25 ft. thick.

Geologically *Mbuga* deposits can conveniently be divided into clay *Mbugas* and limestone *Mbugas*, although all gradations are found between the two. The main formations occurring are clays, often grey and sandy, marls, limestones and often layers of concretionary, more or less solid, limestone. Impure limestone with sand or precipitated silica and diatomite beds also occur. Sandy beds are rare. *Mbuga* deposits may reach a thickness of 400 ft. or more. Geologically speaking, the true *Mbuga* occurs mainly in the Central Province, south-east Masailand, the Lake Province and the part of the Western Province which is more closely associated with the Nile drainage. Many of the *Mbugas* in the Central Province are connected with blockfaulting and the clays and limestones have filled the greater part of the hollows created by the faulting. Others are to be found in areas of old, sluggish, drainage systems connected with widespread peneplanation. Sand deposits are sometimes found (Kongwa) and on a bedrock which appears to have been broken up into sharp-edged blocks later cemented by lime. *Mbuga* limestones may have been formed in pools, ponds, lakes or in oxbows of the old, sluggish, drainage channels. Characteristic of some *Mbugas* is that the clays and marls carry diatomites. Some *Mbuga* limestone beds also carry precipitated silica (Prof. H. Bassett, unpublished report). The presence of diatomites and precipitated silica leads to the belief that some *Mbugas* were laid down in the Pleistocene during periods of high rainfall, when silica was freely leached from soils and superficial deposits. This period can also be connected with the formation of the lateritic hardpans. The very large quantity of lime locked up in the *Mbugas* of the more or less purely granitic areas poses a geological problem, as an adequate source from which all this lime could have been derived has so far not been found. No natural deep cross-sections have been discovered in *Mbugas* and practically all information regarding these deposits is derived from boreholes samples.

The thickest 300 to 400 ft. *Mbuga* deposits have been encountered in the Lake Manyara drainage in eastern Kondoa District, in Kongwa District and in south-east Masailand. Individual *Mbugas* covering 200 square miles or more are to be found within the territory.

It should perhaps be stated here that the word *Mbuga*, used in its geological sense, is not synonymous with the Northern Rhodesian expression, *Dambo*. A *Dambo* is, in general, a treeless, fairly flat, grass-covered tract of country developed by a definite type of drainage often called dendritic on account of the pattern which the water courses present on a map, or viewed from the air. The actual outlines of the *Dambos* themselves resemble "frostblooms" when seen from an elevated position. The drainage pattern varies according to the size, age etc., of the *Dambo*. Often two arms of a stream are developed at the opposite edges of the *Dambo*, and the arms eventually unite down-stream. A good example of this can be seen near Ulete on the main road from Iringa to Mbeya. Trees and bushes commonly grow

(1) DIXEY, F. 1927. The tertiary and post-tertiary lacustrine sediments of the Lake Nyasa Rift Valley. *Quart. J. geol. Soc. Lond.*, LXXXIII, p. 432.

on the banks of the streams running through the *Dambos*. These streams may be perennial or only seasonal, but frequently contain water-holes in the stream-beds, even at the height of the dry season. In the rains the *Dambos* may be flooded; the drainage is slow and very gradual. A *Dambo*, therefore, conserves water and should not be over-cultivated or drained. The soils are often peaty and the depth of superficial deposits above bedrock is not "usually" very great. The *Dambo* system of drainage occurs in Tanganyika in large areas in the Southern Province, the Southern Highlands Province and part of the Western Province. The word *Dambo* should here be used to indicate this particular type of drainage and geological conditions.

Alluvium. Alluvial deposits can be expected, and do, occur, scattered everywhere throughout the territory. Most of these deposits are, however, small and of no general importance as far as groundwater is concerned. There are, however, extensive areas in Kilosa District, in the plains as far out as Kimamba, in which alluvium occurs which has been successfully developed for groundwater. Other large areas in which water-bearing alluvium may be found are situated in the south Kilosa and Ulanga districts. These have so far not been explored. In the well-watered Rungwe District, close to the shores of Lake Nyasa, there are further extensive deposits of alluvium.

(c) Class II

Metamorphic Sediments of the Karagwe-Ankolean and of Karagwe-Ankolean type. The type locality in Tanganyika of these rocks is situated in the western part of Bukoba and Biharamulo districts, south of the Uganda border. The formation is mainly made up of phyllites, schists, quartzites and, in one locality, a conglomerate has been found[1]. The Karagwe-Ankolean is folded and in the type area intruded by younger tin-bearing granites. Other areas where rocks of similar type and metamorphic grade occur are in Kigoma and Mpanda districts of the Western Province, and in the Ukinga area of Njombe District in the Southern Highlands Province. The Karagwe-Ankolean is the youngest Precambrian rock known to have been intruded by granites. The granites brought with them cassiterite, wolframite and tantalite.

(d) Class III

The older supracrustal rocks encountered in Tanganyika are of both volcanic and sedimentary origin, and were originally deposited on the surface of the earth. Outcrops of rocks of this type are to be found in widely separated areas within the territory, but these areas are all confined to regions where granitic rocks occur, and are particularly common where intrusions of younger anatectic granites are concentrated. Rocks of this type have been assigned to various periods and systems, foremost of which are the Nyanzian and Kavirondian. The Ilunga felsites and porphyries, the Ndembera Series and the Upper Lupa volcanic rocks at present cannot be included in the older supracrustal formations. It seems probable that these rock suites are genetically connected with mobilized granite magmas; in fact they may be the extrusive forerunners of granitic intrusions, and in the areas in which they occur were probably derived from the same magma chambers as the granites. Under such circumstances, variations in the rock type of the supracrustal formations could be due to difference in composition and differentiation of the mother magma.

The Nyanzian System, including the Kavirondian, is the most widespread of the supracrustal formations and is to be found within the limits of the mobilized or anatectic granites outlined on the geological map of the territory, mainly south and east of Lake Victoria. The Nyanzian rocks consist, according to Stockley G. M., D. R. Grantham,

[1] Stockley, G. M. and G. J. Williams. 1938. Explanation of the geology: Degree Sheet No. 1 *Bull. geol. Surv. Tanganyika*, 10.

B. H. Temperley and R. B. McConnell, ([1, 2, 3]) of basic and acidic volcanic rocks, including some pillow lavas, the banded ironstone suite composed of quartz-banded ironstones, tuffs, acidic volcanics and possibly some sediments. Furthermore, the weathering products of these rocks, quartzites, feldspathic grits and conglomerates are often placed in the Kavirondian system. In the Kahama District the whole of the above rock system has been estimated to have a thickness of 25,000 ft. The dip of the rocks found within the Nyanzian formation is often steep, and the outcrops now to be found occur as outlines of eroded cupolas. Structural conditions are, in consequence, very complicated. The Nyanzian rocks in the Kahama region were eroded and folded before the formation of cupolas, a development which has been connected with the younger granites. The metamorphic grade of the Nyanzian is relatively low. The relative age of the System is uncertain, but in the Kahama region rafts of highly metamorphic rocks occur in the older migmatitic granites and such rocks are occasionally found in juxtaposition with the Nyanzian rocks. This would indicate that the Nyanzian is definitely younger than the highly metamorphic rocks which are constituencies of the palingenetic granites, and thus that the Nyanzian is in all probability younger than the main palingenetic process itself.

(c) Class IV

Granitic Rocks. It is not possible here to describe or enumerate the many and varying types of granitic rocks found within the territory. It should, however, be made clear that a great many granites, particularly those outlined as granitoid shield on the geological map of the territory, are contaminated by inclusions of the older metamorphic rocks. The inclusions vary in size from small xenoliths to large rafts, or even areas, of these older rocks. The inclusions, irrespective of size, may be highly migmatised or remain undigested with sharp contact boundaries. From the facts quoted above it would seem that the granitoid shield must be considered one vast outcrop of palingenetic granite, mainly composed of rocks of the Basement system, which have at one time been lowered to such temperature and pressure regions that a transformation, with the aid of introduced granitic materials, has taken place, and which eventually has resulted in a rock of granite type. The granitoid shield occupies a large area in the centre of the territory, but outcrops of palingenetic granites of great general interest also occur in the Songea District, Southern Province. The older rocks of this area were granulites and charnockites and in one locality the various stages of transformation can be followed,([4]) from these rocks into a palingenetic granite. The boundaries of the granitoid shield are occupied by wide, often crushed, zones of migmatic rocks which show the various stages of transformation from a rock of Basement type to a palingenetic granite. Inliers occur, however, scattered throughout the shield and may be part of the upper undigested layers of the old metamorphic rocks. More difficult to explain is the presence of areas of schists of a relatively low metamorphic grade in the palingenetic granites of the Dodoma, south Singida and Tabora regions. These schists have, in the Tabora region, been intruded by pegmatites which also criss-cross the palingenetic granite in that locality. In addition to the palingenetic granite, a great number of anatectic or intrusive granites are to be found, particularly in the Lake Victoria region, but also in the Singida District, the Lupa Goldfields, Uruwira mineral fields, the Ufipa plateau and in the Mbarali River area of the Southern Highlands. These granites are often gold-bearing and connected with other mineral deposits. The intrusive tin-bearing granites of the Bukoba and Biharamulo districts are considered to be the youngest granites so far found in the territory. The oldest of the anatectic type may be represented in the residual mountains of south-east and north-east Masailand, which rise 3,000 to 4,500 ft. above the general level of the surrounding country. The rocks encountered in these mountains vary from grey gneissose granites and charnockitic intrusions in Longido Mountain to grey or pink gneissose

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([1])Stockley, G. M. 1935. Outline of the geology of the Musoma District. *Bull. geol. Surv. Tanganyika*, 7.

([2])Grantham, D. R., B. H. Temperley and R. B. McConnell. 1945. Explanation of the geology of Degree Sheet No. 17 (Kahama). *Bull. geol. Surv. Tanganyika*, 15.

([3])Stockley, G. M. 1947. The geology of the country around Mwanza Gulf. *Short Pap. geol. Surv. Tanganyika*, 29.

([4])James, T. Geologist. Verbal communication.

granites in the Lossogonoi and Rotian mountain areas. No pegmatites have so far been found connected with the above granites. It is possible that Longido Mountain is of a type known as a gneiss dome, as the gneisses at the base of the mountain to the north-west and north seem to wrap round the outlines of Longido Mountain. Other rocks of the granitic clan, such as syenites, occur to the south of Smith Sound in the Lake Victoria region, in Maswa District and in the Rungwa area of Chunya District; the latter syenite is porphyritic. Quartz porphyries are to be found over large areas in Sumbawanga District on the Ufipa plateau (McConnell) and minor outcrops of porphyries are known from south-west Songea.(1) Both are connected with granites.

(f) Class V

The Basement System. This formation covers by far the largest total area of any system or even group of rocks in Tanganyika. The true origin of the Basement rocks cannot always be determined, but within the system there are to be found rocks of sedimentary origin such as quartzites, para-schists and para-gneisses, limestones and dolomites; other rocks are of volcanic origin. A great number of basic dykes and sills also occur, and finally large areas of the Basement consist of rocks of plutonic or hypabyssal origin including charnockites. Mica-carrying pegmatites of many types are also characteristic of the Basement. All these rocks, except the pegmatites, have, in greater or lesser degree, been transformed or metamorphosed by forces acting upon them within the deeper parts of the earth's crust. The accepted geological stages of the transformation process can briefly be described; 1. dynamo-metamorphic, when schistose rocks have been formed; 2. regional metamorphic during which rocks such as gneisses and migmatites were developed; and, lastly, the palingenetic stage, when advanced melting took place and the granitoid shield came into being. The transformation as a whole was in the main effected by the sinking, or perhaps rather down-bulging, of the earth's crust, which at the time was thin and had relatively little strength, under a load of rocks which has since been removed by erosional forces. In this manner the original rocks, were exposed to high temperatures and pressures and, in addition, received new material from the interior of the crust. The result is a complex pattern of rocks in places varying within a short distance in structure, texture and mineral composition. On the other hand, similar rocks of the Basement type are to be found in the Shield regions of the world and a rock outcrop on, for instance, the west coast of Greenland, may be very little different from one found in the Uluguru Mountains of Tanganyika. Components of the Basement belong to the oldest rock formation on the globe and is classified as Precambrian; also called the Primitive system in South Africa. A short non-technical description of the more common rock types is given below, as these rocks will be referred to in following chapters.

Rocks of Sedimentary Origin.

Quartzites. The Basement quartzites range from hard, white to grey, semi-translucent to types which superficially resemble sandstones, but no preliminary textures such as bedding or sorting etc., can be observed under the microscope in any Basement quartzites. In all probability, two, or even three, different age groups are represented by quartzites. The largest area covered by these rocks is situated in Loliondo District of the Northern Province. Other extensive, but smaller, areas are to be found in the north Iringa District, in Kondoa District and in Mbulu District. Minor outcrops of quartzite are found scattered throughout the Basement areas of the territory, except in south and west Songea District. The quartzite may contain graphite,(2) garnet, kyanite and a chromium mica, apart from more common accessory minerals.

Schists. These are of many kinds, the most common being mica and hornblende schists. Graphite schists are, as a rule, connected with the limestone dolomite rock suite.

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(1)James, T. Geologist. Verbal communication.

(2)Grantham, D. R. 1955. The geology and ecology of the Nachingwea region. *Bull. geol. Surv. Tanganyika*, 26.

The crystalline limestone/dolomite rock suite. These rocks occur in the eastern part of the territory in discontinuous, sinuous, lenticular bodies or bands, large or small, from below the Makonde Plateau through the Nachingwea District, Mahenge, Eastern Uluguru Mountains, Bagamoyo[1] District to Handeni, and from there into south-east Masailand, where outcrops of these rocks form big ranges of hills and mountains. The most northerly outcrop of the crystalline limestone/dolomite is to be found at the north-western foot of Kilimanjaro; over the Kenya border limestone is found north of Namanga. The crystalline limestone in the Southern Province is less dolomitic than the Masailand outcrops, which are pure dolomites. Accessory minerals such as tremolite and kyanite are found at Ngasumet and south of Lossogonai Mountain respectively. The crystalline limestone/dolomite rock suite, when exposed, often shows folding and contortion of the folds. These rocks may, therefore, be connected with the old lines of folding. In the western part of the territory there are crystalline limestones or dolomite outcrops in the Ruhuhu River basin on the border between Songea and Njombe districts, near Igawa in the northern Njombe District, possibly in the Lupa Goldfields and in the north Ufipa and Mpanda districts of the Western Province. Calcareous rocks of a highly metamorphic type are also found on the Lupa and in the Kiboriani Mountains, Mpwapwa District. The Basement areas in the northern and western part of the Northern Province appear to be devoid of crystalline limestone. This also applies to the Pare-Usambara group of mountains, but north-west of Moa in the Umba flats large outcrops of crystalline limestone occur.[2] In the south-western Songea District no outcrops of crystalline limestone have so far been found. In general, crystalline limestones and dolomites are of great importance from a groundwater point of view.

Gneiss. This rock name is used for a highly metamorphic quartz, biotite, feldspar rock with a definite strike. The feldspar is a potassium feldspar or an acidic plagioclase.

Augen Gneiss. A gneiss with large eyes, usually of potassium feldspar, in which the feldspar shows a definite directional arrangement.

The typical rocks show narrow bands from a few inches to perhaps 2 ft. of mica-hornblende minerals, alternating with quartz-feldspar material. The bands are probably formed by internal movements, exchange and concentration of the various minerals. This may be due to varying pressure conditions within these rocks during the formation of the bands.

Granulites. These are rocks of varied origin and mineral assembly, which have been subjected to high temperature and high uniform pressure conditions. The mineral composition, structures and texture are a direct result of these high temperatures and pressures. The texture is known as granulitic.

Migmatites. The term migmatite, when used, applies to a rock consisting of older metamorphic rock material mixed with newly formed material which has reached a fluid state, but not sufficiently advanced to destroy all the original characteristics of the older rock.

Granitic Gneiss is used to indicate a gneiss which has been altered by the introduction of granitic material.

Gneissose Granite is essentially a foliated rock which has been formed during regional metamorphism but the character of which definitely shows it to be a granite.

The age relationship between the integral part of the Basement is still uncertain and until the whole system has been mapped no definite classification can be made. Judging from over-thrusting and the occurrence of conglomerate-like beds, the quartzites of the Konse area of Iringa District appear to be younger than the other Basement rocks found to the west in the same area.

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(1) SAMPSON, D. Geologist. Verbal communication.

(2) TEALE, E. O. 1922. Geological survey in the Tanga District. Unpubl. report No. 22.

(g) Class VI

Dykes, Sills and other Intrusive Rocks. These rocks occupy only a relatively small total area, but are widely distributed in the Precambrian rocks. True dykes are uncommon in the Karroo. The dyke described by Spence from the Rufiji(1) is, in all probability, a volcanic plug as other plugs are known from the same area. The dykes and intrusions vary from pure quartz-feldspar rocks, common in the Lake Province, to dolerites and meta-dolerites, which are the most wide-spread type of dykes, and hydrologically the most important. Hornblende-carrying dykes, including appenites, occur in the Iringa District and in the Lupa area. Ultrabasic rocks have been found widely distributed, but the larger intrusions of these rocks (and also of most appenites) seem mainly to be concentrated in the Basement rock areas, often near the boundaries of the granitoid shield. Such larger intrusions have been found in north and south-east Dodoma District, in northern Iringa District and on the Lupa Goldfields. Diorites are also found on the Lupa, and are not uncommon in other areas. Gabbros are found in Ukinga, Njombe District and in the Musoma area. Connected with basic and ultrabasic rocks are numerous occurrences of talcose rocks.(2) A number of other intrusive rocks are also to be found, amongst them the aegerine syenite of the Mbosi area of the Southern Highlands Province.

(h) Class VII

Younger volcanic Rocks and Pyroclastics. Three main areas occupied by these rocks and deposits are to be found in the territory, namely in the Northern Province area, the Tukuyu-Mbeya area in the Southern Highlands Province and the North Mara area of the Lake Province. The Northern Province area is by far the largest, and the highest mountain in Africa, Kilimanjaro, over 19,500 ft., is situated in this area, as well as many other high cones ranging from nearly 15,000 to 9,000 ft. Single cones, such as Mounts Meru, Kitumbeine, Gelai and Oldoinyo Lengai, as well as concentrations of cones, such as in the Oldeani-Ngorongoro highlands and the ranges of Monduli and Essemingor, are to be found in the Northern Province. In addition, there are also extensive lava plains. Geologically, the volcanic areas of the Northern Province are very unevenly explored.

Kilimanjaro has recently been investigated in detail by two expeditions from Sheffield University. The Ngorongoro-Oldeani highlands were explored before 1914 by German Geologists and Oldoinyo Lengai by Guest, but other mountains such as Essemingor, Burka and Monduli are little known geologically. From a groundwater point of view the lack of detailed geological information has been a great drawback. It is hoped that the result of the latest Sheffield University investigation will remedy the matter as far as Kilimanjaro is concerned. Kilimanjaro was, according to Wilcockson,(3) built up in stages by three main volcanoes situated in line, probably along a fracture. The three main cones and volcanic centres are, from the north-west, Shira, in the centre, Kibo and in the south-east, Mawenzi. The lavas from Kibo, the highest point, have spread out over the lavas from both Shira and Mawenzi, thus the volcanic activities in Kibo were the youngest of the three. Parasitic cones on the flanks and even in the plains are also possibly of the same younger date as Kibo. The core of Kilimanjaro is nowhere exposed. During the ice age Kilimanjaro was glaciated, the ice cap reaching down to the 12,000 ft. level.(4) Traces of glaciation have even been found at lower levels. From the presence of glacial materials cemented by lavas it is known that volcanic activities continued into the Pleistocene epoch, but apparently not to a large extent after this time. The main rocks in Kibo show, according to Wilcockson, seven different series, starting with trachy-basalts and changing towards more and more sodium-rich lavas, until the lavas of the inner crater of Kibo became nephelinites and

(1)Spence, J. 1957. The geology of part of the Eastern Province, Tanganyika. *Bull. geol. Surv. Tanganyika*, 28.

(2)Harpum, J. R. 1957. Genetic classification of talc occurrences. Unpublished report.

(3)Wilcockson, W. H. 1956. Preliminary Notes of the Geology of Kilimanjaro. *Geol. Mag.*, Vol. XCIII No. 3.

(4)Nilsson, Erik. 1940. Ancient Changes of Climate in British East Africa and Abyssinia. *Geografiska Analer*, H.T. 2.

nepheline phonolites. It is at present thought that most of the lower parts of the mountain are made up of trachy-basalt and other basaltic rocks. Pyroclastic deposits are found connected with some parasitic cones, and it is believed that the upper part of Mawenzi consists of pyroclastics and flow breccias.

MERU, the next important volcano from a groundwater point of view, is a composite volcano made up of pyroclastics including ash, pumice and lavas. The pyroclastic deposits seem greatly to predominate in the Meru Mountain area. In the Oldonyo Sambu area there is at least 1,000 ft. of these deposits. Meru is heavily eroded on the north-east side; possibly a slide took place in this area while the volcano was still active. The Meru lavas have been described by Finkh, 1911; Oates, 1933 and latterly by Guest and Leedal.(1) The lavas vary in character, but are all of the sodium-rich type, changing from basalt to trachytes and phonolites. Fumaroles are still active on Meru. During drilling at Loljoro to the south-west of Mount Meru, more than 1,000 ft. of vesicular lavas flows were encountered. Many of the individual flows were oxidised. These flows are probably older than Mount Meru and were derived from deep fissures due to faults in a north/south direction. In the south-east Ardai plain, lava flows cover pyroclastic deposits of unknown origin and age. The pyroclastics rest on the Basement. To the north of Mount Meru in the Oldonyo Sambu area towards the boundaries between the volcanics and the Basement rocks, thick (minimum 400 ft.) lava beds occur. Further north, south and south-east of Longido Mountain, small outcrops of tuffs and lavas can be found resting on the Basement. THE ARDAI PLAINS are covered by lavas to an unknown depth, but not less than 400 ft. These lavas are olivine basalts and were probably derived from fissure eruptions. Rising over the Ardai Plains to the north and in the west are the MONDULI RANGE of volcanic rocks, the BURKA MOUNTAIN and the ESSEMINGOR RANGE. The only known sample from Monduli lavas was described as an essexite. Some of the lavas from Essemingor are nephelinites.

THE GREAT HIGHLANDS of volcanic rocks to the west of Lake Manyara, reaching to south of Lake Natron and in the west rising over the Serengeti Plain, were geologically explored by the German Geologist, Jaeger, before 1914. A great variety of rocks occur in these highlands which were built up by lavas from many volcanic centres. Trachytes are common in the Oldeani-Ngorongoro area, but basalts also occur and sodium-carrying rocks, such as nephelinites, have been recorded. The Ngorongoro "Crater" is, in fact, a caldera formed by the destruction of the original cone and crater, probably by the sinking and slumping into the crater itself of huge portions of the crater rim along ring faults. This took place when volcanic activities were dying down in the original crater.

THE RUNGWE-MBEYA VOLCANIC AREA is much smaller than the Northern Province area; it encompasses about 1,200 square miles and stretches from Lake Nyasa in the south to Mbeya Mountain in the north. The area appears not to have been rift-faulted,(2) and the lavas both to the north-east and north-west transgress the sides of the trough. Volcanoes seem to be concentrated along tectonic lines. The main centres of volcanic activity are Rungwe Mountain, Kiejo Mountain and the Tukuyu dome. These centres are considered younger and Katete and Ngosi Mountains to be older. Smaller explosion craters, often containing lakes, are numerous. Rungwe is a composite volcano, being made up of trachytic lavas and pyroclastics; the latter have covered large areas of the surrounding country. Rungwe Mountain reaches a height of just over 9,700 ft. Kiejo is composed of basaltic lavas and phonolitic trachytes. Tukuyu is a dome and would not easily be recognised as a volcanic centre from which basaltic lavas once issued. The lavas from Tukuyu are widespread but often covered by pyroclastics. The Katete cone, just east of Rungwe Mountain, is the most heavily eroded of all the volcanoes and is of composite structure, made up of phonolites and tuffs with basalts at the base. Ngosi, which has a well-known crater lake, is built up of phonolites, phonolitic trachytes and tuffs.

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(1)GUEST, N. J. and G. P. LEEDAL 1956. The volcanic activity of Mount Meru. *Rec. geol. Surv. Tanganyika*, Vol. III, 1953.

(2)HARKIN, D. A. The Rungwe Volcanics. (To be published shortly)

THE NORTH MARA volcanic rock area has been explored by Stockley.(1) The area is comparatively small, perhaps 200 square miles. Lavas are trachytoid phonolites. In the west the thickness of the lava is from 250 to 300 ft. Faults with throws of more than 1,000 ft. occur; some faults are of upthrust type.

SOLITARY VOLCANIC CONES are to be found outside the main volcanic areas. The largest of these solitary cones is Hanang Mountain, over 11,200 ft. high, and Ufiome in the Northern Province. The Hanang cone has been nearly cut in half by erosion; possibly this part of the cone was blown out to begin with and was eroded afterwards. Some of the lavas from Hanang have been involved in rift movements.(2) The lavas of both Hanang and Ufiome are nephelinites and phonolites. Pyroclastics are also to be found in the two localities. Subsidiary craters are common in the Ufiome area and west of Hanang in the Singida District. In the latter area the craters are occupied by lakes.

Craters of a different type occur in the Malagarasi Basin. The volcanic activity here seems to have been of Kimberlite type. In the Rufiji area of the Eastern Province volcanic plugs are known to occur. A small outcrop of phonolitic lava is also found in the Tanga area(3).

BEDROCK CEMENTS, LATERITIC HARDPANS and other superficial deposits will be described in Chapter IV.

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(1)STOCKLEY, G. M. 1935. Outline of the geology of the Musoma District. *Bull. geol. Surv. Tanganyika*, 7

(2)JAMES, T. Geologist. Verbal Communication.

(3)HALLIGAN, R. In the press. The geology of the Tanga area. *Rec. geol. Surv. Tanganyika*, Vol. VI.

CHAPTER FOUR

HYDROLOGICAL PROPERTIES OF ROCKS AND OTHER DEPOSITS

Before describing the hydrological properties of rocks and other deposits in Tanganyika it must be made absolutely clear that there is no *general groundwater table* within the hard rocks and most of the sedimentary rocks, and that even in the unconsolidated sediments there is no hard and fast rule in this respect. There are, therefore, large regions which contain only small scattered areas in which groundwater can be found. In this chapter some reasons for the existence of these small water-yielding areas and an account of the progress made in finding them will be given.

The water-yielding properties of rocks, unconsolidated sediments and other deposits depend on the interstices and voids which exist within such formations. These spaces may be occupied by water and may also constitute the channels in which water can flow, either freely or impeded in its movements by friction caused by constriction of the channels or the roughness of the walls. To overcome this resistance, water moving in an aquifer must be under a pressure-head. Thus there is in nature, as in a man-made water-supply installation, a storage reservoir, a pipeline and a pressure-head.

The intrinsic capacity of rocks and other deposits to store and transmit water is due to their texture, which is directly connected with the way the rock or deposits was first formed. Subsequently, this capacity can be increased or decreased by geological processes overtaking the formation and acting over immense periods of time.

For practical purposes, when only the capacity to store and transmit water is under consideration, rocks and other deposits in Tanganyika can be divided into three main categories:—

(a) Rocks with interlocking grains; in general called hard rocks.
(b) Rocks and deposits with non-interlocking grains; which mainly consist of sedimentary rocks and unconsolidated sediments.
(c) Rocks and deposits of varying and indeterminate texture.

(a) Rocks with Interlocking Grains

When a rock is said to have interlocking grains it means simply that there is no cement or mortar or appreciable void between the mineral grains which form it. One mineral grain fits into the next like the pieces in a jigsaw puzzle. To this category belong all crystalline rocks such as granite, diorite, gabbros, etc., and most of the metamorphic rocks of the territory described as Basement rocks. Some lavas also fall within this group. From the very nature of their texture all these rocks possess few intrinsic voids and little porosity, and such spaces as may exist are of capillary size and not always connected. The fact that rocks of this type frequently yield water largely depends on complicated geological processes to which they have been subjected after their formation.

When searching for water in areas covered by crystalline rocks in Tanganyika by geological and geophysical methods, the aim must therefore be to discover the exact nature of these geological processes or events and the limits of the areas in which they have acted most favourably from a hydrological point of view.

The geological events which may change an interlocking grain type of rock from a solid non-water-yielding formation to an aquifer can be divided into four groups, which may or may not form a sequence in time and location:—

(i) *Rock deformation consisting of faults, joints, folding, etc.*
(ii) *Hydrothermal alteration.*
(iii) *Intrusive rocks consisting of basic dykes and pegmatite and quartz intrusions.*
(iv) *Magmatic contacts, etc.*

Probably the most important factor in the transformation of all rocks, particularly hard rocks of the interlocking grain type, into aquifers is weathering, which will be described under (c) Weathering. The rock deformation and hydrothermal alterations precede and, to a very large extent, regulate and localize the process of weathering.

(i) *Rock deformation.*—Tanganyika is situated in a part of the African continent where the adjustment of stresses and strains in the earth's crust, during at least the later geological periods, have to a large extent been released by faults and fault block movement in a vertical direction. Horizontal movements have been recorded, but only those of small dimensions are common. The block movements connected with faulting are known to have occurred from at least the early Karroo period, and possibly even before then, up to the present day. The newest fault scarp, of a few feet only, was formed in 1927 in the north Rukwa region. It is, therefore, not surprising that the older rocks of the territory are criss-crossed by fault lines of different ages and types. These fault lines do not occur only in the regions of the spectacular Rift valleys, but are distributed over wide areas away from the rifts.

FAULTS. Faults are, by definition, fractures in the earth's crust and are always connected with a displacement parallel to the surface along which the break takes place. The outward sign of a fault is either the fault surface itself, which may be exposed, or the ground-up or altered rocks created by the dislocation. The grooved, striated, and sometimes polished, surface of an exposed fault is known as a slickenside and, as far as groundwater is concerned, is only of interest when locating a fault line along a fault scarp. The ground-up rock has been given various names depending on the size of the particles found in it. Coarse material is referred to as a breccia; a fine, clayey material which fills cavities and is often sticky, is known in mining terminology as a gouge. There are many types of variation between a breccia and a clay gouge. The size, consistence and mineral assembly of the gound-up rock or other fault-filling material is of great importance from a groundwater point of view.

When drilling in hard rocks even the smallest faults can often be detected by the coarsening of the sands produced by the impact of the heavy percussion-drilling tools on the rock. The explanation of this is that the interlocking of the grains has already been partly destroyed by the stresses and strains set up during fracturing.

Cavities created by Faults. When a rock fracture and a displacement takes place the two sides of the fracture, the walls, move relatively to one another. If the break surface is uneven cavities and voids will be created. Such cavities, their shape, possible extension and direction, have been carefully studied in mines and excavations connected with ore deposits related to structural features. Information is, therefore, available on the most likely results of the many and varied types of faults in hard rocks in respect of voids and cavities which are, or might be, filled by valuable ore minerals. There is, however, very little exact information concerning voids and cavities filled by water.

In respect of Basement rocks in Tanganyika it would seem that a fault line crossing the general strike and/or dip of this formation yields more water than a fault parallel to the dip and strike. Examples of cross faults from the Pare-Usambara area will be given later. In granite and allied rocks the direction of the fault appears to have little influence on the yields of boreholes.

Most faults in hard rocks are attended by subsidiary fractures which lead from the main fracture at definite angles, depending on the nature of the rock and the direction and the type of stress which created the fault. Thus, in addition to the cavities and voids that may exist in the main fracture, a network of openings or porous crushed-rock material is formed in which water can be stored and move to lower levels. This network may cover a far larger area than the actual main fault zone itself. Practically all boreholes in Basement, granitic and allied rocks show sub-artesian, rarely artesian, rise of the water level above the point where water was first struck. This rise, or head, is probably mainly due to the water pressure which is exerted by water stored in the higher parts of the subsidiary fault channels and network of fractures.

Extension of fault Zones. The width of a fault zone varies considerably from perhaps a few inches of strained, crushed and altered material in a minor fault to large, compound, fracture zones, spread over fifty to several hundred feet width, and which are connected with a major fault. The total extension along the strike can seldom be accurately determined, but fault lines have been traced in a general direction without large deviation for many miles.

There is little factual information in respect of the vertical depth to which cavities and minor voids remain open. On account of the downward increasing rock pressure it is unlikely that many fissures remain open to a great depth. Judging from the few mines in the territory that have reached a 700-feet level it would seem that water can be expected to this depth in connection with quartz reefs in fracture zones. On the other hand, an overwhelming majority of boreholes in granite and Basement rocks strike water either at less than 300 ft. and 350 ft. respectively, or not at all. It is, therefore, probable that in most cases small fractures and minor fault zones in hard rock are liable to close up at those depths or that weathering conditions have become unfavourable. (See graph X).

Location of fault Lines. In general it is not easy to locate the exact position of even a major fault line, and in areas covered by heavy overburden and superficial deposits such as bedrock cements and laterites it becomes even more difficult. The age of a major fault has a considerable bearing on the actual present position of the fault in relationship to topographical features such as fault scarps, rift walls and steep-sided or sloping hillsides. As an example the Rukwa escarpment, near Saza, may be quoted; here it has been found that in favourable positions the slickenside may still be discerned, i.e. the fault scarp constitutes the original fault line. Along the Pare-Usambara Mountain range results from drilling indicate that one of the original fault lines is from half a mile to a mile distant from the foot of the steep Western escarpment. Further faults appear to be located at even greater distances. At Ngerengere station the fault is several hundred yards from the actual topographical scarp line. There are also many fault lines which are so old that no topographical features remain to indicate their whereabouts.

When superficial deposits cover the ground it may be necessary to survey a large area in the neighbourhood of a borehole site in an endeavour to find outcrops of rock which may show indications or traces of a fault line, and then to project the line of strike by compass-bearing to the vicinity of the borehole site. Outcrops of quartz reefs, pegmatites and basic dykes may also indicate lines of weakness. Cross faults can often be detected by deeply cut river valleys in a fault escarpment. When rocks of different types are found adjacent to one another, it is possible to detect the existence of faults by careful geological mapping, but the trace of the fault is often lost after having been followed for only a short distance.

Borehole Location in fault Zones. In general the most successful boreholes located on fault lines and cross faults are found below the western escarpment of the North Pare, South Pare and Usambara mountains. The first results were obtained near the Bwembwela sisal estate; further successful boreholes were sunk on a cross fault south of Mazinde sisal estate where the highest yield so far met with, 10,000 gallons per hour, was struck. Useful yields have also been obtained at Same Boma, while at Lembeni, large cavities, the upper ones dry, were encountered when drilling on a cross fault and a good water-supply was struck at no great depth. A fairly large number of boreholes is situated along the Pare-Usambara escarpment, and large quantities of groundwater are used daily for the decortication of sisal.

Other useful water supplies have been struck on fault lines in the Dodoma township area. The first fault line was encountered in a Railway borehole which gave 1,200 gallons per hour as against an average of 250 gallons per hour in the surrounding weathered granite. Another fault line in the same area was intersected at 300 ft. but was found to be dry. To the south of Dodoma a wide compound fracture, intersected at from 300 to 365 ft. depth, gave a steady yield of 3,000 gallons per hour over 18 months. This fracture was filled by calcite, chlorite, quartz and other hydrothermal materials.

In general it can safely be stated that any borehole which has been drilled in granite covered by normal granite soils and which shows a yield of more than 1,000 gallons per hour has intersected a fault line or fracture of some kind. The conditions as regards Basement rocks are more uncertain, but if boreholes in these types of rocks yield more than 2,000 to 2,500 gallons per hour they have probably intersected some structural feature.

Adverse Features. As described above, faults act as storage reservoirs and conveyors of water, but, in some cases, by their very nature they can also act as drains which empty large underground storage reservoirs. The visible results of such drainage are the many springs, some thermal, located along the major rift faults. During mining and drilling operations many areas have been encountered where underground water has been drained by fault lines and subsidiary fractures. In the Southern Highlands Province the Saza Mine was comparatively dry, at least to 400 or 500 ft., underground water having been drained to the Rukwa valley situated 400 ft. below and three to four miles away. The Lossogonoi area of south-east Masailand proved unprofitable as far as groundwater was concerned; the underground drainage here is presumably to the Pangani valley.

During drilling operations in the eastern part of the Ardai Plains area south of Arusha, large dry fissures were encountered in the Basement rocks below the lavas. This region drains to the Shambarai depression, a downfaulted block of Basement rocks. The throw of the fault is not less than 1,200 ft. North of Mount Meru the Basement and lava rocks from north of Oldonyo Sambu to south of Lake Natron appear to be drained to a deep hidden rift valley running north of the Monduli Mountains and the Kitumbeni volcanic cone. In this area a number of dry fissures were met with in boreholes sunk to over 300 ft. depth in Basement rocks. All boreholes drilled in the lave formations were also dry to at least 500 ft.

A borehole sunk in a major fault line south-east of Dodoma yielded some water, but the fault line drained the water struck in the bore and the water level fell as the hole went deeper.

Another location which proved dry is above the Iringa-Great Ruaha escarpment. Borehole locations immediately above escarpments are naturally avoided as far as possible, but sheer necessity sometimes requires an experimental borehole. It is also impossible in most cases to decide beforehand to what distance from a major escarpment the rock has been drained and to what depth drainage has taken place.

Dry fissures have also been struck during drilling operations in the Isanga basin, south of Smith Sound, Lake Victoria.

Joints. No generally accepted definition of this term can be quoted. A joint is, however, a fracture in which movements, which are always very small, have taken place at more or less right-angles to the break surface, not parallel to it as in faults. Joints are of many kinds and are best developed in homogeneous rocks of the interlocking grain type, particularly in granites, basalts and other solid lavas.

The main division of joints can possibly be drawn between cooling joints which, for instance, may be developed in basaltic lavas and which give rise to the spectacular six-sided columnar lava found in Rungwe District, and structural joints which are of many kinds and will be dealt with under Weathering. As far as groundwater in hard rocks, particularly granites, is concerned it is probable that joints, in conjunction with weathering, are the most important factor in transforming these rocks into water-bearing formations.

Folding. In the main this type of rock deformation has overtaken only the older rock formations in the territory; the Basement, the Nyanzian and the Karagwe-Ankolean formations. From Bukoban times onwards only restricted areas have been subjected to folding. The Bukoban formation is folded in the Kigoma, Njombe and Musoma Districts, the Karroo in the Rufiji basin, the Jurassic in Morogoro and South Kilwa Districts, and the Cretaceous in the South Kilwa District. The Tertiary rocks of the Lindi and Dar es Salaam areas are disturbed, but whether by folding or faulting is uncertain.

Basement. Apart from the metamorphic processes which have altered plutonic hypabyssal, intrusive, extrusive and sedimentary rocks to form the Basement System, the influence of compression and folding and other stresses has left its mark on these rocks in the form of schistosity and banding. Schistosity is highly developed in mica schists, less so in the granitic and banded gneisses and quartzites, and is nearly absent in the larger crystalline dolomite bodies in south-east Masailand.

The folding of the Basement is of a very complicated nature and has been repeated during several periods, each folding period resulting in a different type of folding and rock deformation. The most important in respect of groundwater are the periods of the formation of the banded gneisses and the folding and contortion of the large bodies of limestone and dolomite which occur intermittently from near the Ruvuma River in the south to the Kenya border in the north. A younger set of folding movements has overtaken the quartzites and biotite gneisses of the Chungai area, Kondoa District, and those of the north-east Serengeti and Loliondo regions.

The result of these folding processes is a complicated pattern of strikes and dips of the Basement rocks, varying from locality to locality, and which have to be surveyed in detail for each individual borehole site. In general, the strike and dip of the schistosity, banding or any other sign of rock deformation, has a definite bearing on the possibilities of striking water in the Basement rocks. Both the strikes and dips prevailing in a borehole catchment area are, therefore, surveyed. If the strike is across the general drainage pattern the chances of water percolating into the rocks, in many cases, is greater than if it is parallel. A very steep dip is unfavourable from a drilling point of view. A dip directed against the general run of the surface drainage is also unfavourable. When a geophysical survey is undertaken in Basement areas, dips and strikes have to be ascertained, as the direction of the lay-out of the resistivity traverses depends on these factors.

There is little information as to the general behaviour of the various rock types of the Basement formation under folding stresses. Some rocks, such as quartzites, and possibly crystalline limestone and dolomite, appear to be competent in relation to mica and graphite schists and biotite gneisses, and thus cavities and voids could be created in synclines and anticlines of these rocks. As far as is known, only in two localities have boreholes been sited with the intention of intersecting certain folded beds. These localities are the Chungai area in eastern Kondoa District and the Nachingwea area of the Southern Province. In the Chungai area boreholes were sited on what is believed to be an anticlinal ridge of quartzite and at least three boreholes, four to five miles apart, intersected broken quartzite, and all showed a yield of approximately 3,000 gallons per hour. In the Nachingwea area it is reported that a syncline of crystalline limestone was successfully explored for water. Other areas such as Longido, in the Northern Province, and Kingolwira in Morogoro District may show similar conditions.

(ii) *Hydrothermal Alterations.*—As the knowledge of the importance of weathering in relationship to groundwater occurrences in hard rocks increases, a connection between hydrothermal alterations to granites and a subsequent higher rate of weathering in these areas seems to be established. The mineral epidote, which is one of the characteristic hydrothermal minerals, has been found in several basins of weathered granite located by geophysical surveys. Such localities are the Dodoma fault zone and at Humweka, north of Dodoma, two borehole sites near Manyoni, some boreholes located in the Lake Province and in the Lupa granites. It seems probable, therefore, that in areas where the granite has been hydrothermally altered favourable weathering conditions are created.

(iii) *Intrusive Rocks consisting of basic dykes, pegmatite and quartz Intrusions.*

BASIC DYKES. The importance of dolerites and other basic dykes in relationship to groundwater has for long been recognised in South Africa and other parts of the African continent. So far such dykes have played a very small part in the search for water in Tanganyika. There are several reasons for this. Many borehole locations are tied to certain limited areas in which no dykes have been found outcropping or been observed by geophysical means. The number of boreholes sunk in granite, in which most of the dykes occur, is relatively very small. The Karroo formation does not, in Tanganyika, carry basic dykes except in one small area. Superficial deposits cover most dykes and, as a result, the number of undetected dykes is very large. This fact was clearly shown by a recent geophysical survey of the Tabora region, where many dykes not visible on the surface were detected by variometer surveys.

The salinity of borehole water struck in or near a dyke has so far proved to be rather high; considerably higher than in an average granite borehole. The number of boreholes adjacent to, or in, basic dykes, is, however, small and no definite conclusions can be drawn from such slender evidence. The question of the importance of basic dykes as indicators of underground water supplies in Tanganyika must, therefore, be left to future exploration.

PEGMATITE DYKES. Many pegmatite and quartz veins have been struck during drilling operations, and in the majority of cases were found to carry useful water supplies.

The best and most consistent example is the Tabora region where practically all water supplies struck in boreholes have as a source a pegmatite vein. The yield of these boreholes, some originally over 1,000 gallons per hour, depends entirely on the number of pegmatites intersected. In some boreholes pegmatite veins were struck at intervals of about 100 ft. In this region not only the granite but a quartz chlorite schist, which, as a rule, occupies the valleys, was also found to have been intruded by pegmatite veins and dykes.

When prospecting for water in granite areas the size, direction and dip of pegmatites should be observed.

Except in mining areas few instances of quartz reefs are known from boreholes, but in such areas yields are high, over 2,000 gallons per hour where reef zones have been intersected.

(iv) *Magmatic contact Zones, etc.*—Major granite contact zones have proved difficult when explored for water. One example is the granite Basement contact zone in the Kongwa area where borehole failures were high. Contact zones between granitic gneisses and more basic gneiss or schist should also be avoided, if possible. Since geophysical surveys became a routine measure many inliers of older rocks in granite areas have been detected on account of lower resistivity. These inliers of, for instance, Basement rock in granite, have been proved to carry water, provided the size of the inlier is large enough. Small inliers in many cases, particularly at Urambo, have been found barren as far as water is concerned. This is due to a more or less complete alteration of a small inlier by the granite; in such cases the inlier becomes part of the granite and cannot, therefore, be expected to yield water.

(b) NON-INTERLOCKING GRAIN TYPES OF ROCKS AND DEPOSITS

The material of these types of rocks and deposits is derived from the decomposition and weathering of older rocks, particularly the hard rocks, and the size of the grains may vary between fine clay or lime particles to large cobbles. The grains themselves can be hard rock minerals, weathering products such as kaolin, or fragments of large pieces of older rocks. The grains may be held together by a cement or mortar of lime, silica, or even clay, or only compacted by pressure without mortar or cement. In the unconsolidated sediments the grains are arranged at random with open spaces between them. At present knowledge of the texture of sedimentary rocks in Tanganyika is not complete and a number of these rocks, particularly the limestones and coral reef limestones along the coast, may not fall within the strict terms of non-interlocking grain texture, but for the sake of brevity of treatment all sedimentary deposits have been included under this heading. The material in most sedimentary rocks of the territory has been graded to a certain degree which distinguishes them from the eluvials, cements and other surface deposits. They also contain voids which in most cases give them a degree of porosity which is characteristic. The intrinsic amount of void and other hydrological properties depends on the following main factors; the shape, size and nature of the material; the degree of sorting; the spacing and type of the original bedding and the bedding planes.

(i) *Sedimentary Rocks and unconsolidated Sediments.*—There is at present very little factual information regarding the percentage of porosity or voids either in sedimentary rock or unconsolidated sediments occurring in Tanganyika. Only a few examples indicating possible trends in the porosity of these can be given.

The KARROO sandstone north of Tanga does not show a high degree of porosity, judging by yields of boreholes sunk in undeformed sandstone. This also applies to Karroo rocks explored by drilling in the Ngerengere area of Morogoro District. On the other hand, Karroo slaty-black shales in the north-western Tanga District show fairly high porosities.

The JURASSIC limestone near Tanga has low porosity, and high yields can be expected only from solution channels and joint plains. Calcareous sandstones and limestones of Jurassic age in the Kidugallo area of Morogoro District probably possess medium porosities, but the Jurassic shales at Magindu, not far from Kidugallo, appear to have only very low porosity at the surface and none at deeper levels down to over 700 ft.

The CRETACEOUS sandstones in the Rukwa Depression have a low porosity. The Makonde sandstone of the same period, judging from the large springs which issue from it below the Newala escarpment, must have a medium to high porosity.

The TERTIARY and recent coral reef limestones along the coast show fairly high porosities and, unless the pressure of fresh water from inland is considerable, penetration by sea-water is common and can be expected.

The EOCENE limestone north of Lindi Bay has low porosity except in areas of solution channels.

The Kitunda sandstones of OLIGOCENE age outcropping south of Lindi Bay have high porosity in places.

The TERTIARY calcareous sandstones north of Sudi Bay are of low to medium porosity. The reef limestones north of Mikindani show high porosity but are penetrated by salt water.

The INLAND LAKE deposits, except limestones, diatomites and sandy layers, have low porosities.

The UNCONSOLIDATED SEDIMENTS vary in porosity to a large degree, which is to be expected from the nature of their formation. Large porosities have been found in gravel and sand beds in the Tanga township area and in the fluviatile deposits in the Dar es Salaam region also show high porosity unless kaolin has been deposited with the sands.

As in the case of hard rocks with an interlocking grain texture geological processes transform the sedimentary rocks and change their hydrological properties. The processes which, in the main, bring about such changes are: ROCK DEFORMATION; SOLUTION; both these processes are favourable; WEATHERING, which can be either favourable or unfavourable, (see (c) Weathering); COMPRESSION and CEMENTATION; the two latter both unfavourable.

ROCK DEFORMATION. Only a few instances of rock deformation due to faulting are known from boreholes sunk in sedimentary rocks. In one locality in the Kilulu area of Tanga District boreholes situated in a faulted zone show good yields from Karroo sandstones. It is also possible that a high yield at Moa Sisal Estate, north of Tanga, also in Karroo rocks, should be attributed to the same cause.

Folded sediments have so far only been explored by drilling in the Lindi Township area. Until recently a landward dip of the strata due to folding has been assumed in this locality and the salinity of the borehole waters caused by sea-water penetration seems to bear out this assumption. A landward dip anywhere along the coast would create favourable conditions for penetration by sea-water.

SOLUTION openings and caves in Jurassic limestone are well-known in the Tanga region. Unless such openings are struck the limestone is a poor aquifer. Cavities up to 30 ft. in depth have been encountered at Maweni Prison; these were, however, dry. Long dry tunnels have been found in the Mkulumusi River area; this river flows underground for considerable distances. The Eocene limestone to the north of Lindi provides several springs which issue from solution openings.

COMPRESSION of the Jurassic shales of the Magindu area may be the cause of the low porosity of these rocks.

On the whole the yield of water from the sedimentary formation exceeds that from the hard rocks, and the maximum yields are considerably higher. Further information will be found in Chapter IX, Borehole Statistics.

(c) ROCKS AND DEPOSITS OF VARYING AND INDETERMINATE TEXTURE

(i) *Older supracrustal rocks.*—The older supracrustal rocks of the Nyanzian and Kavirondian show great contrasts in texture due to the several origins of these rocks. The texture of the basic and acidic lavas is more akin to the "hard rocks". The banded ironstone formation, on the other hand, may be hot spring deposits chemically precipitated in sea-water giving them a banded appearance and uneven texture. The Kavirondian rocks are, in many cases sedimentary in origin and some could be classified under the non-interlocking grain type. Many, however, show metamorphic alterations. In general, the banded ironstone rocks are contorted and tightly folded, which makes it extremely difficult to find correct sites for boreholes. The schists and the basic lavas will be referred to under Weathering. The number of successful boreholes sunk in the older supracrustal rocks is relatively small and, therefore, no general conclusions can be drawn as to the potential water-bearing capabilities of these rocks.

(ii) *Karagwe-Ankolean rocks.*—These rocks, as described in Chapter III, are metamorphic sediments. The texture of the schists, phyllites and quartzites varies considerably and, in consequence, the water-bearing capacity of the different layers is not uniform. In Bukoba District the Karagwe-Ankolean formation shows simple folding, and it has been found that, on the whole, only the quartzite beds carry water, not the interbedded schists. For topographical reasons, however, the quartzites can only be intersected by boreholes sited on the slopes of the ridges which form part of the anticlinal limbs. In the synclines the quartzites are beyond the reach of economic drilling. In east Bukoba District water does, however, occur in the schist.

(iii) *Younger lavas and pyroclastics.*—Many of the LAVAS which fall within this group are vesicular due to the presence of gas which could not escape from the molten lava and thus created cavities. Vesicles or cavities can be filled by minerals and such lavas are known as amygdaloidal. Primarily, the vesicles are not inter-connected, but during flow processes and weathering processes they may be joined up. The total amount of voids in a lava is very large and the fact that a number of these cavities in vesicular lavas must be connected is borne out by the "blowing" of certain boreholes sunk in such lavas. Several "blowing" boreholes have been encountered in the Arusha area. The alternate sucking and blowing of these boreholes is due to the changes in barometric pressure during the day; this phenomenon is well-known and has been studied in the Hawaiian Islands. The individual vesicular lava flows in the Arusha area are approximately 30 ft. thick, and many of these had been weathered before the next flow was erupted. The main difficulty in respect of groundwater in vesicular lavas is not the lack of voids but the absence of solid beds which would prevent the water from percolating below the economic depth for drilling. A borehole sunk at Loljoro, south of Arusha, did not strike water until a depth of nearly 900 ft. had been reached; the total depth of this borehole was 1,063 ft., but the yield could not be estimated as the water did not rise in the hole.

Pyroclastics. The pyroclastic deposits, in the sense used here, are of many origins. They can be waterlain by the condensed steam from volcanic eruptions, or formed by red-hot ashes or pumice having been blown out from volcanic vents or deposited during other volcanic processes. The water-yielding capacity of such deposits is, therefore, generally unpredictable, particularly those laid down in the Northern Province. Certain beds yield small quantities of water and then dry out. The lack of impervious beds, such as agglomerates, which would prevent water from percolating to unknown depths is the main difficulty. A criterion as to whether a borehole in lava or pyroclastic deposits will provide a permanent supply or not, is the rise of the water level after it is first struck. If the rise is steadily maintained after pumping ceases the chances that the supply is permanent are fairly good and indicates the presence of an impervious layer which holds up the water. Should the static water level drop, or if the rise is originally very small, the supply is uncertain. Many pockets of water which were soon exhausted have been struck in lavas and pyroclastics.

(iv) *Cements mainly produced by Rock Weathering*.—From the point of view of texture these deposits cannot be classified with the hard rocks or with the sedimentary deposits. By nature they are more akin to the preliminary stages of soil formation. In general they have been named cements or, in particular, calcretes, if lime is part of the cementing substance or mortar; silcretes, if silicified; claycretes are bound together by clay and ferricretes or ferrocretes if iron is the binding material. The porosity or voids in these rocks vary with the type of the cement. In the Central Province, particularly in the Manyoni area where the Kilimatinde cement is developed, the porosity is slightly higher than in weathered granites. In Iringa fairly large yields of water have been obtained from the banded cements, including ferricretes.

(d) Weathering

As stated earlier the processes of weathering are preceded by rock deformation and probably by hydrothermal alterations of granitic rocks. The influence of rock deformation is chiefly due to one main factor; the faults, and particularly the joint planes, increase the area of exposure to the attacking forces of weathering. Thus with a well-developed system of three sets of joints the potential area of exposure may be increased by as much as five times in comparison with an unjointed rock.

The two main types of weathering are:—

(i) *Mechanical.*

(ii) *Chemical.*

(i) *Mechanical Weathering*.

Expansion and Contraction.—This type of weathering is the more striking and more easily recognised by the general observer than the chemical one. Bare, rounded, granite kopjes or tors, pillars and rocking-stones are met with everywhere in the central shield area of the territory. The shapes and outlines of these are in the final stages the result of mechanical weathering. During the day the sun and air heat the rock causing it to expand; during the night it cools down and contracts. Over long periods fine cracks and fissures known as joints are thereby expanded and opened up, and even solid granite eventually breaks up into small units.

The various rocks react in different ways to changes in temperature, resulting in the many types of outlines and shapes of rock outcrops in general. As far as granite is concerned these depend to a large extent on the joint system. Many granitic outcrops in the Central, Western and Lake Provinces show a rounded, egg-shaped appearance, mostly due to the influence of expansion and contraction during heating and cooling, but in some cases due to a horizontal or slightly curved joint plane. In the latter case spheroidal slabs of rock with a hollow underneath can be found, sprung from the underlying rock as if they had been under tension. The hollow sound which is often noticed when walking over a granite outcrop is due to these circumstances. Other joint systems, vertical, horizontal, or at acute angles to the surface, give rise to various types of granite outcrops, monoliths and rocking-stones, which are common in Dodoma and Shinyanga Districts, and block-strewn hillsides such as in the Singida District. The best examples of the rounded type of mountain are found in south-east Masailand. Mount Rotian is a large example of the egg-shaped type of weathering often called exfoliation.

Weathering followed by erosion is a continuous process and the hills and kopjes which are seen today were once covered by a mantle of decomposed rock and soil removed by water and wind action. In consequence, the shape and outline of granitic, metamorphic and volcanic rocks observed on hills and outcrops have a definite bearing on the type of joint, or fissure, system and weathering which may be expected underground in boreholes. On many occasions when boreholes have been sunk in granitic or volcanic rocks the drillers have reported "boulders" of harder rock which, in shape and size, probably agree well with the type of boulders found outcropping in the hills of the neighbourhood. Before geophysical prospecting was introduced some successful boreholes were sited in granite areas with the aid of observations on the hills in the vicinity of the borehole sites. Beds of boulders of spheroidal outline which are sometimes encountered are, however, mainly the result of *chemical* weathering of basic rocks and have been found in the basic lavas of the Nyanzian formation in the Musoma District, in dolerite dykes and in the younger olivine basalts in Mbeya District. Several boreholes have been abandoned because of boulder beds of this type.

FROST WEATHERING, which is more rapid, depends on the freezing of water in cracks and joints in rocks. When water freezes it expands and, in a short time, will destroy even the most solid rocks. Frost weathering does not play an important role in mechanical weathering in Tanganyika; only Kilimanjaro and a few other high mountains reach to the regions of the atmosphere in which frost regularly occurs.

DESTRUCTION BY EVAPORATION OF SALINE WATER may also play a part in mechanical weathering judging from the results of recent experiments by T. H. Hagerman[1] which show that when saline solutions pass through the capillary channels, of granites, limestones and sandstones, salts are formed by evaporation of the surface. When crystallising these salts destroy the structure of the solid rock. Examples of such rock destruction may be found in some of the salt-licks in the territory, and it is possible that this type of mechanical weathering is of far greater importance than may at first be assumed, particularly in connection with highly saline groundwater.

VEGETATION. Apart from the sun and heated air, a great deal of mechanical weathering is performed or aided by vegetation. The roots of trees and bushes penetrate into fissures and crevices in the rocks in search of water, enlarging them and breaking up the rock. The Ugogo fissure wells are sunk on such indications. Many residual hills are covered by vegetation and such hills must be considered as a more advanced stage in the weathering of the bare, treeless kopjes and tors.

(ii) *Chemical Weathering*.

GENERAL. The final products of both mechanical and chemical weathering, aided by erosional processes, are the soils. A vast amount of information is available on the formation and types of soils and their relationship to geology, climate, vegetation and age. Far less is known of the results of the chemical weathering of rocks below the covering of soils and superficial deposits. This is partly due to the facts that these results are more difficult to observe and that the great majority of boreholes drilled for water, at least in Africa, are sunk by percussion drills, the samples obtained from this type of drilling consisting of a rock-powders which do not readily lend themselves to accurate and detailed examination and analysis.

The soil-forming processes start with the weathering of the mineral constituents of rocks and the type of the end-product or individual soil depends on how far and for how long these processes have been allowed to continue. On the above grounds it can be assumed that rock-weathering below the mantle of soils and superficial deposits proceeds on similar, although not perhaps identical, lines as soil formation in its *preliminary stages*. Of all the many agencies contributing to the weathering of rocks, water, with the solutes and gases contained therein, is the most important, and wherever water can penetrate and find its way chemical weathering starts, and water remains the prime mover and the most active agent from the beginning to the final breaking up of the rock.

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[1]HAGERMAN, T. H. 1956. Teknisk Tidskrift. No. 13. Salt Movements in Rocks.

The main cycle of the chemical weathering of rockforming minerals to soils is progressive, in so far as minerals unstable under the conditions prevailing during the process of chemical weathering are replaced by more stable ones. This replacement is accompanied by the removal of certain elements or compounds in solution or in colloidal form, base exchange, oxidation, reduction and hydration of the minerals that remain. The end products of the true, tropical, chemical-weathering and soilforming processes are deposits of hydrous aluminium and iron oxides. Such deposits have, in Tanganyika, so far only been reported from the east Usambaras and the west Mombo area. The bauxitic soils of the east Usambara Mountain are to be found in an area of high rainfall and presumably good drainage under a tropical rain forest. Similar conditions exist in the eastern Uluguru and Usagara mountains, and it is, therefore, possible that bauxitic soils may also exist in these localities. The old soils and other formations formed by weathering which are generally found in the granitic areas of the Southern Highlands Province are of kaolin type, the thickest section, about 150 ft., found in the Malangali area consists of pink kaolin clays, mainly made up of aluminium silicates and a subordinate amount of iron oxides. During the transition from a solid, unweathered rock to the final end-product stage, which is seldom reached, a chain of reaction has taken place which results in the formation of a sequence of clays and hydrous minerals; this sequence under soil-forming conditions is well-known. The fundamental reason for the stability or non-stability of the minerals of the sequence is also known and is directly connected with their internal molecular or atomic structure. Broadly speaking the common rock minerals found in the hard rocks of the territory are susceptible to weathering in the following order, from highly resistant to less resistant; quartz, potassium feldspar, plagioclase feldspar, biotite, hornblende and other magnesia iron minerals down to limestone and gypsum, the last two being the most easily decomposed. Muscovite seems to be resistant and has been found together with graphite in calcareous sandstones of the Jurassic in the Kidugallo area.

Signs of Weathering. The elements which are derived from the weathering of the above minerals and which are soluble or removable in colloidal form and are found in groundwater are discussed below.

Calcium, magnesium and sodium are the subjects of routine analysis and their occurrence is treated under the Geochemistry of Groundwater. Potassium, alumina and silica are not often found in quantity in ordinary groundwater. It is, however, known that during certain periods, particularly the Pleistocene, a large amount of silica was deposited in the Lake Rukwa area and in the *mbuga*-type limestones and clays in the Dodoma District. The evidence of this is the presence of the diatomaceous clays found in lake beds at Saza and in other localities of the Lake Rukwa region. In the Central Province, diatomites have been found in the Ilindi, Makutopora and Goima *mbugas*, north and north-west of Dodoma. Furthermore, many *mbuga* limestones in the Central Province carry silica precipitated with the limestones; the nature of this silica is not perfectly known. It must, therefore, be concluded that a large amount of silica in solution or colloidal form was carried by overland drainage and possibly by groundwater during the Pleistocene period. Silica accounts for about 8 per cent of the T.D.S. (total dissolved solids) in the Dodoma township water derived from the Makutopora *mbuga*.

Iron is seldom found in colloidal form or in solution in borehole waters from hard-rock areas. The reason for this may be either that weathering has not progressed far enough, or that iron has been absorbed into clay minerals, or occurs only as sands of Fe_2O_3 or F_3O_4.

Potassium occurs in smaller quantities than might be expected from the amount of potassium feldspar present in metamorphic rocks and granites. However, potassium feldspars are resistant to weathering and the element is known to be absorbed in clay minerals, and these two circumstances may account for its scarcity in borehole waters.

Most rock-forming minerals contain aluminium in the form of silicates, rarely of oxides. During the complete soil-forming process these aluminium silicates gradually lose silica, forming the various clay minerals and finally only kaolinites and hydrous oxides of aluminium and iron remain as the end-product. Thus the total percentage of the element aluminium remains fairly constant throughout the weathering and soil-forming process, but relatively the proportion of aluminium in the soil rises. This also applies to iron.

Clay minerals are not frequently found in groundwater derived from Basement or granite rocks. Only a few boreholes remain cloudy after 12 hours pumping, and the indications are that, when a useful water-supply has been struck in hard rocks, weathering has not advanced to the extent of forming colloidal clay minerals, or the clays as they are formed have been removed by groundwater in colloidal form; alternatively, the solutes in the water have flocculated the colloidal clay matter which remains uncompacted in the rock itself. Saline waters, whether surface or derived from boreholes, are invariably clear.

There are a number of other factors which may influence the trend of weathering in underground conditions. Groundwater, as a rule, contains more salt in solution than surface-waters found in soils. The type of salinity may affect the general progress of weathering; it is known that surface coatings of salt can protect minerals such as quartz and feldspar from further rapid decomposition. The presence in excessive quantities of Na, K, Ca and Mg in solution may influence base exchange both in minerals and in the water itself. The pH of groundwater has, in all probability, a decisive influence on many chemical reactions. Furthermore, below groundwater level the opportunity of oxidisation is not always present. As a rule iron oxides are not encountered in borehole samples from alluvium or hard rock below the dry-season water level, but perched and temporary groundwater reservoirs can sometimes be recognized by the presence of iron oxides, and it is therefore advisable to examine borehole samples for signs of these oxides.

Other visible signs that can be observed in borehole samples from hard rocks is the clouding of the plagioclase feldspars, which is but very rarely noticeable in potassium feldspars. The occurrence of a greenish-blue chlorite formed from biotite is another sign of weathering. For visual examination, borehole samples should be washed and panned in a prospecting pan. The grain size of the rock-powder from *hard* rocks is, in many cases, a good indicator of the state of weathering and structural conditions of the rock, and potential drilling-speed can be judged fairly accurately from such samples. Conversely, when drilling-speed is known the state of weathering can be estimated.

The sedimentary rocks were originally formed from material derived from hard rocks and thus their formation can be said to oppose, or inhibit, the continuation of the process of rock-weathering and soil-formation. When such rocks are exposed to renewed weathering the normal weathering process is resumed at the stage where it was interrupted by the erosional processes. For this reason, elements and compounds not met with in waters from hard rocks have been found in sedimentary rocks and deposits. For instance, boreholes at Mtwara and Pangani Districts carry iron and manganese salts in solution. Larger amounts of calcium may also be present in waters from sedimentary rocks.

In general, the total rate of weathering of rocks is dependent on two major factors; THE EXTERNAL FACTOR due to meteorological conditions, rainfall, temperature, vegetation and time, and the INTERNAL FACTOR which depends on the structure, texture, state of deformation and mineral contents of the rock.

EXTERNAL FACTOR. Rainfall and temperature, particularly the former, influence the rate of weathering, which appears to be speeded up under warm, humid conditions. It is possible that in humid areas weathering of the bedrock has progressed too far; i.e. the voids originally opened up have subsequently been closed by more advanced weathered minerals, such as clays. Such excessive weathering may also be connected with major fault lines and saline groundwater.

It is not possible to ascertain how much influence vegetation has on the rate of weathering of rocks below the soil-cover. The amount and type of water which is surplus to the demands of the vegetation and thus is allowed to reach bedrock must, however, have a profound effect, not only on the yield of boreholes, but also on the rate of rock weathering.

INTERNAL FACTOR. The influence of the internal factor on weathering, i.e. the type of rock, texture, structure and deformation, is better known and understood, and of greater importance as far as the search for groundwater is concerned, than climate and vegetation. The order of susceptibility to weathering of rock minerals has been referred to above and, other conditions being equal, is a guide to the distribution and rate of weathering that can be expected in hard rocks, particularly the metamorphic rocks of the Basement.

Basement rocks. When examining borehole logs from these rocks it has been found that in a very high percentage of boreholes water was struck in the basic rock types of the system such as biotite gneisses, some hornblende gneisses, biotite-hornblende-garnet gneisses, amphibolites of many kinds, graphite limestones, calcareous rocks and dolomites. There are but few cases of water having been found in the acidic types such as in gneissose granite, granitic gneisses or in granulitic rocks when undeformed. This is a direct consequence of susceptibility to rock weathering. The magnesium and iron-carrying rocks are more easily weathered than rocks richer in quartz. As far as the granulites are concerned, it is possible that the pressure and temperature conditions under which they were formed have some bearing on the fact that such rocks are poor aquifers when not fractured. Limestones and banded-graphite schists are the most easily decomposed.

Basement rock areas in which it appeared that weathering has progressed deeply and, from a water-yielding point of view, has become excessive, have been encountered in the following localities; at Makutupa on the southern slopes of the Kiboriani Mountain in Mpwapwa District, where boreholes were sunk in weathered biotite gneiss to over 500 ft. without striking a useful water supply (the water struck was saline), in the Busi Chandama area in eastern Kondoa District, where Basement rocks were weathered to approximately 400 to 500 ft. from the surface (water supplies were small) and in the Lake Manyara region, where a highly-shattered and weathered zone of Basement rocks was intersected in one borehole to a depth of more than 500 ft. (the yield, though small, was usable but the salinity was relatively high).

Extensive Basement rock areas in which rock-weathering appears to be less than normal have been found in the Longido region, north to the Kenya border and in the northern Kongwa and south-east Masai country. The Basement rocks of the mountain valleys to the south-east of Mpwapwa also show little sign of weathering.

From statistics based on depth to water struck it appears that weathering does not, in general, penetrate beyond 350 ft. and, as a rule, is limited to certain bands or layers of basic (Fe-Mg) rocks, but area weathering in the shape of basins have been geophysically surveyed in the Kongwa region and at Toronto sisal estate in Lushoto District.

One rule of experience applying only to boreholes in Basement rock should be mentioned, whether it is directly connected with the process of weathering or not. ***When drilling in Basement rocks it nearly always pays to go deeper once water has been struck in rock, even if the quantity first obtained is small. This rule of experience should not be overlooked.***

Granitic Rocks. The rate of weathering in granitic rocks depends to a very large extent on the deformation to which such rocks have been subjected, particularly in the form of joint and fault systems. Unless deformation has taken place or the granite has been altered hydrothermally the weathering of the granitic regions of the central shield has not penetrated to any great depth. A thickness of 30 ft. of weathered granite below soils and cements seems to be the most common in this area.

The boundary surface between weathered and unweathered granite shows, when known, a very uneven outline. This is particularly noticeable when only a shallow mantle of weathered rock occurs. In the more deeply-weathered areas which owe their existence and position to a fault or joint system it has been found that the decomposed portion of the granite forms basin-shaped bodies. In some localities several of these basins are situated adjacent to one another but are not necessarily connected; often there are ridges of hard rock between the individual basins. Judging from geophysical surveys, the results obtained during drilling and borehole-water analyses, individual weathered basins are not very extensive, but several basins may be inter-connected and thus cover an area of as much as one square mile of weathered rock surface, constituting a potential groundwater reservoir. Such large basins probably exist under the limestone *mbugas* in the Central Province and in some places in the Lake Province. In other regions where weathering appears to extend over a large tract of country, such as the Dodoma township area, many separate basins are known to exist. The water obtained from the basins varies considerably in salinity; some basins carry potable water, others saline.

The actual thickness of the decomposed granite in the weathered basins of the central shield varies considerably, not only within one restricted area but also from district to district. In many cases the weathered granite is covered by a bedrock cement, indistinguishable in a borehole sample, and thus the boundary between the two rock types is uncertain. The cements are apparently not the result of the present-day weathering conditions which are now proceeding underneath them. To give a rough idea of the thickness of weathered granite below the soils and superficials in the basins explored by drilling a few figures are given below.

In the Western Province in the Urambo, Kaliua and Nzega areas this thickness does not exceed 130 to 135 ft. of weathered granite. Thicknesses of 80 to 100 ft. are fairly common, but the average is considerably less. In the Central Province exceptionally large thicknesses of weathered granite of over 300 ft. have been recorded in two boreholes north and north-west of Dodoma. It seems that in both these cases the deep weathering was connected with hydrothermal alterations, as epidote was found in the borehole samples. A third borehole with epidote north of Dodoma showed a thickness of weathered granite of 163 ft. Two of the above-mentioned boreholes were complete failures and the third struck only a small quantity of water. It seems possible that weathering in these three cases had proceeded too far. In areas outside the hydrothermally altered granite in the Central Province the weathered granite mantle rarely exceeds 150 ft. in thickness, more commonly it is between 50 and 100 ft. The same figures seem also to apply to the Iringa granite area.

The actual location of weathered basins in the areas of granitic rock does not always coincide with the topographic features of the country; in other words it is not always confined to valleys or depressions. An example is the Ubena Plain country in Njombe District where granite bedrock is outcropping in the valleys and river-beds but where the covering of superficial deposits and probably weathered rocks is fairly thick on the ridges between the drainage lines. In one valley in the granite area north-west of Iringa the southern slope of the valley is deeply covered by superficial deposits, but the northern slope has only a scanty cover; in consequence, boreholes on the southern slope were successful while those on the northern were failures. In the plains region of the Central Province the covering of superficial deposits is very unevenly distributed and borehole sites have been largely confined to valleys covered by mbuga deposits. Only in the western Kongwa District have successful boreholes been located in granitic rocks above the general level of the drainage lines.

In the Itigi area the *mbugas* filled with calcareous deposits show a certain amount of weathering below these deposits; other *mbugas* do not. West of Itigi itself water is found in inliers of Basement rocks consisting of biotite-garnet gneisses. These rocks are apparently more easily weathered than the surrounding granites and thus basins are formed. In the Tabora region no major weathered basins have so far been discovered in the granite. Geophysical exploration indicates that the rock underneath the valleys to the north and west of Tabora is a phyllite consisting of quartz and chlorite; the hills and rock outcrops are granite. The phyllites as well as the granites are penetrated by pegmatite and quartz dykes and veins which weather and carry the only deep groundwater present in the region. In the Lake Province weathered basins in granite are mostly confined to lower-lying ground, but no general rule exists.

Nyanzian. In general, drilling in this formation has been accompanied by many failures particularly in the banded ironstone formation. This formation appears to be resistant to weathering in the Geita area and elsewhere and occurs in hills and mountains rising above the general level of the countryside.

The volcanic rock series connected with the banded ironstone, particularly ash and tuff beds, weathers deeply and in mines where groundwater has been struck in these beds "mud flows" have been encountered and whole levels have collapsed.

The lava flows of the Nyanzian in the Musoma area have weathered into boulder beds which have caused difficulties during drilling to a depth of approximately 120 ft. The Nyanzian schist formation in Singida District has, in some areas, weathered to 170 ft. and yields water. In others, where weathering only reaches to 50 ft., no water has been found.

Karagwe-Ankolean. The quartzites of this formation are resistant to weathering, but the schist weathers deeply to bright yellow and red clays. These clays are aquicludes.

Bukoban. Very little is known regarding the weathering of the Bukoban formation. The water from one borehole sunk in the Bukoban sandstone near Kigoma contains a quantity of colloidal alumina and iron. The sandstone is ferruginous and, from the presence of alumina in the water, it is probable that the material which forms the sandstone was derived from a highly weathered hard rock. The extent of present-day weathering is not known.

Karroo. In the north-west Tanga area a black slaty shale occurs towards the bottom of the Karroo formation. This black shale is not highly weathered, but it is a good aquifer, probably due to a well-developed joint system and, possibly, solution openings. The Karroo sandstone from the same area seems to be solid and unweathered. No iron or alumina appears to be present. Other Karroo sandstones from the Southern Province are solid, well compacted and unweathered.

Jurassic. In the oolitic limestone area of the Tanga District weathering by solution and removal of calcium bicarbonate is fairly widespread. The area distribution of the solution channel and cave formation is still imperfectly known, but appears to be concentrated round the Mkulumuzi and Sigi river drainages. In this region long dry tunnels and caves are known to exist. Caves have also been encountered during drilling in the old Maweni Prison area.

The calcareous mudstone strata below, or interbedded in, the limestones are not weathered, nor do these strata carry water even at a depth of 700 ft.

The Jurassic calcareous sandstones in the Kidugallo area are formed by weathered hard rock material from the adjacent Basement formation and show little sign of weathering except by solution of the lime cement. The oolitic limestone of the same area has so far not been found to contain any large solution channels or caves.

The Jurassic shales of the Magindu area are slightly weathered to about 50 ft.; from this point to a depth of over 700 ft. no weathering has taken place and no water was encountered during drilling.

Cretaceous. The sandstones belonging to this formation, and found on the Makonde plateau, seem loose and fairly easily weathered, and solution or other openings must occur within the body of the sandstone as large quantities of water issue from the base of the plateau. These quantities cannot entirely be accounted for by vertical fissuring or bedding planes in the rock.

Tertiary and Recent formations along the coast. The Eocene limestone north of Lindi is considerably weathered, judging from the pink soils which cover the surface. Solution openings also exist which give rise to a number of springs situated fairly high above sea level.

The Oligocene sandstone at Kitunda, south of Lindi Bay, appears to be pervious; probably the cement or mortar has been removed by solution. The younger limestones, calcareous sandstones and coral reef limestones of the Sudi Bay area vary. The limestone and coral reef limestone must be channelled to a large extent as salt water penetration is common. Young alluvium in the south Mtwara region yields water containing iron and manganese. This alluvium must be derived from material produced by an advanced type of weathering, or the water from the alluvium passes through beds of weathered formation before reaching the point of extraction.

CHAPTER FIVE

SPRINGS

A great number of springs occur within the territory, but their geographical distribution and local concentration is uneven. The main spring areas are to be found in the neighbourhood of the rift valleys and rift scarps and in the regions intersected by major fracture or fault systems. In other areas springs are tied to certain formations such as limestones, quartzites, lavas and sandstones. Large areas of the interior are, however, devoid of springs.

A general classification of springs can be made according to many different systems. The system used in the following is a part adaptation of the classification made by the eminent hydrologist, Oscar E. Meinzer, in his "Outline of Groundwater Hydrology," (U.S.A. Geological Survey. Water Supply Paper 494).

The springs are classified according to the nature of the force which brings the spring water to the surface. Only two main headings are used:—

(a) Gravity Springs.

(b) Springs of deep-seated origin flowing as the result of agencies other than gravity

This system of classification appears to be the most satisfactory for practical purposes in this territory. The springs of category (a) are, in general, potable and useful. The category (b) springs are often saline or carry high amounts of fluorine, and, in many cases, contaminate large areas of groundwater with fluorine.

(a) GRAVITY SPRINGS

The main areas in which such springs occur are confined to the sedimentary rocks of the coastal belt, the Karagwe-Ankolean and Bukoban formations and the regions covered by volcanic rocks.

Southern Province. Examples can be quoted from the Southern Province in the Lind area. In this region fairly large quantities of water issue from solution openings in limestones north of Lindi and north of the Mbemkuru Valley. South of Lindi Bay, springs rise from a sandstone and are probably of the type known as depression springs, i.e. due to a depression having cut into a local groundwater table. The springs occurring at the foot of the Makonde Plateau may also fall into this group. The spring on Kilwa Peninsular issues from below a hill of unconsolidated sands. The water is brought up to the surface by an impervious layer. This type is known as a contact spring. In the Kisarawe District in the *Eastern Province*, several depression springs occur within an area of kaolin-carrying sediment in the vicinity of Kisarawe Boma.

Tanga Province. Springs in the Karroo rocks occur on the border between Kenya and Tanganyika. One spring is probably of the contact type. The mud-volcanoes at Moa close by are, in all likelihood, of the artesian type of springs.

Lake Province. In the Karagwe-Ankolean of the Bukoba, Biharamulo and Nzega districts many springs issue on the contact between the quartzite and the schist or phyllite formation. The Bukoban formation also shows a number of contact springs within the districts where this formation is to be found, such as in Bukoba, Musoma, Kigoma and possibly in west Loliondo.

Gravity Springs in the BASEMENT rocks are often tied to the crystalline limestone formations Such springs occur at Kijungu, below Talamai Mountain and also in Handeni District. The nature of the springs occurring at Mlali, Sagara and Kongwa in the Mpwapwa District, both to the north and south of Kiboriani Mountain, are difficult to classify, but they possibly belong to the fissure type of springs.

From the NYANZIAN formation a spring at Ikoma can be mentioned; it issues from the schist belonging to the Meta-volcanics.

Many small seepages occur throughout the territory, these are borderline cases and cannot strictly be classified as springs. Such seepages occur particularly in the high solitary mountains of Masailand and are by nature more akin to small effluent streams than to springs.

The Lava Areas of the Northern Province and the *Southern Highlands* show numerous examples of contact springs. The largest springs in the territory are on the south-eastern slopes of Kilimanjaro at Miwaleni and in the Kikuletwa River bed. Other large springs, which probably also belong to this type, are to be found near Mbeya, below the north-western Lake Manyara escarpment and at Mangola on the Lake Eyasi flats. At Oldeani the impervious rock above which the springs issue is often a bed of agglomerate, and on Mount Meru a solid lava bed. The impervious rock in the contact springs of Lake Eyasi is of Basement type. As stated above, the water from gravity springs is, as a rule, of low salinity and potable.

Springs in the U.S.A. have been grouped in eight classes according to magnitude of discharge. The three highest of these classes are enumerated below:—

First	100 cusec. or more.
Second	10—100 cusec.
Third	1—10 cusec.

If this classification be applied to Tanganyika, this territory could possibly show one or two of the first magnitude situated south-east of Kilimanjaro and in the Kikuletwa River bed, three or four of the second magnitude at Mbeya and Eyasi, and possibly also in the Lake Manyara region, but of the third magnitude there would probably be a great number from various areas. The springs of the first and second magnitude in this territory all rise in volcanic rocks.

(b) Springs of Deep-seated Origin flowing as the Result of Agencies not connected with Gravity; also termed Juvenile Springs

Springs classified under this category are numerous within certain restricted areas of the territory. The water issuing from such springs has certain common known properties as enumerated below. It is slightly alkaline to alkaline and contains sodium bicarbonate, in some cases sodium carbonate, sulphate and chloride. Although in certain localities large deposits of lime travertine may occur around spring vents, and in the Lake Natron area deposits of magnesite are to be found, the calcium and magnesium content of the water issuing from the present spring vents is relatively low. The silica content is relatively high. Fluorine is almost invariably present in toxic quantities. Potassium may, to a very restricted extent, replace sodium, but this is not common and the proportion is small, of the order of 0·1 per cent. In addition to the soluble salts the water contains gas and the springs emit bubbles of gas. This gas is, in general, carbon dioxide, but nitrogen can be the main gas present. Inert gases have also been found, both in cold and hot spring vents. The water issuing from the springs is often hot, i.e. of a higher temperature than the surrounding ground temperature. A spring of this type occurs in a hot spring area in the Songwe Valley, Mbeya District. This spring area was investigated by T. C. James of the Tanganyika Geological Survey and a short description is quoted from his report:

> "The vent is situated on the crest of a ridge of travertine limestone about 100 ft. above and 300 ft. away from the Songwe River to the north. The bubbling of the gas in the spring is audible for a distance of 100 yards. The water level of the spring appears to be static. The temperature of the spring is that of a hot bath, about 130°F."

A full analysis of the water and the gas of this spring is given in the chapter on Geochemistry of Groundwater.

A discussion of the known and unknown facts in respect of the hydrological conditions connected with the occurrence of non-gravity type of springs is given below.

(i) *Known Facts.*—(1) The majority of springs, whether hot or cold, which contain gas, are encountered within the rift valleys or block-faulted regions connected with major rifts, but some are also found within other fault and fracture zones. Springs in such localities do not necessarily occur adjacent to volcanic rocks, the outcrops of which are observable on the surface. (2) A small number of springs occur in volcanic rocks. (3) Vents are often found connected with basic dykes or intrusions (James). (4) The springs, in many cases, do not issue from the fracture itself. The spring water can find its way through devious channels and rise at points, the location of which conforms to the occurrence of gravity springs. (5) The presence of gas in the water, whether hot or cold, is characteristic of a non-gravity type of spring. The dissolved total salts are not always high, but a fluorine content of 4 p.p.m. and over points definitely towards a non-gravity origin of the spring water. B, Sr, Li, Ba and Fe are absent or present in very small amounts. (6) The water is, in general, clear and contains no colloidal matter. (7) A normal spring temperature is approximately 130°F. with a ground temperature of 80°F. (8) The flow from known springs varies from a mere seepage to a maximum yield of the order of 1¼-1½ cusecs.

(ii) *Unknown Facts.*—How is the water forced to the surface in a hot or cold gas-carrying spring? According to investigations carried out in the U.S.A.(1) and Iceland in connection with hot springs, certain fundamental facts have been established. (1) According to these investigations groundwater must be able to penetrate to a depth where it can be heated by steam of juvenile origin which, in the process, is condensed and releases its latent heat. The quantity of heat which can be conducted through rock or by gas is not considered sufficient for the purpose. It is not known if the pressure of the steam is sufficient to force the water to the surface. (2) The gases contained in the water, particularly when this is cold, may create conditions similar to those which are obtained in an air lift pump, but a gas lift, like an air lift, requires an unbroken pillar of gas-free groundwater to surround the spring channel and vent. It seems most unlikely that such a pillar of groundwater can exist to the depth which is involved. In conclusion, the nature of the force which brings the spring water to the surface cannot be established with any certainty. (3) What is the proportion of recirculated groundwater, i.e. meteoric water, to juvenile water, in a non-gravity spring? Certain facts have been collected by the investigations mentioned above. If the flow of groundwater to a hot spring be interrupted by, for instance, the drying up of groundwater in the summer or by artificial means, the temperature of the spring rises and, in extreme cases, the spring is transformed into a fumarole issuing only steam and gas. The temperature of the spring may thus, under certain circumstances, give an approximate indication of the proportion between groundwater and juvenile water in the spring. A calculation based on temperature consideration in Lassen Peak National Park showed a proportion of 13 per cent juvenile water to groundwater. Great variations must, however, be expected as very many unknown factors operate in the spring vents and channels. (4) The source of the heat, gases and certain of the elements in the non-gravity spring waters is, in all likelihood, a magma body at depth, either crystallising (when large quantities of gas and vapour are released), or only cooling at some unknown stage in its intrusional development.

The main known spring areas of non-gravity type are to be found in the following localities:—

Southern Highlands Province.

Mbeya District. In the Songwe Valley issuing from below the western rift escarpment the region is occupied by lake beds and Cretaceous sediment. In the Rukwa depression at Ivuna the spring water has broken through lake beds but also occurs in Cretaceous sandstones. The temperature in a borehole at approximately 200 ft. depth was 50°C. Further north in the Rukwa valley other thermal springs are to be found. Similar springs also occur near the Great Ruaha River west of Sao Hill.

Rungwe District. Several hot springs occur in fracture zones near Basement fault contacts.

Iringa District. At Tosamaganga hot springs have been investigated; several others are known but have not been explored.

(1)The Volcanic Activity and Hot Springs of Lassen Peak by Arthur L. Day and E. T. Allen. Carnegie Inst. Washington, 1925.

Western Province. Uvinza is a well-known salt spring area; other springs are reported from the Rungwa River area.

Lake Province.

Shinyanga District. At Ibadakuli and other localities of this area.

Musoma District, and in North Mara District a number occur in granitic and metagabbro rocks.

Northern Province. In the Lake Natron, Manyara and Balangida depressions and in the western part of the Serengeti Plains and, in all likelihood, in the eastern Mount Meru area.

Tanga Province. There is a record of a fluorine-carrying spring, possibly of non-gravity type, at Msima in the Handeni District.

Eastern Province. Hot springs occur in south Morogoro and in Rufiji District at Utete.

Central Province. A number of hot or cold non-gravity springs issue along the block-faulted rift escarpment from east of Singida to well south of Manyoni. Nondwa in Dodoma District is the most southerly spring locality. The cold gas-carrying spring at Kondoa is well-known and has been used for many years for drinking and irrigation purposes.

Two of the non-gravity type of springs are utilized for production of salt, namely the Uvinza and Ivuna springs. Many others are saline or unpotable on account of a high fluorine content. The juvenile type of spring is also the source of fluorine contamination of large areas of groundwater in the territory, particularly in the Wembere and western Serengeti.

Juvenile springs in Tanganyika are at present being investigated by T. C. James, Geologist of the Geological Survey, and fuller information on this type of spring must await the results of his survey.

CHAPTER SIX

WATER-HOLES AND WELLS

Water-holes and, to a very minor extent, lined wells, contribute by far the largest proportion of groundwater consumed by the rural population and its livestock. In arid districts where there are no perennial streams, or only solitary ones, such as in Dodoma and Singida districts, perhaps only 10 per cent of the total groundwater consumed is derived from boreholes. The remainder, at the end of the dry season when rain ponds have dried out, is obtained from numerous water-holes and a few lined wells.

Shallow groundwater occurrences accessible near the surface or in extreme cases to 96 ft. depth have, on the whole, been thoroughly explored during a great number of years by the rural native population and their predecessors in the territory who moved in from the north.

As an example of the results of native prospecting for shallow groundwater may be mentioned the many so-called fissure wells scattered throughout the Wagogo country of the Central Province. These fissure wells are excavated in the most unpromising localities, but appear to find water in small quantities in rock fissures and cavities in granitic and Basement rocks. It seems as if the natives in the early days had a definite knowledge of the types of trees and bushes which were capable of sending their roots down into cracks and fissures in search of water. During some thirty years search for shallow groundwater by the Government and the Native Authorities very few major well sites or well-fields have been discovered.

A division of the main shallow groundwater occurrences can probably best be made according to the geological formations in which this type of groundwater is to be found. A schedule of these formations is given below. The main headings are arranged in order of importance.

(a) Alluvium

(i) River-beds of non-perennial rivers.
(ii) Fan deposits below mountains or scarps.

(b) Limestone Formations

(i) *Mbuga* limestone.
(ii) Lake limestone.
(iii) Crystalline limestone.
(iv) Coral limestone and marine limestone.

(c) Lateritic Hardpan (Ironstone, murram)

(d) Eluvium

(i) General.
(ii) In the vicinity of granite tors or kopjes.

(e) Hard Rocks

(i) Fissure wells.
(ii) Weathered cavities, basins and pockets in hard rock.

(f) Beach Sands

(i) Sea-shore.
(ii) Lake-shore or old shore lines.

(a) ALLUVIUM

(i) *River-beds of non-perennial rivers.*—It is possible that more water is extracted from this type of formation than from any other. In the arid and semi-arid parts of the territory a great number of sandy and "dry" river-beds occur where water can be found near the surface all through the dry season. The movement of water in the river-bed sands presents a complicated pattern. In the Central Province there is frequently a clay layer below the sands which are seldom more than 20 ft. in thickness. At the end of the rainy season the river-bed sands are saturated with water which reaches the surface or stands only a few inches below it. Evaporation is almost as high from the river-bed sands as from an open water-surface; as the water-table drops the evaporation decreased until it ceases at the 2 ft. 6 ins. level below the surface of the sands. For a short period after the rains, water in the sands is still being replenished by effluent seepage. Later, when this seepage ceases, the water in the upper part of the river-bed moves slowly down stream leaving that section of the river-bed dry. Eventually, the river-bed will be divided into sections; where the sands are deeper it will still contain water, other sections, possibly divided by rock bars, will be dry. Within the water-holding sections, the water will still move down stream and eventually only a small area will be found carrying water; only these small areas contain permanent water holes. Many old river-beds hidden by 10 to 20 ft. of clays have also been explored by the natives in the Central Province and in such localities large concentrations of water-holes may be found in restricted areas. The reason for the concentration of water-holes in one particular spot is not always immediately clear, but in most cases depends on the following circumstances:

If a very shallow aquifer is struck, such as a thin gravel or sand layer, the rural inhabitants know from experience that the only way to extract all the water from this thin layer is to put the water-holes close together. Another reason is that there are definite tribal customs governing the use and ownership of water-holes. One group or household of cattle-owners often own or have a right over a water-hole they have dug themselves, and prefer to use this instead of a common one over which they have no control.

Sandy river-beds are extensively utilised in all districts of the Central Province. In the Southern Highlands, in the Ubena Plains of Njombe District, in parts of Iringa District and in Chunya, such river-beds are also to be found. In the Northern Province few sandy river-beds of this type exist, except in Mbulu District. In the Western Province sandy river-beds are common and are extensively used in Nzega, Tabora and Kahama districts. In the Lake Province, in Mwanza, Shinyanga, Kwimba and Musoma districts they are also utilised. Groundwater of this type is, in addition, found in all other provinces, but the main areas are the ones enumerated above. Many of these sandy river-beds can be regarded as a pipe-line traversing the arid countryside and in the aggregate supplying large quantities of water at the end of the dry season.

(ii) *Alluvial Fans.*—Such deposits are of very minor importance as providers of surface groundwater, but exist below the Chenene Hills, Dodoma District, in the Chungai area of Kondoa District and in the Kibakwe area of Mpwapwa District. Other examples can be found in Kilosa and in Chunya District below the Rukwa escarpment.

(b) Limestone Formations

(i) *Mbuga Limestone.*—In the Central Province a large number of water-holes are dug in this formation which, in general, consists of clays, marls, siliceous limestone, concretionary limestone and limestone rubble. The deepest wells sunk in *Mbuga* limestone are situated near the present Ikowa dam; they there reached a depth of 96 ft. and present the appearance of a spiral staircase. The stairs are simply sticks placed from wall to wall. In most cases, however, water is struck at far shallower depths, not more than 20 or 25 ft. Many of the *Mbugas* are flooded during the rains and, in consequence, water-holes of this type may be filled with mud, sand, etc., in the rainy season. It was noticed that, to prevent this, the local population in a well-field in East Singida District filled the deep, narrow wells with short pieces of tree-trunks and wood and put a lid on top. Examples of water-holes and wells sunk in *Mbuga* limestone can be found at Itisu, Haneti and Ikowa in Dodoma District, at Ndizi in Singida District and in the disused well-shafts east of Itigi in Manyoni District. Others occur in Masailand. The aggregate number of water-holes or well-shafts sunk in *Mbuga* limestone is large.

(ii) *Lake limestone.*—The best examples of wells sunk in lake limestone come from south-east Masailand, from the very large so-called Makami Pan approximately 35 miles long (north-south) by 4 miles wide, situated in a block-faulted area some 70 miles south of Arusha. The lake beds have a minimum thickness of 60 ft. probably far more along the western fault line. The well-fields are known as Makami and Ndedo and from them 10 to 12 thousand head of cattle are watered every second or third day in the dry season. Each field has probably between 25 and 30 wells.

(iii) *Crystalline limestone and dolomite.*—Well-fields excavated in this formation are mainly found in south-east Masailand. A large number of wells are concentrated in the two main fields at Nambarera and Ngasumet, but many others are to be found in the same region, particularly at Londergess. At Nambarera and Ngasumet the wells are often provided with a ramp down which the cattle walk to the watering troughs. The water is raised in leather buckets passed from hand to hand by four to six Masai standing in the narrow well shaft one above the other, the man at the bottom of the well standing to his waist in water. The history of these wells although imperfectly known, is interesting. Originally the wells consisted of a narrow chimney from 3 ft. to 3 ft. 6 ins. in diameter. Some years ago remains of these chimneys could still be seen in the open cuts of the ramps. Water was reached in the dolomite at approximately 60 ft. depth. It is generally assumed that the people who dug these chimney wells were of non-Bantu origin, akin to the Hottentots and that they came from the north where the knowledge of water in limestone and the construction of deep wells had spread from earlier civilizations. It is not known whether the people in question were the same as those who buried their dead in a sitting position in the cairns found at Makami and at Kitwe in south-east Masailand. These cairns were found near the wells at Makami, and in Kitwe there are good reasons to believe that an old, now abandoned well-field existed.

(iv) *Coral limestone and marine limestone.*—Along the coast a number of wells have been sunk in this formation. The water found in the coral limestone wells is frequently slightly saline.

(c) LATERITIC HARDPAN. (IRONSTONE, MURRAM)

Lateritic hardpan occurs commonly in the western part of the territory and, to a certain extent, in the Iringa District. The hardpan consists of quartz, iron oxides and alumina and many different types may be encountered. The two main types are the vesicular and the more solid. In the latter the vesicles seem to be filled with weathering material. In consequence all lateritic hardpans do not carry water; whether they originally were pervious or only have become pervious through solution and leaching is not known. It is generally considered that these hardpans belong to old weathering surfaces. In the Eastern Province in the Rufiji similar surfaces have been reported.

Hardpans may be found at varying levels and relationships to the position of the bedrock. At Tabora the hardpan is found at from 8 to 17 ft. depth and is from a few feet to 5 ft. thick. At Urambo 20 to 30 ft of this type of rock has been reported from boreholes. The Tabora water-holes and wells sunk in lateritic hardpan have given good yields. For instance, the old electric power station at Tabora relied for many years on such a supply. In the Nzega and Kahama districts the lateritic hardpan is extensively utilised by the population and Railway water supplies have been obtained in wells at Ikusule from this source. Water-holes and small ponds are excavated in this formation and the water issues from the lateritic rock above a clay layer which lies underneath. These water-holes are often situated halfway between the watershed and the streams or drainage channels in this district. The number of water-holes found in the lateritic ironstone is large. In the Sumbawanga District the laterite lies directly on the bedrock and water is found on this rock in shallow water-holes.

(d) Eluvium

(i) *General.*—Eluvium, in the sense used here, comprises a number of weathering products of rocks and other deposits which, in general, lack sorting, such as subsoils, rock rubble and non-lateritic bedrock cements. Many water-holes have been dug in these formations, and it can only be stated that water-holes sunk in eluvium are evenly distributed over the whole territory.

(ii) *In the vicinity of granite tors or kopjes.*—There is, however, a type of water-hole in eluvium which is confined to certain districts. This type is dug near or adjacent to a bare granite tor or kopje and the water supply depends entirely on the large run-off from the bare granite which collects in the sandy eluvium at or near the foot of the kopje. The best examples can be seen in Singida and Maswa districts.

(e) Hard Rocks

(i) *Fissure Wells.*—These wells have already been referred to above. The yield from such wells is, as a rule, small, but in many places is the only water available for miles. Good examples of these occur in the neighbourhood of Dodoma.

(ii) *Weathered cavities, basins and pockets in hard rock.*—In general, only a relatively small number of wells sunk by Europeans in hard rock have been successful, and most obtain their water from the weathered zones of granitic and Basement rocks. One good native well in hard rock is found at Kisima, 76 miles south of Dodoma.

(f) Beach Sands

(i) *Sea-Shore.*—Along the coast of the Indian ocean wells have been dug in beach sands at suitable places from Lindi in the south to Bagamoyo District in the north. The fresh groundwater often rests on the underlying sea-water and the water-level changes with the tides.

(ii) *Lake shores or old shore-lines.*—These formations are not commonly utilised for obtaining surface water-supplies, but examples can be found in the Bahi depression region of the Central Province and probably south of Saza Mines, Chunya District.

(g) Prospecting for shallow Groundwater

Prospecting for shallow groundwater has been carried out by the District Administration from the time the territory came under permanent administration by the British Government after the 1914-18 war. From the middle 1920's to 1940 the Geological Survey Department carried out a large amount of work on well-digging and prospecting for well-sites. Later, this particular type of work was handled by the various departments and executives dealing with water supplies in general, until the Water Development Department was formed shortly after the last war.

During the earlier stages wells were sunk in likely localities and water-holes were lined. From about 1947 prospecting for well-sites by Banka drilling was introduced. The Banka drill is a hand-operated drill, originally designed for tin-prospecting in the islands of Banka and Billeton. This type of drill, which can operate in water-logged ground, has been of great help, not perhaps so much in finding water, as in avoiding the digging of wells where no water or little water can be found. During the period 1947 to 1955 inclusive, approximately 13,000 ft. of drilling was carried out in prospecting for well-sites by the Water-Boring Section operating Banka drills. The results bear out the statement made above that probably the majority of the shallow well-sites within the areas under cultivation or abandoned by the tribal population of the territory have already been located. In fact, cultivation has been, and is, tied to easily accessible shallow groundwater supplies. On an aggregate a very large amount of work and capital expenditure has, however, been allocated to the improvement of and prospecting for shallow groundwater supplies during the past 35 years.

CHAPTER SEVEN

GEOCHEMISTRY OF GROUNDWATER

Up to the present water samples in Tanganyika have been examined for the following main purposes:—

1. To ascertain whether the water is chemically suitable for consumption by human beings and livestock.
2. For suitability for boiler-feed or for use in cooling systems, directly or after softening processes.
3. For the total mineral content for saltworks or for rare minerals.
4. Seasonal variations in salinity.
5. Pollution by sea-water.
6. For use as irrigation water.
7. From a bacteriological angle. (This type of examination does not fall within the scope of this survey).

The water samples thus examined can be divided into four main categories, depending on the source of the sample.

1. The deeper groundwater as struck in boreholes at depths varying from 50 to 900 ft. and mine-waters.
2. Shallow surface waters from wells and water-holes.
3. Spring waters.
4. River and lake waters.

Of these categories only No. 1 and No. 2 fall within the true definition of groundwater. Certain spring waters, particularly the thermal type, must be considered as a mixture of groundwater and juvenile water. Juvenile has been defined by E. Suess as "matter which has not participated in supracrustal cycles". True groundwater in Tanganyika is derived from precipitation in the form of rain, snow or mist which has percolated superficial deposits and found its way into the rocks themselves. Groundwater thus obtains its mineral contents from a particular set of soils, rocks, or other geological formations leached by rain-water. Rain-water itself contains varying amounts of chlorine, derived from the sea (cyclic), depending on the distance from the sea and other circumstances. Carbon dioxide is absorbed from the atmosphere, and rotting vegetation, etc., produces other chemical substances which may act as solvents.

(a) Water Analysis in General and Potability of Water

(i) *Main Salts in Groundwater*.—In the main, groundwater in Tanganyika contains only a small number of elements which combine to form salts in solution. The more common of these salts are listed below.

Salts	*Formula*
Sodium Chloride ...	$NaCl$
Sodium Sulphate ...	Na_2SO_4
Sodium Carbonate ...	Na_2CO_3
Sodium Bi—or Hydrocarbonate...	$NaHCO_3$
Sodium Fluoride ...	NaF
Calcium Chloride ...	$CaCl_2$
Calcium Bicarbonate ...	$Ca(HCO_3)_2$
Calcium Carbonate ...	$CaCO_3$
Calcium Sulphate ...	$CaSO_4$
Magnesium Sulphate ...	$MgSO_4$
Magnesium Carbonate ...	$MgCO_3$
Magnesium Bicarbonate ...	$Mg(HCO_3)_2$
Magnesium Chloride ...	$MgCl$

Potassium, K, Alumina, Al_2O_3, Silica, SiO_2, Phosphate, PO_4, and Iron in various forms also occur. Practically all other elements or compounds which may be found in the groundwaters of the territory are rare and are, therefore, not determined in routine analyses.

Nitrates and nitrites are, in general, found only in water which has been polluted. This also applies to hydrogen sulphide, H_2S, except in mine waters and water percolating through vegetable matter. The presence of nitrates is, therefore, important as an indication of pollution and when they occur the water in question has to be submitted for bacteriological and other tests.

(ii) *Units, and Symbols used in Water Analyses.*—When a water sample is analysed, the result of the analysis of the salt content is expressed in various units. For groundwater in general, the elements and radicals, or salts, are expressed in parts per million (p.p.m.), or in grains per gallon (gr.p.g.). 1,000 p.p.m. equals 70 grains per gallon. Parts per 100,000 (p.p. 10^5) is also often used for boiler water analysis; grammes per litre (g.p.l.) for more concentrated solutions. Concentrations of brine may be stated in percentages. Sea-water salinity is often given as 35⁰/00 which is equal to 3·5 per cent total salts. The symbol pH is frequently found in a water analysis and refers to the alkalinity or the acidity of the water. The symbol denotes the hydrogen-ion exponent and stands in a certain relationship to the hydrogen-ion concentrations of the water. It is sufficient to state that the scale extends from 0 to 14 and pH 7 means, in fact, a water which is neutral, neither alkaline nor acid. Higher figures, such as pH 8·5 and upwards, indicate distinctly alkaline waters. Lower figures from pH 6 to 4·5 indicate acid waters. Neutral to phenolphthalein denotes a pH of between 8 and 9·8, within which range this indicator may turn from colourless to pink. Phenolphthalein does not react to $NaHCO_3$, but will turn faintly pink when Na_2CO_3 is present. Litmus paper will distinguish between neutral, alkaline and acid waters.

Total Dissolved Solids. This means the weight after drying, at 105°C., 120°C. or 180°C. of residual salts obtained by evaporation of a known volume of water. Water samples. are filtered before being evaporated.

Temporary Hardness. This is mainly due to the presence of Ca and Mg bicarbonates in water. These salts are converted to carbonates during boiling which have lower solubility (soft scale in boilers). Temporary hardness is now generally given as parts $CaCO_3$ per 100,000 or parts per million. The old scale degrees (Clark's soap method) was expressed in parts $CaCO_3$ per 70,000 or grains per gallon.

Permanent Hardness. This is caused by calcium and magnesium sulphates and silica. (Hard scale in boilers is mostly $CaSO_4$).

Total Hardness. This is the sum of all the salts present that are likely to produce scale in boilers.

Permanent hardness is often calculated as the difference between Total hardness and Temporary hardness.

Alkalinity. This, in analysis, is expressed as $Ca(HCO_3)_2$, $CaCO_3$, $NaHCO_3$ or Na_2CO_3, but it is fundamentally determined as the sum total of HCO_3 and CO_3 found in the water by titration with dilute hydrochloric acid using either methylorange or phenolphthalein as an indicator.

Conductivity Test. During the earliest stages of groundwater development in the territory, analyses of water for human use and for livestock aimed mainly at assessing total dissolved solids, which were determined by conductivity measurements, i.e. by passing an electric current through the water to be analysed and recording the conductivity in reciprocal ohms from the instrument. The main salts present were then ascertained by qualitative analysis, and the T.D.S. read from empirical graphs based on the most common salts present in groundwater. Conductivity values of this type are still sometimes given by the Geological Survey laboratory. This method, known as the dionic test, is accurate. For repeated tests of the same water, which are often done in respect of seasonal variations in wells and boreholes used for boiler water, contaminated by sea-water and for thermal spring waters, it is a very sensitive and quick method, the whole test taking only a few minutes. Conductivity tests are now extensively used for determining the quality of irrigation waters. In older test apparatus, water for a conductivity test had to be reasonably clear, i.e. free from excess colloidal matter, to enable temperature adjustment to be made. Highly saline waters cannot be tested by conductivity methods.

Complete Analyses. During later years complete analyses have become routine procedure including, since the year 1953, the determination of fluorine (F). At present the results of water analyses carried out by the Government Chemist and the Geological Survey Department are given in parts per million. The Government Chemist, in addition, uses the following symbols.

E.C. = Electrical Conductivity expressed in reciprocal microhms or micromhos at a temperature of 25°C. E.C. values are particularly useful in connection with irrigation waters. P. Alkalinity is phenolphthalein alkalinity expressed as $CaCO_3$. M. Alkalinity is alkalinity by methylorange expressed as $CaCO_3$. TH. or Total Hardness is expressed as $CaCO_3$. Sodium Absorption Ratio or S.A.R. values may also be given for irrigation waters and calculated according to the formula:

$$S.A.R. = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} \quad Mg^{++}}{2}}}$$

In this formula the contents of the elements are expressed in milligram equivalents per litre, which is parts per million divided by the equivalent weight.

(iii) *Potable Water.*—What constitutes potable water from a chemical point of view? The exacting standards laid down for more developed communities cannot be enforced in general or adhered to under the conditions prevailing in Tanganyika. Most groundwater supplies must, therefore, be treated on their own individual merits and the standards adapted to the purposes for which the water is to be used.

The indigenous rural population and their livestock can and do, use water which is far more saline than the generally accepted standard. There is still a great deal of controversy as regards the influence or toxicity to the human and animal body of excessive concentrations of total soluble salts in water. Some authorities regard the osmotic pressure set up by the total amount of salts present in solution in the water as the main guide as to whether the water is harmful or not, for instance, to livestock. Others assign toxic properties to individual salts such as Na_2SO_4, $MgSO_4$ and Na_2CO_3, the latter salt occurring only in alkaline waters. Na_2SO_4 and $MgSO_4$ act as aperients and if present in excess (when sole "harmful" salt present maximum approximately 1,000 p.p.m. for Na_2SO_4) may, in the long run, be harmful to both human beings and animals. This also applies to sodium chloride (maximum approximately 1,400 p.p.m.).

Water containing a concentration of 10,000 p.p.m. of the salts commonly present in Tanganyika groundwater have been used in Australia over short periods, both by man and beast, without harmful effects. In this territory trials were made in a very dry area of watering livestock every third day with an alkaline water containing 16,000 p.p.m. T.D.S. These tests failed as the cattle, in the long run, showed more and more reluctance to drink the water. No deaths were recorded. Cattle are, however, regularly using water which contains more than 4,000 p.p.m. T.D.S. from boreholes. Over short periods, water-holes in the Bahi Depression, where the water contains 9,400 p.p.m. (75 per cent of T.D.S. NaCl) are used for domestic needs and 13,950 p.p.m. for livestock; it is probable that waters of even higher total salinity are used in Masailand. As a rule borehole water containing more than 3,500 p.p.m. of normal groundwater salts without excess of sodium chloride (maximum approximately 1,400 p.p.m. NaCl) is considered unfit for human use, and in some areas it is recommended that any pumping installation from a borehole containing water of 3,300 p.p.m. should be of a temporary and experimental nature only. For small urban settlement supplies the potability limit is drawn at approximately 3,000 p.p.m., provided sodium chloride does not constitute the major portion of the soluble salts, and that other unsuitable salts do not occur in the water. For toxic action of fluorine see under (b) General Considerations (ii).

(b) General Considerations

The type of salinity and the percentage proportion of the salts to total solids is directly influenced by the various superficial deposits and rock formations penetrated by rain-water. The total salinity, however, depends largely on the structural, general geological and topographical conditions which regulate groundwater movements. Free moving water in superficial deposits or rock formations is seldom highly saline. On the other hand, where drainage is impeded and the water remains nearly stagnant, or is collected in a drainage-less basin where the annual increment from surface run-off and percolation is removed only by evaporation from a high water-table or the surface of seasonal lakes and swamps, highly saline groundwaters are developed and, occasionally, even brines.

(i) *Saline Groundwater Areas.*—Large areas of saline groundwater have been encountered in the Lake Rukwa, Wembere and Bahi Depressions, The outskirts of Lake Jipe also appears to be saline. The water in the Amboseli pan on the Kenya boundary is at least partly fresh around the Sinya wells. In many Rift Valley lakes and pans the salinity is increased by the influx of saline water from springs.

Other smaller saline areas outside the drainage-less basins and at some distance from the coast have also been encountered during groundwater explorations. Such areas are the Dodoma and Singida townships, Msagali and Gulwe in the Central Province, the Kingolwira area in the Eastern Province and Shinyanga in the Western Province. In the Tanga Province two main areas at some distance from the coast carry saline groundwater, namely, Ngomeni and West Korogwe. In the Southern Province the Masasi area inland has proved difficult in this respect.

All these areas, with the exception of Shinyanga, are situated within granitic or Basement rocks. The reason for these small saline areas is, in some cases, not clear. Dodoma, Msagali and Gulwe have in common a sluggish drainage. The groundwater at Msagali reached brine concentration. Singida township lies between two lakes which are saline, and some of the groundwater may be contaminated by fissure water derived from these lakes. The rocks of the Kingolwira area contain the mineral scapolite which is chlorine-bearing, but it is also possible that a large fault exists below the Uluguru Mountains which may carry saline water. In one borehole at Tungi T.D.S. reached brine concentration. The Ngomeni saline area stretches to the north below the eastern end of the Usambara Mountains. Large fissures carrying saline water are known to exist in this region. The Shinyanga area is partly invaded by kimberlites, and the schist formation east of the station carries saline groundwater. At Masasi, in the Southern Province, fairly large quantities of saline groundwater have been struck in fissures in the Basement rock, but the origin of the salts is not clear.

Apart from these smaller saline areas, which are located in urban centres and near the railways and, therefore, have been more closely explored for groundwater, many *mbugas* contain saline groundwater which is unfit for consumption by livestock.

The coastal sedimentary rocks and unconsolidated sedimentary formations found near the coast vary to a large degree in texture and structure. In consequence, water encountered in such formations may be highly saline, or potable, depending on the actual location, and often showing variation in amount of total salts within a few hundred yards. The danger of sea-water penetration is, however, always present. Starting in the south, the Mtwara area at one time presented a problem as regards fresh groundwater. Potable water was eventually found just noreth of Mikindani at sea level in a coastal spring area; this water is artesia. The Lindi water supply, which was first obtained from wells in the township, was contaminated by sea-water, and the present supply from springs in Eocene limestone, although potable, has a high chlorine content. The groundwaters of the Lindi Creek area are, as a rule, unpotable. The Kilwa peninsula is supplied by water from sands and is satisfactory as far as salinity is concerned. The Dar es Salaam supply, derived from estuarine sands in buried river-beds, has occasionally been contaminated by sea-water through over-pumping. The Pangani area varies; some boreholes have struck saline water, others fresh. Tanga town derives its water from thin pebble beds in old estuarine deposits, and the quality is reasonably good. The Amboni area is largely occupied by Jurassic limestone and the quality of the water varies. Further to the north, the Moa village area is polluted by sea-water, but reasonably fresh water has been struck south of Moa, one and a half miles from the sea.

In general, sea-water will penetrate inland in any pervious formation unless forced back by fresh water under pressure. Fresh water occurs as a rule above the sea-water except under artesian or sub-artesian conditions. The delicate equilibrium between sea-water and fresh water is governed by Hertzberg's theory based on the specific gravity of sea and fresh water respectively.

The water-level of many wells along the shore-line rises and falls with the tides and contamination by salt water may also vary from the same cause.

North of Dar es Salaam it has been found that the clayey deposits which prevail in this area are penetrated by sea-water. A geophysical survey showed that salt water can be expected from about 150 ft. depth near the shore to 300 ft. depth in the neighbourhood of the Bagamoyo new road. The water supply for Tanganyika Packers, Ltd., was struck in river sands and is fresh.

(ii) *Fluorine, F.*—One of the main problems in respect of potability of groundwater found in Tanganyika is, however, not the occurrence of highly saline water in boreholes, wells or water-holes but the presence of fluorine in the form of sodium fiuoride, NaF, amongst the dissolved salts in practically all groundwater.

Fluorine, even quantities as low as 1·5 p.p.m., (other authorities state 2·5 p.p.m.) attacks the enamel of the teeth of children and, in larger amounts, the teeth of animals. In large quantities it leads to density in the bone structure of both man and beast. The toxic action of fluorine is cumulative; thus watering points with a high fluorine content which are used for, say, only six months of the year are less dangerous than supplies used permanently. The question of total intake of fluorine also arises, as, apart from water, grass and presumably other vegetable matter in contaminated areas contain fluorine. The standard of nutrition also appears to be related to the effect of fluorine on man. All aspects considered, it is difficult to assess the danger of excessive fluorine intake from water, but before stating figures from other countries some facts relevant to the question from this territory should perhaps be set down.

The Dutch Settlement at Oldonyo Sambu, north of Arusha, was established in the early part of the century and, as far as is known, families have lived there and used the springs containing from 11 to 14 p.p.m. fluorine for at least two generations without disastrous results.

The Masai in the Serengeti use water containing 50 to 60 p.p.m. for a short period every year. Another instance of water with a high fluorine content used by the Masai is the Ngare Nanyuki furrow, north of Mount Meru, which contains in places 25 p.p.m. fluorine.

The danger of fluorine, particularly to the teeth of children, was not discovered until 1931, but since then research on this subject in the United Kingdom, the United States and other countries has been continuous. In one area in the United Kingdom where the water contained 5 p.p.m. fluorine, the teeth of 100 per cent of all children examined were affected and damage was serious in 20 per cent of these cases. From Texas, U.S.A., a radiological survey revealed "an increased bone density not associated with functional impairment in 11 per cent of those examined. The water supply used contained 8 p.p.m. fluorine. Examination of a limited number of persons living in an area where the water contained 1·2 to 3 p.p.m. revealed no evidence of fluorosis".

As regards cattle in Tanganyika, G. W. Walker, Research Chemist seconded to the Veterinary Department, in the course of a fluorine survey, came to the conclusion that, in the conditions prevailing in the area under examination, 18 p.p.m. was the maximum amount compatible with good husbandry of cattle, but over this amount an abnormal increase of bone breakages and wear of the teeth was observed.

The main areas in which fluorine occurs in excessive quantities are outlined on the Geological Map attached. The high fluorine content of the water in these areas is the result of the following geological and hydrological processes and conditions.

1. Volcanic Activities.
   (a) Volcanic rock including kimberlites and carbonatites, pyroclastics and ash and salt deposits.
   (b) Thermal springs situated in, or near, deep fractures and fault zones and connected with deep-seated magmas.
2. Concentration through evaporation in drainageless areas of saline groundwaters and mixed juvenile waters.
3. The presence of minerals such as fluorite and apatite in rocks or lake deposits.

The most important example of volcanic rocks, pyroclastics and ash contributing to a high fluorine content of groundwater in general is the east and south-east Meru area, including at least part of the Sanya Corridor between Mount Meru and Mount Kilimanjaro. Borehole water in the south Sanya Corridor has been found to contain up to 96 p.p.m. fluorine. Borehole waters further north show 4 to 8 p.p.m.

A region highly contaminated by fluorine is to be found west of the Ngorongoro "Crater" and the Lemagrut volcanic cone. The fluorine here is derived from springs, probably juvenile, in the Serengeti plain, and possibly from ash-beds deposited there and in the Ol Balbal Depression. Springs at Eremet in the Serêngeti contain 40 p.p.m. fluorine; pans, 120 p.p.m. and water-holes in Ol Balbal up to 140 p.p.m. The ash-beds covering the Serengeti plain continue for at least 40 miles to the north of Ol Balbal into the Loliondo District, and boreholes sunk north of the National Park boundary in Basement rocks have shown fluorine rates of 6 to 10 p.p.m. The high fluorine content of these boreholes is probably due to water percolating ash-beds and finding its way into the Basement rock.

Another area where it is suspected that spring water or ash has contributed to the high fluorine content is the north-eastern Kondoa region, where boreholes show from 4 to 7 p.p.m. and one borehole, in the Chubi *mbuga*, sunk in clays, marls and limestone deposits on Basement rock, contained 80 p.p.m. The total solids found in the water from this borehole is 22,000 p.p.m. and concentration of salts through evaporation is likely to have occurred.

Water from boreholes in kimberlites in the Shinyanga area shows a fluorine content of 110 to 250 p.p.m. and one borehole in alluvium at Seke, north of Shinyanga, 21 p.p.m.; the fluorine in the latter probably also derived from a kimberlite. Other boreholes in the same region show a higher fluorine content than is normal for granitic rocks.

In the north-west Shinyanga area, known as the Isanga basin, a few boreholes show relatively high fluorine content. This has been attributed to the mineral fluorite which is known to occur in the younger granites of the Lake Province.

One of the largest areas known to be contaminated by fluorine is the Wembere Depression, covering an area of more than 4,800 square miles. This depression is filled, in general, to a depth of over 300 feet by lake deposits, calcareous sandstone, limestones, marls and clays and sand occurs above bedrock. Five boreholes, sunk at widely-spaced distances in the depression, all yielded water which showed a fluorine content of from 25 to 40 p.p.m. The reason for this high fluorine concentration is not easily established. Fluorine may have entered the lake during its maximum stage in the Plio-Pleistocene from volcanic emanations or ash, and it is possible that juvenile springs carrying fluorine are still issuing at depth below the lake deposits. Springs near Shinyanga, at Ibadakuli in the Wembere drainage, contain 7 p.p.m. fluorine, and a borehole sunk in the same area 36 p.p.m. The Wembere basin drains into Lake Eyasi, which itself lacks visible drainage and, although only part of the area is subject to high groundwater or surface evaporation during the rains, some concentration of salts has taken place and the groundwater is generally alkaline, which may contribute to the high fluorine content of the water.

Similar conditions prevail in the Bahi Depression, which is over 400 square miles in extent and has no drainage, but in this case the spring areas are known and high salt concentrations, amounting to brine with up to 180 p.p.m. fluorine content, have been reached by evaporation from the water-table and swamps. The groundwater in the Bahi Depression is, however, contaminated beyond the area of lake deposits. Thus groundwater struck in boreholes located in Basement rocks and granite in the vicinity of Bahi show fluorine figures up to 34 p.p.m.

Thermal springs in the north-western part of the territory, in Musoma District, also carry fairly large amounts of fluorine (25 p.p.m.), and in Mbulu District springs containing fluorine (maximum 99 p.p.m.) enter Lake Balangida. Record figures for fluorine, 330 p.p.m., have been obtained from thermal springs in the Lake Natron basin.

(c) Results of Water Analyses from Boreholes

If water analyses from two or more boreholes are to be compared or averaged, the constituents should first be expressed in percentage of total solids in order to eliminate variability in concentration of salts. In the calculation of such percentages it has been found that considerable losses in total solids occur when evaporating, and particularly when drying, solid salts containing large amounts of bicarbonates. These losses will, therefore, affect the calculated percentages of the analyses of certain borehole waters.

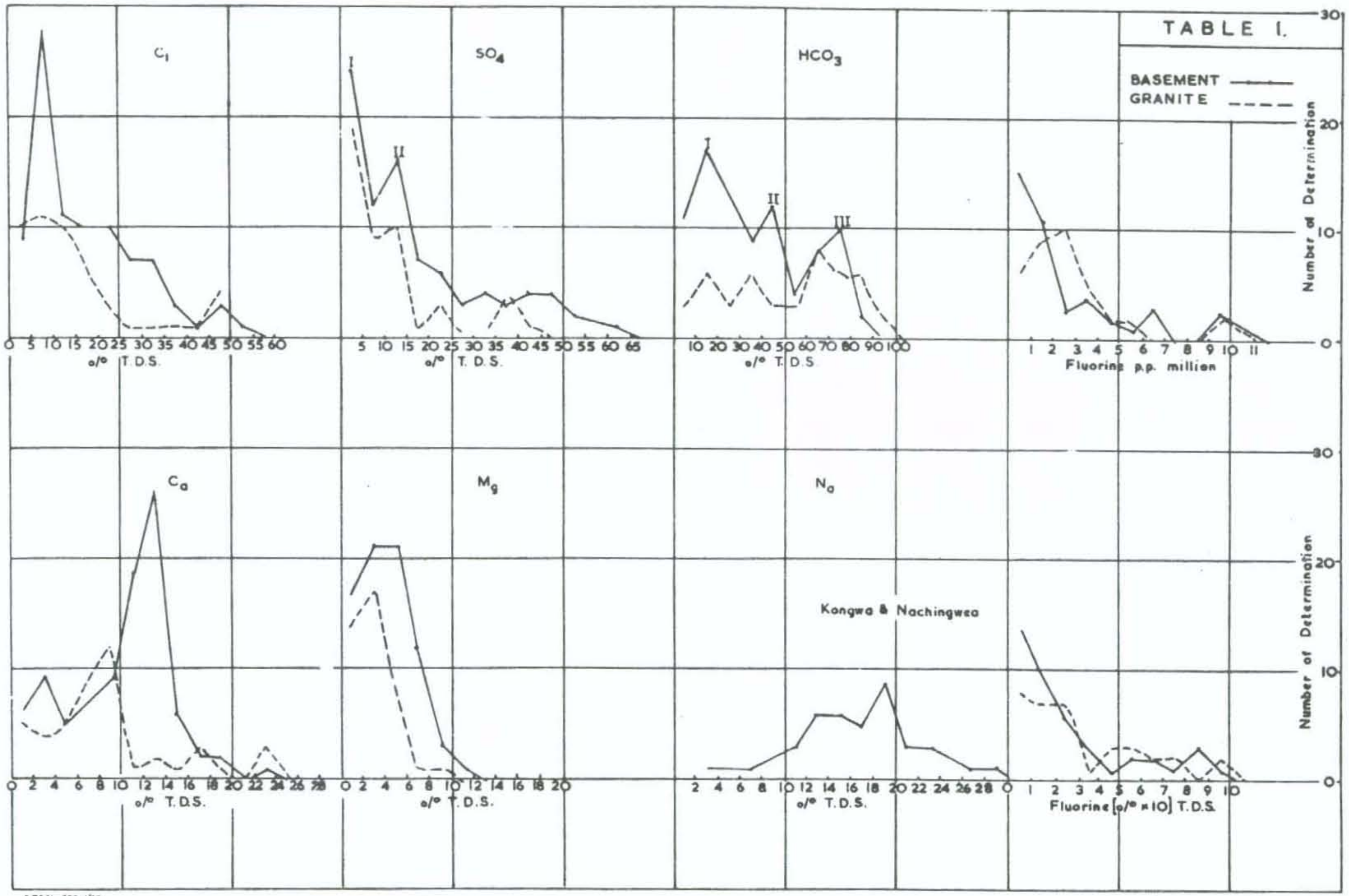
Up to date the number of water analyses that can be used for computing the main elements from boreholes waters or other ground waters in the territory is limited. However, the practical implications of a foreknowledge of the type of water that may reasonably be expected in certain rock formations cannot altogether be disregarded, and a number of analyses from the Basement and granite formations have, therefore, been computed as percentages of total solids. The results have been tabulated in frequency graphs. The radicals and elements shown in these graphs are Cl, SO_4 Na, HCO_3, Ca and Mg. Fluorine has been subjected to special treatment as this element is toxic, and frequency graphs showing fluorine as p.p.m. have, therefore, been included for granite and Basement formations. Furthermore, it has become evident that there is a connection between the percentage of calcium, magnesium, sodium bicarbonate, carbonate and fluorine in water, and that all really high fluorine waters contain sodium bicarbonate and sometimes sodium carbonate. A low calcium-magnesium content combined with a high bicarbonate or carbonate figure is the rule for a high fluorine content. This rule, however, cannot be applied in the reverse sense.

To illustrate the interdependence of fluorine, Ca, Mg and HCO_3 two graphs have been plotted which show the limiting conditions. Fluorine is expressed as $\% \times 10$; Ca, Mg and HCO_3 in per cent of total solids. The fluorine percentage rates of T.D.S. are low in brine but increase to maximum figures in very pure waters. It should be stated, however, that no definite conclusion can be drawn from the relationship between high bicarbonate, low calcium and magnesium and high fluorine content. The number of salts involved, the instability of $CaHCO_3$ at various concentrations, pH values, temperatures and pressures, and the solubility and even existence, of CaF_2 in sodium bicarbonate and carbonate waters requires detailed and complicated investigation before the problem can be elucidated.

(i) *Groundwater derived from the Rocks of the Basement System.*—As stated in Chapter III, this System includes a great variety of rocks, gneisses of different types, mica schists, granulites, amphibolites, limestones, dolomites, quartzites, etc. These rocks are all metamorphic in varying degrees.

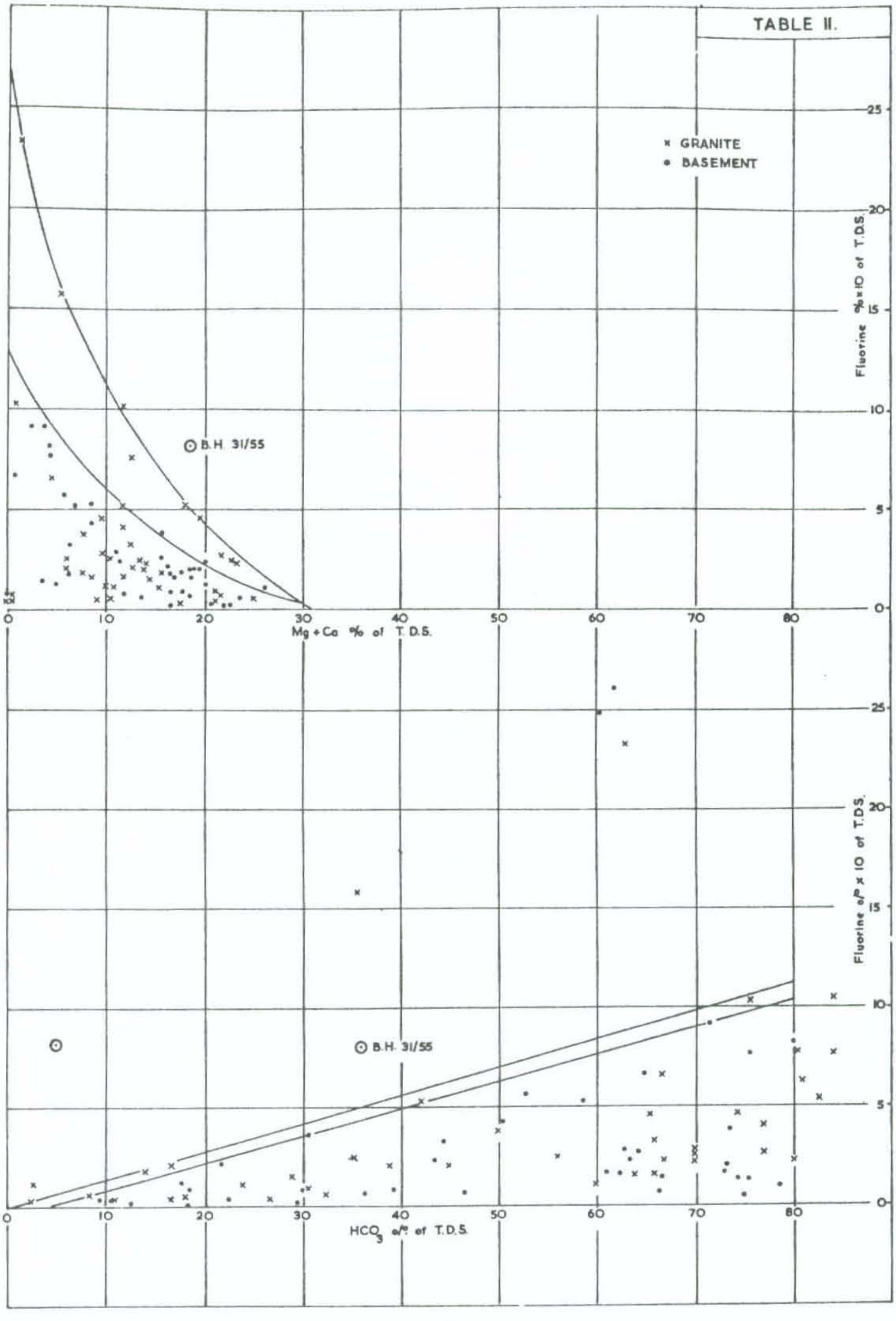
The water found in them is, in general, a sodium-calcium-bicarbonate water with varying amounts of SO_4 and Cl. The most usual transition is from a sodium-bicarbonate to a sodium-bicarbonate-sulphate water, less frequently to a sodium-bicarbonate-chloride water. Water containing chlorides or sulphates only are not common. The frequency diagrams

FREQUENCY PLOTS OF ELEMENTS AND RADICALS IN GROUNDWATER FROM BASEMENT AND GRANITIC ROCKS IN PERCENT OF TOTAL DISSOLVED SOLIDS (T.D.S.)



I 2041 400 1/60

TABLE II.


× GRANITE
• BASEMENT
Fluorine % × 10 of T.D.S.
Mg + Ca % of T.D.S.
B.H. 31/55
Fluorine % × 10 of T.D.S.
HCO_3 % of T.D.S.
B.H. 31/55

(Table I) shown for waters derived from Basement rocks are based on some 84 complete water-analyses. The peaks on the frequency diagrams indicate that certain percentages of Ca and Mg as cations, and CO_3, SO_4 and Cl as anions, are dominant, and that these peak frequencies give at least an indication of what may be considered as a "normal" or average percentage composition of the total dissolved solids in groundwater from the Basement formation in various areas.

The "normal" groundwater from Basement rocks would thus contain 12 to 14 per cent calcium, 2 to 6 per cent magnesium, calculated on T.D.S. (84 analyses) and 16 to 20 per cent sodium (42 analyses only).

The relationship of the anions, CO_3, SO_4 and Cl, are more complex. The HCO_3 frequency graph shows a peak, No. III, at percentages between 70 and 80 per cent HCO_3 of T.D.S. This percentage of HCO_3, although calculated from the analyses, is too high; this is probably due to losses of H_2O and CO_2 when total solids are determined by evaporation of high content bicarbonate waters. In a water containing only sodium bicarbonate the percentage of HCO_3 cannot exceed 72·7 per cent unless free CO_2 is present in the water. Under such circumstances it is more likely that the peak would fall between 60 and 70 per cent and not between 70 and 80 per cent. Waters of the 70 to 80 per cent cum 60 to 70 per cent type occur in the Eastern, Central and Tanga Provinces, and are the rule, except in the vicinity of Kongwa, where lower values of 10 to 20 per cent HCO_3 predominate. The Nachingwea area of the Southern Province shows a peak frequency at between 40 and 50 per cent HCO_3 (peak No. II) and contributes with Kongwa to the high No. I peak at between 10 and 20 per cent.

The SO_4 graph shows two main peaks. No. I represents borehole waters from the Nachingwea area alone, containing low SO_4 concentrations. Peak No. II at between 10 and 15 per cent represents borehole waters from the remainder of the territory. From the SO_4 graph it is also clear that waters containing only SO_4 are relatively rare.

The chlorine graph is, on the whole, simple and the peak frequency between 5 and 10 per cent can be considered as representative for water from the Basement formation in general. Waters containing only chlorides are not common.

The majority of groundwaters obtained from the Basement rocks are neutral to weakly alkaline and pH values lie between 7 and 8. Only in a few localities is sodium carbonate present in waters which must be regarded as brines, and in such localities pH values rise to 9 or 10. Nearly all waters from the Basement must be considered as hard or very hard. This can be deduced from the Ca and Mg frequency graph in conjunction with the average total solids. Fluorine values lie between 0 and 2 p.p.m. in general. The maximum fluorine content so far discovered is 80 p.p.m. and refers to a brine water from Kondoa District. Fluorine frequencies have not been plotted for values in excess of 10 p.p.m. Phosphates are known from Kongwa borehole waters. Silica, SiO_2, occurs up to 7·7 per cent in borehole waters derived from Basement rocks.

The amount of total dissolved solids fluctuates widely for Basement waters from a maximum of 34,000 p.p.m. to 200 p.p.m. The majority of Basement waters fall within the wide group of 500 to 1,000 p.p.m. Areas yielding groundwaters of more than 2,000 p.p.m. occur in the Central Province near Gulwe and Igandu stations on the Central Railway line. Maximum salinities in this region are 5,700 p.p.m. East of Kongwa, in the Pingalame area, maximum salinity is 3,400 p.p.m., in the eastern Bahi Depression area, up to 34,000 p.p.m., while in Kondoa District, a brine of 22,000 p.p.m. occurs. In the Eastern Province the Kingolwira-Tungi region shows high salinities from 13,000 p.p.m. at Tungi to 7,000 p.p.m. in the Kingolwira area. In the Ngomeni area from Muheza north-east to the Sigi River and beyond, waters reaching 20,000 p.p.m. have been recorded. In the Korogwe region, salinities of over 4,000 p.p.m. have been noted. In the Northern Province, one borehole in south-east Masai reached 4,000 p.p.m. In the Nachingwea area three boreholes out of 25 for which analyses are available exceeded 3,000 p.p.m. The total solids shown for these three boreholes are 4,100, 3,300 and 3,700 p.p.m., the first two are sulphate waters, the third is a chlorine water. The total number of boreholes sunk by Government in Basement rocks and which have struck excessively saline water unsuitable for stock or domestic use is not very high. About 12 boreholes out of 170, including failures of all kinds, could not be used, but 16 Government boreholes sunk in Basement rocks yield water of more than 3,000 p.p.m.

(ii) *Granitic Rocks.*—All types of granite and granitic rocks have been included in this group, whether contaminated by inclusions or rafts of older rocks or belonging to the younger or so-called mobilized granites of the Lake Province or Lupa type. Borehole waters derived from these rocks show peak percentage frequencies for Cl and HCO_3 similar to the main groups of the Basement rocks. The frequency diagrams are based on approximately fifty analyses.

The SO_4 graph shows a major peak at low SO_4 percentage between 0 and 5 per cent and a secondary peak between 10 and 15 per cent. The Ca percentage values are lower and lie between 6 and 10 per cent. Mg shows one peak frequency only, at between 2 and 4 per cent.

The great majority of waters struck in granitic rocks contain sodium bicarbonate, but a number of markedly chloride waters occur in the granites. Sulphate-sodium-bicarbonate waters are to be found in the Bahi Depression, in the Itigi area and at Ulaya, Kilosa District. The average fluorine content is higher than in the Basement waters and lies between 1 and 3 p.p.m. The maximum fluorine value so far encountered in water from a borehole sunk in granitic rock by Government is 11 to 12 p.p.m. A borehole sunk by private enterprise north of Shinyanga in granitic rock showed 36 p.p.m. F. Total solids vary considerably from a maximum of 47,000 to 200 p.p.m. The average is slightly lower than that for the Basement rock and lies approximately between 500 and 800 p.p.m. Only a very small number of boreholes show salinities exceeding 3,000 p.p.m. A number of boreholes have for years provided water for locomotive boilers on the Central Railway line. In dry years, when other sources were not available, these supplies proved unsatisfactory and many tests and investigations have been carried out in the past in an endeavour to find a solution to the problem.

All granite waters are neutral to slightly alkaline, with the exception of brines struck in granitic rock in the Bahi Depression with pH values as high as 9.

(iii) *Nyanzian Formation.*—This formation has so far not often been successfully explored by drilling, and very few analyses are therefore available. Analyses from the Ikoma area show high bicarbonate percentages and relatively high fluorine values of more than 4 p.p.m. Analyses from boreholes in the Lake Victoria region conform more closely to granite waters. Total salinities vary from 1,000 to 2,600 p.p.m. with pH value 7·5.

(iv) *Karagwe-Ankolean.*—This formation has been explored by drilling in the Bukoba District only and shows water of low total salinity of 200 to 300 p.p.m. The type is a sodium bicarbonate or bicarbonate chlorine water, in some cases a predominantly chlorine water high in Ca, and low in SO_4 and very low in fluorine, except in the vicinity of tin-bearing granites. These are excellent soft waters, neutral to slightly alkaline.

(v) *Volcanic Rocks and Pyroclastic Deposits.*—The larger of the two main areas of volcanic rocks in Tanganyika is situated in the Northern Province, covering 10,000 square miles; the much smaller area of 1,200 square miles is in the Southern Highlands Province. These areas show a great difference in the amount of rainfall. The southern volcanic area, mainly situated in the Mbeya, Tukuyu and Njombe District, receives a relatively high annual rainfall and is very well watered by rivers and running streams. Only a few scattered areas are dry. In consequence the Southern Highlands volcanic region has only been explored by one borehole, at Mbeya yielding a very pure water.

The groundwater struck by drilling in the Northern Province varies considerably, both in T.D.S. content and in the type of water struck. So far no brines or highly saline waters have been encountered. The highest total solids obtained from a Government borehole is 2,400 p.p.m. from a borehole at Dutch Corner. A few are very low, almost comparable to rain-water. The fluorine content of many boreholes, however, reaches values which make the water toxic, or at least unpotable. The small number of borehole water analyses available indicates that the majority of the waters from volcanic rocks or deposits are sodium-bicarbonate waters; in addition some contain appreciable amounts of Na_2CO_3. Most are, therefore, slightly alkaline to alkaline. No acid waters have been found so far. The Ca and Mg percentages of total solids range from a trace only to 13 per cent Ca and 9·4 per cent Mg. Cl is high at about 29 per cent in the Sanya Plain, and at 11 per cent in the Arusha township, a water which contains 160 p.p.m. of T.D.S. The highest SO_4 values are found in the Sanya boreholes. Fluorine varies from as much as 96 p.p.m. in the south Sanya corridor to 1·2 p.p.m. in the Essemingor area. The latter has the lowest fluorine content so far found in borehole waters derived from lavas. The groundwater in the Arusha Chini area in pyroclastics is a sodium-bicarbonate water low in Ca, Mg and fluorine, with pH 7·9 and T.D.S. 534 p.p.m.

(vi) *Bukoban*.—Only one borehole in this formation has been successful. This yielded pure water of bicarbonate type, T.D.S. 240 p.p.m. Fluorine is low, but iron and alumina in colloidal form are present; pH 7·5.

(vii) *Karroo*.—This formation has been explored by drilling in three areas only; in the coastal belt north of Tanga, in the eastern Morogoro District and in the Songea District of the Southern Province.

In the northern Tanga area, towards the boundary between the Karroo and the Basement and some distance from the sea, waters high in total solids have been encountered, the amounts ranging from 3,300 to 7,000 p.p.m. These waters are of the chlorine-bicarbonate type, high in Cl (50 to 60 per cent) and low in SO_4. Towards the coast there is a reduction in the amount of total solids, but the type of water remains the same. Without exception these are hard or very hard waters and some are unfit for human consumption. The fluorine content is low; pH 7 to 7·5.

The Karroo formation close to Ngerengere, eastern Morogoro District, has only been explored in a few boreholes and the waters struck so far are sulphate-chlorine waters, one borehole near a major fault-line shows relatively high fluorine, 6 p.p.m.

South of the Central Railway line in the large tracts of country covered by rocks of presumed Karroo age and known Karroo age, only two boreholes have been sunk in search of water. These are in the Likonde area of south-east Songea District. The quality of the water is satisfactory, with total solids about 600 p.p.m. This is a sodium-bicarbonate water and soft.

Waters struck during diamond-drilling in the coalfield area known as Ngaka, in Songea District, have been analysed. The results indicate that in this area great variations in the quality of the water may be expected. Total solids range from 108 to 1,258 p.p.m. The waters are of the bicarbonate type with low fluorine values with varying amounts of SO_4, Ca and Mg, but these constituents are not always present. H_2S is present, presumably derived from pyrite in the coal formation. The waters appear to be potable unless the content of H_2S is high.

(viii) *Jurassic*.—This formation has been explored by drilling in the Tanga area and, to a lesser degree, in the Kidugallo region in the eastern Morogoro District. No boreholes have been sunk for water in the Southern Province Jurassic area.

Only a few analyses are available from the Tanga Jurassic. The total solids from the Pongwe-Pigoni area vary from 1,100 p.p.m. to 2,500 p.p.m. and the waters are of the chlorine-bicarbonate type, high in Ca and Mg as can be expected in water derived from exclusively calcareous sediments. Towards the coast at Maweni, the total solids fall to about 600 p.p.m. and within the less calcareous sediments in the north Tanga township area to 550 p.p.m., the type being the same, a bicarbonate-chlorine water with subordinate SO_4. South of Ngomeni station, in the Kumburu area, very low salinities have been obtained from borehole waters, but to the north of this station salinities of 1,000 p.p.m. seem to be moref common.

In the Kidugallo area the majority of the boreholes is situated within a few miles of Kidugallo station. Total solids obtained from these borehole waters range from 700 p.p.m. to 4,500 p.p.m. The type of water found is a chlorine-sulphate-bicarbonate water containing fairly large quantities of Ca and Mg. Most of the waters are hard or very hard. The quality of the water improves with the depth of drilling and also in the beds to the west of the old shallow-water limestones. The waters are neutral to slightly alkaline.

(ix) *Cretaceous*.—No samples of water from definitely known Cretaceous rocks are available, except a brine water from Lake Rukwa which is not representative.

(x) *Tertiary Sediments and Recent Fluviatile Marine Deposits of the Coastal Region*.—It is often difficult to distinguish between Recent and Tertiary formations along the coast of Tanganyika, and a large amount of field work remains to be done before exact boundaries between these formations can be drawn on a map. To a lesser extent this applies to the lake deposits in the large inland depressions. The above grouping has, therefore, been adopted as a convenient division of the post-Cretaceous coastal sediments and deposits.

The groundwaters found in the formation described above vary considerably in type and salinity, and only a rough division can be drawn between the waters found in the true marine sediments and those encountered in fluviatile deposits. Both groups are liable to be polluted by sea-water.

The two largest towns of the territory, Dar es Salaam and Tanga, at present depend largely on water obtained from fluviatile deposits. Water from the old pumping installation at Tanga, a chlorine water, contained 900 p.p.m. T.D.S. in 1940. A test in November, 1955, showed 1,168 p.p.m. The T.D.S. of the Dar es Salaam water supply, which is derived from fluviatile deposits or storage water from similar areas, varies according to the source of supply, the time of the year and the rate of withdrawal by pumping. The Mtoni supply ranges between 203 and 483 p.p.m. A twelve months' average from Gerezani borehole is 1,832 p.p.m. T.D.S., of which 710 p.p.m. is Cl. In September, 1954, Msimbazi River showed 466 p.p.m. T.D.S. The first water supply for Mtwara was obtained through a pipe-line from Mikindani, and contained total solids of approximately 1,150 p.p.m. Mtwara's new supply varies according to borehole and pumping rate; in September, 1955, total solids were 1,436 p.p.m. and included iron and manganese. Other tests show 1 000 to 1,187 p.p.m. The groundwater struck in wells and boreholes at Lindi varied considerably from more than 7,000 p.p.m. T.D.S. in a borehole to 1,800 p.p.m. in wells, with a temporary hardness of 43° (Clark's), and permanent hardness 32°; a very hard water. Lindi town supplies in 1955 showed 1,872 p.p.m. T.D.S., out of which 700 p.p.m. was Cl.

In the region south of Tanga a number of boreholes have been sunk at or within five miles from the coast. At Mwambani, potable water has been encountered in the coral reef very close to the sea. Further south, in the south Tanga and north Pangani districts, the coastal sediments have been explored by drilling. The total solids in these regions vary between 1,000 and 11,200 p.p.m., the average for the area being approximately 1,400 p.p.m. The waters can be classified as a chlorine-bicarbonate type, very low to fairly low in SO_4. They show a neutral reaction and are very low in fluorine; this applies to nearly all waters found along the coast. Hardness varies considerably with the amount of T.D.S. but is, in general, medium to low.

Outside the fluviatile deposits, which are the source of the water supplies for Dar es Salaam township and the factory of Tanganyika Packers, Ltd., drilling at Kunduchi, Temeke, Ubongo and Ukonga indicates that the total solids content of the water varies widely, being highest in the Temeke area at 2,000 p.p.m., lowest at Ukonga, near Pugu, at 500 p.p.m., and medium at Kunduchi and Ubongo at 1,000 p.p.m. and 725 p.p.m. respectively. Salt water has been encountered in several boreholes close to the sea shore north of Dar es Salaam. To the south of Dar es Salaam as far as the south Kilwa District there are no records of drilling. Springs and seepages on the Kilwa peninsula, however, yield reasonably good water with total solids of approximately 600 p.p.m. The area north of Lindi to the Memmkuru River has been explored by drilling, but groundwater was found to be very scarce and when struck in small quantities contained 3,500 p.p.m. T.D.S., mostly chlorides. South of Lindi Bay, in the Oligocene sandstone formation, conditions change, and groundwater of fairly good quality containing total solids of 1,000 to 1,500 p.p.m. has been struck at depth. In the Sudi Bay area, 14 miles south of Kitunda, total salinities vary from 750 p.p.m. to 3,200 p.p.m. North of Mikindani a number of boreholes have yielded water, and salinities of just under 2,000 p.p.m. are prevalent. The Sudi Bay and Mikindani boreholes produce chlorine waters with little SO_4.

(xi) *Lake Beds and Mbugas*.—Large tracts of the drainageless depressions in the interior of the territory are covered by lake beds and much of the water found in such lake beds is saline.

Wembere. In the West Wembere total solids found vary from 16,000 to 3,800 p.p.m. In the East Wembere lower salinities are encountered ranging from 5,100 to 1,100 p.p.m. depending on the depth at which the water was struck. Water from 150 ft. depth in one borehole contained nearly five times the amount of total solids as in water struck at approximately 350 ft. The groundwaters in the Wembere are sodium-bicarbonate—carbonate-chloride waters, fairly high in SO_4, or chloride-bicarbonate waters. They are alkaline and the fluorine content is high. In the western Wembere fluorine shows a concentration of 34 to 40 p.p.m., to the east 26 to 27 p.p.m. Ca and Mg are low.

The Rukwa Depression. This is probably the largest single area covered by lake beds in the territory. The shallow groundwater down to 25 or 30 ft. depth varies considerably in quality, as proved by scores of Banka boreholes, the variation depending on the situation, but in general the water is high in sodium chloride and often unpotable. Deep drilling has so far, been carried out only at Ivuna salt pans for brine, so that no actual information is available as to the salinity in general of the deeper groundwater in this depression. Geophysical surveys in limited areas indicate that unpotable water may be expected at depth. 7·5 p.p.m. fluorine has been encountered in one Banka borehole at Ivumba Camp, Lake Rukwa area.

The Manyara Depression. The lake beds of the Manyara Depression have been explored by drilling only at the northern and southern ends. At Makuyuni, potable water was struck containing T.D.S. of 568 p.p.m. The type can be described as a bicarbonate water low in Cl and SO_4, fairly high in Ca, Mg and SiO_2, with pH 8 to 8·5. Saline water in small quantities was struck at 500 ft. depth 12 miles west of Makuyuni. The salinity of the water occurring in the southern end of the depression is not known, but the shallow groundwater, judging by the fairly large number of water-holes used by the local population, is potable. Spring water from this area varies considerably, from 2,550 to 30,270 p.p.m. in T.D.S. The water is a sodium-bicarbonate-carbonate-chlorine type, high in SiO_2, low in SO_4 and it contains no Ca or Mg. Fluorine has not been determined, but is probably high. Judging from samples taken in August, Lake Manyara water is not highly saline at certain times of the year—380 to 440 p.p.m.—but the only salt present appears to be Na_2CO_3. A sample taken in October, 1952, shows T.D.S. 8,612 p.p.m., i.e., Na_2CO_3 5,150 p.p.m., fluorine 2·8 p.p.m., pH 8·6 and no Ca or Mg present. Water-holes at Kwakuchinja carry potable water; the fluorine content is 7 p.p.m.. A recent borehole 6 miles south-west of Kwakuchinja in calcareous clays and sandy beds struck a sodium-bicarbonate water low in Ca and Mg, but containing 76 p.p.m. fluorine.

The Bahi Depression. From the days of the early exploration of the territory, groundwaters of high salinities have been known to occur in the south Bahi region. Recently these have been investigated by the Geological Survey and show brines from boreholes with a salt content of from 3·8 to 6·2 per cent T.D.S. The fluorine content varies from 7 to 28 p.p.m. Water from shallow pits show salt concentrations up to 20·3 per cent T.D.S. with a fluorine content as great as 180 p.p.m. The brines in the southern part of the depression contain sodium chloride and sulphate and are relatively low in $NaHCO_3$, although they do contain Na_2CO_3. pH values are as high as 10. Calcium and magnesium are present in very small quantities.

The Serengeti Lake Beds. The lake beds covering the eastern part of the Serengeti Plain have not yet been explored by drilling, but springs, wells and water-holes yield saline water with a high fluorine content. Particulars of T.D.S. and the main salt content of some of them are given below.

Ol-Balbal water-holes: T.D.S., 2,400 p.p.m.; $NaHCO_3$, 81 per cent; Na_2CO_3, 3 per cent; fluorine, 130 p.p.m.; low in Cl, SO_4 and Mg; no Ca.

Wells at Lake Magad: A sodium-bicarbonate-carbonate water; T.D.S. 1,180 p.p.m.; fluorine, 12·5 p.p.m. Springs from the same area show a fluorine content of 91 p.p.m., whilst springs from the Moro region show 50 to 70 p.p.m. F.

Springs at Eremet: T.D.S., 2,320 p.p.m.; $NaH(CO_3)_2$, 73 per cent; low Cl, SO_4, Ca and Mg; fluorine, 40 p.p.m.

Potable water of a chlorine-bicarbonate type, T.D.S. 510 p.p.m. and 3 p.p.m. fluorine, is found in the south-east at the Laitoli springs.

The Arusha Chini-Pangani River Basin. Lake beds have been found widely distributed in this area, but no drilling appears to have been done in the true lake beds. It is possible that relatively high fluorine values may be encountered (see under River Waters).

Other Areas. In addition to the better-known lake bed areas many of the block-faulted depressions in the territory have been filled by limestone, marls and clays. The largest so far encountered lies in south-east Masailand, covering approximately 140 square miles, and was explored by pre-Masai peoples in two well-fields in Lake Makama and Ndedo. Water from Makami contains 300 p.p.m. T.D.S. and is a calcium-magnesium-bicarbonate-sulphate water, fairly hard. Water from Ndedo contains 230 p.p.m. T.D.S.; a calcium-magnesium-bicarbonate water, fairly hard. A large number of cattle are watered at both these well-fields.

To the north and north-east of Kongwa, other large areas covered by lake and *mbuga* deposits have been explored by a number of boreholes. The water obtained from these, usually from the underlying Basement rocks, has a high T.D.S. content of 1,200 to 5,000 p.p.m., but in most instances it is potable for domestic use and livestock. Some of the waters are of the sulphate-bicarbonate type, high in Ca and Mg, and therefore very hard and, in most cases, unsuitable for boiler-feed water.

A number of smaller pans and *mbugas* have been explored in south-east Masailand and in the Central Province. At Lolbene, near the Ruvu Escarpment, the water struck was found to be unfit for cattle; T.D.S. 16,000 p.p.m., a sodium-bicarbonate water. In the Kitwe *mbuga*, further to the south but in the same region, potable water containing T.D.S. up to 2,300 p.p.m. was encountered; a sodium-chloride-bicarbonate type with 6 per cent Ca. In Dodoma District many *mbugas* contain potable water. A relatively high percentage of SiO_2 was noted in one at Goima, north of Dodoma, probably from diatomite beds. The Dodoma township water supply which, in the dry season, is derived from boreholes in the Makatupora *mbuga*, contains approximately 700 p.p.m. T.D.S. This is a bicarbonate water with a low fluorine content of 1 to 1·5 p.p.m. This water has been included under granite waters as it is struck in weathered granite. The SiO_2 content is relatively high, nearly 8 per cent of T.D.S.

(xii) *Alluvium.*—Alluvial deposits not connected with the coastal belt have frequently been explored by drilling. The most important single area is the Kilosa District. The salinity of the waters struck varies considerably, both within a small area and with the depth to which drilling has proceeded. The surface waters appear to contain more T.D.S., up to 1,700 p.p.m.; deeper waters may have as little as 350 p.p.m. The surface waters also contain more SO_4, the difference amounting to as much as 11 per cent of T.D.S. There is also more Mg than Ca in certain of the waters, which is unusual. In the deeper-seated groundwater, HCO_3 replaces SO_4. The waters are all nearly neutral and of the bicarbonate-sulphate type and those from depths of below approximately 100 ft. are of good quality and soft. Fluorine is low at 1 p.p.m., but one surface-well water carried 2 p.p.m. Scale-forming salts have been reported from cooling systems using surface-water at Kimamba.

(d) Mine-Waters

Included in Category 1 *on page 50* are mine-waters. These are groundwaters which, in some cases, have absorbed elements and radicals from the minerals in the ore deposits worked in the mine. Some mining areas lack water suitable for the treatment of ores, and even for domestic use, and in consequence, mine-waters have been extensively used in the territory for many purposes, in some cases direct from the mine and in others from water shafts sunk in the vicinity of mine workings. A few analyses from various mining areas in the territory have been given below.

(i) *Southern Highlands Province.*—North-east Lupa Goldfields; Shaft No. 1 T.D.S., 492 p.p.m.; a bicarbonate-sulphate water, fairly hard with little chlorine; fluorine, 1 p.p.m.; pH, 8.

North-west Lupa Goldfield; T.D.S., 510 p.p.m.; an alkaline water high in SiO_2; low ni hard scale-forming compounds, but high in temporary hardness.

(ii) *Central Province.*—General mine-water sample; Sekenke; T.D.S., 3,870 p.p.m.; a chlorine-sodium-bicarbonate-carbonate water, high in SO_4, causing pitting of boiler plates; a hard water forming soft scale. The water in No. 6 shaft contained less salts than the general mine-water sample; T.D.S. 1,200 p.p.m., but the type remained the same. No fluorine tests of the above waters were made. The general sample was highly alkaline and, judging from the situation in the Wembere, it must be assumed that the fluorine content is likely to be high.

(iii) *Lake Province.*—Shinyanga area; mine water from a borehole sunk in mine workings; T.D.S., 340 p.p.m.; a good water with nearly equal quantities HCO_3, Cl, SO_4, Mg and Ca; fluorine, 1·2 p.p.m.

MUSOMA AREA. Mine water; T.D.S., 400 p.p.m.; pH, 7·5; a calcium-magnesium-bicarbonate water with SiO_2, low in Cl and SO_4; fluorine, 1·6 p.p.m.

(iv) *Western Province.*—Coal mine; this water is of a peculiar type; T.D.S., 2,740 p.p.m.; a sodium-calcium-magnesium-sulphate water with hardly any bicarbonate; a very hard water forming hard scale.

(e) WELLS AND WATER-HOLES

Scattered over the whole territory there is a great number of shallow wells and water-holes dug in alluvium, in river-bed sands and surface cements or similar formations. Few analyses are available from these. In general there is a wider variation in the T.D.S. content of surface water than in groundwater from greater depth. This is due to a number of circumstances. For instance, wells close to the shore-line of the Indian Ocean vary in salinity with the tides. Surface waters inland, particularly those in the "dry" sandy river-beds, vary in salinity with the season and the position of the water points along the river-bed. The salinity increases steadily towards the end of the dry season and downstream, but only in exceptional cases does it become so high as to render the water unfit for domestic use. Wells and water-holes are not in general highly saline. A known case of very saline water being used for domestic purposes should be quoted: a water-hole in the Bahi Depression yielding water containing 9,700 T.D.S., of which 75 per cent consists of common salt, is used for human consumption over a short period in the dry season.

The fluorine content of water from wells and waterholes has rarely been examined, but a recent survey of some 30 in the Central Province was undertaken by the District Medical Officer, Dodoma. The water samples from the Central Province were tested for fluorine in the Geological Survey laboratory and results showed that, in general, the fluorine content was below 1·5 p.p.m. Water from a well of 15 ft. depth in Manyoni District showed 5·6 p.p.m. and from one well in a river-bed at Handali, 3 p.p.m.

(f) SPRING-WATERS

The geochemical aspects of waters of these types, particularly those from thermal springs, do not fall within the scope of this survey and are at present under investigation by Mr. T. C. James of the Geological Survey Department. The thermal springs in most cases carry considerable amounts of fluorine, (the maximum so far found is 330 p.p.m. in the Lake Natron area), and such springs are, in many instances, the source of the contamination of groundwater by this element. This applies in particular to the Serengeti, Wembere, Bahi and Shinyanga areas. One analysis from the Songwe River hot springs, Mbeya District, is included as an example. (See page 69).

(g) RIVER-WATERS

A distinction must be drawn between a river-water sample taken during the rains and at the end of the dry season. In the dry season the river flow is supported to a large extent by groundwater seepage, often called base-flow as opposed to the overland run-off during the rains. Quite a number of river-waters have been analysed during recent years, but only a few are given here as a comparison with groundwater analyses from more deep-seated sources.

(i) *Northern Province.*—Ruvu-Pangani River at the proposed dam-site at Nyumba ya Mungu, Same District; T.D.S., 506 p.p.m.; 28th March, 1956; pH, 9·5, containing bicarbonates of Na, Ca, Mg and Na_2CO_3; fluorine relatively high, 2 p.p.m.

Naisulu Stream, Arusha District; pH, 7·5; T.D.S. 230; a sodium-bicarbonate water high in fluorine, 11·2 p.p.m.

Ngare Nanyuki; T.D.S., 300 p.p.m.; a sodium-bicarbonate water high in fluorine, 20 p.p.m.

The two latter rivers have a very low Ca content.

(ii) *Tanga Province.*—Sigi River; T.D.S., 360 p.p.m.; neutral to phenolphthalein; a sodium-bicarbonate water with no SO_4; Ca about 16 per cent, Mg 11 per cent.

Mkulumuzi Stream; T.D.S., 1625 p.p.m.; neutral to phenolphthalein; a bicarbonate-chlorine water high in Ca and containing SO_4.

(iii) *Central Province.*—Miyoma Stream, east of Kongwa; T.D.S., 450 p.p.m.; neutral to phenolphthalein; Cl and SO_4 present, higher in Mg than Ca; considered suitable for boiler feed water.

Idete Stream; Mpwapwa District; T.D.S., 164 p.p.m.; neutral to phenolphthalein; a bicarbonate water; chlorine present; SO_4 absent.

Tambi River; T.D.S., 835 p.p.m.; a calcium-bicarbonate-sulphate water; very hard; unsuitable for boiler feed water.

(iv) *Southern Highlands Province.*—Songwe River, Chunya District; November, 1934; T.D.S., approximately 200 p.p.m.; a calcium-bicarbonate water; a small amount of Na_2CO_3 present, no Cl or SO_4; temporary hardness, $10{\cdot}6^0$ per 10^5; no permanent hardness. The Songwe water was analysed because it is the nearest water supply to the Galula coal-field some 9 miles distant.

Hagafiro River, Njombe District; T.D.S., 35 p.p.m.; contains only Na, Ca, bicarbonate; fluorine, 0·3 p.p.m.

Great Ruaha River bridge, Dodoma-Iringa road; T.D.S., 178 p.p.m.; a calcium-sodium-magnesium-bicarbonate water with 1 p.p.m. chlorine; no SO_4; 1 p.p.m., fluorine; pH, 7·5; 29th February, 1956.

(v) *Eastern Province.*—Great Ruaha River Gorge, Kilosa District; T.D.S., 190 p.p.m.; a sodium-calcium-bicarbonate water with little SO_4 or chlorine; relatively high in SiO_2; pH, 7·5; 27th August, 1954.

Great Ruaha River, Mbuyuni, Kilosa District; T.D.S., 145 p.p.m.; a calcium-sodium-magnesium-bicarbonate water; low in Cl and SO_4; SiO_2 relatively high. Date sample taken 19th August, 1954.

Rufiji River, Mbalinzo; T.D.S., 80 p.p.m.; a calcium-magnesium-sodium-bicarbonate water with some chlorine but no sulphate; pH, 7·5; fluorine, 0·2 p.p.m.

Rufiji River, Utete Ferry; T.D.S., 75 p.p.m.; pH, 7·5; date unknown.

(vi) *Lake Province.*—Waters from three rivers in the west Serengeti, the Seronera, Makungu and Orangi were tested for T.D.S. Salts were qualitatively determined in September, 1938. The T.D.S. were 2,900 p.p.m. (203 gr. p.g.), 1,800 p.p.m. (126 gr. p.g.) and 1,057 p.p.m. (74 gr. p.g.) respectively. The first showed a sodium-carbonate-bicarbonate water with Cl and SO_4 and no Ca, but relatively high Mg. The second is a chlorine-sodium-bicarbonate water with no Cl or SO_4, but both Ca and Mg are present in equal quantities.

Kagera River; June, 1955; T.D.S., 121 p.p.m.; low in Cl, no SO_4.

Seronera Stream, Serengeti; September, ç; T.D.S., 2,234 p.p.m.

Grumeti River, Musoma Road; T.D.S., 285 p.p.m.; including colloidal clay; a calcium-magnesium-bicarbonate water; no SO_4; a trace only of Cl.

Malagarasi River, at Uvinza; a sodium-calcium-magnesium-bicarbonate water with Cl, low in SO_4; temporary hardness, $18{\cdot}85^0$ per 100·000; pH over 8·5; a small amount of Na_2CO_3 is present.

(h) Lake-Waters

Lakes are replenished to a large extent by overland run-off during the rainy season, but the nature of the rock formation in a lake catchment area does nevertheless influence the type of salts found in lake-waters. Few analyses of lake-waters are available, but some are given below:—

Lake Tanganyika. The water from this lake was first sampled in 1892 by E. C. Hore. Some more recent analyses are given below.

Dr. Tornau, (Geological Survey, Berlin); samples taken in May, 1911, 300 metres off-shore at Ujiji; reaction, weak alkaline; specific gravity, 0·9993 at 21·5 degrees Centigrade; total residue at 100 degrees C., 0·0408 g; total residue at 180 degrees C., 0·339 g.

Tornau's sample May, 1911.

100 cc. contained:	
$CaSO_4$	0·0019 grammes.
$CaH_2(CO_3)_2$	0.0026 grammes.
$MgH_2(CO_3)_2$	0·0276 grammes.
K_2CO_3...	0·0069 grammes.
Na_2CO_3	0·0126 grammes.
NaCl	0·0059 grammes.
I	no trace.
Total ...	0·0575 grammes or 575 p.p.m.

Mean quoted by Halbfass:

Cl	37 mg. per litre.
SO_4	41 mg. per litre.
CO_3	180 mg. per litre.
Na	27 mg. per litre.
K	18 mg. per litre.
Ca	37 mg. per litre.
Mg	42 mg. per litre.
SiO_2	2 mg. per litre.
Total ...	462 mg. per litre or 462 p.p.m.

This total is given although the figures add up to 384 only, possibly due to a difference between T.D.S. determined by evaporation test and the total arrived at by the summation of the results of complete analysis of individual salts.

Government Chemist, Dar es Salaam, October, 1913. Residue 408 mg. per litre; loss by ignition 134 mg.; German degree of hardness 11·75.

Cl	33·7 mg. per litre.
SiO_2	2·3 mg. per litre.
SO_3	1·8 mg. per litre.
CaO	16·9 mg. per litre.
MgO	72·6 mg. per litre.
Total ...	127·3 mg. per litre.

Water samples taken by the Chief Engineer, w.w. *Liemba*, July, 1934.
Analyst F. Oates, Geological Survey, Dodoma.

The water is markedly alkaline in reaction both towards litmus and phenolphthalein. The water, therefore, contains alkaline carbonate in addition to Temporary Hardness. Temporary Hardness, 18°—10⁵.

Constituents	Grammes per litre
Organic matter	0·0364
SiO_2	0·0018
Ferric Oxide Fe_2O_3 } Al_2O_3 }	0·0044
Ca	0·0161
Mg	0·0334
Na	0·0361
K	0·0365
CO_3	0·2094
Cl	0·0320
SO_4	0·0035
Total ...	0·4096 By directed determination 0·4072

Water samples of 32·0 cc. taken at:

Lagosa, 6 p.m. 11/11/34.
Kasogi, noon 16/11/34.
Kibwega, 6 p.m. 10/11/34.
Kigoma, 9 a.m. 15/11/35.

These samples were mixed and give the following analysis: T.D.S. by evaporation and drying to constant weight at 110°C. and the residue analysed. Analyst F. Oates, Geological Survey, Dodoma.

Constituents	*Parts per Million*
Organic matter	30·8
SiO_2 and insoluble	2·8
Ferric Oxide and alumina	4·8
Calcium	11·3
Magnesium	31·2
Sodium	54·5
Potassium	34·4
Carbonate	212·4
Chlorine	28·0
Sulphate	9·0
Total ...	419·2 Total solids by experiment 410·2

The water is markedly alkaline.

Possible combination of Salts.

Organic matter	30·8
Silica and undissolved silicates ...	2·8
FeO_3 Al_2O_3	4·8
$CaSO_4$	12·7
$MgCO_3$	109·2
NaCl	46·4
Na_2CO_3	83·1
K_2CO_3...	60·4
Unaccounted for	50·0

The carbonates would most likely occur in the form of bicarbonates in solution before evaporating.

From the above analyses of water samples from Lake Tanganyika certain facts emerge which were originally pointed out by the late F. Oates, Chief Geologist, Tanganyika, such as the very high relative percentage of potassium and magnesium in the water. To this observation it should be added that the ratio between calcium and magnesium is unusual, 1 to 2·7. Oates also observed that the potassium is probably derived from the lavas in the Kivu area of the Belgian Congo which are known to contain minerals carrying potassium. Thermal springs, although their total volume is relatively small, may also have contributed their share. Analysis of water from all the major rivers entering the lake may solve the problem.

Lake Victoria. Sample from Musoma Bay. Analyst, Geological Survey laboratory.

Constituents	*Parts per Million*	*Percentage*
Cl ...	3·0	3·7
SO_4 ...	Nil	
F ...	0·7	
HCO_3 ...	58	71
SiO_2 ...	Not determined.	
Ca ...	7	8·6
Mg ...	2	2·5
T.D.S. ...	80	

The total absence of SO_4 should be noted. Analyses of river-waters entering Lake Victoria may give an indication as to the fact that SO_4 has been entirely eliminated, but more water samples from the lake are, however, essential.

Crater Lakes. Analyses from two crater lakes, namely Lake Duluti, south of Mount Meru, and Lake Igwishi, north of Urambo, showed the following results:

Lake Duluti: T.D.S., 263 p.p.m.; neutral; a sodium-bicarbonate water containing no SO_4 and low in Cl; fluorine 2·6 p.p.m.

Lake Igwishi: T.D.S., 876 p.p.m.; neutral to phenolphthalein; a magnesium-calcium-bicarbonate water with no SO_4; low in NaCl (13 p.p.m.); relatively high in SiO_2, with some $NaHCO_3$.

Sample from the Momela Pan, east of Mount Meru; pH approximately 10; T.D.S., 4,770 p.p.m.; a sodium-bicarbonate water high in SO_4; subordinate Cl; but with an extremely high fluorine content. (170 p.p.m.).

(i) *Variations in Salinity.* Variations in salinity in waters from boreholes and wells have been investigated. As far as boreholes are concerned there is no definite evidence of any large differences, but such variations are not easily established as conditions in the immediate surroundings of the borehole may be changed by the rates of pumping and withdrawal. A well in a river-bed at Bahi showed a variation in T.D.S. of approximately 1,200 p.p.m. between the minimum in the rainy season and the maximum at the end of the dry season. Similar variations may be expected in all wells sunk near seasonal rivers, where the groundwater is diluted by overland run-off during the rains. Seasonal variations in salinity of river-water may be of major importance in respect of perennial streams and rivers intended for use by irrigation and sampling and analyses of such waters are being carried out. A table based on investigations undertaken by the Government Chemist for the East African Railways of the monthly variations in a number of Railway water supplies is, therefore, of value and is shown on page 68. From this table it is clear that the season variation in the T.D.S. content is very large, particularly in the case of such rivers as the Ngerengere, where the flow at the end of the dry season is practically entirely groundwater or base-flow. It has already been mentioned that the salinity of groundwater varies according to the position of the well or water-point in a river-bed or in a large catchment, more saline water being found downstream or in the lower regions of a catchment area.

VARIATIONS IN RIVER AND WELLS

Parts per 100·000 (10^5)

		Gerezani	Kisarawe	Ruvu	Mikese	Ngerengere	Morogoro
pH ...	Average	7·5	7·2	7·6	8·6	7·7	7·4
	Largest	8·5	7·9	8·1	8·7	8·4	8·5
	Smallest	6·6	6·7	6·9	7·3	6·7	7·0
ALKAL ...	Average	7·4	4·1	5·1	59·5	8·2	2·4
	Largest	11·2	9·6	7·2	68·4	20·4	3·2
	Smallest	4·6	2·4	0·4	44·8	4·0	1·2
HARDNESS	Average	8·5	2·4	4·3	26·7	19·2	1·7
	Largest	14·1	12·4	7·3	36·5	44·8	4·4
	Smallest	4·9	0·7	2·0	14·3	2·4	0·7
CL ...	Average	11·1	1·3	0·5	35·1	7·0	0·4
	Largest	26·5	4·8	0·9	41·7	44·2	0·9
	Smallest	4·3	0·5	0·1	14·9	1·1	0·1
T.D. SOLIDS	Average	39·1	27·0	10·9	104·8	31·5	6·3
	Largest	69·1	68·6	24·7	161·4	153·9	19·6
	Smallest	23·9	7·3	6·2	125·9	9·2	1·5
MG ...	Average	0·67	0·42	0·42	3·13	0·89	0·43
	Largest	1·27	1·50	0·87	3·17	4·10	1·53
	Smallest	0·16	0·30	0·12	1·30	0·10	0·10

HOT SPRING—SONGWE VALLEY, MBEYA DISTRICT

	Parts per million
Total dissolved solids dried at 180°C. ...	2,340
Total Hardness, as $CaCO_3$	82
Calcium, as $CaCO_3$	62
Magnesium, as $MgCO_3$	20
Total Alkalinity, as $CaCO_3$ (including that due to silicate)	1,570
Sulphate, as SO_4	163
Chloride, as Cl	223
Nitrate, as N	0·3
Fluoride, as F	8·2
Phosphate, as P_2O_5	0·2
Silicate, as SiO_2	90
Sodium, as Na...	835
Potassium, as K	114
pH value	(8·4)

Corresponding to the following approximate composition:—

	Parts per million
NaCl	196
Na_2SO_4	241
$NaHCO_3$	2,337
NaF	18
KCl	218
$Ca(HCO_3)_2$	100
$Mg(HCO_3)_2$	35
SiO_2	90

(X/5069—J. 4059)

	% by vol.
Carbon dioxide	97·2
Hydrogen sulphide	Not detected
Carbon monoxide	less than 0·1
Oxygen	0·7
Hydrogen	less than 0·1
Hydrocarbons (as methane)	less than 0·1
Helium	less than 0·01
Nitrogen and other inert gases (by difference)	2·1

(X/5069—J. 4058).

CHAPTER EIGHT

PROSPECTING FOR GROUNDWATER

It should be clear from the chapter dealing with the hydrological properties of rocks that a general and detailed knowledge of the geology of all the main rock formations and other deposits is a prerequisite for undertaking any other surveys in connection with groundwater. After the geology of an area has been ascertained, the main scientific aid to finding water is a geophysical survey. Geophysics, like geology, comprises a very large number of branches and sub-branches. The geo-physical methods used for finding water are limited in number, and out of these only two have, so far, been used in the territory, namely resistivity surveys and magnetic surveys.

(a) Resistivity Surveys

Most hard rocks, sedimentary rocks, unconsolidated sediments and other deposits show, when dry, a relatively high to fairly high resistance to an electrical current passing through them. On the other hand, some ore minerals, particularly graphite, which is often met with in the territory, are good conductors. The resistance of rocks in general, however, decreases markedly if any interstices which may be present in the rocks or deposits contain water. Pure water has a high resistance, but does not occur in nature. Groundwater always contains salts in solution and its resistivity decreases rapidly as the salt content increases. The resistivity of rocks and other deposits to an electric current finally depends on the amount of interstices present, the extent to which these interstices are saturated with water and on the salinity of the water. These facts make it possible to utilize the comparative resistivity of rocks and other deposits to an electric current in prospecting for groundwater, and it is the basis on which such methods are founded. The field procedure used in most resistivity surveys for groundwater is relatively simple, but only the method generally used by the Geologist of the Tanganyika Water Development Department is referred to here.

Four steel pegs are driven into the ground at equal distances in a straight line. This is known as the Wenner configuration. The two outer pegs are connected to the AC power unit and are known as the current electrodes. The two inner ones are connected to the measuring unit and are known as the potential electrodes. The resistance, R, between the potential electrodes is either read direct from the instrument or calculated according to Ohm's law, $R = \frac{V}{I}$, where V is the potential difference in volts and I is the strength of the current in amperes. If the formation investigated is homogeneous, (which in nature is very rare) and has a resistivity of ρ, it can be mathematically proved that ρ equals 2 11 a. $\frac{V}{I}$ ohm/cm. (For the Wenner configuration only). (a is the electrode separation expressed in centimetres). If the electrode separation is increased ρ should remain the same and if the quantity 2 11 a $\frac{V}{I}$ is plotted against the electrode separation on a straight line should result. If the formation is not homogeneous, but changes with depth, the current has to pass through layers of different resistivity. Assume that the resistivity of two layers, one H cm. thick with a resistivity of ρ_1, the other of infinite thickness and a resistivity of ρ_2 and that ρ_2 is greater than ρ_1. For electrode separations of much less than H the current will pass through layer ρ_1 only and the resistance will still be ρ_1, but as the electrode separation increases, the current penetrates more deeply and more of the current will pass through the layer with the resistance ρ_2 so that the measured resistance will be somewhere between ρ_1 and ρ_2. This is known as the "average" or apparent resistivity. Finally, at large electrode separations compared to H, the quantity 2 11 a $\frac{V}{I}$ will approach the value of ρ_2. If the values obtained for the quantity 2 11 a $\frac{V}{I}$ be plotted against the electrode separation graphically, a curve will be obtained which shows that the ground is not homogeneous by the departure of the curve from the straight line. The curves thus plotted are known as apparent resistivity curves or depth-probe curves and portray the relationship of apparent resistivity to electrode separation.

From a working point of view it is often assumed that the electrode separation equals depth of current penetration. This is not always true, but for practical purposes and in using the Wenner configuration where potential electrode separation is one third of current electrode separation, the assumption appears to hold good in most cases.

The Tanganyika Water Development Department has used three types of instruments; the Paver resistivity tester, which is the most accurate of the three, the geophysical megger and the A.B.E.M. earth tester. The two latter are direct reading instruments. The geophysical megger unit has been more generally used than either of the other two types. It is robust and has, on the whole, stood up well to much rough treatment in the field.

With the above instruments two main types of surveys have been carried out:—

(i) *By Depth-Probes.*—Where the instrument remains stationary and the electrode separation is expanded by 10 to 20 ft. after each reading until a maximum separation of approximately 500 ft. is reached which, in most cases, is the limit of practical prospecting and also the limit of two of the above instruments. From the readings recorded the apparent resistivity of the ground can thus be said to have been explored at every 10 or 20 ft. to a total depth of 500 ft. below the surface. The result is a depth-probe curve or graph referred to above.

(ii) *By Constant Separation Traverses.*—During this type of survey the distance between electrodes remains constant, and the instrument is moved along a line in the field. The quantity 2 11 a $\frac{V}{I}$ is plotted against the relevant points on the traverse line. The results obtained in a C.S.T. can be used for cross-sections and equal or iso-resistivity contour plans. The choice of electrode separation in a C.S.T. depends on a number of factors connected with geology, weathering, etc., but it is usually determined after several depth-probes have been taken in the area under survey. If an area is to be explored fully and completely a grid system of constant separation traverses is laid out and after the results have been plotted, depth-probes are carried out in areas thus indicated as favourable. This system was used by private firms prospecting geophysically for water in the Overseas Food Corporation development areas at Nachingwea and Urambo, particularly by Geophysical Surveys (Pty) Ltd. Such surveys are expensive and it took years and several teams to cover a relatively small area (perhaps 500 to 1,000 square miles) at Nachingwea. If, however, water is urgently required for development within a given area it is the only reliable method of survey. The grid-plan type of survey has not, so far, been used by the geologist of the Water Development Department, mainly due to lack of time and personnel. Large tracts of country have, however, been explored by more widely-spaced constant separation traverses in the following areas; the Isanga basin south of Smith South Lake Victoria region; the Chungai area of north-east Kondoa District; the Loji-Chipogoro area of Dodoma District; the Lossogonoi area of south-east Masailand and in the neighbourhoods of Tabora and Dodoma townships.

In connection with regional resistivity surveys it should be pointed out that wherever possible the area of such a survey should be limited by geological investigation, as any type of resistivity survey is slow and the expenditure of time and money, in many cases, is not justified by the results obtained.

(iii) *Results of Resistivity Surveys.*—The total number of depth-probes and constant separation traverses (C.S.T.) carried out by the Geologist of the Water Development Department during the last nine to ten years has risen to several thousands. A direct result of such a large number of resistivity surveys, which have entailed a great deal of labour in the field, is that considerable experience has been gained in the most difficult part of such geophysical surveys, namely the interpretation of the graphs. This interpretation can now be made with some confidence.

(iv) *Interpretation of apparent Resistivity Graphs or Curves.*—Correct interpretation of resistivity graphs does, apart from fundamental knowledge of most branches of geology, also require a great deal of experience. New areas, in which no boreholes have been previously sunk and in which no comparison can be made between depth-probe curves and boring logs, as a rule present the most difficult problems. Once a number of boreholes and the respective depth-probes are available, the geologist is on firmer ground. It must, however, be stated that among the many resistivity graphs computed from surveys in the territory only a very small number directly indicate the presence of water. The great majority show only that a formation is either favourable or unfavourable or is a border-line case. In hard rock formations which yield fissure-water, the salinity of such water cannot always be forecast, neither can the yield of a borehole be estimated beforehand with any certainty. When interpreting resistivity graphs or curves two major aspects of these are most carefully scrutinised:

1. The general geometrical shape of the curve, i.e. any change in shape or direction.
2. The actual apparent resistivity values of the various parts of the graph.

The interpretation of curves by using theoretical considerations and mathematically computed graphs appertaining to the two or three layer problems has, so far, only been done on a small scale, and this subject cannot be referred to in this paper.

Before discussing a number of field or apparent resistivity curves it should be made clear that the depth-probe curves shown in the tables attached are more often than not carried out at points determined by constant separation traverses, i.e., in localities which have been indicated as more favourable than the rest of the area under investigation. An example is given on attached, Graph No. 24. The graphs or curves shown in the tables do not, therefore, always give a true picture of the general conditions of the whole region or formation under survey, but only of one small, very limited, area in which a borehole has been sunk. The graphs selected are numbered from 0 to 97 and are direct copies from the results obtained in the field, and which are often plotted during the survey itself. Many sharp jerks and kinks are due to bad contacts or instrumental errors and the idiosyncracies of the instrument and the rest of the equipment. Most of these equipment errors are known to the operators and are disregarded when the curve is interpreted.

The horizontal axis of the various curves gives the apparent resistivity in 1000 ohm-cm. or kilo-ohm-cm. The vertical axis indicates electrode separation in feet. Depth to water struck and total depth of borehole sunk on the site of the depth-probe are shown and yields in gallons per hour are stated. Borehole numbers are marked thus; 17/53 means borehole 17 in the year 1953. A brief description of each graph follows:—

Basement Rocks, Northern Province. Six apparent resistivity graphs Nos. 1 to 6 inclusive compiled from borehole sites in the Loliondo area are shown. The rocks encountered when drilling these sites were quartzite with bands of biotite gneisses. No boreholes had previously been sunk in this area. The first borehole 20/54, GRAPH No. 5, was a failure. Graph No. 5 showed no excessive apparent resistivity values and from 255 to 290 ft. electrode separation a tendency to remain at 3 kilo-ohm-cm. This also applied to greater depths. The borehole was completely dry and the quartzite rock soft and weathered to 451 ft., the full depth of the hole. C.S.T. traverses in the surrounding area showed only very high apparent resistivity values. The second borehole sunk was at the site of No. 2 GRAPH, 55 miles to the south. The occurrence of low values at the top of Graph No. 2 are due to a heavy over-burden of volcanic ash and clays. Water was struck at 290 ft. where the general direction of the slope of the graph flattens out, or at the point where weathered is replaced by unweathered rock. The rock was quartzite with layers of biotite gneiss. Kyanite occurs in the area.

GRAPH No. 1 is of a type similar in many respects to No. 2 but was drilled much later, and possibly lacks the distinct change in slope of No. 2. Apparent resistivity values are relatively low. Only 60 gallons of water per hour were obtained at the full depth of the borehole.

GRAPHS NOS. 3, 4 AND 6 from the West Loliondo area, have a flatter trend and high apparent resistivity values than graphs Nos. 1 and 2. The only general conclusion which could be drawn from Nos. 3, 4 and 6 is that the water-bearing zone evidently falls within the apparent resistivity values of between 3 to 4·5 kilo-ohm-cm. The quartzite in which the water was struck is folded, striking 115 degrees and pitching to the west at a fairly low angle.

Graphs Nos. 7 to 12 inclusive represent a selection obtained on Basement rocks, Nos. 7 and 8 from the Lake Manyara region, Nos. 9 to 12 from south-east Masailand. GRAPH No. 7 indicates a definite zone of weathering between 200 and 250 ft. electrode separation. Water was struck in this zone above harder banded gneisses.

GRAPH No. 8 shows deep weathering to 400 ft. due to intense fracturing connected with the East Manyara fault zone. Slightly saline water was struck at the bottom of the hole. Low apparent resistivity values which can be attributed to rock weathering without a definite rise at deeper levels is, in general, an unfavourable indication. The rock at No. 8 is fractured gneiss with pegmatite intrusions.

Graphs Nos. 9 and 10 are of sites 5 to 6 miles apart. No. 9 GRAPH indicated a layer of relatively lower apparent resistivity between 260 and 330 ft. Water was struck in weathered banded gneiss in this zone but not at deeper levels.

GRAPH No. 10 is similar in trend, but the break in slope is more definite between 160 and 220 ft. and higher resistivity conditions exist at lesser depths. The rock is a banded biotite gneiss with a flat dip.

Graphs Nos. 11, 12 and 13 were taken in the Pangani escarpment region and the boreholes sunk on these graphs were all failures. GRAPH No. 11—the borehole sunk on this graph is reported to have penetrated marls and limestones to 257 ft. and then to have gone into weathered Basement rock.

GRAPH No. 12 site showed, when drilled, limestone, marls and rock rubble to 49 ft., and then a banded pegmatitic gneiss weathered to about 300 ft. A definite rise in apparent resistivity indicates more solid rock. Theoretically the graph showed good promise of striking water at 220 to 300 ft.

GRAPH No. 13 shows far higher apparent resistivity values from the surface downwards, but a definite drop between 400 and 450 ft. The rock, a banded gneiss, is definitely hard at 460 ft. at the bottom of the hole.

The reason for the failure of the sites of Nos. 11, 12 and 13 is considered to be due to fracturing and consequent under-ground drainage to the Pangani Valley to the east.

Graphs Nos. 14, 15 and 16 were obtained in the southern-most part of Masailand on the boundaries of Kondoa District. Nos. 14 and 15 were successful, No. 16 unsuccessful. No. 14 shows a definite steepening at between 200 and 245 ft. electrode separation where, in fact, water was obtained.

GRAPH No. 15 shows no indication of water at a depth where the main supply was struck, and apparent resistivity values are relatively high above 15 kilo-ohm-cm. in the water-bearing zone.

GRAPH No. 16 which, judged by shape and apparent resistivity values, is favourable, proved unsuccessful. The reason for this, found by drilling, is that weathering has proceeded too far.

Some 80 miles east of Loliondo, where depth-probes Nos. 1 and 6 were obtained, but separated from the Loliondo area by the Lake Natron rift valley, is a dry tract of country known as the Longido area, from the 8,600 ft. high mountain of this name. Graphs Nos. 17 and 18 were obtained in this area.

GRAPH No. 17 shows relatively low apparent resistivity values, but a borehole sunk on the site gave only 100 gallons per hour at a slight steepening of the curve which may or may not be coincidence. The rock encountered in the borehole is a granulitic gneiss with some biotite:

GRAPH No. 18 indicates that the rock has weathered to the full depth of the survey, and, therefore, that the rock may contain water. The graph, in general, is featureless.

Graphs Nos. 19 to 23 have been selected as examples of curves obtained in a certain type of *mbuga* in south-east and south-west Masailand.

GRAPH No. 20 is from the extreme south-eastern corner of Masailand. The site, when drilled, showed a relatively thin covering of solid limestone from 0 to 40 ft. gradually turning into sandy limestone and with some marl. Basement bedrock followed at 97 ft. and was weathered to the full depth of the hole.

GRAPH NO. 19 represents a type of *mbuga* with a deep covering of limestones, clays and marls to approximately 205 ft., followed by heavily weathered Basement rock of biotite amphibolite gneiss which continues to the full depth of the hole.

GRAPH NO. 21 represents a very shallow type of *mbuga;* only 33 ft. of limestone with marls were struck in borehole 6/52, followed by a granitic gneiss. Water was struck just inside the hardening gneiss rock. This hardening of the rock is clearly indicated by the high apparent resistivity values on graph No. 21.

GRAPH NO. 22 was obtained in the same *mbuga* as No. 21. The limestone covering is, however, sandy and limonitic, and no marls are present. This deposit is followed at 110 ft. by weathered biotite gneiss to the full depth of the borehole. The water was struck on the biotite gneiss rock.

GRAPH NO. 23 is an example of a fairly common type of resistivity curve often obtained in *mbugas* and pans where clays and marly deposits underlie a relatively even covering of limestone. Apparent resistivity values are usually low, from 800 to 1,000 ohm-cm. or lower when marls and clays have been reached. The lower part of such graphs often shows a vertical trend, with little change in resistivity even when saline water occurs, as in the case of borehole 25/50 which was drilled at the site of graph No. 23.

PLAN NO. 24 AND GRAPH NO. 24A, are an example of a survey where iso-resistivity contours were drawn from constant separation traverses; such traverses, as a rule, proceed most depth-probes. It is also an example of a survey where everything went according to plan, a rare occurrence. Borehole 1/52 struck water in weathered gneiss above unweathered rock of the same type. Depth-probe graph No. 24 finally determined the drilling site.

Graph No. 25. The site was explored by borehole 15/52, which struck water at the relatively great depth of 360 ft. above harder rock of Basement type. Marls and clays which are 75 ft. thick account for the low apparent resistivity values to this depth.

GRAPH NO. 26. The site was drilled and water was struck in weathered basic bands in a banded gneiss and where this rock finally becomes solid and unweathered. The top 75 ft. consist of *mbuga* limestone, marls and clays which is well indicated by apparent resistivities in the graph.

GRAPH NO. 27. This graph, situated in an area of Basement rocks, indicated that the rock is highly weathered to the full depth of 500 ft. of the resistivity survey. The apparent resistivity values 2·5 to 5 kilo-ohm-cm., however, also show that the formation is not clay or marls. Drilling would not normally have been tried on a graph of this type, but water was urgently required for a Native Authority school already being built.

GRAPH NO. 28. This graph shows lower values than No. 27. Bedrock epidote gneiss was, in fact, first struck at a depth of 221 ft. below superficial deposits of clays and marls. The rock is highly weathered to 286 ft. and weathered to 420 ft.

GRAPH NO. 29 shows a similar trend to No. 28 but the geological formation on which it is sited is different, consisting of a quartz chlorite schist of Nyanzian type. The schist was first struck in a highly-weathered condition at approximately 240 ft. depth, but rock-weathering persists to the full depth of the borehole, 420 ft.

Graphs Nos. 30 and 31 are two similar graphs obtained at points 10 miles apart. THE ROCK IN NO. 30 was encountered close to the surface and consisted of a Basement gneiss intruded by a dolerite dyke; a relatively large supply of saline water was struck at 85 ft. The apparent resistivity values fall sharply from this point to the bottom of the borehole. NO. 31 WAS SITED on an alluvial fan deposit. Basement rock was struck at 150 ft., but no water was found. The presence of rock at 150 ft. can be forecast from the graph.

GRAPH NO. 32 shows a curve which is fairly common in granitic gneiss or granite areas and only a slight change in the otherwise straight course of the graph indicates the possible presence of harder or softer rock. In some cases a ruler is laid along the curve and lines are drawn to ascertain the angle between the two limbs of the curve.

GRAPH No. 33 shows a curve which is also common in Basement rocks and only indicates a gradual hardening of the rock towards depth. The apparent resistivity values indicate, however, that weathering persists to about 150 ft. and that water may be found above this depth.

GRAPH No. 34. This graph was taken on an *mbuga* covering amphibolites. The upper part reflects the clays and marls, the centre part weathered amphibolite and the lower part more solid amphibolite.

GRAPH No. 35. The main supply of water was struck in weathered Basement rock just above solid rocks of the same type. The water is of medium salinity but potable.

GRAPH No. 36 was taken on an alluvial fan deposit 140 ft. thick which is reflected in high surface values. Weathered Basement rock was encountered from 140 ft. to 200 ft.; below this is solid Basement rock.

GRAPH No. 37. This graph was taken on *mbuga* deposits, marls, clays and limestone rubble, to 90 ft. At 95 ft. weathered granite gneiss was encountered on which the groundwater was found.

Graphs Nos. 38 to 44 were all derived from a particularly difficult area of Basement rocks in east Kondoa District, and deserve close scrutiny. An area of deep superficial deposits followed by weathered and fissured rock combined in creating abnormal groundwater conditions. Three failures and three successes are depicted on graphs 38 to 40. The reasons for the failures are not immediately apparent and must be considered in relationship to the successful boreholes.

GRAPH No. 39. The formation drilled was superficial clays, sands and rock rubble to 300 ft. and weathered to fresh granite gneiss and biotite gneiss to the full depth of 515 ft. No really hard rock was encountered and no water was struck in the rock.

GRAPH No. 40. This graph was taken in an *mbuga*. Superficial deposits are clays, lime rubble and marls to 306 ft.; then weathered biotite gneiss to the full depth of 370 ft. A small amount of water was struck in pegmatitic material at 315 and 358 ft. When compared with the drilling logs the graph does indicate the break between superficials and bedrock, but this could not have been interpreted beforehand as the low apparent resistivity of the top layer masks the higher apparent resistivity of the bedrock, the apparent resistance of which has not reached a 2 kilo-ohm-cm. at 400 ft. electrode separation. The trend of the curve deviates from the general type of Basement rock curves.

GRAPH No. 38, which is similar in general direction to curve No. 39, shows clays and sands to 110 ft. From 110 ft. to the bottom of the hole the borehole samples indicate fresh or weathered rock, depending on whether a band of acidic or basic banded gneiss has been intersected. Water was obtained in weathered biotite gneiss. The drop in apparent resistivity is maintained over five consecutive electrode separations between 320 and 370 ft. Water was struck in this zone.

GRAPH No. 41. The site was explored by borehole 24/56, which encountered clays and sandy clays to 190 ft., pegmatitic weathered granite from 190 to 260 ft.; unweathered granite gneiss from 260 ft. to 290 ft.; and weathered biotite gneiss, in which water was obtained, from to 290 320 ft.; weathering continues to 365 ft. Fractures occur at between 375 and 385 ft., but the rock has hardened.

GRAPH No. 42 when drilled showed clays, marls and clayey sands to 130 ft., then banded gneiss to 190 ft.; from 190 to 250 ft. the banded gneiss was fractured and unfractured basic granite gneiss from 250 to 300 ft. The vertical trend over nearly eight consecutive electrode separations coincides with the fractured and slightly-weathered rock which is the water-bearing zone.

GRAPH No. 43. Clays and heavily oxidised clayey sands were encountered to 88 ft., in which a small supply of water was struck. From 88 ft., banded gneisses fresh-'to slightly-weathered continued to 510 ft. From the borehole samples there appears to be no reason for the steady drop in apparent resistivity between 100 ft. and 160 ft. electrode separation. Only one thin layer of oxidised rock was struck between 188 and 200 ft. Lateral interference may account for the deviation of the curve, but this is unlikely as tests for such interference are routine measures in surveys of this type.

GRAPH No. 44. The superficial deposits extend to approximately 360 ft. and water in small quantities was struck from 185 ft. downwards, the main supply occurring between 450 and 500 ft. in weathered biotite gneiss.

GRAPHS Nos. 45 and 47 represent resistivity curves carried out over a body of quartzite which is strongly fractured. The superficial deposits at the two sites varies, but the occurrence of water in fractured rock in the boreholes coincides with a very strong deflection of the apparent resistivity graph.

GRAPH No. 46. This graph cannot be accurately interpreted by itself, but in conjunction with the results of drilling at the site of Graphs Nos. 45 and 47, situated 5 and 10 miles to the north of Graph No. 46, and another borehole 4 miles to the south, the site was selected for drilling with good results. Water was struck in broken quartzite.

Graphs Nos. 48 to 50 are examples of *mbuga* resistivity tests from the Central Province where varying thicknesses of limestone were encountered. In a borehole sunk on the site of GRAPH No. 48 no bedrock was encountered. In borehole 24/51, GRAPH No. 49, diatomites were struck under marls from 90 to 100 ft., but bedrock was not reached.

At the site of GRAPH No. 50 a weathered biotite granite was encountered at 160 ft. and water was first struck at 170 ft.

GRAPH No. 53 is also an example of an *mbuga* curve. Clays and marls were struck to an approximate depth of 200. From 200 to 228 ft. weathered granite was encountered and below this to 246 ft. less weathered granite. All formations below 155 ft. are saturated with water of a salinity, T.D.S. 500—600 p.p.m. The borehole is now used for the Dodoma township supply.

The Graphs Nos. 48, 50 and 53 have a common characteristic in that from none of these curves is it possible to determine the exact depth to bedrock from the graph. This is due to the fact that if, in a two layer system, the top layer has very low resistivity compared to the bottom layer, the current will flow nearly exclusively in the top layer and not penetrate into the layer with higher resistivity. The apparent resistivity will, therefore, only change very gradually from a relatively low value to higher values with the expanding electrode separation. In such cases, which are common in the Central Province, knowledge of geology is essential to be able to judge the depth to which drilling should proceed.

Graphs Nos. 53A to 68 is a selection of resistivity graphs from granitic areas including boreholes of the Nyanzian formation.

GRAPH No. 53A. A borehole sunk on this site struck calcareous cement to 45 ft., weathered granite to 105 ft. and solid granite to 110 ft.

GRAPH No. 54. This site is an example of an inlier of biotite-granite gneiss in the central granite shield. The borehole log shows a rock cement and quartz rubble to 75 ft., below this an inlier of biotite-garnet gneiss intruded by pegmatite and quartz. This rock hardens at 154 ft.

GRAPH No. 55—0 to 68 ft. rubble of quartz; weathered hornblende granite to 110 ft. and less weathered to the full depth of the hole.

GRAPH No. 56. This graph is of interest as a borehole sunk at the site encountered 3,000 gallons per hour of potable water badly needed for the Dodoma township in a drought year. The graph does not indicate the large fault zone encountered between 300 and 370 ft. and was not considered particularly favourable before drilling. The relatively low apparent resistivity values to a fair depth were the main reasons for sinking a borehole on the site.

The fault zone itself is filled by a chlorite-epidote limestone rock of hydrothermal origin which has been refractured after its formation. Technical difficulties prevented the hole from being drilled to greater depths. The dip and strike of the fault zone could not be accurately ascertained by variometer surveys or geological means. Weathered granite with epidote was encountered from 45 to 300 ft.

GRAPH No. 57 has been selected to show how difficult it is to forecast formation from the resistivity curves, even if the bedrock of the area is known to be granite. The borehole at the site penetrated rubble, clayey sands and gravels to the full depth.

GRAPH No. 58. The site was drilled and rock cement encountered to 100 ft. depth, below followed decomposed granite to 130 ft. and then hard granite to the full depth of the hole.

GRAPH No. 59 was obtained many years after the borehole was drilled and shows no indication whatsoever of water, or conditions favourable for water. The borehole penetrated a rock cement to 166 ft. and then went 2 ft. into granite. Compare with Graph No. 58. The borehole was sunk on geological grounds and the water struck was of relatively low salinity.

GRAPH No. 60 shows the result of a resistivity survey of a granite gneiss. A borehole sunk on the site was a complete failure. Apparent resistivity values are relatively low, and were reflected by fairly soft, weathered granite gneiss to 170 ft. depth. The trend of the curve, so far as granite curves go, is favourable. Epidote occurs in many of the borehole samples. For further details see under Weathering.

GRAPHS NOS. 61 AND 62 show the advantage of resistivity surveys in a granitic area. A borehole was drilled at the site of Graph No. 62 many years before resistivity measurements became general practice. The borehole was abandoned in hard granite at 40 ft. No. 61 site was drilled in weathered or semi-weathered granite from 15 to 252 ft. The two sites are in the same valley and about a mile apart.

GRAPH No. 63 is of similar trend to Graph No. 57 with lower apparent resistivity values. The borehole at this site encountered a pink aplitic rock from 20 to 110 ft. From 110 to 255 ft. unweathered granite was struck. The reason for the failure at this site is not clear. The shape of the graph and apparent resistivity values are favourable and water was expected at 150 ft. It is possible that the presence of the pink aplitic rock has some bearing on the lower resistivities.

GRAPH No. 64. The borehole drilled at this site shows the following log. Granitic sands and sandy clays to 65 ft.; 65 to 70 ft. weathered granite; 70 to 75 ft. fresh granite; 75 to 135 ft. weathered granite, fractured; 135 to 145 ft. aplitic granite, fractured; 145 to 160 ft. aplitic granite, fairly hard and solid; 160 to 168 ft. fresh hard granite. The fractured granite of the second aquifer is clearly indicated by the drop in apparent resistivity.

GRAPH No. 65. The borehole drilled at this site struck water of relatively high salinity, but potable, at the junction of weathered granite and fairly fresh granite. The surface water was less saline. The salinity of the water, in this case, is indicated by a distinct drop in apparent resistivity.

GRAPH No. 66. The formation tested is an example of alluvium on granitic rock. Dry sands and gravels were encountered to 85 ft., then two aquifers close together, one in alluvium and one in granitic rock were struck at approximately 100 ft.

GRAPH No. 67. See below.

GRAPH No. 68. The borehole sunk in 1948 on the site of this graph was the first indication that quantities of water were available in the Makutopora *mbuga* and was the main reason for further exploratory work. At present the locality yields 200,000 gallons per day and is part of the Dodoma township supply. The boreholes struck clays and marls and, deeper down, *mbuga* limestone was encountered to 240 to 250 ft. From 250 to 300 ft. weathered granite is known to occur. Solid granite has not been reached so far at Makutopora. The graph shows low apparent resistivity values. See also Graphs Nos. 48 to 50 and Graph No. 53.

Older Lavas.

GRAPH No. 67. This graph depicts apparent resistivities obtained in the lava series of the Nyanzian formation of the Musoma District. The type of graph is common. The lava is weathered to approximately 120 ft. and the groundwater is apparently held up by unweathered lava.

Younger Lavas and Pyroclastics.

GRAPH No. 69. The resistivity survey depicted in this graph was carried out in an area where lava was known to overlie Basement rocks. The result of the drilling showed lava to approximately 150 ft., then pyroclastics to 255 ft. From 255 ft. weathered Basement which was strongly fractured was encountered to the full depth of the hole. The fractures drain all potential water supplies. The graph agrees well with the formation encountered. It was not known that pyroclastic deposits existed in the area, hence the curve was interpreted as solid lava but potentially water-bearing from 220 to 255 ft., where the Basement was expected.

GRAPH No. 70. The borehole drilled on the site of this graph shows lava for 15 ft. then pyroclastic rocks to the full depth of the borehole. The nature of the formation which holds up the water is not known, but it is probably a lava or agglomerate bed.

GRAPH No. 71. The borehole drilled at this point showed ash and pyroclastics to 51 ft.; from 51 to 157 ft. solid lava in which water was struck; from 157 ft. to the full depth of the hole vesicular lava, apparently not water-bearing was encountered.

GRAPH No. 88 from a site only a few miles away to the west of the site of Graph No. 71 is shown for comparison. In the borehole sunk at this site solid lava was encountered with the exception of the top 20 ft. This lava was oxidised or fresh. A 20 ft. zone of oxidised lava was found at the bottom of the hole, indicating that at this stage volcanic activities had been quiescent for some time. The relatively high apparent resistivity values indicate the possible nature of the volcanic formation.

GRAPH No. 72 was obtained in an area where groundwater is abundant. The formation from surface downwards consists of lake beds 30 ft. thick, below which are pyroclastic deposits or possibly alluvial fan deposits, waterbearing, to at least 412 ft.

GRAPHS Nos. 73 and 74 were obtained in lava formation. There is no indication of any water-bearing layer in either of these curves to approximately 100 ft. Water was struck at the surface but, unfortunately, it is contaminated by fluorine.

GRAPH No. 75 was obtained in a crater and the siting of the borehole was mainly based on geological observations. The water-bearing zone is in ash and clayey-ash beds.

Basement Areas mainly in Fault-Zones in the Pare-Usambara Region.

GRAPH No. 76. This shows a curve taken in an area where fracturing combined with weathering contributes to the creation of conditions favourable to accumulation of groundwater. The graph shows a vertical trend from about 140 to 160 ft. in which zone the water was encountered in weathered and fractured Basement rock.

GRAPH No. 77. The site was chosen for geological reasons in an area where two large faults or fracture systems were likely to intersect. The borehole was drilled in Basement rocks intruded by quartz veins and pegmatites and large open dry fractures were encountered before the water-yielding fault-zones were intersected. The graph gives no indication of these fracture zones.

GRAPHS NOS. 78 to 81. See below.

GRAPH NO. 82. The graph depicts resistivity conditions connected with the occurrence of large quantities of saline water in a fracture in Basement rocks. The area is situated to the east of the Usambara Mountains where saline waters are known to occur in fractured rock. The sudden drop in apparent resistivity values, which had reached relatively high figures, gives an indication of the quality of the groundwater that could be expected.

Coastal Sediment.

GRAPH NO. 78. This graph shows an example of salt-water penetration within the coastal unconsolidated sediments and coral reef formation. Such graphs must be closely studied. The borehole in question was stopped at 75 ft. immediately after fresh water had been struck. Salt-water can be expected only a few feet deeper. Apparent resistivity figures in the coastal clays penetrated by salt-water show often sudden drops to very small values.

GRAPHS NOS. 79 AND 80 are more or less typical of the apparent resistivity conditions of the solid Jurassic limestone found in the area west of Tanga in which water only occurs in solution channels or in joint systems. No indication of a water-carrying zone can be deduced from these graphs. The curves continue in the same general direction to at least 350 ft. electrode separation.

GRAPH NO. 81 is from the same area but to the south-west. The sedimentary conditions are, however, very different. Clayey marls, marls and beds of solid oolitic limestone were struck within the compass of the resistivity graph below calcareous shales occurred. The borehole was sunk to a depth of 900 ft. and must be considered as a failure.

GRAPHS NOS. 83 TO 85 inclusive were obtained in a Jurassic oolitic limestone within a relatively limited area. Only the borehole logs for Graph No. 85 are available; these show limestone and oxidised clays to 99 ft.; from 99 to 204 ft. blue shales followed by limestone from 204 to 215 ft.; shale from 215 to 235 ft. and limestone to the full depth of the hole. It should be pointed out that water in this hole was struck above the shales, which show lower apparent resistivity than the limestones. The graph would be very difficult to interpret without the borehole logs. This borehole was drilled in 1935 before resistivity surveys were introduced. There are no reliable records of borehole samples from the two private boreholes (Graphs Nos. 83 and 84), but both are reported to have struck limestone from a few feet below surface to the total depth of the holes. The resistivity surveys were carried out during check surveys of boreholes already drilled in the area.

GRAPHS NOS. 86 AND 87 are examples of resistivity surveys in the Karroo area north and north-west of Tanga. They were taken on black Karroo shales probably overlying the bottom conglomerate of the Karroo. The borehole at site 86 struck saline unpotable water. The higher salinity of the water is reflected in the lower apparent resistivities of Graph No. 86. Site No. 87 was drilled and the salinity of the water struck is just above the upper limit of potability, 3,300 p.p.m., but it can be used. Other resistivity surveys from the same type of rock show similar curves. The main water-supplies were struck where the boreholes enter unweathered shale. There is also a change of trend towards higher resistivities at this point.

GRAPH NO. 88. See above.

Alluvium. An alluvial area explored by drilling occurs in the Kilosa-Kimamba region of the Eastern Province. The Kimamba area presents certain aspects in regard to resistivity surveys which will be discussed under Graphs Nos. 89 to 94 inclusive. The main features of the geology of this area is the occurrence of two main aquifers consisting of sands, gravels or even cobbles, interbedded by clays and sandy or calcareous sediments. As far as groundwater is concerned there appears to be no direct connection between the higher aquifer occurring at a depth from 20 to 50 ft., if the quality of the water, which varies considerably, is taken as a criterion of a connection between these beds. The lower aquifer occurs in general below 100 ft. and appears to be continuous and to contain water in large quantities and of good quality. There is a possibility that a third aquifer occurs below 185 ft. or 250 ft. Technical difficulties in the form of running sands in the second aquifer have so far prevented exploration of deeper strata. Graphs Nos. 89 to 94 inclusive were obtained within a radius of two miles.

GRAPH NO. 89. The borehole logs at the site of this graph show the following formation; 0 to 54 ft., sandy clays; 54 to 84 ft., coarse sands and quartz pebbles (aquifer No. 1); 84 to 131 ft., sandy clays and clays; 131 to 135 ft. sand, gravel and cobbles (aquifer No. 2). The graph reflects changes in formation, but it would not have been possible to forecast accurately what these changes mean as regards alluvial material. The difference between apparent resistivity of a possibly dry sandy clay and a water-bearing sand is not large enough for definite identification.

GRAPH NO. 90. The borehole sunk on this graph also intersects two aquifers, the first between 25 and 49 ft. and the second between 108 and 116 ft. The changes in apparent resistivity could not, as in Graph No. 89, have been interpreted with certainty.

GRAPH NO. 91. The borehole drilled on this graph intersected the following strata; 0 to 35 ft., sandy clays; 35 to 110 ft., sands and gravel (first aquifer); 110 to 135 ft., sandy clays; 135 to 157 ft., sands and gravels, possibly a second aquifer. The graph shows falling apparent resistivity values covering aquifer No. 1 and more or less stable values for the lower clay beds and aquifer No. 2, which may or may not be saturated with water.

GRAPH NO. 92 was obtained close to borehole 10/57, but may not accurately depict the formation struck in this borehole. The geological conditions are substantially the same as at site No. 91. Aquifer No. 1 extends from 75 to 110 ft., but it seems probable that aquifer No. 2 is situated below 185 ft., as the bulk of the water was not obtained until an airlift pump had been installed; the pump reduced the head of water and enabled it to break through into the borehole. Drilling conditions in both holes were difficult due to the sands and water in aquifer No. 1.

GRAPHS NOS. 93 AND 94. These sites show similar conditions. Two aquifers of sandy clay layers were intersected in the boreholes, but at site No. 93 a calcareous clay layer was struck below the second aquifer at 150 ft. The positions of the two aquifers are as follows: No. 93 site, first, 48 to 81 ft.; second, 115 to 150 ft.; No. 94 site, first aquifer 35 to 85 ft.; second 105 ft., bottom not reached.

Kilosa Alluvium. The general geological conditions differ considerably from those prevailing at Kimamba. Kilosa is situated below a fault escarpment, but the exact position of the fault line is not known, neither is the amount of throw. The Mukendockwa valley debouches on the plains not far from the borehole sites.

GRAPH NO. 95. The formation struck in the borehole at this site shows the following section: 30 to 40 ft., sandy clays with some water; clay from 40 to 53 ft., below which water was struck in coarse sands. The second aquifer is present between 65 and 70 ft., below thick clays and sandy clays are encountered to the full depth of the borehole.

GRAPH NO. 96. The borehole sunk at this point was tested at 13,500 gallons per hour, the highest yield so far obtained in an inland alluvial deposit. The upper section of the borehole samples does not give the impression of a well-sorted alluvium and the samples show sandy clays, very dark-coloured, from 78 to 82 ft. Most of the water was presumably struck at between 103 and 110 ft., where blocks of amphibolite and dyke rocks were found, possibly resting on a sandy bedrock cement. The borehole is situated approximately 500 yards from the river. Neither graph No. 95 or No. 96 gives any indications as to the existing sub-surface conditions. Solid bedrock may reasonably be expected at 230 and 200 ft. respectively.

GRAPH NO. 97. This graph has been included on account of its position in an area so far not explored for groundwater, and on account of the large yields struck in a strongly-fractured Basement gneiss. The borehole log shows soil from 0 to 30 ft. and from this depth to 108 ft. a chloritic granite gneiss invaded by pegmatitic material. Only a few feet of non-fractured rock occurs in a complete section from 30 to 108 ft. The section 74 to 84 ft. is heavily weathered and traces of an altered dyke rock are found. The graph definitely indicates the hydrological conditions found in the borehole. The water was found to be high in sodium sulphate, but not of excessively high salinity.

(v) *Usefulness of Resistivity Surveys.*—The successes and failures in finding water, and particularly potable water, in the territory by resistivity surveys are directly connected with the geological formations which are subject to exploration during such surveys. This fact is a direct consequence of the resistivity method itself, but should, nevertheless, be stressed.

The usefulness of resistivity surveys when all geological information obtainable has been collected, can be roughly classified by formations according to the following schedule. As geological knowledge and the number of boreholes increases the proportion of successes is likely to rise, but the validity of the classification will probably still obtain unless different geophysical methods, not entirely connected with resistivity are applied.

Most Useful in:

1. Granitic areas.
2. Coastal sedimentary rocks and unconsolidated sediment where salt-water penetration is liable to occur.
3. Tracing sandy alluvium under clays.

Useful in:

1. Basement rocks.
2. Nyanzian schists.
3. Certain *mbuga* deposits.
4. Sedimentary rocks of known stratigraphy.

Less Useful in:

1. Nyanzian banded ironstone formation and older volcanic series.
2. Sedimentary rocks of unknown stratigraphy.

Problematic or even doubtful in:

1. Younger lava series.
2. Karagwe-Ankolean rocks, unless preceded by a very careful geological survey.

Most Useful or less useful depending on the material which makes up such deposits:

1. In alluvial and lake deposits of many kinds.

Most Useful:

1. In granitic areas two major geological facts can be ascertained by resistivity surveys.

Constant separation traverses will establish the presence or non-presence of weathered basins and/or inliers of older rocks and also outline "hardrock" granite areas within a region.

Depth-probes will establish depth of weathered granite and the thickness of other deposits above the weathered granite. Resistivity lows should be checked with a magnetic survey to ascertain type of deposit. The presence of water is, however, very rarely directly indicated by depth-probe graphs on granite unless it is highly saline. In some cases major fracture zones containing water show up in the shape of low resistivity areas or basins, orientated along directional lines.

2. Coastal sedimentary rocks and unconsolidated sediments are often penetrated by sea-water. The sea-water horizon, particularly in clays, is usually distinctly indicated on the resistivity graphs, and the boundary between fresh and salt-water can be determined.

3. The location of river beds and estuary deposits along the coast hidden by clayey deposits is greatly facilitated by constant separation traverse and depth-probes.

Useful:

1. Basement rocks, as a whole, are better aquifers than granites, but also require closer geological exploration before resistivity surveys are carried out. Weathered areas or layers, in general, show up well in constant separation surveys and hard rock areas can, as in granites, be excluded. In many cases, however, the depth-probe graphs are difficult to interpret; so-called lateral interference is common and must be checked by changing the direction of the depth-probe layout or by magnetic survey. Salt-water in fractures not always discernible in depth-probe graphs in Basement rocks. In general, areas not previously explored by drilling cannot with certainty be assessed as to water prospects from depth-probes.

2. Nyanzian Schist. This formation when known to occur within a granite area to a certain extent lends itself to exploration by resistivity surveys in so far as weathered zones and depth of weathering can be detected. This has been particularly noticeable in the Singida District.

3. *Mbuga* deposits of limestone marl type such as are encountered in the Central Province at Kongwa, Loji and Makutopora, often in block-faulted areas, can be explored for maximum depth of the block-fault and greatest development of limestone. This has particularly been proved useful at Kongwa. Groundwater is, as a rule, present in this type of formation. Vertical graphs are common in *mbuga* deposits and not always easy to interpret.

4. Sedimentary rocks of known stratigraphy. Examples of these are rare in the territory.

Less Useful:

1. The banded ironstone series of the Nyanzian does not lend itself to resistivity surveys, and it is doubtful whether the volcanic rock series which occur in this formation would show any better results. The basic volcanic rocks of the Nyanzian show definitely the depth to hardrock on resistivity graphs.

2. In sedimentary rocks of unknown stratigraphy curves can seldom be accurately interpreted beforehand. This has been the case in the Tanga limestone which is often interbedded with shales or mudstones. The same conditions apply to the Makonde plateau where drilling showed formations which were not expected from the results of the resistivity surveys.

Problematic or doubtful:

1. Younger volcanics. The result of resistivity surveys and subsequent drilling in the younger volcanics of the Northern Province has, up to date, been poor. There is so far no known instance where water, or even favourable conditions for striking water, could accurately have been forecast from such surveys. The above conditions also appear to be applicable to the schist and quartzite formation of the Karagwe Ankolean. Drilling in the Karagwe Ankolean formation has, however, been reasonably successful as boreholes in this formation can be sited with the aid of geological surveys. The geology of the younger lava areas is, on the other hand, in most cases unknown.

Most useful or less useful:

1. Sandy alluvium and lake limestone deposits, if of fair thickness, can be discovered under, or interbedded with, clays, marls, etc., by resistivity traverses. In many cases, however, the difference in the apparent resistivity of an aquifer and a non-aquifer is not large enough for accurate forecasting of geological conditions. Similar circumstances arise whenever two different formations with similar, or nearly similar, apparent resistivity occur in juxtaposition.

(b) Magnetic Surveys

The variation of the vertical component of the earth's magnetic field has been used for hundreds of years in the search for magnetic iron ores, and from this early beginning more and more sensitive instruments have been evolved to assist in distinguishing between rock types, and in searching for mineral deposits.

As far as the search for groundwater in Tanganyika is concerned magnetic surveys have been used for finding dykes, kimberlites and lavas, and to distinguish different rock types of the Basement system where the overburden is heavy. Low resistivity areas or basins found by resistivity surveys have also been checked by magnetic surveys to ascertain whether weathered basins or inliers of older rocks were the cause of these resistivity lows. Magnetic surveys have, however, been used to a very limited extent compared to resistivity surveys, and have not, on the whole, been found to be of very great practical help in the location of water in the territory. There is also a great lack of information in respect of the magnitude and variations of the vertical component of the magnetic field from north to south in this territory, as no exact determination of the induced field has so far been made. All determinations of the vertical variation of the field have, therefore, only been made in relationship to an arbitrary station chosen within the area of survey, such as a bare granite outcrop in Tabora, Dodoma or Njombe, or an outcrop of Basement rock in Masailand.

The instruments in use by the Water Development and Irrigation Department are variometers built by Watts and fitted with three auxiliary magnets. Major surveys have been carried out in the Isanga basin south of Lake Victoria; to determine the outlines and boundaries of the banded ironstone formation; at Tabora in an investigation of the trend and occurrence of basic dykes. Within the Central Province kimberlite bodies and dykes have been surveyed. In other localities, such as Kondoa District, Iringa District and Masailand, less extensive surveys have been made, mostly to determine the contacts between various rock formations in the Basement.

(c) Other Methods

New scientific methods and instruments used in prospecting for water are continuously being developed in many countries. The cost of these is often high and not always commensurate with the results achieved. There is, however, one important aid in prospecting for water which is readily at hand and which should be mentioned, namely, the use of air photographs. Approximately three-quarters of Tanganyika has now been covered by air photographs and these should be made available for use in the field by geologists and engineers concerned with water exploration. At present this is not possible because of the high initial cost of a complete set of photographs of the territory. A great deal of information on fault lines, folding, the nature of rock formations, soils and vegetation etc., can be obtained from air photographs. This information is at present laboriously collected in the field.

CHAPTER NINE

BOREHOLE STATISTICS

The main groundwater areas so far explored by drilling within the territory can most conveniently be grouped under the eight provinces constituting administrative and, from a Government development point of view, financial units. The three coastal provinces, Tanga, Eastern and Southern, in which the bulk of the sisal plantations and the two main towns of the territory are situated, contain within their boundaries the largest groups of consumers of underground water. The Northern and Southern Highlands Provinces carry, apart from a large native population, the greater part of the European community settled on the land. The Central, Western and Lake Provinces and the Masailand districts of the Northern Province are almost exclusively occupied by a rural African population practising agriculture and cattle-raising.

The borehole statistics have, therefore, been arranged on a provincial basis, grouped under the main geological formations occurring in each province.

When perusing these statistics it should be remembered that most statistics which are based on too small a number are misleading and, therefore, must be read with discrimination. Included in the statistics are also a number of borehole sites which were drilled in the early thirties, from 1931 onwards, when knowledge of the geology of the country was incomplete, and geophysical methods were not in use. Moreover, conclusions from a comparison between failures and successes cannot be drawn, as in some cases purely explorative drilling was undertaken in previously unexplored regions, while in others drilling in geologically-known areas and under known conditions was carried out.

The statistics do, however, reflect the difference between the general possibilities of striking water and the average yield of boreholes in the various formations and areas of the territory, and also give an indication of the ever present hazards from many causes when drilling. It is known that a number of boreholes, estimated at approximately 300, have been sunk in the territory and of which the detailed records are not available or have been lost. These could, therefore, not be included in the statistics. The total number of boreholes for which records are readily available is approximately 860, and the statistics presented have been prepared from these records. Certain of the main headings under which the statistics are given possibly require more detailed explanation, which is therefore given below.

Geological Formations. This heading refers to the main formation struck in a borehole, but it should be pointed out that, in many cases, the boreholes have intersected soils, superficials or even lake beds and *mbuga* deposits before entering hard rocks, and that water was not necessarily obtained from such hard rocks. In the case of sedimentary rocks, soils and unconsolidated sediments may have been encountered before the sedimentary rock was struck. It was, however, found impracticable to include all such information.

Average depth from surface to which water rises. The level to which water rises in a borehole depends on the hydrostatic pressure prevailing in the area surrounding the borehole during drilling operations, but this level should remain more or less constant when the borehole is not pumped, or at least if depth to water-level is measured and compared during the same period of the year.

Artesian Boreholes. The term is used here in the case of a borehole in which the hydrostatic pressure is large enough to raise the water-level when water is first struck to just above the surface of the ground or higher.

Tested Yield. This means, as far as boreholes sunk by Government are concerned, the maximum yield obtainable after 8 or 12 hours pumping. The capacity of the test pump constitutes, however, an upper limit varying between 2,500 and 4,800 gallons per hour, depending on pumps and drilling equipment. Private drilling contractors carry out similar tests but also estimate yields above the capacity of the pump based on drawdown of the water-level during pumping.(1)

Technical Failures include a variety of drilling hazards such as loss of tools, running sands, steeply dipping rocks and casing difficulties, etc.

Boreholes reported containing saline water. This heading was introduced for the simple reason that many privately drilled borehole records only indicate quality of water in such general terms such as slightly salt, brackish, salty, or salt. Borehole waters reported as brackish, salty or salt have, therefore, been classified as boreholes reported containing saline water. As far as Government boreholes are concerned, practically all borehole waters in the past and all at the present time are subjected to routine tests or chemical analyses. A Government borehole is, therefore, in the statistics, classified as saline if it cannot be used for the purpose for which it was drilled.

Boreholes with a yield considered to be too low to be useful. The interpretation of this heading is, by its very wording, flexible. The yield of a borehole sunk for supplying a sisal decorticating plant may be too low even at 1,000 gallons per hour, but a borehole in the arid Central Province sunk for the rural Native Authorities can be used with a yield below 100 gallons per hour, provided the depth to water is within the reach of a hand-pump. As far as the statistics are concerned no borehole yielding 300 gallons per hour or over has been classified under the above heading.

TANGA PROVINCE BOREHOLE STATISTICS

Geological Formation	Sedimentary rocks and unconsolidated sediments		Basement rocks or in Basement rock areas	
Drilled By	Government	Private Enterprise	Government	Private Enterprise
Total number of boreholes	55	39	29	43
Aggregate footage	12,450	8,612	4,995	10,540
Average depth of borehole in feet	226	221	172	245
Maximum depth of borehole in feet	900	550	370	430
Average depth to water struck in feet	164	144	91	153
Maximum depth to water struck in feet	800	310	255	410
Average depth from surface to which water rises in feet	57	82	48	56
No. of Artesian boreholes	4	Nil	1	—
Aggregate tested yield in gallons per hour	136,210	67,660	60,660	76,880
Average tested yield in gallons per hour	2,900	1,829	2,415	2,107
Maximum yield in gallons per hour	15,000	3,600	10,000	6,000
No. of boreholes reported containing saline water. ...	6	8	5	9
Number of dry holes...	6	2	4	7
Technical failures	2	?	Nil	?
No. of boreholes with a yield too low to be considered useful	1	5	3	3
Total number of failures from all causes	15	15	12	19
Number of successful boreholes	40	24	17	24
Percentage successful boreholes	73%	64%	58%	56%

The number of boreholes sunk in Tanga Province for which records are available is 166, but many more are known to have been drilled; the total probably exceeds 200.

Tanga Province. Tanga Province is the smallest of all the provinces and covers 13,803 square miles. It is known that more than 120 boreholes have been sunk in the sedimentary rocks and unconsolidated sediments in this region. Drilling difficulties and dry boreholes are mainly confined to the Jurassic limestone and the underlying calcareous mudstones, particularly in the KwaKembe and Pongwe areas. Salt-water penetration is most serious

(1)*Safe Yield.* The safe yield of a borehole which it is intended to pump for 24 hours a day continuously is estimated to be approximately 75 per cent of the tested yield obtained during the Government type of test pumping. The tested yield of a borehole can, however, in most cases be maintained if a borehole is pumped for 10 hours out of 24. In arid areas a few instances have been recorded in which there has been a drop in yield compared to the test pump. This decrease occurred at the end of a six or seven month dry season.

in sandy deposits in the Moa area close to the sea. At Tanga itself the coral reef and clays at Razkazone also yield sea-water. South of Tanga in the Maweni area conditions improve. In the region of the Pangani estuary sea-water penetration is unpredictable unless resistivity surveys are carried out. The Basement rocks at the foot of the North and South Pare and Usambara Mountains have been explored by more than fifty boreholes, which show a high average yield of 2,200 gallons per hour. To the east and south-east of the Usambara Mountains fissure water of high salinity can be expected (see under Geochemistry of Groundwater). Away from the main fault-lines and the cross-faults drilling results have been poor and show a large proportion of failures. There seems to be reasonably good prospects of developing underground water on the north-east flanks of the Pare and Usambara mountains should this region require water supplies in the future. The Handeni District, on the other hand, may be difficult to develop. In this district the crystalline limestone series of the Basement should, in the first place, be explored, as large quantities of potable water may be encountered in these rocks and in the interbedded schists. Saline water in fissures can be expected in the Basement rocks east of the foothills of the Usambara Mountains. The Karroo shales inland and to the north of Tanga are also liable to carry saline water.

EASTERN PROVINCE BOREHOLE STATISTICS

Geological Formation	Sedimentary rocks		Basement rocks		Unconsolidated sediment or alluvium	
Drilled by	Government	Private Enterprise	Government	Private Enterprise	Government	Private Enterprise
Total No. of boreholes	23	17	18	12	16	A number drilled but no records available.
Aggregate footage	6,403	—	5,226	3,145	2,471	
Maximum depth of borehole in feet	727	270	494	522	243	
Average depth to water struck in feet	147	109	162	123	89	
Maximum depth to water struck in feet	388	156	440	206	190	
Average depth from surface to which water rises in feet ...	43	55	71	21	89	
No. of Artesian boreholes ...	1	Nil	Nil	1	—	
Aggrega tetested yield in gallons per hour	16,907	5,740	18,868	19,180	37,200	
Average tested yield in gallons per hour	889	718	1,109	1,743	2,800	
Maximum yield in gallons per hour	1,900	1,800	4,000	3,600	8,000	
No. of boreholes reported containing saline water	Nil	2	4	3	Nil	
Number of dry holes	—	6	1	1	Nil	
Technical failures	1	—	Nil	—	3	
No. of boreholes with a yield too low to be considered useful ...	3	1	3	—	Nil	
Total number of failures from all causes	4	9	8	4	3	
Number of successful boreholes	19	8	10	8	13	
Percentage successful boreholes ...	82%	47%	56%	67%	81%	

Eastern Province. The Eastern Province is approximately 42,094 square miles in extent. Very little is known about the underground water conditions in the province outside the Dar es Salaam area and a narrow strip on both sides of the Central Railway line as far as Kilosa. In addition a relatively small area north of Kilosa has also been explored. In the Dar es Salaam region it can be said that water in useful quantities is only to be found in river-beds of the present geological epoch or in old river-beds and fluviatile deposits hidden by clays, coral reefs or other unconsolidated deposits. A large number of boreholes have been sunk in this area with varying success from before 1914 up to the present time. In addition to the river-beds and the fluviatile deposits, the coral reef encountered at about 100 ft. depth from Temeke to, at least, as far as Ubongo, may yield small but useful quantities of water. The salinity of the water obtained from the coral reef will increase towards the sea. The Pugu kaolin sandstone is known to hold fresh water, but the kaolin clays which enter the boreholes with the water are not easily removed. The unconsolidated sands and clays west of Pugu in the Soga area yield some water, but running sands and clays make the extraction difficult. West of the Ruvu River large tracts of country suitable for cattle grazing exist, but the underlying formations, mostly sandy clays, have shown little promise as far as groundwater is concerned. From west of Msua Jurassic silt-stones are to be found, and one borehole in these yielded only 50 gallons per hour. The hole was 700 ft. deep. The water was struck in the top 50 ft. of the silt-stones which were weathered. From Kidugallo and as far as Ngerengere groundwater conditions improve in the shallow-water limestones. Large yields, however, cannot be expected unless fault lines are encountered.

Basement Rocks. The Basement rocks are first met with a few hundred yards west of Ngerengere station. To the north of this station these rocks, on the whole, appear to carry slightly brackish water. To the south of Ngerengere conditions improve, both as regards quantity and quality. The Morogoro region has, in general, shown little promise as regards groundwater. Low yields and high salinities in the Kingolwira area have resulted in many failures. Conditions in the Basement rocks south of Kilosa are favourable and a recent borehole drilled in fractured Basement quartzite gave a yield of more than 10,000 gallons per hour. It seems, therefore, possible that an area below the Usagara escarpment south of Kilosa is well-faulted and fractured and that groundwater conditions here may be similar to the favourable drilling areas below the Usambara Mountain.

Alluvium. This type of formation occurs in the vicinity of old river-beds in the Mkata plains and in the Kimamba-Kilosa-Kidete triangle and has, so far, proved favourable. At Kimamba and Kilosa, at least two aquifers occur and yields of more than 2,000 gallons per hour can be expected. In the Kidete-Rudewa area and at certain points near Kimamba running sands containing water under high pressure have been encountered and some boreholes have had to be abandoned because of these.

Other very large areas of alluvium and possibly lake deposits exist in the Rufiji basin in the Kilombero valley and in the Ruvu valley. Except for successful wells sunk by the Ruvu Sisal Estate in an old oxbow of the Ruvu River, nothing is known about water-bearing properties of the formations in these areas.

SOUTHERN PROVINCE BOREHOLE STATISTICS

Geological Formation	Sedimentary rocks and unconsolidated sediments		Basement rocks	
Drilled by	Govern-ment	Private Enterprise	Govern-ment	O.F.C.*
Total number of boreholes	41	6	6	75
Aggregate footage	8,891	1,494	639	16,249
Average depth of borehole in feet	219	249	106	290
Maximum depth of borehole in feet	552	400	214	480
Average depth to water struck in feet	90	104	25	118
Maximum depth to water struck in feet	238	129	86	280
Average depth from surface to which water rises in feet ...	56	63	13	88
No. of Artesian boreholes	4	—	Nil	Nil
Aggregate tested yield in gallons per hour	69,632	7,300	3,800	30,132
Average tested yield in gallons per hour	2,240	1,820	950	753
Maximum yield in gallons per hour	6,600	3,000	2,400	2,000
No. of boreholes reported containing saline water ...	10	—	2	3
Number of dry holes...	9	2	1	19
Technical failures	1	—	Nil	4
No. of boreholes with a yield too low to be considered useful	4	—	2	5 below 200 g.p.g.
Total number of failures from all causes	24	2	5	31
Number of successful boreholes	17	4	1	44
Percentage successful boreholes	41 %	66 %	16 %	58 %

*From O.F.C. records. Failures and successes calculated on 75, other statistics refer to 67 boreholes only.

Southern Province.—The Southern Province is the second largest in the territory, extending over 55,200 square miles of land area. Drilling in this large and partly unexplored province has, so far, been concentrated in two main regions only, namely, in the sedimentary formations along the coast and in the broad corridor, in which Basement rocks are exposed, situated immediately to the west of the sedimentary coastal strip.

The Sedimentary Coastal Strip. The most northerly borehole sunk in the province in the sedimentary strips was located near the old military road from Kilwa to Lindi. It was sunk in the 1914–1918 War by the Royal Engineers to a depth of 325 ft. and was pumped at 30,000 gallons per day. The formation pierced is probably of Cretaceous age. South of the Mbemkuru River from Mkoe Sisal Plantation to Lindi a number of boreholes was sunk to a depth not exceeding 300 ft. These boreholes struck clays and were unsuccessful. Deep drilling in this area in the Eocene limestones may produce better results, but this is uncertain. The Mbemkuru valley alluvium, unless entirely clayey in nature, should be a favourable drilling area. At Lindi itself all attempts to find water of reasonably low salinity by drilling have failed and groundwater in the area west of Lindi Bay is, in all probability, saline too. Kitunda sandstone outcropping south of Lindi Bay is a good, but somewhat erratic, aquifer. Groundwater conditions in this sandstone also seem to deteriorate inland. South of Kitunda in the Sudi Bay area calcareous sandstone yielded water at less than 300 ft depth. The Mikindani-Pemba Mwita area has been explored by a number of boreholes and it is fairly certain that this area at some stage in its geological history was occupied by a river estuary. The sandy sediments first deposited were covered by coral limestones or clays during a later transgression of the sea. The width of the estuary was probably two to three miles. Several boreholes struck fresh artesian water below sea-level. From the south of Mikindani township and in the Mtwara harbour area drilling results were disappointing. Both the younger sandy sediments and the coral limestone contained water polluted by sea-water. The Mtwara township, first supplied by water from Mikindani, is now served by boreholes sunk in alluvium to the south of Mtwara creek. This supply is liable to contamination by sea-water if pressure levels in the borehole are made to drop too low by over-pumping.

The Basement Corridor.—All attempts to find potable water in Basement rock at Masasi failed. One borehole, which gave more than 2,400 gallons per hour, was very saline and others only struck surface water after much unfissured hard rock of the Basement was encountered and had to be abandoned. This also applies to Chilongula station on the railway line. Of far greater importance to the knowledge of water supplies in the Basement rock in the corridor is the large-scale drilling programme carried out by the Overseas Food Corporation in Nachingwea District. More than 75 boreholes were sunk and the result can be considered as an example of what can reasonably be expected to be achieved when drilling in these rocks. A complete and thorough geophysical survey by resistivity probes preceded the drilling programme and the results were comparatively good. From a geological angle it is stated by the geophysical company, Geophysical Survey (Pty) Ltd., that when minor faults or fractures coincide in direction with the strike or schistosity of the Basement rocks the result in the yield of boreholes drilled therein improves. It is also stated that the crystalline limestone did not appear to be a good aquifer. At Songea Boma one borehole was successfully sunk in weathered Basement rocks by Government. The Karroo formation at Likonde, 30 miles south-west of Songea, was explored by two boreholes. Both struck water at shallow depth and of good quality, but loose sandy strata were encountered in one which had to be abandoned.

Northern Province Borehole Statistics

Geological Formation	Lavas and Pyroclastics		Basement rock or in Basement rock areas	
Drilled By	Govern-ment	Private Enterprise	Govern-ment	Private Enterprise
Total number of boreholes	31	25*	39	2
Aggregate footage	10,505	7,992	11,000	No records
Average depth of borehole in feet	339	215	282	,, ,,
Maximum depth of borehole in feet	1,063	610	569	,, ,,
Average depth to water struck in feet	188	115	221	,, ,,
Maximum depth to water struck in feet	900	460	505	,, ,,
Average depth from surface to which water rises in feet ...	160	161	187	,, ,,
No. of Artesian boreholes	Nil	Nil	Nil	,, ,,
Aggregate tested yield in gallons per hour	19,158	41,470	26,000	,, ,,
Average tested yield in gallons per hour	1,277	1,974	963	,, ,,
Maximum yield in gallons per hour	3,600	5,000	3,300	,, ,,
No. of boreholes reported containing saline water or fluorine above 5 p.p.m. (F. refs. to lavas and pyroc. only)	3	7	Saline 2	,, ,,
Number of dry holes...	13	4	8	,, ,,
Technical failures	1	Not known	2	,, ,,
No. of boreholes with a yield too low to be considered useful	3	1	3	,, ,,
Total number of failures from all causes	20	12	15	,, ,,
Number of successful boreholes	11	13	24	,, ,,
Percentage successful boreholes	35%	52%	61%	,, ,,

*Includes Arusha Chini boreholes.

Northern Province. Land area 33,165 square miles. The Northern Province contains within its boundaries only two major rock formations, the volcanics and the Basement rocks. Unconsolidated deposits are represented by the lake-beds in the Manyara-Natron-Serengeti and Ruvu River areas and in south-east Masailand. The nature of the unconsolidated deposits found north of Kilimanjaro are uncertain. The pyroclastic and alluvial deposits of the Arusha Chini area also partly lie within the boundaries of the province.

More concentrated drilling has only taken place within the following areas; the volcanics and pyroclastics of the Moshi and Arusha districts, the Basement areas of south-east Masailand, Longido and the Loliondo District. In the Babati area and around Essemingor Mountains and in Kitumbeine-Gelei area borehole locations are widely scattered. Drilling in the volcanics at Moshi has, in many instances, been successful, but some deep holes to over 600 ft. have proved to be failures. The salinity and fluorine content in the south-east Moshi area is not high. The area to the west of Kilimanjaro, the so-called Sanya corridor, has been the scene of many disappointments. The fluorine content of the water has proved to be high, increasing towards Mount Meru and has, in one borehole, reached the high figure of 96 p.p.m. Large concentrations of fluorine are also known to occur in the rivers rising on north-east Meru. Conditions improve in the lower Sanya plain and towards the Usa River. The south Sanya plains carry good water supplies of fair salinity but west of the Usa River conditions become more difficult and the pyroclastics south of the old Moshi/Arusha road yield only small supplies of which many are only of a temporary nature.

West of Nduruma Chini stream boreholes failed to strike water. This also applies to all boreholes drilled in the Loljoro farm lands, except one which struck water at approximately 900 ft. Similar conditions seem to exist west of the Arusha aerodrome at Musa and Monduli and in the southern part of the Ardai plain. To the west of Arusha township itself a number of boreholes struck good water supplies, but in some the fluorine content is as high as 9 p.p.m. Boreholes north of Oldonyo-Sambu sunk in lavas failed to get water at 400 ft. depth. The Basement area of south-east Masailand has been explored by a number of boreholes. The great majority have struck water, but two highly saline supplies are recorded from the Amboseli pan. The Kitwei calcareous beds of the *mbuga*-type all yielded water, but in one case this was slightly saline. The Longido area has already been referred to under the heading of Faults, and a relatively large proportion of the boreholes sunk in this area have been failures.

The Loliondo District, which only recently has been explored for groundwater, is occupied by quartzites and drilling conditions have, on the whole, been favourable there. The fluorine content of the groundwater is, however, high, 10 p.p.m. towards the south where the Serengeti ash-beds occur. Other widely scattered areas in the Northern Province have been explored by a number of boreholes. The Esseminger volcanic mountain area yielded water only to the south. To the east and north-east boreholes were dry. At Babati a successful borehole was sunk in a subsidiary crater north-west of the Ufiume volcanic cone. A borehole failure is recorded in the volcanic rocks to the south-west of the Ngorongoro caldera. Large tracts of lake-beds and unconsolidated sedimentary deposits which exist in the Northern Province have, so far, only been explored by a relatively small number of boreholes. The great majority of these are situated at the Arusha Chini sugar plantation. These were sunk in pyroclastics passing through presumed lake-beds at the surface, and were all successful both from the point of view of quantity and quality. In the Manyara depression two boreholes were sunk at the northern end, one in lake-beds, the other in what appears to be a mixture of clays and pyroclastics. The borehole in the lake-beds was successful. One private borehole is believed to have been sunk in the southern end of the Manyara basin. The Lake Natron rift valley has not been explored nor has the large tract of lake-beds and unconsolidated sediment, probably ash beds, to the west of the Ngorongoro Highlands in the Serengeti. The latter area is, however, known to carry saline spring—and surface-water, high in fluorine. (See under Geochemistry of Groundwater).

CENTRAL PROVINCE BOREHOLE STATISTICS

Geological Formation	Basement rocks, including Nyanzian type rocks in Dodoma District			
District	Dodoma	Kondoa	Kongwa and Mpwapwa	
Drilled by	Government	Government	Government	O.F.C.*
Total number of boreholes	26	29	44	56?
Aggregate footage	5,790	8,170	13,142	10,435
Average depth of borehole in feet	214	281	291	186
Maximum depth of borehole in feet	420	550	562	?
Average depth to water struck in feet	162	215	275	150
Maximum depth to water struck in feet	405	406	428	349
Average depth from surface to which water rises in feet	110	138	192	133
No. of Artesian boreholes	None	None	None	None
Aggregate tested yield in gallons per hour	29,670	35,810	29,530	36,240
Average tested yield in gallons per hour	1,185	1,705	922	1,340
Maximum yield in gallons per hour	3,300	3,000	3,000	5,800
No. of boreholes reported containing saline water	1	1	3	?
Number of dry holes	1	7	10	25
Technical failures	2	1	—	1
No. of boreholes with a yield too low to be considered useful	2	2	3	4
Total number of failures from all causes	6	11	16	30
Number of successful boreholes	20	18	28	26
Percentage successful boreholes	76%	62%	63%	46%

*Overseas Food Corporation.

Central Province Borehole Statistics

Geological Formation	Granitic rocks and *Mbuga* on Granite	Granitic rocks, Nyanzian schists and Lake Beds
District	Dodoma	Singida and Manyoni
Drilled By	Government	Government
Total number of boreholes	30*	28
Aggregate footage	6,094	6,557
Average depth of borehole in feet	203	235
Maximum depth of borehole in feet	466	500
Average depth to water struck in feet	127	150
Maximum depth to water struck in feet	290	439
Average depth from surface to which water rises in feet	66	82
Number of Artesian boreholes	None	None
Aggregate tested yield in gallons per hour	19,594	25,353
Average tested yield in gallons per hour	1,150	1,014
Maximum yield in gallons per hour	5,500	3,000
Number of boreholes reported containing saline water	1	2
Number of dry holes	9	3
Technical failures	1	None
No. of boreholes with a yield too low to be considered useful ...	6	4
Total number of failures from all causes	17	9
Number of successful boreholes	13	17
Percentage successful boreholes	40%	60%

*Only three boreholes out of 15 sunk at Makutopora have been included.

Central Province. This province covers approximately 36,410 square miles, and is the province in which the greatest number of boreholes has been drilled for the rural Native Authorities. The number of boreholes sunk in the various districts is, in consequence, regarded as large enough for the statistics to be treated on a district basis. Taking into consideration the difficulties met with in finding water in the granitic rock areas, the results have been encouraging, and except for certain limited localities it has been possible to provide water for the large cattle population of this province even in drought years. The quality of the water has, with a few exceptions, been found suitable for watering livestock and also for the slightly higher standard required for human consumption. The Basement rock areas have proved to be more favourable than the granitic areas, and drilling successes in the Basement considerably higher. Concentrated drilling has taken place in the Kongwa and north-east Kondoa districts and a fairly large number of boreholes has been sunk within a radius of 30 miles from Dodoma township. In the Kongwa District both the Government and the former Overseas Food Corporation have, by providing boreholes and pumps, considerably increased potential grazing and cultivation areas. In Kondoa District over a thousand people who, with their livestock, have had to be moved from the badly-eroded highland areas to the plains below, have successfully been provided with water under a Government development plan. Approximately 90 pumping installations are maintained by the Government on behalf of the Native Authorities within the Central Province. Furthermore, the Dodoma township at the height of the dry season can be supplied with 200,000 gallons per diem from boreholes at Makutopora. This pumping installation is operated by the Public Works Department. Singida is also supplied with water from boreholes.

SOUTHERN HIGHLANDS PROVINCE BOREHOLE STATISTICS

Geological Formation	Granites and Basement rocks	
Drilled By	Government	Private Enterprise
Total number of boreholes	15	13
Aggregate footage	2,756	3,194
Average depth of borehole in feet	183	246
Maximum depth of borehole in feet	315	490
Average depth to water struck in feet	110	225
Maximum depth to water struck in feet	260	375
Average depth from surface to which water rises in feet	55	80
Number of Artesian boreholes	2	Nil
Aggregate tested yield in gallons per hour	14,620	9,787
Average tested yield in gallons per hour	1,100	815
Maximum yield in gallons per hour	2,800	4,000
Number of boreholes reported containing saline water	Nil	Nil
Number of dry holes	2	1
Technical failures	2	?
Number of boreholes with a yield too low to be considered useful	1	4
Total number of failures from all causes	5	5
Number of successful boreholes	10	8
Percentage successful boreholes	66%	62%

Southern Highlands Province. Land area 45,470 square miles. Within the province no less than nine major geological formations are met with, but only four have been explored for groundwater up to the present. Drilling has been concentrated in two main areas only.

The Iringa Area. This area encompasses a tract of country within 35 miles radius from Iringa township. Basement rocks have been drilled with varying success to the north and east of Iringa and in granitic rocks closer to the town itself. The results obtained in Basement rocks are more or less normal. Fractures may be of importance. The successful boreholes in granitic rocks depend, as in most cases elsewhere, on the presence of weathered granite or over-lying pervious superficials. Fractures apparently do not play a major part in the occurrence of groundwater within the area.

The Lupa Gold Fields. During the period of active gold-mining in the Lupa a number of boreholes were sunk. Groundwater, in general, is not, however, deep-seated and few shafts were sunk to 100 ft. without encountering water. Some granitic and dioritic areas are unweathered and carry little water but, in general, the Lupa area is not unfavourable from a drilling point of view, except in the neighbourhood of the main rift valleys. Fracture lines are of major importance.

Other Boreholes. Only one borehole has, so far, been sunk in the lava formations of the Southern Highlands. This hole was sunk on the Mbeya aerodrome and struck good water in pyroclastic deposits and lavas. Two boreholes have been drilled for brine in a sandstone which is believed to belong to the Cretaceous. Three boreholes were sunk in alluvium and Basement rocks near Mbosi; difficulties arose from kaolin clays entering the boreholes, but were finally overcome. Two of the boreholes were artesian.

Potential Drilling Areas. The Southern Highlands are, on the whole, well watered by perennial streams, but such regions as the Ubena Plains and the flat tract of country immediately east of Mbeya may have to be explored for groundwater in the future. For observations on the Ubena Plain see under Weathering. The present waterless volcanic are east of Mbeya may provide groundwater if continuous lava-beds stretch across from the volcanoes in the south to the rift fault in the north at the foot of the Mbeya range. The geology can best be seen in the east in the steep Usango escarpment. In addition to the hard rocks, sedimentary deposits and volcanic rocks, large tracts of the Southern Highlands are covered by lake-beds and alluvium. These are to be found in the Rukwa depression and the Ruaha basin, particularly the Buhora "flats". Many Banka-drilled holes have been sunk in the Rukwa depression and, as often as not, these struck saline water or slightly saline water. The Ruaha basin has not been explored by drilling. One fact is however, known; during the dry season the Ruaha River receives little or no effluent seepage in the reach from the Ruaha Bridge on the Iringa-Dodoma road to approximately 30 miles upstream.

WESTERN PROVINCE BOREHOLE STATISTICS

Geological Formation	Granitic rock		Nyanzian type of rocks	Wembere Lake beds
Drilled by	Govern-ment	O.F.C.*	Govern-ment	Govern-ment
Total number of boreholes	27	49?	13	4
Aggregate footage	4,661	9,555	2,948	1,274
Average depth of borehole in feet	166	194	226	318
Maximum depth of borehole in feet	550	260	445	490
Average depth to water struck in feet	80	81	165	134
Maximum depth to water struck in feet	228	246?	335	250
Average depth from surface to which water rises in feet	47	45	68	85
No. of Artesian boreholes	Nil	Nil	Nil	Nil
Aggregate tested yield in gallons per hour	4,395	11,073	5,284	2,700
Average tested yield in gallons per hour	292	335	400	675
Maximum yield in gallons per hour	600	1,500	2,600	1,100
No. of boreholes reported containing saline water or fluorine above 18 p.p.m.	Nil	Nil	Nil	3
Number of dry boreholes	11	16	1	Nil
Technical failures	Nil	?	Nil	Nil
No. of boreholes with a yield too low to be considered useful	5	10?	5	Nil
Total number of failures from all causes	16	26?	6	3
Number of successful boreholes	11	23?	7	1
Percentage successful boreholes	44%	46%	53%	25·%

*Overseas Food Corporation.

Western Province. The Western Province is the largest of all the provinces with 78,400 square miles of land area and it also includes the part of Lake Tanganyika which falls within the territorial boundary. Drilling has, on the whole, been centred in two relatively small areas, namely, in the vicinity of Tabora and in the region formerly occupied by the Overseas Food Corporation at Urambo. Practically all the drilling has been carried out in granitic rocks or in the Nyanzian type of rock frequently found in the neighbourhood of Tabora and Kahama. Many inliers of Basement rock have also been encountered. Groundwater is, in general, very scarce in all these formations, but when struck is of relatively good quality. Both at Tabora and Urambo extensive resistivity surveys were carried out before siting a number of boreholes. The drilling results at Urambo indicate that even after a careful and competent survey (by Geophysical Survey (Pty) Ltd.) the chances of striking water supplies in the region of 1,000 gallons per hour are small. At Tabora it is clear that within a radius of 10 to 12 miles no underground water-supplies exist which are large enough to supply a township the size of Tabora. Conditions similar to those met with at Tabora and Urambo can therefore in all probability, be expected in all the granitic areas of the province lying within the Congo basin drainage. The large area of Basement rock within the province is almost completely unexplored as far as groundwater is concerned. This also applies to the Bukoban rocks. Lake-beds and unconsolidated sediments have been explored in the Lake Rukwa and Wembere depression with little real success, due to the high salinity of the groundwater. Furthermore, in the Wembere, high fluorine content complicates matters. The Malagarasi basin has so far only been surveyed for water in the lower regions of the Igombe, or Ngombe River, which rises north of Tabora. This exploration was carried out by the Overseas Food Corporation during the period of development at Urambo. The Igombe River is reported to be perennial between Uyowa and Luagwa Lake and the water is potable. The Malagarasi basin is possibly one of the major development areas of the Western Province and groundwater exploration is, sooner or later, bound to take place within this basin. At present little information is available on the subject. In general, as far as groundwater in the province is concerned, smaller supplies between 150 and 300 gallons per hour are not unobtainable and many minor trading settlements or similar concentrations of population can, in the future, be expected to be supplied by boreholes of this capacity.

LAKE PROVINCE BOREHOLE STATISTICS

Geological Formation	Granitic rocks and granitic areas		Nyanzian		Karagwe Ankolean	
Drilled by	Govern-ment	Private Enterprise	Govern-ment	Private Enterprise	Govern-ment	Private Enterprise
Total No. of boreholes	31	Min. 30 No records	18	2	9	Not known
Aggregate footage	6,003		3,743	540	2,398	
Average depth of borehole in feet	193		207		266	
Maximum depth of borehole in feet	503		506		450	
Average depth to water struck in feet	97		175		138	
Maximum depth to water struck in feet	250		450		205	
Average depth from surface to which water rises	70		66		84	
No. of Artesian boreholes ...	Nil		Nil		Nil	
Aggregate tested yield in gallons per hour...	25,542		4,846		6,620	
Average tested yield in gallons per hour...	982		538		752	
Maximum yield in gallons per hour	3,400		1,400		2,000	
No. of boreholes reported containing saline water	Ni		1		Nil	
Number of dry boreholes ...	5		8	2	Nil	
Technical falures	Nil		Nil		Nil	
No. of boreholes with a yield too low to be considered useful ...	3		4		3	
Total number of failures from all causes	8		13		3	
Number of successful boreholes	23		5		6	
Percentage successful boreholes	74%		28%		66%	

Lake Province. This province covers approximately 39,130 square miles of land area and, including Lake Victoria to latitude 1° south, 52,548 square miles.

Drilling in the province has so far taken place in widely-scattered areas. Only at Shinyanga and Ukiruguru have more than four boreholes been sunk within a relatively small tract of country.

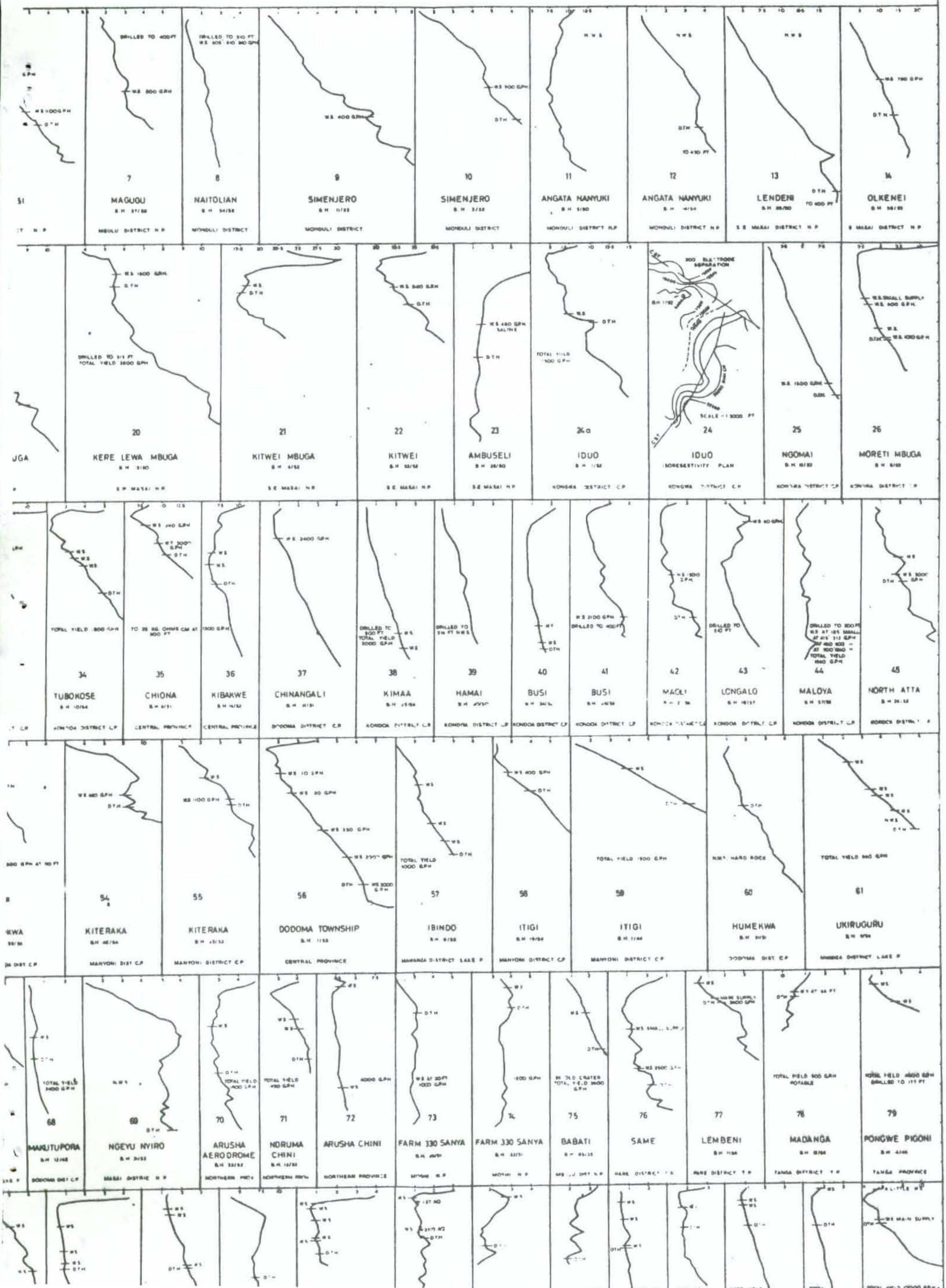
The main formations drilled are the granitic rocks, the Nyanzian rocks and the Karagwe Ankolean metamorphic sedimentary rocks.

The Nyanzian rocks have proved to be poor aquifers and failures have been frequent. Only in the Musoma District have the basic volcanic rocks of this formation been found to be reasonably good aquifers.

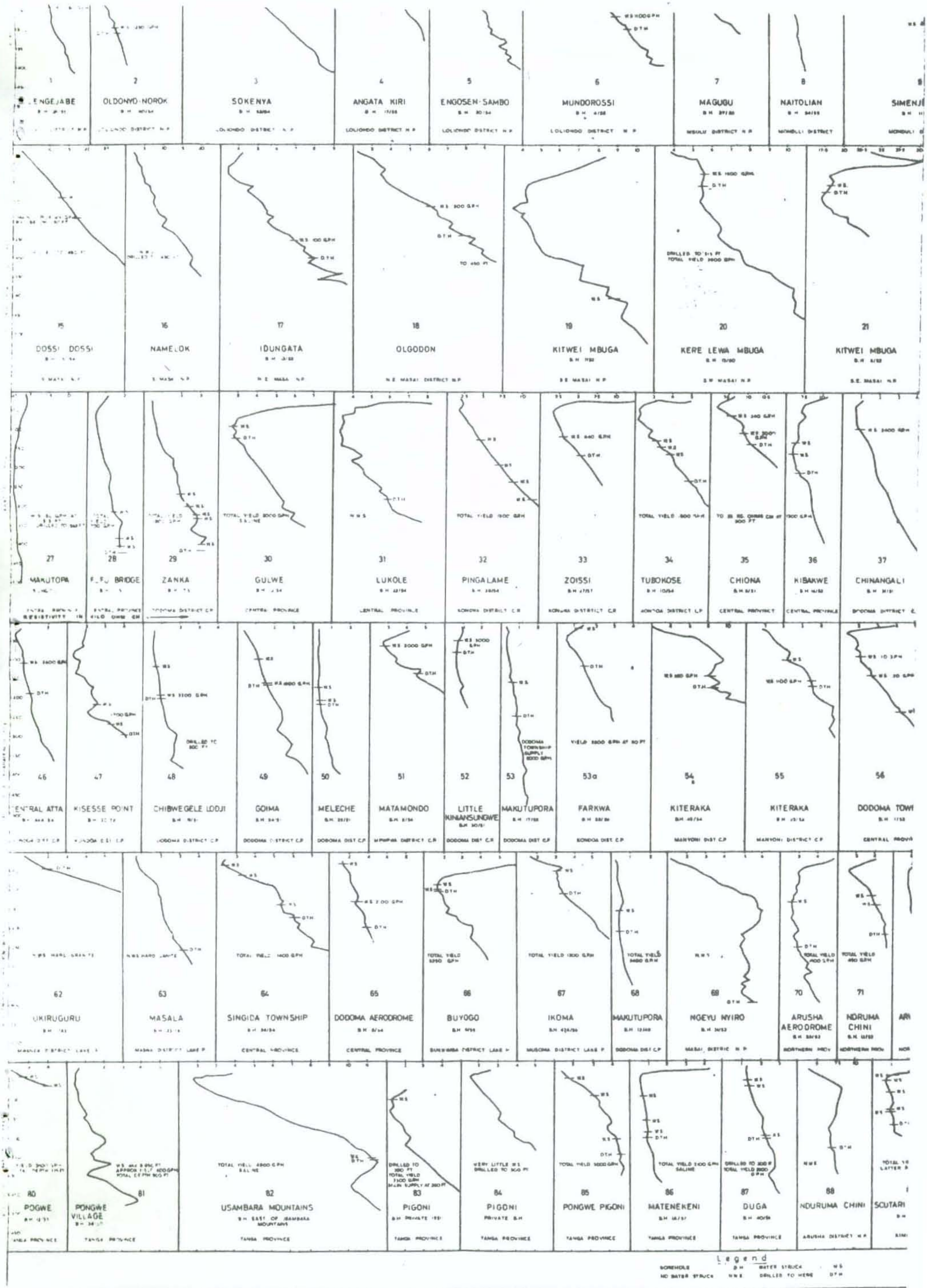
The granites covered by alluvium and other superficial deposits have shown far higher yields, in general, than the same type of rocks in the Western Province. The geological reason for this is not known with certainty, but it may be suggested that the Nile drainage has a different geological history during, at least, the Miocene-Pleistocene period, to that of the Congo drainage basin, and that the occurrence of thicker superficial deposits in the Nile basin and of patches of deeper weathering may have contributed to the better yields of boreholes sunk in granitic areas of the Lake Province.

The Karagwe Ankolean rocks of the Lake Province situated in the Bukoba District have only in the last few years been explored by drilling and the results, as far as quality of water struck, have been very satisfactory. Until recently only quartzites appeared to be good aquifers, but it would seem that the schist formation, where not excessively weathered, may show fair yields.


RESISTIVITY IN KILO OHM CM
1 LENGEJABE
2 OLDONYO-NOROK
3 SOKENYA
4 ANGATA KIRI
5 ENGOSEN-SAMBO
6 MUNDOROSSI
7 MAGUGU
8 NAITOLIAN
SIMEN
15 DOSSI DOSSI
16 NAMELOK
17 IDUNGATA
18 OLGODON
19 KITWEI MBUGA
20 KERE LEWA MBUGA
21 KITWEI MBUGA
27 MAKUTOPA
28 FUFU BRIDGE
29 ZANKA
30 GULWE
31 LUKOLE
32 PINGALAME
33 ZOISSI
34 TUBOKOSE
35 CHIONA
36 KIBAKWE
37 CHINANGAL
46 CENTRAL ATTA
47 KISESSE POINT
48 CHIBWEGELE LOOJI
49 GOIMA
50 MELECHE
51 MATAMONDO
52 LITTLE KINIANSUNGWE
53 MAKUTUPORA
53a FARKWA
54 KITERAKA
55 KITERAKA
56 DODOMA
62 UKIRUGURU
63 MASALA
64 SINGIDA TOWNSHIP
65 DODOMA AERODROME
66 BUYOGO
67 IKOMA
68 MAKUTUPORA
69 NGEYU NYIRO
70 ARUSHA AERODROME
71 NDRUMA CHINI



7
MAGUGU
MBULU DISTRICT N.P.
DRILLED TO 400 FT
W.S. 800 G.P.H.
8
NAITOLIAN
MONDULI DISTRICT
9
SIMENJERO
MONDULI DISTRICT
W.S. 400 G.P.H.
10
SIMENJERO
MONDULI DISTRICT
D.T.H.
11
ANGATA NANYUKI
MONDULI DISTRICT N.P.
N.W.S.
12
ANGATA NANYUKI
MONDULI DISTRICT N.P.
N.W.S.
D.T.H.
13
LENDENI
S.E. MASAI DISTRICT N.P.
N.W.S.
D.T.H.
14
OLKENEI
S. MASAI DISTRICT N.P.
D.T.H.
20
KERE LEWA MBUGA
S.E. MASAI N.P.
D.T.H.
TOTAL YIELD 3600 G.P.H.
21
KITWEI MBUGA
S.E. MASAI N.P.
W.S.
D.T.H.
22
KITWEI
S.E. MASAI N.P.
D.T.H.
23
AMBUSELI
S.E. MASAI N.P.
SALINE
D.T.H.
24a
IDUO
KONDOA DISTRICT C.P.
W.S.
D.T.H.
24
IDUO
ISORESISTIVITY PLAN
KONDOA DISTRICT C.P.
ELECTRODE SEPARATION
25
NGOMAI
KONDOA DISTRICT C.P.
26
MORETI MBUGA
KONDOA DISTRICT C.P.
W.S. SMALL SUPPLY
34
TUBOKOSE
KONDOA DISTRICT C.P.
W.S.
D.T.H.
35
CHIONA
CENTRAL PROVINCE
D.T.H.
36
KIBAKWE
CENTRAL PROVINCE
W.S.
D.T.H.
37
CHINANGALI
DODOMA DISTRICT C.P.
38
KIMAA
KONDOA DISTRICT C.P.
W.S.
39
HAMAI
KONDOA DISTRICT C.P.
40
BUSI
KONDOA DISTRICT C.P.
W.S.
D.T.H.
41
BUSI
KONDOA DISTRICT C.P.
42
MAOLI
KONDOA DISTRICT C.P.
D.T.H.
43
LONGALO
KONDOA DISTRICT C.P.
44
MALOYA
KONDOA DISTRICT C.P.
TOTAL YIELD
45
NORTH ATTA
KONDOA DISTRICT C.P.
W.S.
D.T.H.
54
KITERAKA
MANYONI DIST C.P.
D.T.H.
55
KITERAKA
MANYONI DISTRICT C.P.
D.T.H.
56
DODOMA TOWNSHIP
CENTRAL PROVINCE
W.S.
D.T.H.
57
IBINDO
MANYONI DISTRICT
W.S.
D.T.H.
TOTAL YIELD 1000 G.P.H.
58
ITIGI
MANYONI DISTRICT C.P.
W.S. 400 G.P.H.
D.T.H.
59
ITIGI
MANYONI DISTRICT C.P.
TOTAL YIELD 1500 G.P.H.
60
HUMEKWA
DODOMA DIST C.P.
D.T.H.
61
UKIRUGURU
LAKE P.
W.S.
D.T.H.
68
MAKUTUPORA
DODOMA DIST C.P.
W.S.
D.T.H.
69
NGEYU NYIRO
MASAI DISTRIC N.P.
D.T.H.
70
ARUSHA
AERODROME
NORTHERN PROV.
W.S.
D.T.H.
71
NDRUMA
CHINI
NORTHERN PROV.
W.S.
D.T.H.
72
ARUSHA CHINI
NORTHERN PROVINCE
W.S.
73
FARM 330 SANYA
D.T.H.
74
FARM 330 SANYA
W.S.
D.T.H.
75
BABATI
W.S.
D.T.H.
76
SAME
PARE DISTRICT
D.T.H.
77
LEMBENI
PARE DISTRICT
W.S.
78
MADANGA
TANGA DISTRICT
TOTAL YIELD 900 G.P.H. POTABLE
79
PONGWE PIGONI
TANGA PROVINCE
W.S.
W.S. MAIN SUPPLY
D.T.H.



1 ENGEJABE
2 OLDONYO-NOROK
3 SOKENYA
4 ANGATA KIRI
5 ENGOSEN-SAMBO
6 MUNDOROSSI
7 MAGUGU
8 NAITOLIAN
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LOLIONDO DISTRICT N.P.
MBULU DISTRICT N.P.
MONDULI DISTRICT
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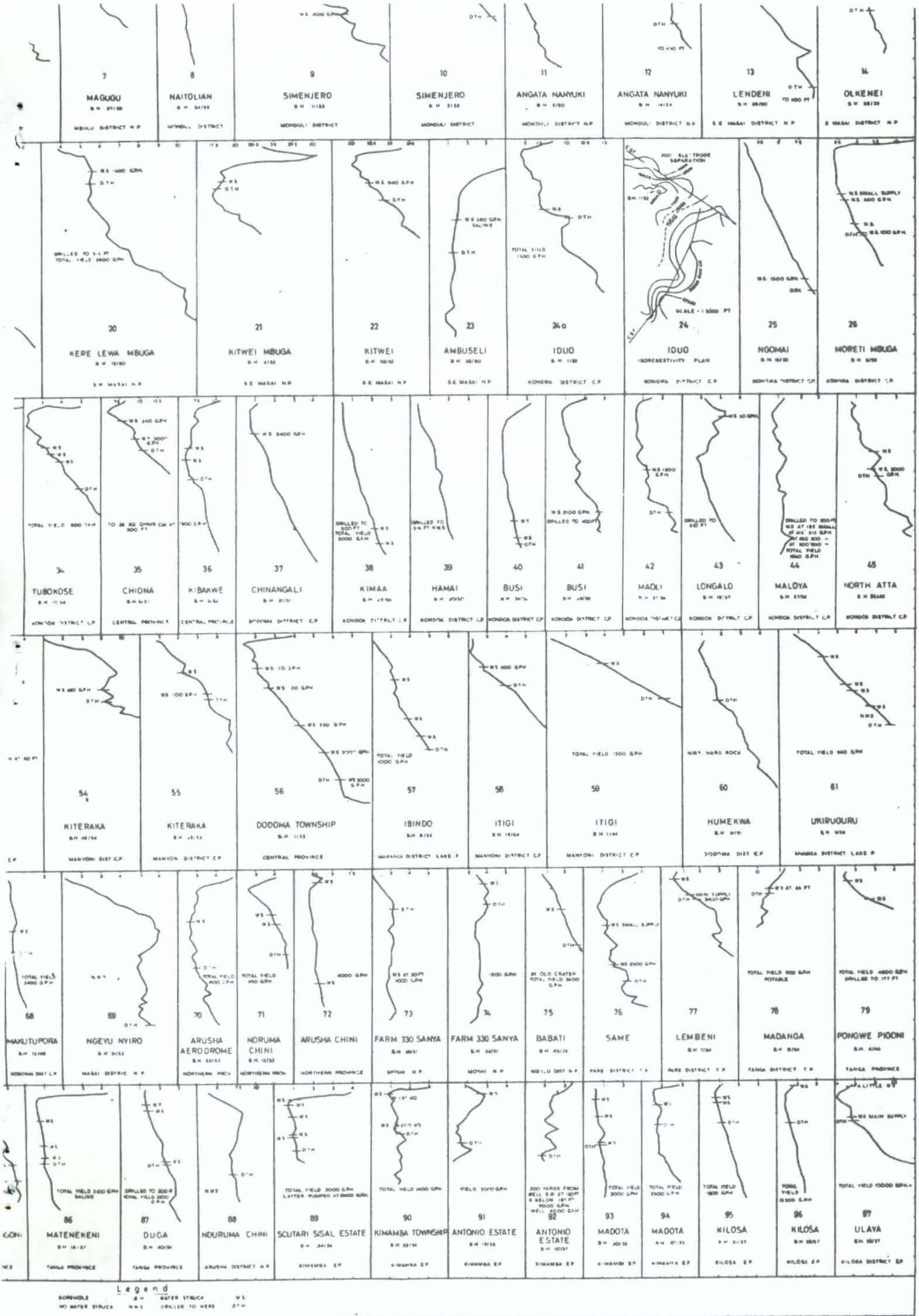
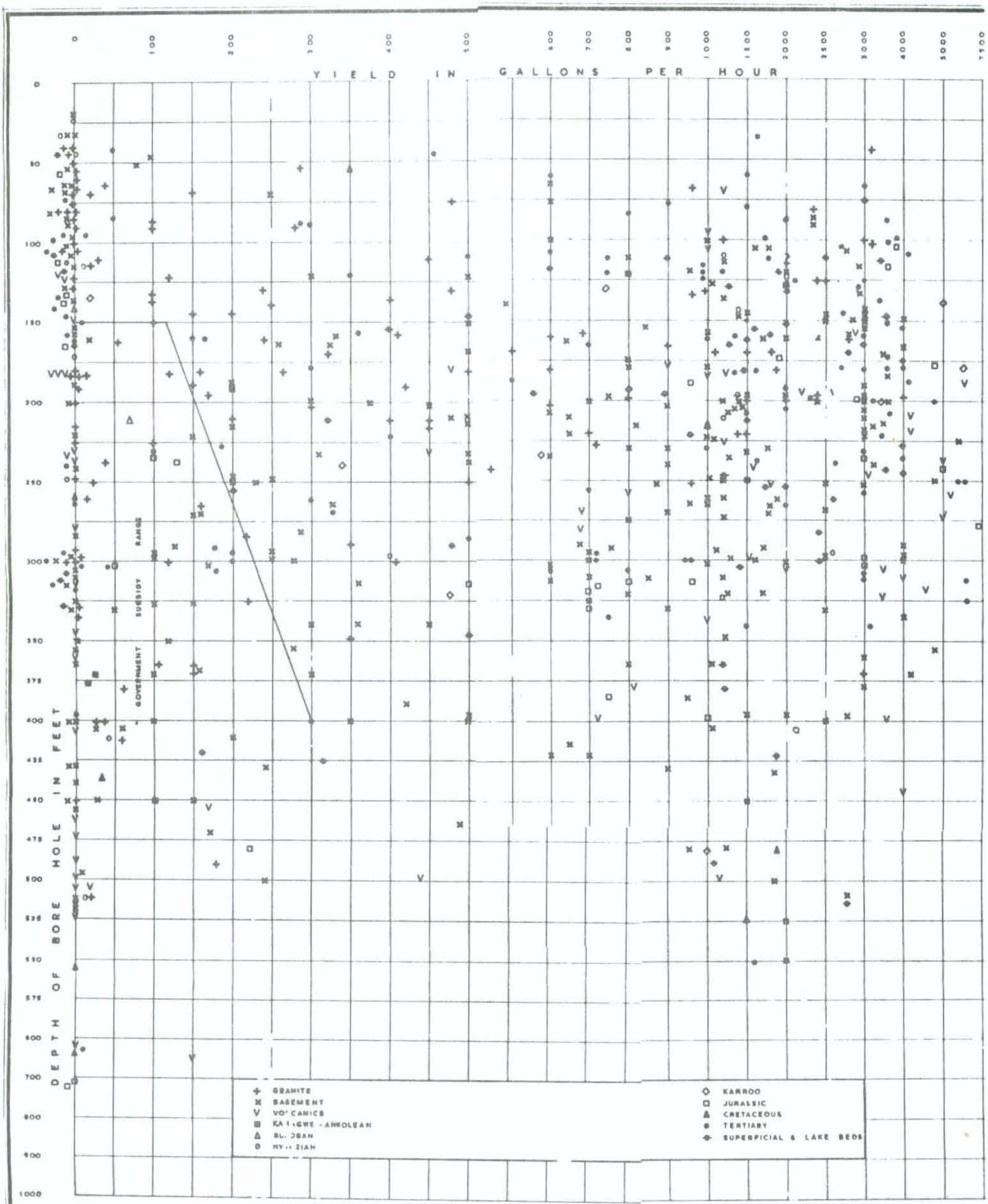
32 PINGALAME
33 ZOISSI
34 TUBOKOSE
35 CHIONA
36 KIBAKWE
37 CHINANGALI
CENTRAL PROVINCE
DODOMA DISTRICT C.P.
KONDOA DISTRICT C.P.
46 CENTRAL ATTA
47 KISESSE POINT
48 CHIBWEGELE LODJI
49 GOIMA
50 MELECHE
51 MATAMONDO
52 LITTLE KINIANSUNGWE
53 MAKUTUPORA
53a FARKWA
54 KITERAKA
55 KITERAKA
56 DODOMA TOWN
MANYONI DIST. C.P.
62 UKIRUGURU
63 MASALA
64 SINGIDA TOWNSHIP
65 DODOMA AERODROME
66 BUYOGO
67 IKOMA
68 MAKUTUPORA
69 NGEYU NYIRO
70 ARUSHA AERODROME
71 NDRUMA CHINI
CENTRAL PROVINCE
MASAI DISTRICT N.P.
NORTHERN PROV.
80 POGWE
81 PONGWE VILLAGE
82 USAMBARA MOUNTAINS
83 PIGONI
84 PIGONI
85 PONGWE PIGONI
86 MATENEKENI
87 DUGA
88 NDURUMA CHINI
SCUTARI
TANGA PROVINCE
ARUSHA DISTRICT N.P.
Legend
BOREHOLE B.H.
NO WATER STRUCK N.W.S.
WATER STRUCK W.S.
DRILLED TO HERE D.T.H.

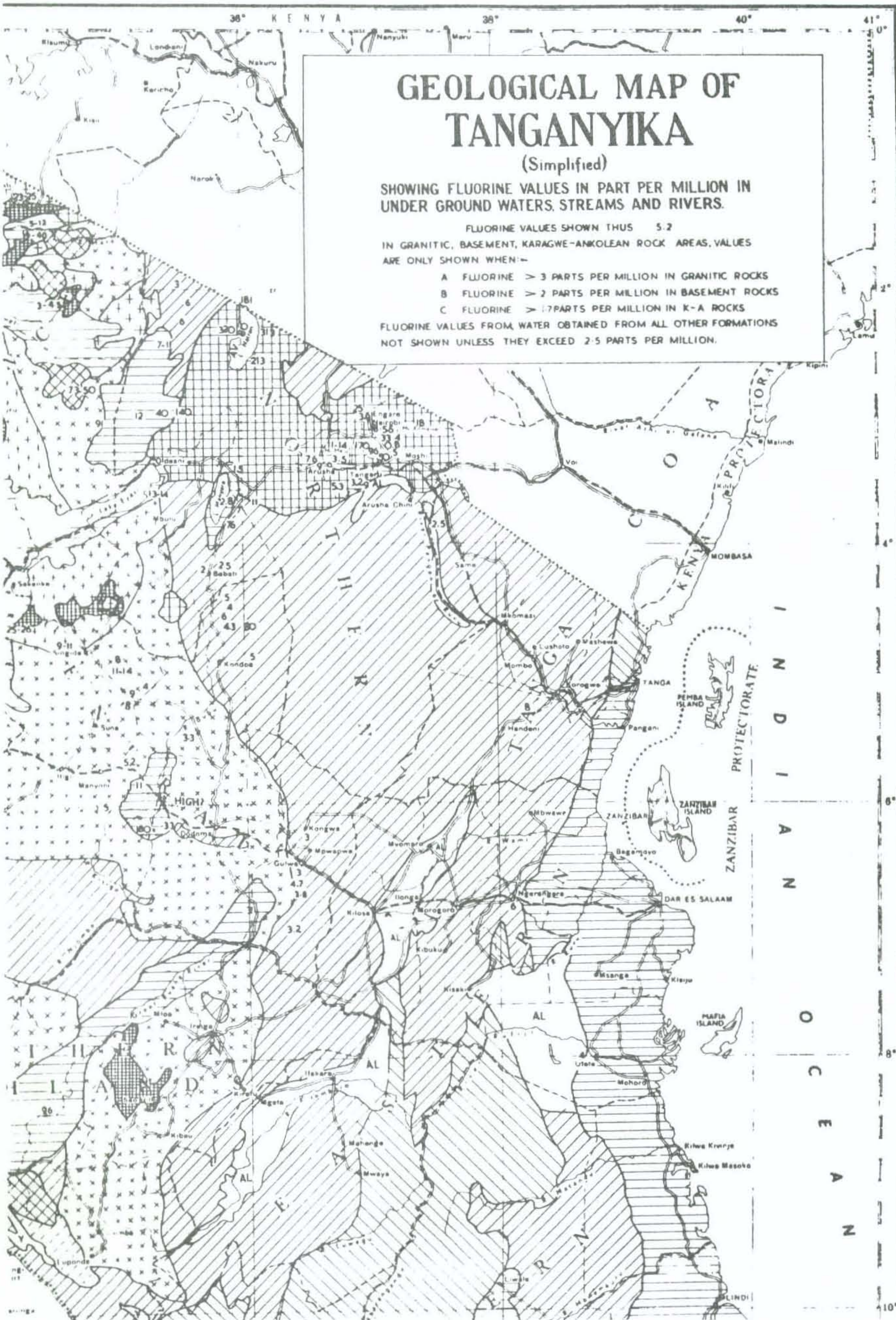


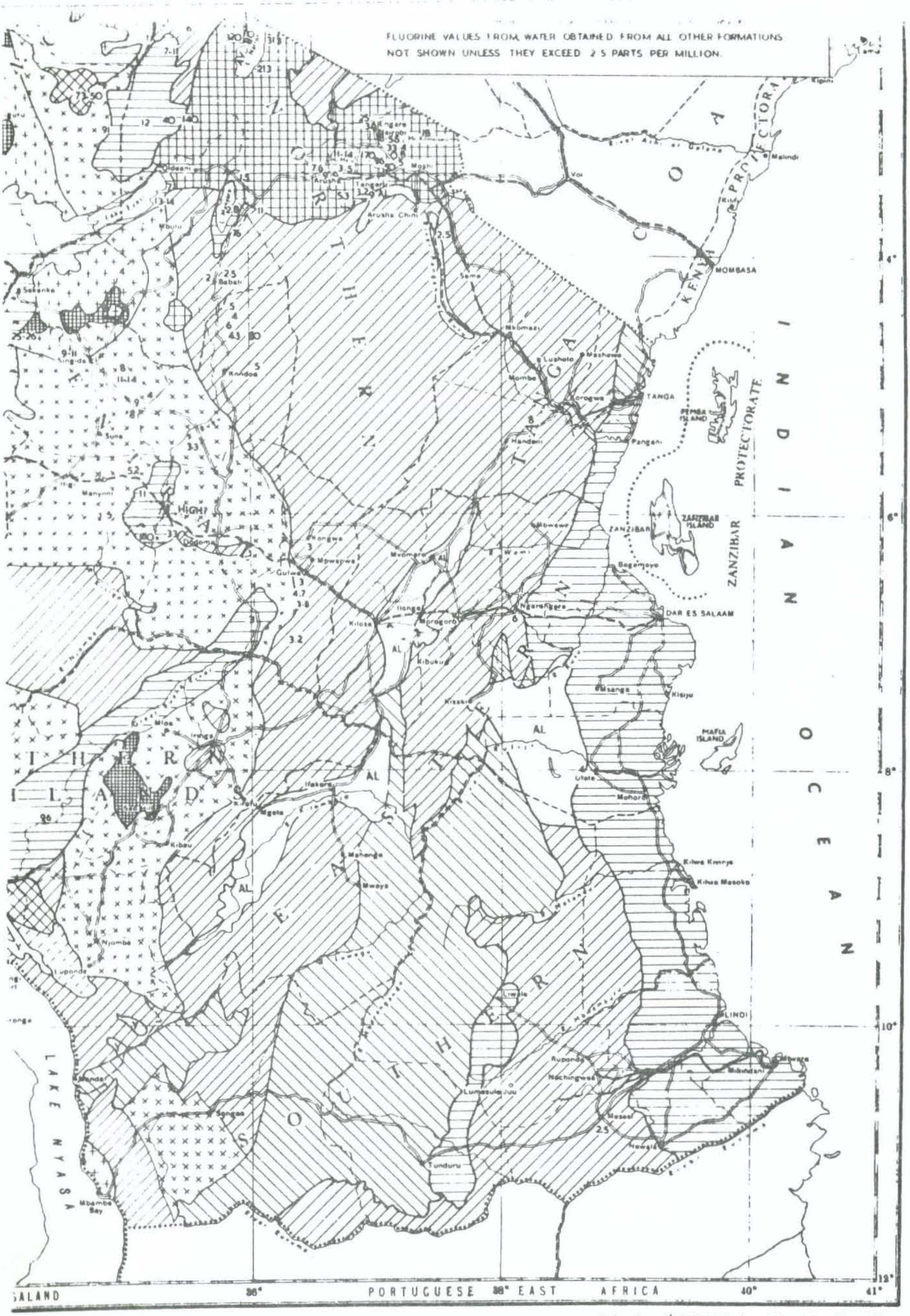
7 MAGUGU
8 NAITOLIAN
9 SIMENJERO
10 SIMENJERO
11 ANGATA NANYUKI
12 ANGATA NANYUKI
13 LENDENI
14 OLKENEI
20 KERE LEWA MBUGA
21 KITWEI MBUGA
22 KITWEI
23 AMBUSELI
24a IDUO
24 IDUO
ISORESISTIVITY PLAN
25 NGOMAI
26 MORETI MBUGA
34 TUBOKOSE
35 CHIONA
36 KIBAKWE
37 CHINANGALI
38 KIMAA
39 HAMAI
40 BUSI
41 BUSI
42 MAOLI
43 LONGALO
44 MALOYA
45 NORTH ATTA
54 KITERAKA
55 KITERAKA
56 DODOMA TOWNSHIP
57 IBINDO
58 ITIGI
59 ITIGI
60 HUMEKWA
61 UKIRUGURU
68 MAKUTUPORA
69 NGEYU NYIRO
70 ARUSHA AERODROME
71 NDRUMA CHINI
72 ARUSHA CHINI
73 FARM 330 SANYA
74 FARM 330 SANYA
75 BABATI
76 SAME
77 LEMBENI
78 MADANGA
79 PONGWE PIGONI
86 MATENEKENI
87 DUGA
88 NDURUMA CHINI
89 SCUTARI SISAL ESTATE
90 KIMAMBA TOWNSHIP
91 ANTONIO ESTATE
92 ANTONIO ESTATE
93 MADOTA
94 MADOTA
95 KILOSA
96 KILOSA
97 ULAYA
Legend
BOREHOLE B.H.
WATER STRUCK W.S.
NO WATER STRUCK N.W.S.
DRILLED TO HERE D.T.H.



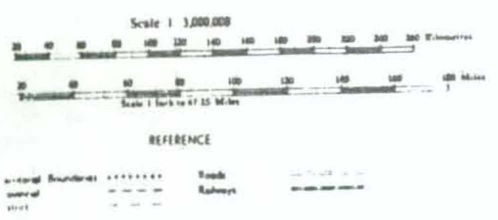
YIELD AND DEPTH OF BOREHOLES

TANGANYIKA

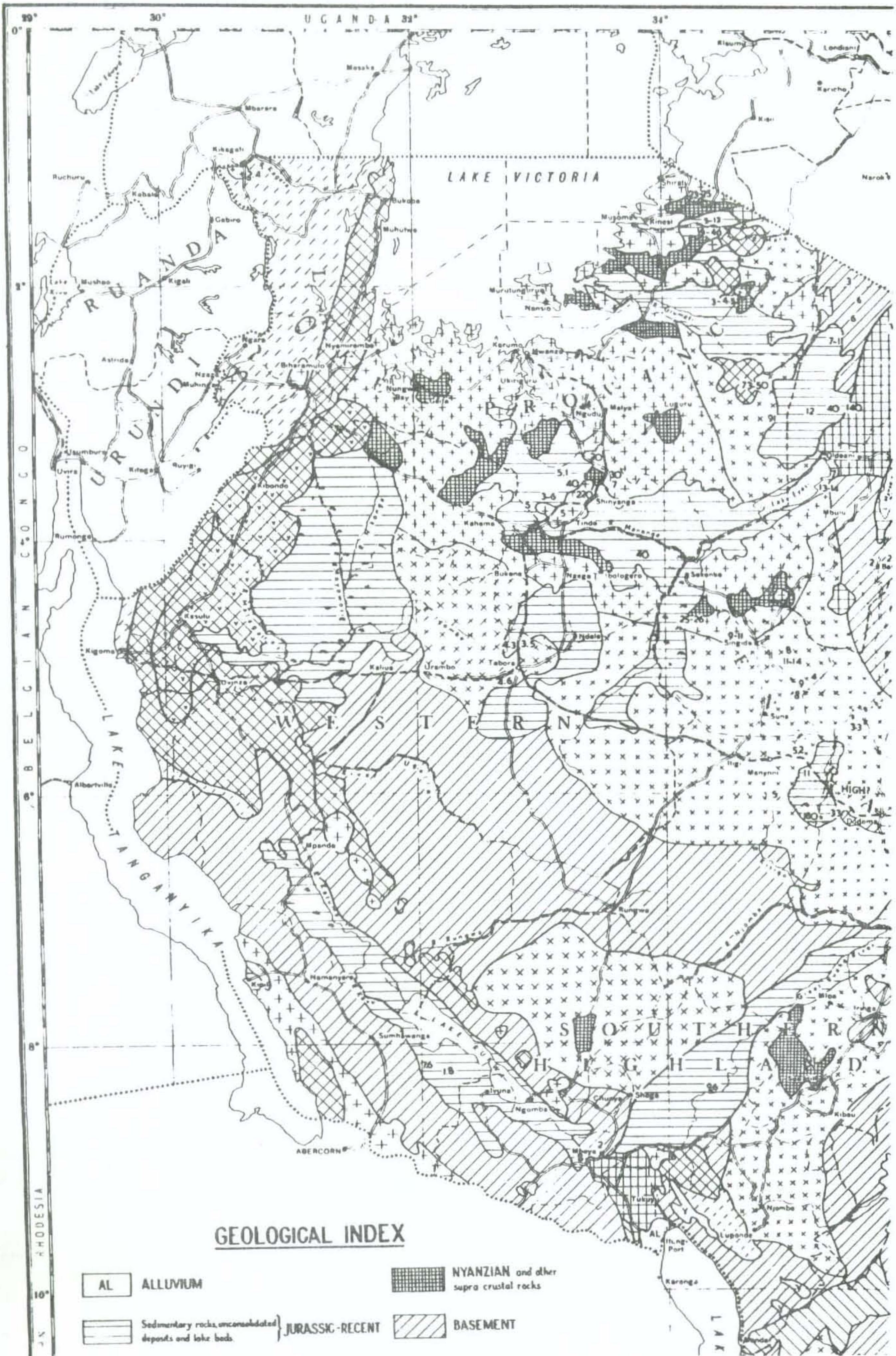

GEOLOGICAL MAP OF
TANGANYIKA
(Simplified)
SHOWING FLUORINE VALUES IN PART PER MILLION IN UNDER GROUND WATERS, STREAMS AND RIVERS.
FLUORINE VALUES SHOWN THUS 5.2
IN GRANITIC, BASEMENT, KARAGWE-ANKOLEAN ROCK AREAS, VALUES ARE ONLY SHOWN WHEN:-
A FLUORINE > 3 PARTS PER MILLION IN GRANITIC ROCKS
B FLUORINE > 2 PARTS PER MILLION IN BASEMENT ROCKS
C FLUORINE > 1.7 PARTS PER MILLION IN K-A ROCKS
FLUORINE VALUES FROM WATER OBTAINED FROM ALL OTHER FORMATIONS NOT SHOWN UNLESS THEY EXCEED 2.5 PARTS PER MILLION.
KENYA
INDIAN OCEAN
MOMBASA
TANGA
DAR ES SALAAM
ZANZIBAR
PEMBA ISLAND
MAFIA ISLAND
Arusha
Dodoma
Kondoa
Morogoro
Kilosa
Bagamoyo
Pangani
Kilwa Masoko
Kilwa Kivinje
Lindi
Malindi
Nairobi
Voi



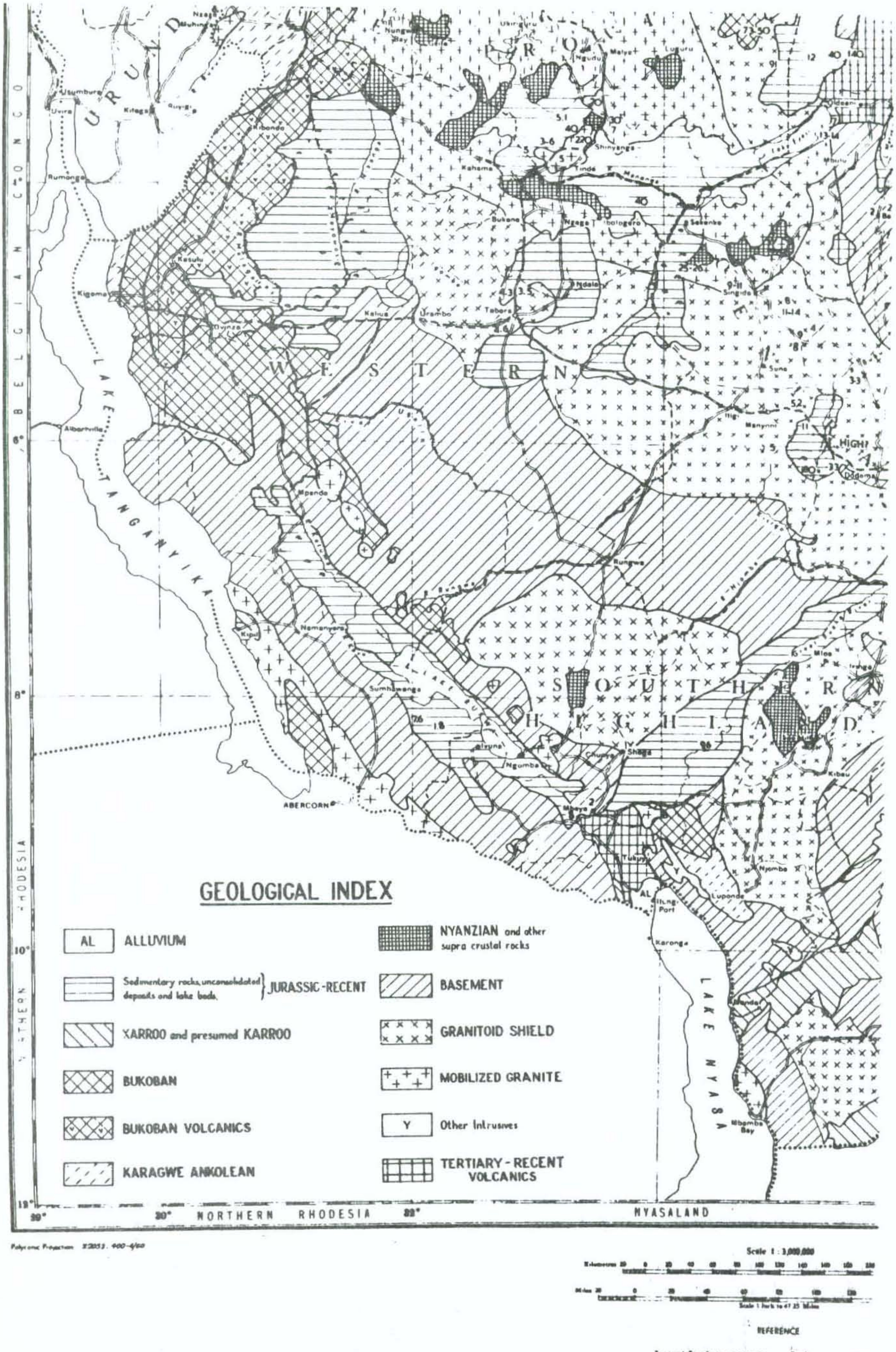
Geology from 1/2,000,000 Geological Map of East Africa 1954, of the Geological Survey Dept. Dodoma



TANGANYIKA



UGANDA
LAKE VICTORIA
RUANDA
URUNDI
BELGIAN CONGO
LAKE TANGANYIKA
WESTERN
SOUTHERN HIGHLANDS
RHODESIA
Kigoma
Tabora
Mwanza
Shinyanga
Singida
Mbeya
Mpanda
Sumbawanga
Abercorn
Albertville
Usumbura
Bukoba
Musoma
Kibondo
Kasulu
Uvinza
Kahama
Nzega
Iringa
Njombe
Tukuyu
Karonga
GEOLOGICAL INDEX
AL ALLUVIUM
Sedimentary rocks, unconsolidated deposits and lake beds } JURASSIC-RECENT
NYANZIAN and other supra crustal rocks
BASEMENT


GEOLOGICAL INDEX
AL ALLUVIUM
Sedimentary rocks, unconsolidated deposits and lake beds. } JURASSIC-RECENT
KARROO and presumed KARROO
BUKOBAN
BUKOBAN VOLCANICS
KARAGWE ANKOLEAN
NYANZIAN and other supra crustal rocks
BASEMENT
GRANITOID SHIELD
MOBILIZED GRANITE
Y Other Intrusives
TERTIARY - RECENT VOLCANICS
WESTERN
SOUTHERN HIGHLAND
LAKE TANGANYIKA
LAKE NYASA
BELGIAN CONGO
NORTHERN RHODESIA
NYASALAND
URUNDI
Usumbura
Uvira
Kitega
Rumonge
Kigoma
Kasulu
Kibondo
Uvinza
Albertville
Mpanda
Kipili
Namanyere
Sumbawanga
Abercorn
Kahama
Shinyanga
Tinde
Bukene
Nzega
Igalula
Tabora
Urambo
Kaliua
Ndala
Ngudu
Malya
Singida
Sekenke
Itigi
Manyoni
Dodoma
Rungwa
Chunya
Mbeya
Tukuyu
Itungi Port
Karonga
Iringa
Mlolo
Kibau
Njombe
Lupanda
Mbamba Bay
Ngomba
Utengule
Mbulu
Polyconic Projection
Scale 1 : 3,000,000
Kilometres
Miles
REFERENCE
Territorial Boundaries
Provincial
District
Roads
Railways