HYDRO CHEMICAL FACIES OF GROUND WATER IN THE WESTERN PROVINCES OF SUDAN

by

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STATEMENT BY AUTHOR

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ABSTRACT

The ground water in the Nubian Sandstone and Umm Ruwaba aquifers in the area under investigation is a good quality calcium-sodium bicarbonate water. It has low total dissolved solids and hardness, and it is slightly basic. In Jabal El Hilla and Ghazala Gawazat the total dissolved solids are much higher and the chloride ions are the dominant anions. This high chloride and solid content may be due to the mixing of water of the main ground water body with water of higher chloride and solid derived from (1) mudstone of the Nubian series, (2) deep ground water layers of higher salinity and/or (3) waters which have dissolved solids from evaporite beds in the sedimentary sequence.

The basement complex, where it crops out or is covered by a thin layer of Quartinary sediments is only a minor source of ground water. Little is known concerning the shape of the basement complex water table and only one complete chemical analysis from this source is presently available. However, incomplete data indicate that water quality varies over a wide range, and that nitrates are present and in some places fluorides are high. The nitrate is believed to be of organic origin whereas the fluoride is believed to be from weathering of fluoride-bearing rocks.

CHAPTER I

INTRODUCTION

Nature and Scope of Work

Over a significant part of the western Sudan the water supply is obtained primarily from ground water. For the most part, the present sources of ground water do not contain objectionable quantities of dissolved solids. However, there are problems of high salt concentration in some parts of the area, and in other areas there are problems due to high concentrations of fluoride or other ions, which exceed the limits for potable water.

An understanding of the cause and the source of the high concentration of the salts which are present in those areas, and the general distribution of salts in the aquifer is necessary for any future development of the water resources, and for the improvement of the present conditions.

Location, Population and Resources

The area of study covers the greater part of the western Sudan. It forms the western part of Kordofan Province, and the eastern part of Darfur Province (figures 1 and 2). It is rectangular in outline, with the dimensions

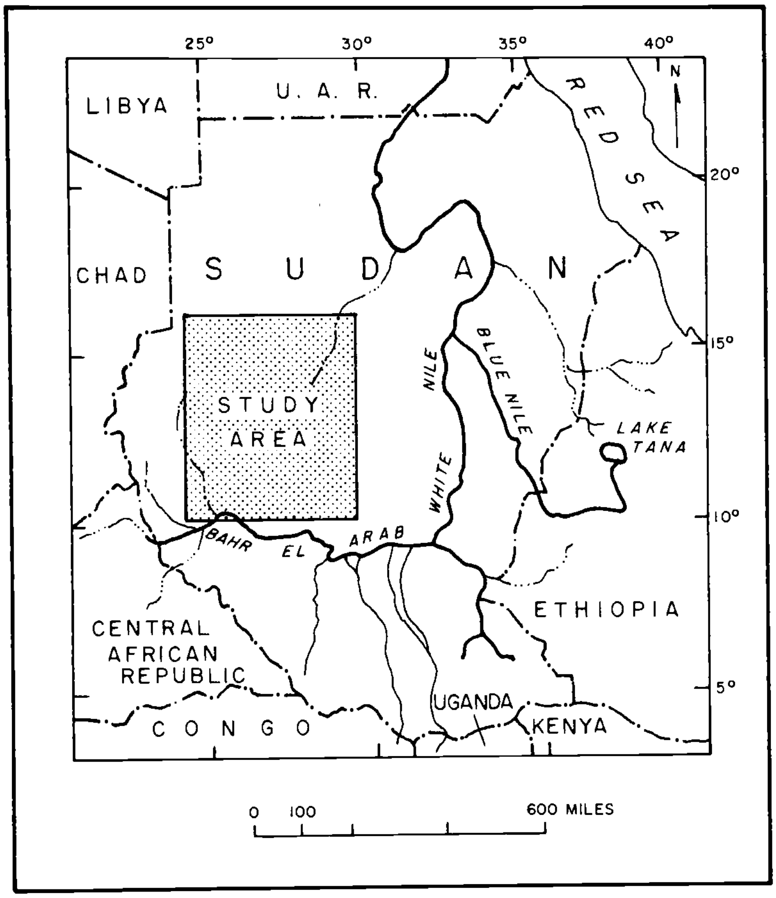
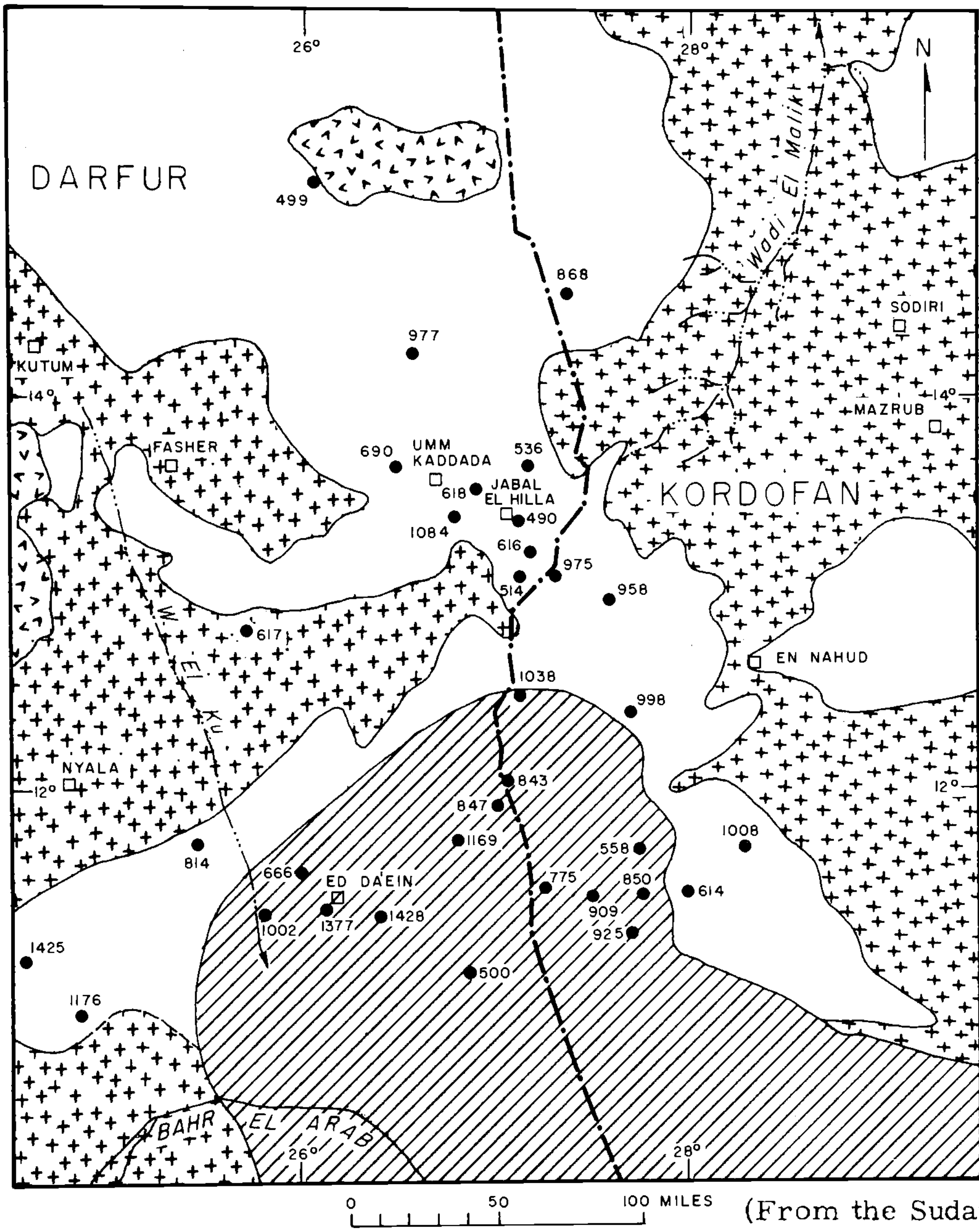


Figure 1.--Map of the Sudan showing the location of the area of study.



(From the Sudan Geologic Map 1962)

EXPLANATION

Umm Ruwaba Series	Volcanic rocks	Nubian Series	Basement complex
Pleistocene-Pliocene	(Late Tertiary)	Upper Paleozoic	Precambrian

Figure 2. --Map showing the geology of the area and the location of selected bore holes.

of 430 miles from north to south and 340 miles from east to west. It lies between latitude 24° 30'E. and 29° 30' E., and longitude 10°N. and 16°N.

The principal cities are El Fasher, the capital city of Darfur Province, and Kutum, Nyala, Ed Da'ien and Umm Kaddada: the population is estimated at 750,000. The southern part of the area is more densely populated than the northern part, the majority of the population being nomadic tribesmen who continuously move in search of grazing land and water for their cattle, camels, and sheep.

Millet, peanuts, and watermelon are cultivated during the rainy season, which occurs between July and September. No irrigated farming is practised in that part of the country. The economy of the region is based on its animal resources, which are exported to the United Arab Republic and other Arab countries, and on gum Arabic which is also exported. At the present time there is neither industry nor mining activity in the area.

Previous Work

The geology and hydrology of the western provinces of the Sudan have been studied by several workers, but little has been mentioned about the chemical quality of the water.

Moon, (1954) stated that:

> At the neck of the Nubian series aquifer connecting with the Umm Ruwaba series of Southern Darfur there is a disturbance of the static water surface suggesting a subsurface barrier north northeast on a line between Burush (Bore 618) and J. El Ella (Bore 490). It is significant that the Bore at J. El Hilla and at Umm Shanga (Bore 616, below the southeast of the assumed barrier), yield highly saline water (7900 and 12400 p.p.m. total solids respectively) such as to be expected in a back-water off the main stream. Further confirmation of the existence of the barrier is afforded Bore hole 514 at Umm Kerein, a few miles to the west of Umm Shanga, where the basement complex was struck at only a small depth below the static water surface in the Nubian.

The evidence Moon gave for the presence of the subsurface barrier is rather vague, and his reference to a back-water off the main stream might be applied to a surface water body, but is misleading when applied to ground water flow.

Rodis, Ishag, and Wahdan (1963) state that "the low dissolved solids content of water suggest that there is little soluble material in the rocks of the Nubian series, exceptions to the generally good quality of the water from Nubian aquifers occur locally"; they further stated that "the total dissolved solids content of water from Umm Ruwaba aquifers averages 1050 p.p.m. and ranges from a low of 420 p.p.m. to a high of more than 3000 p.p.m.". They also stated that "the water in the Umm Ruwaba aquifers in western Kordofan are generally of better quality than in the eastern part of the province".

Source of Data

The data used in this report were collected partly by field parties of the Sudan Geological Survey, and partly from water samples analysed by Wellcome Laboratory, Ministry of Health, Sudan.

In an effort to study the ground water resources of the western Sudan, two parties were sent to the area by the Geological Survey Department; the first party, consisting of Harry Rodis of the U. S. Geological Survey, Abdulahi Ishage and Lutfi Wahdan of the Sudan Geological Survey, went to Kordofan Province in 1961-62 field season; the next year they went to Darfur Province where the writer joined them.

Well water samples are analysed by the Wellcome Laboratory of the Ministry of Health to determine its suitability for human and animal consumption. These samples do not represent individual horizons, but give the chemical composition of the water pumped from several horizons. Also, samples were stored in ordinary glass containers for three to five weeks before analysis; during this time certain constituents such as carbonate and bicarbonate ions, sodium ions, pH, and perhaps others may have changed in value.

CHAPTER II

GEOGRAPHICAL FEATURES

Topography and Drainage

The surface elevation of the area under study ranges from a low of approximately 1500 feet above M.S.L., in the southern part, to a high of approximately 2200 feet above M.S.L. in the northern part. The greater part of the area is composed of a gently undulating surface, which dips very gently towards the south; in the west lies Jabel Murra plateau, which averages about 3500 feet above M.S.L. and marks the western limit of the River Nile watershed.

Most of the area of the report falls in the Bahr (river) El Arab watershed (figure 3), which drains to the south and is tributary to the Nile. Bahr El Arab is the only perennial stream in the area; Wadi El Ku flows only for short periods during the rainy season and no data are available for the amount and duration of its discharge.

North of (approximately) latitude 15°N. the water drains toward the northeast to the middle course of the Nile; Wadi El Malik which is the main stream in the watershed conveys water to the Nile only during occasional floods.

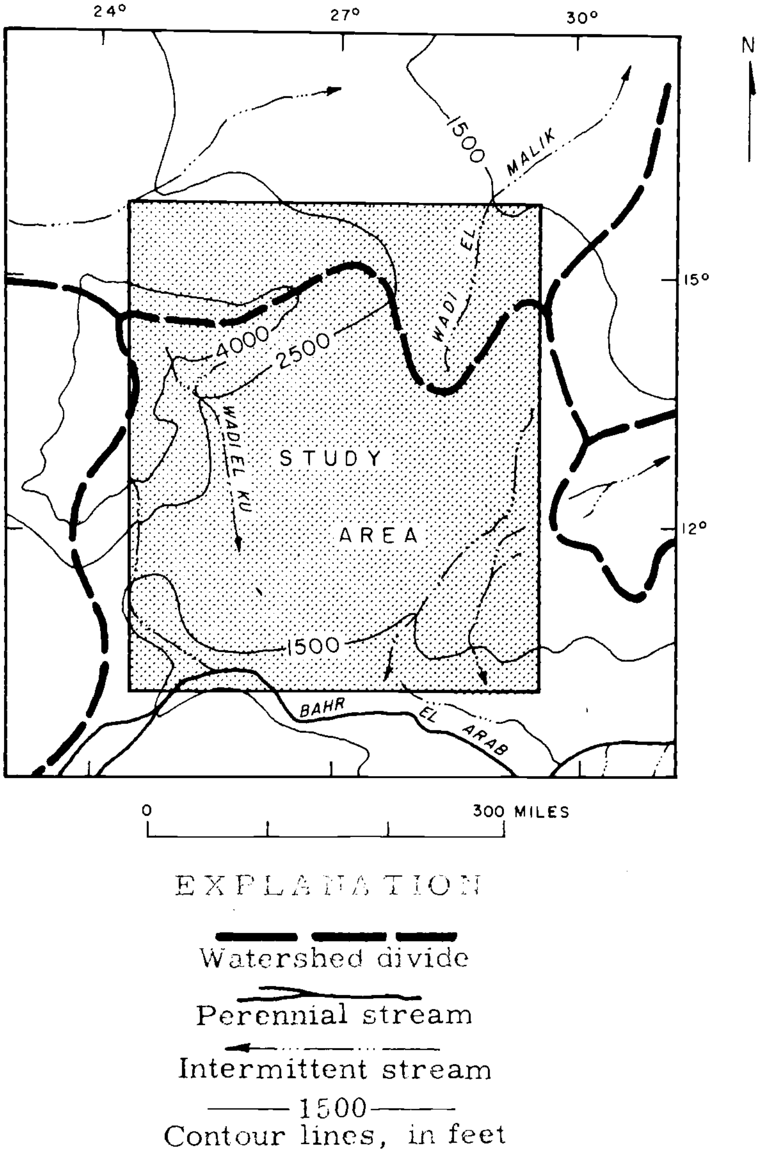


Figure 3.--Map showing the topography, drainage, and watersheds.

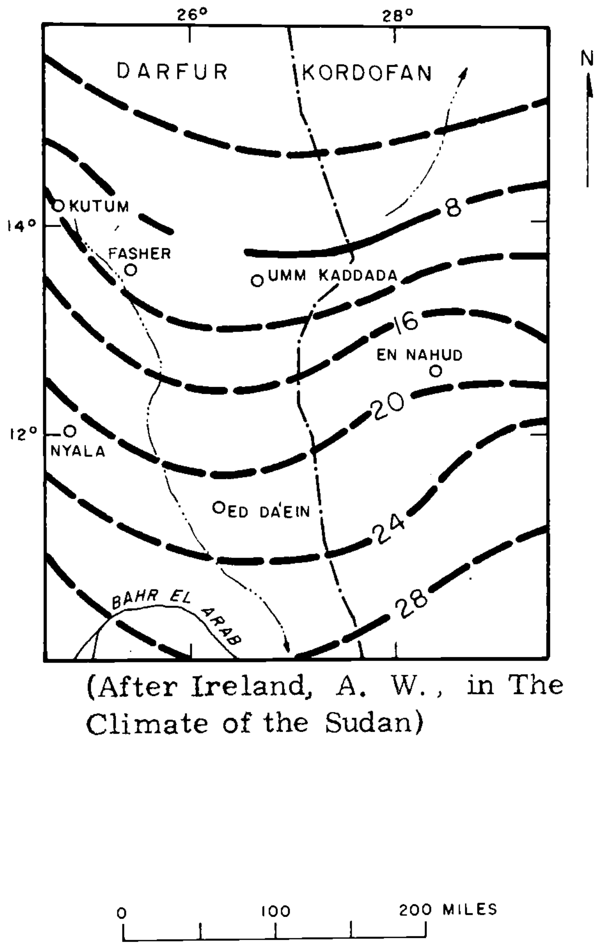
Climate and Vegetation

The climate of this area is continental and ranges from semi-arid in the north to sub-equatorial in the south. The rainfall is maximum in the south and decreases northward (figure 4); the rainy season is longer in the south with most of the rain occurring as convectional storms. There is a marked diurnal maximum in the afternoon and in the evening.

The climate changes more or less gradually from north to south. It is possible, on the basis of vegetational changes, to divide the area into three climatic regions. These are (figure 5): the northern semi-desert, the central region, and the southern subtropical region.

1. Northern Semi-desert, or Acacia Desert Scrub Region. This region has an annual rainfall from 2 to 12 inches, with a drought period of about 8 months. The dominant type of flora is the Acacia species. The vegetation is in general scattered and areas may occur without trees and which support only scanty flora.

2. Central or Acacia Short-grass Scrub Region. This region covers a narrow belt and has a rainfall ranging from 12 to 20 inches, with a drought period of about six months. The Acacia species are the dominant trees with occasional Haraz



(After Ireland, A. W., in The Climate of the Sudan)

Figure 4. --Mean annual rainfall, in inches.

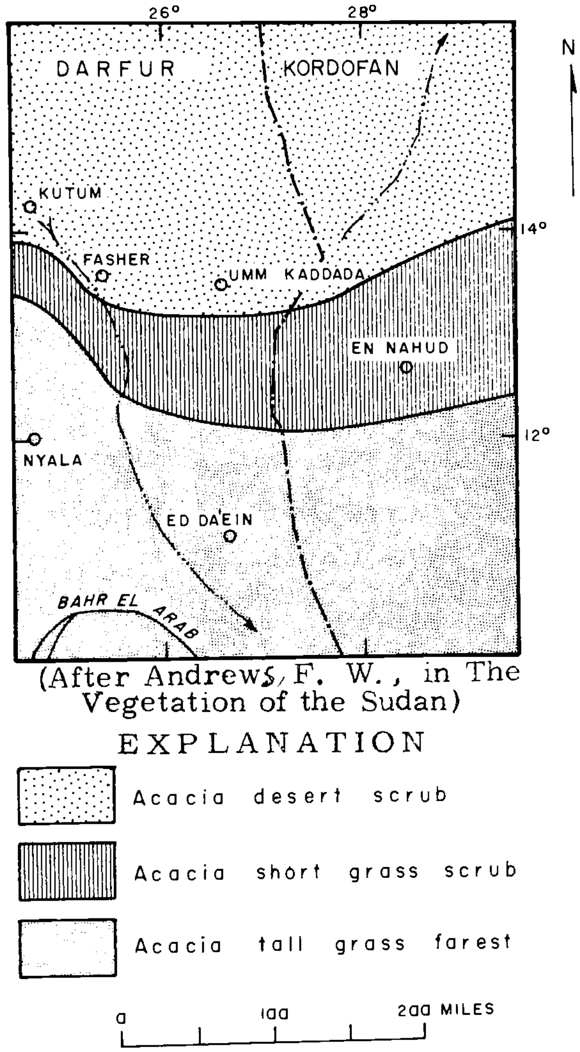


Figure 5. --Map showing the vegetation.

(Acacia albida Dei.) and a number of grasses mixed with drought resistant plants. Here Hashab (Acacia sinegai Willd.) covers a fairly continuous open forest which yields the gum Arabic.

3. The Southern Subtropical or the Acacia Tall-grass Forest Region. This region has an annual rainfall ranging from 20 to 40 inches. It is bounded on the south by Bahr El Arab. The Acacia species are still prominent but the introduction of other broader-leaved trees alters the appearance of the landscape. There is thick vegetation with heavy ground cover that is in distinct contrast to the other regions.

CHAPTER III

GEOLOGY

Summary of the Stratigraphy and Geologic History

The rock formations that underlie the area according to Andrew, (1948) include a basement complex of Precambrian age, the Nubian Sandstone series of Mesozoic age, volcanic rocks of Tertiary age, the Umm Ruwaba fluvial and lacustrine series of Pliocene to Pleistocene age, and the surficial deposits of Quaternary age.

The areal distribution of the basement and sedimentary rock units is shown in figure 2.

The basement complex constitutes the oldest rocks in the region; they are Precambrian in age. Following the emplacement of these rocks the region was subjected to a prolonged period of erosion which apparently lasted from the Precambrian until the Mesozoic. During the Mesozoic era the clastic sediments of the Nubian series were deposited unconformably over the basement complex in continental and/or near shore marine environments. At the close of Mesozoic time the seas receded as the region was uplifted. The Nubian rocks were then subjected to a prolonged period of erosion, during which most of the Nubian was stripped away; only those parts occupying deeper basins in the basement rocks were left intact.

Tectonic movements in east Africa, probably occurring during late Tertiary time, resulted in the formation of several structural basins in the Nubian and basement rocks, and in the extrusion of the volcanic rocks of Jabel Murra in the western part of the area and the Maidob Hills in the northern part. During the Pliocene and the Pleistocene time the basins were filled with fluvial and lacustrine deposits that comprise the Umm Ruwaba series. Finally, relatively thin deposits of Pleistocene and Recent age (not shown on figure 2) cover large areas of the older formations. These surficial deposits are not continuous and are of several types. In the central and northern part of the area they are mainly sand dunes; in the southern part, they occur as extensive plains of clay and silt.

Geologic Units and Their Water-bearing Properties

Basement Complex (Precambrian)

The basement complex consists of granite, gneiss, schist, quartzite, basalt, marble, and other igneous and metamorphic rocks. Since the emplacement of these rocks they have been subjected to prolonged periods of erosion and structural deformation.

Wells dug in the basement complex are found in areas where the basement outcrops or where it is covered by a thin veneer of later deposits.

Because of the paucity of the hydrological data from wells dug into the basement rocks, little is known about its ground water potentialities. Ground water is present in the weathered zone of the basement rocks as well as in cracks and fissures; the weathered zone forms small discontinuous shallow aquifers. The geohydrologic characteristics of these aquifers differ according to the nature of the original basement rock type and the depth of the weathered zone.

Nubian Sandstone Series (Mesozoic)

The Nubian Sandstone series underlies a large part of the area of study; in most of the northern part the Nubian Sandstone is covered by a thin mantle of surficial deposits and is exposed only in the wadies and jabels. In the southern part most of the Nubian Sandstone is overlain by the Umm Ruwaba series.

The Nubian strata consist of friable to well-consolidated sandstone, mudstone, and conglomerate unconformably overlying the basement complex. Although the Nubian strata may be correlated for long distances, yet abrupt changes in the lithology are common. The outcrop of the Nubian in the northern part of the area is about 300 miles wide but narrows southward to a width of about 40 miles and then broadens again. The Nubian sandstone is generally flat-lying or dips gently toward the north; it forms flat or gently undulating smooth surfaces with isolated flat-topped mountains of relatively low relief.

The Nubian Sandstone is subdivided into three units: the basal series, the middle series, and the upper series.

The basal series consists of an alternation of light brown, coarse to very coarse-grained silicified sandstone and conglomeratic beds. The basal series is cemented with silica thus rendering the formation very hard and resistant to weathering and erosion; where exposed it forms mesas of basal conglomerate capping hills of the basement complex. It weathers into rough, iron-stained, gravelly surfaces.

The middle series is composed of mudstone and sandstone beds, with mudstone being the dominant lithology. The middle series is multi-colored and exhibits a variation in grain size from coarse-grained sand to silt and clay. The sandstone is quartzitic; the clay varies in composition with bentonitic clay being most common. The middle series is poorly cemented and friable; it weathers into undulating surfaces with a thick sandy cover.

The upper series is composed of brown and buff, poorly sorted sandstone. Its grain size ranges from medium to fine sand to silt and clay. The sandstone is friable, poorly cemented, and quartzitic in composition.

The maximum thickness of the Nubian Sandstone in the area is not known; it may exceed 500 feet in places. In the Nubian section the sandstone and the conglomerate are the water bearing formations, the water being under a low artesian head of only a few feet.

Volcanic Rocks (upper Tertiary)

The volcanic rocks are generally assumed to be of the Upper Tertiary to Miocene age. The predominant rock is basalt, but trachites and phonolite are locally common; pyroclastic rocks occur near the volcanic craters, e.g. Malha crater in the Maidob Hills in the northern part of the area (figure 2).

Basaltic lava forms extensive plateaus; the Maidob Hills in the north and Jabal Murra in the west are examples.

The presence of ground water in the volcanic rocks of the Maidob Hills is very doubtful due to their being at an elevation above that of the regional water table. On the other hand the Jabal Murra plateau, which is about 10,000 feet above mean sea level, has heavy precipitation; the pyroclastic rocks there are saturated with water which drains as surface and subsurface flow into the Chad watershed to the west.

Umm Ruwaba Series (Pliocene to Pleistocene)

The Umm Ruwaba series are lacustrine and fluvial deposits, which are present in the southern part of the area; they rest unconformably over the Nubian Sandstone series (figure 2). Although in general the Umm Ruwaba series is underlain by the Nubian Sandstone, in the extreme southern part of the area the Nubian may be absent and the Umm Ruwaba may directly lie on the basement complex. Outcrops of Umm Ruwaba are rare, because they are covered in most places by a thin, but almost continuous veneer of surficial deposits.

The Umm Ruwaba strata, which are generally less consolidated than the Nubian Sandstone, are flat lying and are composed mostly of mudstone, sandstone and conglomerate. Facies and bedding changes within relatively short distances are common. The Umm Ruwaba series attains a maximum thickness of 600 feet or more in this part of the country. The Umm Ruwaba series are similar to the Nubian Sandstone in many aspects, such as bedding and facies. The geohydrologic characteristics are quite similar, ground water being confined with a low artesian pressue; the two aquifers, the Nubian and Umm Ruwaba, are hydraulically connected and may be treated as a single aquifer system.

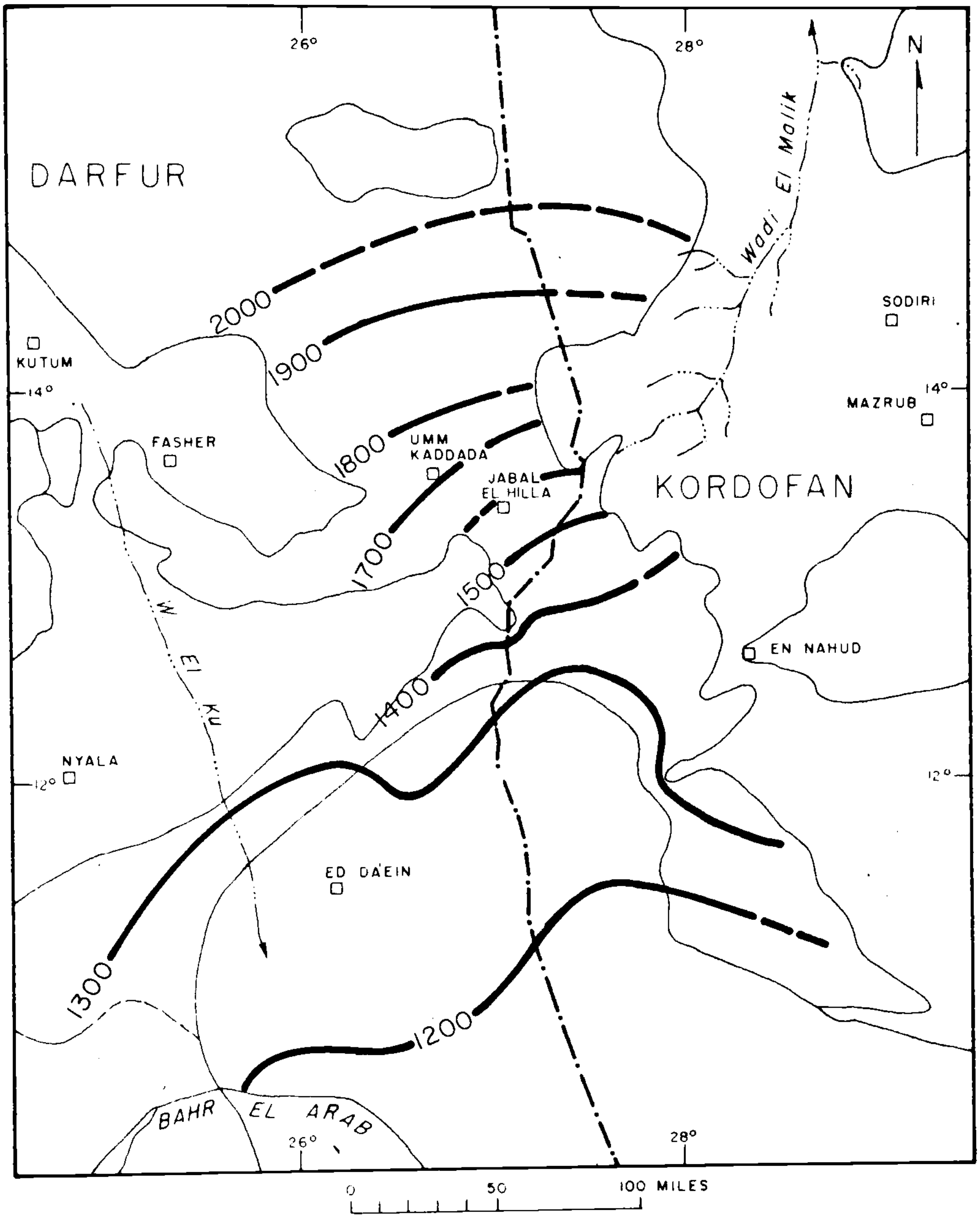
CHAPTER IV

MOVEMENT OF GROUND WATER

In the sedimentary rocks of the Nubian and Umm Ruwaba aquifers the ground-water body moves towards the south, i.e. towards Bahr El Arab (tributary to the Upper Nile). Figures 6 and 7 show the general configuration of the piezometric surface and the direction of flow respectively.

The ground-water divide in the north is not known due to scarcity of data. It may be parallel to the surface water divide of Bahr El Arab watershed which extends from Jabel Matariq north of Kutum to the Maidob Hills and thence in an easterly direction towards the White Nile near Dueim (14^{o} 13'N.) (figure 3).

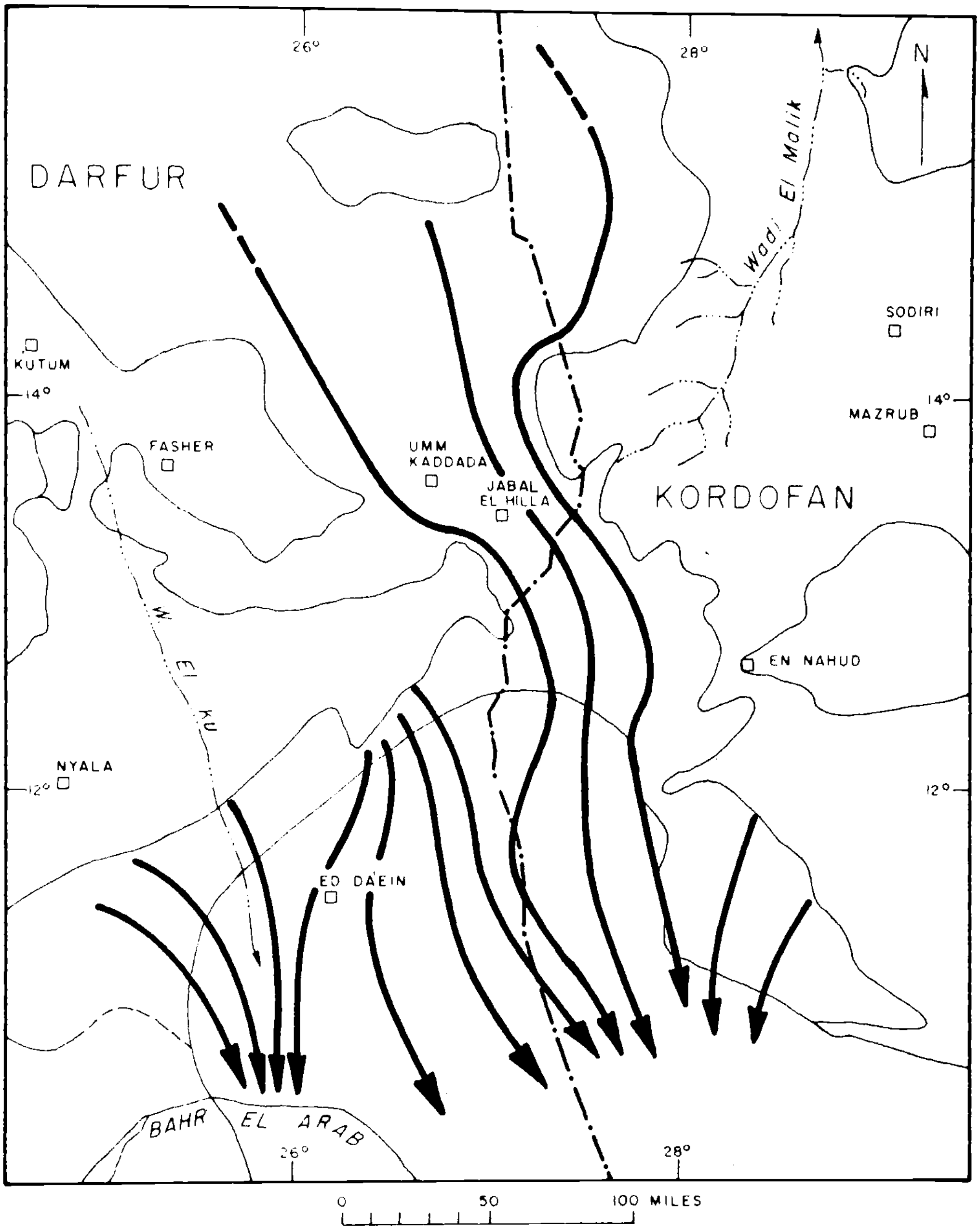
In the basement complex, which forms small discontinuous aquifers in regions of outcrop, ground water movement is controlled by local conditions. The direction of movement in these aquifers is not known due to scarcity of data, but may be presumed to follow surface topography.



(The piezometric surface in Kordofan is after Rodis, 1962)

Geologic Boundary (see figure 2) ————

Figure 6. --Map showing contours of the piezometric surface in feet of the zone of saturation in the Nubian and Umm Ruwaba aquifers.



Geologic Boundary (see figure 2)

Figure 7. --Map showing the generalized direction of flow of ground water in the saturated zone of the Nubian and Umm Ruwaba aquifers, based on contours of the piezometric surface (shown on figure 6).

CHAPTER V

QUALITY OF WATER

Physical Characteristics

The ground water in the sedimentary rocks of the Nubian and Umm Ruwaba aquifers is clear in appearance and odorless; however, in some cases the odor of hydrogen sulphide is reported, but this is generally due to contamination from organic matter from the surface.

Temperature

The temperature of the ground water in the area ranged between 80° and 100°F. The rate of increase of temperature with depth, i.e. the geothermal gradient, could not be established with the data available because the produced water was derived from different horizons.

The diurnal and seasonal variation in surface temperature has no effect on the temperature of the ground water, because the water table is too deep.

Chemical Quality

The ground water in the study area is generally of good chemical quality. The total dissolved solids average about 300 parts per million (p.p.m.), according to the analyses of the ground water samples made by the

Wellcome Laboratory of the Sudan Ministry of Health. Almost all the samples taken from that area are suitable for human and animal consumption. However, in certain areas the water has abnormally high salinity, e.g., in and around Jabal El Hilla. Also, in some parts there may be an overabundance of certain ions, such as nitrates and fluorides, which exceed the acceptable limits of water potability.

The following is a discussion of some of the chemical properties and of the ions in solution in the ground-water samples from the area of study. Most of the definitions and chemistry are taken from the text written by John D. Hem (1959), "Study and Interpretation of the Chemical Characteristics of Natural Water".

Hydrogen-ion Concentration (pH)

The hydrogen-ion concentration of a solution is a measure of its acidity or alkalinity and is expressed in terms of pH units. The pH unit is defined as the negative logarithm of the concentration of the hydrogen ions in moles per litre.

In the area of study the ground water has pH ranging from 6.5 to 7.5; these values are determined in situ by colorimetric method. The colorimetric method used in the field was quite satisfactory for the nature of study. Its drawback is the large range of error which is 0.25

pH units. The laboratory measurements are more precise but probably less accurate and more questionable due to the change of the pH value during storage. These changes consist of the reaction of the water with the container, escape of CO_2 gas due to the reduction of confining pressure, the precipitation of $CaCO_3$ due to the changes in the temperature, or the oxidation of the ions when they come in contact with the atmosphere. In the present case, the laboratory measurements are slightly higher than field determinations, the laboratory measurements being more inclined toward the basic side; they range between 7 and 8.3.

In general the pH data available show that the ground water ranges from slightly acid to slightly basic and there is no significant difference in the pH between samples taken from different formations.

Hardness

Although the concept of hardness is of wide useage in the literature of water analyses, yet the property of hardness is difficult to define, or rather there are conflicting definitions in general use.

Hardness is a measure of the amount of calcium and magnesium present, since they have the predominant effect on soap. However, free acids, heavy metals, and other alkaline earths also yield insoluble products with soap.

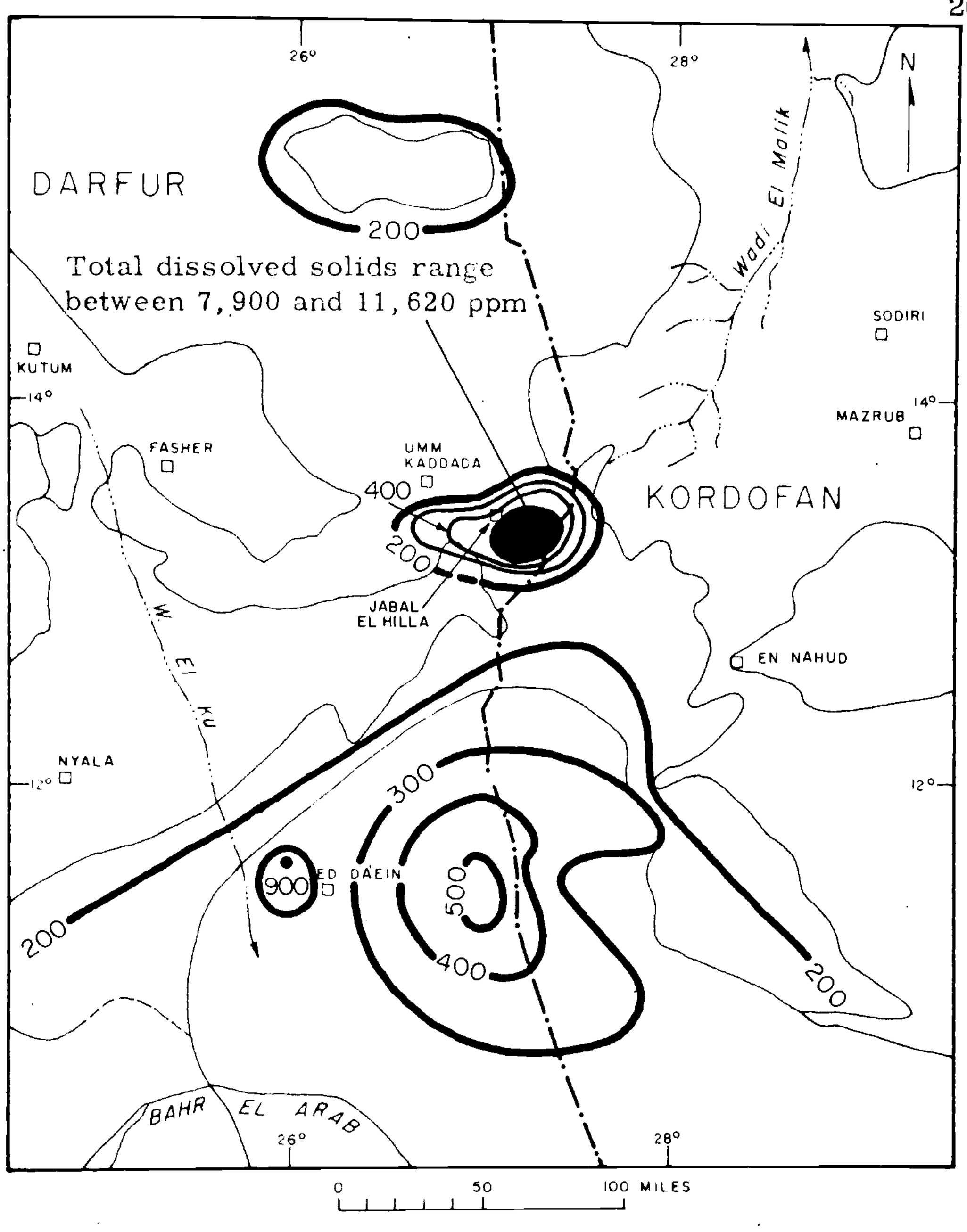
In this report hardness is reported in terms of equivalent amounts of calcium carbonate in parts per million. In the area covered by this report the hardness ranges from less than 100 to about 200 p.p.m.

The hardness varies with location as well as with depth, but figures 9 and 10 show that there is a general increase in hardness toward the south which is also the direction of ground water flow. In the Nubian aquifer the total hardness ranges from less than 100 p.p.m. to 200 p.p.m., which is rather low, but in Jabel El Hilla area the water is abnormally hard being 3400 p.p.m. in Bore hole 616 (20 miles south of Jabel El Hilla).

On the other hand, the water in the Umm Ruwaba aquifer is slightly harder than in the Nubian, having in general more than 200 p.p.m. (figure 9). However, the greater hardness in the Umm Ruwaba may simply be the result of increasing distance of travel, this formation being downgradient to the Nubian.

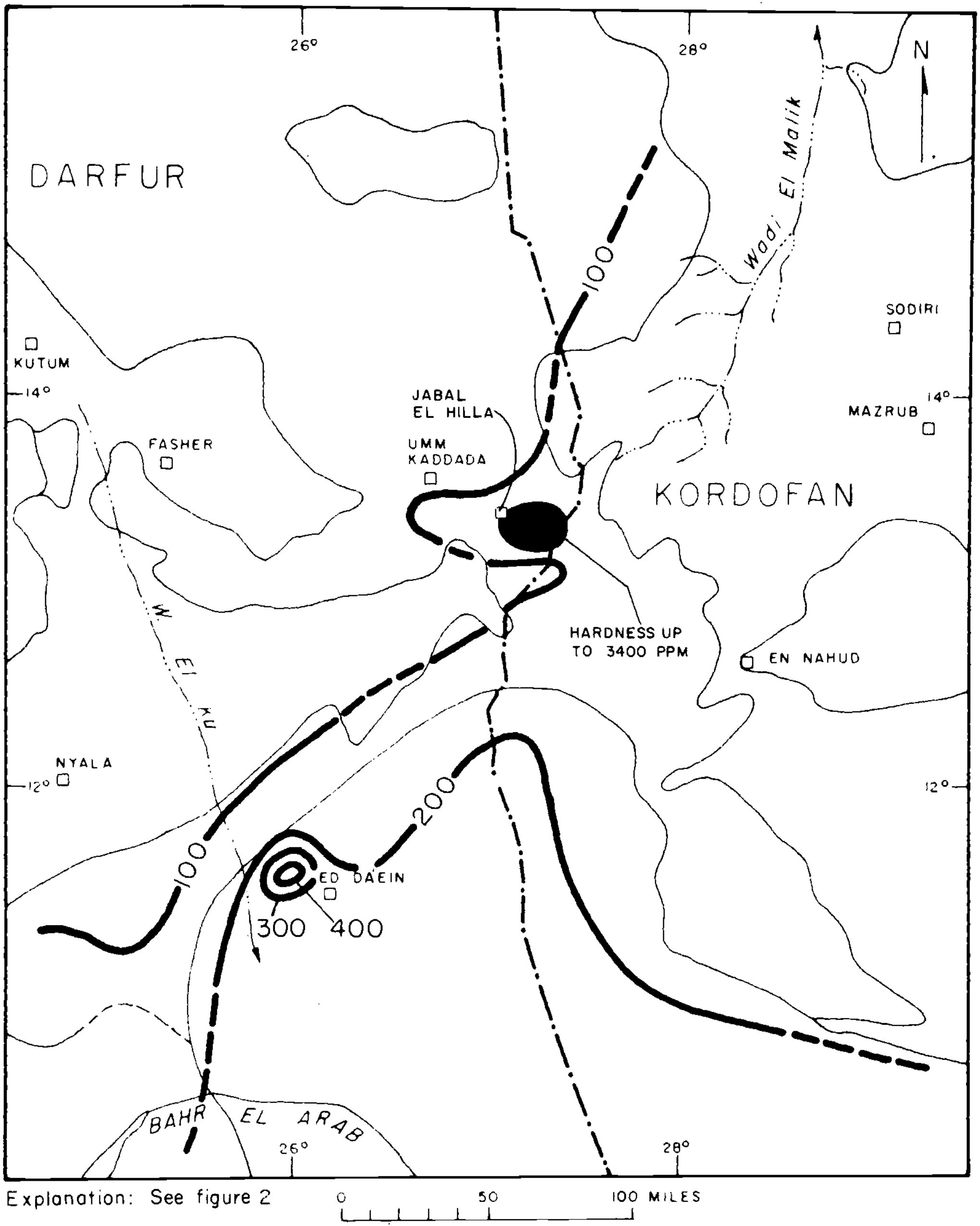
Total Dissolved Solids

The total concentration of dissolved material is determined from the weight of the dry residue after the evaporation of the water sample at 180°C. This solid residue does not completely coincide with the dissolved material that was originally in solution since dissolved gases are lost and bicarbonate is converted to carbonate with the loss



Geologic Boundary (see figure 2) ______

Figure 8. --Map showing the distribution of the total dissolved solids in ppm.



EXPLANATION

Geologic Boundary (see figure 2)

200

Equivalent Calcium carbonate in ppm

Figure 9.--Map showing the distribution of hardness.

of carbon dioxide; also some solid salts may be volatilized at the drying temperature.

In the area of study the total dissolved solids reported range from less than 100 p.p.m. up to 500 p.p.m., there being a general tendency of increase of the total dissolved solids toward the south parallel to the direction of flow (figures 7 and 8). In the Nubian aquifers the total dissolved solids in solution is rather low, averaging 150 p.p.m. In Bore hole 977 in the northern part of this area the total dissolved solids is 120 p.p.m. and increases steadily toward the south. Around the outcrop of the volcanic rocks of the Meidob Hills in the north there is an increase in the total dissolved solids.

In Jabel El Hilla and its surrounding area the total dissolved solids are abnormally high; for Bore hole 490 it is 7900 p.p.m. and for 616, it is 11,350 p.p.m.

In the Umm Ruwaba rocks the ground water has higher total dissolved solids than in the Nubian rocks, the average being 300 p.p.m. However, these samples do not represent the ground water in the Umm Ruwaba rock only, because most of the wells penetrate both the Umm Ruwaba and the Nubian series. In the Umm Ruwaba plus Nubian the total dissolved solids ranges between 200 p.p.m. to 480 p.p.m. In the Ghazale Jawazat Bore hole 666 the total dissolved solids are reported as 900 p.p.m. which is a comparatively

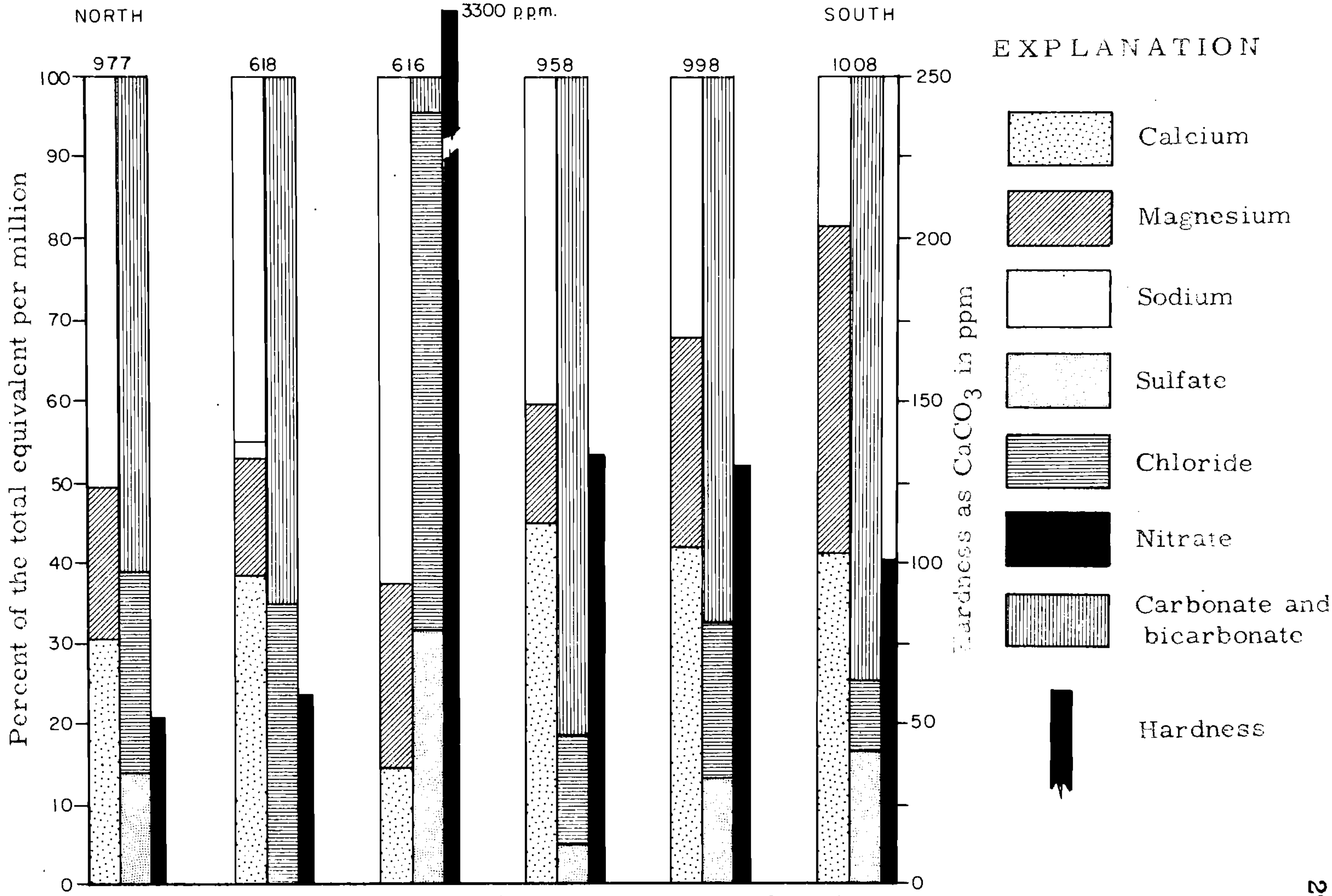


Figure 10. --Analyses represented by bar pattern based on the percent of the total equivalent per million of water samples from wells penetrating the Nubian aquifer in a section from north to south.

high figure.

There is a wide variation in the total dissolved solids present in samples from wells dug or drilled in the surficial deposits and from samples from similar wells bottoming in the weathered basement complex where the basement complex crops out or is covered by only a thin veneer of surficial deposits. The variation is dependent upon the chemical composition of the rock, and the configuration of the basement complex surface, as well as the permeability. Due to the sparsity of chemical analyses of water samples obtained from the surficial and weathered basement complex aquifers, and because of the discontinuity of these aquifers, no wide scale correlation could be made.

Constituents Reported in Water Analyses

Silica: Except for oxygen, silicon is the most abundant element in igneous, sedimentary, and metamorphic rocks. In rocks, silicon is in the form of the oxide silica (SiO_2) or combined with metals in the form of silicates. Crystalline SiO_2 as quartz is a major constituent of many igneous rocks, and constitutes the bulk of the grains of most sandstones. Quartz is one of the most resistant of all rock minerals to attack by water. The cryptocrystalline and amorphous forms of silica, such as chert and opal, are considerably more soluble in water than quartz. Decomposition of silicate minerals, such as feldspars, may give clay minerals and in most cases a surplus of silica which goes into solution.

In water analysis, silicon is reported in terms of the oxide, silica SiO_2. From the area of the report various concentrations of silica are reported ranging from 10 p.p.m. to 80 p.p.m.; the average is 20 p.p.m. The distribution of silica in the area does not follow any pattern. It is possible that the relatively high silica content and its random distribution in the area is not a function of the geological conditions of the aquifer, but is a function of the period of storage before analysis, because the samples are collected in ordinary soft glass containers which are readily attacked by water with small amounts of silica going into solution.

Calcium: Calcium is of widespread occurrence in rocks and soils. It is usually combined with silicates, carbonates, and sulphates. Weathering of calcium silicates such as calcium-bearing feldspars, pyroxenes, and amphiboles may yield soluble calcium compounds which go into solution leaving a residue of clay minerals. Calcium carbonates and sulphates dissolve in water wihout undergoing any chemical decomposition.

Calcium reported in the water analyses falls within a wide range of concentration ranging from 10 p.p.m. to about 500 p.p.m., but the ratio of calcium to other cations present in solution is relatively constant over most of the area. Figures 10, 11, and 12 show analyses represented

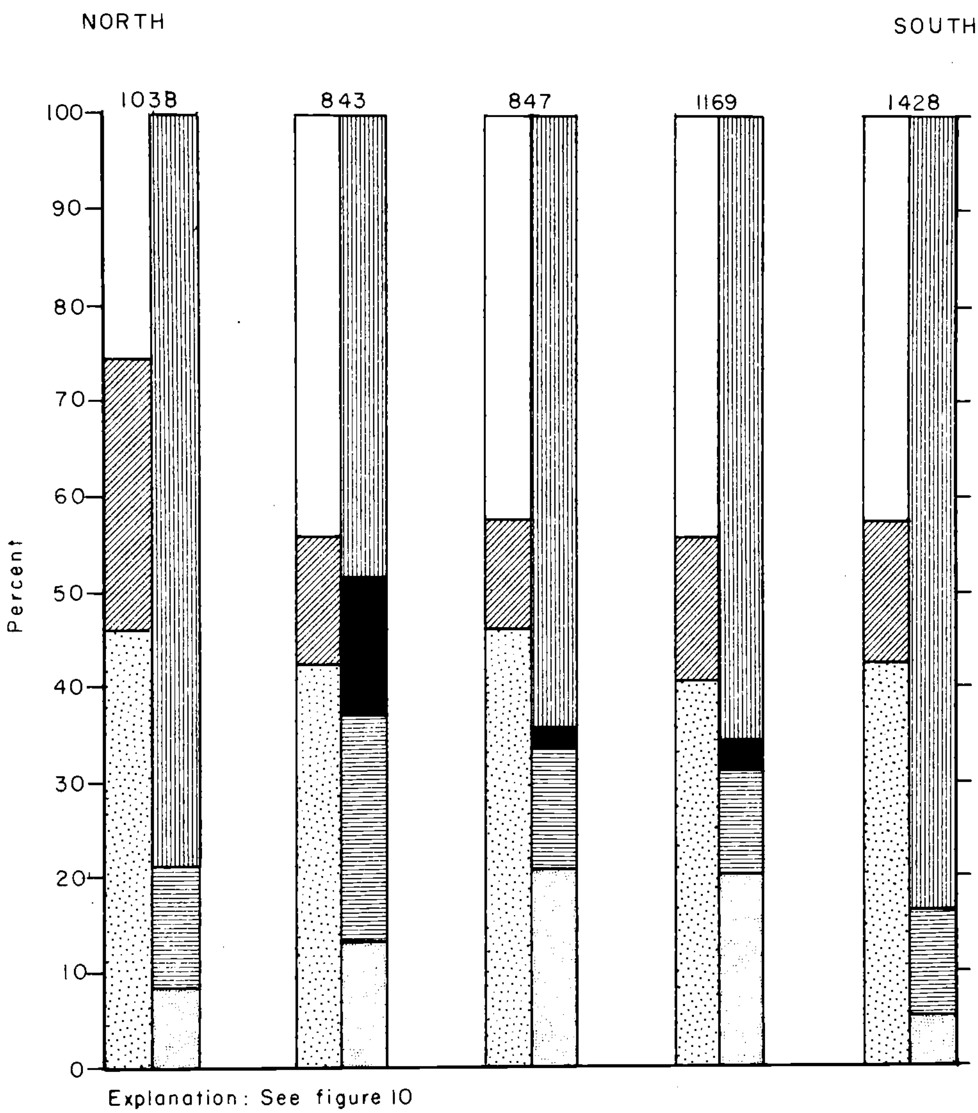


Figure 11.--Analyses represented by bar pattern based on percent of total equivalent per million of water samples from bore holes penetrating the Umm Ruwaba and the Nubian rocks, extending from north to south.

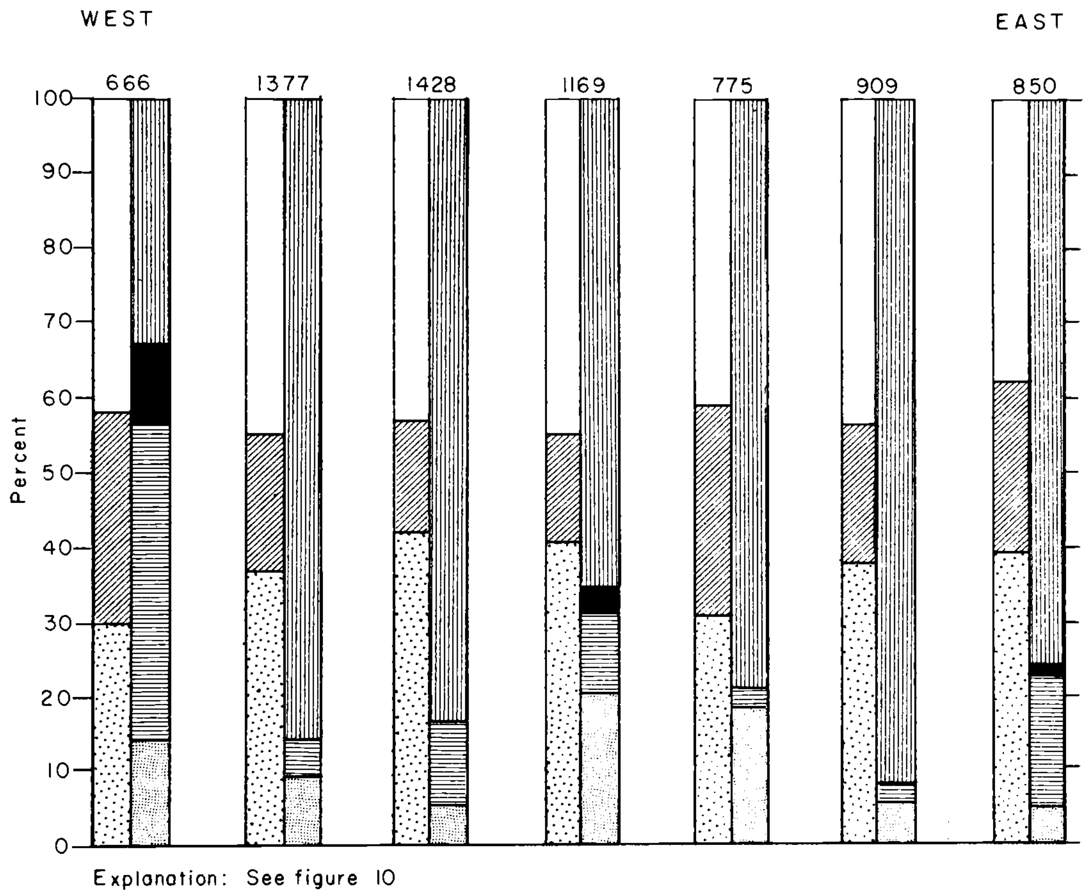


Figure 12. --Analyses represented by bar pattern based on percent of total equivalents per million of water samples from wells penetrating the Umm Ruwaba and the Nubian rocks in a section (east-west).

by bar patterns based on percentage of total equivalents per million: the calcium constitutes about 40% of the total cations present.

In the Nubian aquifers the average concentration of calcium in solution is about 20 p.p.m., being less in the north and increases toward the south. In the Umm Ruwaba series the average calcium ion concentration is 50 p.p.m. and constitutes about 40% of the total cations in solution.

Magnesium: Magnesium is a component of numerous silicate minerals found in the dark-colored ferromagnesium and ultra-basic rocks. Such minerals as olivene, pyroxenes, amphiboles and dark colored micas are attacked readily by water in the presence of carbon dioxide. In non-silicate minerals, magnesium is present mainly as a magnesium carbonate, or as the double carbonate with calcium in dolomite, or as a magnesium limestone.

In the area of study the magnesium ion concentration ranges from 5 p.p.m. to 100 p.p.m.. The average magnesium ion concentration in the Nubian water is 6 p.p.m. to 8 p.p.m., while in the southern part, in wells penetrating both the Nubian and Umm Ruwaba aquifers, it averages between 15 p.p.m. and 20 p.p.m.

Sodium and other Cations: Sodium is one of the alkali metals present in the igneous rocks in the form of alkali alumino-silicate minerals such as soda-rich feldspars, the feldspathoids, muscovite, and so forth. Evaporites, where present, may contain halite or merabilite which are sources of sodium readily available for solution. However, no evaporites have been reported in the drilling logs from the Nubian or Umm Ruwaba aquifers. In the analyses all cations except calcium and magnesium are reported as sodium, thus "sodium" includes such elements as potassium, iron,manganese, aluminum, and others.

Although potassium is less abundant than sodium, both of them are alkali-metals and resemble each other in many chemical qualities. Potassium behaves differently in the process of weathering, in that sodium has much more affinity to stay in solution than potassium which easily recombines with other products of weathering. Potassium is present in a number of the common silicate rock-forming minerals. Thus, these potassium-bearing feldspars are attacked in the same way as the sodium-bearing feldspars. However, although some potassium goes into solution, a larger part is retained in the clay minerals formed. Potassium in sedimentary rocks is mainly present in the form of unaltered silicate and clay minerals. It is not possible to give the range of concentration of potassium in the area of study, since the available data do not give figures.

Although iron is abundant in rocks and soils, it is present in many waters only in concentrations in the range of trace constituents. Iron is usually present in the dark colored silicate minerals such as the pyroxenes, amphiboles, and dark-colored micas. In non-silicate minerals, iron occurs as its sulphide pyrite, or in complex sulphides which include metals other than iron, and as oxides, particularly hematite and magnetite. Iron may exist in solution either in the bivalent (ferrous) form or the trivalent (ferric) form, the latter being much less soluble than the former. Field analyses indicate very low concentrations of iron in waters derived from either the Nubian or Umm Ruwaba series. The amount ranges between 0.5 p.p.m. and 2 p.p.m.

Manganese resembles iron in its chemical behavior and occurrence in natural water. Manganese is present in dark-colored silicate minerals, and occurs in large amounts in some metamorphic and sedimentary rocks.

Aluminum despite its abundance in many rocks, in natural water rarely exceeds 0.5 p.p.m. due to its extremely low solubility under normal conditions.

In summary, compared to potassium, iron, manganese, and aluminum, sodium is by far the most abundant, and for practical purposes, in this report the concentration given of all other cations except calcium and magnesium is added to the concentration of "sodium".

The concentration of sodium and other cations ranges between 10 p.p.m. and 150 p.p.m., averaging about

40% of the total cations in equivalents per million (see figures 11, 12, and 13). But in Bore hole 616 the sodium is 63% of the total cations in solution.

Alkalinity (Carbonate and Bicarbonate): The property of alkalinity of water is its ability to neutralize acid, and is usually reported either in terms of equivalent amount of calcium carbonate, as is the case at the Wellcome Laboratory, or in terms of equivalent amounts of bicarbonate, carbonate, and hydroxide as is done by the U. S. Geological Survey.

The anions that contribute to alkalinity are those which form weakly dissociated acids such as carbonates and bicarbonates. Other anions which may produce alkalinity include hydroxides, silicates, phosphates, borates, possibly fluoride, and certain organic anions, but in most natural waters these are present only in very small amounts.

Alkalinity is determined by titrating a known volume of solution against a standard acid. The first end point is at a pH of 8.2. This point is reached when theoretically all the carbonate ions are converted into bicarbonate; the second end point is reached at a pH of 4.5 and indicates all the bicarbonates has been converted into the undissociated carbonic acid.

The alkalinity reported in terms of equivalent

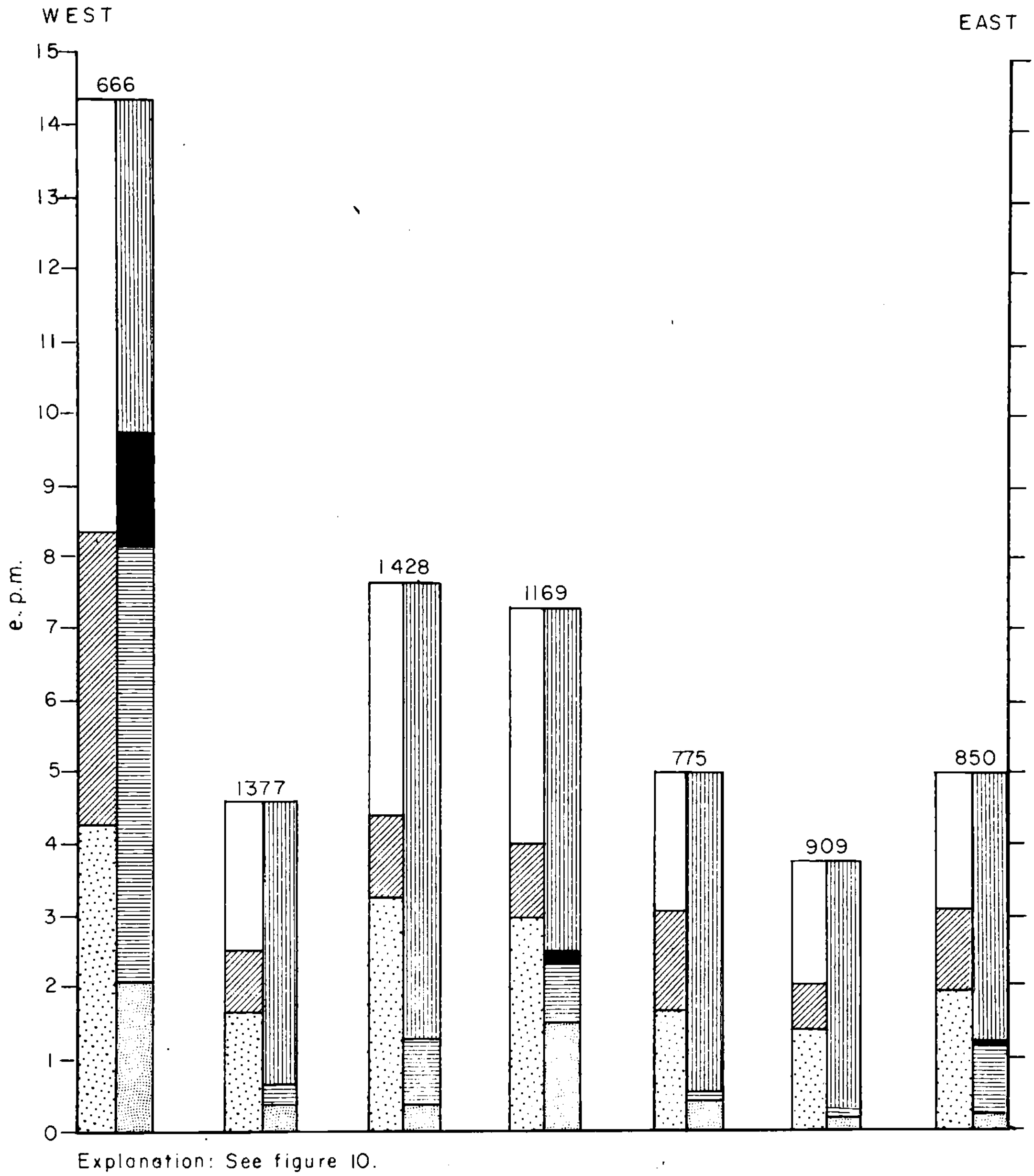


Figure 13.--Analyses represented by bar graphs of equivalent per million of water samples from bore holes penetrating the Umm Ruwaba and the Nubian rocks.

amounts of calcium carbonate ranges between 52 p.p.m. in Bore hole 977 in the north to 240 p.p.m. in Bore hole 973 in the south. The average alkalinity in the north is 60 p.p.m. and increases southward up to 200 p.p.m. (figure 10). In some localities high alkalinity figures are reported, such as Bore hole 614, where the alkalinity is 334 p.p.m., and is 440 p.p.m. for Bore hole 616.

The bicarbonate ion concentration in solution is obtained directly from the alkalinity by multiplying by 1.2194 to convert the calcium carbonate into the equivalent amount of bicarbonates in p.p.m., and by multiplying the values obtained by 0.01639 to convert the parts per million of bicarbonate into equivalent per million. Similar to the alkalinity the bicarbonate concentration increases toward the south, but as is seen on figures 10, 11, and 12, its ratio to the other anions is rather constant.

Chloride: Chloride is the most abundant member of the halogen group of elements found in natural water. Chloride is present in some igneous rock minerals, such as the feldspathoids, sodalite and the phosphate mineral apatite, but igneous rocks are a minor source. The most important source is from sedimentary rocks which have been laid down in a marine environment, or in closed basins where chloride ions were present.

Chloride constitutes a small but not insignificant portion of the anions present, being much less than bicarbonate ions. The percent chloride ion concentration decreases toward the south (figures 10 and 11). For the southern portion of the area, in Bore holes penetrating the Umm Ruwaba rocks only, the water contains a very small amount of chloride ions, not more than 5%.

In Jabel El Hilla area (Bore holes 490 and 616) the order of abundance of anions present is reversed, e.g. in Bore hole 616 chlorine ions form 63.4%, sulphate 31.8%, and the bicarbonate 4.7%.

Sulphate: Sulphur is mainly present in natural water as sulphate (SO_4^{--}). Sulphides are less common, and usually occur as dissolved hydrogen sulphide. Sulphur is uncommon in igneous rocks. Resistates and hydrolyzates may contain unaltered sulphide minerals. The major source of sulphur-bearing compounds in the ground water is from evaporites such as gypsum and anhydrite. Rain water contains small amounts of sulphate ions mainly derived from gypsiferous dust, incomplete combustion of coal, and smelters.

Sulphates are present in various concentrations ranging from zero to 80 p.p.m. They average about 25% of the total ions in solution. In some localized areas there are high concentrations of sulphate ions, e.g. well 616 where the sulphate ion concentration is 2825 p.p.m. The distribution of the sulphate ion concentration in the area varies, and does not have any preferred direction of change (figures 10 to 13).

Nitrate: A greater portion of the element nitrogen occurs in the atmosphere in an uncombined form, lesser amounts are found in proteins in living organism. In rocks, nitrogen occurs in small quantities. Nitrogen occurs in several forms depending on the level of oxidation. In ground water nitrogen occurs mainly in the highest oxidation form, nitrate (NO_3^-). A source of nitrate in ground water is from the atmosphere. which is combined into nitric oxides by lightning discharges. In the subsoil the nitrate content is increased by certain plants which take nitrogen from the air and fix it in soil as nitrate. These nitrates are added to those derived from the decay of plant debris, animal excrement, and leached from rocks.

Water from the Nubian aquifer contains negligible concentrations of nitrates, usually ranging between a fraction of a p.p.m. to 3 p.p.m. But in the Umm Ruwaba the nitrates in certain locations form up to 15% of the total dissolved anions, e.g. Bore holes 666 and 843 which contain 23.2 and 17.4 p.p.m. of nitrate. Elsewhere in the Umm Ruwaba the average nitrate concentration is generally low and does not exceed 2 to 3 p.p.m.

On the other hand, in water obtained from weathered basement and surficial deposits, the nitrate ion concentration varies considerably, and high concentrations are more common. Because the water table in basement complex aquifers is near to the surface (from 20 to 40 feet), organic matter on and in the soil is more significant in the production of nitrate ions than the weathering processes of igneous and metamorphic rocks.

Fluoride: Fluoride is a member of the halogen group, and occurs in igneous rocks in the form of calcium fluoride as in the mineral fluorite, and also in complex fluoride-bearing minerals as in apatite.

The fluoride ion concentration in the ground water of the Nubian and Umm Ruwaba aquifers ranges between zero and 1 p.p.m. In surficial deposits and weathered basement complex aquifers the concentration of fluoride ions varies. In most cases it is less than 1 p.p.m., but in Sodari and El Mazroub in the northeastern part of the area of study, concentrations of more than 7 p.p.m. are reported from shallow wells dug in the basement complex; the origin of such high concentration is most likely of local origin.

CHAPTER VI

DISCUSSION

Summarizing the important aspects of the physical and chemical qualities of the ground water, the ground water body in the sedimentary rocks of the Nubian and the Umm Ruwaba series is to a large extent homogenous and continous, flowing from the north to the south. The water is clear in appearance and odorless: however, in some cases the odor of hydrogen sulphide is reported, but this is generally due to contamination from organic matter from the surface. The temperature ranges from 80°F. to 100°F., increasing with depth.

The water is, in most cases, slightly basic with pH ranging between 6 and 8.

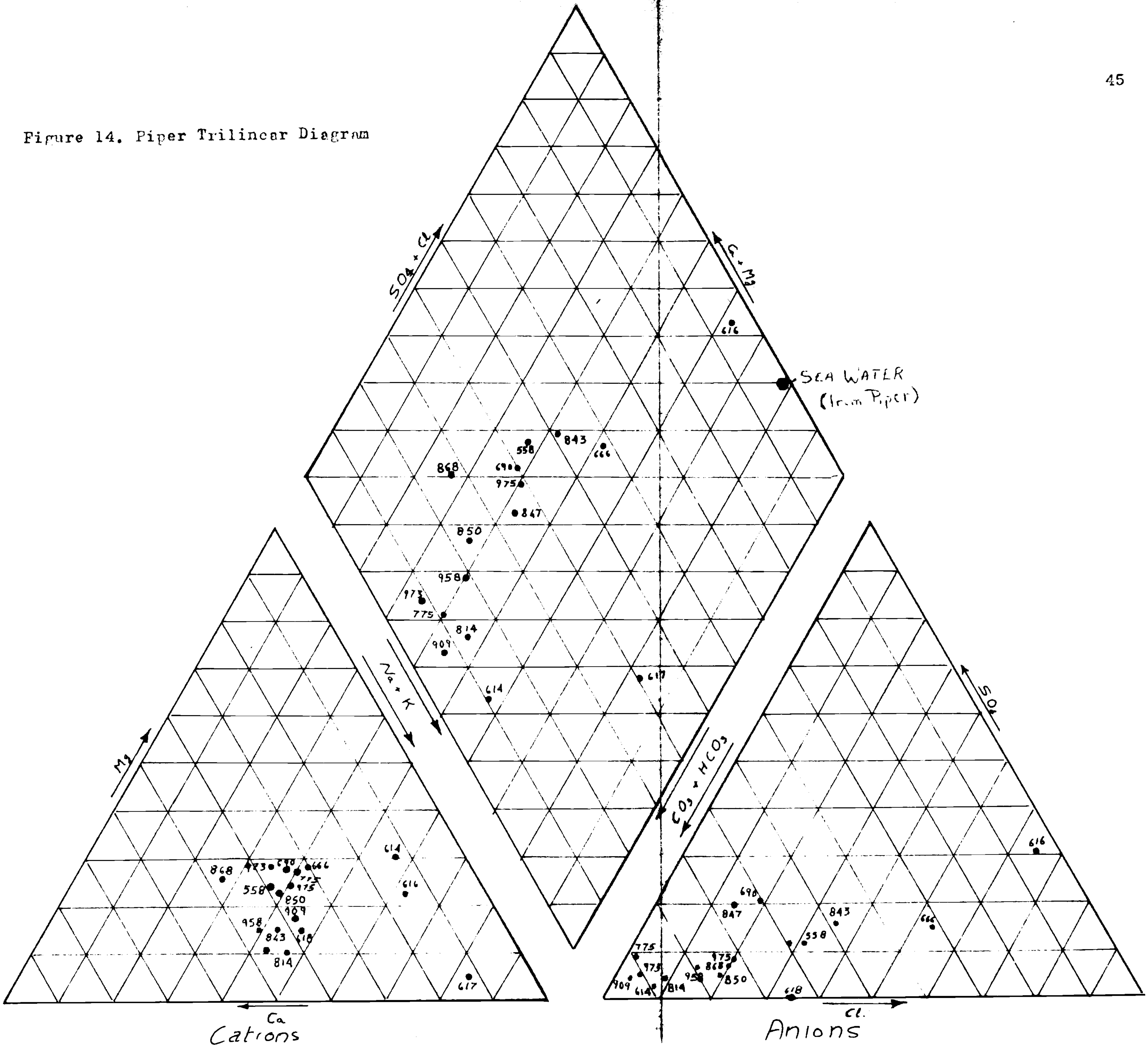
The hardness normally ranges between 100 and 300 p.p.m., being less in the north and increasing toward the south. Similarly, the total dissolved solids range between 100 and 500 p.p.m. There seems to be no ion-exchange reaction taking place between the ions in solution and those of the aquifer rocks, since the percentages of the ions in solution are more or less constant. The continuous increase of the total dissolved solids toward the south is due to the solvent action of the water on the rocks, and also because no significant recharge is taking place during most of the course of its travel. However, in the southern part, due to the increase in rainfall, the ground water is diluted through recharge, and the trend of the increase of the total dissolved solids is reversed (figure 8); the comparatively small increment in the total dissolved solids compared to the distance of travel is because of the relatively insoluble nature of the sandstone and the conglomerate rocks of the Nubian and Umm Ruwaba aquifers.

The cations present in solution are calcium, magnesium, and sodium; other cations such as potassium, iron, manganese and aluminum are present in minor amounts and are not reported in the analyses available. The ratio of the cations in solution is nearly constant.

In the Piper diagram (figure 14) the cations plot in the lower portion of the cation triangle. Nearly all of them fall within a circle whose center has the coordinates of calcium 40%, sodium-potassium 40%, and magnesium 20%. The points plot inside the circle at random showing no relation to the direction of flow or the type of aquifer. The range of the percentage of the cations within the circle is 8 ± %.

The anions present are the bicarbonates, chlorides, sulphates, and to a lesser extent, nitrates and fluorides.

Figure 14. Piper Trilinear Diagram



The bicarbonates are the most abundant, averaging about 65% to 75% of the anions in solution, and affecting the chemical quality of the water by their contribution to its hardness and alkalinity. The alkalinity is a direct measure of the bicarbonate in solution, although it is reported in terms of equivalent amount of calcium carbonate: the bicarbonate ion concentration may be obtained by multiplying the alkalinity by the appropriate conversion factors.

The anion triangle in figure 14 shows that the sulphates form a minor portion of the anions present, ranging from zero to 20% of the total anions in solution, percentages between 4% and 9% being common. On the other hand, there is a noticeable gradual increase in the bicarbonate ion percentage towards the south parallel to the direction of flow of the ground water and a decrease in the chloride ion percentage; this change is probably not through ion-exchange reaction because chloride ions have more affinity to stay in solution than bicarbonate ions, and it is very unlikely that the bicarbonate would replace chlorine ions from solution.

The cause of this change could be attributed to the effect of the marine origin of the Nubian rock, and/or due to the recharge which takes place in the Umm Ruwaba rocks in the south.

The Nubian Sandstone was thought to be of aeolian origin by many workers, but all the recent authors attribute a marine origin to the Nubian Sandstone. Hume (1934) considers the bedding, the presence of coarse conglomerates at the base of the formation in many localities, the extreme rounding of the quartz pebbles, the unbroken passage into marl containing marine faunas, as evidence of marine origin. Shukri and Said (1944) regard the non-fossiliferous sandstone as having been deposited under water in a near shore marine environment. They have shown (1944) that the mineral composition of the sandstone is mainly quartz with a small assortment of stable minerals, and show that these sandstones could not have been derived from the underlying basement complex. The Nubian series is more likely to be of marine origin in the north than in the south. On the other hand, in the southern part of the area, the Umm Ruwaba rocks which overlie the Nubian Sandstone, according to Andrew (1948), are of continental origin. Therefore, the chloride ions in the ground water could be of marine origin, either as the result of the solution of evaporites (halite) found in the sandstone, or more probably from connate water trapped in the mudstones of the Nubian series. The decrease of the chloride ion percentage toward the south is possibly due to the change from the marine deposits of the Nubian in the north to the continental deposits of the Umm Ruwaba in the south, and/or due to the dilution of the ground water by recharge, which is greater in the south and decreases toward the north.

The increase in the bicarbonate concentration percentage is most likely due to the solvent action of the water on the minor amounts of carbonate in the aquifers. The ground water in the Umm Ruwaba contains higher concentrations of bicarbonate ions than the Nubian; this might be either because the Umm Ruwaba contains more carbonates and/or due to the fact that the carbonates found in the Umm Ruwaba water have been derived from both the Nubian and Umm Ruwaba formations during its migration.

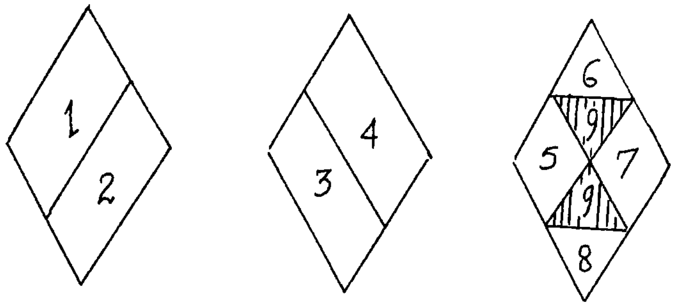
Fluoride is normally present in the Nubian and Umm Ruwaba aquifers in concentrations not exceeding 1 p.p.m. In aquifers in the surficial and weathered basement complex rocks the fluorine ion concentration also is generally not greater than 1 p.p.m. However, in Sodari and Mazroub concentrations exceeding 5 p.p.m. are reported. The fluoride in those areas is believed to be of local origin from the basement complex.

Nitrates are usually present in negligible concentrations in the Nubian and Umm Ruwaba aquifers but in the Umm Ruwaba occasional relatively high concentrations are reported (e.g. in Bore holes 666 and 843). These local anomalies may be due to contamination from the surface. Shallow wells dug in surficial deposits and weathered basement complex contain higher percentages of nitrates and the origin of the nitrates is undoubtedly from contamination from the surface, arising from the decay of organic matter.

The diamond-shaped field in figure 14 gives the water types; the subdivisions of the diamond-shaped field are given in figure 15. According to this classification the ground water body in the Nubian and Umm Ruwaba aquifers is of secondary alkalinity (carbonate hardness) exceeding 50%; i.e., the chemical properties of the water are dominated by alkaline earths and weak acids.

The ground water in Jabal El Hilla area is of a very poor chemical quality. This area includes Bore hole 490 in Jabal El Hilla and 616 in Umm Shanga (shaded area in figures 8 and 9). Total dissolved solids range between 7900 p.p.m. and 11620 p.p.m., and hardness ranges up to 3400 equivalent p.p.m. of calcium carbonate.

Although the main ground water body is primarily calcium-sodium bicarbonate water, the analyses of Bore hole 616 shows that in this well it is calcium-sodium chloride water, the chlorides forming 63.4% of the total anions in solution, and the bicarbonate ions forming only 4.7%. Bore hole 666 in Ghazala Gawazat shows similar relationship in chemical composition to 616, both of them plotting in area number 7 (in Piper diagram) in the diamond-shaped field in figure 14. Although 666 is less saline



Differentiation of water-types.

Area 1, alkaline earths exceed alkalies;

Area 2, alkalies exceed alkaline earths;

Area 3, weak acids exceed strong acids;

Area 4, strong acids exceed weak acids;

Area 5, secondary alkalinity ("carbonate hardness") exceeds 50%--that is, chemical properties of the water are dominated by alkaline earths and weak acids;

Area 6, secondary salinity ("non-carbonate hardness") exceeds 50%;

Area 7, primary salinity ("non-carbonate alkali") exceeds 50%--that is, chemical properties are dominated by alkalies and strong acids--ocean water and many brines plot in this area, near its right-hand vertex;

Area 8, primary alkalinity ("carbonate alkali") exceeds 50%--here plot the waters which are inordinately soft in proportion to their content of dissolved solids;

Area 9, no one of the cation-anion pairs in PALMER'S classification exceeds 50%.

Figure 15 - Subdivisons of the Diamond-Shaped Field of Piper Diagram.

than 616 (total dissolved solids is 900 p.p.m.), it is by far more saline than the wells around it.

Bore hole 616 and 666 plot in the diamond-shaped field in figure 14 in area number 7. According to Piper, this area in the diamond-shaped field represents primary salinity (non-carbonate alkali exceeds 50%), i.e., chemical properties are dominated by alkalies and strong acids. Ocean water and many brines plot in this area (figure 14).

Due to the paucity of the data from these two areas the origin of the saline water could not be ascertained; however, the following present some possible sources which might be responsible for the high salinity in the area.

1. Moon, P. A. (1954) suggested that there is a subsurface barrier, i.e., a fault, and that this explains the abrupt change in the chemical quality of the water in the Jabal El Hilla area, and the increase in the water table gradient. This might be true; but if the water is fixed in the fault zone, as he assumed, then how can the high chloride ion concentration be explained?

The increase of the hydraulic gradient could be explained by the following formula (which is a form of Darcy's law) rather than by Moon's hypothesis.

$$Q = T.\ I.\ L.$$

Where Q is the discharge, T is the coefficient of transmissibility, I is the hydraulic gradient, L is the width of the aquifer. Since L decreases (figure 2), and T decreases due to the decrease in thickness and to the presence of a thick section of mudstone in that area, and Q is constant, then I must increase.

2. In the diamond-shaped field in figure 14, analyses of Bore hole 616 and 666 plot in area number 7 (see figure 15). Sea water falls in this area. The chemical composition of sea water is given in table 1. It might be assumed that connate water in the mudstone of the Nubian series is being released slowly to the aquifer through leakage. In Jabal El Hilla area the wells penetrate a thick section of mudstone. Bore hole 666 in figure 14 shows that there might be mixing of water from the main ground water body and connate water from the mudstone of the Nubian. The ground water in Bore hole 616 has nearly the same percentages of elements as sea water, although calcium is more abundant than in sea water. But as in sea water the chloride is the most abundant anion followed by sulphate then bicarbonate, and sodium is the most abundant cation. Other indications in favor of this theory are:

a. Minerals containing chloride ions are very rare in the area.

b. The decrease of the chloride ion concentration toward the south, could be explained by the absence of the marine mudstone in the Umm Ruwaba series, and the dilution of chloride ions by recharge in the Umm Ruwaba.

TABLE 1

Major Constituents of Sea Water*

Ion	Parts Per Thousand
Cl^-	18.9799
SO_4^{--}	2.6486
HCO_3^-	0.1397
Br^-	0.0646
F^-	0.0013
H_3BO_3	0.0260
Na^+	10.5561
Mg^{++}	1.2720
Ca^{++}	0.4001
K^+	0.3800
Sr^{++}	0.0133

Total dissolved solids 34,481.6 p.p.m.

*Based on Rankama and Sahama GEOCHEMISTRY, 1949.

However, since the Nubian strata are now considered to be in part laid down in the sea, and the sea receded by the end of the Mesozoic age, and all the sea water in the sandstone layers has been flushed out, how could this connate water still be present in the mudstone?

Although mudstone has a low permeability, still it is permeable enough to flush this water over such a long period of time.

3. Another theory to account for the origin of chlorine ions and the source of high concentration of salts in those two areas is the possibility of the presence of evaporite deposits in the area, which might contain halite. Shukri and Said (1944) regarded the Nubian series as having been deposited under water in a near-shore marine environment. This environment may result in local deposition of evaporites, and thus the presence of a halite lens in an area may affect the quality of the ground water due to its high solubility in water. But up to the present day, no halite or any other evaporite has been reported in the Nubian Sandstone. Also, would not these evaporite rocks all have been leached out by water since under the prevailing conditions they could have been only minor deposits?

4. Layering of ground water is an established fact; the flow is laminar and little vertical mixing occurs. As a general rule, the bottom layers are older than upper layers and contain more dissolved solids due to the longer period during which they were in contact with aquifer rocks. Thus as the ground water passes through Jabal El Hilla area, the aquifer becomes very narrow and the basement Complex surface rises and the thickness of the Nubian series is

reduced. At 514 the basement complex occurs at a depth of about 280 feet. Thus as the ground water passes through this area (figure 7), the bottom layers rise to shallower depths, and in Jabal El Hilla area Bore holes 490 and 616 are deep enough (about 400 feet) to pump water from the bottom layers. But this theory does not explain why other deep wells not too far away did not find these deep layers of high salt content. In Ghazala Gawazat (Bore hole 666) the depth is 880 feet, penetrating 560 feet of water saturated sand. The high salt content in this case may be explained by assuming that the well is deep enough to receive water from the bottom layers. However, this does not explain why Bore holes 1002 and 1377 a few miles away from 666 and having similar depths, yield water of better chemical quality, and of a different composition (figures 12, 13, and 14).

CHAPTER VII

SUMMARY AND CONCLUSION

The ground water body in the sedimentary rocks of the Umm Ruwaba series and the Nubian Sandstone is, to a large extent, homogeneous and continuous, flowing from north to south. The ground water in these aquifers is of good chemical quality; the total dissolved solids range from 100 p.p.m. in the north to 500 p.p.m. in the south. The ions reported in analyses are calcium, magnesium, sodium, bicarbonate, chloride, sulphate, nitrate, and fluoride. The ratio of the cations is almost constant; the ratio of calcium to sodium to magnesium is 2:2:1. Sulphates form a minor part of the anions, not exceeding 5% of the total anions and almost constant in proportion to the other anions; the bicarbonate percentage increases toward the south while the chloride decreases. This change may be because of the marine origin of the Nubian Sandstone in the north as contrasted to the more continental origin of the Umm Ruwaba series to the south and/or because of the dilution by increased recharge in the south.

In figure 14 Bore holes 616 and 666 plot separately (in area number 7 in figure 15). These two Bore holes are characterized by higher salinites than average wells drilled in the Nubian and Umm Ruwaba, indicating that there is mixing between the main ground water body and a foreign type of water; mixing is less in Bore hole 616 than in 666. This foreign type of water may be due to one or more of the following:

1. Moon suggested a subsurface barrier.
2. Leakage of connate water from the mudstones of the Nubian.
3. By the action of water on an evaporite deposit.
4. Wells tapping deep water of higher salinity.

The basement complex forms small discontinuous aquifers of low ground water potentialities. The quality of the water differs according to the rock type, geometry, and the hydraulic characteristics of the aquifer. With the available data it is impossible to give any comprehensive picture of the water quality.

In conclusion, this is a reconnaissance of the chemical quality of the ground water in the area of study. For any further development in the area or for the improvement of the water quality, a more detailed investigation is needed.

APPENDIX A

LABORATORY CHEMICAL ANALYSES OF GROUND WATER FROM SELECTED WELLS

Bore Hole Number	490 ppm	499 ppm	500 ppm	514 ppm	536 ppm	558 ppm	614 ppm	616 ppm
Silica	20	24	6	30	20	20	10	50
Calcium	120	40	28	28	40	40	19	464
Magnesium	66	15	10	16	nil	15	25	570
Sodium	-	-	-	-	nil	45	103	2663
Bicarbonate	-	-	-	-	-	182	407	536
Chloride	1164	21	21	121	.5	60	14	4060
Sulphate	1144	2	13	99	nil	30	10	2750
Nitrate	25	0.25	nil	.32	nil	nil	2.9	5.8
Fluoride	1.9	0.44	.96	6.5	nil	.48	0.6	.28
Total dissolved solids	3872	208	235	452	150	330	430	11620
Hardness as $CaCO_3$	40	12	8	90	100	160	150	3300
pH (Lab.)	6.8	6.8	7.6	7.3	6.8	7.4	8.2	8.1

APPENDIX A (Continued)

Bore Hole Number	617 ppm	618 ppm	666 ppm	775 ppm	814 ppm	843 ppm	847 ppm	850 ppm
Silica	20	20	80	40	25	40	30	10
Calcium	18	17	86	33	42	73	54	39
Magnesium	4	4	49	17	6	14	8	14
Sodium	135	24	139	49	53	89	57	66
Bicarbonate	257	84	280	290	256	256	231	232
Chloride	24	26	216	4	16	72	26	32
Sulphate	40	nil	100	20	10	53	58	10
Nitrate	19	.6	23	.5	.7	17.4	1.2	1.5
Fluoride	.4	.6	.8	.5	.2	0.4	.3	.6
Total dissolved solids	450	120	900	260	260	600	400	260
Hardness as $CaCO_3$	60	60	416	150	130	240	166	156
pH (Lab.)	7.5	7.0	7.2	8.3	8.4	7.8	7.9	8.3

APPENDIX A (Continued)

Bore Hole Number	868 ppm	909 ppm	958 ppm	975 ppm	977 ppm	998 ppm	1002 ppm
Silica	15	8	10	15	10	5	10
Calcium	27	28	40	18	13	33	78
Magnesium	9	8	8	8	5	12	21
Sodium	10	38	41	23	25	29	146
Bicarbonate	122	207	219	109	85	150	207
Chloride	16	2	22	18	14	26	180
Sulphate	10	10	10	10	14	24	125
Nitrate	2.6	.9	.5	.8	1.0	1	12
Fluoride	.5	.2	.9	.6	.6	.7	.5
Total dissolved solids	180	200	240	120	90	220	600
Hardness as $CaCO_3$	104	104	134	80	52	130	284
pH (Lab.)	7.2	7.8	8.2	8.1	8.1	8.0	7.9

APPENDIX A (Continued)

Bore Hole Number	1008 ppm	1038 ppm	1084 ppm	1169 ppm	1176 ppm	1377 ppm	1425 ppm	1428 ppm
Silica	10	8	10	44	60	10	6	22
Calcium	21	45	24	59	69	34	61	65
Magnesium	12	17	26	13	7	10	10	14
Sodium	11	29	66	75	81	47	33	75
Bicarbonate	110	232	171	293	378	267	244	390
Chloride	8	22	92	28	20	10	4	30
Sulphate	19	19	29	72	38	14	10	19
Nitrate	1.3	1	3	3	nil	.5	.7	.7
Fluoride	.3	.7	1	.3	.4	.4	.7	.4
Total dissolved solids	100	240	340	360	290	280	250	460
Hardness as $CaCO_3$	100	180	168	20	202	128	144	218
pH (Lab.)	8.3	8.3	8.0	8.0	8.3	8.0	8.3	8.3

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