Regional Geology and Ground-Water Hydrology of the Sāḫil Sūsah Area Tunisia

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-G

Prepared in cooperation with the Sous-Direction de l'Hydraulique et de l'Équipement Rural, Tunisian Secretariat of State for Agriculture, under the auspices of the United States Agency for International Development

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By L. C. DUTCHER *and* H. E. THOMAS

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

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[Plates are in pocket]

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REGIONAL GEOLOGY AND GROUND-WATER HYDROLOGY OF THE SĀḤIL SŪSAH AREA, TUNISIA

By L. C. Dutcher and H. E. Thomas

ABSTRACT

This report discusses the regional geologic and hydrologic features of the Sāḥil Sūsah (coastal area) and the large bordering area in central Tunisia west of Sūsah. It considers the ground-water geology of the region and the general occurrence and movement of ground water within this area of more than 24,000 square kilometers. The purpose of the report is to provide an answer to the question of where water can be obtained for the people of central Tunisia, of whom about 80 percent inhabits the coastal area and the bordering Low Steppes.

The mountains of the Tell, with crests 1,000 to 1,500 meters above sea level in the Sāḥil drainage basin, receive an average precipitation two to four times as great as that upon the Sāḥil. What happens to that precipitation depends upon the characteristics of the soil and rock materials of the mountains, where more than 3,000 m of sedimentary rocks and alluvial deposits, ranging in age from Triassic to Recent, are exposed. Some of the rock materials are sand and sandstone permeable enough to absorb part of the rainfall and permit it to flow through them; some are limestone, which may also be permeable and capable of becoming more permeable as the water dissolves the soluble rock. The great bulk of the mountain mass, however, is made up of clay and silt and the rocks formed by the compaction of these fine-grained materials; such materials do not absorb water readily—they are relatively impermeable—and rainwater runs off overland in streams that erode and quickly become laden with mud.

During the latest period of mountain making, sediments accumulating in the lowlands and the bordering Mediterranean typically ranged from very fine sand to clay, reflecting the fine texture of the rock masses from which they came. The prevailingly fine texture and relative impermeability of most of the rocks in the mountains are fundamental characteristics of the sediments on the steppes and Sāḥil lowlands. Ever since the mountains attained their present altitude, streams have carried vast quantities of sediment to the lowlands, and in several areas there has been progressive subsidence as the sediment accumulated. Man has accelerated the process in many places by laying the soil bare, by deforestation, cultivation, grazing, burning, construction, and other activities.

The mountains were formed by folding of flat-lying marine sediments, together with faulting into major blocks, which were lifted, dropped, or thrust, the result being that the present geologic pattern resembles a complicated jigsaw puzzle. The area now is divided by these structures into three large ground-water basins

and by local faults and folds which divide the large basins into numerous smaller ground-water subunits. The marine sediments now found in the mountain ranges were once continuous with marine sediments that underlie the Sāḩil and steppes, but in the lowlands marine sediments are generally buried under riverborne sediments and are now far below sea level.

The regional geology necessarily sets the framework for the regional hydrology, which is concerned with the occurrence and movement of water within the drainage basin tributary to the Sāḩil. The permeable layers of limestone, sandstone, and fine sand have become the underground waterbearers (aquifers). Water movement is by gravity and therefore downgradient and generally from the mountains (where precipitation is greatest) toward the Sāḩil. The movement of water underground is interrupted where the rocks have been folded or faulted. Where rainwater is unable to filter into the ground or where ground water reappears at the land surface, the water continues downslope as surface water. In the arid lowlands, however, evaporation rates are so high that the flow of surface water from the Sāḩil to the sea is negligible. When water evaporates, any salts dissolved in it are left as residues; therefore a byproduct of evaporation over the years has been saline ponds, salt-incrusted depressions, and saline soils in many parts of the Sāḩil and Low Steppes.

The faults and folds that interrupt the continuity of movement of water serve as excellent boundaries for numerous separate and distinct subbasins of various sizes and shapes. Two such zones are especially significant: (1) the north-trending Bū Dīnār–Shurayshīrah–Sawāţīr zone of faulting and folding, which constitutes an underground separation between the Tell and High Steppes (on the west) and the Low Steppe and Sāḩil, and (2) the northeast-trending Shurbān–Az Zarāmidīn fault zone, which subdivides the Low Steppes and Sāḩil into Al Qayrawān–Sāḩil basin (on the north) and Al Jamm–Al Mahdīyah basin.

Although most of the rock materials underlying the drainage basin tributary to the Sāḩil are relatively impermeable, it is possible to find ground water, shallow or deep, beneath any point in the region; much of that water, however, is saline and unsuitable for use. The marine sediments contained sea water originally, and those that have remained below sea level still do; the salt water has been flushed out only where the sediments have been elevated to permit fresh water to circulate through them. Under present conditions of aridity, salts are left on the land surface as water evaporates, and the proportion of salts increases with increasing aridity toward the Sāḩil. Similar aridity prevailed during much of the time that riverborne sediments accumulated in the lowlands, as indicated by soluble salts on the soil and in the ground water. Thus the deeper ground water is saline throughout the Sāḩil and Low Steppes, and shallow ground water is also saline at many places, particularly near the coast.

INTRODUCTION

This is the third of four reports prepared in Tunisia during a project of technical assistance in hydrologic mapping and training extending from January 1960 to June 1963, and it is the second of three reports on the Sāḩil Sūsah area. All four reports are prepared under a project agreement between the Governments of Tunisia and the United States of America which provided for three objectives: (1) to review existing data in the office of the Subdivision Spéciale des Sondages (SSS) of the Sous-Direction de l'Hydraulique et de l'Équipement Rural (HER), (2) to study the geology and the occurrence of ground water in Tunisia and to provide instruction in hydrologic techniques to Tunisian technicians, and (3) to explore and develop ground water. It was planned that the second and third objectives were to be pursued chiefly in the coastal plain area (Sāḥil) of central Tunisia, south of Sūsah.

Lassaâd Ben Osman, Chief Engineer, Sous-Direction of the HER, under Tunisia's Secretariat of Agriculture, originally designated for hydrologic mapping an area covered by six 1:50,000 topographic maps (Dutcher and Mahjoub, 1963a): No. 64 (Sidi el Hani), No. 65 (Djemmal), No. 66 (Moknine), No. 72 (Oued Cherita), No. 73 (Karkar), and No. 74 (Mahdia). These maps cover an area 16 kilometers wide extending from the Mediterranean coast westward about 33 km nearly to the longitude of the city of Al Qayrawān. It was proposed that the hydrology of each 1:50,000 map be depicted on six sheets: a geological map, a hydrological map, a geochemical map, geological sections, hydrological sections, and geochemical sections, according to standards already in use by the Société Centrale pour l'Equipement du Territoire (SCET) and the Société Générale des Techniques Hydrauliques et Agricoles (SOGETHA) in hydrologic mapping of other areas in Tunisia. Ben Osman listed several localities within this assigned area where there are special problems of water supply: (1) the Ṭabulbah area, on first priority, (2) Az Zarāmidīn dome area near Banī Hassān, as a possible source of increased supplies, (3) the south flank of Az Zarāmidīn dome, as a source of water for Bū Mirdās and Sīdī Bū Qubrīn, (4) alluvium of the Wādī Glat, as a source of water for Quṣūr as Sāf, and (5) the 'Uqlat ar Ramādah (Karkar dome), as a source of water for Al Jamm.

The study of the Ṭabulbah area was completed in 1962, and the report (Dutcher and Thomas, 1966b) constitutes the first of four on central Tunisia. Another report evaluates precipitation, evaporation, runoff, and the general surface-water features of the Sāḥil Sūsah area (Dutcher and Thomas, 1966a). Ground water in Az Zarāmidīn dome area, including the south flank near Bū Mirdās, in the Wādī Glat, and in the 'Uqlat ar Ramādah is discussed in another report (Dutcher and Thomas, unpublished data, 1968).

All information indicates that the area covered by the six quadrangles—and indeed the entire Sāḥil Sūsah—is not well endowed with water resources and that the resources may be inadequate for the needs of the existing population. Already the larger cities in the Sāḥil receive water by pipeline from the Wādī Marq al Layl drainage basin west of Al Qayrawān, and additional supplies will come eventually by another pipeline from the Wādī Nabhānah area. A detailed, meticulous investigation of the Sāḥil, involving extensive exploratory drilling and geophysical prospecting for aquifers, may locate some fresh-water reservoirs not now known. It will also delineate the large areas where sedimentary rocks are impermeable or where ground water is of inferior quality, but in these areas it will leave unanswered the question of the residents: "Where, then, can we get water?"

The field studies indicate thousands of dug wells within the area first assigned for study. These are the principal source of water for rural domestic and stock uses; the smaller villages and several of the larger communities obtain all their water from dug wells, of which several have been equipped with motor-driven pumps. Many dug wells are used for irrigation of small gardens, generally by scupper hole and camel power, although there are several pumped irrigation wells also. These dug wells generally penetrate only 2 or 3 m into the shallowest water-bearing zone. They provide data on the depth, form, continuity, and irregularities of the water table and on the quality of the superficial water, and from these data the directions of movement of ground water may be inferred. In extensive areas where no wells are found, it is possible that no attempts have been made to construct wells; but in a country where wells have been commonplace for many centuries, it is more likely that there are no aquifers within depths that can be dug by hand, or that the water within reach is not usable.

The dug wells provide no information as to the thickness of the uppermost saturated zone and no data as to the quantity and quality of water that may occur in aquifers at greater depth. Thus they are of little value in evaluation of the total ground-water resources and their potential for development and utilization.

As of December 1961, 45 holes had been drilled within the six quadrangles to depths ranging from 41 to 831 m, the average depth being 237 m. Screens were placed in 20 of these holes in efforts to develop production wells, but 8 yielded water of inferior quality (dissolved solids ranging from 2,700 to 10,000 parts per million), and 11 others were subsequently abandoned because of difficulties with very fine sand. The nine drilled wells that are currently in operation are all producing water from the sand of the Oum Douil Formation of Vindobonian age in Az Zarāmidīn dome; when all are pumped they yield a total supply of about 90 lps (liters per second), of which about 70 lps goes into the pipeline that supplies the towns of Jammāl, Al Muknīn, and Al Mahdīyah. Further exploratory drilling is needed to establish the extent and limits of the fresh-water zone in the Oum Douil Formation, to explore the Quaternary alluvium (which is known to contain fresh water at Ṭabulbah), and to search for other aquifers. Greater proficiency is needed in the difficult job of developing production wells in the prevailing fine sand. These needs have long been recognized, and as a part of the project of technical assistance, a Failing-1500 rotary drilling rig was purchased specifically for test drilling and for training. Two years was too short a time to progress either in exploratory drilling or in development of production wells.

PURPOSE AND SCOPE

The purpose of this report is to provide an answer to the question of where water can be obtained for the Sāḩil Sūsah and the Low and High Steppes in central Tunisia, largely on the basis of data which were collected before 1960 and supplemented by the records which have slowly accumulated between that date and June 1963 from the continuing test-drilling programs. A following report (Dutcher and Thomas, unpublished data, 1968), discusses how much water can be obtained for use in the Sāḩil Sūsah area.

Because there is a lack of data on the deeper aquifers and deposits, geohydrologic maps and sections cannot be completed for the area originally assigned by the HER. Also, there is only a limited potential for ground-water development within that area, and thus the maps would serve little purpose. In addition, plans are being made for the construction of costly water reservoirs and distribution systems in several places adjoining the area of the six maps, and this work is without the benefit of a survey of the water potential of the region and of the distribution of water in time and place. Thus, with the encouragement of the HER, the geohydrologic studies were broadened from the plan covering the six topographic maps to a reconnaissance and appraisal of the entire watershed tributary to the Sāḩil Sūsah. This appraisal included studies of precipitation, evaporation, runoff, and surface water (Dutcher and Thomas, 1966a); regional geologic and hydrologic features of the area (this report); and the perennial and nonrenewable ground-water resources of the area (Dutcher and Thomas, unpub. data, 1968).

ACKNOWLEDGMENTS AND SOURCES

This report is based on work by Mission Thomas, a subsection of the Sous-Direction of the HER, Secretariat of Agriculture, Tunisia. Mission Thomas was established as a training project to introduce new geohydrologic-mapping techniques in Tunisia, within the scope of the Technical Assistance Program of the U.S. Agency for International Development (US AID).

The work was under the direction of Lassaâd Ben Osman, Chief Engineer, Sous-Direction of the HER. The first phase was under the supervision of H. E. Thomas, geologist in charge of Mission Thomas, and the later phases were under the supervision of L. C. Dutcher. Messrs. Thomas and Dutcher, of the U.S. Geological Survey, Water Resources Division, worked under the direction of G. C. Taylor, Jr., Chief, Foreign Hydrology Section, in a participating-agency agreement with US AID.

The writers acknowledge the field help and assistance of the Mission Thomas staff, which included Mohammed Lahmar, Thamri Youssef, Abdelaziz el Ghali, Abderrazak el Ghali, El Aloui Tahar, Roland Guez, and others. The drafting work was done mainly by Ben Abdallah Hamadi. Also acknowledged is the work of the men and drilling crews of the SSS under the direction of Ahmed Khouadja, Principal Engineer, Chief of Service, without whose assistance the test wells could not have been drilled.

Particular acknowledgment is given for the help and cooperation of Habib Zebidi, Engineer in Charge of the Bureau de l'Inventaire des Ressources Hydrauliques (BIRH); the engineers and personnel of his staff, who provided data and administrative support during the investigation; and Ahmed Azzouz, Principal Engineer, Service of Mines, who provided data on the shallow deposits penetrated by oil-test wells. Acknowledgment is also given for the technical and administrative support of the staff of the US AID Mission to Tunisia under the direction of D. C. Lavergne.

The geohydrologic data available at the beginning of the investigation included the catalogs of dug and drilled wells maintained by the BIRH, SSS, and other agencies. Additional information was collected during the fieldwork, including principally data for production wells and for new test wells drilled in the Sāḩil.

Hydrologic data have been assembled in two separate reports (Dutcher and Mahjoub, 1963a, b). Tables in these reports include water levels in wells, drillers' logs of wells, data for sondages (test wells), data for forages (production wells) such as a record of their status at the time of the field visit and their specific yield, and chemical analyses of water samples from the producing wells and streams. Also given are tables of precipitation at selected stations and data for hand-dug wells equipped with motor-driven pumps. Maps and illustrations in the data reports show the locations of sondages and forages, dug wells with pumps, water-sampling points on streams, and index maps showing the areas of geologic and geohydrologic mapping and areas of the BIRH catalogs of well data. The SSS maintains an individual file for each sondage and forage drilled in the area and these files, together with the two data reports, supplement this report.

Many unpublished and a few published reports contain geohydrologic data and are available for inspection at the BIRH and the Service Météorologique; many reports on small areas include texts written by engineers and geologists who investigated parts of the basins previously. Much of the geologic information for the maps and sections was supplied by oil companies.

LOCATION AND EXTENT OF AREA

The Sāḥil area of central Tunisia is the area bordering the Mediterranean Sea along the bulge between the Khalīj al Ḥammāmāt and the Khalīj Qābis. It extends from An Nafīḍah (100 km south of Tunis) southward to Al Maḥras. The part of the Sāḥil north of Ra's Kabūdīyah is designated the Sāḥil Sūsah, and that to the south, the Sāḥil Ṣafāqis (fig. 1).

The Sāḥil Sūsah merges westward into the steppes that border the south flank of the Grande Dorsale, or Tell, of the Atlas Range. The wadis (streams) draining this south flank flow southeastward and eastward toward the Sāḥil. Most of the wadis tributary to the Sāḥil Sūsah flow only seasonally, but some have a small perennial flow. The Sāḥil Ṣafāqis to the south is similar to the Sāḥil Sūsah, but its bordering steppes are desert and not contiguous to the mountains. The wadis there are dry except during rare intense rainstorms.

The area considered in this report, virtually the area tributary to the Sāḥil Sūsah, is a rudely rectangular area of about 24,000 km^2 (9,300 square miles) whose northern boundary extends along the crest of the Dorsale from the Algerian frontier east-northeastward about 200 km to the Mediterranean and whose eastern border is about 125 km of the Mediterranean coast between An Nafīḍah and Ra's Kabūdīyah. The southern and western boundaries of the area are formed by the ridges and hills that constitute the divide between wadis flowing, respectively, toward the Sāḥil Sūsah and toward the Sāḥil Ṣafāqis or the closed basins of southern Tunisia.

PHYSICAL GEOGRAPHY

The Sāḥil Sūsah is the coastal plain that extends westward from the Mediterranean between An Nafīḍah and Ra's Kabūdīyah (Dutcher and Thomas, 1966a, pl. 1). Most of this plain is less than 100 m above sea level; it is broken by isolated hills, having altitudes generally less than 200 m, and extends inland for distances up to 40 km. The coastal plain merges inland with the Low Steppes and is not clearly distinguishable from it; indeed the Sāḥil is frequently considered as the lower part of the Low Steppes. A characteristic feature of the area is the sabkhas (depressions occupied by ephemeral saline lakes), of which some near the coast are below sea level and others, as much as 60 km inland, are at altitudes exceeding 60 m.

The Low Steppes include alluvial plains that rise to 200 m or more above sea level and encompass hills and mountains which ap-

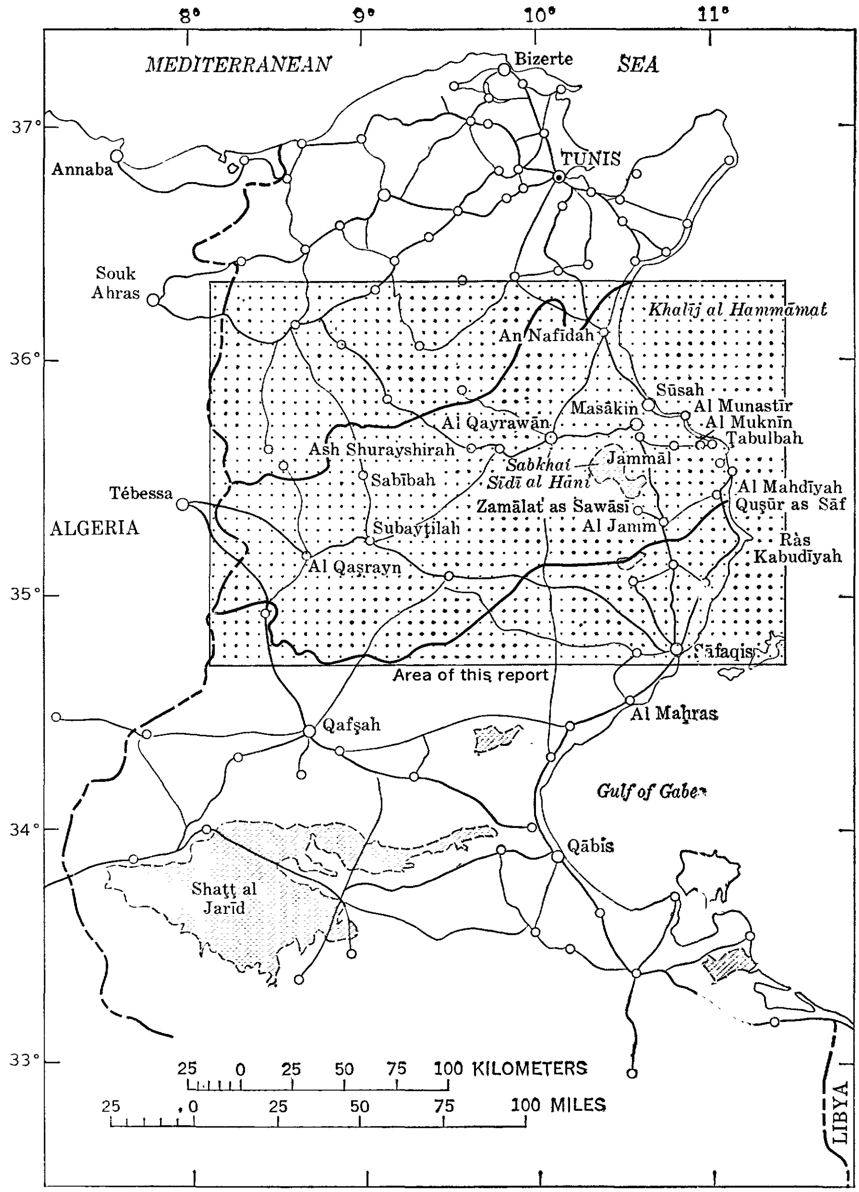


FIGURE 1.—Tunisia, including roads and area studied.

proach altitudes of 1,000 m. The Low Steppes also contain some small sabkhas at altitudes as great as 200 m. The High Steppes include the higher alluvial plains, some of which attain altitudes as great as 900 m. Northwest of the steppes are the mountains of the Dorsale, or Tell, which attain altitudes exceeding 1,500 m, the highest in Tunisia.

There is practically no runoff from the Sāḩil Sūsah to the Mediterranean. If the Sāḩil and its hinterland were in a humid region, they would have an integrated drainage system, with some of the northernmost wadis flowing directly into the sea but with most of the Dorsale and the steppe land being drained by a river that might be named the Zurūd in honor of the longest (225 km) wadi (drainage basin of about 10,000 km^2; Dutcher and Thomas, 1966a, pl. 1). However, the Wādī Zurūd channel continues only to the plains south and east of Al Qayrawān; the Wādī Marq al Layl and Wādī Nabhānah similarly drain part of the Dorsale and then flow out on these plains. From these flatlands there is discharge into Sabkhat al Kalbīyah, which thus has a tributary drainage basin exceeding 15,000 km^2 (Dutcher and Thomas, 1966a, pl. 1). Occasionally the Sabkhat al Kalbīyah fills sufficiently to overflow to the Mediterranean. Also, the Zurūd during major floods contributes to the Sabkhat Sīdī al Hāni', and that sabkha at high stages overflows into the Sabkhat al Kalbīyah. Along the coast, the sabkhas near Al Muknīr and Al Munastīr receive the floodwaters from storms in the Sāḩil. The surface-water features and climate of the Sāḩil Sūsah area are discussed in a separate report (Dutcher and Thomas, 1966a).

ECONOMIC GEOGRAPHY

The Sāḩil Sūsah includes most of the Gouvernorat de Sousse, which in 1956 had a population of 447,000. With an average of 70 persons per km^2, this gouvernorat is one of the most densely populated in Tunisia, especially near the coast where the population exceeds 200 per km^2. The Gouvernorat de Kairouan, population 205,000 in 1956, occupies most of the Low Steppes; parts of the Gouvernorat de Kasserine (pop. 164,000) and a small part of the Gouvernorat du Kef occupy the High Steppes and mountains.

The economy of the Sāḩil is one of sedentary agriculture, including especially olives but also citrus fruits, vegetables, and grains. To the west the agricultural economy becomes increasingly one of pasturage and stockraising, with a more nomadic population. The great majority of the people, both in the Sāḩil and in the interior, are on a meager subsistence economy, and in some years the crops are insufficient to provide even bare subsistence.

REGIONAL GEOLOGY

GENERAL GEOHYDROLOGIC RELATIONS

Ground water occurs beneath the land surface wherever all the pores are saturated, these pores including the spaces around boulders, pebbles, sand grains, and clay particles, as well as the cracks, fissures, and caverns in consolidated rocks. Porosity is prerequisite to the occurrence of ground water, and many rocks are not aquifers because of their low porosity. In order to yield water, the rock material must also be permeable. Permeability is a characteristic that permits water to move through rock and enter a well by gravity flow. Clays and other fine-textured rocks are not aquifers, even though porous and saturated, because of their low permeability. Permeability is a factor also in the infiltration of water into the soil, the downward percolation from the soil to ground-water reservoirs, and the seepage of ground water to or from streams or lakes. An understanding of ground water and of its relation to soil moisture and to surface water requires study of the rocks through which water can move, as well as of rocks which impede movement. The following sections outline the stratigraphy, structure, and geologic history of the region, based largely upon Burollet's (1956) stratigraphic study of central Tunisia.

STRATIGRAPHY

Almost all the rocks that crop out in Tunisia, as well as those subsurface rocks penetrated by wells, are of sedimentary origin. The rocks within the Sāḩil and its tributary basin portray a stratigraphic record from the Triassic Period to the present. The geologic map series for Tunisia, which provide coverage of most of the country at a scale of 1:200,000 and more detailed coverage of many areas at 1:50,000, show the areas of outcrop classified according to chronostratigraphic units (system, series, stage)—that is, units characterized by a thickness of sediments deposited during a unit of time, or chronogeologic unit (period, epoch, age). The classification is based primarily on paleontologic evidence, using units defined originally in Europe. Correlations with Tunisian sedimentary strata are difficult and dubious at some places, particularly for strata that are not fossiliferous. Nevertheless diagnostic fossils provide the best means for precise dating of the events of geologic history.

So far as ground-water hydrology is concerned, however, the chronostratigraphic units based on paleontologic evidence are not adequate, because they may include highly permeable rocks in one locality, and contemporaneous but less permeable or impermeable rocks in another locality. For ground-water hydrology lithostratigraphic units (group, formation, member) are preferred because these units are based primarily on lithology, although these also are commonly defined without reference to permeability. Burollet (1956) has facilitated the understanding of the ground-water geology by summarizing the lithostratigraphic units which appear in central Tunisia and by showing their correlation with the chronostratigraphic units that have been used in geologic mapping. The accompanying diagram (fig. 2) is based largely upon his correlation chart (Burollet, 1956, pl. 1) and discussions of the formations.

More than 40 map units are shown on the existing geologic maps, and each represents a division of geologic time. Plate 1 is a geologic map compiled from existing maps, field reconnaissance, and data from geophysical explorations.

On plate 1 the geologic units and their symbols have been grouped into nine major units, as follows: Quaternary deposits (Qu); formations and deposits principally of Miocene and Pliocene age but also including deposits of Oligocene age (QTpmo); formations of Eocene and Paleocene age (Tep); Abiod Formation (Kab); Aleg Formation (Kal); locally permeable formations of Late and Early Cretaceous age including the Zebbag Formation, Fahdène Shale, Serdj Limestone, Gafsa Formation, and Boudinar Sand (Ksl); Meloussi Formation and Sidi Kralif Shale (KJmsk); Jurassic rocks (J); and Triassic rocks (R̶) (fig. 2, pl. 1).

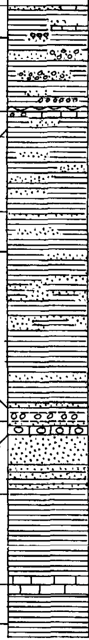
The structure of the ground-water basins and the stratigraphic relationships of the rocks are shown on the generalized geologic sections (pl. 1). Where the vertical scale made it possible, the major units were divided into formations in order to show details of the aquifers and aquicludes. Thus, in places the deposits of Oligocene, Miocene, and Pliocene age (QTpmo) are shown on the sections as the Sēgui, Oum Douil, Aīn Grab, and Hakima Formations and the Fortuna Sandstone; the rocks of Eocene and Paleocene age (Tep) are shown as the Souar Shale (Souar or Djebs on the sections), Metlaoui Formation, and 'El Haria Shale ('El Haria on sections); and the rocks of Early and Late Cretaceous age (Ksl) are shown as the Fahdène Shale, Zebbag Formation, Serdj Limestone, Gafsa Formation, and Boudinar Sand.

The geologic sections were compiled from existing geologic maps, field reconnaissance, data from water and oil test wells, and geophysical exploration. In many areas the structure, depth, and thickness of formations and the sequence, as shown on the sections, are conjectural; in places the sections will require revision as additional data accumulate from wells and detailed mapping. However, they indicate the most favorable areas where exploratory water wells should be drilled and the probable depth to the formations which contain aquifers.

TRIASSIC ROCKS

Outcrops of rocks of Triassic age are very sparse in the Sāḥil and its tributary basin. Among the most noteworthy is the diapir (piercement fold of rocks) of Jabal Ghawīṣ southeast of Sīdī Bū Zayd, where Burollet (1956, p. 27–29) measured sections totaling more than 1,600 m, which he called the Rheouis beds, largely gypsiferous and correlated

Era	System and Series		Stage	Formation	Thickness, in meters	Aquifer
CENOZOIC	QUATERNARY	Recent	Acheulian	Lime hardpan, dune sand, alluvium, mud, and evaporite	Maximum of 30	Superficial sheets of alluvium and dune sand
		Pleistocene		Older alluvial deposits in shallow basins	Maximum of 30	Lenses of sand and gravel
			Villafranchian	Sĕgui Formation	400–1000	Sandstone and fine sand
	TERTIARY	Pliocene	Astian Plaisancian			
		Miocene (NEOGENE)	Pontian			
			Vindobonian	Oum Douil Formation	400–1100	
			Burdigalian	Aïn Grab Formation	20–50	
		NUMMULITIC	Aquitanian	Hakima Formation	50	
		Oligocene	Numidian Medjanian	Fortuna Sandstone	550–860	
		Eocene	Priabonian Upper Lutetian Londinian	Souar Shale Djebs Formation	400–500	
		Paleocene	Thanetian Montian	Metlaoui Formation	50–100	
				'El Haria Shale	100–300	



Era	System	Series	Stage	Formation	Thickness	Hydrologic unit
MESOZOIC	CRETACEOUS	Upper Cretaceous	Maestrichtian	Abiod Formation	100-540	Limestone
			Campanian			
			Santonian Lower Senonian Coniacian	Aleg Formation	400-1000	
			Turonian	Fahdéne Shale	300-800	Sandstone and limestone
			Cenomanian	Zebbag Formation	200-800	
		Lower Cretaceous	Albian	Serdj Limestone	170-220	
			Aptian	Gafsa Formation	80-1000	
			Barremian	Boudinar Sand	0-600	
			Hauterivian	Meloussi Formation	340-1000	
			Valanginian Berriasian Neocomian	Sidi Kralif Shale	480-1080	
	JURASSIC		Portlandian			
			Kimmeridgian Sequanian Argovian Callovian Bathonian Lias	Nara Limestone	170-560	Limestone, locally permeable
	TRIASSIC		Keuper	Rheouis beds	1600+	
			Muschelkalk			

FIGURE 2.—Correlation of chronologic, stratigraphic, and hydrologic units in central Tunisia.

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with the Muschelkalk and Keuper stages of the Triassic System. A similar diapir is along the northward prolongation of the Jabal Maghīlah in the Wādī al Ḫaṭab (Oued Hathob) basin at Jabal al Halfā' (Castany, 1951a) and a smaller one occurs northwest of Sīdī Bū Zayd. Within the Tell the Triassic rocks crop out in several places, especially in the basins of the Wādī al Ḫaṭab (Oued Hatab) and Wādī Marq al Layl, where they may underlie Jurassic rocks in normal sequence and were brought to the surface by faulting or intense folding.

Generally in the Sāḫil and its tributary basin the Triassic rocks are deeply buried, far below the depths reached by water wells. This is fortunate, for any water in Triassic sedimentary strata is probably of poor quality because of the abundance of gypsum (calcium sulfate) and other soluble salts. The principal hydrologic significance of the Triassic rocks is that they may contribute mineralized water locally to younger formations, with resultant deterioration of water quality.

JURASSIC ROCKS

Jurassic rocks appear on plate 1 only in the chain of Jabal Sīdī Khalīf and Jabal Manārah (Nara) (extending northward from Jabal Ghawīṣ) and near the northernmost point of the mapped area, near Jabal Zaghwān. In the Jabal Manārah the Jurassic rocks are chiefly massive limestone—the Nara Limestone; they are partly dolomitic and include shaly limestone and some shale near the middle of the section, of which the total exposed thickness exceeds 170 m.

Although the Nara Limestone is permeable enough to constitute a good aquifer, it is not known to be exploited by any wells within the Sāḫil Sūsah or its tributary basin. Far to the south, however, between Taṭāwīn and Adh Dhahībāt (not shown on pl. 1), some wells and springs yield water from limestones identified as Kimmeridgian (Late Jurassic) in age. In the Sāḫil the Nara Limestone may be a potential source of water, but probably is excessively deep in most places.

CRETACEOUS ROCKS

The Cretaceous strata include dominantly shaly sedimentary rocks (Sidi Kralif Shale) at the base, alternating sandstone and dolomitic limestone (Meloussi Formation), a thick series dominantly of limestone and sandstone and some shale (Boudinar Sand, Gafsa Formation, Serdj Limestone, and Zebbag Formation), the Fahdéne Shale and another formation (Aleg) that is chiefly shaly, and the calcareous Abiod Formation.

The Sidi Kralif Shale consists chiefly of dark gray to black shales and in its lower part contains some beds of Jurassic age that lie conformably upon the Nara Limestone. The formation includes some calcareous and sandy beds and becomes increasingly sandy in south

Tunisia, but throughout central Tunisia it is dominantly shale and thus relatively impermeable. It probably serves as an aquiclude between formations below and above.

The Meloussi Formation includes fine sand and sandstone alternating with dolomite or dolomitic limestone and shale. It is correlated with the Hauterivian stage of the Lower Cretaceous on the basis of scant fossil evidence. South of the latitude of Subayṭilah the thickness of the Meloussi in several sections ranges from 350 to 500 m, and in the Jabal Maghīlah it exceeds 1,000 m. Farther north, in the Tell, the sedimentary strata of equivalent age appear to be more argillaceous and probably include beds of Barremian age.

The Boudinar Sand constitutes a massive unit formed entirely of medium and coarse sand, irregularly stratified and crossbedded in many places. It attains a thickness of 600 m in Jabal Sīdī'Aysh, thins markedly to the east and north, and is not found north of the latitude of Sabībah.

The Gafsa Formation is composed of a thick series of continental or deltaic deposits commonly including alternating sandstone, limestone, shale, and sporadically gypsum at its base; a fine sand member; and an upper member of limestone and dolomite. Lateral variations in thickness and lithology, and an erosional discordance at the top, are characteristic of the formation, which is thickest in the vicinity of Qafṣah south of the mapped area and thins to the east and northeast. Within the basin tributary to the Sāḩil Sūsah, the Gafsa Formation locally comprises more than 500 m of sand, dolomite, and shale.

The Serdj Limestone is massive limestone and dolomite which constitute the marine and reef equivalents of the Gafsa Formation. Within the drainage basin of the Sāḩil Sūsah, these occur chiefly north and northwest of a line from Al Qayrawān to Sīdī Bū Zayd and attain their maximum thickness in the Jabal as Sarj near Makthar.

Generally the Gafsa Formation and the Serdj Limestone constitute the permeable strata of the Albian and Aptian stages of the Lower Cretaceous. The aggregate area of outcrop within the drainage basin tributary to the Sāḩil is small and offers little opportunity for direct replenishment of ground water; however, these outcrops are in the mountain ranges where precipitation is greater than in the nearby lowlands, and some recharge may also be contributed by wadis crossing the outcrops.

The Zebbag Formation, in the Jabal Meloussi along the south boundary of the area mapped on plate 1, includes chiefly dolomite and limestone at the base, a middle member of gypsum with dolomite and shale, and an upper member of dolomitic limestone. To the south and southwest the formation includes an increasing proportion of evaporites, but most of the drainage basin tributary to the Sāḩil

Sūsah is a broad transition zone between the typical limestone of the Zebbag Formation and the argillaceous equivalents (of Cenomanian and Turonian age) which are found in the Tell. The limestones of the Zebbag are productive aquifers in south Tunisia, and they are tapped by artesian wells in the vicinities of Qabis, Qibilī, and the Nafzāwah (south of the mapped area). Where the limestones are dominant in the broad transition zone, they may constitute part of a single aquifer that includes also the underlying permeable parts of the Gafsa Formation and the Serdj Limestone.

The Fahdène Shale is roughly the time equivalent of the Zebbag Formation, notably in those parts of the transition zone where they rest upon the Serdj Limestone. In the Tell, however, where the Serdj is absent, the Fahdène rests directly upon the Sidi Kralif Shale, so that the lower part of the Fahdène is contemporaneous with the Serdj and Gafsa Formation.

The Aleg Formation is composed mostly of shale which rests upon the Zebbag Formation, or in the absence of that formation is separated from the Fahdène Shale by a thin bed of Bahloul Limestone. The Aleg Formation is thin or absent in the southernmost part of the area mapped on plate 1 (where the Zebbag is thickest), and it increases to about 300 m in thickness at Al Qaṣrayn and to more than 700 m in the vicinity of Tālah.

The Abiod Formation throughout Tunisia and eastern Algeria is of remarkably constant character: chalky limestone and minor amounts of shale, resting upon the Aleg Formation. This is in contrast to the marked variations in lithology that characterize the deposits during previous epochs of the Cretaceous Period. In central Tunisia the Abiod is thin or absent within the triangle Ḥājib al'Uyūn–Furrīyānah–Al Miknāsī (the site of the "Isle of Al Qaṣrayn" that became prominent in the Eocene Epoch). Elsewhere the thickness of the Abiod Formation commonly exceeds 100 m, reaching a maximum of 800 m in the basin of the Wādī Nabhānah, but beneath the Sāḥil near Sūsah it may exceed 1,000 m.

TERTIARY ROCKS

The Tertiary sedimentary strata in central Tunisia include: the 'El Haria Shale, whose lowermost beds are recognized to be of Cretaceous age; the Metlaoui Formation, which includes limestone (especially at the top), gypsum, phosphate, and shale and which in part is contemporaneous with the 'El Haria Shale and in part overlies it; the Souar Shale; the Fortuna Sandstone, which is continental in part; the Hakima Formation, dominantly red beds; the transgressive Aïn Grab Formation composed of conglomerate at the base; The Oum Douil Formation, chiefly argillaceous but including much fine sandstone and some lignite; and the Sēgui Formation, dominantly of continental origin.

The 'El Haria Shale commonly includes some thin-bedded limestone near the middle, and is fairly uniform throughout Tunisia. The formation is 100 to 200 m thick in the Sāḩil Sūsah, but increases to 500 m in the basin of Wādī al Birkah northwest of Al Qayrawān. In central Tunisia the 'El Haria Shale is absent in the area southwest of the line Makthar–Ḩājib al'Uyūn–Sīdī Bū Zayd–Al Miknāsī (the Isle of Al Qaṣrayn). The formation includes the upper beds of the Maestrichtian stage (Cretaceous) in its lower part and beds of the Montian and Thanētian stages of the Paleocene in its upper part.

The Metlaoui Formation is comprised chiefly of limestone in northern Tunisia and of evaporite in southern Tunisia. In central Tunisia it is absent in the Isle of Al Qaṣrayn area bounded by Tālah, Ḩājib al'Uyūn, Al Miknāsī, Qafṣah, and the Algerian frontier. In the Sāḩil and Low Steppes northeast of Al Qaṣrayn area, it is 50 to 100 m thick, increasing to more than 200 m in the Jabal al Halfā' northwest of Al Qayrawān. The Metlaoui rests upon the 'El Haria Shale, and phosphate beds are widespread at its base. The chronostratigraphic stages designated in the geologic series as Londinian, Lower Lutetian, lower Eocene, and middle Eocene are considered to represent the Metlaoui Formation.

The Souar Shale attains a maximum thickness greater than 1,000 m in the basins of Wādī Nabhānah and contiguous Wādī al Krisna, but is absent in the area of the Isle of Al Qaṣrayn (Subayṭilah–Al Miknāsī–Qafṣah–Algerian frontier). Although the formation is dominantly argillaceous in central Tunisia, it has an increasing proportion of limestone to the west; it consists of chemically precipitated limestone east of Ḩājib al'Uyūn and is dominantly gypsum east of Sīdī Bū Zayd. Beds of equivalent age in south Tunisia are evaporites of the Djebs Formation. The Souar Shale and the Djebs Formation have generally been mapped as middle and upper Eocene (Upper Lutetian and Priabonian stages).

The Fortuna Sandstone represents the sedimentation in northern and central Tunisia during the Oligocene Epoch and includes alternations of sand and shale in the lower (Medjanian) part and coarser sandstone in the upper part (Numidian). The formation attains a thickness of more than 700 m in the Tell east of Makthar and 900 m in the Sāḩil near Al Jamm, but thins to 200 m between these localities. The Fortuna Sandstone is absent southwest of a line extending from Tālah southeastward through Subayṭilah.

The Hakima Formation comprises the red beds of the Aquitanian stage at the beginning of the Miocene Epoch. These argillaceous and sandy beds or their equivalents are about 30 m thick in many exposures, but they are more than 200 m thick south of Subayṭilah and are absent in many places.

The Aïn Grab Formation is relatively thin and consists chiefly of limestone with conglomerate at the base. It represents the Burdigalian stage of the Miocene Epoch.

The Oum Douil Formation is predominantly argillaceous, but also contains considerable thicknesses of very fine sand or sandstone, numerous veins of lignite, and some veins of gypsum. The formation includes all the marine Miocene sedimentary strata above the basal Aïn Grab Formation and thus may correspond in part to the Burdigalian, Helvetian, and Tortonian stages; these sedimentary strata have generally been grouped as Vindobonian on geologic maps.

The Sēgui Formation, like the Oum Douil, is a thick series of dominantly argillaceous sedimentary strata but with numerous layers of sandstone and some gypsum; it also contains conglomerate in some places. The Sēgui, however, is nonmarine in origin, and the deposits commonly are not as well sorted as those composing the Oum Douil, which was deposited in shallow seas and lagoons. The Sēgui Formation generally lies upon the Oum Douil, but in places that were emergent during the Miocene it rests upon older rocks. Beneath the Sāḥil Sūsah, marine sedimentary strata of Pliocene age are found in many places along the present coast and extend as much as 15 km inland; in some places these overlie the Sēgui beds, in others they are intercalated among the continental deposits.

The Sēgui Formation includes beds considered to be of the Pontian stage of the Miocene—where that stage has been discriminated from the Vindobonian—and the overlying continental deposits of the Pliocene. The top of the Sēgui may represent the Villafranchian stage of the Quaternary Period, which includes red clays with grains of coarse sand, overlain by concretionary limestone that commonly forms a carapace or lime hardpan at the top. This red zone appears to be formed by pedologic processes.

QUATERNARY DEPOSITS

The deposits of shallow basins are unconsolidated alluvial deposits of clay, silt, sand, and gravel, similar in many respects to the sediments of the Sēgui Formation, but localized in the several subsiding basins which have been described by Castany (1948).

Post-Chellean deposits, which have accumulated since the Villafranchian uplift and orogeny, include chiefly the alluvium in the present valleys of the wadis, the dunes of which some have become consolidated, the argillaceous sedimentary strata that have accumulated in the sabkhas, and the lime hardpan (croûte calcaire) that has been formed in many parts of the Sāḥil, some at the land surface and some at horizons several meters below the present surface.

GEOLOGIC HISTORY

The geologic history of central Tunisia is the interpretation of the sequence of events which must have occurred to bring about the present character and distribution of the formations described in the preceding section. The following summary, based largely upon the more complete account by Burollet (1956), attempts to bring out especially the events in the geologic history that have been of significance to ground-water hydrology: The history of (1) the permeable formations, or parts or groups of formations, that are today's aquifers, (2) the impermeable rocks that serve as barriers or confining layers in the present flow system, and (3) the structural changes that have created the separate basins or compartments in which usable ground water occurs today.

Insofar as the presently known ground-water resources are concerned, the geologic history of significance begins in the Cretaceous Period, but these events were shaped to a considerable degree by characteristics inherited from the more remote past. The marine sedimentation that prevailed during the Cretaceous continued into the Eocene Epoch, was followed by uplift and erosion of part of central Tunisia, and eventually by continental deposition and erosion throughout the region. Another event of major significance was the mountain building of the Pleistocene which, with subsequent erosion and deposition and minor structural adjustments, is responsible for the present physiography.

HERITAGE FROM PRE-CRETACEOUS GEOLOGY

Several structural features that had formed prior to the Cretaceous Period persisted throughout the Cretaceous and left their mark on subsequent history. A central north-south axis extended from the eastern end of Shatt al Fijāj (in southern Tunisia), north through Al Miknāsī, Jabal Bū Dīnār, Jabal ash Shurayshīrah, and Ḥājib al 'Uyūn, along the Dhirā 'as Sawāṭīr, and thence toward Ra's aṭ Ṭib (Cape Bon). This axis (p. G25) separated a fairly stable eastern platform, beneath the present Sāḥil and Low Steppes, from a relatively unstable southwestern platform, beneath the High Steppe south of Ḥājib al 'Uyūn. North of central Tunisia, sediments, chiefly clay, accumulated in a geosynclinal area—the Tunisian trough—continuously over a long period of geologic time, until their aggregate thickness was several thousand meters.

As to the pre-Cretaceous sedimentary strata, they are generally at such great depth that they have been reached by very few wells, and practically nothing is known about the quantity or quality of water that might be yielded from them. Paleographic maps (Furon, 1959) indicate that northwest Africa was inundated during much of the Paleozoic Era, including the Silurian, Devonian, and Carboniferous Periods; thus marine sedimentary strata of Paleozoic age probably underlie central Tunisia, but at depths so great that they have not been identified in any of the deep exploratory holes.

The oldest rocks that crop out in central Tunisia are of Triassic age. Judging by the great thicknesses of gypsum, dolomite, salt, and other evaporites, these sediments accumulated in shallow seas and lagoons in an arid climate. Today these Triassic rocks might contribute soluble salts to ground water, but their areas of outcrop are small and in desertic mountains, so that they receive little recharge. Under most of central Tunisia the Triassic rocks are too deeply buried to have a significant effect upon the usable fresh-water supplies. The Jurassic rocks include the Nara Limestone and may include other permeable zones, but they are at greater depths than wells have yet penetrated, so that the quantity and quality of water in them are unknown.

CRETACEOUS AQUIFERS AND THEIR CONFINING LAYERS

The Cretaceous sedimentary strata include two major water-bearing zones in limestone and sandstone, separated in most places from each other, from the underlying Jurassic limestones, and from the overlying Miocene sands, by thick blankets of relatively impermeable argillaceous sedimentary rocks. Although the limestone and sandstone aquifers are entirely of Cretaceous age, the deposition of the underlying Sidi Kralif Shale began late in the Jurassic Period, and the deposition of the overlying 'El Haria and Souar Shales continued throughout the Eocene. Thus the sedimentary strata that confine the water within the Cretaceous aquifers, producing artesian pressure in many localities, are not limited in age to the Cretaceous.

The Cretaceous Period began with depositional conditions similar to those of the Jurassic. During the Berriasian and Valanginian stages, the deposition of the Sidi Kralif Shale continued in a slowly subsiding deep marine basin; these clays form an impermeable separation between Jurassic limestones and deposits of later age. The Hauterivian stage was marked by a mild regression of the sea and by deposition of the Meloussi Formation in much shallower waters.

During the Barremian stage much of central Tunisia was covered by shallow seas and lagoons, or even low plains above sea level, which received continental deposition of the Boudinar Sand from the Saharan platform to the south. This sand is now a good aquifer in favorable places. Locally evaporites were deposited in closed basins south of Al Qaṣrayn.

During the Aptian and Albian stages, sandstone, limestone, and shale were deposited in a subsiding marine basin which was subjected from time to time to minor uplifts. These permeable rocks constitute good aquifers in many places today. West of the central north-south axis, a part of the southwest platform near Al Qaṣrayn was uplifted to form the Isle of Al Qaṣrayn, where marine limestone was exposed to erosion and dissolving action. This Isle of Al Qaṣrayn received no further sediments until Oligocene time.

By contrast with the Lower Cretaceous, the Upper Cretaceous sedimentary strata are characterized by general absence of sand and by evidence of landmass stability after the general invasion of North Africa by the sea during the Cenomanian stage. Nevertheless, local structural features caused compartmentation in central Tunisia with marked variations in the rocks deposited during the Turonian, Coniacian, and Santonian stages. West of the central north-south axis, the sediments were chiefly shales of the Aleg Formation, and these serve to separate the Lower Cretaceous from the Upper Cretaceous aquifers. To the east, beneath the Sāḩil and Low Steppes, limestones were deposited upon the stable platform.

The Campanian and Maestrichtian stages are represented by the Abiod Formation, which is a homogeneous limestone throughout its extent and is the uppermost Cretaceous aquifer. This limestone progressively overlaps the other Cretaceous rocks of the eastern platform, east of the Isle of Al Qaṣrayn. The formation is of course absent in the emergent area of that island, and is thin to the north of it, where shoal waters were evidently extensive.

Toward the end of the Maestrichtian, the accumulation of the 'El Haria Shale indicates some regression of the sea. This deposition of clay in stagnant or closed basins continued into Eocene time; locally land areas emerged and were subjected to erosion with consequent development of intraformational unconformities. Short cycles of subsidence and uplift caused the depositional environment to vary considerably. Although some marine limestone was deposited, as seen in the Metlaoui Formation, the Eocene deposits consist predominantly of shale. The 'El Haria and Souar Shales together serve generally as an aquiclude and confining layer above the Cretaceous limestones and sandstones and below the Miocene sands.

TERTIARY UPLIFT AND SEDIMENTATION

The regression of the seas that began in Eocene time culminated during the Oligocene Epoch. Roland Dégallier (1952, p. 13) has stated that the emerging land surface was probably not flat but undulating and that the folds had a general northwest-southeast trend. As evidence he cited the alinement of Jabal Khashm al Kalb and Jabal Dheroia (between Al Qaṣrayn and Furrīyānah), and noted that major faults at Sabībah, Ḩājib al'Uyūn, and Al Qaṣrayn have a similar alinement, suggesting that these faults too may have been initiated during the Eocene Epoch. The area of the Isle of Al Qaṣrayn increased, and a few other small areas emerged from beneath the sea. In the Sāḩil platform considerable subsidence occurred in the vicinity of Al Jamm, although the Sūsah area remained stable. Movements on the Shurbān–Az Zarāmidīn fault zone (p. G26) occurred for the first time.

At the end of the Oligocene Epoch the western part of the country was folded. A marine embayment extended into the area of the present valley of Al Qaşrayn nearly as far as Furrīyānah, and the entire Isle of Al Qaşrayn was submerged. In eastern Tunisia, little or no folding occurred at this time; there the first known folding took place during the Miocene Epoch.

The Miocene Epoch began with folding and uplift of the Tell, and local and minor tectonic activity continued throughout the epoch. The Tell, which includes part of the former geosynclinal Tunisian trough area, became the source of fine clastic sediments now found extensively in central Tunisia. Several folds in the Tell had northeast-southwest axes—notably Al Qaşrayn–Zaghwān massif, the Jabal ash Shurayshīrah, and Al Abeïd—and other parts of the Tell area became broad synclinal basins, such as those of Aş Şawwāf and Ḩājib al 'Uyūn. East of the central north-south axis there was general subsidence of the Sāḩil. Thus in central Tunisia the shallow Miocene seas covered practically all the area east of the central north-south axis and only the synclinal basins to the west of it; these were the sites of deposition of the transgressive Aïn Grab and the Oum Douil Formations. Shallow early Miocene seas covered the area and received deposits consisting mainly of clay, plus beds or lenses of well-sorted fine sand. In the Oum Douil Formation, mainly of Vindobonian age, such sand beds now constitute satisfactory aquifers in those places where fresh water has flushed out the ocean water. The Oum Douil Formation marks the end of extensive marine deposition in central Tunisia.

The Vindobonian stage was followed by orogenic movements, including locally intense folding, and a general uplift of the land and regression of the sea. Tilting or folding of the continental deposits of Miocene and Pliocene age is commonplace in nearly all of central Tunisia. During the subsequent period of erosion, saline water was flushed from many of the sand lenses of older formations. The products of this erosion were deposited on land having low relief and presumably an arid climate; drainage of the land was poor, numerous closed depressions received poorly sorted sediments, and salts accumulated with the clays and fine sands. Gypsum is common in these deposits, which locally have permeable lenses of sand or gravel containing water of inferior quality. Transgressions of the sea during the Pliocene reached as much as 15 km inland from the present coast. The earliest deposits of the Pleistocene Epoch are virtually indistinguishable from the beds of Miocene and Pliocene age.

QUATERNARY OROGENY AND SEDIMENTATION

During the Villafranchian stage of the Pleistocene Epoch, the climate changed from hot and arid or semiarid to hot and humid, or to a climate having distinct wet and dry seasons, as attested by the red soils of later Villafranchian age. The major structural revolution in Tunisia began late in the Villafranchian, and most of the present relief dates from that time. The Tell was again uplifted, the Sāḩil and High and Low Steppes were formed as they are today, and numerous structural basins were left by faulting. Many of these faults and the cores of the mountains constitute hydrologic boundaries as shown on the geologic and hydrologic maps (pls. 1, 2). The Villafranchian orogeny included several distinct phases which continued into the Acheulian and Mousterian stages.

These structural changes were followed by intense erosion. Clastic material, mainly fine grained, was eroded from the highlands and carried by streams to the lowlands where it accumulated as poorly assorted older alluvium. Solution doubtless increased the permeability of some of the limestone and thus improved the water-bearing and water-yielding properties. Recent structural movements have become progressively less intense although the areas occupied by sabkhas are still subsiding.

The level of the Mediterranean Sea oscillated through a narrow range during the Pleistocene Epoch and resulted in minor marine transgressions and in accumulations of dune sand. Shallow marine embayments near the present coast received thin sandy deposits and some calcareous deposits. Also, terraces were cut in several places during these minor oscillations of sea level.

Within historic time the principal changes in the aspect of the countryside in central Tunisia are traceable to exploitation of the land. Erosion has been severe in many places: the effects of the removal of the natural grass cover by overgrazing, removal of shrubs and trees, and other practices during nearly 2,000 years of recorded human activity can be seen in the cutting of new stream channels, removal of soil, development of badland topography in extensive areas, denudation of large areas by wind, high sediment content in streamflow, and extensive areas of deposition on the flood plains of streams.

REGIONAL HYDROLOGY

This section discusses the geologic framework through which—or over which—water moves from the time it falls as precipitation upon the earth until it is returned to the atmosphere or enters the Mediterranean. Necessarily this section is based largely upon the regional geology already described, but it gives emphasis to the contrasting permeabilities of the rocks that transmit the water and those that impede its movement and also to the structural features that control or influence the movement of water. This section provides a foundation for the consideration of the quantitative aspects of the occurrence of ground water, its storage and movement, quality, and the problems of development and use of wells, which are the subject of a separate report (Dutcher and Thomas, unpublished data, 1968).

To provide a basis for such quantitative analysis of the flow system, this section divides central Tunisia into hydrologic units and outlines and describes the hydrologic boundaries for each unit. These units and their boundaries are defined on the basis of data from areal geology and from wells. The location of the production wells and the principal test wells is shown on plate 2. The water-level contours shown are based mainly upon data from production wells. Much geologic information used in compiling the geologic sections (pl. 1) and the maps showing the subsurface extent of the water-bearing formations (pls. 2, 3, fig. 3) was supplied to the HER and the Service des Mines by oil companies. These data were collected during the drilling of exploratory petroleum wells and are available for inspection by authorized persons at the Service Géologique.

STRUCTURAL DIVISIONS

The characteristics of ground-water occurrence and availability in the Sāḩil Sūsah area are sufficiently different in the three major structural units that it is desirable to consider the ground water as similarly divided laterally by major faults and folds into three bodies that are for the most part hydrologically distinct. These structural provinces are: (1) the High Steppes and Tell, (2) the Low Steppes and Sāḩil, and (3) Al Jamm–Al Mahdīyah plain, which is physiographically a part of the Low Steppes and Sāḩil but is hydrologically distinct. These provinces are bordered by the dominant structural features of the area and by the Mediterranean Sea. The ground-water bodies in the High Steppes and Tell are bordered on the northwest by the surface- and ground-water divide along the crest of the High Tell, or Dorsale, and are separated from the Low Steppes and Sāḩil on the east by the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone, a major folded zone and line of faulting which strikes approximately along the central north-south structural axis that has persisted in central Tunisia since Jurassic time. Ground water in the Low Steppes and Sāḩil is divided into two main parts by the Shurbān–Az Zarāmidīn fault zone, which strikes northeastward from Jabal Khashm al Artsouma to Al Munastīr and effectively separates the Low Steppes and Sāḩil into two distinct areas; the southern part is herein called Al Jamm–Al Mahdīyah ground-water basin, and the northern part is called Al Qayrawān–Sāḩil ground-water basin.

TUNISIAN DORSALE

The Sāḩil Sūsah area as shown on plate 1 is bordered along the northwest by the ranges and valleys of the Tell, which is drained mainly by streams tributary to the Wādī Majardah but in part by the Wādī Nabhānah, Marq al Layl, Zurūd, and others which flow to the steppes and Sāḩil. Northeast of Sabībah Valley (pl. 1) movements along major faults have uplifted Cretaceous limestones on the northwest. Annual rainfall, averaging more than 400 mm on Jabal Barqū and Jabal as Sarj (Dutcher and Thomas, 1966a, fig. 3), provides some recharge to these limestones. The base flow of the Wādī Nabhānah is derived from limestone formations exposed in the drainage basin, principally the Serdj Limestone of the Jabal Barqū.

The position of the ground-water divide between the Majardah River basin and the streams tributary to the Low Steppes cannot be determined, but in most places the ground- and surface-water divides probably coincide closely. However, because the dips of the water-bearing rocks along the surface-water divide are variable, northwest in some places and southwest in others, there is undoubtedly minor ground-water inflow and outflow across the topographic divide. The ground-water resources of the Tell were not studied in this reconnaissance because few wells have been drilled and few hydrologic data are available.

BŪ DĪNĀR–SHURAYSHĪRAH–SAWĀṬĪR STRUCTURAL ZONE

The central north-south axis of faulting, folding, and uplift which extends with but minor interruption from Jabal Bū Dīnār on the south, along the east flank of Jabal Manārah, through Jabal Shurayshīrah, and along the Dhirā'As Sawāṭīr on the north is here called the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone. This structural zone has persisted since the Jurassic and is characterized by several quasiparallel thrust faults that have been mapped in the central reach near Jabal Manārah and by stratigraphic unconformities resulting from periods of uplift and erosion. Numerous unconformities have been observed in the strata cropping out in the hills and mountains uplifted along the zone.

The geologic sections shown on plate 1 which cross the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone were compiled from the existing geologic maps of the area, from geologic mapping during this investigation, and from subsurface geologic data from geophysical explorations and oil-test or water wells. Six of the sections (*C–C′* and *I–I′* through *M–M′*) cross the structural zone and show its general features. Insufficient data are available to show precisely the configuration of the folds, the dips of faults or thrusts, or the thicknesses of the geologic formations. Many of the contacts and other features shown will doubtless require modification as additional data become available.

The Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone forms an effective barrier to ground-water flow nearly everywhere along its reach and separates the ground-water bodies of the High Steppes and Tell from those of the Low Steppe and Sāḥil downstream. In many places the virtually impermeable Souar Shale has been uplifted and prevents the downstream flow of ground water in the overlying permeable formations. Locally, it is the upturned shale of the Aleg Formation which forms a barrier to downstream flow of ground water. In many places impermeable fault gouge probably prevents flow. In two places, however, there appear to be gaps where flow could continue downstream across the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone: one near Jabal Bū Dīnār and the other north of Al Qayrawān between Jabal al Bāṭin and the south end of Dhirā'As Sawāṭīr. There may be flow across the structural zone at Jabal Bū Dīnār in older formations, including the Zebbag and Gafsa Formations or the Boudinar Sand. There may be little or no barrier to ground-water flow in the formations older than the 'El Haria Shale along the entire reach from Jabal al Bāṭin to the Dhirā'As Sawāṭīr or even farther north, but in that reach the older formations are at great depth and likely to contain water of poor chemical quality. Also along that reach of the structural zone there is only a partial barrier to ground-water flow in the deposits of Quaternary age.

SHURBĀN–AZ ZARĀMIDĪN FAULT ZONE

A major zone of faulting extends with but monor interruption southwestward from the coast near Al Munastīr to Jabal Khashm al Artsouma (pl. 1). Data from water and oil-test wells, geophysical explorations, and subsurface geologic studies indicate that structural movements along several of the individual faults of the zone may have begun during the Eocene Epoch. There was a relatively long period of inactivity beginning in the Pontian stage of the Miocene Epoch and ending during the Pliocene, but movements probably continued periodically until recent time. The zone constitutes one of the major structural features of central Tunisia, and influences the occurrence, movement, and chemical quality of ground water.

The Shurbān–Az Zarāmidīn fault zone is named for two of the faults previously known. Oil-test and water wells have been drilled near the zone at Az Zarāmidīn, Jammāl, Zamālat as Sawāsī, Shurbān, Awlād Faraj Allāh, and elsewhere. Data from these wells, from geophysical explorations, and surface geologic mapping were used to construct the geologic sections shown on plate 1. Sections *A–A′* and *B–B′* are drawn approximately parallel to the fault zone on the south and north, respectively. These sections show our interpretation of the geologic conditions which control the occurrence, movement, and chemical quality of ground water in the two main parts of the Low Steppes and Sāḥil which are separated by the fault zone. Admittedly the configuration, thickness, and extent of the formations are only approximate because of insufficient data, and many of the features shown may require modification as additional data become available. However, a program of drilling in the Sāḥil has been in progress since January 1963. The sites for the exploratory wells were chosen on the basis of preliminary studies and the geohydrologic data summarized on the sections. Five test wells had been drilled by July 1963, and data from these indicate that the sections, as drawn, represent the general geologic and hydrologic conditions.

In the Low Steppes and Sāḥil the surface expression of the Shurbān-Az Zarāmidīn fault zone is restricted mainly to four low anticlinal structures or domes which have been raised along the south and east sides of the structure. Of these, Az Zarāmidīn dome is the highest and best known. Southwestward from that feature are the so-called Karkar dome, Shurbān anticline, and Awlād Faraj Allāh uplift (pl. 1). Near Jabal Muṭlaq the Shurbān–Az Zarāmidīn fault zone approaches the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone, and the topographic expression across the fault zone is reversed—the anticlinal structure of Jabal Khashm al Artsouma is uplifted to a height of about 655 m on the north side of the fault zone.

Data on the movement and amount of displacement of the formations across the zone are not available in the reach between the Jabal Khashm al Artsouma and the west end of the Shurbān anticline. The geologic interpretations shown on the map in that area and on section *K–K′* (pl. 1) are largely conjectural. Before the geology can be determined with greater precision, it will be necessary to drill test wells or carry out geophysical explorations.

The relative displacement of the thrust fault which flanks the Shurbān anticline on the north is shown on section *M–M′* (pl. 1). The vertical displacement of the top of the Abiod Formation is more than 1,200 m down on the south, but here the geology is complicated by the presence of two main faults. An oil-test well drilled north of the surface trace of the fault reportedly penetrated a repeated Cretaceous section between the two faults. The dips of the faults are not known but must be rather low and may be less than 35°. The steep inclination of the fault planes shown on plate 1 is due to the exaggeration of the vertical scale.

The relative displacement of the fault which flanks Az Zarāmidīn dome on the northwest is shown on section *N–N′* (pl. 1). According to geophysical studies, the displacement across this fault zone is also about 1,200 m, but recent movements have been relatively down on the northwest whereas the area of subsidence during the Miocene was on the southeast, as shown by the much greater thickness of marine deposits on that side. Numerous exposed minor faults cut the Oum Douil and Sēgui Formations east of the main fault zone.

The great influence of the Shurbān–Az Zarāmidīn fault zone during Tertiary time is clearly shown by comparing geologic sections *A–A′* and *B–B′* (pl. 1). Section *A–A′*, as drawn, extends from the Mediterranean southwestward about parallel with the fault zone and shows the progressively decreasing thickness of the Oum Douil Formation toward the southwest and the relatively increasing thickness of the Fortuna Sandstone. The great thicknesses of the Sēgui Formation, the Pliocene marine and Quaternary deposits, in the area of subsidence near the Sabkhat Matā'al Muknīn are also shown. In contrast, section *B–B′*, which extends approximately parallel to section *A–A′* but along the northwest side of the fault zone, shows that all the Tertiary formations older than the Sēgui are much thinner, and in places are probably absent. Also shown on section *B–B′* is the area near the Shurbān anticline where the formations are unconformable and the Oum Douil probably rests upon the Abiod Formation of Cretaceous age. This increase in the thickness of the Tertiary formations older than the Sēgui on the southeast side of the Shurbān–Az Zarāmidīn fault zone is also shown on sections *K–K′*, *M–M′*, and *N–N′* (pl. 1).

Although the ground-water recharge to Al Qayrawān–Sāḩil basin northwest of the fault zone is meager, that basin does receive recharge from the streamflow and ground-water inflow, which are practically absent in Al Jamm–Al Mahdīyah basin southeast of the fault zone. The Shurbān–Az Zarāmidīn structure forms a barrier to ground-water flow from the north, significant surface streams are absent south of the fault zone, and permeable deposits are everywhere deeply covered by clay and shale except on the flanks of Az Zarāmidīn dome where sand of the Oum Douil Formation crops out. Thus, except near Az Zarāmidīn dome, there is virtually no deep penetration of rain and no direct recharge to ground water in Al Jamm–Al Mahdīyah basin, and in most of the basin the water is of poor chemical quality.

AL JAMM–AL MAHDĪYAH BASIN

All the Sāḩil Sūsah area southeast of the Shurbān–Az Zarāmidīn fault zone and east of the Bū Dīnār–Shurayshīrah–Sawāţīr structural zone is herein called Al Jamm–Al Mahdīyah basin. It extends south beyond the area investigated, perhaps as far as Şafāqis, but the south boundary is unknown. The geologic structure of this large plateaulike area is rather simple, and no large faults or internal barriers to ground-water flow were discovered. Minor exposed faults cut the Tertiary deposits between Al Munastīr and Az Zarāmidīn.

The occurrence, movement, chemical quality, and availability of ground water are controlled by strictly local conditions; ground water of usable chemical quality has been found only where opportunities for recharge are more favorable than in the basin as a whole and where the permeability of the surface favors penetration of recharge and that of the underlying deposits favors water storage. Isolated bodies of fresh ground water have been found in the more favored parts of the basin, but these are small and each contains a relatively limited amount of water. Except for these, most of the ground water in Al Jamm–Al Mahdīyah basin is saline or brackish.

WATER IN THE QUATERNARY DEPOSITS

Ground water occurs in the Quaternary deposits of Al Jamm–Al Mahdīyah basin in three areas of structural subsidence, as follows: (1) In the Ţabulbah area on the east, (2) in the Bū Mirdās syncline in the center, and (3) in the Bilād ar Irqāb area on the west.

The shallow water in the Bū Mirdās syncline is limited in quantity and inferior in chemical quality; in the Bilād ar Irqāb area two production wells have been drilled (now unused), and many dug wells yield water from relatively thin Quaternary deposits.

Ground water in the Ţabulbah area is the subject of a separate report (Dutcher and Thomas, 1966b). The shallow water body in the Quaternary and underlying continental deposits of Pliocene age is heavily developed, and the water levels in wells are declining. However, it was estimated that about 61 million m^3 of usable ground water was still available for use at the end of 1962 and that the supply was probably sufficient to continue the current average annual rate of pumping for 20 to 25 years, under proper management.

WATER IN THE TERTIARY DEPOSITS

The probable subsurface extent of the Oum Douil Formation beneath Al Jamm–Al Mahdīyah basin is shown on plate 3, and its stratigraphic relation to other formations and the geologic structure near the Shurbān–Az Zarāmidīn fault zone are shown on sections *A–A′*, *K–K′*, *M–M′*, and *N–N′* (pl. 1). The formation contains saline water in many places and is absent in the western part of the basin.

Piezometric contours drawn on the basis of measurements in deep wells penetrating principally the Oum Douil Formation are shown on plate 2. The contours, as drawn, show that the water flows generally northeastward nearly parallel to the Shurbān–Az Zarāmidīn fault zone in most of the basins; but from Az Zarāmidīn dome movement is toward Sabkhat Matā'al Muknīn and Sabkhat

Sīdī al Hānī', and in the southwest part of the basin movement is toward the Sabkhat Mashāqīq.

In the vicinity of Az Zarāmidīn dome, the formation contains water of good chemical quality beneath an area of about 250 km². There is limited local recharge by direct penetration of rainfall and from percolation from small streams which cross the sandy outcrops exposed on the flanks of the dome (sections *A–A'* and *N–N'*, pl. 1). Elsewhere, however, recharge, if any, is limited to downward percolation from overlying formations—or perhaps in the western part of the area from upward leakage of water from the Abiod or Zebbag Formations (sections *K–K'* and *M–M'*, pl.1). Some underflow may cross the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone from the Sidi Khalīf subunit of Al Qayrawān–Sāḥil basin on the west, and some runoff from the hills on the west doubtless enters the Quaternary, Miocene, and Pliocene deposits to recharge the Oum Douil Formation farther east.

The extent of the fresh water near Az Zarāmidīn dome could not be determined precisely, but additional test wells are planned. The fresh water of Az Zarāmidīn dome area is contained in the "Zone B sand," as defined by Burollet (1956, p. 202); figure 3 includes a diagrammatic electric log of test well Quṣaybat Sūsah 10522 and a stratigraphic section compiled from the logs of oil-test well 7064/4 and an unnumbered deep well at Al Baher and from measurements of a section exposed near the crest of the dome. Where data are available, the approximate interval of the Zone B sand which contains fresh water is shown on sections *A–A'* and *N–N'* (pl. 1).

Four flowing wells have been drilled in the basin near Al Mahdīyah, and it seems likely that the hydrostatic pressure in sand aquifers is higher than at the land surface in an area of about 400 km², as is shown on plate 2.

NEED FOR ADDITIONAL DATA AND TEST WELLS

In Al Jamm–Al Mahdīyah basin the principal needs for data include the following: (1) Water-level measurements in deep observation wells, principally in Az Zarāmidīn dome area, (2) additional aquifer tests to determine the coefficients of storage and transmissibility of the Zone B sand for use in planning the spacings of new wells and in determining their optimum yield, (3) additional test wells in the same area to determine the extent of the beds bearing fresh water, and (4) additional deep test wells in the Awlād Faraj Allāh–Bilād ar Irqāb area to determine the geologic structure and the stratigraphic sequence, the water-bearing characteristics of the rocks and deposits, and the chemical character of the ground water, partic-

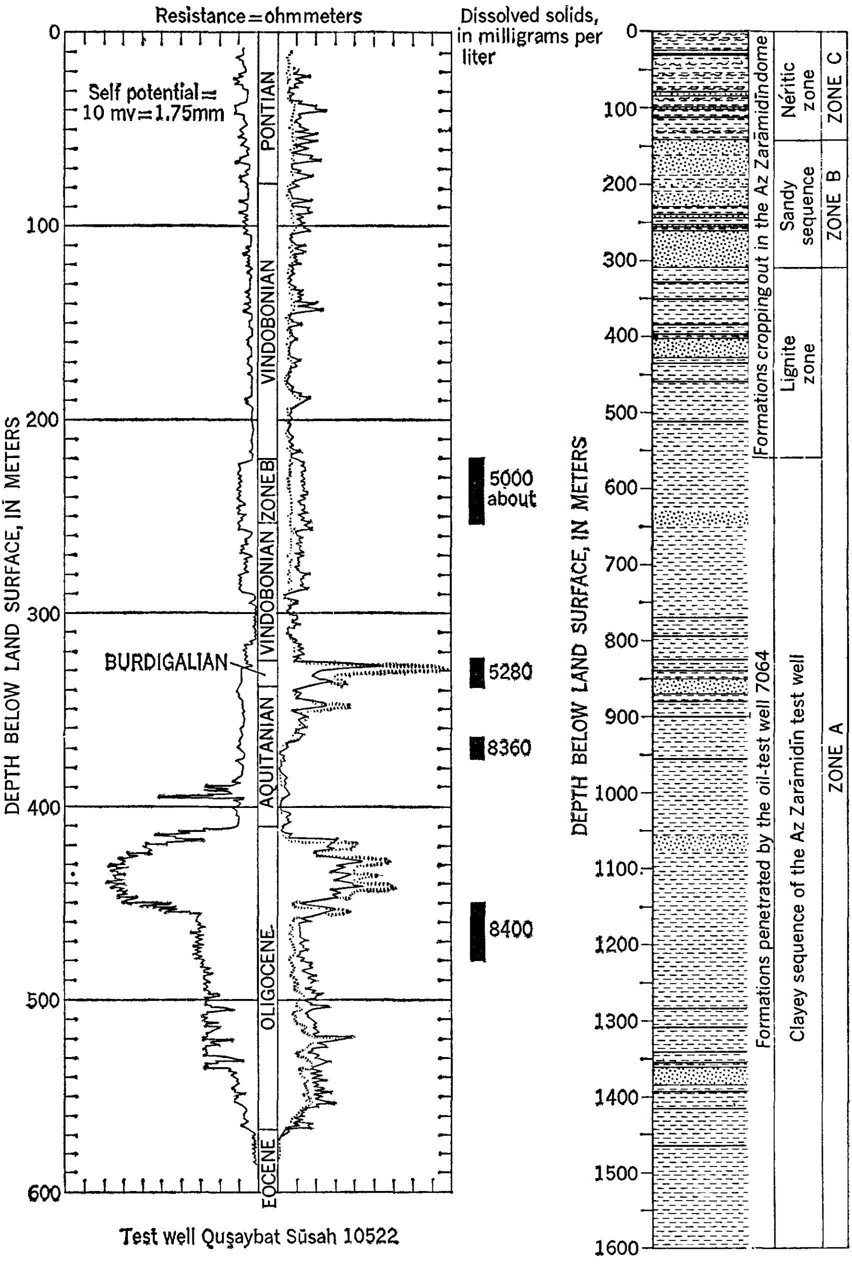

FIGURE 3.—Diagrammatic electric log and stratigraphic sections

ularly in the older formations, such as the Fortuna Sandstone and Zebbag Formation.

AL QAYRAWĀN–SĀḨIL BASIN

That part of the Sāḩil Sūsah area which is bordered on the southeast by the Shurbān–Az Zarāmidīn fault zone and on the west and northwest by the Bū Dīnār–Shurayshīrah–Sawāţīr structural zone is herein called Al Qayrawān–Sāḩil basin. It includes most of the Sāḩil and much of the Low Steppes (Dutcher and Thomas, 1966a, small map of physiographic provinces on pl. 1) . The geologic structure of this large area is simple, and the undulating land surface in many places reflects the faulting and folding of the underlying formations.

Although Al Qayrawān–Sāḩil basin is smaller than the Jabal-Bilād basin of the High Steppes to the west, it is the most populous of the large ground-water basins of central Tunisia. The volume of ground-water recharge is larger and the quality of water is generally better than in Al Jamm–Al Mahdīyah basin. However, the chemical quality of the ground water in most parts of Al Qayrawān–Sāḩil basin is inferior to that of the Jabal–Bilād basin discussed in the next section.

INTERNAL GEOLOGIC STRUCTURE

Al Qayrawān–Sāḩil basin occupies a structural block of the earth's crust that has remained relatively stable in relation to the adjoining areas during much of the geologic past. It has been downdropped in relation to the block northwest of the Bū Dīnār–Shurāyshīrah–Sawāţīr structural zone and during most of geologic time has been higher than the block south of the Shurbān–Az Zarāmidīn fault zone.

High hills in the west part of the basin, numerous anticlines and synclines, and at least five faults influence the occurrence and movement of the ground water within the basin. The principal structural features are shown on the geologic map and on geologic sections *C–C′* and *K–K′* through *N–N′* (pl. 1). Section *B–B′* is within the basin and was drawn approximately parallel to the Shurbān–Az Zarāmidīn fault zone. The contrast between the structures on the two sides of the fault, as shown on section *A–A′* on the south and *B–B′* on the north, is great. Both sections are drawn approximately parallel to the fault zone, but some of the irregularities resulted from drawing them as near as possible to the control wells.

The central part of the basin is more elevated than the margins. In the area between Sūsah and the Quţayţīr fault, only the area occupied by the Sabkhat Sīdī al Hāni' is topographically low. The large alluvial fan of Wādī Marq al Layl and Wādī Zurūd covers the formations of Tertiary age in the west part of the basin. Along the northwest margin southeast of the Dhirā'as Sawāţīr, a long synclinal basin or subsiding area extends nearly continuously from Al Qayrawān to An Nafīḑah; this is the site of the Sabkhat al Kalbīyah. Along the opposite margin of the basin, northwest of the Shurbār–Az Zarāmidīn fault zone, another long synclinal basin or subsiding area extends from southwest of the Sabkhat ash Sharīṭah, through the Jammāl Valley, to the coast near Al Munastīr.

The structures of the central part of the basin are better known, largely owing to geophysical explorations and geologic studies of the exposed Tertiary formations. There are several anticlines near the coast (section *N–N′*, pl. 1) and three large faults, whose surface and subsurface traces resemble crescents. These faults are known from limited exposures, geophysical explorations, and deep oil-test wells near Quṭayṭīr; from east to west, they are called the Manzil Kāmil, Sīdī al Hānī', and Quṭayṭīr faults, respectively. As shown on section *C–C′* (pl. 1), the Manzil Kāmil fault has displaced the Oum Douil Formation downward on the west side relative to the east by about 50 m; the Sīdī al Hānī' fault zone has displaced the Oum Douil downward on the east side, but by a maximum of about 500 m; and the Quṭayṭīr fault probably has also displaced the Oum Douil downward on the east side relative to the west by about 300 m. The relative displacements shown on section *C–C′* are poorly controlled, and the postulated extensions of the faults beneath the Quaternary deposits are based mainly on water levels in wells.

A barrier to ground-water flow—probably a concealed fault—strikes nearly east beneath the Wādī Marq al Layl alluvial fan about 12 to 15 km southwest of Al Qayrawān. This barrier, named the Hanshīr al Qurayn fault (pls. 1, 2), causes a difference in water level of about 35 m between wells 7620/4 and 8587/4 near Hanshīr al Qurayn.

It is not certain whether the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone extends northeast beyond the Dhirā'as Sawāṭīr, but the zone probably continues northward to the margin of the area as shown on the geologic map. The known fault shown near An Nafīḑah may curve westward to join the main structure, and it apparently forms a barrier to ground-water flow in the vicinity of the Wādī al Brek.

GROUND-WATER SUBUNITS

Al Qayrawān–Sāḩil basin is divided into five ground-water subunits by faults and folds which influence the occurrence, movement, and chemical quality of ground water. These are shown on the piezometric contour map (pl. 2). The ground-water subunits, from west to east, are herein called the Sīdī Khalīf subunit, Marq al Layl–Quṭayṭīr subunit, and Ash Sharīṭah–Sūsah subunit; also, Al Qayrawān–An Nafīḑah subunit along the northwest margin and

Wādī al Brek subunit at the northeast corner of the basin. The Ash Sharīṭah–Sūsah ground-water subunit is divided by the Sīdī al Hāni' and Manzil Kāmil faults into three smaller areas called the Sabkhat Sharīṭah, Sabkhat Sīdī al Hāni', and Masāken areas.

SĪDĪ KHALĪF SUBUNIT

The Sīdī Khalīf ground-water subunit in the southwest part of Al Qayrawān–Sāḩil basin west of the Jabal Sharāhīn, is virtually separated from the remainder of the basin by the impermeable Souar Shale, which crops out in the Jabal Sharāhīn above the regional water table and prevents ground-water flow toward the east.

Water-level contours based on water levels in deep aquifers could not be drawn; production well 7100/5, screened in the interval 13 to 179 m, has been the only one completed in the subunit. However, on the basis of the electric log for test well 9124/4, 915 m deep, it appears that the Tertiary deposits may contain water of usable chemical quality, ranging from 2,800 to 3,400 ppm dissolved solids.

Near its northern end the Sīdī Khalīf subunit is crossed by the Wādī Zurūd between Sīdī Sa'd and the north end of the Jabal Sharāhīn. Here saturated alluvial deposits are underlain by the poorly permeable Sēgui Formation, the more permeable Oum Douil and Aïn Grab Formations, and the Fortuna Sandstone (pls. 3, 4). The alluvium is saturated nearly to land surface along much of the stream channel; thus there is little space for recharge from the river during periods of flood runoff. If ground-water levels in the north part of the basin were lowered by pumping from wells, it might be possible to increase the recharge to the subunit, by creating temporary or cyclic ground-water storage space to receive recharge during periods of flood runoff. However, because much of the shallowest ground water is of poor chemical quality, it might be necessary first to pump and dispose of much of the water presently in storage.

Although the Sīdī Khalīf ground-water subunit is large—about 580 km^2—it has not yet been a major source of ground water. A large amount of usable ground water may be in storage, but annual recharge is small and is mainly from runoff in small wadis which drain the Jabal Manārah and Jabal Sharāhīn, from direct deep infiltration of rainfall infrequently when monthly precipitation is much larger than average, and from influent seepage of the Wādī Zurūd.

MARQ AL LAYL–QUṬAYṬĪR SUBUNIT

The Marq al Layl–Quṭayṭīr ground-water subunit is that part of Al Qayrawān–Sāḩil basin which is bordered by the Jabal Sharāhīn and the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone on the west, the Hanshīr al Qurayn fault on the north, the Quṭayṭīr fault on the east, and the Shurbān–Az Zarāmidīn fault zone on the south. It is probably the subunit with the greatest potential recharge and ground-water storage in the entire Sāḫil Sūsah area.

The ground-water contours shown on plate 2 are based on water levels principally in wells that penetrate the Quaternary alluvium but also a few in wells in the Oum Douil Formation. These show that ground water moves generally eastward from Wādī Marq al Layl, Wādī Zurūd, and Jabal Sharāhīn toward the Sharīṭah-Sūsah ground-water subunit, and northeast toward the Hanshīr al Qurayn fault and Al Qayrawān–An Nafīḏah subunit. Recharge to the subunit is mainly from percolation from the Wādīs Zurūd and Marq al Layl and in small part from runoff in small streams which drain the Jabal Sharāhīn on the west. There may be minor recharge from direct infiltration of rain on the land during periods of exceptionally heavy precipitation, but this is negligible during most years.

Discharge is mainly by subsurface flow across the Quṭayṭīr fault to the Sharīṭah–Sūsah subunit on the east and across the Hanshīr al Qurayn fault to Al Qayrawān–An Nafīḏah subunit on the northeast. The total discharge includes pumpage from less than 20 wells, which probably accounts for a large part of the discharge during most years.

There are three aquifers of economic importance: the Quaternary alluvial deposits and the Sēgui and Oum Douil Formations. Deeper aquifers in the Aïn Grab and Hakima Formations and the Fortuna Sandstone may contain fresh water, but these have not been penetrated by wells. The probable subsurface extent of the Oligocene and Miocene formations is shown on plate 3. The Sēgui Formation is a very minor aquifer in the Marq al Layl–Quṭayṭīr subunit, but electric logs of test wells drilled in the west part of the subunit indicate that permeable sand lenses in the formation yield water to some deep wells.

AL QAYRAWĀN-AN NAFĪḎAH SUBUNIT

Al Qayrawān–An Nafīḏah ground-water subunit is in the northwest part of Al Qayrawān–Sāḫil basin between the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone and An Nafīḏah and Hanshīr al Qurayn faults. The boundary between this subunit and the Sharīṭah–Sūsah subunit to the southwest is imperfectly known; on the east the boundary is presumed to be along the crest of Al Qal'Ah al Kubrá anticline, along a line extending southwest from the west end of that anticlinal axis to the Sīdī al Hāni' and Quṭayṭīr faults (pl. 2).

Piezometric contours as drawn on plate 2 show that the ground water flows northeast from the Hanshīr al Qurayn fault and the Wādīs Marq al Layl and Zurūd toward the Sabkhat al Kalbīyah. Northeast of the sabkha the few available water-level measurements indicate that flow is toward the central lowlands between An Nafīḍah and Sīdī Bū'Alī and ultimately toward the coast.

Northeast of Al Qayrawān five wells having artesian flow have been drilled in the lowlands of the Wādīs al'Ālim, al'Atf, Zurūd, and Marq al Layl. The hydrostatic pressure in semiconfined sand lenses of the alluvium and Sēgui Formation is probably higher than at the land surface in an irregular-shaped area of about 330 km^2 which extends into the Bilād Sīsab subunit of the Jabal–Bilād basin (pl. 2).

From the standpoint of potential ground-water recharge—from the Wādīs Marq al Layl and Zurūd—and the availability of usable ground water in storage which could be developed by wells, Al Qayrawān–An Nafīḍah subunit, particularly that part between the Hanshīr al Qurayn fault and Al Qayrawān, is one of the more important subunits of the Sāḩil Sūsah area.

ASH SHARĪṬAH–SŪSAH SUBUNIT

The Ash Sharīṭah–Sūsah ground-water subunit occupies the southeast part of Al Qayrawān–Sāḩil basin and is bordered on the northwest by Al Qayrawān–An Nafīḍah subunit and on the west by the Quṭayṭīr fault and the Shurbān–Az Zarāmidīn fault zone. Usable ground water occurs in the Quaternary deposits and in the Sēgui and Oum Douil Formations. The older formations have been tested in several places but were found to contain saline water.

The piezometric contours shown on plate 2 are based mainly on water levels in wells which tap the Zone B sand of the Oum Douil Formation. Very few deep wells have been drilled, and data are available only in the area near the western margin of the Sabkhat Sīdī al Hāni'; thus the contours are partly conjectural.

Recharge to the subunit is mainly by subsurface inflow from the adjoining subunits on the west and south, but locally there is some deep penetration of rainfall from the land surface. Discharge is mainly by evaporation from bare-soil surfaces and transpiration by salt-tolerant plants near the Sabkhat Sharīṭah and Sabkhat Sīdī al Hāni'. There may be, however, some outflow to the sea through the deeper aquifers. As of 1962, discharge by pumping was limited to four wells in the Sīdī al Hāni' area, and the quantities withdrawn were negligible.

Well 10,522/4, the only deep well drilled in the subunit, yielded water containing more than 8,000 ppm dissolved solids (fig. 3) by artesian flow from sandstone of the Hakima Formation. Flowing wells probably could be obtained in three areas; near the Sabkhat Sharīṭah, downstream from the Sīdī al Hāni' fault near 'Ayn Ghrasesia, and in a large area near the Sabkhat Sīdī al Hāni'. The approximate areas where deep wells would flow at the land surface are shown on plate 2 and the total surface of the three areas, as drawn, is about 630 km^2.

A deep test well north of Sīdī al Hāni' (pl. 2) is to be drilled to test for permeable aquifers containing usable water in the northwest part of the subunit. Unless the sand beds of the Oum Douil Formation at the test well contain water having less than 4,000 ppm dissolved solids, it is doubtful that fresh water will be found anywhere in the Ash Sharīṭah–Sūsah subunit northeast of the Manzil Kāmil fault in the formations older than the Quaternary deposits.

WĀDĪ AL BREK SUBUNIT

In the northeast corner of Al Qayrawān–Sāḩil basin is the small ground-water subunit of Wādī al Brek, which is bordered on the north by the ground-water divide at the margin of the Sāḩil Sūsah area, on the west by the northern extension of the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone, and on the south by An Nafīḑah fault.

The piezometric contours indicate that ground water flows southeastward toward the sea and toward the northern part of Al Qayrawān–An Nafīḑah subunit. Recharge is mainly from runoff in the Wādī al Brek, less from the Wādī al Bawl (Oued Khiarate), and in minor part from the hills on the west and from deep penetration of rain which falls on the surface. Discharge is from four drilled wells, from many dug wells, and by subsurface outflow to the sea and to Al Qayrawān–An Nafīḑah subunit.

NEED FOR ADDITIONAL DATA AND WELLS

In Al Qayrawān–Sāḩil basin the principal needs for data include: (1) Periodic water-level measurements in deep observation wells in all parts of the basin, (2) additional streamflow and sediment-load records for the major streams, (3) aquifer tests to determine the coefficients of storage and transmissibility of the aquifers, and (4) additional deep test wells. Deep test wells are needed: Near the Wādī Zurūd in the Sīdī Khalīf ground-water subunit to determine whether the Oum Douil, Aïn Grab, and (or) Hakima Formations or the Fortuna Sandstone include permeable aquifers containing fresh water; in the Marq al Layl–Quṭayṭīr subunit to test the Oum Douil Formation; in the Sharīṭah–Sūsah subunit near Sabkhat Sīdī al Hāni' and north of the sabkhat, also to test the Oum Douil Formation; and in the Sīdī Khalīf subunit to determine whether pumping from shallow and deep wells near the Wādī Zurūd would increase the ground-water recharge during periods of runoff.

The greatest need for data is in the areas of the alluvial cones of the Wādīs Marq al Layl and Zurūd to determine whether suitable sites exist where artificial ground-water recharge basins could be build, the rates at which the deposits at such sites would accept recharge, and whether the flows in the wadis can be economically controlled for diversion into such basins.

JABAL–BILĀD BASIN

That part of the Sāḩil Sūsah area bordered on the east and southeast by the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone, on the west and north by the drainage divide along the crest of the Dorsale, on the west by the Tunisian-Algerian frontier, and on the south by a surface-water divide in the High Steppes which separates the south-flowing wadis in the adjoining basin from the north-flowing wadis tributary to the Wādī al Ḩaṭab (Oued Hatab) is herein called the Jabal–Bilād basin. It lies mostly in the High Steppes but includes the southeastern slopes of the Dorsale. The geologic structure of this large area is complex, and the basin has been separated into numerous ground-water subunits by faults and folds which greatly influence the occurrence and movement of ground water.

The Jabal–Bilād basin is larger than either of the two basins discussed previously and, because most of the surface water of the Sāḩil Sūsah area originates therein, the potential ground-water recharge to the basin is larger than in the two basins of the Low Steppes and Sāḩil. Because the basin has first chance at the surface water available for recharge and the higher altitude results in better drainage, the water quality is generally better than in either of the other large basins.

Because of the generally mountainous topography, the existing ground-water development is chiefly in the valleys along the major streams. These valleys are large downdropped structures containing permeable deposits mainly of Tertiary and Quaternary age that serve as ground-water reservoirs. Our studies in the Jabal–Bilād basin were mainly of the ground water in these structurally downdropped areas, because data are lacking to appraise the potential for ground-water supplies in the hilly and mountainous uplands.

Overall knowledge of the ground-water conditions in Jabal–Bilād basin is less complete than that of Al Qayrawān–Sāḩil basin because of the greater area and the paucity of wells in many of the structural subunits. However, the general features of the Jabal–Bilād basin have been investigated previously by numerous hydrologists. Some of the subunits have been studied in more detail than have the subunits of Al Qayrawān–Sāḩil basin. The reports available include: Jabal Maghīlah (Djebel Mrhila) (Archambault, 1943); the Sīdī Marzūq (Sidi Merzoug) syncline, (Azzouz, 1950); the Awlād Mūsá (Ouled Moussa) syncline, (Azzouz and Dégallier, 1950); the Furrīyānah (Feriana) region (Berkaloff, 1931; Strohl and Dégallier, 1946); Waslātīyah (Ousseltia) region (Berkaloff, 1953); Al Qasrayn (Kasserine) region (Castany, 1950); Subayṭilah (Sbeitla) region (Compagnie

Africaine de Géophysique, 1948; Dégallier and Azzouz, 1948); Sabībah (Sbiba) region (Roland Dégallier, 1949); Haffūz (Haffouz) region (Ernst Dégallier, 1952); Ḥajib al 'Uyūn (Hadjeb el Aioun) area (Schoeller, 1934a); and the Bilād Sīsab (Bled Sisseb) area (Société Grenobloise d'Etudes et d'Aménagements Hydrauliques, 1959). Other studies are listed in a bibliography of hydrologic work in Tunisia (Groupe de l'Hydrauliqueset des Amenagements Ruraux, 1961). Many of the above reports were consulted during the course of this investigation.

INTERNAL GEOLOGIC STRUCTURE

The Jabal-Bilād basin occupies the structural block of the earth's crust between the old Tunisian trough, an area on the northwest which experienced deep marine subsidence during past geologic time, and the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone. This structural block, wedged as it is between these dominant structural features, has been subjected to repeated movements along the faults and since Miocene time to folding. The deformation and faulting during the Pleistocene orogeny has divided the basin into several largely independent ground-water subunits.

The principal structural features are shown on the geologic map and on the geologic sections *C–C′* through *M–M′* (pl. 1). Section *E–E′* was drawn about parallel with the general structural trend of the major folds bordering the Dorsale between Al Qaṣrayn syncline on the southwest and the Jabal Barqū on the northwest. Most of the sections are drawn northwest-southeast—across the grain of the general structural trends in the basin—but several fault systems which probably date from the Miocene also trend northwest-southeast across the general structural trend. Several of these are shown on section *E–E′* flanking Al Qaṣrayn and Sabībah Valleys. The structural origin of Al Qaṣrayn Valley is indicated on section *D–D′*.

For convenience of discussion the Jabal-Bilād basin is divided on the basis of the major faults and folds into three wedge-shaped regions: (1) the "Highlands" region in the southwest part of the basin bordered on the east by the line of faulting and folding extending from the Jabal az Zaytūn fault on the south, the Subayṭilah–Jabal Maghīlah fault and its continuation to the Jabal al Abeïd fault in the center, and the Jabal Trozza–Haffūz fault zone and its northward continuation of faults and folds which extend northward through the Jabal al Juḥāf to the Dorsale; (2) the "midlands" region in the southeast part of the basin which extends to the area of Eocene outcrop north of Haffūz and is bordered by the features just described and the Bū Dīnār–Shurayshīrah–Sawāīṭīr structural zone; and (3) the "lowlands" region in the northeast part of the basin which is also bordered on the southeast by the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone and on the west by the Haffūz fault zone and its northward continuation of faults and folds.

Each of these three regions is further divided by faults, large folds, or mountains into individual structural basins which are called ground-water subunits. The structures which border the ground-water subunits consist mainly of the northwest or west-trending faults shown on the geologic map. Most of these features are known from surface exposures, but some are based on subsurface information. Available data, principally water levels in wells, confirm the existence of many of these structural features.

Displacement on many of the faults is large and on some is known to exceed 300 m, but the total displacement on most of these features is unknown. Al Qaṣrayn fault is probably the largest and best known of the west-trending faults. The interpretation shown on section *D–D′* (pl. 1) and the geologic map is after Castany (1951b), as shown on his geologic map of Al Qaṣrayn (Kasserine), scale 1:50,000. The Sabībah fault zone which borders Sabībah Valley on the south is another large zone of faulting (section *E–E,′* pl. 1), as are the Subayṭilah fault (section *G–G′*) and the Ḥājib al'Uyūn fault.

In Tunisia many of the faults which form barriers to ground-water flow have been the sites of springs since antiquity and are called seuils (in French), or thresholds, because they are thought of as being the hydrologic equivalents of sills. Rising ground water at many of the seuils in the Jabal-Bilād basin was developed by the Romans, who built dams, galleries, and other structures for diverting the flows from the streams crossed by the faults, at many places such as Sufetula (Subayṭilah) and Masclianae (Ḥājib al'Uyūn). Modern development of ground water at several of these sites is patterned after the works used by the Romans.

Other major faults which influence the occurrence and movement of ground water in the basin are the Bin 'Abd Allāh fault (section *K–K′*, pl. 1) and Al Waslātīyah and Haffūz faults (section *L–L′*). Where the Wādīs Marq al Layl and Zurūd cross the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone, the individual thrust faults and normal faults associated with the main structural zone also influence ground water. In addition to the faults and mountains which form barriers to ground-water flow, there are numerous synclinal structures of folded permeable deposits which form natural ground-water reservoirs.

GROUND-WATER SUBUNITS

The highlands region of the Jabal-Bilād basin is divided into 10 ground-water subunits, the midlands region has 6, and the lowlands region has 3. These ground-water subunits as shown on the water-level contour map (pl. 2) are separated by faults and folds which influence the occurrence, movement, and chemical quality of ground water. The probable subsurface extent of the water-bearing formations of Oligocene and Miocene age which figure prominently in the basin are shown on plate 3.

SUBUNITS OF THE HIGHLANDS REGION

AL QAṢRAYN SYNCLINE SUBUNIT

The southwest part of the Jabal-Bilād basin south of Al Qaṣrayn fault between the Jabal Sallūm and Jabal ash Sha'nabī is a large synclinal basin herein called Al Qaṣrayn syncline subunit. Geologic sections *D–D′*, *E–E′*, and *F–F′* (pl. 1) show an interpretation of the major geologic features of the subunit. Aquifers mainly in the Oum Douil and Zebbag Formations contain fresh water, but permeable zones in the Aleg Formation have been tested in a few wells. Arrows on plate 2 show that the ground-water flow is generally toward the center of the syncline from the marginal uplands, and the water-level contours show flow north toward the fault. Throughout a reach of about 8 km upstream from the fault, there is rising ground water in the Wādī ad Darb which is deeply incised into the Oum Douil Formation; the average flow from ground water is probably about 290 lps according to studies by Société Centrale pour l'Equipement du Territoire (oral commun., 1962).

Recharge is mainly by precipitation on the upland areas which surround the subunit and from influent seepage of minor streams which cross the permeable rocks of Cretaceous and Miocene age. Discharge is from rising ground water and underflow across Al Qaṣrayn fault to Al Qaṣrayn Valley subunit on the north. Pumpage from wells will supply water to a paper-pulp plant recently built near the fault.

Al Qaṣrayn syncline subunit is one of the few areas in central Tunisia which has a perennial yield that can be developed and used annually and forever. This yield, known through long use, consists of the low-flow discharge of the Wādī ad Darb, about 290 lps, plus an unknown quantity of water which is presently being lost across the fault as outflow that could be salvaged if the water levels were lowered below the stream level, plus an unknown quantity of water which would percolate during periods of storm runoff into the sandy channel deposits of the Wādī ad Darb. Along the 8-km reach now saturated at all times, new storage would be created if a large volume of water were pumped and all rising water dried up by the pumps.

AWLĀD MUSA SUBUNIT

East of Al Qaṣrayn syncline subunit, between the Jabals Sallūm and Az Zaytūn and Kharrūb, is a basinlike area herein called the

Awlād Mūsá subunit. This subunit is also bordered on the north by Al Qaşrayn fault. Geologic section *C–C′* (pl. 1) shows the general structural features and stratigraphic relationships of the water-bearing rocks and deposits, which include mainly the Sēgui and Zebbag Formations.

Deep wells have not been drilled in this subunit, but the arrows shown on plate 2 indicate the probable general direction of ground-water flow. Because there are no major streams or areas of rising water, the subunit probably does not have a perennial yield of consequence but contains usable ground water in storage.

AL QAŞRAYN VALLEY SUBUNIT

The large grabenlike structure between Al Qaşrayn and Jabal Marqabah faults shown on the geologic map (pl. 1) and sections *D–D′* and *E–E′* is herein called Al Qaşrayn Valley subunit. The depth of the Quaternary fill of this downdropped valley is unknown but exceeds 300 m where tested. Only the zones deeper than about 100 m appear to be moderately permeable.

Ground water is contained mainly in thick sand beds in the Quaternary deposits and the flow, as shown by the water-level contours on plate 2, is generally northeast from Al Qaşrayn fault toward the Wādī al Ḩaţab (Oued Hatab), where a small amount of water rises in the stream channel opposite Jabal Sallūm (this discharge is estimated at 150 lps), and toward the Subayţilah'al Aţash subunit north of the Jabal Marqabah fault.

Numerous areas of wet lands show that shallow ground water is common in the valley (Castany, 1951b) and indicate that under existing conditions floodflows in the Wādī al Ḩaţab have little opportunity to recharge the subunit because in much of the valley ground-water storage space is not available. Large scale pumping from wells in the valley could dewater the upper part of the alluvial deposits and induce recharge during times of surface flow; unfortunately, except for some dune sand at the surface, the upper few meters of the deposits are mainly clay and silt of low permeability, and it might not be possible to induce infiltration into the bed of the Wādī al Ḩaţab.

A minimum "safe yield" could be developed by pumping from shallow wells in the subunit to withdraw the rising water at the lower end of the valley and also the water now being evaporated or transpired in the areas of shallow ground water. Wherever surficial materials are sufficiently permeable, this yield might be increased considerably by dewatering the shallow deposits and thereby creating cyclic storage space for recharge by seepage from the stream during periods of runoff.

FŪSĀNAH SUBUNIT

The large synclinal basin northwest of Al Qaṣrayn Valley, bordered on the north and east by the Jabal Sammāmah fault and on the south by Jabal Sha'nabi, has been named the Fūsānah subunit. The occurrence and movement of ground water are known only from shallow dug wells. Our interpretation of the structure and stratigraphy of the subunit is shown on section *F–F'* (pl. 1). Ground water flows generally east down the axis of the valley, and there is rising ground water in the Wādī al Ḥaṭab (Oued Hatab) in the lower reach of the subunit.

Even if the deposits beneath the stream are permeable, recharge in the lower end of the subunit is rejected when the wadi flows. The permeability of the stream bed is unknown, however, and may be so low that recharge would be small even if the deposits were dewatered by pumping. The subunit has a small but unknown safe yield which could be salvaged by pumping water from wells near the wadi in the lower part of the subunit; the minimum yield would be the average annual rising water in the stream, plus the water salvaged by stopping most of the evapotranspiration, plus any additional recharge from the wadi induced by pumping prior to periods of runoff. Salvage of this safe yield would require large-scale pumping and the removal of water from storage to make additional space available for recharge.

SĪDĪ MARZŪQ SUBUNIT

The basinlike structure north of the Fūsānah subunit between the Jabals Bīranaw and Sammāmah is called the Sīdī Marzūq subunit. Little is known concerning ground water in this area, but our interpretation of the probable geologic conditions is shown on section *G–G'* (pl. 1). There are no large streams in the area and, except for water which might be salvaged from subsurface outflow by pumping from wells penetrating the Fortuna Sandstone near the Jabal Sammāmah fault, there is little or no perennial yield; pumping of ground water must be principally from storage.

SUBAYṬILAH 'AL AṬASH SUBUNIT

The structurally complex ground-water subunit bordered on the west by the Jabals Sammāmah and Ṭawāshah, on the north by the Sabībah Valley, on the southwest by Jabal Maghīlah and the Subayṭilah fault, and on the south by Jabal Marqabah fault is herein called the Subayṭilah 'al Aṭash subunit. The water-bearing rocks and deposits include: the Quaternary alluvium, the Sēgui and Oum Douil Formations, and the Aleg, Abiod, and Zebbag Formations. Many of the wells drilled west of the Subayṭilah fault penetrate several aquifers in the rock of Miocene and Cretaceous age.

In the southern part of the subunit, ground-water flow is mainly east and southeast toward the Subayṭilah fault, where a water gallery has been constructed and several deep flowing wells have been drilled which are used mainly to supply about 160 lps through the pipeline to Ṣafāqis on the coast about 150 km southeast of Subayṭilah. Also in the southern part of the subunit, ground water in the Miocene sand beds is in direct hydraulic continuity with that in the underlying Aleg and Abiod Formations; but in the northern part of the subunit, the Souar Shale separates the Miocene aquifers from those in the Cretaceous rocks. The separate systems cause the ground-water conditions to be greatly different in the northern and southern parts of the subunit.

An interpretation of the geohydrologic conditions is shown on sections *D–D′* and *G–G′* (pl. 1). Ground water was first developed in this subunit by the Romans at the sites of springs just upstream from the Subayṭilah fault. The southern part of the area—the region where the Souar Shale was removed by erosion before the Miocene deposition—has a safe yield which long experience has shown to be about 240 lps. The direction of ground-water flow in the northern part of the subunit appears to be toward the north, and it is doubted that water could be developed with any assurance of perennial supply. The quantity of water in ground-water storage in the northern part of the subunit is probably large, but usable water in storage in the Cretaceous limestone formations cannot be estimated from available data.

SABĪBAH VALLEY SUBUNIT

The large structural basin bordered on the south by the Sabībah fault zone, on the north by the Bin Ḩabbās fault zone, and on the east by Jabal al Halfā' and the Nebika fault is called the Sabībah Valley subunit. The west border of the area is not known but probably is at the outcrop of the Eocene shale. Ground water is contained in the Quaternary deposits, the Fortuna Sandstone, and the Abiod Formation and perhaps in the older rocks. Few wells have been drilled in the subunit, so limited hydrologic information is available. The subunit has perennial yield of about 10 million m^3 per year of surface and ground water at the small dam constructed on the Wādī Sabībah about 4 km southwest of the town. The low flow of the Wādī Sabībah reportedly averages about 180 to 250 lps. Ground water pumped from wells 6821/4, 7133/4, and 7133b/4 supplements the water supply at the dam, and four new wells will increase the quantity available so that about 2,000 hectares (5,000 acres) of land can be irrigated, according to the HER.

AL‘ALĀ’ SUBUNIT

Al‘Alā’ subunit shown on plate 2 occupies the structural depression north of the Jabal al Abeïd between the Jabal Trozza fault on the east and the Nebika fault and the crest of the Ma'Azil anticline on the west. The subunit is crossed by section *J–J′* (pl. 1; see also section *I–I′*). Little is known of the ground-water hydrology of the subunit because only two wells, 8751/4 and 9739/9 have been drilled. These penetrate the Sēgui and perhaps the Oum Douil Formation and are not used. There is a small ground-water discharge from the subunit as rising water in the Wādī al Ḥaṭab (Oued Hathob) north of Jabal al Abeïd, but the perennial yield is probably small and pumping would be required near the Wādī al Ḥaṭab (Oued Hathob) to increase it.

ḤAFFŪZ SYNCLINE SUBUNIT

The Ḥaffūz syncline subunit as shown on plate 2 includes only the deposits of the sharply folded syncline near Ḥaffūz just upstream from the Ḥaffūz fault shown on the geologic map and section *K–K′* (pl. 1). Production is from the Sēgui Formation and Souar Shale (limestone in this area) at wells 7599/4 and 8691/4 and a water gallery. The water goes into a pipeline to the Sāḥil for domestic use. Recharge is from seepage from the Wādī Marq al Layl and from ground-water flow from Al'Alā' and Al Waslātīyah Valley subunits on the southwest and north. Discharge is from the wells and the water gallery and by underflow to the small ground-water subunits downstream from the Ḥaffūz fault.

The safe yield of the Ḥaffūz subunit has been developed by lowering the water levels in the shallow deposits which are recharged by the Wādī Marq al Layl and which in turn recharge the deeper formations of Tertiary age. Ground-water development in the Ḥaffūz syncline subunit is unusual in central Tunisia in the sense that here is a small area (less than 90 km^2) where it is possible to pump ground water on a relatively large scale. This continuous pumping is possible only because there is water available for recharge during each successive flood on the Wādī Marq al Layl. But recharge would be impossible without available storage space for the water; by continuously depleting the water in storage, additional space is made available which is refilled by infiltration during successive floods. This is the most effective method of developing ground water in central Tunisia, and this cyclic use of ground and surface water should be tried wherever conditions in the other small subunits of the Jabal-Bilād basin permit.

The perennial yield of the Ḥaffūz syncline subunit averages about 250 lps, based on the discharge from wells and the water gallery, and this discharge has been accomplished during many years without permanently depleting the storage or the annual yield of the subunit.

AL WASLĀTĪYAH VALLEY SUBUNIT

The large synclinal valley between the Dorsale and the Ḥaffūz fault and its structural extension to the north is underlain by deposits of Quarternary age and by the Fortuna Sandstone. The aquifers for the most part are of low permeability, and the geologic structure of the subunit is imperfectly known. Al Waslātīyah and Bin'Abd Allāh faults may form local barriers to ground-water flow, but ground-water contours showing the flow in the deeper deposits could not be drawn; the probable direction of flow is indicated by arrows on plate 2.

SUBUNITS OF THE MIDLANDS REGION

BILĀD SEGDAL SUBUNIT

The Bilād Segdal subunit is in the southeast part of the midlands region of the Jabal-Bilād basin, but ground-water flow, principally in the Quaternary deposits and Sēgui Formation, appears to be southward out of the subunit past the east end of Jabal Meloussi and is not tributary to the Wādī Zurūd nor to the other subunits of the region. Ground water in the Quaternary deposits may be draining southward through permeable zones in the underlying Zebbag Formation or Boudinar Sand. Recharge is by influent seepage from minor streams and from deep infiltration of rainfall during exceptionally wet years. Discharge is by wells and an unknown amount of subsurface outflow to the south. Similar to most of the other subunits of the midlands region, the Segdal subunit contains a large volume of usable ground water in storage but has virtually no safe yield which can be developed and used continuously.

SĪDĪ BŪ ZAYD–CHEGAF–ḤAJAL SUBUNIT

The very large ground-water subunit south of the postulated Jabal Zāwiyah fault, east of the Jabal Az Zaytūn fault, and north of the Bilād Segdal subunit is called the Sīdī Bū Zayd–Chegaf–Ḥajal subunit and is named for three large and somewhat independent areas. From the standpoint of size, potential recharge, possible surface-water supply, and usable ground water in storage which can be pumped from wells, the Sīdī Bū Zayd–Chegaf–Ḥajal subunit is one of the most important areas in central Tunisia. In spite of this apparently large potential, there has been little development of ground water. Surface water, when available in the wadis, is used to irrigate a large area, but this use is limited because the flood flows are uncontrolled and ground-water recharge by seepage from the wadis is limited by the low permeability of the surface deposits and by shallow ground water which in some places prevents recharge.

Recharge in the north part (Chegaf area) is by seepage from the Wādīs Subayṭilah and Jilmah; in the south (Sīdī Bū Zayd area) recharge is principally by seepage from the Wādī al Ḥaṭab (Oued Hatab) and Wādī al Fakkah. The northeast part of the subunit is drained by the Wādī Ḥajal, which also carries runoff from the entire area infrequently when there is throughflow of surface water; the Wādī Ḩajal in the lower part of the subunit also drains off rising ground water of poor chemical quality.

Ground water is contained principally in the Quaternary deposits and Sēgui Formation. Our interpretation of the geologic conditions is shown on sections *C–C′* and *I–I′* (pl. 1), and the ground-water contours shown on plate 2 are based on water levels in production wells, test wells, and selected dug wells. As shown on the water-level contour map, ground water flows generally eastward from the Subayţilah fault toward the gap north of Jabal as Sawdā′ and then northeast toward the Wādī Zurūd in the area drained by the Wādī Ḩajal. In the Sīdī Bū Zayd area south of the Jabal Ḩamrā′, the ground-water flow in the Quaternary deposits and Sēgui Formation is northeastward to the Wādī Ḩajal. Near the town of Sīdī Bū Zayd the ground-water contours show a depression which may result from pumping at wells 5248/5 and 5588b/5 or, as suggested by Roland Degallier (1952), from water draining into the deeply buried permeable rocks of Cretaceous age. However, if recharge to the Cretaceous rocks occurs in this area, the following question arises: Where does the water exit from the deep formations? Whether southward-flowing ground water could cross all the intervening structures to find an exit at lower altitude far to the south can neither be proved nor disproved without much additional work and the drilling of many test wells; but the possibility that a large volume of water from the shallower aquifers recharges the Cretaceous rocks appears unlikely. If the Zebbag Formation or Boudinar Sand receive any recharge beneath the Sīdī Bū Zayd subunit, the volume is probably small.

In the area from Sīdī Bū Zayd north to the Wādī Jilmah, the surface gradient is very flat and the land is poorly drained. Only the largest floods on the Wādī al Ḩaţab (Oued Hatab) cross this area to reach the Wādī al Ḩajal and ultimately the Wādī Zurūd. There is much ponding of water which eventually evaporates and leaves its dissolved matter on the surface; the residue is redissolved during later floods or transported by the winds, which disperse the salt crystals over a wide area. As a consequence, the low flow of the Wādī al Ḩajal is of poor chemical quality and not suitable for most uses.

The Quaternary deposits for several miles downstream from the Subayţilah fault are of limited thickness and nowhere exceeded 15 m where observed in the walls of several hand-dug wells. Moreover, the deposits are poorly sorted clay and clay with sand and gravel, which are of low permeability and afford little opportunity for influent seepage from the streams during flood.

The Sīdī Bū Zayd–Chegaf–Ḥajal subunit has a potential yield from surface water estimated to exceed 10 million m³ annually (Schoeller, 1934b), but in most years much of the surface runoff is wasted by evaporation in the poorly drained parts of the subunit (Dégallier, Roland, 1952) or is inefficiently used to flood large irrigated areas planted in cereal crops. A large dam has been considered where the Wādī al Ḥaṭab (Oued Hatab) crosses the north end of the Jabal Kharrūb to impound water for irrigation but, because of the high annual evaporation and the characteristics of the streamflow, a surface reservior has not been constructed.

The Sīdī Bū Zayd–Chegaf–Ḥajal subunit has a relatively large perennial ground-water yield which could be developed by pumping water from properly spaced wells. This pumping would check the discharge of rising ground water to streams, and salvage all ground water now lost by evaporation from bare-soil surfaces and transpiration by plants in the lower parts of the subunit. Schoeller (1934b) estimated the water losses from evaporation to be about 300 lps (nearly 10 million m³ per yr). The perennial yield undoubtedly would be increased if the water levels beneath all the stream channels were lowered by pumping so that recharge could occur whenever there is runoff in the wadis; however, because of the poor chemical quality, it might be necessary at first to pump and dispose of much unusable water.

Data are not available for determining whether a dam on the Wādī al Ḥaṭab (Oued Hatab) near Jabal Kharrūb would benefit the Sīdī Bū Zayd region; the cost of constructing a dam and water-distribution system might exceed the long-term benefits. Salvaging the streamflow for use is important, but this might be accomplished by draining the low areas to increase available storage space which could be recharged naturally during periods of streamflow, or by building structures to artificially recharge ground water. A more economical method of water development might be the extraction by pumping of the water stored in the relatively shallow deposits.

These same possibilities exist in the Wādī Zurūd and Wādī Marq al Layl drainage basins, where the question of building large dams has been raised. Here also studies should be made to determine whether such projects are feasible.

ḤĀJIB AL'UYŪN SUBUNIT

The Ḥājib al'Uyūn subunit is bordered on the southeast by the postulated Jabal Zāwiyah fault, on the west and northwest by the Subayṭilah and Jabal Maghilah faults, and on the north by the Ḥājib al'Uyūn fault. On the basis of the quantity of ground water produced, the subunit is one of the most important in the Jabal-Bilād basin.

Ground water occurs principally in deposits of Miocene age, presumably mainly in the Oum Douil Formation. Our interpretation of the geologic conditions in the subunit is shown on sections *H–H′* and *I–I′* (pl. 1). There may be several small faults which extend westward from the Ḩājib al'Uyūn fault and influence the flow of ground water in the north part of the subunit; the positions of these postulated faults are shown on the geologic and water-level contour maps (pls. 1, 2).

The ground-water contours shown on plate 2 are based on water levels in drilled wells, test wells, and dug wells and show that ground water flows generally northeast through the subunit toward the Ḩājib al'Uyūn fault. Most of the wells were drilled just south of the fault, and seven now in use have artesian flow. Recharge is mainly by subsurface inflow from the Subayṭilah–'al Aṭash subunit and seepage from small streams which drain the Jabal Maghīlah.

Periodic measurements have not been made in wells, so it is difficult to know what the change in water level near the fault has been; but on the basis of the reported history of the wells, it seems likely that water levels are slowly declining and that much of the water has been derived from ground-water storage.

The subunit has a limited but undetermined perennial yield. Water has been salvaged in the area because wells have dried up the formerly extensive wet land and springs near the fault and have thus reduced loss from evaporation. Presumably ground-water outflow across the fault has also been reduced by pumping and flow from the wells, but the quantity of underflow salvaged annually has probably been small.

ḨAṬAB (HATHOB) VALLEY SUBUNIT

The downdropped valley north of the Ḩājib al'Uyūn fault has been studied by several hydrologists who have noted the similarity of this valley to Al Qaşrayn Valley of the highlands region. However, the Ḩaṭab (Hathob) Valley is small, its area being only about 65 km^2. Our interpretation of the geologic conditions is shown on section *J–J′* (pl. 1). Although the Wādī al Ḩaṭab (Oued Hathob) flows down the valley, the surface deposits are of low permeability and much of the soil is saline owing to the evaporation of shallow ground water. For this reason there is little recharge from the stream.

Ground water in the Quaternary deposits and Miocene formations flows from the northwest down the valley to the Bilād Zāmilah subunit just west of the Bū Dīnār–Shurayshīrah–Sawātīr structural zone (pl. 2). Some recharge is rejected because locally the subunit is saturated to land surface and storage space is not available; pumping from shallow wells would induce additional recharge, but at first it might be necessary to pump the water as waste because of its high salinity.

BILĀD ZĀMILAH SUBUNIT

The sharply folded long, narrow syncline between the Wādī al Ḥaṭab (Oued Hathob) and Wādī Marq al Layl just west of the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone is called the Bilād Zāmilah subunit. The water-bearing rocks include the Quaternary deposits, the Sēgui, Oum Douil, and Hakima Formations, and possibly the Fortuna Sandstone (pl. 3). Except near the north end where the syncline is crossed by the Wādī Marq al Layl, the opportunity for ground-water recharge apparently is limited; however, most shallow wells produce water of good chemical quality. On the basis of conditions in the Ḥaffūz syncline northwest of this area, it appears that more ground water could be pumped from this subunit if wells were placed in relation to sources of recharge on the Wādī Marq al Layl.

BILAD HARQALAH SUBUNIT

The northeast-trending syncline between the Jabal Trozza fault and the Bū Dīnār–Shurayshīrah–Sawāṭīr structural zone west of Jabal Shurayshīrah contains ground water in the Quaternary deposits and the formations of Tertiary age. This syncline is called the Bilad Harqalah subunit and is crossed by geologic section *K–K′* (pl. 1). Ground-water recharge probably is mainly by seepage from the Wādī Marq al Layl. Few wells have been drilled in the subunit. Pumping could be greatly increased without materially lowering the water levels because dewatered stoarge space beneath the Wādī Marq al Layl probably would be refilled during subsequent floods.

Locally the ground water is shallow and of poor chemical quality—it might be necessary to pump some water as waste to provide storage space and to flush the salts from the soil before using the subunit as a cyclic storage basin similar to the Ḥaffūz syncline subunit.

SUBUNITS OF THE LOWLANDS REGION

RU'AYSĀT SUBUNIT

The Ru'aysāt subunit is in the southwest part of the so-called lowlands region of the Jabal-Bilād basin, and ground water probably is contained mainly in the Abiod Formation—and perhaps in older rocks of Cretaceous age. Data for deep water wells are not available, but one oil-test well (Ru'aysāt 1) has been drilled which indicated fresh water in permeable zones in the relatively shallow Cretaceous rocks. Our interpretation of the geology of the subunit is shown on section *L–L′* (pl. 1).

JABINYĀNAH SUBUNIT

The ground-water subunit near Jabinyānah is underlain by the Quaternary deposits and the Fortuna Sandstone (or equivalent rocks of Oligocene age) and locally by the formations of Miocene age (fig. 3; section *M–M'*, pl. 1). The permeability of the water-bearing deposits is low in the large synclinal structure, and little is known of the ground-water conditions in the southwest part of the subunit southwest of Jabinyānah. Ground-water recharge is mainly infiltration in the bed of the Wādī Nabhānah and smaller streams which drain the Dorsale, and ground-water discharge is mainly underflow to the Bilād Sīsab subunit on the south. A dam is being constructed on the Wādī Nabhānah at Sīdī Mas'ūd, but the effect that this will have on recharge to the subunit is unknown. Presumably its effect on ground water will be negligible because the seepage losses from the Wādī Nabhānah now mainly recharge the Quaternary deposits of the Bilād Sīsab subunit.

The safe ground-water yield of the subunit is small and presumably would be changed little by pumping. However, there is much usable ground water in storage, and presumably large quantities could be pumped from wells for use during a rather long period before the supply was seriously depleted.

BILĀD SĪSAB SUBUNIT

The large alluviated area in the northeast part of the Jabal-Bilād basin west of the Dhirā'as Sawāṯīr and south of the Jabinyānah subunit, between the Bū Dīnār–Shurayshīrah–Sawāṯīr structural zone and Subaykhah, is called the Bilād Sīsab subunit. This large area has been studied recently by hydrologists in search of sites where wells can provide water to supplement water from the Wādī Nabhānah dam now under construction. The dam at Sīdī Mas'ūd will impound the flow of the Wādī Nabhānah, but the need for water in the Low Steppes and Sāḫil is greater than the expected supply from the new reservoir.

NEED FOR ADDITIONAL DATA AND WELLS

Additional hydrologic data must be collected in the Jabal-Bilād basin before the potential can be determined or plans made on how the available water can best be developed. More stream gages should be installed, and the sediment loads must be measured regularly. Modifications should be made so that all used and unused wells can be measured periodically with a steel tape. The well-measuring program of the BIRH should include trimonthly measurements of water levels in at least two drilled wells in each ground-water subunit, and in other wells as necessary. A continuous water-level recorder should be operated in one well near Ḥājib al'Uyūn, in one near Ḥaffūz, and if possible in others near Subayṭilah and Al Qaṣrayn.

Data will be needed on the permeabilities of the stream-channel deposits along all the major streams if large-scale ground-water recharge projects are undertaken—or if studies are planned to determine whether such projects are feasible. Shallow test wells, preferably cable tool, should be drilled along all the major wadis so that data on lithology, water levels, permeability, thickness, and other hydrologic characteristics of the stream-channel deposits will be availible.

Deep test wells should be drilled at selected sites to test for production from the Cretaceous rocks. Proposed sites for such wells are not shown on plate 2, but the geologic sections shown on plate 1 may serve to indicate several locations.

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