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Geological Framework of Saudi Arabia Groundwater Resources

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ABSTRACT. Tectono-sedimentary units, containing major groundwater resources of Saudi Arabia, border the Arabian Shield on three sides. They are the Tabuk Basin, Wadi as Sirhan Basin, Widyan Basin Margin, Northeast Interior Homocline, Arabian Gulf Margin, East Interior Homocline, Rub' al Khali Basin, and Wajid Basin. These eight units, with thick permeable clastic bodies, contain almost all the groundwater reserves of the Kingdom, conservatively estimated at 208×10^9 m^3.

Most basins contain multiple aquifers with huge amounts of good quality groundwater. The Tabuk Basin aquifers are the thick Cambro-Ordovician Saq, Ordovician-Silurian Lower, Middle, and Upper Tabuk, the Silurian Tawil, and the Devonian Jauf. Argillaceous aquicludes separate these Lower Paleozoic sandstone aquifers.

The Wadi as Sirhan Basin contains productive Quaternary sands and less productive porous Quaternary volcanics and Paleogene chalks of the Hibr Formation. The Mid-Cretaceous Sakaka Sandstone Aquifer, exposed on the Hail-Rutbah Arch, extends under the southeastern Wadi as Sirhan Basin. In the Widyan Basin Margin joint Wasia-Biyadh Cretaceous aquifers are up to 650 m thick with abundant groundwater.

The Northeastern Interior Homocline has a sequence of Cambrian to Cretaceous aquifers (Saq, Tabuk, Khuff, Jilh, Minjur, Dhruma, Wasia-Biyadh and Aruma) dipping gently northeastward off the Arabian Shield. Along the southwestern margin of the Arabian Gulf Basin, good Tertiary aquifers, primarily the Umm er Radhuma, Dammam, Hadrukh and Dam are utilized. In the Eastern Interior Homocline, the Jurassic Minjur-Dhruma and Cretaceous Wasia-Biyadh are the main aquifers.

Throughout the Rub' al Khali, the Umm er Radhuma is the principal aquifer with a recently discovered shallow Neogene aquifer. On the southern margin of the Arabian Shield, the distinctive Cambro-Ordovician Wajid Sandstone forms an immense aquifer with groundwater reserves of $> 30 \times 10^9$ m^3.

Introduction

In considering the major groundwater resources of Saudi Arabia from a geological viewpoint, the crystalline rocks of the Arabian Shield can be omitted, since the have low permeabilities and are only significant in providing extensive, higher areas for surface runoff, or shallow subsurface wadi underflow (Burdon 1982).

To the north, east, and south of the Arabian Shield, there are very large sedimentary basins with many thick, highly permeable aquifers, which contain the majority of groundwater resources of the Kingdom (Fig. 1).

Many large wadi systems in Saudi Arabia also contain significant quantities of shallow groundwater in their alluvium, such as wadis Fatimah, Khulays, Hanifah, Rimah and Najran.

Northern Saudi Arabian Tectono-Sedimentary Province

The sedimentary areas to the north of the Arabian Shield, as far as the Jordan-Iraq borders, have been referred to as the Nafud Basin in the 'Water Atlas of Saudi Arabia' (Ministry of Agriculture and Water 1984). This northern area is not, however, a single sedimentary basin, but four distinct tectono-sedimentary provinces, each with its own distinctive aquifers. The major tectono-sedimentary basins comprising this northern area (Edgell 1987a) are the Tabuk Basin,

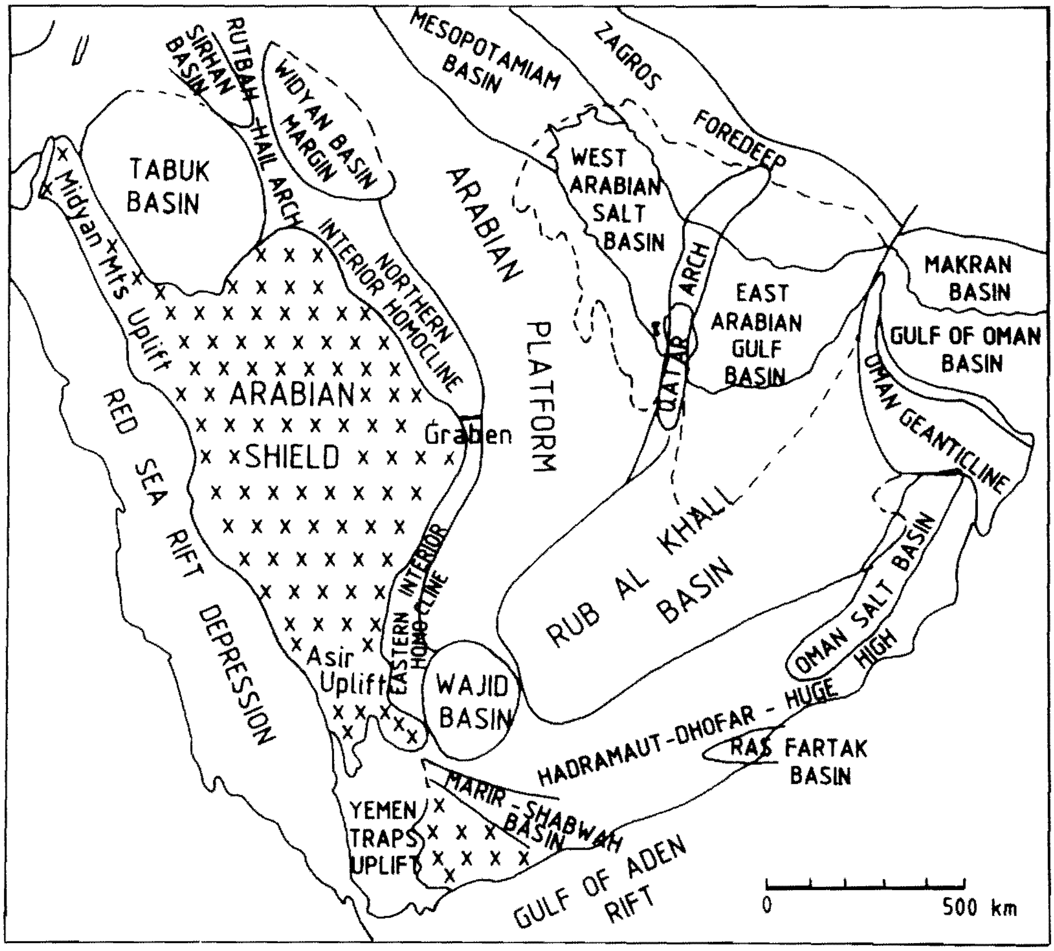

FIG. 1. Tectono-sedimentary provinces in Saudi Arabia and adjacent areas.

Wadi as Sirhan Basin, Widyan Basin Margin, and the Northeastern Interior Homocline (Fig. 2). The north-northwesterly trending Ha'il-Rutbah Arch (Khouri 1982) separates the Wadi as Sirhan Basin on the west from the Widyan Basin Margin on the east, while deeper parts of the Lower Paleozoic Tabuk Basin extend beneath the southern part of the primarily Cenozoic, Wadi as Sirhan Basin.

On the east side of the Hail-Rutbah Arch, the extensive Arabian Gulf Basin occurs. That part of this major basin, which lies in northern Saudi Arabia and extends to the western borders of Iraq and Kuwait, has been named the Widyan Basin Margin (Powers *et al.* 1966) because of the many wadis (widyan) flowing eastward, mainly on the exposures of the Cretaceous Aruma Formation. The water-bearing strata in the Widyan Basin Margin consist primarily of thick, permeable Cretaceous sandstones.

Paleozoic and Mesozoic formations dip northeastward off the Arabian Shield and comprise a tectono-sedimentary province, known as the Northern Interior Homocline (Fig. 3), which extends from just east of Ha'il to the vicinity of Riyadh and the Central Arabian Grabens. The main aquiferous strata in this province are of Paleozoic age, especially the Saq Sandstone (Abderrahman *et al.* 1988), which is extensively used in the Qasim area.

Eastern Saudi Arabian Tectono-Sedimentary Provinces

Within eastern and northeastern Saudi Arabia, four major tectono-sedimentary provinces can be recognized. One of these is the Arabian Platform, stretching from Kuwait to the Gulf of Salwa and lying primarily in northeastern Saudi Arabia. It is distinguishable from the Northern Interior Homocline by its very low-dipping strata, generally about 1/2° towards the northeast (Naimi 1965). In the Arabian Platform, water-bearing strata are mainly of Peleogene age (Bakiewicz *et al.* 1982), such as the Umm er Radhuma and Dammam formations, although Neogene strata in Al Hasa

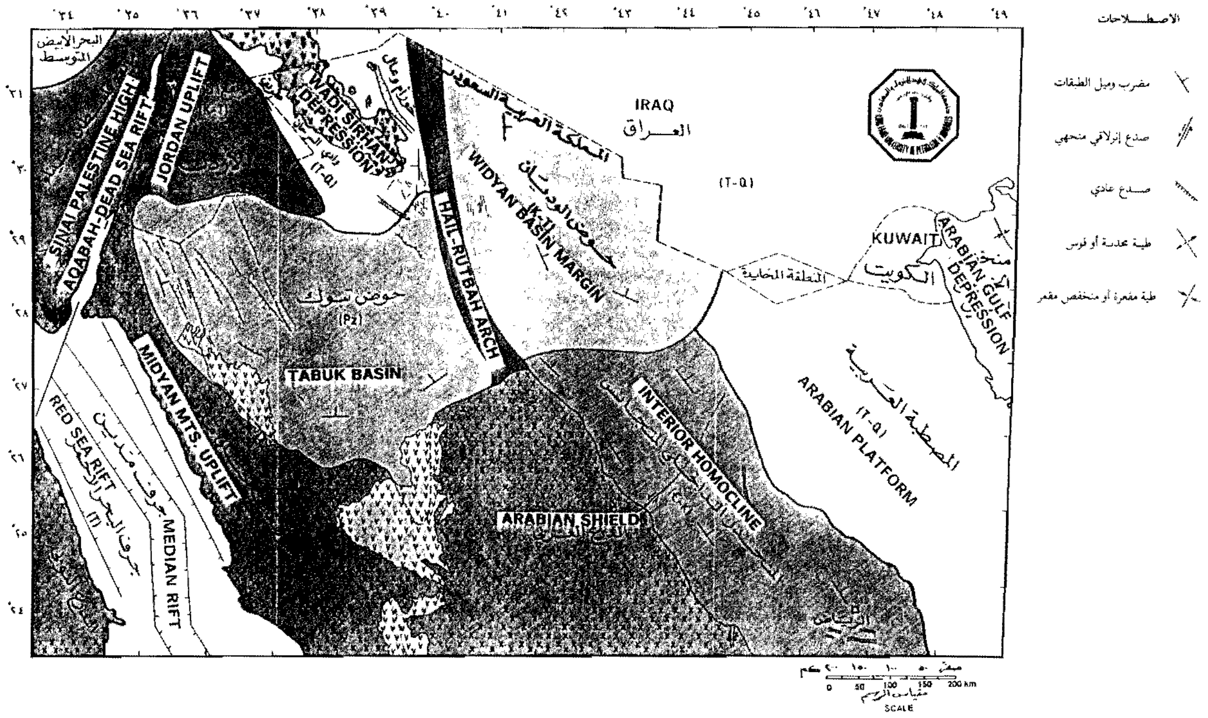

FIG. 2. Structural geology framework of northern Saudi Arabia.

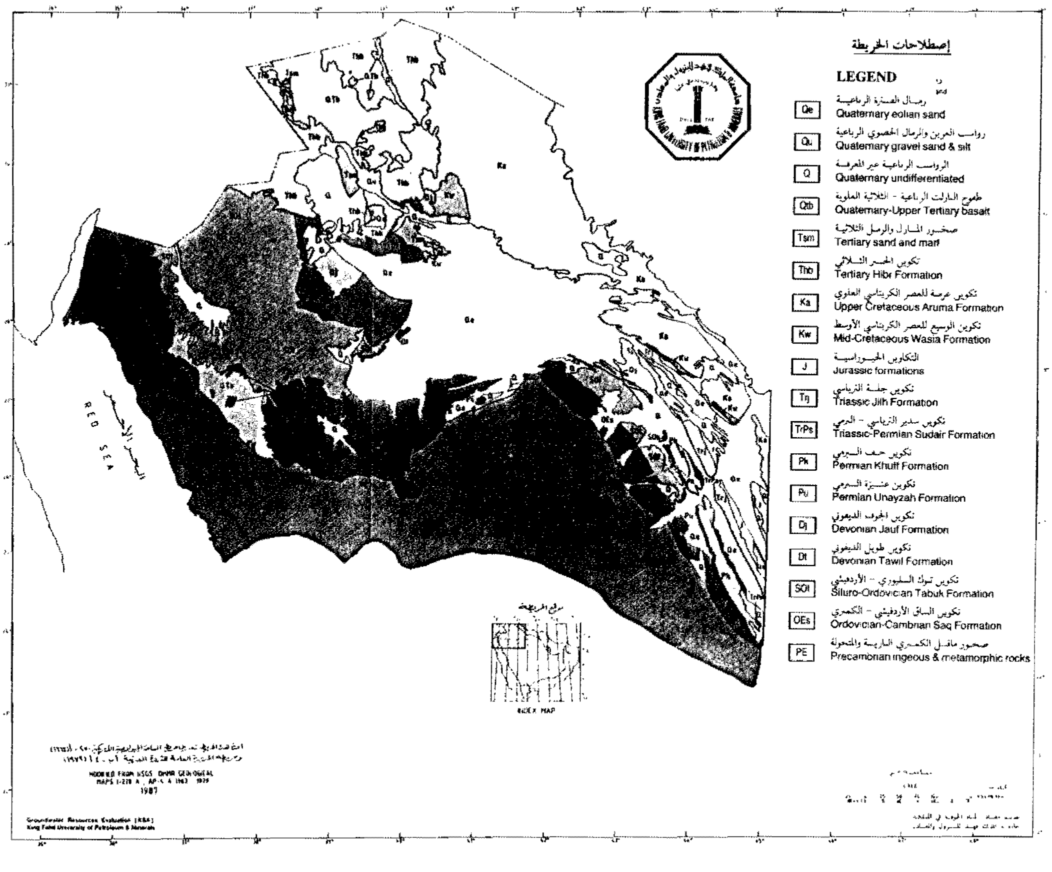

FIG. 3. Geology of the northwestern area.

area (B.R.G.M. 1977, Hötzl *et al.* 1978) provide large quantities of high quality water.

The Arabian Platform can be subdivided into smaller tectono-sedimentary units, such as the Summan Platform, Dibdibah Trough, Khurais-Jauf Arch, Central Basin, An Nala Trend (including Ghawar), and the Eastern Platform (including Al Hasa). It is terminated to the east by the north-south trending Qatar Arch (Fig. 4).

The Eastern Interior Homocline, south of the Central Arabian Arch to the latitude of As Sulayyil, comprises another tectono-sedimentary province of eastern Saudi Arabia. Large quantities of water are contained in sandstone aquifers of this province, especially in the Lower Cretaceous Buwaib and Biyadh formations, which form lakes in the area of Al Layla.

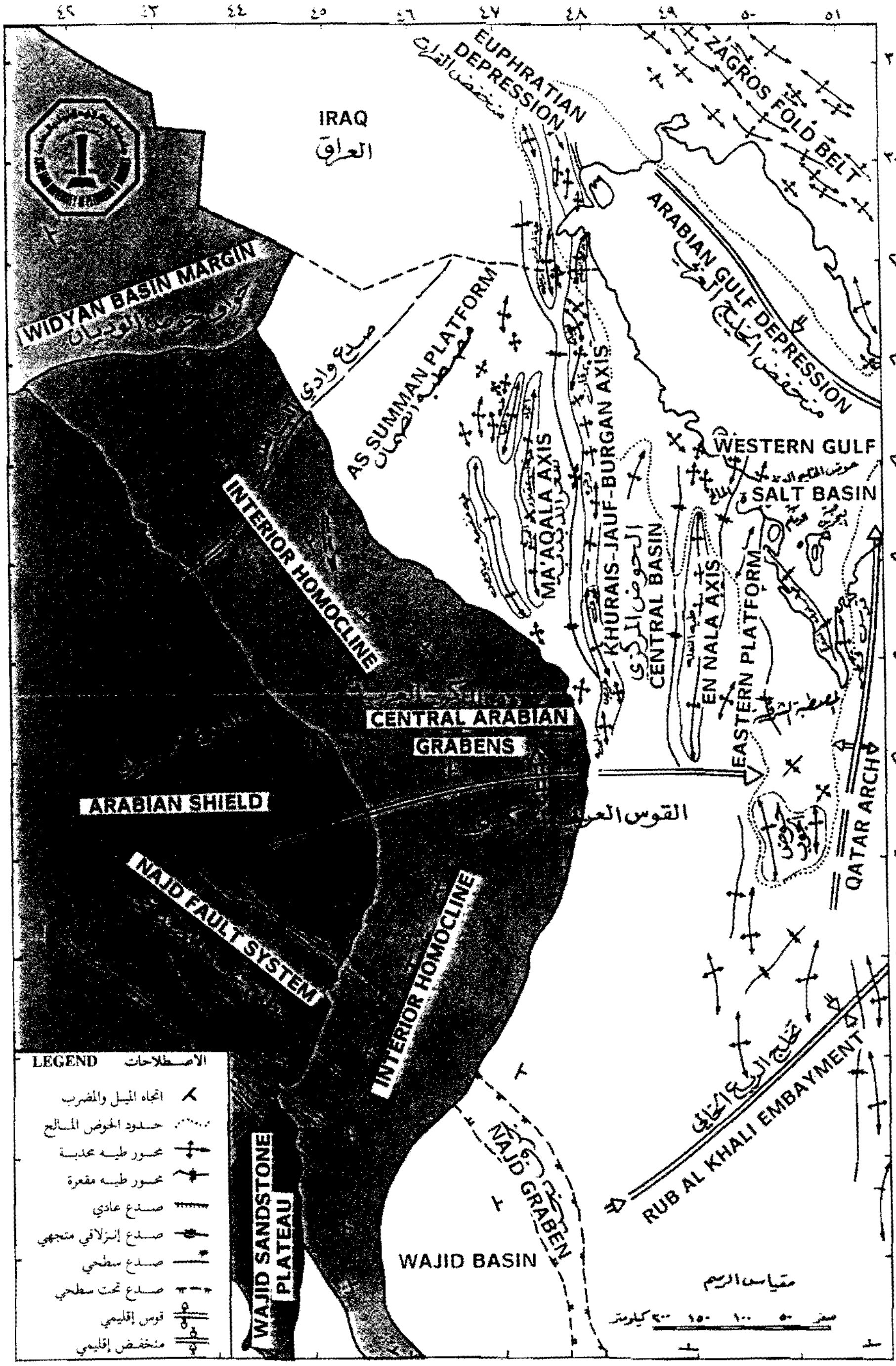

FIG. 4. Structural framework of the Eastern Province and adjacent areas.

The Qatar Arch, extending south to about Latitude 23°N, forms a structural ridge separating the Arabian Platform from the immense Rub' al Khali Embayment to the east (Brown 1972). Its growth began in the Late Jurassic and ended in Late Tertiary times. Aquifers in the Qatar Arch are found mainly in Lower Tertiary carbonate units, such as the Dammam and Umm er Radhuma formations.

Clearly, the largest tectono-sedimentary province in eastern Saudi Arabia is the Rub' al Khali Embayment (Edgell 1987a), which is a giant, U-shaped depression, whose axis plunges gently northeast to the Arabian Gulf. This very large, pericratonic basin has undergone slow and continuous subsidence since Late Jurassic but had reached its present form by the end of the Pliocene. The main water-bearing formation throughout the Rub' al Khali Embayment is the Umm er Radhuma Formation, while the Dammam Formation also contains useful aquifers in the northeast of the embayment, near Buraimi and in adjacent areas of Abu Dhabi. Recently, seismic surveys in the central Rub' al Khali have shown a shallow reflector at depths of about 66 m, which has proved to be a quite extensive Neogene aquifer.

Southern Saudi Arabian Tectono-Sedimentary Province

The southern part of Saudi Arabia, inland from the Asir Highlands and their crystalline rocks, consists essentially of one large, oval-shaped, tectono-sedimentary basin of Lower Paleozoic rocks, known as the Wajid Basin. This is the depositional basin of the Cambro-Ordovician to Carboniferous Wajid Sandstone, an important aquifer up to 900 meters thick, which covers an area of at least 196,000 km^2 (Fig. 5). On the southernmost borders of Saudi Arabia, the taphrogenic Marib-Shabwah Basin occurs, trending southeast between the two ancient towns from which the basin is named. This basin, between Yemen and southernmost Saudi Arabia, contains aquifers in Lower Cretaceous sandstones.

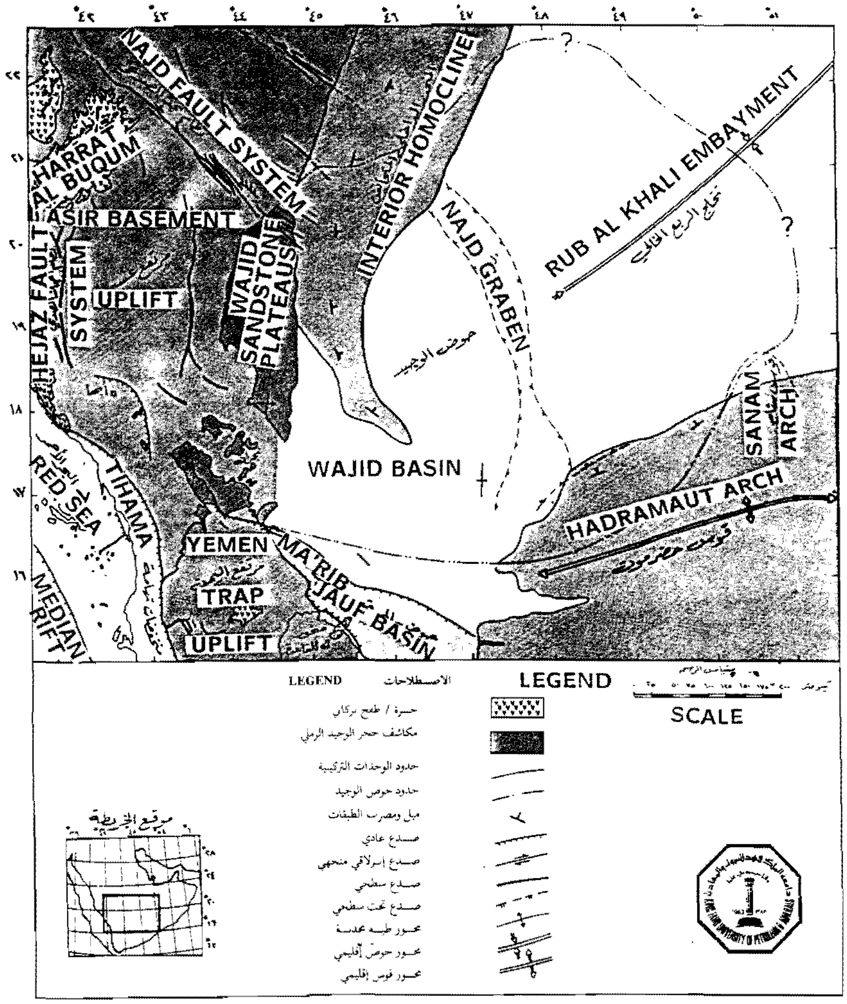

FIG. 5. Structural framework of the Wajid Basin and adjacent areas.

Aquifers and Aquicludes of Saudi Arabia

In the sedimentary basins of Saudi Arabia, there are major aquifers and aquicludes, as well as some aquitards. They are briefly described below in ascending stratigraphic sequence.

Saq Sandstone Aquifer

In northern Saudi Arabia, the major aquifer is the Saq Sandstone of Cambro-Ordovician age, which rests directly on crystalline rocks of the Precambrian basement. It consists of medium- to coarse-grained, brown to tan, friable, quartzose sandstone, with a moderately-bedded, basal conglomerate, up to 928 m thick at Ri'al Fuhah, west of Tabuk. It has a general thickness of 400 to 500 m in the southern Tabuk Basin and increases in thickness northwards. All along the southern edge of the Tabuk Basin, from Al 'Ula and Abu Taqah to just west of Jubbah, the Saq Sandstone is exposed and forms a widely accessible, unconfined aquifer. Since the formation dips gradually towards the north-northwest, it exists as a confined aquifer throughout most of the Tabuk Basin, with an estimated area of almost 300,000 km^2, being found at a subsurface depth of 360 m in the city of Tabuk (Al-Sagaby 1978) and at much greater depths further northwards. Effective porosity of the Saq Sandstone generally exceeds 15% (range: 10-20%) with transmissivity ranging from 9×10^{-3} to 3.8×10^{-2} m^2/sec, and storativity in the unconfined areas of 1.2×10^{-3} to 7×10^{-2}. Where the Saq Aquifer is confined, storativity ranges from 10^{-4} to 2×10^{-3} (KFUPM 1987). Isotopic age of water in the Saq Sandstone shows that it is fossil groundwater, 22,000 to 28,000 years old, indicating very little recharge at present, but major recharge in the Quaternary Ice Age pluvial interval.

Wajid Sandstone Aquifer

A very similar Cambro-Ordovician sandstone is found in southwestern Saudi Arabia, in an area of 196,000 km^2 between Wadi Najran and Ash Sharawrah in the south, and Wadi ad Dawasir in the north. This thick, well-sorted, coarse-grained, cross-bedded, quartz sandstone (Alabouvette and Villemur 1973) forms one single aquifer system, known as the Wajid Aquifer. Between Najran and Wadi ad Dawasir, there are extensive outcrops of the Wajid Sandstone, as well as outliers in the Asir Highlands, as at Habella, which act as unconfined aquifers over an area of about 26,000 km^2. The Wajid Aquifer dips gently eastward from the Asir Highlands, with a dip of about 1° (Greenwood 1980), under Permo-Carboniferous and Mesozoic strata of the southwestern Rub' al Khali, so that there is an area of some 170,000 km^2 where the Wajid Sandstone is a confined aquifer (Fig. 6). Thickness of the Wajid Aquifer varies from 200 to 900 m (Edgell 1987a). Effective porosity of this aquifer is in the order of 20%, and water stored in the aquifer is very conservatively estimated at 30 billion m^3 (Ministry of Agriculture and Water 1984). Water quality is good, with less than 1,000 mg/l of total dissolved solids. Isotopic determinations of the age of the groundwater in the Wajid Aquifer show that it is more than 30,000 years old (Ministry of Agriculture and Water 1979) and represents fossil water. Transmissivity varies between 5.7×10^{-4} and 2.1×10^{-2} m^2/sec, while storativity (Authman 1983) ranges from 2×10^{-4} to 2×10^{-1} in the large confined part of the Wajid Aquifer.

Hanadir Shale Aquiclude

The Hanadir Shale Member is the lowest member of the Tabuk Formation and consists of greenish gray to dark gray shale, with minor greenish gray, silty shale interbedded in its upper part. This shale member is Lower Ordovician (Powers *et al.* 1966), as indicated by frequent *Didymograpus protobifidus* Elles, and is a persistent lithostratigraphic unit throughout the northern area, although thickening slightly towards the north. It has a thickness of 53.8 m at the type locality of Jabal Hanadir and reaches a thickness of 100 m about 55 km south-southwest of Sakaka. The Hanadir Shale is of considerable hydrogeological significance as an aquiclude overlying the Saq Sandstone Aquifer.

Tabuk Aquifer

Within the Tabuk Formation, there is an alternation of aquifers and aquicludes. In ascending sequence, three major aquifers can be readily recognized, namely the Lower Tabuk Sandstone Aquifer, the Middle Tabuk Sandstone Aquifer, and the Upper Tabuk Sandstone Aquifer consisting of the combined Tawil and Sharawra members (Fig. 7).

Lower Tabuk Aquifer

The Lower Tabuk Sandstone Aquifer is an unnamed Lower Ordovician sandstone member of the Tabuk Formation. It consists of fine- to medium-grained, micaceous sandstone with thin, minor siltstone and shale intercalations in its upper part. This aquifer has a thickness of 54 m near Buraydah, 140 m at Tabuk, and up to 389 m in the Turabah Water Well (Parsons Basil Consultants 1968). It has good characteristics as a confined aquifer with an effective porosity from 8 to 20%, and is sandwiched between the Hanadir and Ra'an Shale members. Transmissivity of the Lower Tabuk Aquifer averages about 2×10^{-3} m^2/sec, while its storativity varies from 2×10^{-2}, where the aquifer is unconfined, to 6×10^{-4} where confined.

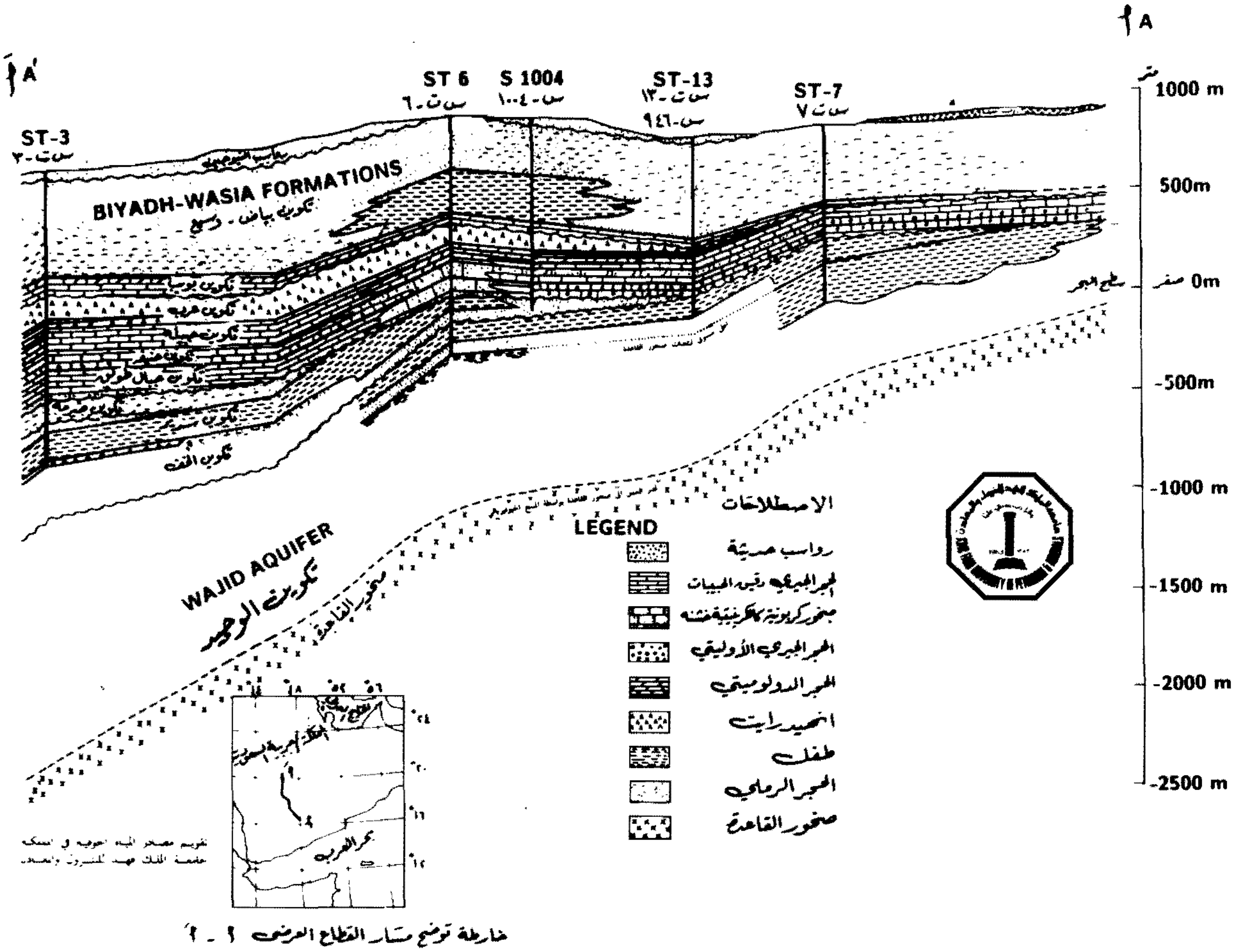

FIG. 6. Cross section showing successive strata in the southwest of Saudi Arabia.

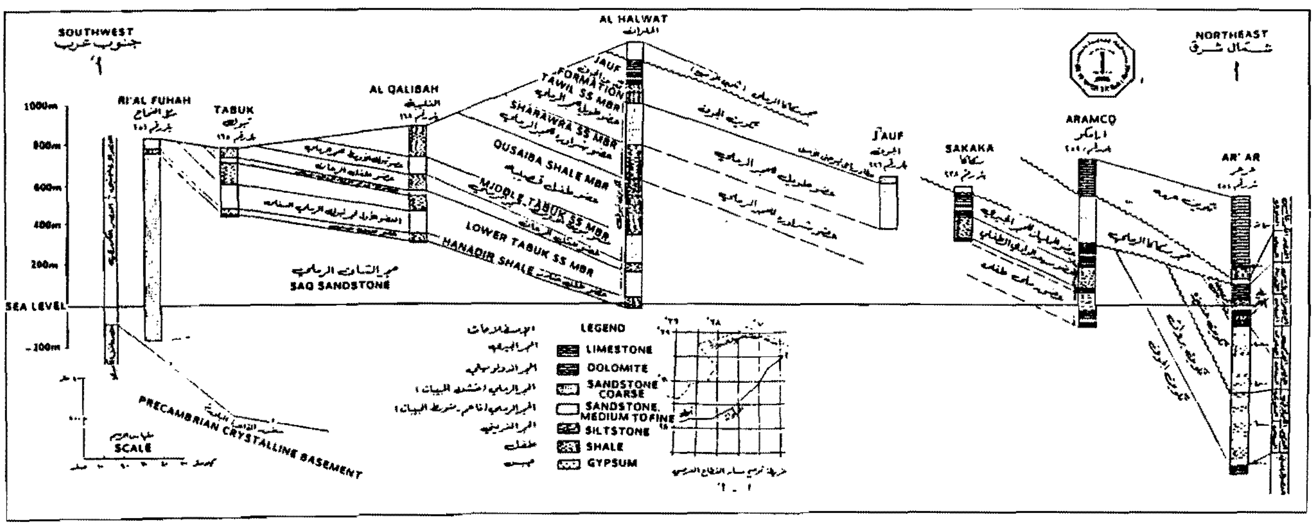

FIG. 7. Stratigraphic cross section from southwest to northeast across the Tabuk and Widyan basins, northwestern Saudi Arabia.

Ra'an Shale Aquiclude

A distinctive, purplish gray to greenish gray, micaceous, graptolitic shale directly overlies the Lower Tabuk Sandstone Aquifer and acts as its upper aquiclude. This is the Upper Ordovician Ra'an Shale Member, which varies in thickness from 14 to nearly 100 m, with its thickest drilled sequence of 94 m in the Tabuk Water Well.

Middle Tabuk Aquifer

The Middle Tabuk Sandstone Aquifer comprises another member of the Tabuk Formation, consisting mainly of fine- to medium-grained, micaceous, cross-bedded, quartz sandstones with a basal conglomerate up to 1 m thick. Except for a thin basal conglomerate, whose striated boulders represent Late Ordovician glaciation (McClure 1978), the majority of the Middle Tabuk Sandstone Aquifer is of Early Silurian age. It is a confined aquifer with an effective porosity of at least 10% in the north-central Tabuk Basin, being 83 m thick near Tabuk. In the Interior Homocline, it occurs north of Al Qasim and is 242 m thick in a well at Al Qusayba. At Al Qalibah, in the central Tabuk Basin, the Middle Tabuk Aquifer has a thickness of 197 m (Parsons Basil Consultants 1968). In the Tabuk area, transmissivity is about $1.7 \times 10^{-3} m^2/sec$, and its storativity is 2×10^{-4}, where unconfined, and 1×10^{-3} where confined (KFUPM 1987).

Qusaiba Shale Aquiclude

The Qusaiba Shale member forms an important aquiclude confining groundwater in the Middle Tabuk Aquifer. It consists of varicolored, red, gray and gray-green, graptolitic shales with some ferruginous siltstones in its upper part, and is of Early Silurian age with frequent *Monograptus* spp. Thickness of this aquiclude varies from 49 m at Al Qusayba to 206 m in the At Tawil Well.

Upper Tabuk Aquifer

Comprising the Upper Tabuk Sandstone Aquifer are two sandstone members of the uppermost part of the Tabuk Formation. They are the Lower Silurian Sharawra Sandstone Member and the Lower Devonian Tawil Sandstone Member, which overlies it disconformably (Powers 1968). The Sharawra Sandstone Member, although quite thick (*e.g.*, 379 m at Turayf and 765 m in the At Tawil Well), is a fine-grained sandstone, with much interbedded shale in the lower part. The hydrological characteristics of the Tawil Sandstone are much better (10 to 20% effective porosity), as it consists of gray to brown, medium- to coarse-grained, sometimes pebbly, dominantly cross-bedded, quartz sandstone. The thickness of the Tawil Sandstone Members reaches 200 m in outcrops near At Tawil, and 189 m in a well at Turabah. The total thickness of the Upper Tabuk Sandstone Aquifer is, thus, up to 965 m, although averaging about 500 m. Transmissivity of this aquifer ranges from 10×10^{-3}, to $7 \times 10^{-4} m^2/sec$, while storativity varies from 1.4×10^{-3} where it is confined, to 3.5×10^{-2} in unconfined parts (KFUPM 1987).

Jauf Aquifer and Basal Aquiclude

The Devonian Jauf Formation directly overlies the Upper Tabuk Sandstone Aquifer in the northeast, Al Huj area, of the Tabuk Basin, and the sandy shaly Shaibah Member constitutes a local aquiclude for the Upper Tabuk Sandstone Aquifer. Other units of the Jauf Formation, such as the Qasr Limestone and Hammamiyat Limestone members are water-bearing. The formation also contains sandstones to the north and west of Jauf, which yield good quality water (300 mg/l TDS). Transmissivity for the Jauf Aquifer is generally lower at $1.1 \times 10^{-3} m^2/sec$, where confined, and higher at $3 \times 10^{-3} m^2/sec$, where unconfined. Storativity ranges from 2×10^{-2} in unconfined parts, to about 2×10^{-3} where confined.

Berwath Aquifer

The Carboniferous Berwath Formation is not exposed, and occurs mainly in the subsurface of the Midyan Basin Margin to the north of Turabah (Al-Laboun 1986). It consists of fine- to coarse-grained, argillaceous sandstone with common interbeds of siltstone and some shale, averaging about 250 m in thickness. Interbedded sandstones of the Berwath Formation provide fair to moderate yields of good quality water for 50 km to the southeast of 'Ar'ar. An average transmissivity value is $3 \times 10^{-3} m^2/sec$, and storativity is about 1×10^{-3}.

'Unayzah Aquifer

In the Interior Homocline, Carboniferous and mostly Lower Permian clastics of the 'Unayzah Formation unconformably overlie and overlap various formations from Cambrian to Devono-Carboniferous. Lithologically, the 'Unayzah Formation comprises cross-bedded, fine- to coarse-grained fluvioglacial sandstones with siltstones, green-gray and purple claystones, and thin beds of impure limestones (Al-Laboun 1987). It is 33 m thick in its type locality at 'Unayzah and thickens northward to some 400 m on the southern border of Kuwait. In the Al Hawtah area, 150 km south of Riyadh, it thickens locally to 45 m. This formation also extends to the southern part of the Interior Homocline, where it is known locally at the Faw Formation and yields modest amounts of groundwater. In general, the 'Unayzah Aquifer has a relatively low yield and low storativity.

Khuff Aquifers

The Upper Permian Khuff Formation extends in outcrop all along the Interior Homocline, from Jabal al Qasdah in the south to near Turabah in the southeastern Nafud, a distance of over 1,200 km. It is widespread in the subsurface, from the southern Rub' al

Khali northwards into Iraq, but it does not extend into the Tabuk or Wadi as Sirhan basins. Lithologically, it consists of limestones and dolomites, with some anhydrite aquicludes, which divide it into four permeable carbonate units, named Khuff A, B, C and D, in descending order (Al-Jallal 1987). They act as rather poor aquifers (3% effective porosity) with mineralized water. Thickness of the Khuff Formation averages about 250 m, thickening generally towards the northeast to 600 m in the Ash Shu'bah area. Aquifers of the Khuff Formation are secondary aquifers in Saudi Arabia, due to low storativity and low yield.

Sudair Shale Aquiclude

The Sudair Shale (Steineke *et al.* 1958) averages 200 m in thickness, and acts as a widespread aquiclude for the Khuff aquifers in the Qasim area and for the Upper Tabuk Sandstone Aquifer in the Turayf area. The Sudair lithology is mainly brick- to dark-red, massive shale with minor gypsum interbeds. This formation is mainly of Early Triassic age.

Jilh Aquifer

A poor aquifer of thin-bedded, Middle Triassic limestone, with minor shale and gypsum, conformably overlies the Sudair Shale, and is known as the Jilh Aquifer. This aquifer is exposed along the Northern Interior Homocline in a belt about 20 km wide and forms the Jilh Scarp. Thickness of the Jilh Aquifer is from 360 to 400 m. It also occurs in the Wadi as Sirhan Basin, where about 130 m of sandstone with limestone interbeds were penetrated in the Turaif Water Well. The Jilh Formation generally forms a secondary aquifer, owing to its poor water quality, caused by dissolved calcium sulfate from anhydrite and gypsum layers in the formation. East of Riyadh, in the areas of Batin and Thamamah, a number of deep wells were drilled in 1984 to tap the Jilh Aquifer, with yields averaging 63 l/sec from sandstones (Ministry of Agriculture and Water 1984).

Minjur Aquifers

The Minjur Sandstone comprises two major aquifers, namely the Upper Minjur Aquifer and the Lower Minjur Aquifer, consisting of cross-bedded, coarse- to very coarse-grained, quartz sandstone separated by the Middle Minjur shales and mudstones in the Riyadh area (El Khatib 1980). It also contains minor interbeds of limestone, conglomerate and gypsum. It crops out mainly along the Northern Interior Homocline, but thins and becomes shaly north of Latitude 27°N.

In the Riyadh area, the Minjur Formation is 400 m thick, and comprises two sandstone aquifers. These two aquifers are of considerable importance, since they yield 90% of the groundwater supply to the City of Riyadh (Ministry of Agriculture and Water 1984). In the Sudair-Riyadh-Aflaj area), it is estimated that the Minjur aquifers contain 460 million m^3 of sufficiently good quality water for general use (El Khatib 1980). As an aquifer, the Minjur has good transmissivity and good quality water, 1,400 mg/l TDS at Riyadh, and 1,600 mg/l TDS at Sudair. However, the water quality becomes poorer southward and, at Al Aflaj, it is as high as 4,100 mg/l of total dissolved solids. The major part of the Minjur Sandstone belongs to Upper Triassic, while the thinner upper part is Lower Jurassic. The Minjur Sandstone acts primarily as a confined aquifer, although south of 23°N it forms a single aquifer complex with the sandy Dhruma Formation. Transmissivity of the Minjur in the Riyadh area varies from 1.7×10^{-3} to 7.2×10^{-3} m^2/sec, while its storativity as a confined aquifer is 1.3×10^{-4}.

Marrat Aquiclude

The Lower Jurassic Marrat Formation, some 120 m thick, directly overlies the Minjur Sandstone north of Riyadh, and is exposed in outcrops along the Northern Interior Homocline, as far north as Wadi ar Rimah. It mainly consists of aphanitic and calcarenitic limestone, but contains interbedded shale, siltstone, and sandstone towards its base. The lower thin sandstones generally contain small quantities of fair to good quality groundwater and is counted as the uppermost part of the Minjur Aquifer. The shales, siltstones, and aphanitic limestones of the Marrat Formation generally act as an aquiclude to the important Minjur Aquifer.

Dhruma Aquifer

Middle Jurassic limestones of the Dhruma Formation succeed the Marrat Formation, and are 375 m thick in the type section. The Dhruma Formation becomes dominantly sandstone with limestone interbeds in the area south of Latitude 22°N along the Interior Homocline, where it has moderate to good yields of good quality groundwater. In this southern area, it joins with the Minjur Sandstone to form one interconnected aquifer, often referred to as the Minjur/Dhruma Aquifer (Ministry of Agriculture and Water 1984), with transmissivity values from 1×10^{-2} to 1.6×10^{-2} m^2/sec.

Upper Jurassic Aquitards

As ascending sequence of Upper Jurassic formations overlies the Dhruma Formation. It comprise the Tuwaiq Mountain Limestone, Hanifa Formation, Jubaila Formation, Arab Formation, and the Hith Anhydrite, which are all exposed along the Interior

Homocline (Steineke *et al.* 1958), although towards the north and northwest they are all truncated by the Pre-Wasia Unconformity (Edgell 1987b), just south of Wadi ar Rimah. These Upper Jurassic formations have very limited hydrogeological significance, since they are either dense, aphanitic and argillaceous limestones, which act as aquitards such as the Tuwaiq Mountain Limestone and the Jubaila Formation, or they contain much anhydrite, as with the Arab Formation and Hith Anhydrite, which both yield only limited amounts of highly mineralized water.

Hanifa Aquifer

Only a massive bed of oolite-pellet calcarenite at the top of the Hanifa Formation has good permeability downdip, and this bed provides limited amounts of groundwater from wells in Wadi Hanifah.

Sulaiy-Yamama-Buwaib Local Aquifers

Limestone formations, such as the Sulaiy, Yamama and Buwaib in ascending sequence, comprise the lower part of the Lower Cretaceous in the Interior Homocline. They are generally unimportant for groundwater, with a few local exceptions. Thus, in Wadi as Sulaiy, about 20 km southeast of Riyadh, calcarenites in the lower Sulaiy Formation act as a minor local aquifer with water quality of 1,000 to 3,000 mg/l of total dissolved solids. Elsewhere, the Sulaiy Formation consists of low permeability, aphanitic and calcarenitic limestones, about 150 m thick. Its outcrop only extends for 100 km to northwest of Riyadh, after which it is truncated in the subsurface by the Pre-Buwaib Unconformity (Edgell 1987b). The overlying Yamama Formation comprises about 50 m of tightly cemented, pellet-calcarenites with aphanitic limestones in the lower part. It is also of little importance from a hydrologic viewpoint, except in the Layla lakes area ('Uyun Al Aflaj), where dissolution of the underlying Hith Anhydrite by groundwater has caused the Sulaiy, Yamama, and Buwaib formations to collapse and become brecciated, so that good secondary permeability is developed and groundwater circulates freely (Ministry of Agriculture and Water 1984). This area was developed in ancient times by falaj, or qanats, around a lake about 4 km^2 in area (Ritter 1981, Fig. 1), although it is now reduced to seventeen small lakes.

The Buwaib Formation consists of completely interbedded shale, siltstone, dolomite, calcarenite, and aphanitic limestone. It is only 17.7 m thick in outcrop at its type section and thickens in the subsurface to 100 m at Khurais with a generally similar lithology, and has no known groundwater potential other than the local occurrence at 'Uyun al Aflaj.

Wasia-Biyadh Aquifer

The sandy, largely non-marine, Lower Cretaceous Biyadh Formation is a major aquifer in northeastern and eastern Saudi Arabia (B.R.G.M. 1976). It crops out along the Interior Homocline from just east of As Sulayyil to Wadi Atk, some 125 km north-northwest of Riyadh. In its type section, just south of Riyadh, the Biyadh Formation consists of 425 m of cross-bedded, quartz sandstone, with some shale and conglomeratic layers (Powers *et al.* 1966). The quality of water from the Biyadh Sandstone is very good in the Nisah Graben (500-900 mg/l TDS) and fair at Kharj, but is poor at depth, and in the Eastern Province (De Jong *et al.* 1989). It gives good yields of groundwater in Wadi Nisah. The Biyadh Sandstone thins northwestward in outcrop, being truncated by the Pre-Wasia Unconformity.

Although the Biyadh Sandstone is unconformably overlain by sandstones of the Wasia Formation, they both form one immense aquifer system in the Eastern Interior Homocline and the Widyan Basin Margin area, with an estimated recharge in 1967 of 480 million cubic meters per year from runoff from Jabal Tuwayq, and wadi underflow (Ministry of Agriculture and Water 1984). A short distance downdip, fluid communication between the Biyadh and Wasia formations is restricted and each operates as an isolated hydrogeologic system, due to development of shales towards the northeast at the top of the Biyadh Sandstone. Near Kharj, water in this aquifer was shown to be 8,000 years old, and some 16,000 years old downdip at Khurais (SOGREAH 1967).

The Mid-Cretaceous Wasia Formation is a transgressive and porous, cross-bedded, quartz sandstone, with green shale interbedded in the lower part. It is exposed along the Interior Homocline from Wadi ad Dawasir to as far north as Turabah and occurs on the Ha'il-Rutbah Arch at Sakaka, where it is often referred to separately as the Sakaka Sandstone, although palynological studies of core samples by Saudi Aramco have shown it to contain distinctive Cretaceous spores (McClure, personal communication 1989). Exposures of the Mid-Cretaceous sandstones, in the Rutbah area of western Iraq, provide recharge southwestward into Cenozoic strata of the Wadi as Sirhan Basin (Khouri 1982). In the northern area around Sakaka, the Wasia Formation is about 200 m thick and is a good aquifer with high effective porosity ranging from 10 to 29%. It also has good hydraulic characteristics, with an average transmissivity of 3×10^{-4} to 2.8×10^{-3} m^2/sec, increasing northeastward to 15×10^{-3} m^2/sec. The average storage coefficient ranges from 3×10^{-2} to 5×10^{-2} in the unconfined part and is about 7 ×

10^{-3} in its confined part (KFUPM 1987). The sandstones of the Wasia Formation join with those of the underlying Biyadh Sandstone to make a single hydraulic unit along most of the Interior Homocline. This joint Wasia-Biyadh Aquifer is one of the largest potential aquifers in Saudi Arabia with very large amounts of water in storage, estimated at several billion m^3 in the Riyadh area alone (Area V) (El Khatib 1980). It supplies raw water to Riyadh and has excellent hydrological properties. At Khurais, it has good yields of groundwater containing 550 to 1,500 mg/l of total dissolved solids. Basinward, the Wasia Formation divides into seven members and groundwater quality becomes increasingly poor towards the northeast, where it ultimately forms oil field brines in many areas of offshore Saudi Arabia.

Aruma Aquifer

A transgressive, marine, Upper Cretaceous lithostratigraphic unit, known as the Aruma Formation, underlies almost all the Arabian Platform, but does not extend into the Tabuk Basin. It forms an escarpment along the entire Interior Homocline. Northwards, in the Widyan Basin Margin, it covers a large surface area of at least 170,000 km^2. The lithology of the Aruma Formation consists primarily of fine-grained to chalky, or calcarenitic limestone, with some shale and dolomite towards the top.

The Aruma Aquifer is a secondary aquifer with relatively poor quality groundwater, although its groundwater is used by wells on the pipeline stations of Badanah and Rafha. Downdip, in the subsurface, water quality decreases, so that the eastern edge of potable water can be taken as a line from Hafar al Batin to the southwestern end of Ghawar. The Aruma Formation varies in thickness from about 60 to 140 m. In the Wadi as Sirhan Basin, it is mostly shale and shelly marl, with a few thin limestone interbeds and acts as an aquitard, allowing water from the Wasia Formation to seep upwards into Paleogene limestones and Neogene sands (Khouri 1982, Fig. 6, 12).

In the area east of Wadi ad Dawasir, the Aruma Formation occurs in sandy facies and combines with the Wasia and Biyadh sandstones to form the Cretaceous Sand Aquifer (Ministry of Agriculture and Water 1984). It has usable groundwater with about 1,800 mg/l of total dissolved solids. Transmissivity is 7×10^{-3} m^2/sec, and storativity, where the aquifer is unconfined, is about 2×10^{-2}.

Umm er Radhuma Aquifer

The Paleocene-Lower Eocene Umm er Radhuma Formation is a very extensive, tabular, carbonate unit, which forms one of the most important aquifers (Naimi 1965) throughout the Eastern Province (Fig. 9). It extends beneath almost the entire Rub' al Khali from northern Hadramaut and western Oman to the Saudi/Iraq border. Lithologically, it consists of calcarenitic limestone with some dolomitic limestone, dolomite, minor marl and shale, and aphanitic, argillaceous limestones in the lower part (Powers *et al.* 1966). In the exposed reference section at Wadi al Batin, the Umm er Radhuma is 243 m thick, but its thickness in the subsurface varies between about 300 and 700 m. It has an extensive outcrop area along the Interior Homocline from Latitude 22°N, northwards through the Summan Plateau (Felber *et al.* 1978), the Widyan Basin Margin and into western Iraq. It is often karstified in outcrop and, probably, also in the subsurface (Italconsult 1969). The Umm er Radhuma is not one complete interconnected aquifer, due to the presence of intercalated marls, shales, and argillaceous limestones. It may also contain thin stringers of anhydrite. However, it yields good to poor quality groundwater, mostly from aquifers in the upper third of the formation, where horizons of porous foraminiferal calcarenite, or of small dolomite rhombs (as at Ain Dar) constitute the zones with highest yield of up to 95 l/sec, as at Haradh. This is fossil water, 10,000 to 28,000 years old. Springs in Al Hasa provide large volumes of water through Neogene strata (Hötzl *et al.* 1978), but this mostly originates from the Umm er Radhuma Aquifer. The quality of groundwater from the upper part of the Umm er Radhuma Formation is generally good but can be quite poor from the lower part of this lithostratigraphic unit. Water quality also declines towards the northeast from less than 1,000 ppm near outcrop to 6,000 ppm along the coastal area (Naimi 1965), although it is always of better quality on structural highs, such as the Dammam Dome, due to absence of anhydrite in the Rus Formation. Shales and argillaceous limestones at the base of the formation form an aquitard between the Aruma and Umm er Radhuma aquifers. The vertical connection between the Wasia-Biyadh aquifer system and the Umm er Radhuma aquifer system has been computed as only 0.05 l/sec/km^2 (B.R.G.M. 1977) and the two aquifer systems behave independently. There is, however, considerable vertical leakage from the Umm er Radhuma upward, where the Rus Formation is thin, as at Wadi al Miyah, into the Dammam Formation aquifers. In the Ghawar area, transmissivity ranges from 3×10^{-3} to 5×10^{-4} m^2/sec. Storativity ranges from 5×10^{-5} to 5×10^{-3} where the Umm er Radhuma aquifer system is confined, and from 2×10^{-3} to 7×10^{-2} where unconfined.

Hibr Aquitard

West of the Hail-Rutbah Arch, Paleocene-Lower

Eocene strata exist in a different lithofacies, known as the Hibr Formation (Powers 1968). It consists of thin-bedded, chalky and cherty limestone and marl from 150 to 485 m thick. The Hibr Formation acts as an aquitard in the Wadi as Sirhan Basin (Khouri 1982), although containing a minor chert aquifer.

Rus Aquiclude

The Lower Eocene Rus Formation, consisting of interbedded marl, dolomite, limestone and anhydrite, forms an aquiclude which generally caps groundwater in the Umm er Radhuma Formation over most of the Eastern Province. On structural highs, the Rus Formation is mainly composed of dolomite and can yield small amounts of poor quality water by upward leakage from the Umm er Radhuma Aquifer, whereas in structural troughs it mostly consists of impermeable anhydrite, gypsum, and marl. Eroded Rus occurs on South Ghawar (Fig. 8)

Province from Wadi as Sahba to the coast at Qatif. Although widespread, the Khobar Aquifer generally has low productivity and transmissivity of 2×10^{-3} to 10^{-4} m^2/sec and storativity of 1×10^{-3} to less than 10^{-4} (B.R.G.M. 1977), although it has a high transmissivity zone in the northeastern part along the Arabian Gulf coast, with good productivity (Yaziçigil *et al.* 1986). The Alat Aquifer has low matrix porosity and is generally fine-grained, so that it is a relatively minor aquifer with transmissivity of 2.6×10^{-5} m^2/sec at Wadi Al Miyah to 2.3×10^{-3} m^2/sec at Ras Tanura, where its storativity ranges from 1.32 to 5.34×10^{-4} (Ministry of Agriculture and Water 1984).

Neogene Aquifers

Disconformably overlying the Middle Eocene Dammam Formation, in most of the Eastern Province, is a Neogene complex, consisting in ascending sequence of the Hadrukh, Dam, Hofuf and Kharj for-

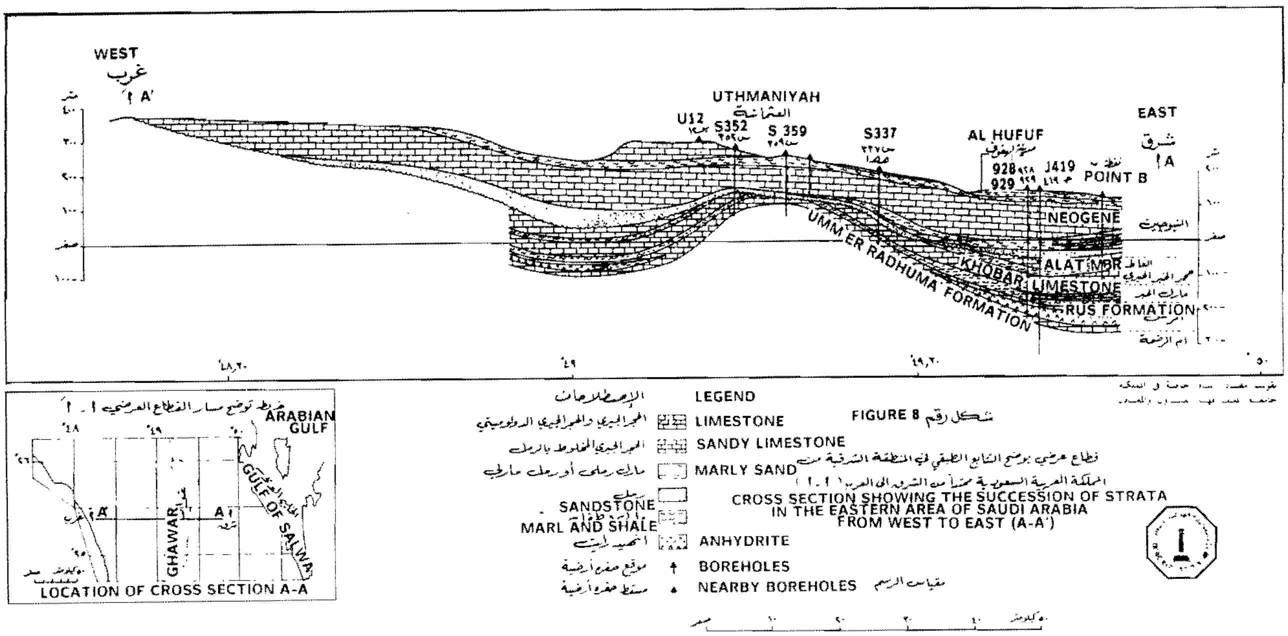

FIG. 8. Cross section showing the succession of strata in the eastern area of Saudi Arabia from west to east (A-A').

Dammam Aquifers (Alat & Khobar)

Middle Eocene limestones throughout northeastern and eastern Arabia are known as the Dammam Formation and are generally from 50 to 75 m thick. There are five members of this formation, but only the upper two are water-bearing. These form the Alat and Khobar aquifers, poorly separated by the Alat Marl aquitard, and yield moderate amounts of groundwater in Al Hasa and Wadi al Miyah. The Alat Aquifer is of more limited extent, and the Khobar Aquifer, which is karstified and fissured, provides water for domestic and agricultural purposes in many parts of the Eastern

mations. They are briefly described as basal calcareous sandstones and sandy marls (Hadrukh Formation), disconformably overlain by marls and clays with some subordinate limestones (Dam Formation), and further disconformably overlain by coarse-grained sandstones and conglomerates with thin marls (Hofuf Formation), upon which rest conglomerates and thin limestones of the very locally developed Kharj Formation.

This mainly clastic, Mio-Pliocene sequence is about 300 m in thickness. The conglomeratic and sandy Kharj Formation is Pliocene and only locally developed in southeast of Riyadh and has no hydrologic importance. Sandstones of the Hofuf Formation also lack any significant groundwater.

Hadrukh and Dam Aquifers

Only the basal detrital Hadrukh Formation of Miocene age and the fissured and karstified limestone of the Middle Miocene Dam Formation contain good quality groundwater. The basal Hadrukh Formation is in contact with an eroded window to the Umm er Radhuma aquifer (B.R.G.M. 1977) in the south of the Ghawar Anticline (Fig. 9) and there is a general northeastern flow of water in the Hadrukh Aquifer, with highest permeabilities being recorded to the southwest of Hofuf. Transmissivity of the Hadrukh Aquifer around Hofuf varies from 7×10^{-4} to 4×10^{-2} m^{-2}/sec, while storativity is about 2×10^{-4} in its confined part, and 1×10^{-2} where it is unconfined (B.R.G.M. 1977). The overlying, fissured Dam Aquifer has transmissivity which locally exceeds 10^{-2} m^2/sec on the Ghawar Anticline, with fissures being infilled with sand and gravel. The Dam Formation becomes a marly sand towards the east, and has poor hydraulic characteristics. Although these Neogene formations are well-mapped between Ras as Saffaniyah and Yabrin, they are not distinguished on the more general mapping of the Summan Plateau, or of the Rub' al Khali. Recently, seismic surveys for Saudi Aramco in the central Rub' al Khali have indicated a shallow reflector in the Neogene, which has proved to be a widespread Neogene aquifer.

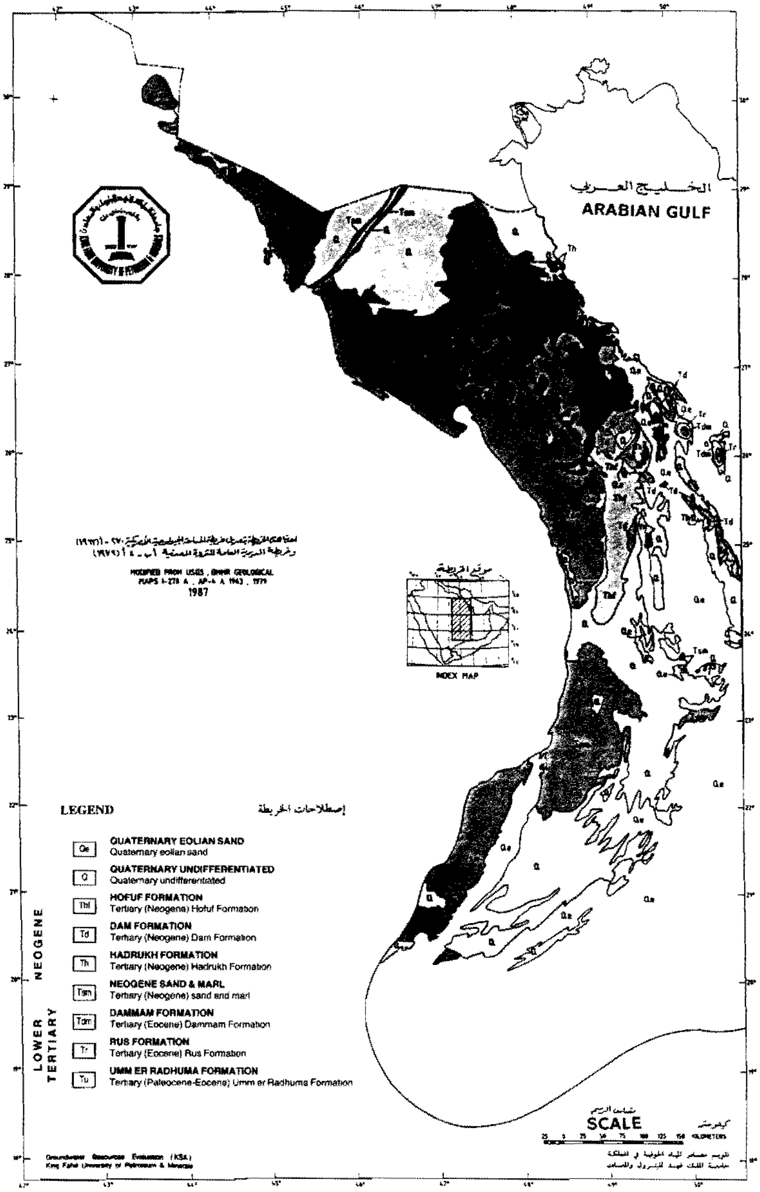

FIG. 9. Geology of the eastern area.

Mio-Pliocene Aquifers (Wadi as Sirhan Basin)

In the Wadi as Sirhan Basin, there are continental Mio-Pliocene calcareous sandstones, sandy marls and minor freshwater limestones up to 200 m thick, which have good permeability and constitute the main aquifer in that area. Transmissivity of this Mio-Pliocene sandy aquifer is about 15×10^{-3} m^2/sec in northwestern Wadi as Sirhan and 40×10^{-3} m^2/sec in its southeastern part. Storativity ranges from 1×10^{2} to 3×10^{-2}, where the aquifer is confined, and is about 2×10^{-3} where it is confined (KFUPM 1987).

Basalt Aquifers

Late Tertiary and Quaternary basalts of the Harrat al Harrah extend along a northwest-southeast trend parallel to Wadi as Sirhan. These basalts act as low yield aquifers with very variable transmissivity due to changing fracture system, weathering, and the amount of volcanic breccia. Water has been obtained in considerable quantities from similar basalts and pyroclastics in Syria and Jordan (El Khatib 1980).

Quaternary Alluvial Aquifers

Considerable groundwater development in Saudi Arabia has taken place in alluvium-filled wadis, such as those of the Red Sea coast, interior Asir, the Riyadh area, the Rimah-Batin system, and Wadi as Sirhan.

Significant agricultural development has already taken place along the wadis of the Red Sea coast, namely in Wadi Jizzan and Wadi Dhamad in the Tihama district (El Khatib 1980), where shallow groundwater exists in the wadi alluvium. Earlier use of wadi underflow, important to the growth of Saudi Arabia, has taken place in wadis Fatimah, Lith, Khulays, Rabigh, Baysh, and Hali. It is estimated that these large wadis draining to the Red Sea have a storage of 14,250 million m^3 and a potential development capability of 105 million m^3/year of poor to good quality, shallow groundwater (Ministry of Agriculture and Water 1979). Wadi Fatimah supplies shallow alluvial groundwater to both Makkah and Jeddah, while groundwater in Wadi Khulays has also been developed to supply Jeddah.

The highland city of Taif is also supplied with water from shallow groundwater in the alluvium of nearby Wadi Wajj and Wadi Liyyah, as well as that piped from wells in Wadi Turabah (El Khatib 1980).

Draining eastward from the Asir Highlands, the Wadi ad Dawasir valley, backed by drainage from Wadi Bishah and Wadi Tathlith, provides good alluvial aquifers of Quaternary to Pliocene age, up to 100 m thick, which provide large quantities of relatively good quality groundwater for pivotal irrigation systems. This Asir-Dawasir alluvial wadi system can provide some 17,700 million m^3 of groundwater for irrigation, with a potential development of more than 25 million m^3/year (Ministry of Agriculture and Water 1979).

In southern interior Asir, the eastward flowing non-perennial watercourse of Wadi Najran draining from the uplands of the Asir and north Yemen, contains good quality shallow groundwater in the alluvium of the valley center with a storage of 33,350 million m^3 and good recharge due to rainfall up to 500 mm/year in the headwaters of the Wadi Najran (El Khatib 1980).

In the Riyadh region, the alluvium-filled valleys of Wadi Birk, Wadi Nisah and the upper reaches of Wadi as Sahba contain considerable poor to good quality groundwater (14,100 million m^3/year), which is much used for irrigation purposes.

The northeast flowing Wadi ar Rimah-Wadi al Batin system drains over a large area of the Arabian Shield. It contains usable supplies of shallow groundwater of generally poor quality, which are used mainly in the areas near Al Badaya' and 'Unayzah.

Along Wadi as Sirhan, Quaternary and Pliocene sands contain significant shallow groundwater, with an average TDS of 2,000 mg/l, often exploited by hand dug wells (Ministry of Agriculture and Water 1979).

Groundwater Stratigraphy of Individual Tectono-Sedimentary Basins

Each tectono-sedimentary province in the sedimentary areas to the north, east, and south of the Arabian Shield, has its own distinctive sequence of aquifers. These are :

Tabuk Basin

The descending succession of aquifers is as follows :

Jauf Aquifer *(Devonian)*

Secondary aquifer; limestones and some sandstones 200 to 400 m thick. $T = 1.1 \times 10^{-3}$ m^2/sec (confined), and 3×10^{-3} m^2/sec (unconfined); $S = 2 \times 10^{-2}$ (unconfined) to 2×10^{-3} (confined).

Upper Tabuk Aquifer *(Siluro-Devonian)*

Primary aquifer; sandstone 200 to 500 m thick; ϕ 10 to 20%. $T = 10 \times 10^{-3}$ to 30×10^{-3} m^2/sec; $S = 1.4 \times 10^{-3}$ (confined) to 3.5×10^{-2} (confined).

Middle Tabuk Aquifer *(Lower Silurian)*

Primary aquifer of sandstone 80 to 150 m thick.

$T = 1.7 \times 10^{-3}$ m²/sec in Tabuk area. $S = 2 \times 10^{-2}$ (unconfined) to 1×10^{-3} (confined).

Lower Tabuk Aquifer *(Lower Ordovician)*

Primary aquifer of sandstone 130-200 m thick; ϕ 8 to 20%. $T = 2 \times 10^{-3}$ to 8×10^{-4} m²/sec; $S = 2 \times 10^{-4}$ (unconfined) to 6×10^{-4} (confined).

Saq Aquifer *(Cambro-Ordovician)*

Primary sandstone aquifer of major importance, 400-500 m thick. $T = 9 \times 10^{-3}$ to 3.8×10^{-2}; $S = 1.2 \times 10^{-3}$ to 7×10^{-2} (unconfined) 10^{-4} to 2×10^{-3} (confined). $\phi = 15\%$.

Wadi as Sirhan Basin

Basalt Aquifers *(Quaternary-Late Tertiary)*

Secondary aquifers in fractured basalts, up to 100 m thick; low yield.

Neogene Sandstone Aquifer

Primary aquifer; sandstone up to 200 m thick; good permeability. $T = 15 \times 10^{-3}$ in the northwest to 40×10^{-3} m²/sec in the southeast. $S = 1 \times 10^{-2}$ to 3×10^{-2} (unconfined) and 2×10^{-3} (confined).

Hibr Formation *(Paleogene)*

Mostly aquitard; contains minor thin chert aquifer.

Wasia Aquifer (= Sakaka Sandstone)
Mid-Cretaceous)

Primary aquifer; sandstone 140 to 290 m thick; only on northeast flank of Sirhan Basin: ϕ 10-29% around Sakaka. $T = 3 \times 10^{-4}$ to 15×10^{-3}/ m² sec; $S = 3 \times 10^{-2}$ to 5×10^{-2} (unconfined) to 7×10^{-2} (confined).

Upper Tabuk Aquifer *(Siluro-Devonian)*

Primary aquifer; sandstone, at excessive depth in Sirhan Basin. (*e.g.* 660 m below surface in the Turayf Well, where 440 m thick). $T = 10 \times 10^{-3}$ to 7×10^{-4} m²/sec; $S = 3.5 \times 10^{-2}$ (unconfined) to 1.4×10^{-3} (confined).

Widyan Basin Margin

Umm er Radhuma Aquifer *(Paleogene)*

Secondary aquifer; karstified limestone about 250 m thick; minor amounts of poor quality groundwater $T = 4 \times 10^{-5}$m²/sec (or more); $S = 5 \times 10^{-5}$ (confined).

Aruma Aquifer *(Upper Cretaceous).*

Secondary aquifer; 60 to 140 m thick, poor quality water.

Wasia-Biyadh Aquifer *(Middle to Lower Cretaceous)*

Primary sandstone aquifer 400-600 m thick; with excellent hydrologic properties and potential; yields poor to good quality water (raw water supply for Riyadh). $T = 1.5 \times 10^{-2}$ to 9.7×10^{-2} m²/sec; $S = 2 \times 10^{-4}$ (confined).

Berwath Aquifer *(Carboniferous)*

Primary sandstone aquifer, + 250 m thick; moderate yields of good quality water. $T = 3 \times 10^{-3}$ m²/sec (average); $S = 1 \times 10^{-2}$ (confined).

Interior Homocline

Aruma Aquifer *(Upper Cretaceous)*

Secondary aquifer; limestone 60 to 140 m thick, poor quality water.

Wasia-Biyadh Aquifer *(Middle to Lower Cretaceous)*

Primary sandstone aquifer; up to 600 m thick; with excellent hydrologic properties and potential; yields fair to good quality water (raw water supply for Riyadh). $T = 1.5 \times 10^{-2}$to 9.7×10^{-2} m²/sec; $S = 2 \times 10^{-4}$ (confined).

Dhruma Aquifer *(Middle Jurassic)*

Secondary aquifer; mostly limestone north of Riyadh; south of Riyadh becomes increasingly sandy and is a good aquifer and joins with the Minjur Aquifer. $T = 1 \times 10^{-2}$ to 1.6×10^{-2} m²/sec.

Minjur Aquifer *(U. Triassic-L. Jurassic)*

Primary sandstone aquifer of major importance with good transmissivity, 200 to 400 m thick, fair quality water and major groundwater supplier for Riyadh. $T = 4 \times 10^{-3}$ m²/sec (average); $S = 1.3 \times 10^{-4}$ (confined).

Jilh Aquifer *(Middle Triassic)*

Secondary aquifer of thin-bedded limestones, with anhydrite interbeds averaging 250 m thick and yielding poor quality mineralized water.

Khuff Aquifers *(Upper Permian)*

Secondary aquifers; Khuff A,B,C, & D limestones, average total of 200 m thick, with intervening anhydrite or dense limestone aquicludes. Poor quality water and only about 3% effective porosity.

'Unayzah or Faw Aquifer *(Lower Permian to U. Carboniferous)*

Secondary aquifer of sandstone and siltstone, yielding modest amounts of water in the Wadi ad Dawasir area. Mostly low storativity where confined.

Middle Tabuk Aquifer *(Lower Silurian)*

Primary sandstone aquifer in the northern part of the Interior Homocline, from 40 to 250 m thick; ϕ 10% and good quality water. $T = 1 \times 10^{-3}$ to 1.6×10^{-3} m^2/sec; $S = 2.7 \times 10^{-4}$ to 2.5×10^{-3}, (confined).

Lower Tabuk Aquifer *(Lower Ordovician)*

Primary confined sandstone aquifer 54 m thick at Buraydah; ϕ 8 to 20% and good quality water. $T = 4 \times 10^{-4}$ to 1.5×10^{-4} m^2/sec; $S = 1 \times 10^{-3}$ (confined).

Saq Aquifer *(Cambro-Ordovician)*

Primary sandstone aquifer of major importance, over 400 m thick, in the Qasim area with excellent ϕ 20 to 30% and k of 0.5 to 3.4. Yields abundant good quality water. $T = 4 \times 10^{-4}$ to 2.7×10^{-2} m^2/sec; $S = 1.3 \times 10^{-3}$ (confined) to 7×10^{-2} (unconfined).

Eastern Shelf and Basin

Including Summan Plateau, Al Hasa, and Rub' al Khali Basin.

Dam Aquifer *(Lower & Middle Miocene)*

Secondary aquifer of karstified limestone, about 30 to 100 m thick; developed in Al Hasa, yielding fair quality water, due to its good secondary porosity. $T = 10^{-2}$ m^2/sec (Ghawar).

Hadrukh Aquifer *(Lower Miocene)*

Primary sandstone aquifer from 20 to 120 m thick, with good hydraulic properties and yielding up to 50 l/sec of good to fair quality water, especially in Al Hasa and Wadi al Miyah. $T = 7 \times 10^{-4}$ to 4×10^{-2} m^2/sec; $S = 2 \times 10^{-4}$ (confined) to 1×10^{-2} (unconfined).

Neogene undifferentiated *(Mio-Pliocene)*

Secondary aquifer in calcareous sandstones of the Summan Plateau (Tsm) and central Rub' al Khali.

Alat Aquifer *(Middle Eocene)*

Secondary aquifer of porous, karstified and fissured limestone; aquifer locally in the northeast Arabian Shelf around Qatif, Dammam and Al Hasa, from 10 to 50 m thick with moderate yields. Underlain by the Alat Marl Aquitard or combined as Alat-Khobar Aquifer. $T = 2.6 \times 10^{-5}$ to 2.3×10^{-3} m^2/sec. $S = 1.3 \times 10^{-4}$ to 5.34×10^{-4}.

Khobar Aquifer *(Middle Eocene)*

Secondary aquifer in calcarenitic and slightly dolomitic limestones, 5 to 15 m thick, locally karstified and fissured with moderate yield due to restricted permeability. $T = 2 \times 10^{-3}$ to 10^{-4} m^2/sec; $S = 1 \times 10^{-3}$ to $< 1 \times 10^{-4}$.

Umm er Radhuma Aquifer *(Paleocene-Lower Eocene)*

Major carbonate aquifer throughout the Rub' al Khali and northeast Saudi Arabia; 300 to 700 m thick with calcarenite or dolomite zones of high permeability. Water is artesian to subartesian and of poor to good quality. $T = 3 \times 10^{-3}$ to 5×10^{-4} m^2/sec (Ghawar); $S = 10^{-5}$ to 5×10^{-3}.

Cretaceous Aquifer *(Upper to Lower Cretaceous)*

Sandstones of the Wasia and Biyadh combine with sandy facies of the Aruma east of Wadi ad Dawasir in the southwest Rub' al Khali to form one aquifer with good permeability. Basinward, the Wasia and Biyadh become separate aquifers and are too saline to be useful. $T = 7 \times 10^{-3}$ m^2/sec; $S = 2 \times 10^{-2}$ (unconfined).

Wajid Basin

Wajid Aquifer *(Cambro-Ordovician and younger)*

Primary sandstone aquifer, 300 to 900 m thick, extending over 196,000 km^2 in the southwestern Rub' al Khali. Effective porosity about 20% and yields good quality water (1000 mg/l TDS). Major source of groundwater for agriculture in Wadi ad Dawasir. Confined by Carboniferous shale or by Jurassic Tuwaiq Mountain Limestone to the south. $T = 5.7 \times 10^{-4}$ to 2.1×10^{-2} m^2/sec; $S = 2 \times 10^{-4}$ (confined) to 2×10^{-1} (unconfined).

Types of Aquifers According to Origin

The many aquifers of the sedimentary provinces of Saudi Arabia can be classified, by origin, into two broad groups, namely, aquifers of primary origin and aquifers of secondary origin. Each group can be further subdivided as follows :

Aquifers of primary origin include Quaternary sands of wadi systems, quartzose sandstones, and conglomerates with primary porosity, calcarenites, coquinites and oolitic limestones with primary porosity and agglomerates, or volcanic breccias, with some original pore space.

Examples of Quaternary sand aquifers are found in the Wadi ar Rimah and Wadi al Batin drainage systems, where shallow supplies of poor quality water (specific conductivity 2,000 to 5,000 Mhos/cm) are used locally for irrigation.

Quartzose sandstones, such as those of the Saq, Wajid, Tabuk, Minjur, Wasia-Biyadh, and Hadrukh formations, all have high primary intergranular porosities and form the most important aquifers in the

Kingdom.

Calcarenites of the Dammam and Umm er Radhuma Formations also form extensive and important aquifers, with much of the primary porosity between grains of lime sand still preserved. Coquinite horizons, composed of larger foraminiferids, constitute aquiferous zones of high primary porosity in the top third of the Umm er Radhuma Formation.

Oolitic limestones occur in the limestones of the Arab Formation, where their primary porosity is most notable for their oil content. In some areas near to outcrops, the primary porosity in the oolitic Arab Formation limestones provides usable amounts of very poor quality water, mineralized by contact with interbedded anhydrites.

Volcanic breccias, or agglomerates, of the Quaternary and Late Tertiary lava fields (harrats) have a limited natural porosity providing small amounts of water, as in the Harrat al Harrah, and sub-basalt sands with good porosity produce usable water in the Khaybar area, north of Al Madinah.

Aquifers of secondary origin consist primarily of limestones, which have undergone secondary solution or dolomitization, and karstified limestones, such as the Umm er Radhuma, Dammam and Dam Formations. However, the influence of regional stresses has caused fracturing and well-developed joint systems in most carbonates, sandstones and even Quaternary-Late Tertiary basalts.

Secondary solution within limestones is a major cause of permeability in the Khobar and Alat Members of the Dammam Formation, as well as in the Umm er Radhuma Formation, where lost circulation cavities are commonly encountered in drilling.

Karstified and fissured limestones act as aquifers, such as the Dam Formation and Alat Member. The northern outcrop areas of the Alat Limestone are extensively karstified, with many 'dahls' or sinkholes which trap local surface runoff. These lithostratigraphic units are also fissured by karstification along joints, and the Dam Formation is an aquifer with good permeability in Al Hasa area.

The diagenesis of limestones produces dolomites or dolomitic limestones, often with good effective porosity. An example of this is seen in the subsurface Umm er Radhuma Formation at Ain Dar, where a horizon with loose dolomite rhombs provides the main water-bearing zone.

Almost all carbonate formations are brittle enough to have been become thoroughly transected by joint sets. In outcrop, these joints are often open and provide a means of recharge, while in the subsurface, joint systems provide useful secondary porosity enabling water to move downdip in confined limestone formations. Jointing and subsequent fissuring is important in producing permeability in the Umm er Radhuma Formation. A peculiar case of jointing is seen in Al Aflaj area, where local dissolution of the underlying Upper Jurassic Hith Anhydrite by groundwater has produced strong jointing and brecciation in the Lower Cretaceous Sulaiy, Yamama, and Buwaib formations, so that good secondary permeability is produced.

Many sandstone formations show well-developed jointing, such as is seen in the Cambro-Ordovician Wajid Sandstone. Fractures facilitate the penetration of outcrops by water, allowing its movement downdip where the aquifer is confined.

Fractured basalts, such as the Harrat al Harrah in the Wadi as Sirhan Basin, have several, well-developed trends of jointing (Khouri 1982), which also provide secondary permeability for these Quaternary-Pliocene basalt flows.

Recharge Conditions of Major Saudi Arabian Aquifers

In general, the very low rainfall conditions that prevail throughout most of the Kingdom do not allow substantial recharge to most aquifers in their exposed and unconfined parts. This is borne out by isotopic evidence showing that most aquifers contain fossil groundwater, which is tens of thousands of years old and was evidently recharged during previous pluvial intervals during the Quaternary. The fragility of most aquifers in Saudi Arabia cannot be overemphasized and their too rapid exploitation has led in some places to dramatic falls in the groundwater table, *e.g.* greater than 100 m fall of the groundwater table in the Saq Aquifer in the Qasim area.

Estimated recharge of all aquifers from rainfall in the northwestern area of Saudi Arabia (Area 1) is about 1,520 million m^3. In the Qasim area, recharge on outcrops of aquifers of the Saq, Lower Tabuk, Middle Tabuk, Khuff, Jilh and Minjur is some 293 million m^3/year. Total annual recharge to the Saq Aquifer from rainfall and wadi flow is estimated to be some 290 million m^3/year (KFUPM 1987). Recharge to the Lower Tabuk Aquifer in the Tabuk Basin and Northern Interior Homocline is about 49 million m^3/year, while that to the Middle Tabuk in the same area is about 39 million m^3/year. The Upper Tabuk Aquifer has an annual recharge of 52 million m^3 in this northwestern area of Saudi Arabia. The volume of annual recharge to the Devonian Jauf Aquifer is much lower and is about 15 million m^3. There are no figures for recharge of the Carboniferous Berwath Aquifer, since it is not exposed at the surface.

Estimated annual recharge of the Permian Khuff Aquifer in the Northern Interior Homocline is some 80 million m^3, and for the Triassic Jilh Aquifer in the same region, recharge is estimated at 60 million m^3/year (KFUPM 1987). Recharge of the Lower Jurassic Minjur Aquifer in the same area is estimated at 99.6 million m^3/year, but is probably several times more over its entire outcrop from approximately Latitudes 22°N to 25°N, because it is supported by inflow from major wadis, such as Wadi Birk, and combined towards the south with sands in the Dhruma Formation, as in the Minjur-Dhruma Aquifer.

The recharge to the large outcrops of the Wasia-Biyadh Aquifer from underflow from wadi alluvium and runoff from Jabal Tuwayq has been estimated at 480 million m^3 (SOGREAH 1967).

The Upper Cretaceous Aruma Formation is widely exposed in the nothern part of Saudi Arabia (Widyan Basin Margin) and along the Northern Interior Homocline. Recharge of the Aruma Aquifer is estimated to be about 80 million m^3/year in these areas, based on rainfall figures (KFUPM 1987).

Mean annual recharge from rainfall for the Paleogene Umm er Radhuma Formation has been calculated at 1,048 million m^3 (Bakiewicz *et al.* 1982), but is probably supplemented by considerable upward flow from the Aruma Aquifer and downward flow from the Dammam and Neogene, plus lateral flow, making a total recharge of 2,256 million m^3 (Groundwater Development Consultants 1979). Discharge from the Umm er Radhuma Aquifer alone is estimated between 3,660 and 11,238 times more than the recharge. Out of 60 mm annual rainfall, only 4 to 8 mm percolates into the aquifer. Recharge by rainfall on the Middle Eocene Dammam aquifers is also low and much of their groundwater comes from the underlying Umm er Radhuma Aquifer, where the Rus Formation is thin and acts as a leaky aquitard. Most of the water in the Dammam and Umm er Radhuma aquifers infiltrated into these aquifers between 30,000 to 50,000 years ago, during pluvial Quaternary climatic conditions, according to B.R.G.M. (1977). The Neogene Hadrukh and Dammam aquifers have a low annual recharge by rainfall, but are supplemented by water from an erosional window in the Rus Formation in south Ghawar Anticline (Fig. 8). Mean annual recharge is about 10 m^3 sec (El Khatib 1980).

In the southwestern part of the Kingdom, the recharge to the Cambro-Ordovician Wajid Sandstone Aquifer is relatively high, due to high annual rainfall of 250 to 350 mm in outcrop areas in the east Asir Highlands. Recharge of the Wajid Aquifer is estimated to be 500 million m^3 year (KFUPM 1987), but the age of the groundwater, given as 30,000 years old (Ministry of Agriculture and Water 1984) shows that the rate of flow through the aquifer is very slow and that the existing reservoir is very large.

Recharge for the Quaternary alluvial aquifers is relatively low, being estimated at 940,000 m^3/year, with the dominant recharge of 330,000 m^3/year in the wadis of the Red Sea, which receive drainage from the higher rainfall areas along the Red Sea Escarpment. Wadi ad Dawasir and its tributary wadis received 260,000 m^3/year, with a further 140,000 m^3/year recharge in the alluvium of the drainage systems of wadis Birk, Nisah, and Sahba (El Khatib 1980). Despite these seemingly large present-day recharge quantities for various aquifer systems, they are small when considering the very large area of Saudi Arabia, and isotope age determinations of groundwater in the Kingdom give clear evidence that it is mostly fossil groundwater derived from earlier Quaternary intervals of much greater rainfall, especially from 17,000 to 36,000 years ago. Infiltration and recharge through sand dunes has been studied by Dincer *et al.* (1974) and Dincer (1978) as a mechanism for aquifer recharge and movement of water through coarse-grained sand dunes, and has been traced by Tritium measurements. However, the movement is very slow and rarely complete and the little water seeping through dunes often encounters less permeable substrata and does not necessarily contribute to major aquifer to recharge. The use of Tritium has also been demonstrated by Hötzl *et al.* (1980), who showed that at Al Qatif and Al Hasa waters are almost Tritium free due to their age, while Wadi Hanifah wells are an exception and show relatively high Tritium concentrations, proving recent (< 50 years BP.) local rainfall recharge to groundwater.

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الهيكل الجيولوجي لمصادر المياه الجوفية في المملكة العربية السعودية

ستيورت إدجل
جامعة الملك فهد للبترول والمعادن ، الظهران ، المملكة العربية السعودية

المستخلص . تُحَدُّ الوحدات الرسوبية التكتونية ، المحتوية على المصادر المائية في المملكة العربية السعودية ، الدرع العربي من ثلاثة جوانب . وتنقسم هذه الوحدات إلى :

حوض تبوك ، وحوض وادي السرحان ، وحوض الوديان ، وحوض الخليج العربي والهضبة الداخلية الشمالية الشرقية والهضبة الداخلية الشرقية ، وحوض الربع الخالي وحوض الوجيد . وتتميز هذه الوحدات المائية بطبقات سميكة ذات مسامية عالية ، والتي تحتوي على معظم المياه الجوفية في المملكة العربية السعودية ، وتُقدر بـ ٢٠٨ × ١٠^٩ م^٣ .

ومعظم الأحواض تتكون من خزانات متعددة ذات مياه جيدة وبكميات وافرة . فحوض تبوك يتكون من تكوينات : الساق الكمبروأُردفيشي ؛ وتبوك الأردفيشي - السليوري الأدنى والأوسط والعلوي ؛ وتكوين طويل السيلوري ؛ وكذلك تكوين الجوف الديفوني . كما تتميز خزانات هذا الحوض بوجود بعض من الطبقات الطينية التي تسببت في فصله إلى عدة خزانات .

يتكون حوض وادي السرحان من خزانات رملية من الحقب الرباعي ذات إنتاجية عالية ، وكذلك من خزانات ذات إنتاجية قليلة تعود في أصلها إلى صخور بركانية من الحقب الرباعي وصخور طباشيرية تعود إلى تكوين الحِبر الباليوجيني . وتتكشف صخور خزان مياه سكاكا الرملي التكوين في قوس الرطبة - حائل والذي يمتد تحت حوض وادي السرحان من الطرف الجنوبي الشرقي . ويبلغ سمك خزان المياه الطباشيري العصر ذو المياه الوافرة في منطقة التقاء رواسب حوض الوديان ورواسب الوسيع - بياض حوالي ٦٥٠ م .

أما الهضبة الشمالية الشرقية فتتميز بوجود عدد من الخزانات التي تعود في أصلها من التكوينات الكمبرية حتى الطباشيرية وهي الساق ، تبوك ، خُف ، جِلْه ، منجور ، ظُرمة والبياض - وسيع وكذلك عَرُمة ، والتي يغلب عليها ميل الطبقات للناحية الشمالية الشرقية من الدرع العربي ، كما أن اغلب خزانات المياه على طول الطرف الجنوبي الغربي من حوض الخليج العربي تعود في نشأتها إلى صخور التكوينات الثلاثية لأم الرَّضُمَة والدَّمَّام والهيدروخ والدام . أما في الهضبة الداخلية الشرقية فتوجد خزانات المياه الرئيسة ضمن صخور تكوينات ظُرمة - المَنْجور الجوراسية ، وكذلك في تكوين الوسيع - بياض الطباشيري العصر .

ويتركز خزان المياه الرئيس في منطقة الربع الخالي في تكوين أم الرَّضُمَة مع وجود خزان مياه سطحي في صخور النيوجين . أما في الجزء الجنوبي من الدرع العربي ، تُكوِّن صخور الوجيد الرملية الكمبرو - أُردوفيشية النشأة خزانًا مائيًا شاسع الاتساع تبلغ سعته أكثر من ٣٠ × ١٠^٩ م^٣ .