AQUIFERS OF SAUDI ARABIA AND THEIR GEOLOGICAL FRAMEWORK

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الخلاصة :

تأتي أهمية المكامن الصخرية المائية في المملكة العربية السعودية لوقوعها في مناطق رسوبية شمالية، وشرقية وجنوبية بالنسبة للدرع العربي. وتشمل أحواض المنطقة الشمالية كلاً من حوض تبوك والساق إضافة إلى مكامن تبوك الحجرية الرملية ومكمن نيوجين الرملي في حوض وادي السرحان. كما وتحتوي المنطقة الداخلية الهموكلينكية المتجانسة والامتداد الطبقي العربي شمال شرق المملكة العربية السعودية أكثر المكامن المائية انتاجاً واستغلالاً في المملكة، وهذه تشمل أحواض تبوك، والساق، ومكامن الحقبة الوسطية والوسيع في الرياض. وشرقاً تحتوي طبقات الحقبة الثلاثية الكربونية المائية مكامن أم الرضمة، والدمام، والدام، والهدروخ. وفي الجنوب تشكلّ الطبقة البازلتية ذات السماكة حوض الوجيد الذي يحوي كميات كبيرة من نوعية جيدة من المياه. ومن الملاحظ أن مناخ السعودية القاري لايسمح إلاّ بتغذية قليلة من مياه الامطار للمكامن المائية. ويقدّر عُمر المياه الجوفية بنحو من عشرة آلاف سنة إلى (٣٦) ألف سنة. وعلى الرغم من أنّ كمية المياه الجوفية المُختزنة والممكن إستعمالها يُقدّر بنحو (٢٠٠٠) مليار متر مكعب إلاّ أنه يجب أن يكون هناك تخطيط بعيد المدى لاستخدام المياه في المملكة.

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ABSTRACT

Aquifers of Saudi Arabia of major significance occur in sedimentary regions to the north, east, and south of the Arabian Shield. On the north, they include the Tabuk Basin with the immense Saq and Tabuk sandstone aquifers and a Neogene sandy aquifer in the Wadi as Sirhan Basin. The Interior Homocline and adjacent Arabian Platform of northeastern Saudi Arabia contain the most utilized and prolific aquifers of the Kingdom. These are the Saq and Lower and Middle Tabuk aquifers, plus the major Mesozoic Minjur and Wasia–Biyadh sandstone aquifers. Eastward, Tertiary carbonate aquifers include Umm er Radhuma, Dammam, and Dam, overlain by the sandy Hadrukh Aquifer. The Umm er Radhuma Aquifer underlies almost all the Rub' al Khali. In the south, thick Paleozoic sandstones of the Wajid Aquifer contain large amounts of good quality water. The present-day hyperarid climate of Saudi Arabia allows minimal recharge, so aquifers contain 'fossil' ground water 10 000 to 36 000 years old. Although usable ground water in Saudi Arabian aquifers totals 2000 billion cubic meters, development should only take place under a plan for the long-term use of the Kingdom's finite groundwater resources.

AQUIFERS OF SAUDI ARABIA AND THEIR GEOLOGICAL FRAMEWORK

INTRODUCTION

Extreme aridity characterizes virtually the entire Kingdom of Saudi Arabia so that its groundwater resources and their proper conservation are of fundamental importance to the entire population of Kingdom and future generations. Groundwater in Saudi Arabia is found almost entirely in the many thick, highly permeable aquifers of large sedimentary basins to the north, east, and south of the Arabian Shield. Only very minor amounts of subsurface water occur in the fractured, Precambrian crystalline rocks of the Arabian Shield, which is more significant in providing extensive, higher, relatively impermeable areas for surface runoff, and localized, shallow wadi underflow, according to Burdon [1].

The major geological structures of the Arabian Plate determine the sedimentary basins containing Saudi Arabia's groundwater resources. This affects not only their location but also their attitude, lithology, and the permeability of their strata, especially as regards their aquifers. In general, the stratabound aquifers of all sedimentary basins of Saudi Arabia dip outward from the higher Arabian Shield, which forms the structural nucleus of the country.

While the major aquifers in the north of Saudi Arabia consist of multiple, Lower Paleozoic arenaceous permeable formations with interdigitated impermeable argillaceous strata, those of eastern Saudi Arabia include both karstified Tertiary carbonates and Mesozoic to basal Paleozoic arenaceous formations. To the south of the Arabian Shield, a single thick basal Lower Paleozoic sandstone formation constitutes a high yield aquifer.

The primary groundwater reserves in the numerous aquifers of the sedimentary basins of the Kingdom are very large, being estimated at 1919×10^9 m^3 by Al Alawi and Abdulrazzak [2], with deeper secondary reserves of 160×10^9 m^3 (U.S. Department of Agriculture, quoted in 'The Economist' June 1989). It should be remembered, however, that almost all of these reserves consist of fossil groundwater derived from earlier Quaternary intervals of much greater rainfall, especially from 17000 to 36000 years ago, as noted by Edgell [3]. Under the present hyperarid conditions in Saudi Arabia, the prevailing very low rainfall conditions do not allow significant recharge to most aquifers in their exposed and unconfined parts. The need for planned development of Saudi Arabian aquifers must be emphasized, since their uncontrolled exploitation has caused dramatic falls in the groundwater table (*e.g.*>100 m in the Saq Aquifer at Qasim).

TECTONIC SETTING

The sedimentary provinces containing all the main aquifers of Saudi Arabia are controlled by the major geological structures, or tectonics, of the Arabian Peninsula. These are dominated by the trapezoidal Precambrian massif of the Arabian Shield, uplifted on the southwest against the Red Sea Rift System and tilted down towards the northeast beneath the huge, elongate Arabian Gulf Basin. This megabasin extends for 2600 km from the eastern Mediterranean to the Indian Ocean and is a strongly asymmetrical, margin sag-interior sag basin containing sedimentary strata from Upper Proterozoic to Recent and thickening northeastward to 18000 m of sediment just south of its margin at the Main Zagros Reverse Fault. From a plate tectonic viewpoint, the Arabian Gulf Basin has developed along the northern and northeastern edges of the Arabian Plate where it is subducting beneath the Turkish and Iranian plates. From the viewpoint of hydrogeology, all groundwater resources of any significance in Arabia are found within the Arabian Gulf Basin. The exposed and truncated edges of its sedimentary strata adjoining the massif of the Arabian Shield have formed the major recharge areas for Saudi Arabian aquifers and still do, to a very limited extent.

Structural trends along four main directions control the location of sedimentary provinces containing the aquifers and groundwater resources of Saudi Arabia. Among these, the NW–SE Erythraean Trend of Von Wissman *et al.* [4], is the dominant one controlling subsidence, folding and sediment distribution in the Arabian Gulf Basin. The Red Sea, Wadi as Sirhan Basin and the Northern Interior Homocline also follow this structural alignment (Figure 1). The N–S Arabian Trend forms the 'old grain' of Arabia and is seen in the northerly trending Hail–Rutbah Arch, Eastern Interior Homocline, En Nala Axis, and Qatar Arch. The Ha'il–Rutbah Arch effectively separates the Tabuk Basin from the Widyan Basin Margin further to the east, while the Qatar Arch separates the Arabian Platform from the Rub' al Khali Basin, as well as dividing the Gulf into a West Arabian Gulf Basin and an East Arabian Gulf Basin (Figure 2). A number of northerly uplifts cut the Arabian Platform affecting watertable conditions. From west to east, these are the Khufaisah–Mubayhis Uplift, Jaham–Ma'aqala–Wariah Uplift, Khurais–Wafra–Burgan Uplift, En Nala Axis, and Qatif Uplift (Edgell [5]). The NE–SW Aulitic Trend can be seen in the axis of the Hadramaut–Dhofar Arch bordering Saudi Arabia on the south and in the synclinal axis of the Rub' al Khali Depression. This trend is also evident in coastal and offshore northeast Saudi Arabia, as in the axes of Abqaiq Anticline, Khursaniyah Field and the Jana Anticline. An E–W structural trend is clearly seen in the Central Arabian Arch of the easternmost Arabian shield, which is cut by the Central Arabian Graben System as described by Al-Kadhi and Hancock [6] and Hancock and Al-Kadhi [7]. Its eastward continuation truncates the En Nala Axis and the southern end of the giant Ghawar anticline causing local changes in the groundwater table.

Domed or ovoid structures caused by deep-seated salt diapirism are found in coastal and offshore Saudi Arabia. These also influence the local distribution of groundwater and are best seen in the Dammam Dome, Abu Hadriyah Field, Berri Field, and the nearby Bahrain Dome.

The Arabian Shield has a north-northwesterly extension towards the Gulf of the Aqaba and is uplifted along the Eastern Red Sea Fault to form the Midyan Mountains Uplift with crest elevations of up to 2130 m at Jabal al Lawz. The Midyan Mountains Uplift effectively forms the western border of the multi-aquifered Tabuk Basin. There is another spur of the Arabian Shield towards the south-southeast forming the Asir Mountains Uplift with its maximum elevation of 3050 m at Jabal as Sauda. These high mountains form the western edge of the large Wajid Basin, with important groundwater reserves in a thick, Lower Paleozoic sandstone aquifer. The eastern border of the Wajid Basin is formed by the western end of the Hadramaut–Dhofar Arch. Strata of the Wajid Basin dip gently beneath the large, northeast trending Rub' al Khali Basin, which lies in a structural depression between the Eastern Interior Homocline–Qatar Arch and the Hadramaut–Dhofar Arch and Oman Mountains.

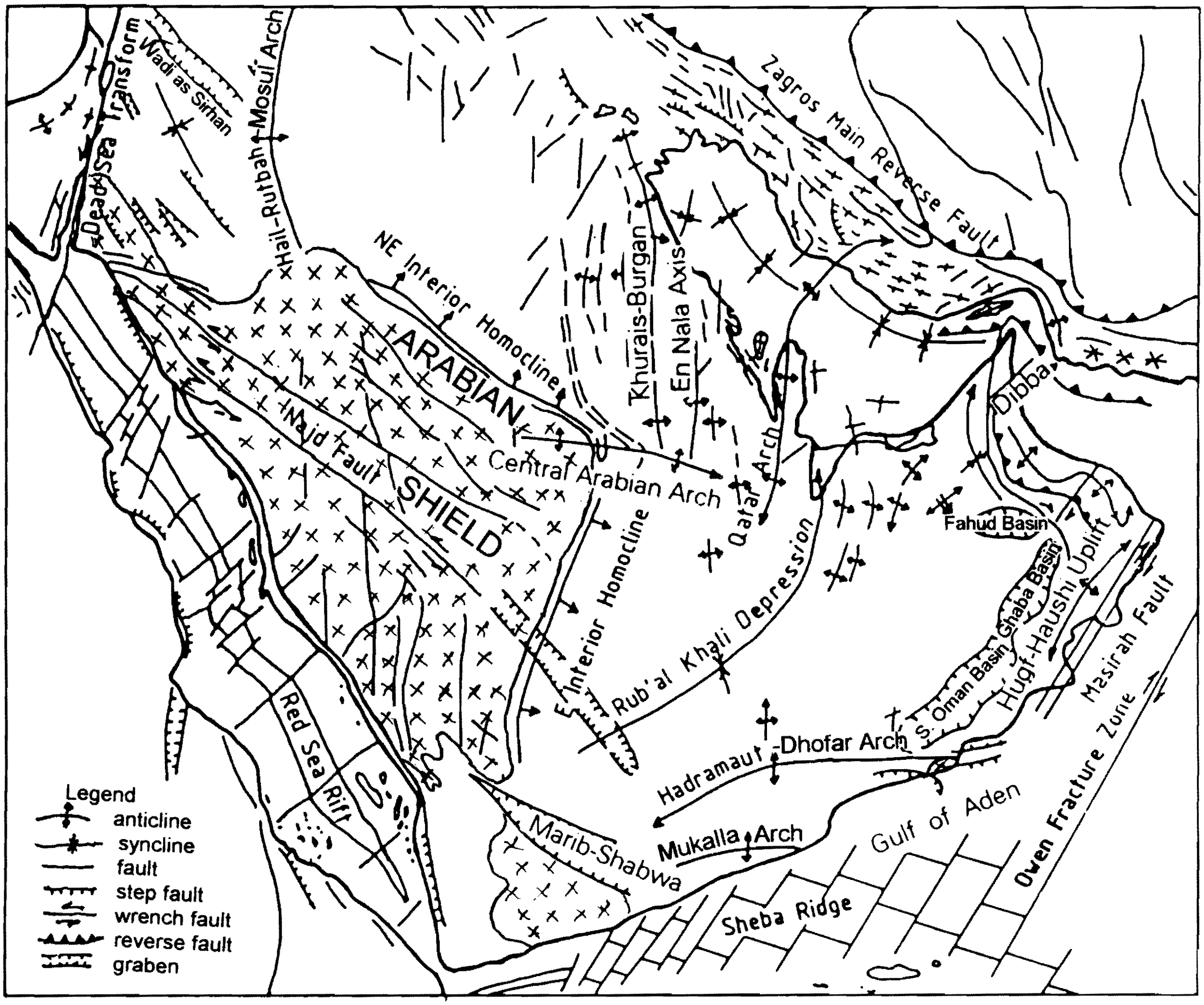

Figure 1. Tectonic Framework of Saudi Arabia and Adjacent Areas.

SEDIMENTARY PROVINCES

There are at least eight sedimentary provinces in Saudi Arabia which hold almost all of the aquifers and groundwater resources of the country. These tectonically controlled sedimentary provinces, or tectono–sedimentary units, are best grouped into three according their position to the north, east, or south of the uptilted Precambrian massif of the Arabian Shield.

The Northern Saudi Arabian Sedimentary Provinces extend from the north edge of the Arabian Shield as far as the Kingdom's borders with Jordan and Iraq. They have previously been referred to as the Nafud Basin in the 'Water Atlas of Saudi Arabia' of the Ministry of Agriculture and Water [8], although this is not a single basin, but three distinct tectono–sedimentary basins, each having its own distinctive aquifers. These sedimentary basins in the northern area as given by Edgell [9, 10] are the Tabuk Basin, Wadi as Sirhan Basin, and Widyan Basin Margin (Figure 3). The north-northwesterly trending Ha'il–Rutbah Arch of Khouri [11] separates the Wadi as Sirhan Basin on the west from the Widyan Basin Margin on the east, while the deeper parts of the Lower Paleozoic Tabuk Basin underlie the southern part of the mainly Cenozoic Wadi as Sirhan Basin. To the east of the Ha'il–Rutbah Arch lies the extensive Arabian Gulf Basin. That portion of this megabasin which occurs in northern Saudi Arabia and extends to the Kingdom's borders with Iraq and Kuwait, has been termed the Widyan Basin Margin by Powers *et al.* [12], from the numerous wadis (widyan), which flow eastward mainly on exposed limestones of the Upper Cretaceous Aruma Formation. Aquifers in the Widyan Basin Margin consist primarily of thick, permeable, Middle and Lower Cretaceous sandstones.

The Eastern Saudi Arabian Provinces include five separate tectono–sedimentary units recognized as the Arabian Platform, Northern Interior Homocline, Eastern Interior Homocline, Qatar Arch, and the Rub' al Khali embayment (Figure 4). The

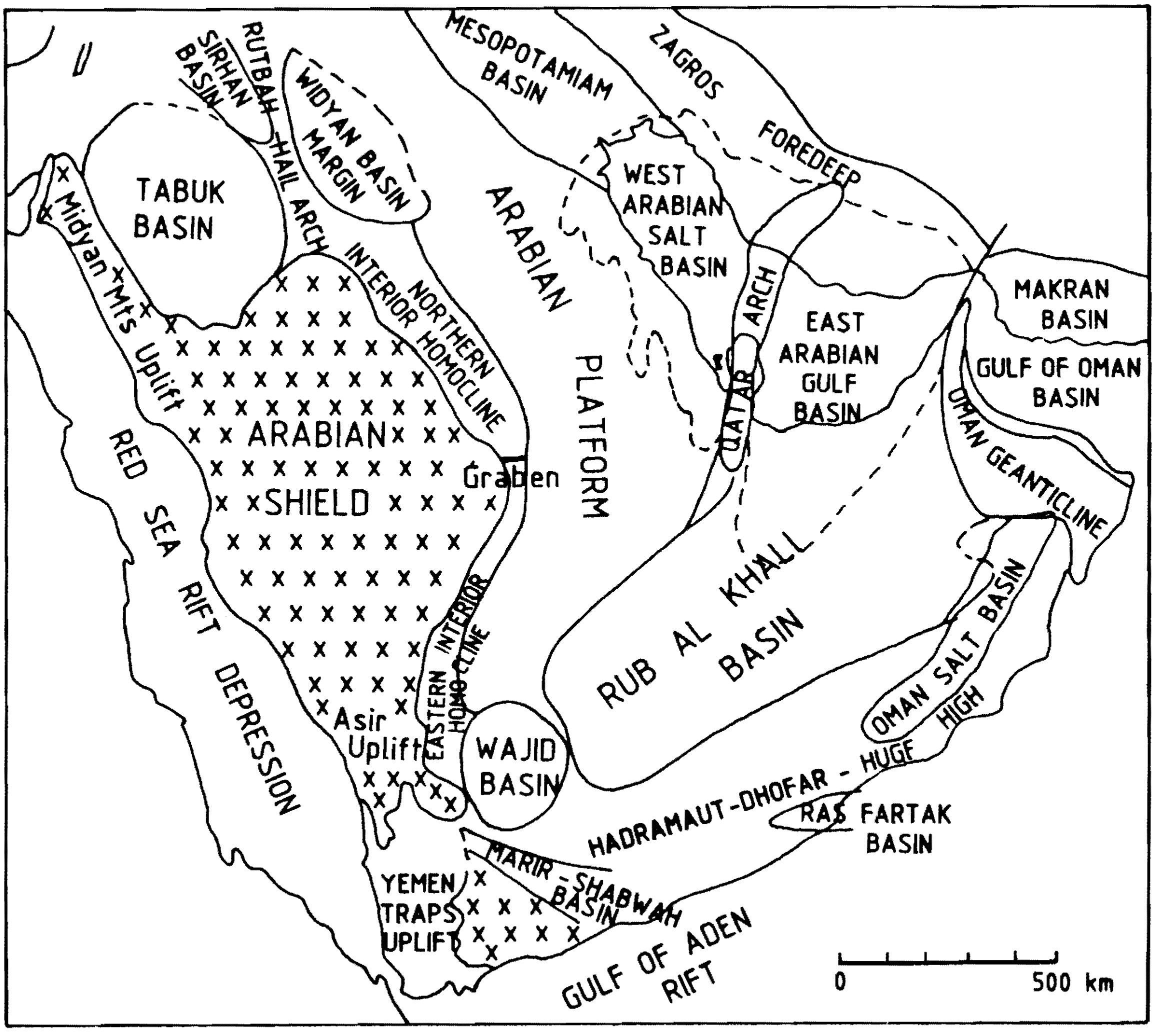

Figure 2. Tectono-sedimentary Provinces of Saudi Arabia and Adjacent Areas.

Northern Interior Homocline extends from just east of Ha'il to the vicinity of Riyadh and the Central Arabian Graben System. It consists of Paleozoic and Mesozoic formations dipping northeastward off the Arabian Shield. The principal aquifer in the Northern Interior Homocline is the Lower Ordovician Saq Sandstone (Abderrahman *et al.* [13]), which is extensively used in the Qasim area, but other sandstone aquifers are also important, such as the Mesozoic Wasia–Biyadh and Minjur aquifers. It is provisionally separated from the more southerly Eastern Interior Homocline by a change in trend around the Central Arabian Arch. In Saudi Arabia, the Arabian Platform stretches from the southern border of Kuwait to the Gulf of Salwa. It can be distinguished from the Northern Interior Homocline by its very gently dipping strata, generally about $^1/_2°$ to 1° towards the northeast (Naimi [14]). Aquifers in the Arabian Platform are mainly of Paleogene age (Bakiewicz *et al.* [15]), including the Umm er Radhuma and Dammam aquifers, although Neogene strata in the Al Hasa area (B.R.G.M. [16]), (Hötzl *et al.*, [17]) yield large quantities of high quality water. Several tectono–sedimentary subdivisions can be recognized in the Arabian Platform, such as the Summan Platform, Dibdibah Trough, Khurais–Wafra–Burgan Axis, Central Basin, En Nala Anticlinal Axis (including Ghawar), and the Eastern Platform (including Al Hasa).

The Qatar Arch constitutes a distinct tectono–sedimentary unit as a large, structural ridge separating the Arabian Platform from the immense Rub' al Khali Embayment to the east described by Brown [18] and McClure [19], with Lower Tertiary aquifers, primarily in carbonate rocks of the Dammam and Umm er Radhuma formations. Growth of the Qatar Arch began in the Late Jurassic and ended in Late Tertiary times.

By far the largest sedimentary province in eastern Saudi Arabia is the Rub' al Khali Embayment (Edgell [9, 10]), which forms a giant U-shaped depression with its axis plunging gently northeastward to the eastern Arabian Gulf. This large, pericratonic basin has undergone slow and almost continuous subsidence since Late Jurassic and reached its present form at the end of the Pliocene. The very widespread Umm er Radhuma Formation carbonates form the main aquifer throughout the Rub' al Khali Embayment, while the carbonates of the Dammam Formation also contain useful aquifers towards the northeast near Buraimi and in adjacent areas of Abu Dhabi. Seismic surveys in the central Rub' al Khali have indicated an extensive shallow aquifer at about 60 m in Neogene strata.

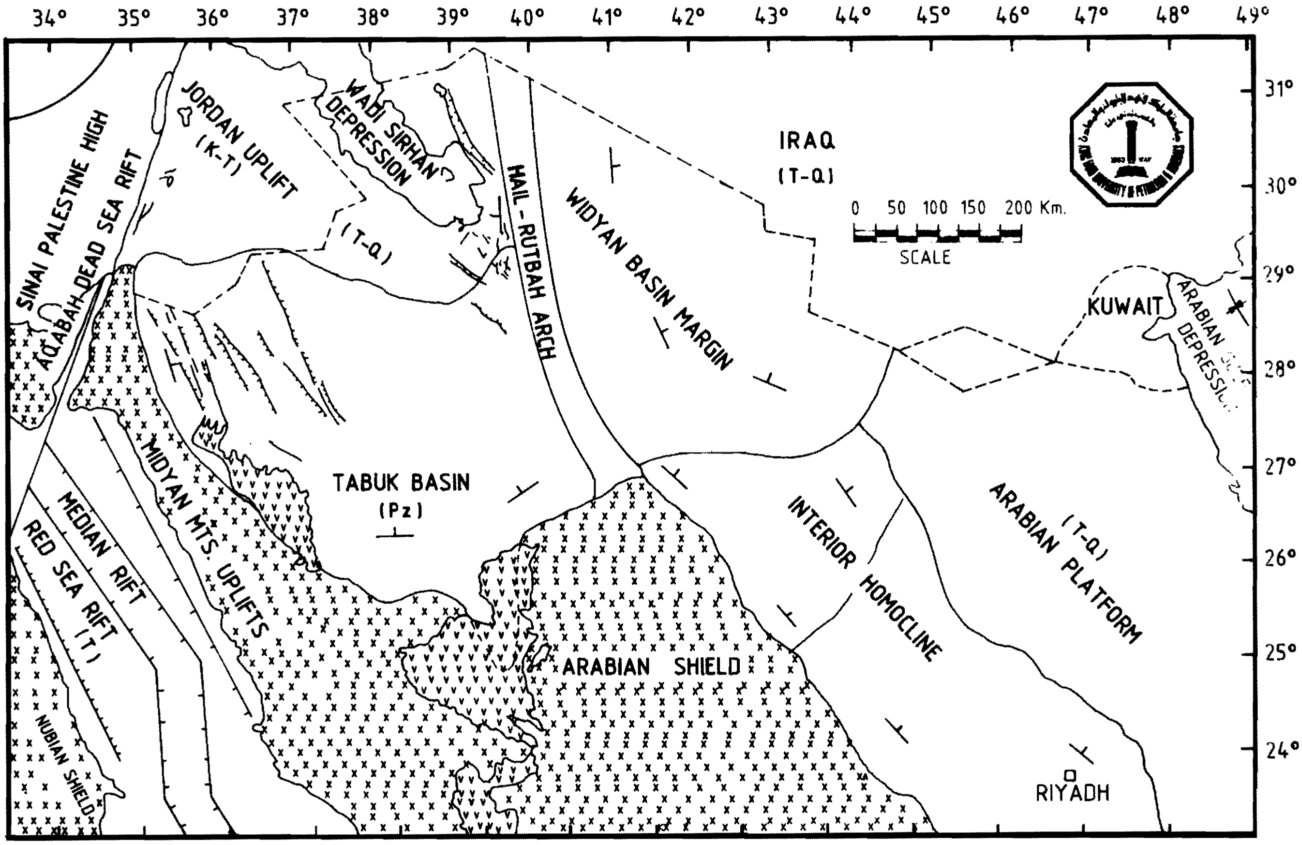

Figure 3. Structural Geology Framework of Northern Saudi Arabia.

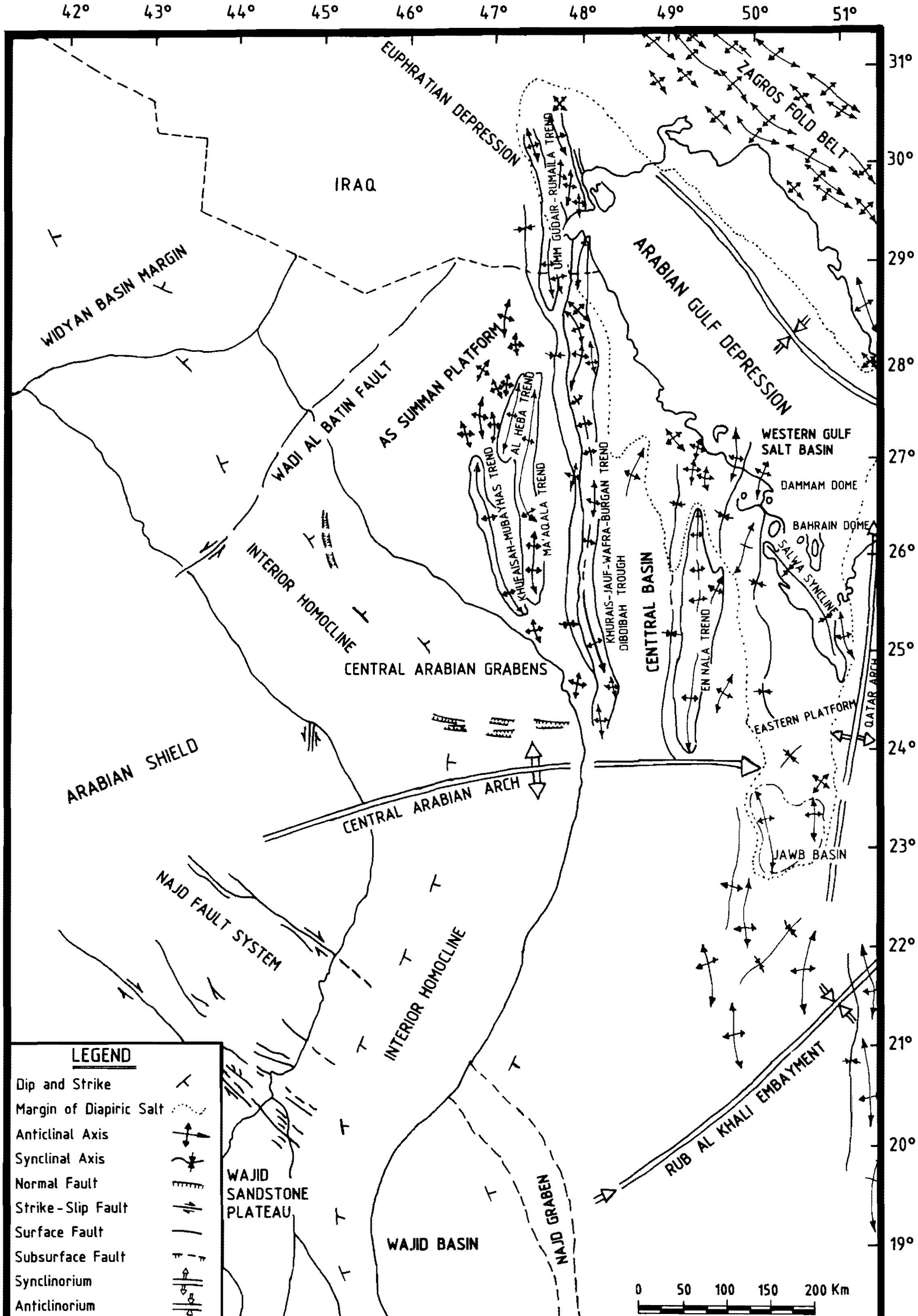

Figure 4. Structural Geology Framework of the Eastern Province.

Southern Saudi Arabian Sedimentary Provinces consist almost entirely of one large, oval-shaped, tectono–sedimentary basin of Lower Paleozoic sandstones, known as the Wajid Basin (Figure 5). This is the depositional basin of the Lower Ordovician Wajid Sandstone (Powers *et al.*[12], Brown *et al.*[20]) and forms an important aquifer up to 900 m thick covering an area of at least 196 000 km^2. The Wajid Basin is gently tilted towards the northeast, so that it partly underlies the younger strata at the southeast end of the Rub' al Khali Basin. On the southernmost borders of Saudi Arabia with Yemen, the taphrogenic Marib–Shabwah Basin occurs containing aquifers in Lower Cretaceous sandstones of the Tawilah Group. The north flank of the Hadramaut–Dhofar Arch also lies in southern Saudi Arabia to the east of the Wajid Basin and its Lower Tertiary strata contain potable groundwater in the carbonates of the Umm er Radhuma Formation.

AQUIFERS AND AQUICLUDES

The major aquifers and aquicludes of Saudi Arabia all lie in its sedimentary basins, as well as some leaky confining strata, or aquitards. They are described below in ascending stratigraphic sequence.

Saq Sandstone Aquifer

The major aquifer in northern Saudi Arabia is the Saq Sandstone, which is of Early Ordovician age, and widely exploited. It is composed of medium- to coarse-grained, brown to tan, friable, quartz sandstone with a moderately bedded, basal conglomerate. This basal conglomerate has an exceptional thickness of 928 m at Ri'al Fuhah, west of the city of Tabuk. In the southern Tabuk Basin, the Saq Sandstone has a general thickness of 400 to 500 m, but it increases in thickness to over 1500 m towards the north. Along the southern edge of the Tabuk Basin, from Al 'Ula to just west of Jubbah, the Saq Sandstone is exposed forming a widely accessible unconfined aquifer. Since the formation dips gradually towards the north-northwest in the Tabuk Basin, it exists as a confined aquifer throughout most of the basin. The area of the Tabuk Basin is almost 300 000 km^2, and the Saq Sandstone Aquifer is found at a subsurface depth of 360 m in the city of Tabuk (Al-Sagaby [21]) and, northwards, at increasingly greater depths. In the Interior Homocline, the Saq Sandstone is a primary aquifer of major importance with excellent effective porosity and permeability. Water from the Saq Aquifer is of good quality (300–1500 ppm) and is often initially artesian, with recorded pressures up to 12.3 atmospheres. A well at Turabah encountered the Saq Aquifer at a depth of 2252 m with a free flow of 31.5 l/sec of good groundwater (600 ppm TDS). It is over 400 m thick in the Qasim area and yields abundant good quality water which has been locally overexploited, so that the groundwater table has been lowered by over 100 m in places. In addition, isotopic age of water in the Saq Sandstone Aquifer is from 22 000 to 28 000 years old, so that it contains 'fossil' groundwater with very little present-day recharge. Reserves of groundwater in the Saq Aquifer have been estimated by Al Alawi and Abdulrazzak [2] at 280×10^9 m^3.

Wajid Sandstone Aquifer

An extensive, thick, mature, quartz sandstone rests nonconformably on the south and southeast edge of the crystalline Arabian Shield. This Lower Ordovician formation (Brown *et al.* [20]) extends over an area of 196000 km^2 between Wadi Najran and Ash Sharawrah in the south, and Wadi ad Dawasir on its northern margin. It also forms spectacular, cliffed outliers to the west in the Asir Mountains, which act as unconfined aquifers over an area of some 26000 km^2. The Wajid Sandstone is well-sorted, coarse-grained and well-bedded with distinct, large-scale, planar cross-bedding. It contains thin conglomerate lenses and its basal part contains gritstone layers with well-rounded quartzose pebbles. From a hydrogeological viewpoint, the Wajid Sandstone forms a single aquifer. It dips gently east northeastward from the Asir Mountains, with a dip of about 1° (Greenwood [22]), under Permo–Carboniferous and Mesozoic strata of the southwestern Rub' al Khali, so that it is a confined aquifer over an area of 170000 km (Figure 6). Where confined, as at As Sulayyil, it is often artesian (9.1 atmospheres) and yields good quality water (450 to 900 ppm TDS). The thickness of the Wajid Aquifer varies from 200 m to 900 m and was originally calculated to be 950 m thick in its type locality at Jabal al Wajid (Powers *et al.* [12]). Water stored in this aquifer has been estimated by Al Alawi and Abdurazzak [2] to be 205 billion m^3. Isotopic age determinations of the age of the groundwater in the Wajid Sandstone Aquifer show that it is more than 30000 years old according to the Ministry of Agriculture and Water [8] and thus represents 'fossil water'.

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

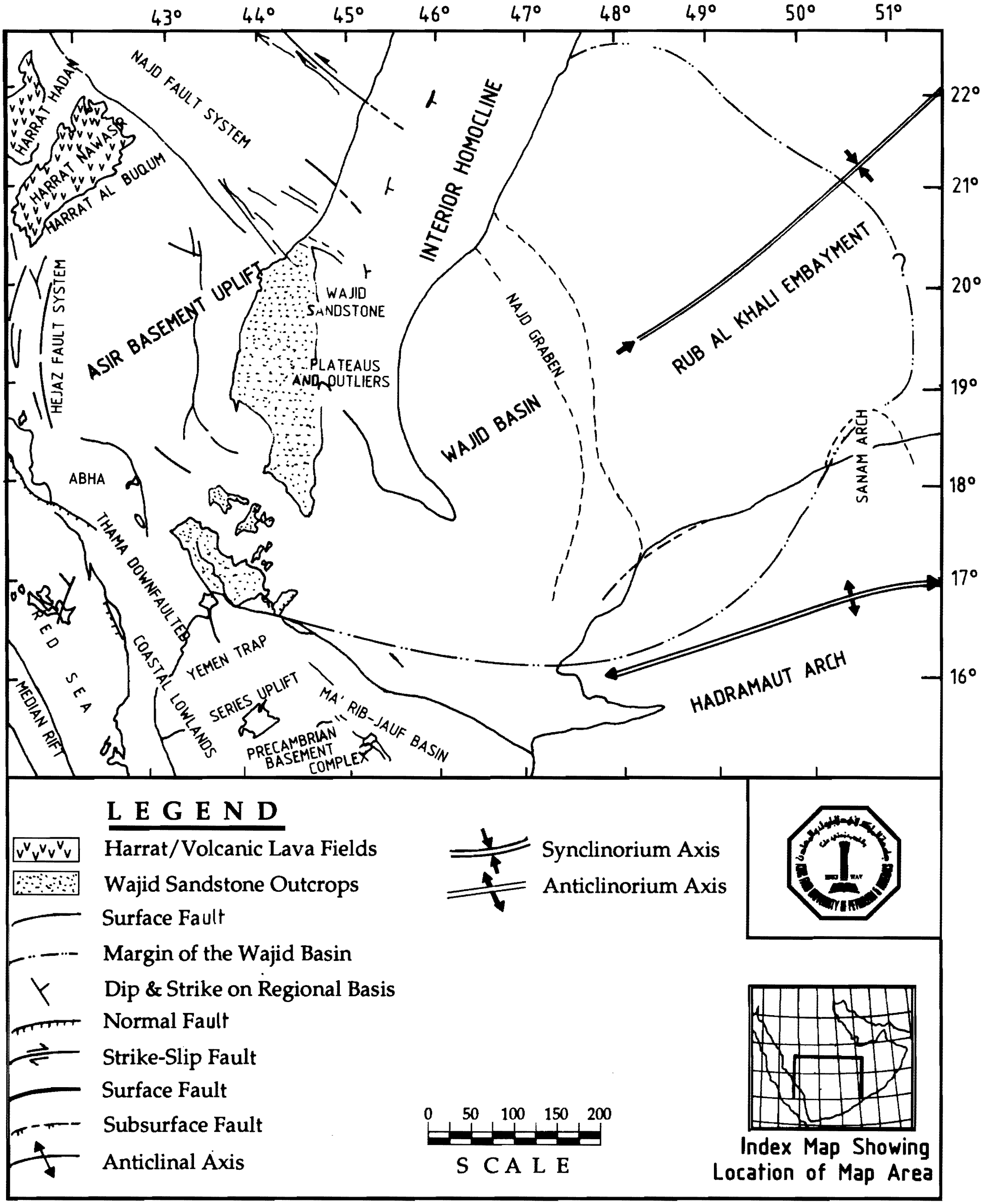

Figure 5. Structural Framework of the Wajid Basin and Adjacent Areas.

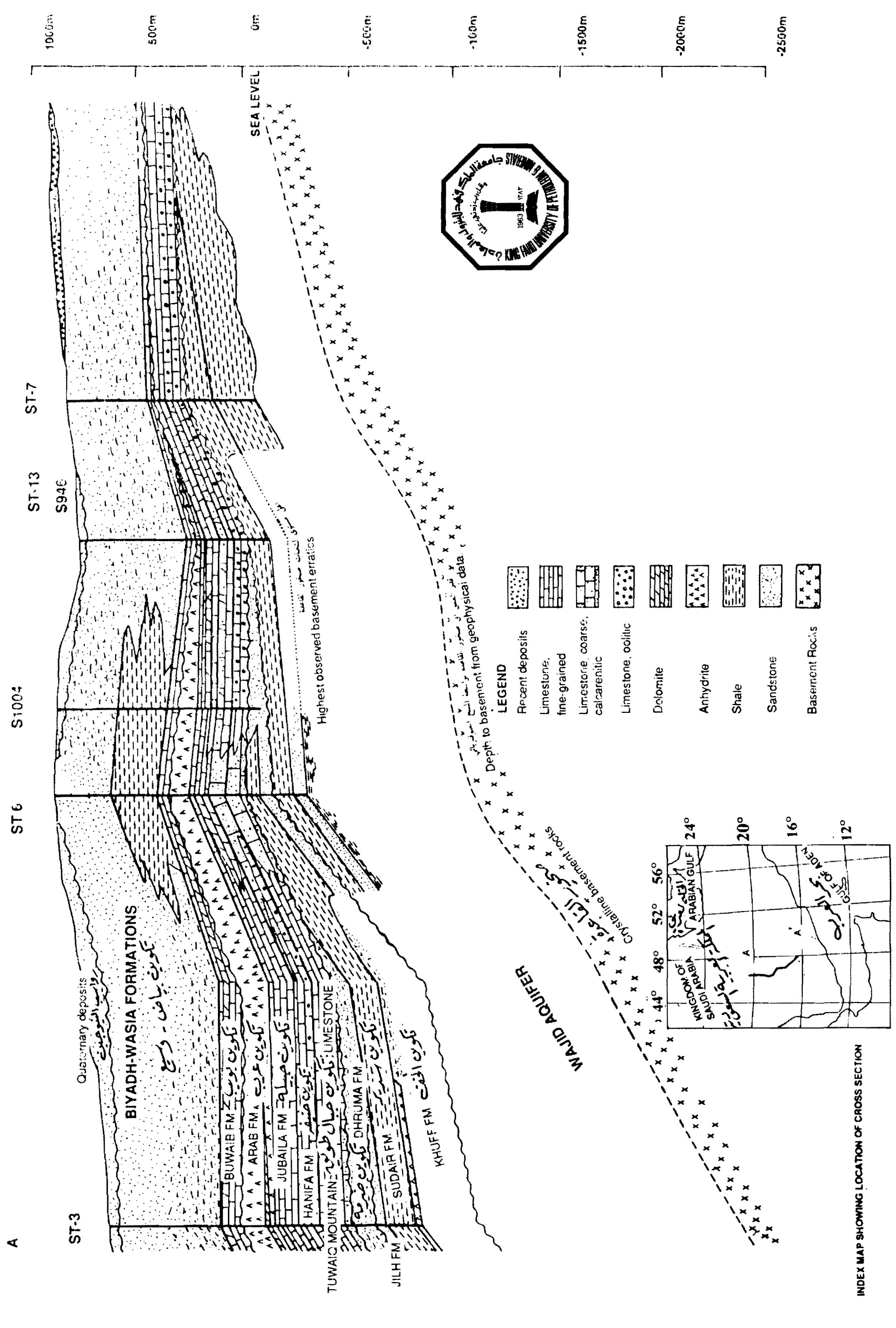

Figure 6. Geological Cross Section of the Southern Wajid Basin.

et al. [12]), 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 Sakakah, while 87 m were penetrated in a well at Turabah. The Hanadir Shale was deposited in a very broad basin north of the Arabian Shield, between the Midyan Mountains to the west and Wadi al Batin to the east. It is a very persistent lithostratigraphic unit in the Tabuk Basin and Northern Interior Homocline (north of 26° N) and of considerable hydrogeological significance as an impermeable shale aquiclude directly overlying the Saq Sandstone Aquifer. Three aquifers separated by shaly aquicludes occur in the Lower Paleozoic Tabuk Formation above the Hanadir Shale in the Tabuk Basin and the lower two are found in the Northern Interior Homocline.

Lower Tabuk Aquifer

This aquifer directly overlies the impermeable Hanadir Shale and is an unnamed Lower Ordovician sandstone member of Tabuk Formation. It consists of fine- to medium-grained, micaceous sandstone with thin, minor siltstone, and shale intercalations in its upper part. The thickness of this aquifer increases northwards, so that it has a thickness of 54 m near Buraydah, 140 m at Tabuk, and is up to 389 m thick in Turabah Water Well as given by Parsons Basil Consultants [23]. It is a significant confined aquifer in the Tabuk Basin and Interior Homocline and is the most important of the three Tabuk aquifers, which contain groundwater reserves calculated by Al Alawi and Abdulrazzak [2] to be 205 billion m^3.

Ra'an Shale Aquiclude

A distinctive, purplish gray to greenish gray, micaceous, graptolitic shale of Late Ordovician (Caradocian) age forms the Ra'an Shale, which is widespread in the Tabuk Basin and Interior Homocline, north of the town of 'Unayzah. The thickness of the Ra'an Shale varies from 14 m to nearly 100 m, the thickest sequence of 94 m being penetrated in the Tabuk Wadi Well. The Ra'an Shale forms an effective aquiclude to the permeable sandstones of the underlying Lower Tabuk Aquifer.

Middle Tabuk Aquifer

This aquifer comprises a middle member of the Tabuk Formation, consisting mainly of fine- to medium-grained, micaceous, cross-bedded, quartz sandstones. Except for a thin basal conglomerate, whose striated boulders represent Late Ordovician glaciation, as shown by McClure [19], the majority of the Middle Tabuk Sandstone Aquifer is of Early Silurian age. It is both a confined and unconfined aquifer in the Tabuk Basin, being 83 m thick near Tabuk and having a thickness of 197 m at Al Qalibah in the central Tabuk Basin. In the Interior Homocline, it occurs north of Al Qasim and is 242 m thick in a well at Al Qusayba', but has a relatively low transmissivity.

Qusaiba Shale Aquiclude

The Qusaiba Shale consists of varicolored, red, gray and gray-green, graptolitic shales with some ferruginous siltstones in its upper part. It is Lower Silurian (Llandoverian) on the basis of frequent *Monograptus* spp., and the trilobite *Platycorphe dyaulax* Thomas. Thickness of this aquifer increases northwards from 49 m at Al Qusayba' to 206 m in the At Tawil Well and it is absent at Tabuk city, since it is higher in the Lower Paleozoic sequence (Figure 7; between pages 14 and 15). From a hydrogeological viewpoint, the Qusaiba Shale forms a good aquiclude to the underlying Middle Tabuk Aquifer.

Upper Tabuk Aquifer

Two sandstone members of the uppermost part of Tabuk Formation comprise the Upper Tabuk Sandstone Aquifer. They are the Lower Silurian Sharawra Sandstone Member and the Lower Devonian Tawil Sandstone Member, which overlies it disconformably (Powers [24]), thus excluding the Upper Silurian. The Sharawra Sandstone Member is one of the thickest members of the Tabuk Formation, being 765 m thick in At Tawil Well. It is also quite thick at Turayf, where 379 m were penetrated, and in the Widyan Basin at Mudarra (about 40 km NNE of Al Qusayba'), where 423 m were drilled. Lithologically, it consists of alternating, fine-grained, micaceous sandstones with minor, laminated, gray shale and siltstone towards the base and top. The Tawil Sandstone Member has greater effective porosity and consists of gray to brown, medium- to coarse-grained, sometimes pebbly, dominantly cross-bedded, quartz sandstone. Its thickness reaches 200 m in outcrop at At Tawil and 189 m in a well at Turabah. In general, it is found in the north-central part of the Tabuk Basin and underlies the southeast part of the Wadi as Sirhan Basin. It also underlies the Widyan Basin Margin, but is excluded from the Interior Homocline.

Jauf Aquifer and Basal Aquiclude

In the northeast of the Tabuk Basin, the Devonian Jauf Formation directly overlies the Upper Tabuk Aquifer, with its basal, sandy shaly Shaibah Member forming a local, upper aquiclude for that aquifer. Other units of the Jauf Formation, such as the Qasr Limestone and Hammamiyat Limestone members are also water-bearing. The Jauf Formation is 299 m thick in its type locality near the town of Al Jawf and extends under the southern Wadi as Sirhan Basin and the Widyan Basin Margin, reaching a subsurface thickness of 700 m at Sakakah and towards the border with Iraq. This formation also contains sandstones to the north and west of Al Jawf, which yield good quality water (300 mg/l TDS). Reserves of groundwater of quality 400–5000 ppm in the Jauf Aquifer and Sakaka Sandstone have been put at 100×10^9 m^3 by Al Alawi and Abdulrazzak [2]. This figure is somewhat misleading, as the Sakaka Sandstone is now known by Aramco geologists (personal communication) and Edgell [9, 10] to be the Middle Cretaceous Wasia Formation and not related to the Devonian Jauf Aquifer.

Berwath Aquifer

The Carboniferous Berwath Formation is found only in the subsurface of the Widyan Basin Margin and it occupies an embayment south of the Saudi–Iraq border from Badanah to Al Jumaymah. Isopachs of the formation show that it thickens northwards from Turabah, so that it is 1000 m thick near the southern border of Iraq as shown by Al-Laboun [25]. It consists of fine- to coarse-grained, argillaceous sandstone with common interbeds of siltstone and some shale. Interbedded sandstones of the Berwath Formation provide fair to moderate yields of good quality water for 50 km to the southeast of 'Ar 'ar.

'Unayzah Aquifer

The Carboniferous and Lower to Middle Permian transgressive clastics of the 'Unayzah Formation unconformably overlie and overlap various formations from Lower Ordovician to Devono–Carboniferous and rest nonconformably on the crystalline rocks of the Precambrian Arabian Shield. Lithologically, the 'Unayzah Formation consists of cross-bedded, fine- to coarse-grained, fluvioglacial sandstones and thin beds of impure limestone (Al-Laboun [26]). Although it is only 33 m thick in its type locality at 'Unayzah, it thickens northwards along the Northern Interior Homocline and Widyan Basin to some 400 m on the southern borders of Iraq and Kuwait. In the Al Hawtah area, 150 km south of Riyadh, this formation is 57 m thick locally and occupies subsurface channels, probably due to glacial scour. It also extends to the southern part of Eastern Interior Homocline, where it is known locally as the Faw Formation and yields modest amounts of water. In general, the 'Unayzah Aquifer has a relatively low yield.

Khuff Aquifers

The extensive Upper Permian Khuff Formation crops out along the Interior Homocline from Jabal al Qasdah in the south to near Turabah in the southeastern Nafud, over a distance of 1200 km. Although limited to the west by the Arabian Shield and the Ha'il–Rutah Arch, the Khuff Formation extends under all the Rub' al Khali and Arabian Platform, as well as under most of the Arabian Gulf. This formation is composed of limestones and dolomites, with some anhydrite interbeds which act as aquicludes and divide it into four permeable, carbonate, aquifer units with low effective porosity, termed Khuff A, B, C, and D in descending order (Al-Jallal [27]). The Khuff Formation thickens northwards to some 600 m on the Saudi–Iraq edge of the Widyan Basin and the Saudi–Kuwait border and has a general thickness of about 250 m in the Northern Interior Homocline and the Qasim area. Total groundwater reserves in the Khuff Aquifers are given by Al Alawi and Abdulrazzak [2] as 30×10^9 m^3, with poor water quality of 3800–6000 ppm.

Sudair Shale Aquiclude

The uppermost Permian (Tatarian) to Lower Triassic (Scythian) Sudair Shale is 220 m thick in outcrops in At Tarafiyah area. It is exposed widely elsewhere along the Northern Interior Homocline and extends in the subsurface throughout eastern Saudi Arabia, as well as northwards into the Widyan Basin Margin and the Wadi as Sirhan Basin. In lithology, the Sudair Shale consists of brick- to dark red, massive shale with some calcareous siltstone and fine-grained sandstone, as well as minor gypsum interbeds. It forms a widespread aquiclude for the Khuff aquifers and locally for the Upper Tabuk Aquifer in the Turayf area.

Jilh Aquifer

Conformably overlying the Sudair Shale is a sequence of thin-bedded Middle Triassic limestones, with minor shale and gypsum interbeds comprising the Jilh Formation. It forms a secondary aquifer, usually with poor water quality, due to dissolved calcium sulfate from interbedded anhydrite and gypsum layers. The Jilh Aquifer is exposed along the Northern Interior Homocline in a belt about 20 km wide and forms the Jilh Scarp. Its thickness varies from 130 to 400 m, being 166 m thick in outcrop near Al Qusayba' and generally thickening northwards. A number of deep wells have been drilled to the east of Riyadh, in the areas of Batin and Thamamah according to the Ministry of Agriculture and Water [8] with average yields of 63 l/sec from sandstones of the Jilh Aquifer. An estimate of the total groundwater reserves of the Jilh Aquifer having a water quality of 3800–5000 ppm is listed by Al Alawi and Abdulrazzak [2] as 115×10^9 m^3.

Minjur Aquifers

Two major aquifers known as the Upper Minjur Aquifer and Lower Minjur Aquifer occur within the Upper Triassic to Lower Jurassic Minjur Sandstone. This formation consists of cross-bedded, coarse- to very coarse-grained, permeable quartz sandstones separated by the Middle Minjur shales and mudstones in the area of Riyadh (El Khatib [28]). Minor interbeds of limestone, conglomerate, and gypsum also occur in the Minjur Formation. It is exposed in outcrop along the Northern Interior Homocline, becoming thin and shaly north of Latitude 27° N. The two Minjur Sandstone aquifers are of considerable economic importance, yielding 90% of the groundwater supply for the City of Riyadh as estimated by the Ministry of Agriculture and Water [8]. It is calculated by El Khatib [28] that the Minjur aquifers contain 460 million m^3 of sufficiently good water for general use in the Sudair–Riyadh–Aflaj area alone. Water quality decreases southward, being as high as 4100 mg/l of total dissolved solids at Al Aflaj. Primarily, the Minjur Sandstone acts as two confined aquifers, but south of 23° N it forms a single aquifer complex with the sandy Dhruma Formation. The age of groundwater in the Minjur aquifer system is 15 000 years old in its intake area and 35 000 years old some 100 km downdip to the northeast, suggesting low recharge.

Marrat Aquiclude

Overlying the Minjur Aquifers with an unconformable contact is the Lower Jurassic Marrat Formation. It is exposed along the Northern Interior Homocline as far north as Wadi ar Rimah and is 102.5 m thick in its type area at Khashm adh Dhibi (80 km southwest of Riyadh). This formation consists of aphanitic and calcarenitic limestones, but contains interbedded shale, siltstone, and some sandstone in its lower part. The lower thin sandstones contain small quantities of fair quality groundwater (1700 ppm TDS) and are counted as the uppermost part of the Upper Minjur Aquifer. Shales, siltstones and aphanitic limestones of the Marrat Formation generally act as an aquiclude to the important Minjur Aquifers. The Marrat Formation thickens slightly to 120 m in Well ST-27 (Lat. 26° 53′N; Long. 45° 19′E), but it is truncated by the Pre-Wasia Unconformity and is not present in the Widyan Basin Margin north of Latitude 29° 55′N. This formation does not extend into the Sirhan and Tabuk basins.

Dhruma Aquifer

The Middle Jurassic Dhruma Formation is 375 m thick in its type section just west of Riyadh, where it crops out as shallow water limestones and marine shales. Although it is generally replaced by a shaly facies towards the north, it yields fair quality water at Zulfi, east of Qasim. South of Latitude 22° N, along the Eastern Interior Homocline, it becomes predominantly sandstone, with limestone interbeds and 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 by the Ministry of Agriculture and Water [8]. The Minjur/Dhruma aquifer system is estimated to contain groundwater reserves of 180×10^9 m^3 of water quality 1100–20000 ppm by Al Alawi and Abdulrazzak [2].

Upper Jurassic Aquitards

These consist of Upper Jurassic formations, including in ascending sequence, the Tuwaiq Mountain Limestone, Hanifa Formation, Arab Formation, and the Hith Anhydrite. They are exposed along the Interior Homocline (Steineke *et al.* [29]), and underlie the Arabian Platform, although truncated towards the north and northwest by the Pre-Wasia Unconformity (Edgell [30]), just south of Wadi ar Rimah. These Upper Jurassic formations are of very limited hydrogeological significance due to their low permeability. They are either dense, aphanitic, and argillaceous limestones, such as the Tuwaiq Mountain Limestone and Jubaila Formation, or they contain much anhydrite, as with the Arab Formation and uppermost Jurassic Hith Anhydrite, both of which yield only limited amounts of highly mineralized water.

Hanifa Aquifer

Amongst the Upper Jurassic formations only a massive bed of oolite–pellet calcarenite at the top of the Hanifa Formation has good permeability downdip. This bed provides limited amounts of groundwater from wells in Wadi Hanifah.

Sulaiy–Yamama–Buwaib Local Aquifers

Lower Cretaceous limestones are generally unimportant for groundwater, with a few local exceptions. These include the Sulaiy, Yamama, and Buwaib formations in ascending sequence, which are found along the Interior Homocline. Calcarenites in the lower Sulaiy Formation act as a local minor aquifer about 20 km southeast of Riyadh with water quality of 1000 to 3000 mg/l of total dissolved solids.

In the Layla lakes area ('Uyun Al Aflaj), dissolution of the underlying Hith Anhydrite by groundwater has caused the Sulaiy, Yamama, and Buwaib limestone formations to collapse and become brecciated with the local development of good secondary porosity containing good groundwater (Ministry of Agriculture and Water [8]). In ancient times, falaj, or qanats, were developed in this area around a lake (about 4 km^2 in area as proved by Ritter [31] (Figure 1), although now reduced to seventeen small lakes).

Wasia–Biyadh Aquifer

Although the Lower Cretaceous Biyadh Formation is unconformably overlain by sandstones of the Middle Cretaceous Wasia Formation, they combine to form one immense aquifer system in the Northern Interior Homocline and the Widyan Basin Margin. This aquifer contains very large amounts of groundwater, estimated at several billion m^3 in the Riyadh area alone by El Khatib [28] and has overall groundwater reserves of quality from 900 to 10 000 ppm estimated at 590 billion m^3 by Al Alawi and Abdulrazzak [2]. It supplies raw water to Riyadh and at Khurais has good yields of groundwater with 550 mg/l of total dissolved solids. The Wasia–Biyadh Aquifer has a recharge of 480 million m^3/year from runoff from Jabal Tuwaiq and wadi underflow, as calculated by the Ministry of Agriculture and Water [8]. Each formation acts as an isolated hydrogeologic system a short distance downdip, and fluid communication between the Biyadh and Wasia sandstones is restricted due to the development of shales at the top of the Biyadh Formation sandstone towards the northeast and the interdigitation of the Middle Cretaceous Shu'aiba Formation shales.

The Biyadh Formation is sandy and largely non-marine, consisting of cross-bedded, quartz sandstone with some shale and conglomerate layers in its 425 m thick type section, just south of Riyadh described by Powers *et al.* [12]. It crops out along the Interior Homocline from just east of As Sulayyil to Wadi Atk, about 125 km north-northwest of Riyadh. In the subsurface, the Biyadh Formation thickens rapidly northwards from less than 20 m in Well ST-27 (Lat. 26° 53'N, Long. 45° 19'E) to more than 350 m in Well ST-29 (Lat. 28° 40'N; Long. 44° 58'N). It changes to the Zubair Formation sandstones at the southern Iraq border and is limited by the Ha'il–Rutbah Arch on the west. In northeastern and eastern Saudi Arabia, the arenaceous Biyadh Formation forms a major aquifer (B.R.G.M. [32]). The quality of groundwater from the Biyadh Aquifer is very good in the Nisah Graben (500 to 900 mg/l TDS) and fair at Kharj, where its saturated thickness is given as 65 m by Bazuhair [33]. At depth in the Eastern Province its water/quality has been shown to be poor by De Jong *et al.* [34]. Near Kharj, water in this aquifer proved to be 8000 years old, and some 10 000 years old downdip at Khurais from isotopic studies by SOGREAH [35].

The Albian to Turonian Wasia Formation is the single most important lithostratigraphic unit for the water resources of Saudi Arabia. Reasons for its hydrologic significance are that is primarily an extensive, porous, transgressive, cross-bedded, quartz sandstone, which increases up to 300 m in thickness in the subsurface. It is exposed along the Interior Homocline from Wadi ad Dawasir in the south to Turabah in the north. The Wasia Formation also occurs as the so-called Sakaka Sandstone at Sakakah on the Ha'il–Rutbah Arch. Exposures of this Middle Cretaceous sandstone in the Rutbah area of western Iraq provide recharge southeastward into Cenozoic strata of the Wadi as Sirhan Basin as proved by Khouri [11]. The Wasia Formation is about 200 m thick and is a good aquifer in the northern area, around Sakakah, with high effective porosity ranging from 10% to 29%. It underlies the Arabian Platform and has been encountered at depth in the central Rub' al Khali with a thickness of 600 m. Basinward, it divides into seven members with groundwater becoming increasingly saline towards the northeast (Naimi [14]), where it ultimately forms oilfield brines in many areas of offshore Saudi Arabia. Isotopic age determinations of groundwater from the Wasia Aquifer indicate that it is 'fossil groundwater' over 20 000 years old.

Aruma Aquifer

The Upper Cretaceous Aruma Formation is of wide extent underlying almost all the Arabian Platform. It forms an escarpment along the Interior Homocline and crops out over a large surface area of at least 170 000 km^2 in the Widyan Basin. In its type area at Al'Aramah (Lat.25° 28'N; Long. 26° 23'E) it consists mainly of interbedded, fine-grained to chalky or calcarenitic limestones and dolomites, with some shale and dolomite towards the base. The same shallow water carbonates form extensive outcrops in the Widyan Basin. In the subsurface, downdip northeast from its outcrops in the Northern Interior Homocline, the Aruma Formation is divided into two members. These are the Lower Aruma, predominantly shale, separated by a disconformity from the Upper Aruma, which is almost entirely limestone with a thin shale bed in the topmost part of the formation.

The Aruma Formation is from 60 to 140 m thick and forms a secondary aquifer known as the Aruma Aquifer with relatively poor quality groundwater used by wells at the pipeline stations of Badanah and Rafha. Water quality decreases downdip, with the eastern edge of potable water along a line from Hafar al Batin to the southern end of Ghawar. Reserves of groundwater in the Aruma Aquifer of quality 1600 to 2000 ppm are estimated by Al Alawi and Abdulrazzak [2] to be 85×10^9 m^3.

To the east of Wadi ad Dawasir, the Aruma Formation occurs in sandy facies combining with the Wasia and Biyadh sandstones to form the Cretaceous Sand Aquifer as named by the Ministry of Agriculture and Water [8], with usable groundwater having about 1800 mg/l of total dissolved solids.

Umm er Radhuma Aquifers

One of the most important and extensive aquifer systems throughout the Eastern Province is formed by the Paleocene–Lower Eocene Umm er Radhuma Formation (Naimi [14]). Lithologically, it consists of calcarenitic limestone with some dolomitic limestone, dolomite, minor marl, shale, and aphanitic, argillaceous limestones in the lower part as described by Powers *et al.* [12]. It extends from the northern Hadramaut and western Oman to the Saudi–Iraq border and underlies almost all the Rub' al Khali. In thickness, the Umm er Radhuma is 243 m in its exposed reference section at Wadi al Batin, but its subsurface thickness varies from about 300 m to 700 m. It crops out extensively along the Interior Homocline from Latitude 22° N northwards through the Summan Plateau (Felber *et al.* [36]) and the Widyan Basin Margin, commonly being karstified in outcrop as shown by Edgell [37, 38] and also, in the subsurface according to ITALCONSULT [39]. The best aquifers beds seem to lie in the higher, Lower Eocene part of the formation and the Umm er Radhuma is not one complete interconnected aquifer, due to intercalated marls, shales, argillaceous limestones, and some thin stringers of anhydrite. As a result, the formation has poor vertical permeability, although certain horizons show good horizontal permeability values. It yields good to poor quality groundwater, mainly from the upper third of the formation, where horizons of porous, foraminiferal calcarenite, or of small dolomite rhombs (as at Ain Dar) form zones with the highest yield of 95 l/sec, as at Haradh. At Wadi al Miyah, it is 490 m thick and is artesian with a head of 7 atmospheres. Water quality declines markedly in the lower part of this formation and, also, northeastward from <1000 ppm TDS near outcrop to 6000 ppm TDS along the coastal area as described by Naimi [14]. Better quality subsurface water is found on structural highs, such as the Dammam Dome, due to the local absence of anhydrite in the overlying Rus Formation. Shales and argillaeous limestones at the base of the formation act as aquitards between the Aruma and Umm er Radhuma aquifers. Vertical connection between the Wasia–Biyadh and the Umm er Radhuma aquifer systems has been calculated as only 0.05 l/sec/km^2 by the B.R.G.M. [16], so that the two aquifer systems behave independently. Isotopic age determinations show that groundwater in the Umm er Radhuma aquifer system is 'fossil water', being 10000 to 28 000 years old. Springs in Al Hasa area yield large volumes of water through Neogene strata as mentioned by Hötzl *et al.* [17], most of which originates from the upper Umm er Radhuma aquifer. Ground-water reserves in the Umm er Radhuma aquifers of water quality 2500–15 000 ppm are given by Al Alawi and Abdurazzak [2] as 190×10^9 m^3.

Hibr Aquitard

To the west of the Ha'il–Rutbah Arch, Paleocene and Eocene strata, roughly equivalent to the Umm er Radhuma Formation, exist in a different lithofacies, termed the Hibr Formation by Powers [24]. Its lithology consists of thin-bedded, chalky, and cherty limestone and marl from 150 to 485 m thick. In the Wadi as Sirhan Basin, the Hibr Formation acts as an aquitard as proven by Khouri [11], although containing minor aquifers in fractured chert layers.

Rus Aquiclude

The Lower Eocene Rus Formation is widespread in the subsurface of the Rub' al Khali, Eastern Province and Arabian Gulf areas. It is exposed only in two small areas as a narrow outcrop for some 180 km northward of Wadi as Sahba and as a nearly circular outcrop some 10 km in diameter in the breached core of the Dammam Dome described by Powers [24]. Its thickness varies from less than 30 m in Ghawar to 225 m in the central Rub' al Khali. Lithologically, it consists of white, compact, finely crystalline anhydrite with interbedded green shale on the flanks of structures and in structural lows. On structural highs, it appears as chalky and dolomitic limestone, locally containing poor quality groundwater, and is interbedded with gray marl and shale, as well as thin geodal quartz layers. It forms an imperfect aquiclude to the underlying Umm er Radhuma aquifer system, as well as to the overlying Middle Eocene Khobar Aquifer.

Khobar Aquifer

The widespread and predominantly Middle Eocene Dammam Formation is from 28m to 192m thick and consists of five members. In ascending sequence, these are the Midra Shale, Saila Shale, Alveolina Limestone, Khobar, and Alat members. The lower shale members, together with the Alveolina Limestone, act as containing beds, in conjunction with the Rus Aquiclude, for the Umm er Radhuma aquifer system (Abderrahman *et al.* [40]). The Khobar Member is up to 75m thick and consists of skeletal, detrital, porous, friable limestone, dolomitic limestone, and marl in the lower part, described by B.R.G.M. [17]. Limestones of the Khobar Member are karstified and fissured forming the Khobar Aquifer, which provides moderate amounts of groundwater in the Eastern Province from Wadi as Sahba to Qatif, especially in Al Hasa area.

Alat Aquitard

The lower part of the Alat Member consists of dolomitic marl with thin limestone interbeds and is up to 35 m thick. These marly beds, also known as the "Orange Marl", act as a leaky confining layer, or aquitard, poorly separating the Khobar and Alat aquifers. Because of poor separation, the Khobar Aquifer and Alat Aquifer are sometimes referred to as the Dammam Aquifer (Yazicigil *et al.* [41]) and contain groundwater reserves of 45×10^9 m^3 (Al Alawi and Abdulrazzak [2]) with water quality of 2600 to 6000 ppm.

Alat Aquifer

The upper part of the topmost member of the Dammam Formation consists of porous, skeletal, dolomitic limestone up to 110 m thick, forming the Alat Aquifer. Its uppermost part, which directly underlies the Pre-Neogene Unconformity, commonly shows local silicification. Although eroded from the Dammam Dome, it forms a semiconfined to unconfined aquifer to the north of it, and also occurs as the 'A' aquifer in nearby Bahrain. It has low and very variable horizontal permeability mentioned by Naimi [14].

Neogene Aquifers

Throughout most of the Eastern Province, Middle Eocene strata of the Dammam Formation are disconformably overlain by Upper Tertiary, or Neogene, beds up to 300 m thick. This mainly clastic Mio–Pliocene sequence consists in ascending sequence of the Hadrukh, Dam, Hofuf and Kharj formations. Of these, only the detrital Hofuf and karstified limestones of the Dam have any significance as aquifers, as the upper two lie in the vadose zone. In 1994, Al Alawi and Abdulrazzak [2] calculated the groundwater reserves with water quality of 3700–4000 ppm in Neogene aquifers at 130×10^9 m^3.

Hadrukh Aquifer

Sandy strata of the Hadrukh Formation cover a lowland belt about 100 km wide along the Arabian Gulf coast from the Saudi–Kuwait border almost to Abqaiq, ranging in thickness from 20 to 120 m. The formation consists of a basal few meters of calcareous sandstone, followed upward by interbedded marls, sandstones and clays, with abundant chert in some layers, and minor gypsum. A locally occurring limestone member of the Hadrukh formation is the karstified Sab Sab Limestone Member, developed towards Wadi al Batin and in the northern parts of the Ma'aqala–Faridah–Wariah uplift and reaching a thickness of 30 m.

The Hadrukh Formation sandstones form the Hadrukh Aquifer, with highest permeabilities to the southwest of Hofuf. An eroded window to the Umm er Radhuma aquifer system in the south of the Ghawar Anticline (Figure 8) allows groundwater flow into the Hadrukh Aquifer, shown by B.R.G.M. [16]. There is a general northeast flow of water in this aquifer and it supplies good quality groundwater in Al Hasa area.

Dam Aquifer

The Middle Miocene Dam Formation consists of interbedded marine marls, limestones, and clays directly overlying the Hadrukh Formation. It is from 30 to 101 m thick and is found in the Al Hasa area, where its limestones are karstified and fissured with an underground karst cave supplying the large 'Ayn Khudud spring (Figure 9). Springs from the Dam Aquifer in the Al Hasa area yield 12 m^3/sec to 14 m^3/sec.

Mio–Pliocene Aquifers (Wadi as Sirhan Basin)

In the Wadi as Sirhan area, continental, Mio–Pliocene calcareous sandstones, sandy marls and minor freshwater limestones are up to 200 m thick. The sandstones have good permeability and form the main aquifer in that area, both in confined and unconfined situations described by KFUPM [42].

Late Tertiary and Quaternary basalts of the Harrat al Harrah extend along a northwest–southeast trend parallel to Wadi as Sirhan. Some of these basalts, which are fractured, weathered, or contain volcanic breccia, act as local low yield aquifers.

Quaternary Alluvial Aquifers

Ground water has also been developed in many of the large, alluvium-filled wadis of Saudi Arabia, such as those of the Red Sea coast, interior Asir, the Riyadh area, the Rimah–Batin wadi system, and in Wadi as Sirhan.

Along the Red Sea coast, wadis such as Jizzan, Dhamad, Fatimah, Lith, Khulays, Rabigh, Baysh, and Hali have a storage of 14250 million m^3 and potential development of 105 million m^3/year of poor to good quality, shallow groundwater as estimated by the Ministry of Agriculture and Water [43].

The city of Ta'if is also supplied with groundwater from the alluvium of nearby Wadi Wajj and Wadi Liyyah, as well as that piped from wells in Wadi Turabah according to El Khatib [28].

Wadi ad Dawasir valley provides alluvial, sandy aquifers up to 100 m thick, which supply relatively good groundwater for pivotal irrigation systems. According to the Ministry of Agriculture and Water [43], the Dawasir alluvial system, including its major tributaries in the Asir Mountains, can provide 17000 million m^3 of groundwater for local irrigation.

Wadi Najran, in southern Asir Province, contains shallow, good quality water in its alluvium with a storage of 33350 million m^3 and good recharge, due to rainfall of up to 500 mm/year in its headwaters (El Khatib [28]).

Alluvium-filled valleys in the Riyadh region, such as Wadi Birk, Wadi Nisah, and the upper reaches of Wadi as Sahba, contain considerable amounts of poor to good quality groundwater (14100 million m^3/year) locally used for irrigation purposes.

A large area of the northern Arabian Shield is drained by the northeast-flowing Wadi ar Rimah–Wadi al Batin system, whose alluvium contains shallow, poor quality groundwater used around Al Bayada and 'Unayzah.

Quaternary alluvial sands along Wadi as Sirhan contain shallow groundwater with an average TDS of 2000 mg/l, often exploited by hand dug wells (Ministry of Agriculture and Water [43]).

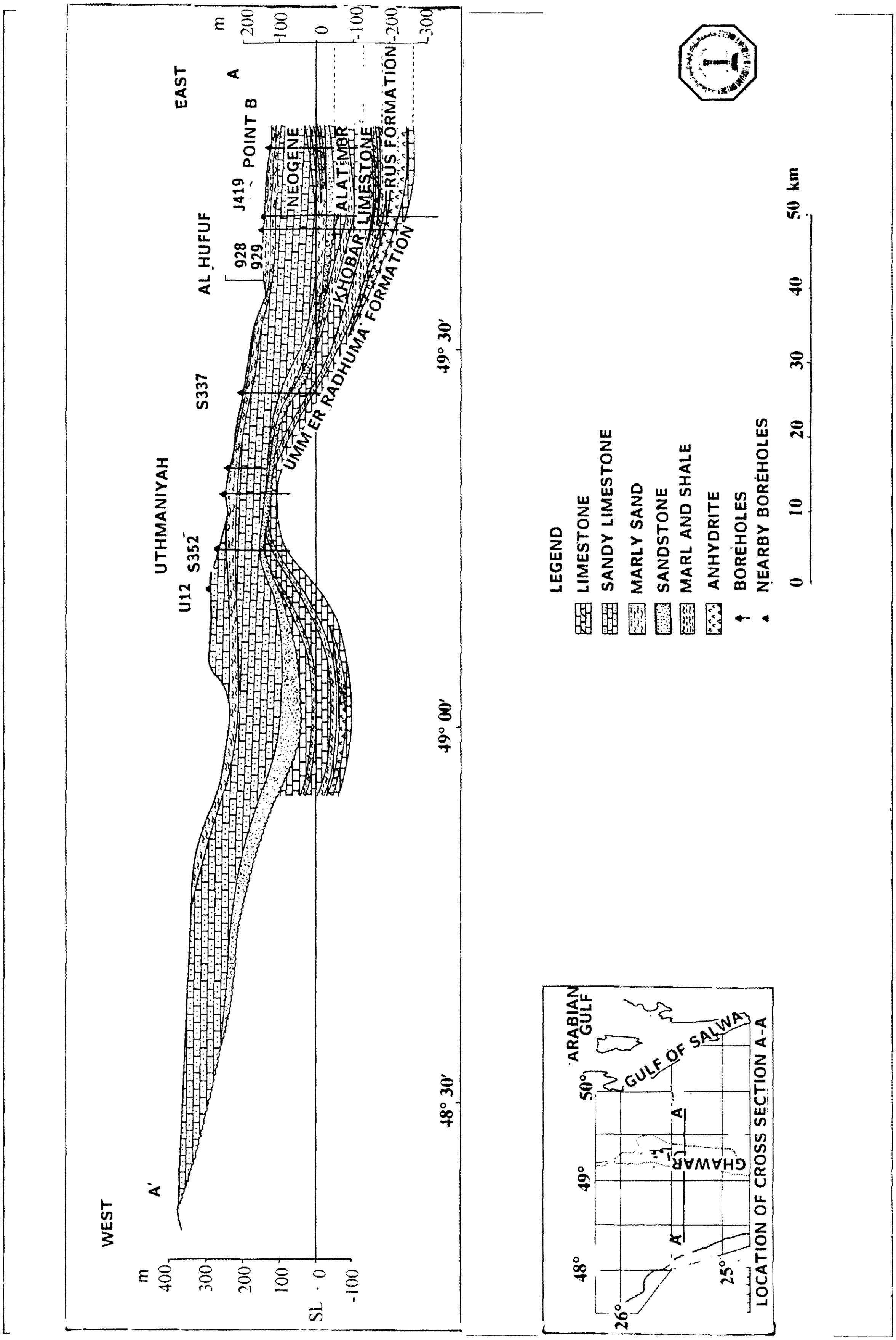

Figure 8. Geological Cross Section of Tertiary Strata across Ghawar Anticline to Al Hofuf (after B.R.G.M. [16]).

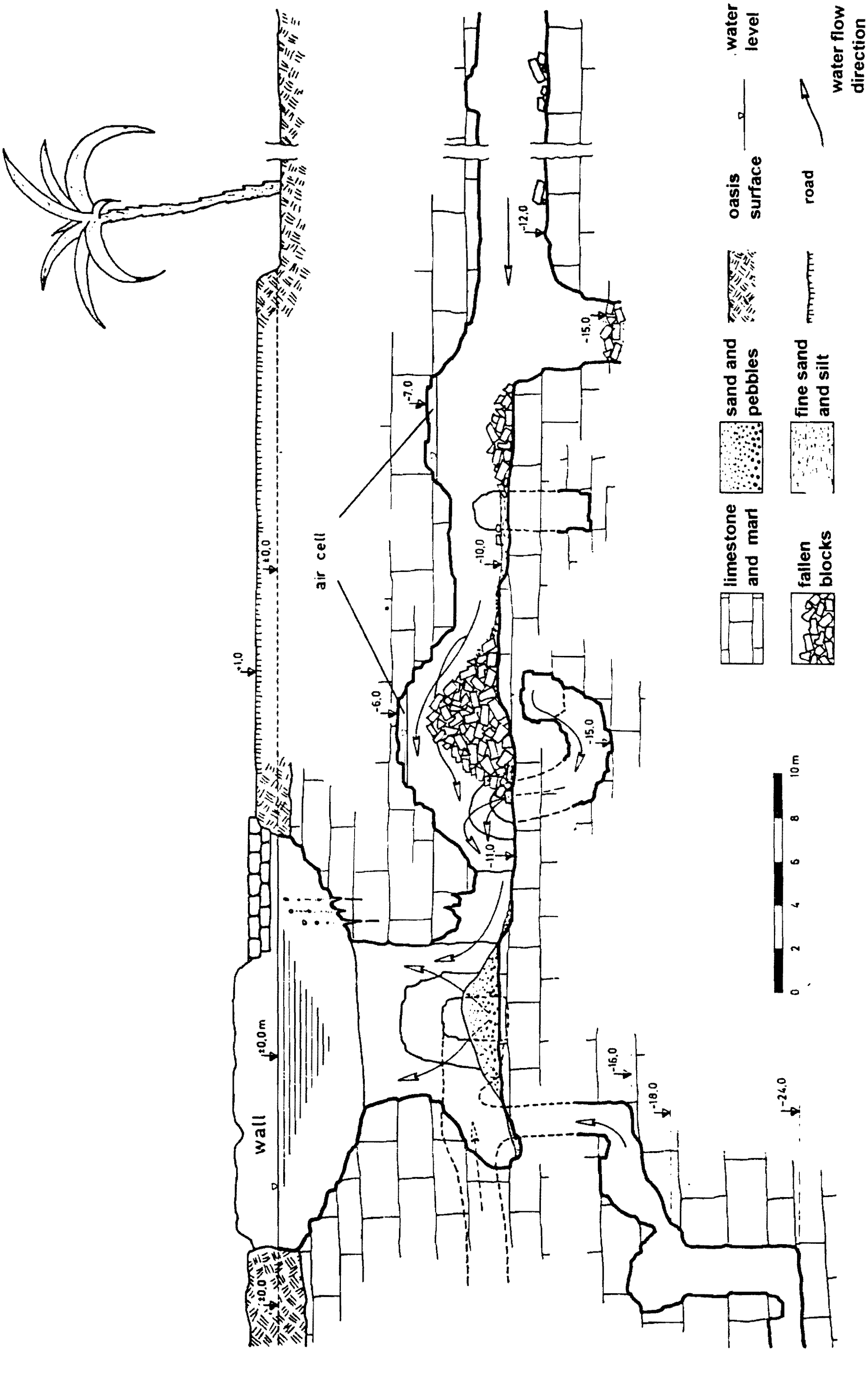

Figure 9. Karst Cave System in the Dam Aquifer at 'Ayun Khudud, Al Hasa Area (after Hötzl et al. *[17]).*

It should be emphasized that water held in wadi alluvium in Saudi Arabia is only a very minute fraction of the billions of cubic meters of groundwater in the sedimentary basins of the Kingdom.

Aquifer Types According to Origin

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.

Primary Aquifers

Primary aquifers include quartz sandstones, conglomerates, calcarenites, coquinites, and oolitic limestones with primary porosity. This also includes unconsolidated alluvial sands of Quaternary wadis. In addition, agglomerates, or volcanic breccias, have some original pore space. Permeability is proportional to the first power of porosity and inversely proportional to the second power of the specific surface (cm^3/cm^2). Thus, the coarser the grains, the smaller the specific surface and the larger the permeability as shown by Pettijohn [44]. Fortunately, the majority of Saudi Arabia's aquifers consist of medium- to coarse-grained sandstones with resultant high permeabilities.

High, primary, intergranular porosity is found in quartz sandstones, such as those of the Saq, Wajid, Tabuk, Minjur, Wasia–Biyadh, and Hadrukh aquifers. These form the most important aquifers in Saudi Arabia.

Much primary porosity is still preserved between the grains of lime sand, which make up calcarenites of Umm er Radhuma aquifer system. Coquinite zones, especially those composed of larger foramiferids, also form aquiferous zones of high primary porosity in the top third of the Umm er Radhuma Formation and form an high yield aquifer on the eastern edge of the Rub' al Khali.

A limited primary porosity also exists in volcanic breccias of Quaternary and Late Tertiary lava fields as in Harrat al Harrah, while sub-basalt sands with good primary porosity produce usable groundwater in the Khaybar area.

Secondary Aquifers

Secondary aquifers occur in carbonate sediments, primarily limestones, where later diagenetic changes have generally increased the original porosity. Examples are the Dam, Alat, Khobar, and Umm er Radhuma aquifers, all of which have undergone secondary solution, or dolomitization, as well as karstification and fissuring. Regional stresses have also caused fracturing, giving addition fracture porosity. Karstified and fissured limestones act as good aquifers. The northern outcrops of the Alat Aquifer are extensively karstified with many 'dahls' or sinkholes, which trap local surface runoff. This karstification is also seen in the Dam Aquifer giving it good porosity and permeability in Al Hasa area (Figure 9). Between Ma'aqala–Shawiyah and the Saudi–Iraq border, outcrops of the Umm er Radhuma Formation are extensively karstified with many prominent sinkholes and cave systems controlled both by more soluble limestone layers and fracture systems, resulting from regional stresses. Joints of these fracture systems are often open and provide some surface recharge, while in the subsurface they provide useful secondary porosity allowing groundwater to move downdip in confined limestone aquifers. Good secondary porosity has been formed in the Al Aflaj area where local dissolution of the underlying Upper Jurassic Hith Anhydrite has caused strongly jointed Lower Cretaceous limestone of the Sulaiy, Yamama, and Buwaib formations to collapse, producing brecciation and good secondary permeability.

Diagenesis in limestones produces dolomite or dolomitic limestone with an increase in effective porosity. An example is the Umm er Radhuma aquifer system at Ain Dar, where a horizon with loose dolomite rhombs provides the main water-bearing zone.

Well-developed trends of jointing occur in fractured basalts of the Sirhan Basin (Khouri [11]) providing secondary permeability. In outcrops of the thick, Ordovician Wajid Sandstone, jointing is also well-developed facilitating penetration of outcrops by water and the downdip movement of groundwater where the Wajid Aquifer is confined. Permeability of the Wajid Aquifer is shown by its spectacular artesian flow from recently drilled wells in the As Sulayyil area, with artesian heads of 26 m.

AQUIFER CHARACTERISTICS

Each of the aquifers in the tectono–sedimentary basins of Saudi Arabia has its own hydrogeological characteristics. These properties include their age, origin, thickness, effective porosity (ϕ), permeability (k), transmissivity (T), and storativity (S), and are listed below for aquifers in each basin.

Tabuk Basin

The descending sequence of aquifers in the Tabuk Basin is as follows.

Jauf Aquifers (L. to M. Devonian)

Secondary aquifer; limestones and fine-grained, micaceous sandstones;
200 to 400 m thick; $\phi = 10\%$ to 23%; $k_h = 190$ mD and $k_v = 154$ mD;
$T = 1.1 \times 10^{-3}$ m^2/sec to $T = 2 \times 10^{-3}$ m^2/sec (confined) and $T = 3 \times 10^{-3}$ m^2/sec (unconfined);
$S = 2 \times 10^{-2}$ (unconfined) to $S = 7 \times 10^{-3}$ (confined); yields good quality water.

Upper Tabuk Aquifer (Siluro–Devonian)

Primary aquifer; quartz sandstone; 200 to 500 m thick;
$\phi = 10\%$ to 21%; $k_h = 190$mD; $T = 10 \times 10^{-3}$m^2/sec to $T = 30 \times 10^{-3}$ m^2/sec;
$S = 1.4 \times 10^{-3}$ to 2×10^{-3} (confined), $S = 2 \times 10^{-2}$ (unconfined), and $S = 3.5 \times 10^{-2}$ (semi-unconfined).

Middle Tabuk Aquifer (U.Ordovician–L. Silurian)

Primary aquifer; fine- to medium-grained, quartz sandstone; 40 to 250 m thick;
$\phi = 10\%$ to 12%; $k_h = 490$ mD; $T = 1.7 \times 10^{-3}$ m^2/sec in Tabuk area;
$S = 2 \times 10^{-2}$ to max. $S = 5 \times 10^{-2}$ (unconfined), $S = 1 \times 10^{-3}$ (confined).

Lower Tabuk Aquifer (Lower Ordovician)

Primary aquifer; fine- to medium-grained quartz sandstone; 130–200m thick;
$\phi = 8\%$ to 20%; $T = 2 \times 10^{-3}$ m^2/sec (unconfined) to $T = 2 \times 10^{-4}$ to 8×10^{-4} m^2/sec where confined north of Tabuk;
$S = 2 \times 10^{-2}$ (unconfined) to $S = 6.7 \times 10^{-4}$ (confined).

Saq Aquifer (Lower Ordovician)

Primary aquifer of major importance; medium- to coarse-grained, quartz sandstone;
400–928 m thick; $\phi = 15\%$ (12%–20%); $k_h = 290$ mD to $k_v = 350$ mD;
$T = 9 \times 10^{-3}$ m^2/sec to $T = 3.8 \times 10^{-2}$ m^2/sec; $S = 1.2 \times 10^{-3}$ to 7×10^{-2} (unconfined),
$S = 1 \times 10^{-4}$ to $S = 5 \times 10^{-3}$ (unconfined).

Wadi as Sirhan Basin

In this basin, the aquifers in descending sequence have the following characteristics.

Basalt Aquifers (Quaternary–Late Tertiary)

Secondary aquifers in fractured basalts up to 100 m thick; groundwater of hydrocarbonate–chloride type;
salinity 400 to 1900 mg/l; low yield.

Neogene Sandstone Aquifer (Mio–Pliocene)

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

Hibr Formation (Paleocene–U.Eocene)

Mostly a chalky aquitard 180–485 m thick but contains minor chert aquifer.

Wasia Aquifer (= Sakakah Sandstone) (Mid Cretaceous)

Primary aquifer; coarse- to medium-grained quartz sandstone; up to 285 m thick;
$\phi = 10\%$ to 29%; $T = 3\times10^{-4}$ m^2/sec to $T = 2.8\times10^{-2}$ m^2/sec increasing NE to 15×10^{-3}m^2/sec;
$S = 3\times10^{-2}$ to 5×10^{-2} (unconfined) and $S = 7\times10^{-3}$ (confined).

Upper Tabuk Aquifer (L.Silurian–L.Devonian)

Primary aquifer; quartz sandstone; 440 m thick in the Turayf Well (where at excessive depths of 660m below the surface);
$T = 10\times10^{-3}$ m^2/sec to $T = 7\times10^{-4}$ m^2/sec; $S = 1.4\times10^{-3}$ to 2×10^{-3} (confined).

Widyan Basin Margin

Hydrogeologic characteristics of aquifers in descending sequence are as follows.

Umm er Radhuma Aquifers (Paleocene–L. Eocene)

A secondary aquifer system in karstified limestone and dolomite zones; about 250 m thick;
yields minor amounts of poor quality groundwater; intergranular porosity up to 30%;
effective porosity $\phi = < 10\%$; $k_h = < 30$mD; $T = 4\times10^{-5}$ m^2/sec;
$S = 4\times10^{-4}$ (average), range $S = 5\times10^{-3}$ to $S = 5\times10^{-5}$ (confined), also unconfined over an area of 54 793 km^2 in this basin near the Saudi–Iraq border.

Aruma Aquifer (Upper Cretaceous)

Minor secondary aquifer; interbedded dolomite and limestone with lower shales; 60 to 140 m thick; $\phi = 2\%$;
yields poor quality water; mostly exposed at the surface over the Widyan Basin Margin.

Wasia–Biyadh Aquifer (Mid to Lower Cretaceous)

Primary aquifer; quartz sandstone; 285 to 600 m thick (from 285 m thick outcrop at Sakakah, it thickens northeastward beneath the impermeable shaly beds of the Lower Aruma);
Average value of $T = 3\times10^{-4}$ m^2/sec to $T = 2.8\times10^{-3}$ m^2/sec (unconfined).
In the subsurface, $T = 15\times10^{-3}$ m^2/sec (confined); $S = 3\times10^{-2}$ to 5×10^{-2} (unconfined) and $S = 7\times10^{-3}$ (confined).

'Unayzah Aquifer (M. Permian–U. Carboniferous)

Primary aquifer; poorly sorted, fine- to coarse-grained, micaceous quartz sandstone and siltstone; 0 to 400 m thick;
$\phi = 28\%$ to 31% at 'Ar'ar; $k = 1.4$ D to $k = 1.5$ D; low transmissivity.

Berwath Aquifer (Carboniferous)

Primary aquifer; quartz sandstone; > 250 m thick; moderate yields of good quality water;
$T = 3\times10^{-3}$ m^2/sec (average); $S = 1\times10^{-3}$ (confined).

Interior Homocline

Hydrogeological characteristics of aquifers are discussed below in descending sequence and, for practicality, both the Northern Interior Homocline and Eastern Interior Homocline are grouped together.

Aruma Aquifer (Upper Cretaceous)

Secondary aquifer; limestone and dolomite; 60 to 142 m thick; poor quality water; low yield.

Wasia–Biyadh Aquifer (Mid to Lower Cretaceous)

Primary aquifer; sandstone; up to 600 m thick; yields fair to good quality water; $\phi = >10\%$; $k = 7.6$ mD to $k = 53$ mD; $T = 1.5\times10^{-2}$ m^2/sec to $T = 9.7\times10^{-2}$ m^2/sec; $S = 2\times10^{-4}$ (confined).

Dhruma Aquifer (Middle Jurassic)

Secondary aquifer; primarily limestone; 375 m thick near Riyadh, shales out to the north, while to the south it becomes increasingly sandy and is a good aquifer, joining with the Minjur Aquifer; $T = 1\times10^{-2}$ m^2/sec to $T = 1.6\times10^{-2}$ m^2/sec.

Minjur Aquifers (U. Triassic to L. Jurassic)

Primary aquifers; coarse-grained sandstone; 185–400 m thick;
fair quality water (major groundwater supplier for Riyadh); $\phi = > 3\%$;
$T = 1.7\times10^{-3}$ m^2/sec to $T = 7.2\times10^{-3}$ m^2/sec, average $T = 4\times10^{-3}$ m^2/sec;
$S = 1.3\times10^{-4}$ (confined). Isotopic age 15 000 to 35 000 years old.

Jilh Aquifer (Middle Triassic)

Secondary aquifer, thin-bedded limestone with minor shale, gypsum, and sandstone interbeds.
Thickness 130 m–400 m; $\phi = 2\%$; yields poor quality mineralized water.

Khuff Aquifers (Upper Permian)

Secondary aquifers in Khuff A, B, C, and D limestones separated by anhydrites;
thickness 250m; $\phi = 3\%$; yields poor quality water.

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

Secondary aquifer of fine- to coarse-grained sandstone; thickness, 33m–400m; $\phi = 10\%$ to 30%; $k = <1.0$ D;
mostly low storativity where confined, low transmissivity and relatively low yield.

Middle Tabuk Aquifer (Lower Silurian)

Primary sandstone aquifer in Northern Interior Homocline; 40 to 250 m thick;
$\phi = 10\%$ to $\phi = 21\%$; $k_h = 2.8$ D, $k_v = 1.5$ D; good quality water; $T = 1\times10^{-3}$ m^2/sec to $T = 1.6\times10^{-3}$ m^2/sec (Qasim);
$S = 2.5\times10^{-3}$ to 2.7×10^{-4} (confined).

Lower Tabuk Aquifer (Lower Ordovician)

Primary aquifer; fine- to medium-grained, quartz sandstone;
54 m thick near Buraydah to 389 m thick in Turabah Water Wells; $\phi = 8\%$ to $\phi = 20\%$;
$T = 1.7\times10^{-3}$ m^2/sec (unconfined, north of Qasim), $T = 4\times10^{-4}$ m^2/sec to $T = 1.5\times10^{-4}$m^2/sec (confined);
$S = 2\times10^{-2}$ (unconfined) to $S = 1\times10^{-3}$ (confined).

Saq Aquifer (Lower Ordovician)

Primary major aquifer, medium- to coarse-grained quartz sandstone;
$\phi = 12\%–30\%$; > 400 m thick in Qasim area; $k_h = 0.35$ D to $k_h = 5.58$ D,
$k_h = 0.26$ D to $k_v = 3.33$ D; $T = 4\times10^{-4}$ m^2/sec to $T = 2.7\times10^{-2}$ m^2/sec near Qasim;
average $S = 1.3\times10^{-2}$ to 7×10^{-2}; yields plentiful good quality water.

Eastern Shelf

Including Al Hasa, Summan Plateau and Dammam–Qatif areas.

Dam Aquifer (Middle Miocene)

Secondary aquifer; karstified, fissured limestones with interbedded marl and clay;
30 m to 101 m thick; good secondary porosity, $\phi = 3\% - 10\%$;
$T = 10^{-2}$ m²/sec (Ghawar) to $T = 70 \times 10^{-3}$ (Al Hasa); yields good quality water.

Hadrukh Aquifer (Lower Miocene)

Primary aquifer; sandstone with interbedded marl, and clay; 20 m to 120 m thick;
$\phi = > 3\%$; $T = 7 \times 10^{-4}$ m^2/sec to $T = 4 \times 10^{-2}$ m^2/sec;
$S = 1 \times 10^{-2}$ (unconfined) to $S = 2 \times 10^{-4}$ (confined); yields good to fair quality water in Al Hasa and Wadi al Miyah.

Alat Aquifer (Middle Eocene)

Secondary aquifer; skeletal karstified limestone; 10 to 50 m thick;
$T = 2.6 \times 10^{-5}$ m^2/sec to $T = 5.1 \times 10^{-3}$ m^2/sec; $S = 1.3 \times 10^{-4}$ to $S = 2.6 \times 10^{-5}$; yields moderate amounts of potable water at Ras Tanura, Dammam, and Nariya, as well as irrigation water around Qatif and Tarut Island.

Khobar Aquifer (Middle Eocene)

Secondary aquifer; karstified, skeletal, calcarenitic limestones and dolomites;
up to 80 m thick (truncated on *S*. Ghawar anticline); $\phi = >3\%$;
$T = 1 \times 10^{-2}$ m^2/sec to $T = 3 \times 10^{-6}$ m^2/sec; $S = 1 \times 10^{-3}$ to $S = <1 \times 10^{-4}$ (confined);
Fossil water > 30000 years old; provides good quality water in
Uthmaniyah–Hofuf area, at Abqaiq, and as irrigation water around Qatif.

Umm er Radhuma Aquifers (Paleocene–Lower Eocene)

Major secondary aquifer in upper third of formation; lower aquifers are too saline; limestone and dolomite with porous lattice of loosely cemented dolomite rhombs forming main water-bearing zone (Naimi [14]);
300–700 m thick; $\phi = 0.5\%$ to $\phi = > 5\%$; $k = 32$ mD to $k = 443$ mD;
$T = 1 \times 10^{-2}$ m^2/sec to $T = 1 \times 10^{-3}/m^2$ sec; $S = 5 \times 10^{-5}$ to $S = 5 \times 10^{-3}$ (confined), with an average $S = 4 \times 10^{-4}$ (confined);
fossil water 20000 to 23000 years old; yields good quality water in Al Hasa area and raw water in the Dammam area.

Rub' al Khali Basin

Several aquifers of widespread extent occur in the desert region of the Rub' al Khali. In descending stratigraphic sequence the aquifers and their characteristics are summarized below.

Neogene Aquifer (Mio–Pliocene)

Primary aquifer; calcareous sandstone; thin; found at depths of over 20 m;
extensive throughout the central Rub' al Khali.

Dammam Aquifer (Middle Eocene)

Secondary aquifer; calcarenitic limestone; about 30 m thick;
water-bearing in the subsurface of U.A.E. and at the surface at Shishur in interior Dhofar, probably extends under the northern Rub' al Khali in Saudi Arabia; undeveloped.

Umm er Radhuma Aquifer (Paleocene–Lower Eocene)

Secondary aquifer of major importance; limestone with dolomite interbeds; 150 to 400 m thick;
high permeability in certain coquinite and dolomite zones;
water artesian to subartesian, generally good quality; yielded 2.6 l/sec on southern edge of Rub' al Khali Desert (*i.e.* Saudi–Oman border).

Cretaceous Aquifer (Upper to Lower Cretaceous)

Primary aquifer; quartz sandstone; several hundred meters thick (sandstones of the Wasia and Biyadh combine with sandy facies of the Aruma east of Wadi ad Dawasir to form one aquifer);
good permeability; good quality water in the southwestern Rub' al Khali but too saline basinward;
$T = 7\times10^{-3}$ m^2/sec; $S = 2\times10^{-2}$ (unconfined).

Wajid Basin

Only one large Lower Paleozoic aquifer occurs in the Wajid Basin. Its characteristics are summarized below.

Wajid Aquifer (Lower Ordovician)

Primary aquifer; well-sorted, coarse-grained, quartz sandstone; 200 m to 900 m thick; $\phi = 20\%$;
$T = 5.7\times10^{-4}$ m^2/sec to $T = 2.1\times10^{-2}$ m^2/sec; $S = 2\times10^{-4}$ (confined) to $S = 2\times10^{-1}$ (unconfined);
yields good quality water about 1000 mg/l TDS; covers 196000 km^2 of the southwest Rub' al Khali.

RECHARGE OF MAJOR SAUDI ARABIAN AQUIFERS

Most aquifers in the sedimentary basins of the Kingdom contain fossil groundwater and isotopic dating shows that their groundwater is tens of thousands of years old, usually from –10000 to –36000 years. These aquifers were evidently recharged during previous pluvial intervals of the Quaternary when rainfall was similar to that in European Mediterranean countries today. The very low rainfall conditions prevailing throughout most of Saudi Arabia in the present-day do not allow substantial recharge to most aquifers in their exposed and unconfined parts. Similar arid conditions have persisted for the last 6000 years.

Total annual recharge to the Saq Aquifer from rainfall and wadi underflow is estimated to be about 290 million m^3/year by KFUPM [42], while annual discharge from this aquifer is greater. This has resulted in the fall of the groundwater table by more than 100 m in places in the Qasim area. Recharge to the Lower Tabuk Aquifer in the Tabuk Basin and Northern Interior Homocline is about 49 million m^3/year. The Middle Tabuk Aquifer has an annual recharge of about 39 million m^3, while recharge to the Upper Tabuk Aquifer in northern Saudi Arabia is 52 million m^3/year. Recharge of the Devonian Jauf Aquifer is much lower, being about 15 million m^3/year. There is no evidence of recharge of the Carboniferous Berwath Aquifer, as it is not exposed anywhere at the surface.

The Permian Khuff Aquifer has a recharge of 80 million m^3/year and the Triassic Jilh Aquifer a recharge of 60 million m^3/year, in their outcrop area in the Northern Interior Homocline, estimated by KFUPM [42]. In the same area, recharge of the Triassic–Jurassic Minjur Aquifer is an estimated 99.6 million m^3/year, but may be several times more since its outcrop extends from 21° 40′ N Lat., to 26° N Lat., with inflow from large wadis, such as Wadi Birk.

Recharge of the Middle to Lower Cretaceous Wasia–Biyadh Aquifer in its large outcrops is estimated at 480 million m^3 by SOGREAH [35] and occurs directly, by runoff from Jabal Tuwayq and by wadi underflow.

The Upper Cretaceous Aruma Aquifer has a recharge of 80 million m^3/year as calculated by KFUPM [42] in outcrops along the Northern Interior Homocline and extensive exposures in the Widyan Basin Margin.

Average annual recharge of the Paleogene Umm er Radhuma aquifer system is estimated at 1048 million m^3 by Bakiewicz *et al.* [15], compared with a discharge between 3660 and 11238 times greater than the recharge. Estimates by Hötzl *et al.* [45] of groundwater recharge at 47% of the annual precipitation, where the Umm er Radhuma is exposed and karstified in the As Summan Plateau lack credibility. This is because of the very low average annual rainfall (100 mm/year), very high evapotranspiration, and general absence of tritium in the local groundwater. Recharge by rainfall of the Khobar Aquifer is low and mostly from its western intake areas, although supplemented by downward penetration of meteoric water through overlying Neogene sediments along the truncated edge of the Khobar Member to the west as shown by Naimi [14]. Annual lowering of the Khobar Aquifer is calculated at 2 m to 5 m per year by the B.R.G.M. [16], with expected drawdown of 40 m in the Abqaiq area by the year 2000 estimated by Abderrahman *et al.* [40]. The Alat Aquifer also has a relatively small recharge, except for an area northwest of Ma'aqala around Al Ataliyah between 26° 30′N and 27° 00′N where numerous sinkholes, or dahls, allow the entry of runoff and produce localized good usable groundwater.

A mean annual recharge of 10 m^3/sec is given by El Khatib [28] for the Neogene Hadrukh and Dam aquifers. They have low rainfall over their outcrops, but are augmented by groundwater from the Umm er Radhuma aquifer system from an erosional window in the Rus Formation in south Ghawar Anticline.

The Lower Ordovician Wajid Aquifer has a relatively high recharge due to high annual rainfall (250–350 mm) in outcrop areas in the east Asir Mountains and is estimated at 500 million m^3/year by KFUPM [42]. Isotopic age of the groundwater in the Wajid Basin is 30000 years, according to the Ministry of Agriculture and Water [8], indicating a relatively slight recharge in the relation to the huge volume of groundwater in the Wajid Aquifer.

Quaternary alluvial aquifers have a relatively low recharge of 940000m^3/year. A large part of their recharge (330000 m^3/year) is in wadis flowing from the Red Sea Escarpment to the Red Sea. Wadi ad Dawasir and its tributaries draining the Asir Mountains receive 260000 m^3/year of recharge, and wadis Birk Nisah and Sahba draining the Central Arabian Shield have a combined recharge of 200000 m^3/year as estimated by El Khatib [28]. Recharge through present-day sand dunes was studied by Dincer *et al.* [46] and Dincer [47] as a means of recharge of underlying strata, and has been traced by tritium measurements. This infiltration movement is very slow and rarely complete and the little water that actually completely penetrates through dunes either encounters less permeable beds or buried wadi alluvial systems. Hötzl *et al.* [48] showed that groundwater at Qatif and Al Hasa is tritium-free, indicating no recent recharge. Only wells at Wadi Hanifah proved an exception, showing through relatively high tritium content that there has been some local rainfall recharge of groundwater.

Isotopic age determinations prove that almost all the groundwater in the major aquifers of Saudi Arabia is fossil groundwater. This accumulated during the Last Glacial Maximum from 17000 to 36000 years ago, and in a Neolithic Wet Phase from 6000 to 10000 years ago as indicated by Edgell [49]. Quaternary pluvial conditions then prevailed, and there is, thus, a great necessity for controlled usage and conservation of groundwater from the Kingdom's major aquifers.

CONCLUSIONS

Structurally controlled sedimentary basins to the north, east, and south of the Arabian Shield contain all the major aquifers of Saudi Arabia. They hold a conservative minimum of 1919 billion cubic meters of groundwater and probably hold much more.

In the north, the largest groundwater basin is the Tabuk Basin, with the smaller Wadi as Sirhan Basin situated towards the northeast. Both are separated from Widyan Basin Margin by the northerly, Hail–Rutbah Arch towards the east. All of the aquifers in the Tabuk Basin are Lower Paleozoic and almost all consist of quartz sandstones, mostly with high permeabilities. Basically, the ascending sequence of aquifers in this basin is the Saq, Lower Tabuk, Middle Tabuk, and Upper Tabuk, all separated by shaly aquicludes. Only the overlying secondary carbonate-fine sandstone Jauf Aquifer is an exception. The 400–500 m thick Saq Aquifer has high permeabilities, and effective porosities from 12% to 30%, and is the major aquifer, yielding good quality water, while the three Tabuk aquifers are also important with their sandstones becoming generally finer upward. In the Wadi as Sirhan Basin, Neogene sandstones constitute the primary aquifer and the Middle Cretaceous Wasia Aquifer is also significant, although the Upper Tabuk Aquifer is too deep for general use. The Widyan Basin Margin, north of 28° N, yields small amounts of groundwater from the Upper Cretaceous Aruma Aquifer and has good yields of water from the thick Middle Cretaceous Wasia Sandstone Aquifer. Deeper, good quality groundwater is contained in sandstones of the Carboniferous Berwath Aquifer.

To the east of the Arabian Shield, the main tectono–sedimentary units are the Interior Homoclines, separated into the Northern and Eastern Homocline by the Central Arabian Arch, and the adjoining Arabian Platform, as well as the very large and undeveloped Rub' al Khali Basin. Plentiful good quality groundwater is again found in sandstones of the Saq Aquifer with high effective porosity and horizontal permeability from 1 to 5 darcys. Overlying sandstone aquifers, such as the Lower Tabuk and Middle Tabuk also yield abundant good quality groundwater. Higher, major sandstone aquifers are the Triassic–Jurassic Minjur Aquifer and Middle to Lower Cretaceous Wasia–Biyadh Aquifer, both with plentiful fair quality groundwater.

Tertiary carbonate aquifers are most important in the Arabian Shelf. They include the extensive Paleocene–Lower Eocene Umm er Radhuma aquifer system with its best aquifer in dolomites and calcarenites of its upper third, yielding poor to good quality water and extending under most of the Rub' al Khali. The Mid Eocene Dammam Aquifers of the Arabian Shelf comprise the Khobar Aquifer and Alat Aquifer, divided by a poor aquitard. Neogene aquifers of the Al Hasa area compose the sandstones of the Hadrukh Aquifer and the karstified limestones of the Dam Aquifer. All aquifers of the Arabian Shelf become increasingly saline downdip towards the northeast, so that their water is rarely usable along the Gulf coast of Saudi Arabia, except for Tertiary carbonate aquifers around the Dammam Dome, Qatif, and Ras Tanura.

South of the Arabian Shield, the 300–900 m thick sandstones of the Wajid Sandstone form the Wajid Aquifer, occupying an area of 196000 km and yielding abundant good quality groundwater

All the major aquifers of Saudi Arabia contain fossil groundwater 10000 to 36000 years old. They constitute an important, non-renewal, water resource, since there is only very limited, present-day recharge. Although they can supply useful water in the arid area of Saudi Arabia for a projected 150 years, it is important that they be developed under a controlled groundwater management plan.

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