Chapter 5
Interior Shelf

5.1 Geologic and Geographic Set-Up

5.1.1 General Geologic Structure

After peneplanation of the Arabian Shield in the late Precambrian, detrital sediments were deposited on the outer slopes of the uplifted shield during the Paleozoic. Sandstone sedimentation continued until the Lower Cretaceous with various intervening periods of marine or lagoonal carbonate deposition. Widespread marine transgression since the Upper Cretaceous covered large parts of the Arabian Shelf with carbonate formations, leaving an outcrop belt of Paleozoic–Lower Cretaceous rocks in a structurally uplifted zone surrounding the Arabian Shield. That belt, in which Upper Cretaceous–Tertiary marine sediments were not deposited or have been eroded, is defined here schematically as "Interior Shelf" (Sect. 1.1.1.3).

The outcrop belt of Paleozoic to Lower Cretaceous prevailingly detrital rocks of the Interior Shelf surrounds the Arabian Shield in a semi-circle from the Tabuk–Disi area in the north over the Widyan basin margin and the Tuwayq mountains in the northeast and east into the Wajid basin in the southeast. Cambrian to Permian formations of the Interior Shelf overlie discordantly the crystalline rocks of the basement. The Interior Shelf is sub-divided into four major structural elements, which are, from north to south, the Tabuk–Disi segment, northern and southern Tuwayq segments, and Wajid sandstone segment (Figs. 5.1 and 5.2).

The Tabuk–Disi and Wajid segments, in the north and south of the Interior Shelf, comprise vast outcrops of Paleozoic sandstones and shales. On the northern and southern Tuwayq segments of the shelf, Paleozoic and Mesozoic formations are exposed consecutively in relatively narrow but very long outcrop strips.

The northeastern margin and the southern tip of the Interior Shelf are covered by the sand seas of the Great Nefud and Rub al Khali deserts.

The Paleozoic–Mesozoic formations of the Interior Shelf dip generally in gentle slopes toward east–northeast plunging under younger formations of the Interior Shelf and under the Upper Cretaceous–Paleogene–Neogene cover of the Arabian Platform. Uplift and tilting created the homoclinal structure of the Interior Shelf and caused erosion of deposits of the shelf during various phases between the late

W. Wagner, *Groundwater in the Arab Middle East*,
DOI 10.1007/978-3-642-19351-4_5,

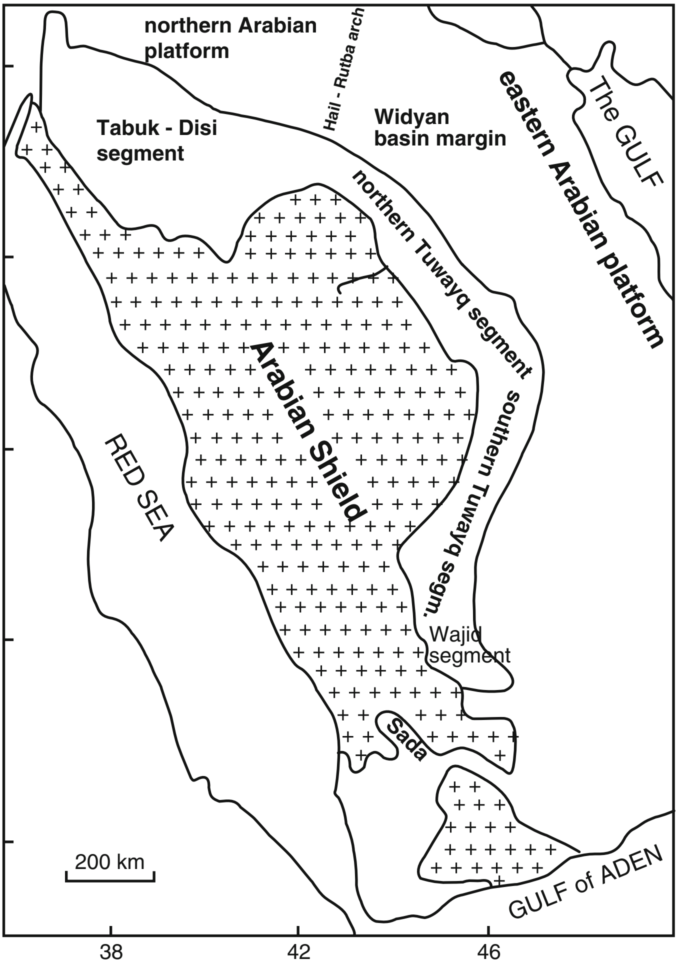

Fig. 5.1 Interior Shelf, main geologic units. After Edgell (1997), ESCWA (1999b)

Carboniferous and the Neogene. The most important uplift movements occurred during the early Oligocene and continued during the Miocene.

East of the clearly defined belt of the Interior Shelf, Paleozoic or Cretaceous sandstone formations are exposed in zones of structural uplift in erosional windows within the cover of the Cretaceous–Paleogene carbonate sequence of the Arabian Platform: the Hail–Rutba arch in the north and the Hadramaut arch in the south of the platform area. Sandstones of the Devonian Jauf formation and the Cretaceous Sakaka formation are exposed in the Sakaka and Jauf areas along the uplift zone of the Hail–Rutba arch, which adjoins here the margin of the Widyan segment of the eastern Arabian platform. On the Hadramaut arch, the Cretaceous Mukalla sandstones appear at or near the surface in the Wadi Hadramaut canyon. The sandstones are covered by

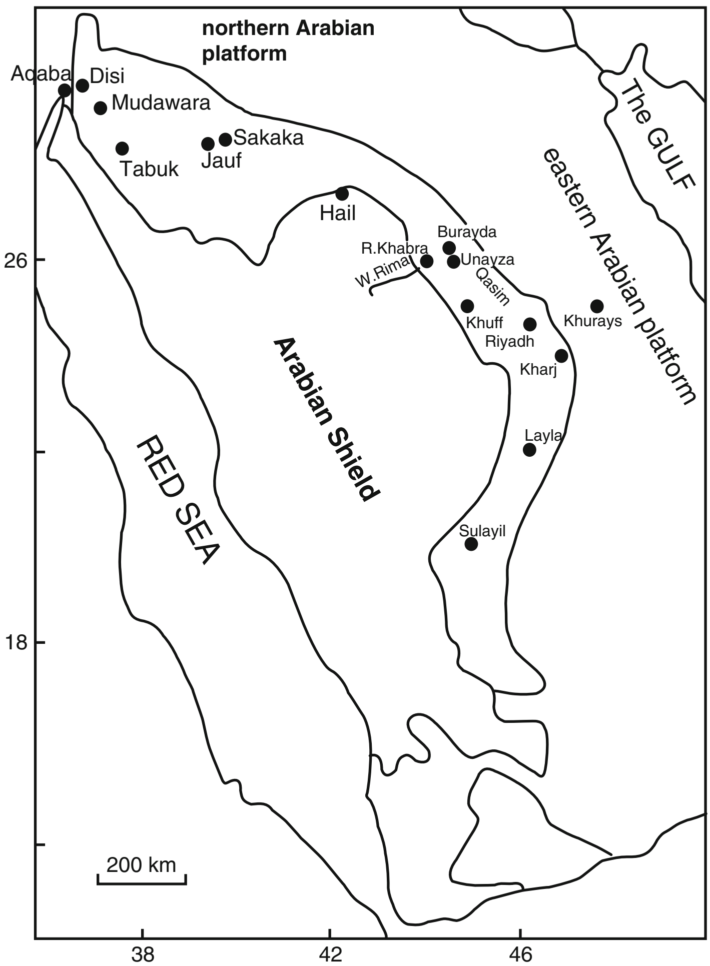

Fig. 5.2 Interior Shelf, location map

Quaternary sediments in wide parts of the canyon and by deposits of the Paleogene Hadramaut group in the plateau areas north and south of the canyon.

5.1.2 Climate and Landscape

5.1.2.1 Climate

The climate of the Interior Shelf is arid to hyper-arid. Mean annual rainfall ranges from 150 mm to less than 25 mm (Sect. 1.4.3.1). The catchment areas of some major wadi systems extend far into areas with mean precipitation of up to 250 mm/a within the Arabian Shield.

5.1.2.2 Morphology

The Interior Shelf extends, to a high percentage, over desert landscapes. Main types of landscapes are sandstone plateaus in the north and south of the Interior Shelf and elongated mountain belts with a series of prominent escarpments in the Tuwayq segments. Elongated sand dune belts extend between the mountain areas of the Interior Shelf. In the north and south, the mountain ridges disappear under the sand seas of the Great Nefud and Rub al Khali deserts.

The desertic plateaus and mountain ridges of the Interior Shelf are interrupted, in several areas, by zones of oases, such as Tabuk, Disi, the Qasim area in the north, Al Kharj in central Saudi Arabia, Al Aflaj in the south. Most of the oasis areas are, at present, irrigated by groundwater extraction from boreholes.

5.1.2.3 Tabuk–Disi and Wajid Segments

The Tabuk–Disi and Wajid segments in the north and south of the Interior Shelf, respectively, comprise extensive sandstone plateaus, which have been eroded to plains with local hills and ridges. The outcrops of Paleozoic sandstones form vast featureless plains, but also, in some areas like Wadi Rum in southern Jordan, bizarre landscapes of hills and inselbergs with steep erosional escarpments and gorges. The land surface of the sandstone plateaus in the Tabuk–Disi segment rises to peaks of 1,754 m asl at Jebel Rum northeast of Aqaba and 2,403 m at Jabal al Lawz northwest of Tabuk.

Surface drainage of ephemeral streamflow in wadis in the Tabuk–Disi segment is directed toward major closed basins: Mudawara, Tabuk, Wadi Sirhan.

5.1.2.4 Tuwayq Segments

The morphology of the northern and southern Tuwayq segments of the Interior Shelf is characterized by mountain ridges bordered by escarpments, which extend in a generally north–south directed up to 200 km wide belt between the Arabian Shield in the west and the Ad Dahna sand fields and the plateaus of the Arabian Platform in the east.

The escarpments correspond to the erosional edges of Permian–Mesozoic sedimentary beds, which dip gently toward east, and comprise, in a total length of 1,400 km, a series of five prominent and various secondary morphological steps: The most prominent morphologic step, the Tuwayq escarpment west of Riyadh, is formed by Upper Jurassic limestones and extends along 800 km at an average elevation of 840 m asl, 240 m above the adjoining plains in the west. Further east, the 250 km long Aruma escarpment, capped by Upper Cretaceous limestones, marks the boundary between the Interior Shelf and the Arabian platform. The summit of the Aruma escarpment is situated at 540 m asl, 120 m above the plain.

Several lower and shorter escarpments run through the western part of the Tuwayq mountain zone roughly parallel to the main Tuwayq escarpment. In general, resistant limestones form the summits of escarpments, while sandstones extend over plains between the mountain ridges. Sinkholes and solution cavities are found at the base of scarps, where anhydrite and gypsum have been dissolved. Elongated depressions between the mountain ridges comprise sand dune areas of limited extent – nefuds – but also belts of small oases along wadi courses following the morphologic depressions.

Three major wadi systems, originating in the crystalline areas of the Arabian Shield, dissect the Tuwayq mountains in a general west–east direction: Wadi Rima (or Ruma), Wadi Nisa – Wadi Sahba in the fracture zone of the central Arabian arch, and Wadi ad Dawasir. Development of the wadi systems started mainly in the Pleistocene. Along part of the breakthrough of the wadis through the Tuwayq mountains, deep gorges have developed.

5.1.3 Stratigraphic Sequence

The Interior Shelf comprises a sequence of Cambrian to Cretaceous sedimentary formations with a total thickness of up to 4,000 m. The deposits of the Cambrian to Carboniferous of the Interior Shelf are prevailingly sandstones with shale intercalations. After a regional unconformity in the late Carboniferous – early Permian, the nature of the sediments changed to limestone, dolomite and evaporites. The Triassic and Jurassic sediments comprise alternating series of shales, limestones and sandstones, and, at the late Jurassic, evaporitic deposits; during the early Cretaceous, clastic sedimentation prevailed on the Interior Shelf; Lower Cretaceous sandstones and shales overlie unconformably Paleozoic to Jurassic formations.

During the Upper Cretaceous, shelf carbonates were deposited over wide areas of the eastern Arabian platform. The upper limit of extent of the Upper Cretaceous shelf carbonates is here defined as the boundary between Interior Shelf and Arabian Platform.

The Cambrian to Upper Cretaceous sandstone complexes extend over the Tabuk and Wajid segments in the north and south of the shelf and form outcrops along some stretches of the Tuwayq mountains. Permian, Triassic, Jurassic and Lower Cretaceous carbonate–shale formation form major chains of the Tuwayq mountains.

5.1.3.1 Paleozoic Sandstone Formations

The stratigraphic succession of sedimentary rocks of the Interior Shelf starts with a Cambro–Ordovician sandstone complex, which was deposited mainly under fluviatile conditions. Shallow marine sediments form the top section of the Ordovician sandstones. The Cambro–Ordovician sandstones, denominated Disi formation or Rum group in Jordan, Saq formation in northern Saudi Arabia and Wajid sandstone in southern Saudi Arabia and Yemen, extend over the Tabuk–Disi segment in the north of the Interior Shelf and the Wajid segment in the south. The complex is composed mainly of medium to coarse grained sandstones with intercalations of thin beds of shale. The formation overlies the Precambrian crystalline rocks, the base of the sandstone complex is generally formed by a conglomerate. The thickness of the sandstone complex ranges from 200 m in the west to approximately 600 m in the Sada area in Yemen and to more than 2,000 m under the sedimentary cover of the eastern Arabian platform.

The Saq–Disi sandstone complex is followed, in northern Saudi Arabia and Jordan, by an Ordovician–Devonian sequence of alternating shales and sandstones: the Tabuq formation in Saudi Arabia and Khreim formation in Jordan, which reach a thickness of up to 1,700 m.

The Cambrian–Devonian Saq and Tabuk formations extend in outcrops at the western rim of the northern Tuwayq mountains, but are truncated on an erosional unconformity in central Saudi Arabia, where the Permian Khuff formation directly overlies the Precambrian basement (Khuff unconformity).

5.1.3.2 Devonian–Lower Cretaceous of the Tabuk–Disi Segment and the Hail–Rutba Arch

In the Jauf area on the margin of the Widyan segment of the eastern Arabian platform ("Widyan basin margin" Edgell 1997: 7), the Silurian–Lower Devonian Tawil member of the Tabuk formation is overlain by the Devonian Jauf formation, which is composed of limestones, dolomites, shales and sandstones with a total thickness of 285 m.

Lower Cretaceous sandstones with intercalations of siltstones and shale overlie the Paleozoic formations in the Sakaka and Jauf areas in northern Saudi Arabia and in southern Jordan (Sakaka formation in Saudi Arabia, Kurnub sandstone in Jordan). The thickness of the Sakaka and Kurnub formations ranges from 90 to around 200 m. In the surroundings of the Jawf area, the Upper Cretaceous Aruma formation and the Paleogene Hibr formation overlie, over erosional surfaces, the Sakaka formation or directly the Jawf formation. Outcrops of the Jawf and Sakaka formations on the Widyan basin margin are situated in a morphologic depression, which is adjoined, in the north, by a series of steep escarpments and, in the south, by the Great Nefud sand desert.

A more than 150 m thick complex of clastic rocks of Permo–Carboniferous age crops out in the centre of the morphologic Gaara depression in southwestern Iraq: the Gaara formation, composed of clay and quartz sandstone with 16 m saliferous marl and shale on the base. The Gaara formation is overlain in the Rutba–Gaara area by:

- The Upper Triassic Mulussa formation, 160 m dolomite, marly dolomite, sandstone, limestone
- A 180 m thick Jurassic sequence of dolomite, limestone, sandstone, argillite
- The Lower Cretaceous–Cenomanian Rutba sandstone
- Upper Cenomanian limestones with sand intercalations (Msad formation)
- Maastrichtian limestones and dolomites with marl intercalations

5.1.3.3 Permian–Lower Cretaceous of the Tuwayq Segments

On the northern and southern Tuwayq segments, Permian, Triassic, Jurassic and Cretaceous formations are exposed in relatively narrow but very long strips. In the sedimentary sequence of Permian–Mesozoic rocks of the Tuwayq mountains, marine shelf carbonates alternate with fluviatile, coastal and lagoonal deposits (Table 5.1). Limestones and dolomites of the Permian Khuff formation rest directly on the Precambrian crystalline rocks. The Permian and Triassic clastic rocks consists of nearly 1,000 m of alternating non-marine and marine clastic units with some thick calcareous sections. The sequence begins, at the base, with the Khuff formation: 250–600 m of limestones and dolomites, alternating with gypsiferous shale. The 280–650 m thick Lower Triassic Sudair formation is made up mainly of continental shale beds intercalated with siltstone, limestone and gypsum and, in the north, lenses

Table 5.1 Sedimentary sequence of the Tuwayq mountain zone. After Edgell (1997), MAW (1984), Powers et al. (1966)

Stratigraphic age	Formation	Prevailing lithology	Average thickness (m)
Lower Cretaceous	Wasia	Sandstone, shale	18–100
	Biyadh	Sandstone	425
	Buwaib	Calcarenitic limestone	18
	Yamama		50
	Sulay	Limestone	170
Jurassic	Hith	Anhydrite	90
	Arab	Argillaceous limestone, anhydrite	124
	Jubaila	Limestone, calcarenite	118
	Hanifa		113
	Tuwayq Mountains		200
	Dhruma	Sandstone with limestone interbeds	375
	Marat	Limestone, shale, sandstone	100
Triassic	Minjur	Sandstone with shale and mudstone	315
	Jilh	Limestone, shale, gypsum	100–400
	Sudair	Shale	115
Permian	Khuff	Limestones and dolomites	250–600
Cambrian–Ordovician	Saq/Wasia	Sandstone	Generally 400–500, eroded over central Arabian arch

of limestone. The middle–upper Triassic is represented by sandstones with shale and limestone intercalations (Minjur formation, 400 m). Toward south, limestones become dominant in the middle Triassic (Jilh formation). During the late Triassic, continental conditions prevailed over the Interior Shelf. In the central part of the Arabian Peninsula, upper Triassic and lower Jurassic sediments are absent.

After a wide-spread sedimentation gap from the late Triassic to early Jurassic, the sedimentary succession of the lower Jurassic begins with shales and shallow marine limestones (Marrat formation).

Sediments of Bathonian–Bajocian age, consisting of shallow water limestones and shale of some 500 m thickness, crop out along the Tuwayq mountains. Toward south, the sediments change into continental sandstones.

The middle–upper Jurassic sediments comprise mainly carbonates: limestones deposited on the continental shelf with high percentage of clastic materials, alternations of neritic limestone and dolomite with anhydrite horizons (Dhruma, Tuwayq, Hanifa, Jubaila, Arab formations). The late Jurassic is represented prevailingly by anhydrites with minor intercalations of limestones and dolomites (Hith formation). The sedimentary rocks of the late Jurassic extend in the Tuwayq mountains over a strip of about 1,000 km length.

Between the late Jurassic and early Cretaceous, most of the western part of the Arabian Peninsula was elevated; extensive erosion followed the orogenic movement, which started during the late Jurassic.

The Lower Cretaceous comprises detrital limestones, which are overlain by continental clastics of the Biyadh formation: sandstones with shale and conglomerate, and sandstones with carbonate intercalations. The clastic deposits comprising sandstones, conglomerates, quartzite, shale and siltstone indicate prevailing fluviatile and terrestrial sedimentation. The carbonates, mainly dolomites and oolitic limestones, appear related to shallow marine and coastal conditions (Table 5.1).

5.1.3.4 Jurassic–Cretaceous of the Hadramaut Arch

On the Hadramaut arch in southeastern Yemen, the Cretaceous Mukalla sandstones have been uplifted to near surface zones and are exposed in some deeply eroded wadis. The Mukalla formation includes a thick complex of fine to medium grained sandstones, which is overlain by shale, limestone, sandstone layers and underlain by a calcarenite, sandstone, limestone sequence. The formation may be correlated to the Cretaceous Tawila sandstones of the shield area in northwestern Yemen. The thickness of the Mukalla formation averages 300–400 m and probably reaches 1,000 m in the Shabwa area. The formation rests, in the west, on up to 3,000 m thick marly and calcareous Jurassic deposits. Further east, the formation overlies probably directly the Precambrian basement.

5.1.3.5 Upper Cretaceous–Quaternary

After an erosional phase, which continued until the middle part of the Cretaceous, a marine transgression spread over wide parts of the Arabian Peninsula during the late Campanian and Maastrichtian. The transgression left an extensive cover of carbonates on the eastern Arabian platform (Aruma formation) east of the Interior Shelf. On the Hail–Rutba arch northeast of the Interior Shelf, the cover of Upper Cretaceous marine deposits of the Widyan basin margin encloses outcrops of Paleozoic–Lower Cretaceous sediments in erosional/structural windows.

Accumulations of Pleistocene to Recent terrestrial deposits are found on the Interior Shelf in wadis and morphologic depressions. The wadis, which dissect the mountainous landscapes of the Interior Shelf, contain gravel and silt deposits with lenses of sabkha sediments.

References. Al-Sayari and Zötl (1978), Alsharhan et al. (2001), Beydoun (1991), Edgell (1997), Faroog and Rogers (1980), Helal (1965).

5.2 Main Aquifers

The Interior Shelf comprises very extensive sandstone aquifers with considerable thickness, the most important of which are the Cambro–Ordovician Saq–Disi and Wajid aquifers. Detrital deposits also form productive aquifers in the:

- Ordovician–Devonian Tabuk and Jauf formations
- Triassic Jilh and Minjur formations
- Lower Cretaceous Kurnub, Sakaka, Biyadh and Wasia formations
- Cretaceous Mukalla formation

In the Permian to early Cretaceous succession of shales, carbonates, sandstones and evaporites of the Tuwayq segments, aquicludes and aquitards alternate with aquiferous sections with minor or local importance. An extensive carbonate aquifer is found in the Permian Khuff formation. Pleistocene–Quaternary detrital deposits constitute shallow aquifers along major wadi courses and in morphologic depressions.

5.2.1 Cambro–Ordovician Sandstone Aquifers

5.2.1.1 Saq–Disi Aquifer

The Saq–Disi aquifer is composed mainly of medium to coarse grained sandstones with thin shale intercalations. The base of the aquifer is formed by the crystalline basement, on top the aquifer is followed by the Ordovician–Devonian Tabuk–Khreim formation, in the western highlands of Jordan directly by the Lower Cretaceous Kurnub formation. The thickness of the Saq–Disi aquifer increases from several hundred metres in the outcrop areas to more than 2,000 m toward east and northeast. In the southern Tuwayq segment, the Saq aquifer disappears in the Khuff area, where the formation is truncated by the Permian erosional unconformity.

The outcrop of the Saq–Disi formation extends over around 70,000 km^2 in an about 1,300 km long belt between southern Jordan and the Khuff area in central Saudi Arabia. The total extent of the Saq–Disi aquifer in the outcrop areas and in the subsurface is estimated at around 350,000 km^2. In the subsurface, the aquifer reaches far into the northwestern mountain and rift zone, the east Jordanian limestone plateau and the eastern Arabian platform.

The Saq–Disi aquifer is unconfined at and near the outcrop areas in the western part of the Tabuk–Disi segment (around Tabuk and on the eastern flank of the highlands of Jordan) and in the Tuwayq mountains. Depth to groundwater in the unconfined ranges of the aquifer is around 80–150 m.

In some areas near the boundary with the Arabian Shield, the Saq–Disi sandstones are unsaturated or contain local discontinuous groundwater lenses. Around Wadi Rum in southern Jordan, local groundwater occurrences in sandstone hills discharge above the impervious granite basement in numerous small seasonal springs and a few perennial springs.

In wide parts of the Tabuk–Disi segment, the Saq–Disi aquifer is confined under shale aquitards of the Tabuk–Khreim formation: the Hanadir shale in Saudi Arabia and Hiswa shale in Jordan. The confined Saq–Disi aquifer extends from the Saq–Disi segment of the Interior Shelf toward north and northeast under the northern Arabian platform. The top of the aquifer is situated at 400 m below land surface at Mudawara and descends to more than 1,000 m in the Jordanian limestone plateau and more than 2,000 m below land surface in Wadi Sirhan.

The confined Saq–Disi aquifer is under artesian conditions in some areas with flowing wells, e.g., in the Tabuk area and in Jordan south of the Karawi dike.

In the western highlands of Jordan east of the Dead Sea graben, the Khreim aquitard is missing and the Disi sandstones form a joint aquifer system with the overlying Kurnub sandstone.

5.2.1.2 Wajid Sandstone

In the south of the Interior Shelf, the Wajid sandstone extends over around 200,000 km^2 in southwestern Saudi Arabia and northern Yemen. It can be assumed, that the Cambro–Ordovician sandstone formations in the Tabuk–Disi and Wajid segments were deposited in a continuous sedimentary basin and were separated by uplift and erosion on the eastern margin of the Arabian Shield during the Carboniferous–Permian.

The Wajid formation is composed mainly of poorly cemented sandstones with a thickness of 200–900 m. In the Sada basin in Yemen, the Wajid sandstones occur in a downfaulted graben structure under a 30–60 m thick cover of Quaternary deposits.

These unconsolidated deposits are largely unsaturated, but they are effective in tapping surface water flows from the surrounding mountains and contribute thus to the recharge of the Wajid sandstones. The Wajid sandstones generally have low hydraulic conductivities, but their thickness under the Sada plain reaches 300–600 m. Continuous moderate transmissivities and large permissible drawdowns make the sandstone aquifer easily exploitable, but present abstraction rates exceed the average recharge by one order of magnitude.

5.2.1.3 Tabuk–Khreim Formation

The Ordovician–Devonian Tabuk–Khreim formation consists of alternating sequences of shales and sandstones. The Tabuk formation in Saudi Arabia comprises marine shales and continental to littoral sandstones in a total thickness of up to 1,700 m. The formation includes three main aquiferous sections separated by shale aquicludes or aquitards (Table 5.2).

The upper sandstone members are present mainly in the eastern part of the Tabuk segment. The sediments of the Khreim group in Jordan generally act as aquitard. Locally, however, groundwater can be exploited from aquiferous sandy layers, e.g., in the Mudawara area.

The Tabuk–Khreim formation extends over around 80,000 km^2 in Saudi Arabia and southern Jordan. The thickness of the Tabuk formation decreases in the Tuwayq mountain zone, where it is truncated by the Permian discontinuity south of Qasim. The equivalent Khreim formation in Jordan disappears toward west on the eastern slope of the Jordanian highlands. Apart from the outcrop areas in the west, the Tabuk sandstone aquifers are generally confined under shale members of the Tabuk formation.

5.2.1.4 Jauf Formation

In the Jauf area in northern Saudi Arabia, the Tabuk formation is overlain by the Devonian Jauf formation, an 85 m thick sequence of sandstones, limestones, dolomites and shales. The sandstone members of the formation provide an aquifer, the extent of which is mainly restricted to the western slopes of the paleogeographic

Table 5.2 Hydrostratigraphic scheme of Paleozoic–Lower Cretaceous formations in the Tabuk–Disi segment of the Interior Shelf. After Hobler et al. (1991), MAW (1984)

	Jordan			Saudi Arabia		
Stratigraphic age	Formation	Prevailing lithology		Formation	Prevailing lithology	
Lower Cretaceous	Kurnub	Sandstone, shale	Aquifer	Sakaka	Sandstone	Aquifer
Ordovician–Silurian	Khreim	Siltstone, shale, sandstone	Aquitard	Tabuk	Sandstone and shales	Alternating aquifers and aquitards
Cambro–Ordovician	Disi (Ram)	Sandstone	**Major aquifer**	Saq	Sandstone	**Major aquifer**

Hail arch. The main outcrops of the Jauf sandstones occur in the tectonic–morphologic Jauf depression, which is adjoined by steep 200 m high escarpments. In the depression, the Jauf sandstones form a shallow aquifer with water levels of less than 25 m below surface. Toward east, the Jauf formation dips to great depth below Carboniferous to Mesozoic formations; toward south, the sandstone outcrops disappear under the sand seas of the Great Nefud desert.

The Paleozoic Gaara sandstone is an important aquifer in the Rutba–Gaara area. The prevailingly calcareous Mulussa formation (Upper Triassic) forms an aquifer of local importance in the Rutba area.

5.2.2 Permian–Jurassic Aquifers of the Tuwayq Segments

5.2.2.1 Khuff Formation

The Upper Permian Khuff formation, consisting of limestones and dolomites with anhydrite intercalations, extends in the subsurface from the southern Rub al Khali over the Tuwayq segments into southern Iraq. The carbonate units of the formation act as generally brackish water aquifers with low productivity. Anhydrite aquicludes separate the formation into several aquiferous units (Table 5.3).

5.2.2.2 Triassic–Jurassic Formations

In part of the Tuwayq mountains, sandstones of the Triassic–Jurassic Jilh, Minjur, Marat and Dhruma formations form an aquifer complex with the Minjur sandstones

Table 5.3 Hydrostratigraphic scheme of Paleozoic–Cretaceous formations in the Tabuk–Sakaka area. After Alsharhan et al. (2001), MAW (1984)

Stratigraphic age	Formation	Prevailing lithology	Thickness (m)	
Cretaceous	Sakaka sandstone	Sandstone	42	Aquifer in Sakaka area
Devonian	Jauf formation	Limestone, shale, sandstone	300	Aquifer in Al Jauf area, local aquitard
	Tawil sandstone	Sandstone	190	Upper Tabuk aquifer
Silurian	Sharawa sandstone	Sandstone	380–765	
	Qusaiba shale	Shale	50–200	Aquitard
	middle Tabuk sandstone	Sandstone	83–242	Middle Tabuk aquifer
Ordovician	Raan shale	Shale	14–100	Aquitard
	lower Tabuk sandstone	Sandstone	54–390	Lower Tabuk aquifer
	Hanadir shale	Shale	54–100	Aquitard
Cambrian	Saq	Sandstone		Deep brackish water aquifer

as main productive aquifer unit. The extent of the Minjur sandstones is limited mainly to central Saudi Arabia. In the Riyadh area, the Minjur formation consists of a 400 m thick sequence of coarse grained quartz sandstones with shale and sandstone intercalations. The thickness of the formation decreases toward north and south. The Minjur aquifer complex includes, in some areas, sandstone layers of underlying or overlying formations, which are developed, in different parts of the Tuwayq mountains, in carbonate–shale or in detrital facies.

East of Riyadh and in the Qasim area, sandstones of the Triassic Jilh formation form the lower member of the Triassic–Jurassic aquifer complex. The general base of the aquifer complex is formed by the Triassic Sudair shale aquiclude underlying the Jilh formation. Sandstone layers at the base of the Lower Jurassic Marat formation constitute an upper member of the Minjur aquifer. The top of the Minjur aquifer complex is generally formed by shales, siltstones and aphanitic limestones of the Marat formation.

In the Qasim area, the Jilh aquifer unit consists of 180–250 m thick fine to medium grained sandstones.

The Upper Jurassic sequence of limestones, argillaceous limestones and anhydrites (Tuwayq mountain limestone, Hanifa, Jubaila and Arab formations, Hith anhydrite) contain, in the Tuwayq segments, a succession of aquiferous carbonate sections with intercalated aquitards or aquicludes. The productivity of the aquiferous carbonate is generally low, the groundwater is prevailingly brackish to saline. Limited amounts of fresh to brackish water are extracted from wells in Wadi Hanifa.

5.2.2.3 Lower Cretaceous Carbonate Formations

The Lower Cretaceous carbonate formations in central Saudi Arabia (Sulaiy–Yamama–Buwaib formations) provide generally no aquifers with economic importance, with a few local exceptions:

- Calcarenites of the Sulaiy formation form a local aquifer with brackish groundwater (1,000–3,000 mg/l TDS) in Wadi Sulaiy, 20 km southeast of Riyadh.
- In the area of the Layla lakes (Uyun al Aflaj), dissolution of anhydrites of the Hith formation has caused collapse structures in the overlying Lower Cretaceous carbonates. Groundwater discharge from the karstic carbonate formations is collected in an area with a number of small lakes, extending previously over 4 km^2.

5.2.3 Cretaceous Sandstone Aquifers

The lower Cretaceous of the Interior Shelf comprises sandstone aquifers of considerable thickness:

- Kurnub aquifer in Jordan
- Sakaka aquifer on the Widyan basin margin
- Biyadh–Wasia aquifer in the Tuwayq segments
- Mukalla sandstone on the Hadramaut arch

5.2.3.1 Kurnub Sandstone

The Kurnub formation is composed mainly of fine to medium grained sandstones with siltstone and clay intercalations. The sandstones are exposed in the southern desert of Jordan on an escarpment, which may be considered the eastern boundary of the Interior Shelf. Toward north and east, the Kurnub sandstones dip under the Upper Cretaceous–Paleogene cover of the northern Arabian platform and extend, in the subsurface, far into the platform area of the shelf. In the platform area, outcrops of the Kurnub formation occur near Amman in eroded anticlinal and domal structures and in deeply incised wadis on the Dead Sea–Jordan escarpment.

The thickness of the Kurnub sandstones generally ranges from 100 to 300 m. The top of the formation descends from the outcrop areas to depths of a few hundred metres below land surface in the platform areas and to more than 1,000 m below land surface in the Azraq area.

The Kurnub sandstones are generally unsaturated in the outcrop areas. In most of its extent, the Kurnub aquifer is confined under aquicludes of overlying younger formations, in particular shales of the Upper Cretaceous Ajloun formation.

The saturated thickness of the confined Kurnub is generally in the order of 150–200 m. The thickness of the formation decreases toward east and southeast and the sandstones disappear on the southern edge of the Sirhan depression.

The Rutba sandstone, together with sandstone intercalations in the overlying Msad formation, have been tapped west and northwest of Rutba at depths of 230–290 m. The groundwater appears to be generally unconfined to semi-confined. Specific well yields range between 0.4 and 9 m^3/h/m.

5.2.3.2 Sakaka Sandstone

In the area between the Turayf and Tuwayq segments of the Interior Shelf, the homoclinal structure of the shelf is modified by the uplift of the Hail–Rutba arch, which separates the northern Arabian platform from the eastern platform. Outcropping Paleozoic–Cretaceous sandstones form aquifers on the uplift structure in the Rutba–Gaara and Jawf areas.

The Cretaceous Sakaka sandstone formation constitutes an aquifer in the Jawf and Sakaka areas in northwestern Saudi Arabia. The thickness of the Sakaka aquifer, which overlies the Devonian Jauf formation, is around 200 m.

5.2.3.3 Biyadh and Wasia Formations

Sandstones of the Lower Cretaceous Biyadh and Wasia formations constitute an extensive aquifer complex in the Tuwayq mountains and, in the subsurface, over wide parts of the eastern Arabian platform. The Biyadh formation consists of quartz sandstones with shale and conglomeratic layers. The Wasia formation comprises mainly sandstones with shale intercalations and some limestone layers. The thickness of the Wasia–Biyadh aquifer reaches up to 600 m. In eastern and northern Saudi Arabia, the Biyadh and Wasia sandstones form one hydraulically connected aquifer system. Further downdip on the eastern Arabian platform, hydraulic connection between the two formations is restricted by shale aquitards in the top sections of the Biyadh formation.

References. Al-Sagabi (1978), Alsharhan et al. (2001), Bassam (1998), Bazuhair (1989), Edgell (1997), Hobler et al. (1991), Lloyd and Pim (1990), Margane et al. (2002), MAW (1984), Sharaf and Husein (1996), Sowayan and Allayla (1989), Sunna (1995), WAJ-ODA (1994).

5.3 Groundwater Regimes

5.3.1 Hydraulic Parameters

Permeabilities of the sandstone aquifers of the Interior Shelf are generally moderate. The high potential of some of the sandstone aquifers, such as the Saq–Disi aquifer and the Biyadh–Wasia aquifer, is related to the great saturated thickness and their huge extent. Hydraulic conductivities are rather moderate, reported values range from 3×10^{-6} to 10^{-4} m/s, but the aquifer thicknesses of 400 to >3,000 m in the Saq–Disi aquifer and of 200–900 m of the Wajid aquifer support a high productivity. Transmissivities of the Cambro–Silurian sandstone aquifers are reported as 80–3,000 m^2/day for the Saq aquifer, 300–1,000 m^2/day, with an average of 700 m^2/day, for the Disi aquifer, and 50–1,800 m^2/day for the Wajid aquifer.

In the Paleozoic Tabuk sandstone aquifer complex, hydraulic conductivities range from 2×10^{-6} to 5×10^{-5} m/s, the total thickness of aquiferous sections reaches 400–900 m. Transmissivities for each of the three aquifer members of the Tabuk formation are in the order of 18–2,600 m^2/day. Similar transmissivity values are found in the Lower Cretaceous Wasia aquifer; a mean transmissivity of 664 m^2/day is estimated for the Biyadh sandstone aquifer. Transmissivities of the Lower Cretaceous Kurnub sandstone aquifer are rather low with 20–80 m^2/day. Mean hydraulic conductivity of the Kurnub sandstones is in the order of 10^{-5} m/s, of the overlying Khreim aquitard in ranges of 10^{-7}–10^{-9} m/s.

Transmissivities in carbonate formations of the Interior Shelf are generally low. High transmissivities in the order of 2,800 m^2/day are found in the Upper Jurassic Arab formation in areas, where solution openings and collapse structures in evaporite layers create an elevated hydraulic conductivity.

The productivity of the Jawf aquifer is generally low to moderate. The Sakaka sandstones, overlying the Jawf aquifer in parts of the Al Jawf area and of the platform area further east, constitute an aquifer with relatively high productivity and storativity.

5.3.2 Groundwater Recharge

Present-day groundwater recharge rates in the arid Interior Shelf, with mean annual precipitation of 100 mm, are very low. For the extensive outcrop area of the Saq aquifer, a recharge volume of 310×10^6 m^3/a has been estimated. The Biyadh–Wasia aquifer in central Saudi Arabia may be replenished by 480×10^6 m^3/a from infiltration of runoff from the Tuwayq mountains and subsurface inflow in wadis (data of 1967). For the central Tuwayq area, a recharge volume of $7–8 \times 10^6$ m^3/a has been estimated, corresponding to an infiltration of 5% of the precipitation over a recharge area of 1,500–1,800 km^2.

For the Riyadh and Al Kharj areas in the central Tuwayq zone, recharge rates were calculated from meteorologic data. Mean annual rainfall is between 40 and 60 mm with main rainfall events from January to April. Recharge occurs mainly during January–February with minor recharge contributions during November–December. Recharge in March–April is insignificant because of high evaporation rates. The calculated recharge rates are 12.7 mm/a for the Saq aquifer at Riyadh (data for 1964–1986) and 3.8 mm for the Wasia–Biyadh aquifer at Al Kharj (data for 1970–1983), or 22% and 9% of mean annual rainfall, respectively. Other estimates of recharge for the same area range from 3 to 6.5 mm/a with a weighted average of calculated recharge of 4.0 mm/a for the central Tuwayq area and Al Kharj, or around 10% of annual precipitation.

A dynamic model of the annual water balance for local climatic and soil parameters was applied for estimates of recharge rates for the Minjur and Wasia sandstones aquifers in the Riyadh area in central Saudi Arabia. The estimates indicate a probable median annual recharge of 15 mm for the Minjur outcrop area (11.5% of the mean annual precipitation), and of 3 mm for the Wasia outcrop area (3.8% of the mean annual precipitation). The Minjur aquifer is exposed in an area west – upstream – of the Tuwayq mountains with mean annual rainfall of 130 mm, the Wasia outcrop area, east of the Tuwayq mountains, has a mean annual rainfall of 80 mm. The calculated recharge volumes are 31.4×10^6 m^3/a for the outcrop area of 2,092 km^2 of the Minjur aquifer and 2.4×10^6 m^3/a for the outcrop area of 807 km^2 of the Wasia aquifer.

Table 5.4 Estimated recharge rates on the Interior Shelf in central Saudi Arabia

Area	Aquifer	Estimated recharge rate (mm/a)	References
Central Tuwayq and Kharj	Wasia–Biyadh aquifer	4.0	Subyani and Sen (1991)
Riyadh area		12.7	
Wadi as Sahba	Wasia–Biyadh aquifer	3–5	Sogreah (1968)
Central Saudi Arabia	Wasia–Biyadh aquifer	5.2 6.5	SMMP (1975) BRGM (1976)
Central Saudi Arabia	Minjur aquifer Wasia	15 3	Caro and Eagleson (1981)
Khurais area	Sand dunes	20.0	Dincer et al. (1974)

Recharge rates in the sandstone and sand dune areas in north central Saudi Arabia may be around 1–1.5 mm/a; recharge rates in the southern parts of the Interior Shelf are probably even lower. For sand dune areas with a mean rainfall of 75 mm/a, recharge rates of 1.5% of rainfall during average and wet years have been calculated or approximately 1,500 $m^3/km^2/a$.

Reported estimates of recharge rates are summarized in Table 5.4.

5.3.3 *Groundwater Flow Systems and Flow Volumes*

In the sandstone aquifers of the Interior Shelf, groundwater moves generally from the outcrop areas in direction of the homoclinal dip of the strata toward east–northeast.

The Cambrian–Triassic aquifers of the Tuwayq mountain zone have been classified in Saudi Arabia as rejecting aquifer systems: Low hydraulic conductivity in the overlying aquicludes prevents significant leakage into the aquifer systems of the eastern Arabian platform downstream of the Tuwayq zone. Groundwater from the rejecting aquifers discharges in springs and into shallow aquifers within the Tuwayq zone. In the platform area, the rejecting aquifers constitute deep aquifers with prevailingly stagnant brackish or saline groundwater.

The Wasia–Biyadh aquifer is considered a depleting aquifer system: Groundwater moves in a generally eastward direction from the Tuwayq zone into the eastern Arabian platform, where the Wasia–Biyadh formations constitute a deep aquifer. Groundwater leakage from this deep sandstone aquifer into the overlying aquifer system of the platform occurs mainly in zones of tectonic fracturing or dislocations.

In the Tabuk–Disi segment of the Interior Shelf, groundwater flow in the Saq–Disi aquifer is, in general, directed from the outcrop areas toward north–northeast into the adjoining limestone plateau of the northern Arabian platform. The Lower Cretaceous Kurnub aquifer contains a distinct groundwater flow system in the east Jordanian limestone plateau, separated from the underlying

Disi aquifer by the Khreim aquiclude. In the western highlands of Jordan, the Disi and Kurnub aquifers become hydraulically connected with the disappearance of the Khreim formation and constitute a single deeper sandstone aquifer complex. Groundwater from the Disi–Kurnub aquifer discharges in springs and leakages along the Dead Sea graben and in wadis on the western escarpment of the highlands of Jordan.

In the Jafr area, the northward groundwater flow in the deeper sandstone aquifer turns westward to the Dead Sea graben.

The groundwater flow system in the Saq–Disi aquifer extends in the Tabuk–Disi segment of the Interior Shelf and the adjoining areas of the northern Arabian platform over 74,000 km^2 from the Tabuk area in the south to the northern tip of the Dead sea.

Locally, the groundwater movement is modified in the Paleozoic–Lower Cretaceous sandstone aquifer by structural features: A structural high in the area between Disi and Quweira in southern Jordan separates the Wadi Yutm groundwater basin with southeastward flow toward the Red Sea coast from the main Saq–Disi groundwater basin with general northward groundwater flow. The northwest–southeast trending Kharawi dyke in southern Jordan acts as a hydraulic barrier causing local deviations of groundwater flow. Artesian groundwater flow is found in an area around Mudawara south of the dyke.

The following estimates of groundwater flow through aquifers of the Interior Shelf, sustained by present-day recharge, have been made:

Saq aquifer, total flow in Saudi Arabia	290×10^6 m^3/a
Disi aquifer, inflow from outcrops on the Interior Shelf into limestone area in Jordan	50×10^6 m^3/a
Wajid aquifer	500×10^6 m^3/a
Lower, middle and upper Tabuk aquifers	140×10^6 m^3/a
Jauf aquifer	15×10^6 m^3/a
Khuff aquifer	80×10^6 m^3/a
Jilh aquifer	60×10^6 m^3/a
Minjur aquifer in northern Saudi Arabia	100×10^6 m^3/a
Wasia–Biyadh aquifer	480×10^6 m^3/a
Mukalla aquifer	500×10^6 m^3/a

The estimates indicate rather high figures of groundwater flow volumes and of present-day recharge. Considering the vast extent of the various aquifer complexes, rates of groundwater flow and recent recharge appear, however, small corresponding to only a very minor part of the large volumes of the prevailingly brackish groundwater stored in the aquifers. Any larger groundwater exploitation therefore leads to mining of the fresh water resources.

Groundwater velocities in the sandstone aquifer complex have been estimated to be around 2 m/a.

The following estimates of stored volumes of groundwater in different aquifers on the Interior Shelf and their extension into the adjoining eastern Arabian platform have been made:

Saq	280×10^9 m^3	
Wajid	205×10^9 m^3	
Tabuk (three members)	205×10^9 m^3	
Jauf	100×10^9 m^3	
Khuff	30×10^9 m^3	Brackish groundwater
Jilh	115×10^9 m^3	Brackish groundwater
Minjur	460×10^9 m^3	In the Sudair–Riyadh–Aflaj area, fresh to slightly brackish groundwater
Dhruma	180×10^9 m^3	Brackish groundwater

References. Bazuhair (1989), Caro and Eagleson (1981), Edgell (1997), El Naser and Gedeon (1996), FAO (1979), Hobler et al. (1991), Lloyd and Pim (1990), Sharaf and Husein (1996), Subyani and Sen (1991), WAJ-ODA (1994), Wolfart (1961).

5.4 Groundwater Salinity and Hydrochemistry

5.4.1 Sandstone Aquifers

On the Interior Arabian Shelf, two major types of sandstone aquifers with different lithologic–hydrochemical environments can be distinguished:

- The Cambro–Silurian sandstone sequence of prevailing continental origin composed mainly of quartz sandstones of the typical Nubian sandstone facies.
- Paleozoic–Mesozoic sandstones of epicontinental to shallow marine origin comprising interlayering sandstones, limestones and shales.

More or less pure continental sandstones constitute the Saq–Disi aquifer in northern to central Saudi Arabia and southern Jordan and the Wajid aquifer in southern Saudi Arabia and Yemen.

Paleozoic–Mesozoic sandstone aquifers deposited under coastal marine to fluviatile conditions include the Tabuk, Jauf, Kurnub, Biyadh and Minjur aquifers.

5.4.1.1 Saq–Disi Aquifer

The Saq–Disi aquifer consists generally of quartz sandstones with siliceous cements and small amounts of kaolinite. The hydrochemical composition of groundwater in the Disi aquifer in part of its outcrop areas is typical for an aquifer matrix with low hydrochemical reactivity. Near the outcrop area in Jordan, groundwater salinity is generally low with 200–300 mg/l TDS in the unconfined sector, increasing slightly to 300–400 mg/l in the confined sector. The low salinity groundwater is Ca–HCO_3 type water with mean anion concentrations of around 120 mg/l HCO_3, 40 mg/l Cl, 30 mg/l SO_4.

Similar hydrochemical conditions prevail in the Saq aquifer within and near the outcrop area in Saudi Arabia around Tabuk, where salinity is generally less than 400 mg/l and frequently less than 200 mg/l TDS.

The Ca–HCO_3 type groundwater with low salinity is found, in particular, in wide parts of the Tabuk–Disi segment between Tabuk, Hail and southern Jordan. On the Widyan basin margin and the northern Tuwayq segment, Na–Cl type groundwater prevails with moderate to elevated salinities (500–1,000 mg/l TDS, up to 1,500 mg/l TDS in some areas).

Most of the low salinity Ca–HCO_3 type groundwater contained in the aquifer appears to originate from Pleistocene recharge, retention periods being estimated at 10,000–30,000 years (Sect. 5.5.1). Present-day recharge derived from wadi runoff from the basement is characterized by Ca–Na–HCO_3 or Na–Cl type groundwater.

Generally low HCO_3 concentrations between 100 and 200 mg/l indicate a very limited impact of carbonate dissolution. Silicate hydrolysis may be a major source of HCO_3 concentrations.

Brackish Na–Cl type groundwater is found in the Saq–Disi aquifer on the Arabian Platform downstream of the aquifer outcrop and around wadi courses, where Holocene recharge from runoff water is accompanied by elevated salinity.

In undisturbed conditions, the hydrochemical pattern in the aquifer near the outcrop area appears dominated by:

- Fossil Ca–HCO_3 or Na–HCO_3 type groundwater
- Mixing of Na–Cl type groundwater with low to moderate salinity with the fossil groundwater

On the Arabian Platform, where the Saq–Disi sandstones are overlain by a thick sequence of younger deposits, the groundwater salinity increases in direction of groundwater flow and the water is generally Na–Cl type water. In southern Jordan, the Disi aquifer is overlain by marly deposits of the Ordovician–Silurian Khreim group, which contain in aquiferous layers Na–Cl water with salinities of 900–9,000 mg/l TDS.

A gradual salinity increase is observed over the around 250 km long distance between the Disi outcrop area and the discharge zone in the Dead Sea valley: In the unconfined and confined parts of the aquifer south – upstream – of the Kharawi dyke, groundwater salinity ranges from 200 to 300 mg/l TDS. North of the dyke, the groundwater salinity in the Disi aquifer increases from 250 to 400 mg/l TDS in direction of groundwater flow – toward north and then west – to around 700 mg/l in the Maan area, 1,350 mg/l in Wadi Mujib and 1,000–3,000 mg/l TDS in the Dead Sea area.

The Ca–HCO_3 type groundwater changes to Na–Cl type water at a salinity of around 700 mg/l TDS. The change in salinity and of hydrochemical composition is attributed mainly to leakage of brackish water from overlying aquifers or aquitards.

In northern Saudi Arabia, Na–Cl type water has been tapped in the Saq aquifer through deep wells far away from the outcrop of the formation. The main source of

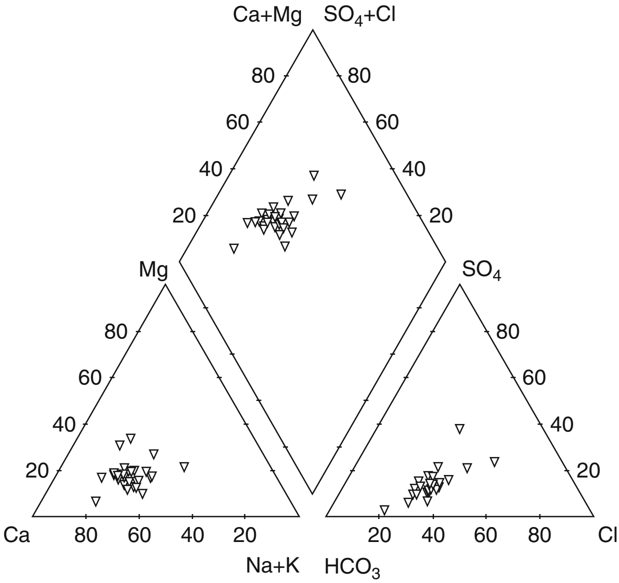

Fig. 5.3 Piper diagram: Groundwater samples from the Disi aquifer, southern Jordan. Data from Hobler et al. (1991)

the salinity increase is assumed to be downward leakage from overlying brackish water aquifers, especially in the Qasim and Sirr areas.

Elevated salinities are found at the outlets of some large wadis entering the sandstone outcrops from the area of the Arabian Shield. Groundwater in wells tapping the Saq aquifer at the downstream ends of Wadi Rima and Wadi Rishe in the Unayza–Burayda area is generally brackish Na–Cl type water with salinities ranging from 1,000 to 8,700 mg/l TDS.

According to Lloyd and Pim (1990) "lower Cl concentrations occur in some parts of the aquifer further down the hydraulic gradient, than under the outcrop area. This is attributed to the diminution of recharge with time. The lower concentrations represent significant past recharge ~10–30,000 years B.P. and the higher concentrations relate to more recent recharge derived from runoff from the basement under predominantly arid conditions; and also salination from localised groundwater evaporation".

Elevated salinity in the Saq aquifer along Wadi Rima appears to be caused primarily by evaporative salt concentration in a sporadic wadi flow regime. Nitrate concentrations are high with an average of around 200 mg/l.

The drainage area of Wadi Rima extends over around 71,000 km^2 and is the largest stream basin in Saudi Arabia, reaching far into the Arabian Shield. Wadi Rima crosses the outcrop of the Saq sandstones along a stretch of about 40 km. At present, wadi runoff reaches the Saq outcrop area during a few days generally once or twice a year. During the pluvial periods of the Pleistocene, the aquifer was probably filled with groundwater of low salinity. With the significant reduction of the volume of wadi flow in the arid Holocene climate, mainly fine grained sediments are deposited along the wadi channel and the flood plain. Surface outflow from the wadi is restricted by sand dune barriers, and water flooding the wadi is, to a considerable extent, evaporated leaving a cover of soluble salts, in particular NaCl and gypsum. NaCl is flushed through following floods into the groundwater, while sulfate salts are mainly accumulated in the wadi sediments.

In the Riyadh el Khabra area, a plain at the confluence of tributary wadis with Wadi Rima, groundwater in the Saq aquifer is brackish Na–Cl type water with TDS values between 1,600 and 8,700 mg/l. The occurrence of brackish groundwater is attributed mainly to irrigation return flow, as:

- Groundwater salinity is relatively low in newly constructed wells, but increases in the following years.
- Salinity in the upper layers of the aquifer tends to be higher than in deeper sections of the aquifer and a decrease of water salinity is generally observed from the beginning of pumping to later hours of operation.

NO_3 concentrations reach up to 370 mg/l.

5.4.1.2 Lower Cretaceous Sandstone Aquifers

Fresh groundwater with salinities of 600–1,000 mg/l TDS occurs in the Sakaka sandstones in the Al Jauf–Tabuk area. In the morphologic Jauf depression, fresh Ca–HCO_3 type groundwater is probably related to recent recharge in the ramifying wadi system. Na–Cl type water with salinities of up to 3,000 mg/l TDS, which has been tapped in the Permian–Lower Cretaceous sandstone aquifer complex of the Jauf depression, may represent fossil groundwater.

Groundwater in the Kurnub sandstone aquifer in southern Jordan is prevailingly brackish. Groundwater salinity increases from 1,400 mg/l TDS on the northern margin of the Interior Shelf to nearly 3,000 mg/l in the Jafr area on the east Jordanian limestone plateau.

The groundwater appears to be generally Na–Cl type water. In the subsurface, fresh groundwater occurs in the Kurnub sandstone aquifer on the southwestern slopes of the western highlands of Jordan with EC values of 530 μS/cm in Wadi Hasa; EC values increase to 600–800 μS/cm further north on the highlands and, on the Jordan valley escarpment, to around 3,000 μS/cm in hot springs and up to 7,000 μS/cm in boreholes.

Groundwater in Cretaceous sandstone aquifers of the Tuwayq segments is prevailingly brackish (Fig. 5.4). Water in the Minjur aquifer has salinities of 1,400 mg/l TDS near Riyadh and 1,600 mg/l at Sudair. The salinity increases toward south and reaches 4,000 mg/l TDS at Al Aflaj.

Fresh to slightly brackish groundwater occurs in the Biyadh–Wasia aquifer in Wadi Nisa (500–900 mg/l TDS), Khurais (550–1,500 mg/l TDS) and Al Kharj ($>$1,000 mg/l TDS). The salinity of the aquifer increases with depth and toward the

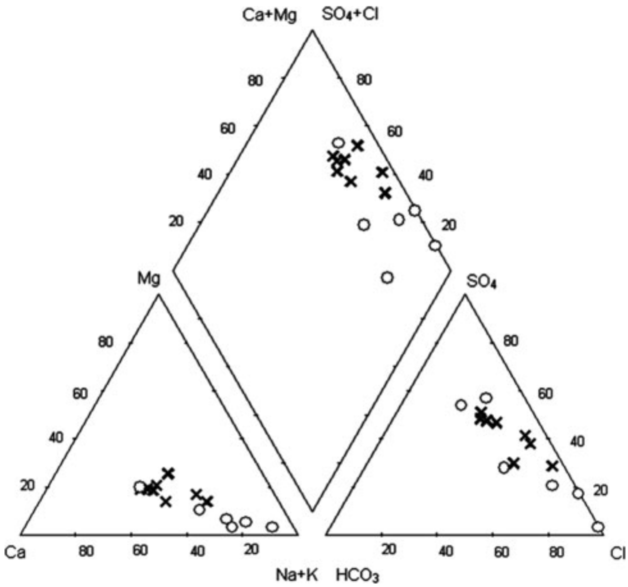

Fig. 5.4 Piper diagram: Groundwater samples from the Minjur and Wasia aquifers, Saudi Arabia. ○ Minjur aquifer, × Biyadh–Wasia. Data from Otkun (1972) aquifer

confined sections of the aquifer under the eastern Arabian platform; in many offshore areas of the Gulf, the formation contains brines.

5.4.2 Carbonate Aquifers

Groundwater in the Permian–Cretaceous carbonate aquifers of the Interior Shelf is generally brackish.

In the Upper Permian Khuff formation, composed of limestones and dolomites with some anhydrite, groundwater salinity ranges from 3,800 to 6,000 mg/l TDS.

The Middle Triassic Jilh aquifer contains water with 3,800–5,000 mg/l TDS; the elevated salinity is caused mainly by dissolution of $CaSO_4$ from anhydrite and gypsum layers.

In calcarenites of the Lower Cretaceous Sulaiy aquifer, groundwater with a salinity of 1,000–3,000 mg/l TDS is found 20 km southeast of Riyadh.

References. Al-Sagabi (1978), Al-Sayari and Zötl (1978), Bassam (1998), Edgell (1997), El Naser and Gedeon (1996), Handy and Alomani (1984), Hobler et al. (1991), Jado and Zötl (1984: 187 ff), Lloyd and Pim (1990), Salameh and Rimawi (1984, 1987b), Sharaf and Husein (1996), Sowayan and Allayla (1989), van der Gun and Ahmed (1995), WAJ-ODA (1994).

5.5 Recent and Pleistocene Groundwater: Information from Isotope Data

5.5.1 Groundwater Age

Groundwater in the Paleozoic–Cretaceous sandstone aquifers of the Interior Shelf is prevailingly fossil. The following ranges of groundwater ages have been calculated from ^{14}C data:

- Saq aquifer generally 22,000–28,000 years
- Wajid aquifer in Saudi Arabia generally >30,000 years
- Minjur aquifer on outcrop 15,500 years, 100 km downstream further east 34,800 years
- Wasia–Biyadh aquifer:
  - Near the outcrop at Kharj 8,000 years
  - At Khurais 16,000 years
  - 70 km east of the outcrop 20,760 years
  - At Abqaiq 250 km east of the outcrop 22,500 years
- Sakaka aquifer in the Tabuk–Jauf area 21,000–>30,000 years

^{3}H is below detection level in most samples from the Paleozoic–Mesozoic sandstone aquifers.

In the outcrop area of the Disi sandstone aquifer, tritium values of >4 TU were analysed in groundwater from a few wells in southern Jordan, "but other outcrop wells at similar groundwater elevations do not have tritiated water. This is seen as demonstrating that modern recharge occurs but only with a variable distribution in time and location and is consistent with the hypothesis that sporadic recharge to the system is through infiltration loss from run-off during flash floods" (Llloyd and Pim 1990, data mainly of 1970s).

In samples taken from the Disi aquifer of southern Jordan in 1987 to 1993, tritium contents were below detection level.

Most groundwaters in the outcrop areas of the Disi aquifer are "modern" in ^{14}C terms with values of 38.1–41.9 pmc, but also old waters are present under the sandstone outcrops with values of 18.1–22.8 pmc. ^{14}C ages of 6,000–20,000 years are found in the confined area close to the outcrop.

Relatively low Cl concentrations (<100 mg/l) in some parts of the confined aquifer are assumed to represent recharge before about 10,000–30,000 years, while higher Cl^{-} concentrations occur in groundwater related to more recent recharge under predominantly arid conditions.

In the area of Riyadh el Khabra, where Wadi ar Rima crosses the Interior Shelf on the northern rim of the Tuwayq mountain zone, ^{3}H values of groundwater in wells tapping the Saq sandstone aquifer are low, ranging from less than detection level to 2.5 TU. In water from a deep well tapping the Minjur sandstone aquifer, ^{3}H was below detection level (data of 1974).

In the central Tuwayq mountain zone, significant ^{3}H values are generally restricted to shallow groundwater in wadi sediments. In Wadi Hanifa, which crosses the Interior Shelf in the Riyadh area, tritium values of 54–74 TU were found in groundwater of the 60–80 m thick wadi sediments (data from 1973 to 1974). In the shallow aquifers of the Wadi Hanifa catchment "all waters having tritium values of more than 10 TU were collected from upper and central parts of valley provided with both a nearby and a remote recharge area, whereas waters with less than 4 TU leave parts of broad valleys or else come out of Al Kharj basin far away from the recharge area" (Al-Sayari and Zötl 1978: 226).

In Wadi ad Dawasir, groundwater from deep artesian wells and from shallow wells reaching the Wajid sandstone aquifer has low ^{3}H values (less than detection level to 2.8 TU). ^{3}H values of samples from shallow wells in the wadi sediments range from 1.5 to 45 TU (data of 1975).

5.5.2 Stable Isotopes of Oxygen and Hydrogen

The clusters of $\delta^{18}O$ and $\delta^{2}H$ values of groundwater from the Interior Shelf show several specific scatters in different areas, apparently related to Holocene or pluvial Pleistocene climate conditions and various sub-regional meteoric regimes. $\delta^{18}O$ values of Pleistocene groundwaters are generally in a range of −5.5 to −8‰; groundwaters originating from Holocene recharge have significantly less negative $\delta^{18}O$ values in a range of −1.25 to −3.3‰.

$\delta^{18}O$ values of groundwater in the Disi sandstone aquifer of southern Jordan are in a range of generally −6.5 to −7.2‰ with d values scattering around +12‰ (Fig. 5.5). "The groundwaters do not correlate directly with the Mediterranean rainfall type relationship" (Lloyd 1981). Recent recharge of Mediterranean origin is indicated in some samples from the Disi sandstone outcrop area in Jordan by d values of around +20‰.

The general pattern of $\delta^{18}O/\delta^{2}H$ values in the Disi aquifer appears comparable to the distribution in aquifers of the semi-arid to arid plateau areas of eastern Jordan and southeastern Syria, indicating an origin from precipitation in a generally dry Pleistocene–Holocene climatic environment.

Wadi ad Dawasir crosses the Interior Shelf on an about 150 km long west–east stretch in the southern Jebel Tuwayq area over outcrops of the Wajid sandstones, Jurassic formations and Quaternary clastic sediments. Groundwater with low salinity from artesian boreholes tapping the Paleozoic–Mesozoic aquifers have $\delta^{18}O$ values between −6.06 and −8.02‰, d values scatter around +6‰ (Fig. 5.6). The most negative $\delta^{18}O$ values are found in groundwaters of Jurassic aquifers downstream of the Wajid outcrop area. In brackish groundwater of shallow wells in the Fara area, the following ranges of $\delta^{18}O$ values were found:

- Wells tapping the Wajid sandstone aquifer below a cover of Quaternary sediments: $\delta^{18}O$ −4.39 to −5.68‰ (d on average of +3.8‰)

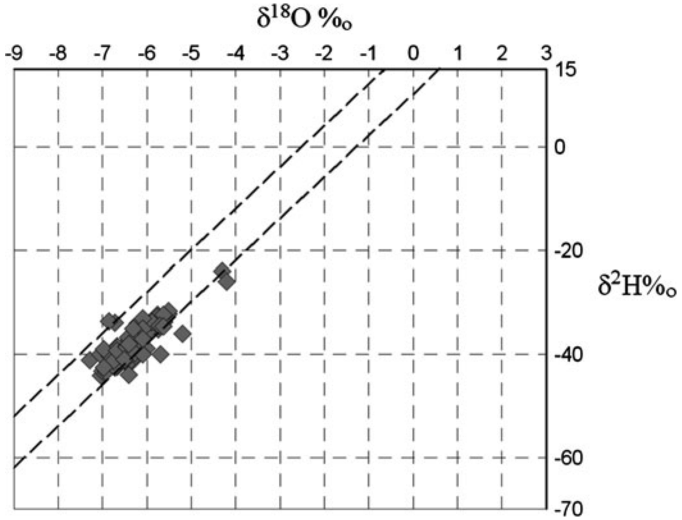

Fig. 5.5 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Disi aquifer in southern Jordan. Data from El Naser and Gedeon (1996)

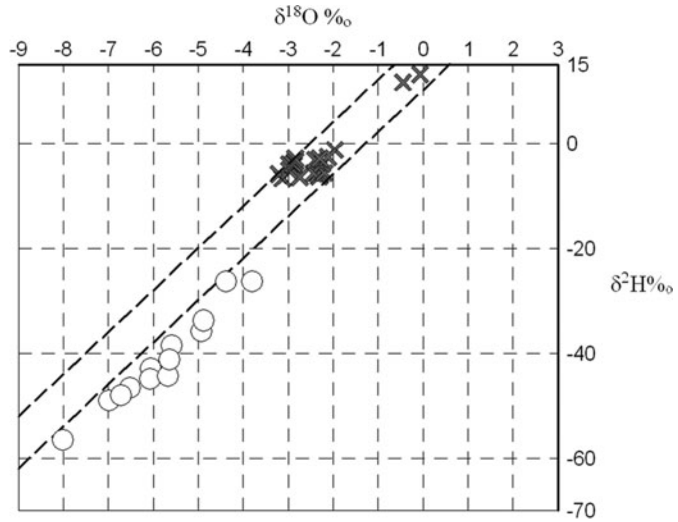

Fig. 5.6 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Tuwayq mountains. × Groundwater in wadi sediments, ○ fossil groundwater in sandstone aquifers. Data from Al-Sayari and Zötl (1978)

- Groundwater from Quaternary sediments: $\delta^{18}O$ −3.61 to −4.89‰ (d +2.6 to +6.3‰)
- One sample with high ^{3}H (45 TU): $\delta^{18}O$ −2.0‰ (d +10.3‰)

"…the enrichment of isotopes as well as the mineralization in hand-dug wells may be explained by an admixture of recent shallow groundwater to old sandstone water"..."the mineralization of wells in Wadi Ad Dawasir most likely occurs on account of mixing of recent, more or less salty and shallow groundwater with qualitatively superior old waters originating in the Wajid Sandstone" (Al-Sayari and Zötl 1978: 250, 252). In detail, variations of the relationship between isotopic composition and salinity of the groundwater appears to be complicated by different mixing proportions and salinization processes.

Brackish groundwater extracted from the Minjur aquifer in a deep well in Wadi Hanifa (salinity 1,200 mg/l TDS) has a $\delta^{18}O$ value of −5.46‰ and a d value of +4.8‰. These values, deviating significantly from values of groundwater in shallow wells in wadi aquifers of Wadi Hanifa, apparently represents Pleistocene recharge.

Groundwater from wadi aquifers in Wadi al Hawta and Wadi Birk in the central Jebel Tuwayq area have d values of +18 to +19.9‰ and $\delta^{18}O$ values between −2.8 and −3.3‰, which may be representative for the general range of Holocene groundwaters of the Arabian Peninsula. From the stable isotope data, generally moderate groundwater salinity (450–670 mg/l TDS) and significant ^{3}H values (up to 30 TU), recent recharge without considerable evaporation impact may be assumed. "Both δD and $\delta^{18}O$ increase together with the tritium content, whereas the water temperature falls with the rising content of tritium and of stable isotopes. It may thus be concluded that warmer waters that are free from tritium and contain less D and $\delta^{18}O$ become mixed with cool affluents enriched with tritium and stable isotopes. Presumably, these tritium-containing affluents have a relatively short infiltration time, which points to a nearby recharge area. They probably flow in from the rather steep and short tributaries in the valley flanks of the breaching. Their recharge area of the older, tritium-free component may be the area west of the breaching" (Al-Sayari and Zötl 1978: 224).

$\delta^{18}O/\delta^{2}H$ values from the Sakaka sandstone aquifer in the Sakaka–Jauf area in northwestern Saudi Arabia deviate significantly from the pattern in the Disi aquifer: d values are negative varying mainly between −5.1 and −13‰, $\delta^{18}O$ values range from −0.6 to −1.3‰. The samples represent fossil groundwater with calculated ages of 21,000 to >36,000 years.

Samples of brackish fossil groundwater (12,000 to >35,000 years) in Paleogene–Quaternary aquifers in southern Wadi Sirhan have $\delta^{18}O$ values of −1.13 to −2.68‰ and d values of −4.4 to −11.1‰. These values possibly result from mixing of groundwaters with different age.

$\delta^{18}O$ values of groundwater from the Saq sandstone aquifer in the Riyadh al Khabra plain on Wadi Rima range from −1.25 to −2.37‰, d values from +1.5 to +8.06‰. These values are probably affected by evaporation effects of irrigation return flow (Al-Sayari and Zötl 1978: 188, 192).

Groundwaters in the Quaternary aquifers of the Wadi Hanifa drainage system in the central Jebel Tuwayq area (Wadi Hanifa, Wadi Nisa, Wadi al Luhy, Al Kharj plain) have $\delta^{18}O$ values between −2.0 and −3.3‰ and d values between +12 and +16.6‰. The group of samples with rather uniform stable isotope composition represents fresh to brackish groundwaters with salinities between 440 and 3,000 mg/l TDS and highly different tritium values in different wadi sections.

The groundwater may be assumed to originate from Holocene to Recent recharge under a Mediterranean type meteorologic regime with, however, less negative $\delta^{18}O$ values than groundwaters on the northern Arabian platform. An impact of evaporative isotopic enrichment of infiltrating wadi runoff and of irrigation return flow may have modified the stable isotope values.

References. Al-Sayari and Zötl (1978), El Naser and Gedeon (1996), Lloyd (1980a, 1981), Lloyd and Pim (1990), Salameh and Rimawi (1984, 1987b), Wagner and Geyh (1999).