Chapter 8
Oman Mountains

8.1 Geographic and Geologic Setup

The southeastern margin of the Arabian Peninsula is accompanied by the Oman mountains, a sickle-shaped 700 km long and up to 140 km wide range, which reaches a peak elevation of more than 3,000 m asl. The core of the Oman mountains is formed by a sequence of autochthonous formations of Precambrian to Cretaceous age, which is overlain by allochthonous complexes: the partly metamorphic sedimentary rocks of the Hawasina unit and the Semail ophiolites.

8.1.1 Morphology and Climate

The Oman mountains separate the coastal belt along the Gulf of Oman from the Rub al Khali. The mountain ranges of Al Hajar al Gharbi and Al Hajar ash Sharqi form a nearly continuous morphologic barrier with altitudes of 1,000–2,000 m asl, which is interrupted by a few passes with lower elevation, in particular at Wadi Semail west of Muscat, and further north near Al Ain–Buraimi. The Jebel Hajar al Gharbi is occupied by high mountain massifs above 2,000 m asl at Jebel Akhdar, Jebel Nakhl and Jebel Khawr, cumulating in Jebel Akhdar with 3,009 m asl. The Jebel Hajar ash Sharqi south of Wadi Semail reaches altitudes of 2,251 m asl at Jebel Tawa and 2,223 m asl at Jebel Khadar.

In the north, the high mountains of Al Hajar al Gharbi are followed by a zone of prevailingly ophiolite hills and mountains with moderately high altitudes of 500–1,100 m asl, situated mainly on territory of the United Arab Emirates. On the northern tip of the Oman mountains, the Musandam peninsula with the up to 2,087 m high Ruus al Jibal limestone massif protrudes as an about 30 km wide spur into the Strait of Hormuz which connects the Gulf of Oman with the Arabian–Persian Gulf (Figs. 8.1 and 8.2).

The eastern slopes of the Oman mountains descend, along the northern and southern stretches, in partly abrupt escarpments directly to the coast of the Gulf of Oman. Between Fujayra and Seeb, an around 30 km wide coastal plain, Al Batina,

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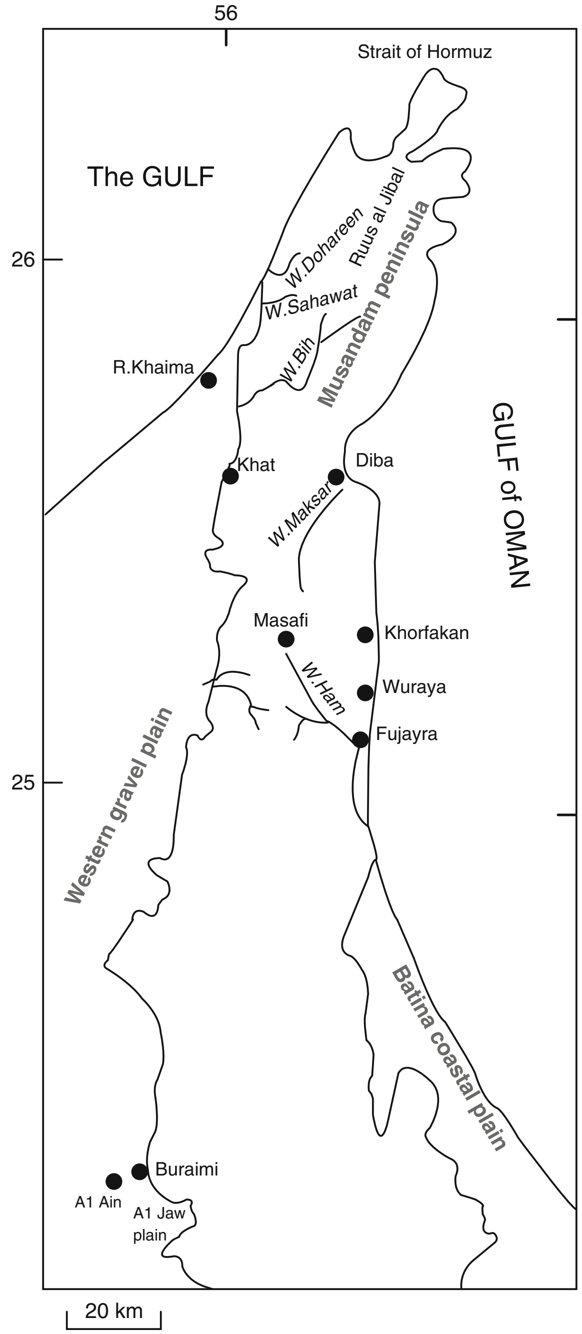

Fig. 8.1 Northern Oman mountains, location map

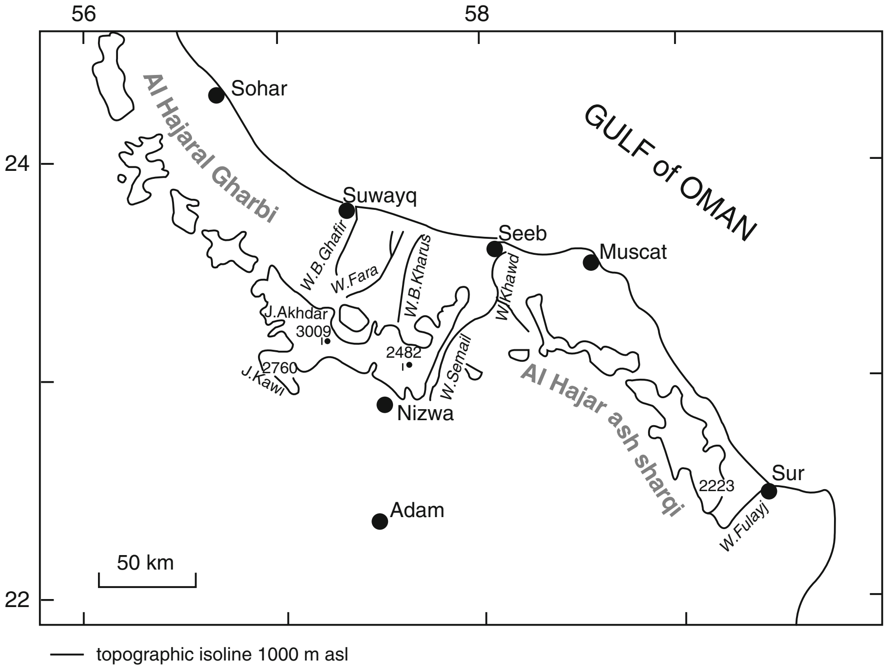

Fig. 8.2 Oman mountains, location map of Al Hajar al Sharqi and Al Hajar al Gharbi

extends for nearly 300 km between the mountains and the coast line. In the west, the Oman mountains are adjoined by a flat gravel plain which grades further east into the sand desert of Rub al Khali. In the southwest, the foothills of the Oman mountains descend into the Rub al Khali and the desert Jidda al Hararis.

The crest area of the Oman mountains forms approximately the main surface water divide between the Gulf of Oman in the east and the Rub al Khali and the Gulf coast in the west. The wadis draining toward the Batina coastal plain in the east are frequently deeply incised on the mountain slopes; wadis directed toward the Rub al Khali in the west have generally a more flat broad morphology.

The climate in the Oman mountains is mainly arid with mean annual precipitation ranging from generally 100–150 mm to more than 300 mm at elevations above 2,000 m asl in the high mountain zone of Jebel el Akhdar. Two types of rainstorms predominate:

- Storms related to frontal depression systems, which originate over the Mediterranean Sea and trace into Oman and the United Arab Emirates during the winter months
- Orographic or convectional rainfall in the mountains during summer

Depression systems occur a few times per season or may be absent for 2 or 3 years. Convectional rainfall is relatively frequent in Oman, but is an exceptional event in the northern part of the Oman mountains in the United Arab Emirates.

The moisture of winter as well as of summer rainfall is derived from vapour masses of the Gulf of Oman and of the Gulf between the United Arab Emirates and Iran.

Barren rocks with very limited soil cover dominate the landscapes of the arid Oman mountains. Scarce vegetation with shrubs and bushes is found on the ophiolite outcrops and on the higher mountain areas. The high mountain massif of Jebel el Akhdar is covered by a vegetation of grass, bushes and low trees. Small oases extend along some stretches of larger wadis with intensive cultivation in the wadi channels and broader valleys.

8.1.2 Geology

The Oman mountains are built up of three main geologic units (Fig. 8.3):

- An autochthonous sequence of Precambrian to Cretaceous rock units
- Two allochthonous sequences: a lower sequence, the Hawasina nappe, composed of sedimentary rocks and metasediments, and the ophiolites of the Semail nappe as upper sequence

The autochthonous units, the Hawasina sequence and the Semail sequence occupied initially consecutive belts: the sediments of the mainly Mesozoic Hajar group on the Arabian Shelf in the west, the Semail oceanic crust in the east, and the Hawasina sediments overlying older oceanic crust in between. During the Upper Cretaceous, the Hawasina and Semail sequences were thrust as tectonic nappes over the autochthonous units, the Hawasina being stacked above the Hajar sediments and the Semail nappe above the Hawasina with partly metamorphic alterations of the Hawasina sediments. The stacked nappes probably formed a chain of low-relief islands along the site of the present mountain chain. The thrust tectonics stagging the Hawasina and Semail series over the autochthonous may be attributed to horizontal crustal compression in response to relative movements of the Arabian Plate and adjacent micro-continents toward the southwest edge of the Asian continent (Glennie 1995: 68).

The orogenic uplift and consecutive erosion processes, creating the present Oman mountain chains, followed in the Oligocene–Miocene.

8.1.2.1 Autochthonous Sequence

The autochthonous sequence has been sub-divided into a lower and upper autochthonous, corresponding to Precambrian–Lower Permian and Upper Permian–Cretaceous rock units, respectively. The lower autochthonous comprises the Precambrian basement, Eocambrian to Ordovician limestones, dolomites, siltstones and quartzites, and sandstones of the Carboniferous–Lower Permian Haushi group. The upper autochthonus is made up prevailingly of limestone and dolomite formations of the Hajar group. The lower autochthonous is exposed in relatively limited areas of the Oman mountains in some domal structures of Jebel Akhdar and Saih Hatat in the Hajar al Gharbi massif west of Muscat.

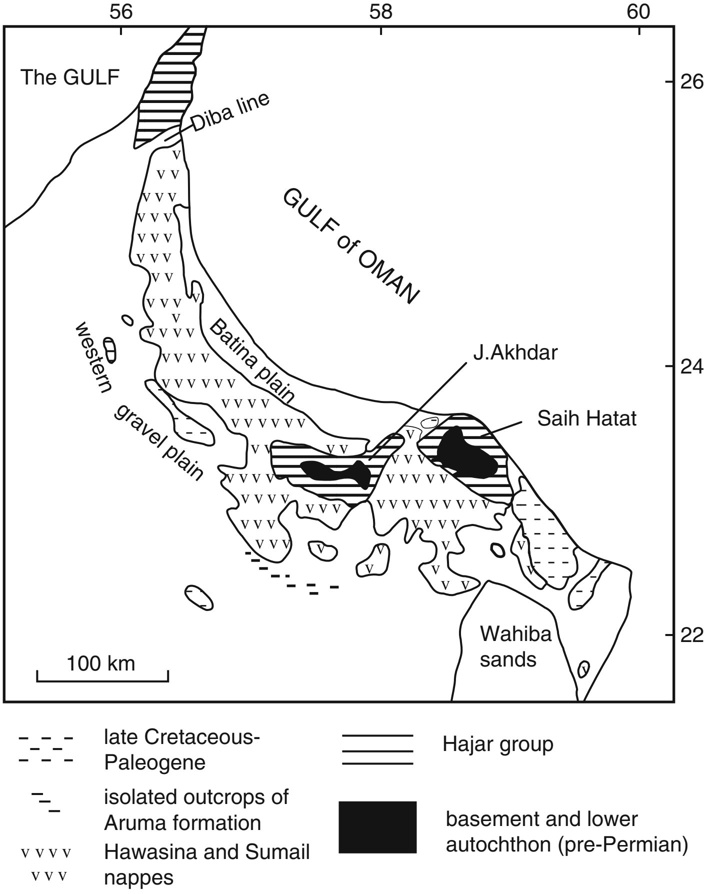

Fig. 8.3 Outcrops of main geologic units in the Oman mountains. After Glennie (1995), generalized

The Hajar group of the upper autochthonous is an up to 3,000 m thick sequence of limestones with some dolomite intercalations that was deposited in shallow marine waters on the Arabian continental shelf. The group is separated from the siliciclastics and dolomites of the underlying strata by a regional erosional unconformity and is followed stratigraphically by the late Cretaceous Aruma group. The parautochthonous Hajar limestone massif of the Musandam peninsula is, in the south, separated from the ophiolite mountains by a major fault zone, the Dibba zone.

The late Cretaceous–Tertiary sequence of the upper autochthonous comprises:

- Carbonates of the Campanian–Maastrichtian Aruma formation, which has been subdivided in Interior Oman into two units:
  - Fiqa formation below: shales and carbonates, with conglomerates and turbidities (Muti formation) at the base
  - Simsima formation above: mainly shallow marine limestones

- The late Cretaceous Juweiza formation on the northwestern boundary of the Oman mountains, composed of detrital deposits of the uplifted allochthonous units
- The Paleogene Hadramaut group with the Umm er Radhuma formation, the gypsiferous Rus formation and the Damam formation

The shallow marine limestones of the Maastrichtian Simsima formation and of the Paleogene Hadramaut group were deposited above the autochthonous–allochthonous units of the Oman mountains after the nappe emplacement. These late Cretaceous–Paleogene rocks were deformed during the mid-Tertiary, when the Oman mountains were uplifted into the present arched structure.

8.1.2.2 Allochthonous Sequence

The Hawasina consists, to a large percentage, of calcarenites that were deposited as turbidities in deep waters northeast of the Arabian continental shelf at roughly the same time span as the Hajar group. The thickness of the Hawasina reaches 1,600 m and decreases probably to around 200 m at distal points of the sedimentation area. The series comprises metasediments, rocks in chert–limestone facies and volcanic intercalations, including the following rock types:

- Metamorphics: quartzite, various types of schists with bands of crystalline marble and enclosures of amphibolites
- Chert–limestone facies: bedded chert and limestone with shale layer
- Volcanics: intermediate and basic lavas, partly vesicular, porphyritic or with pillow structures, agglomerates, tuff beds

The Semail sequence represents principally an 8–15 km thick slate of former oceanic crust of the Tethys sea floor and constitutes the largest and best preserved ophiolite complex of the world. The main rock units of the ophiolite sequence range from ultrabasics to gabbro, sheeted diabase dikes and volcanics. These units include the following lithological types:

- Ultrabasics: peridotite to serpentinite and harzburgite with magnesite and chrysotile veins and silicified alteration products
- Gabbros and ultrabasics: gabbro with intermixed ultrabasic rocks
- Gabbros: coarse grained leucocratic and melanocratic gabbro varieties, commonly layered and with zones of serpentinites, breccias and pegmatites
- Sheeted dikes: medium to fine grained diabase, which forms swarms of sub-parallel sub-vertical dikes
- Volcanis: basaltic lavas with pillow structure

The dolerite dikes, the basalt, and, to a lesser extent, the gabbro underwent secondary hydrothermal alteration (greenschist facies metamorphism) when they were part of the ocean ridge. The peridotite was affected by secondary hydrothermal alteration resulting in a conversion of main minerals to serpentinite.

References. Alsharhan (1989), Glennie (1995).

8.2 Hydrogeologic Conditions in the Hajar Limestone Areas

8.2.1 The Aquifer

Limestones and dolomites of the Permian–Cretaceous Hajar supergroup constitute an important aquifer in the outcrop areas of the Musandam peninsula in the northern Oman mountains, in Jebel Akhdar and in some areas of Jebel Hajar esh Sharqi (Table 8.1).

8.2.1.1 Musandam Peninsula

On the Musandam peninsula, the Hajar carbonate complex forms the Ruus al Jibal mountain range rising with steep morphologic relief from sea level to around 2,000 m asl. The aquifer is here composed of carbonate formations with a total thickness of more than 3,000 m, which are karstified to a depth of several hundred metres below surface. On sub-regional scale, the karstified carbonate complex possibly behaves as one continuous aquifer system, zones of preferential groundwater flow may, however, be concentrated to the deeply incised major wadi systems.

Major wadis in the Ruus al Jibal massif contain unconsolidated wadi sediments with around 30 m and up to more than 100 m thickness. The wadi sediments constitute, in some areas, an aquifer which is in contact with the underlying karst aquifer but with locally higher – perched – water levels.

The mountain massif is crossed by major fault systems with NNW–SSE to N–S and WSW–ESE orientation and by a few extensive west–east trending faults. The fault zones appear to be accompanied by particularly intensive karstification and are followed, along some stretches, by the courses of the westward oriented main wadis: Wadi Bih, Wadi Dohareen, Wadi Sahawat.

The karstic complex is bounded by:

- The sea coast in the northwest and in the east
- A regional fault zone, assumed to constitute a thrust fault, in the west
- The Dibba fault system in the southeast, delimiting the carbonate rocks against the allochthonous Hawasina and Semail units

Along the sub-regional fault line in the west, the karst aquifer is in lateral contact with unconsolidated Quaternary sediments (“gravel fans”) which overlie marls and limestones of the Upper Cretaceous Juweiza formation. In some areas, the Hajar aquifer is adjoined to the west by outcrops of rocks with low permeability, e.g., in the Khat area, where hot springs discharge along the outcrop boundary of the karst aquifer.

8.2.1.2 Jebel Akhdar

The Hajar aquifer of Jebel Akhdar is composed mainly of shallow marine bioclastic and clayey limestones and dolomites with a total thickness of 2,000–3,000 m.

Table 8.1 Hydrostratigraphic sequence in the Oman mountains

Stratigraphic age		Autochthonous		Allochthonous		Western mountain foreland	
		Formation or group	Aquiferous properties	Unit	Aquiferous properties	Unit	Aquiferous properties
Tertiary	Neogene					Fars	Brackish water aquifer
	Paleogene					Hadramaut limestone, chalk, marl	*Aquifer*
Cretaceous	Maastrichtian–Coniacian			Semail ophiolite	*Shallow* fissured *aquifer*	Aruma limestone	Mainly aquitard
	Cenomanian–Lower Cretaceous	Hajar limestone and dolomite	*Major aquifer* in Musandam peninsula and Jebel Akhdar	Hawasina nappe, metasediments, metavolcanics	Generally aquitard		
Jurassic–Permian							

On the southern flank of Jebel Akhdar, the Hajar group dips steeply beneath the alluvial plain and re-emerges 80 km further south in the frontal Adam mountains.

In the synclinal structure between Jebel Akhdar and Jebel Adam, the Hajar aquifer is overlain by a marl aquitard of the Aruma formation.

8.2.2 Groundwater Regimes

8.2.2.1 Hydraulic Parameters

For the Hajar aquifer in Wadi Bih, a mean hydraulic conductivity of 7.7×10^{-4} m/s and a mean transmissivity of 2,000 m^2/d were deduced from pumping tests. In the overlying wadi sediments, horizontal hydraulic conductivities range from 4×10^{-4} to 8×10^{-4} m/s.

Transmissivities of fractured limestones and dolomites of the Hajar aquifer in the Jebel Akhdar area are in the order of 1.7–1,500 m^2/d.

8.2.2.2 Groundwater Recharge and Groundwater Flow

Groundwater recharge on the outcrop of the Hajar aquifer on the Musandam peninsula was estimated at 15 mm/a corresponding to 10% of the mean annual precipitation. Estimates of the recharge volume in the Wadi Bih catchment for the period 1996–2005 amount to a mean of 3.66×10^6 m^3/a, corresponding to 10% of the mean annual precipitation of 150 mm over a catchment of approximately 500 km^2. Annual groundwater withdrawal reaches around 11.2×10^6 m^3/a.

Fresh water replenishment in the Hajar aquifer of the Musandam peninsula may depend prevailingly on indirect recharge from flood flows in the deeply incised main wadis. Groundwater movement in most of the Hajar aquifer of the Ruus al Jibal massif appears to be directed toward west to northwest. Deep groundwater levels in the major wadi systems, the zones of preferential groundwater flow, may reflect a rather smooth sub-regional water table.

Groundwater from the southeastern part of the Hajar aquifer in the Ruus al Jibal massif discharges in springs in the Khat area at the contact of karst limestones with low permeability rocks. The spring water, which is considered to represent deep groundwater flow, rising probably from a depth of around 400 m below land surface. Groundwater discharge of 1.46–2.06×10^6 m^3/a in the Khat springs indicates a recharge rate of 12 mm/a over the catchment of 125 km^2, or 8–11% of annual rainfall.

North of Khat, groundwater probably moves as subsurface outflow from the karst aquifer into Quaternary sand and gravel deposits, which extend in the coastal area west of the limestone massif and from which large quantities of groundwater are extracted mainly for irrigation. Under undisturbed conditions, subsurface outflow from the northern part of the Ruus al Jibal limestone massif probably entered coastal sabkhas or the sea.

In the east of the Ruus al Jibal massif, some groundwater flow probably reaches the coast of the Gulf of Oman.

In the Hajar aquifer of Jebel Akhdar, groundwater flow is directed:

- To springs at intermediate altitude of the northern mountain slope
- To the Batina coastal plain
- To the piedmont zone adjacent to the southern mountain slope

8.2.3 Groundwater Salinity and Hydrochemistry

Groundwater in the Hajar aquifer of the Musandam peninsula is prevailingly brackish, but fresh water occurs at various locations in the larger wadis. EC values range from 550 to 15,000 µS/cm. The following salinity ranges and water types have been found in wadi courses and in well fields at the foothill zone of the mountains:

- Wadi Dohareen, Wadi Ghalila, Sahawat well field: fresh water with equal percentages of major anions or Cl type fresh water and brackish Na–Cl water with EC values generally between 660 and 6,000 µS/cm, increasing during exploration up to 15,000 µS/cm
- Wadi Bih: prevailingly brackish Na–Cl type water, fresh Cl type groundwater at some locations; salinity between 600 and 7,000 mg/l TDS with an average of 2,122 mg/l
- Burairat well field downstream of Wadi Bih: brackish Na–Cl water with salinities between 1,000 and 6,640 mg/l TDS, on average around 4,000 mg/l

In the Khat area, brackish Na–Cl type groundwater with EC values around 2,500 µS/cm discharges in springs and has been tapped in boreholes.

The fresh water occurrences are possibly restricted to relatively shallow water layers in major wadi courses, sustained by recent recharge mainly through infiltration of sporadic runoff, while groundwater under the mountain plateaus and at greater depth below the wadis is brackish to saline.

Groundwater in sand and gravel fans in the foothill zone west of the Ruus al Jibal mountains appears similar in its hydrochemical composition to brackish groundwater contained in the Hajar limestone aquifer with, on average, higher Na and Cl concentrations.

The hydrochemical composition of groundwater from the Hajar aquifer of the Musandam peninsula appears to reflect a mixture of fresh groundwater and brackish Na–Cl water with varying proportions of fresh and brackish groundwater in different areas (Fig. 8.4).

The major ion contents in the fresh groundwater (EC values 600–1,500 µS/cm) result probably from:

- Slightly enriched atmospheric inputs (Cl and SO_4 contents of 35–150 mg/l)
- Dissolution of soil and rock carbonate through interaction with biogenic CO_2 (HCO_3 contents of 130–230 mg/l and equivalent cation contents)
- Mixture with varying amounts of brackish water (Na and Cl contents above 150 mg/l)

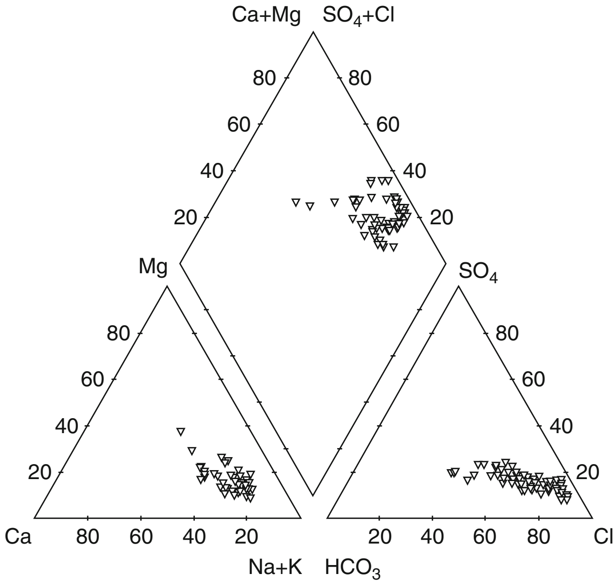

Fig. 8.4 Piper diagram: Groundwater samples from the Hajar aquifer of the Musandam peninsula, United Arab Emirates. Data from files of Ministry of Agriculture and Fisheries and Ministry of Agriculture and Water Resources, Dubai

According to the hydrochemical composition of the brackish to saline groundwater, recent sea water intrusion is apparently not the source of elevated groundwater salinity. "Evaluation of the chemistry of the water, in particular the Ca/Mg and the Cl/SO$_4$, suggests that the end member is not modern sea water, but rather a variable degree of water–rock reactions, with Na–Cl rich evaporite systems or brine". Hydrochemical modelling "confirms that sea water intrusion is not the source of the higher salinity, but suggests a mix of groundwater with an older and possibly deeper source of water and younger groundwater, both from the same recharge area" (Alsharhan et al. 2001: 298).

"Some Ca, HCO$_3$ and Mg is added by rock weathering, most of the solutes appear to be added from a regional brine that is lower in Mg and SO$_4$ and higher in Cl and K than sea water" (Rizk et al. 2007).

The ranges of major ion concentrations of fresh water samples and of a hypothetical brackish water component are listed in Table 8.2.

Ratios between total salinity (EC values) and Na and Cl concentrations of groundwater from the Hajar aquifer of the Musandam peninsula follow rather closely a simple mixing line, indicating that the elevated groundwater salinity originates from one major source.

In the recharge areas of the Hajar aquifer in Jebel Akhdar, Ca–HCO$_3$ type water prevails, Mg–HCO$_3$ water is found at a few locations. Groundwater salinity ranges from 315 to 550 mg/l TDS.

Table 8.2 Major ion concentrations (mg/l) of fresh and brackish components of groundwater in Hajar aquifer of the Musandam peninsula (from Wagner 1996c, data from UAE Min. Electricity and Water)

	EC (μS/cm)	HCO_3	SO_4	Cl	Ca	Mg	Na + K
		(mg/l)					
Fresh water component, range	550–1,500	128–232	35–135	40–333	30–116	12–63	40–233
Brackish water component, assumed	8,500	200	650	2,400	250	130	1,400

Higher groundwater salinity is observed in limestone aquifers of Jebel Akhdar outside the wadis or morphologic depressions (plateau section, mean groundwater salinity 720 mg/l TDS). The differences in groundwater salinity are "seen as reflecting different recharge conditions existing between the bare limestone surface of the plateau and the 20 m thick gravel deposits with its capacity to easily accept and store large volumes of flood water" (Macumber 1995: 484).

In the Adam mountains, the Hajar aquifer, emerging on an anticlinal structure 80 km south of Jebel Akhdar, contains Na–Cl type groundwater under reducing conditions with a salinity of 1,477–3,093 mg/l TDS.

References. Al-Sayari and Zötl (1978), Alsharhan et al. (2001), Harress (1975), IWACO (1986), Macumber (1995), Matter et al. (2006), Rizk et al. (1997, 2007), Wagner (1995a, 1996b).

8.3 Groundwater in the Ophiolite Mountains

8.3.1 Aquiferous Zones

The term "ophiolite mountains" is applied here to the areas in the Oman mountains, which are covered by rocks of the Semail and Hawasina nappes. Aquiferous layers are found in these rock complexes in near-surface weathering zones and in fracture zones. Shallow groundwater occurs, in particular, along wadi courses which follow stretches of intensive fracturing and/or are filled with coarse stream deposits (Table 8.1).

The metasediments and metavolcanics of the Hawasina nappe have generally low permeabilities and act as aquitards.

The Semail ophiolite complex comprises peridotites of the earth mantle and crustal rocks: basaltic pillow lavas, dolerite dikes, gabbro. The crustal rocks have been affected by hydrothermal alteration, creating veins with minerals which produce clayey material during weathering. "The peridotite is affected by secondary hydrothermal alteration, resulting in a conversion of the main minerals to serpentine. Subaerial meteoric weathering of peridotite led to the formation of oxides and clay minerals, commonly rendering the peridotite very friable and porous" (Dewandel et al. 2005: 712).

Hydraulic conductivities in the ophiolite complex are attributed to fissure conductivity and fracture conductivity. Significant fissure conductivity is generally restricted to a near surface zone down to a depth of around 50 m below surface. Apparently, most fissures are closed at a depth of a few tens of metres.

Fissure hydraulic conductivity is generally higher in gabbro and dolerite than in peridotite, probably because many of the fissure openings in the peridotite are partly or completely sealed by carbonates.

Fracture hydraulic conductivity is superimposed on the fissure conductivity and can reach much deeper than 50 m below surface, creating locally extensive secondary porosity. The hydraulic conductivity of tectonic fractures affects all types of ophiolitic rocks and the most productive wells are located in zones of tectonic fracturing.

8.3.2 Groundwater Regimes

8.3.2.1 Hydraulic Parameters

The following values for hydraulic conductivity and transmissivity of ophiolite rocks in the Oman mountains have been estimated:

Fissure hydraulic conductivity of gabbro and dolerite	10^{-5} to 10^{-7} m/s
Fissure hydraulic conductivity of peridotite	10^{-7} m/s
Fracture hydraulic conductivity	10^{-5} m/s
Fracture transmissivity values	9–8,600 m^2/d, geometric mean 90 m^2/d
Transmissivity of fractured and weathered peridotite	7–8 m^2/d

In Wadi Dibba, on the margin of the ophiolite mountains, transmissivities of Quaternary wadi bed gravels range from 19 to 13,700 m^2/d.

8.3.2.2 Groundwater Recharge

Recharge rates in the ophiolite mountains of Oman are about 7% of the mean annual precipitation of 250 mm or 18 mm/a. Absence of soil favours recharge rather than evapotranspiration.

The following estimates of groundwater recharge in the ophiolite mountains of Oman have been reported:

- Recharge to the shallow peridotite aquifer: 18 ± 8 mm/a or 7% of mean precipitation, in rainy years up to 10% of total precipitation
- Average annual recharge in wadis in the ophiolite mountains of the northern part of Oman in wadis Ghalaji, Kabir, Hajr, Asih: 9–12% of the rainfall of 73–149 mm/a
- Recharge to deep groundwater (thermal springs): less than 0.1% of total precipitation

Recharge to crustal rock aquifers was estimated at about 20 mm/a (8% of total precipitation).

Total – direct and indirect – recharge in the Wadi Ham catchment (Fujayra Emirate) upstream of Wadi Ham dam may be in the order of 7–9% of mean rainfall ($2.0–2.5 \times 10^6$ m^3/a over 190 km^2 or 10–13 mm/a).

For the Wadi Wuraya catchment, a mean recharge of 14 mm per year, equal to 10% of rainfall has been assumed. This recharge rate is supposed to sustain perennial surface flow of about 60 l/s in a particular section of the wadi, where perennial base flow sustains waterfalls within the wadi.

Recharge in the catchment of the Khat springs is estimated at 8–11% of mean annual rainfall of 150 mm, or 12–16 mm/a.

The estimates obviously imply high uncertainties and can indicate only that mean groundwater recharge may be in the order of 15 mm/a or 10% of rainfall. This includes direct recharge from rainfall as well as indirect recharge from flood flows in wadi sediments.

8.3.2.3 Groundwater Flow and Flow Volumes

Groundwater flow in the ophiolite mountains is directed toward east to the coastal plain on the Gulf of Oman and toward west or southwest to the gravel plain in the foreland of the Oman mountains. The courses of major wadis may act as zones of preferential groundwater flow in many cases. The groundwater divide between flow to the Gulf of Oman and the western gravel plain on the fringes of the Rub al Khali sub-basin probably coincides approximately with the surface water divide on the crest of the Oman mountains.

To some extent, groundwater discharges in springs within the mountain areas, prevailingly in stream channels, and is used for water supply, diverted for local irrigation or re-infiltrates further downstream in the wadi bed. A major part of groundwater flow in the ophiolite mountains reaches the plains adjoining the Oman mountains in the east and west through subsurface inflow along the main wadi courses. Some diffuse subsurface flow appears also to reach the plains over wider stretches of the boundary between ophiolite outcrops and Quaternary cover.

A tentative water balance of Wadi Ham with a catchment area of 190 km^2 upstream of the Fujayra coastal plain has the following components:

Rainfall	27.6×10^6 m^3/a
Surface runoff	5.35×10^6 m^3/a
Subsurface flow	2×10^6 m^3/a
Evapotranspiration	20.2×10^6 m^3/a
Subsurface outflow to the coastal plain	0.5×10^6 m^3/a
Consumptive use of shallow groundwater in the mountain area	1.5×10^6 m^3/a

Recharge 7% of 145 mm mean annual rainfall or 10 mm/a.

Baseflow in the Wadi Wuraya waterfall area is around 1.8×10^6 m^3/a from a catchment of 128 km^2.

In Jebel Hajar ash Sharqi, the peridotites are, in general, exposed in the upstream parts of the mountainous ophiolitic catchment, while crustal rocks (gabbro, dolerite, basalt) tend to occupy the downstream areas. Many of the wadis in the peridotite area have perennial flow; base flow in the wadis decreases abruptly, where the wadi reaches the gabbro.

The peridotite aquifer has a low hydraulic conductivity but a relatively high storage capacity, which can maintain base flow over large periods (0.1–0.4 $l/s/km^2$ over 6 months). The base flow drained from the peridotite aquifer infiltrates downstream into the gabbro aquifer, which has a higher hydraulic conductivity, providing an annual water input into the gabbro of 1.7×10^4 m^3/km^2.

Storm runoff infiltration into the gabbro reaches around $32 \times 10^3 m^3/km^2$.

8.3.2.4 Groundwater Exploitation Through Falaj Systems

In the ophiolite mountain area, many oases are irrigated by falaj systems. A falaj is a drainage gallery, which in its upstream section cuts below the groundwater surface and acts as drainage collector of groundwater. The downstream sections of the falaj conduct the collected water to the surface, where the water discharges in free outflow. The main tunnel of the falaj may reach a depth of 30 m, which decreases gradually as the falaj approaches the surface.

The gallery is connected to the surface by shafts at distances of 15–30 m. The shafts serve for aeration, for transport of the excavated material to the surface and for access during maintenance and repair of the gallery. Falaj systems in the ophiolite mountains generally extend over distances of 1–5 km.

A falaj can be deepened down to a few metres below the groundwater surface only, implying a limitation of the volume of collected groundwater. The discharge of a falaj is determined mainly by the volume of water drained in the uppermost section of the gallery.

Construction or maintaining of falaj systems can be particularly suitable in shallow aquifers with relatively low permeability, where over a moderately extended drainage section adequate volumes of groundwater can be collected. The traditional groundwater exploitation through a falaj has advantages in that:

- Costs of investment for construction, maintenance and operation are relatively low
- No devices and no energy for water lifting are required
- Water can be drawn from shallow aquifers with relatively low permeability

Disadvantages are that the water discharge is highly dependent on seasonal rainfall, it cannot be adapted to actual water demands and is strongly affected by natural or artificial decline of the water level.

Falaj irrigation systems – also known as qanat or karez – have been constructed since around 800 BC. During the sixth century BC, when Persian rule extended from the Indus to the Nile, technology of constructing falaj systems spread throughout the empire from Mesopotamia to the shores of the Mediterranean Sea, parts of Egypt, Afghanistan and central Asia.

The falaj systems of Oman and United Arab Emirates have provided communities with water for irrigation and domestic purposes for the last 1,500–2,000 years. In Oman in 1993, about 55% of the cropped land was irrigated by falaj water in 1990, and 4,800 active falaj systems delivered some 900 × 10^6 m^3/a of water representing 60% of the country's total water usage (Information of Ministry of Water Resources, Sultanate of Oman). In the United Arab Emirates, falaj systems are part of the agricultural heritage, but recently many have run dry because of low rates of recharge and excessive groundwater pumping.

8.3.3 Groundwater Salinity and Hydrochemistry

8.3.3.1 Shallow Groundwater

Groundwater salinity in the near surface aquiferous zones of the ophiolite complex is generally low to moderate with TDS values of 300–400 mg/l. Most wells in the ophiolite mountain area are located in wadis and tap low salinity groundwater which is recharged from infiltration of wadi runoff. Outside the main wadis, recharge rates are certainly much lower, the infiltrating water may therefore be affected to a higher degree by evaporative processes leading to an increase of major ion concentrations and in particular of Na and Cl contents.

Surface water and shallow groundwater within the fissured and fractured peridotites is Mg–HCO_3 type water with a groundwater salinity of 245–1,187 mg/l TDS and Mg/Ca ratios of 2.94–6.25 (Fig. 8.5).

Groundwater in Wadi Wuraya in the northern ophiolite mountains (United Arab Emirates) is Mg–Cl–HCO_3 water with a salinity of 280–340 mg/l TDS.

Aquiferous peridotites of Jebel Hajar ash Sharqi contain shallow groundwater of Mg–HCO_3 type with EC values of less than 850 μS/cm.

Groundwaters in the ophiolite mountains of Oman show wide ranges of Mg/Na and HCO_3/Cl ratios, Ca and SO_4 percentages are generally low (Fig. 8.6). Ranges of electrical conductivity are reported as 416–3,820 μS/cm in peridotites and 630–7,500 μS/cm in gabbro.

Groundwater salinity in ophiolite aquifers on the southern foothills of Jebel Akhdar range from 245 to 810 mg/l TDS, Cl concentrations from 51 to 202 mg/l. These ophiolite groundwaters, which were sampled from strongly serpentinized peridotites, are mainly Mg–HCO_3 type waters.

According to Neal and Stanger (1984), the Mg–(Na)–HCO_3–(Cl) type waters are the result of weathering and evaporative processes in a system open to the atmosphere. The high magnesium and bicarbonate concentrations are attributed to the dissolution of near surface brucite according to

$$Mg(OH)_2 + 2\ CO_2 \rightarrow Mg^{2+} +\ 2HCO_3^{-}.$$

The wide spread occurrence of Mg–HCO_3 type surface and shallow groundwater in serpentinized rocks results from a high solubility of brucite. Brucite dissolution in the

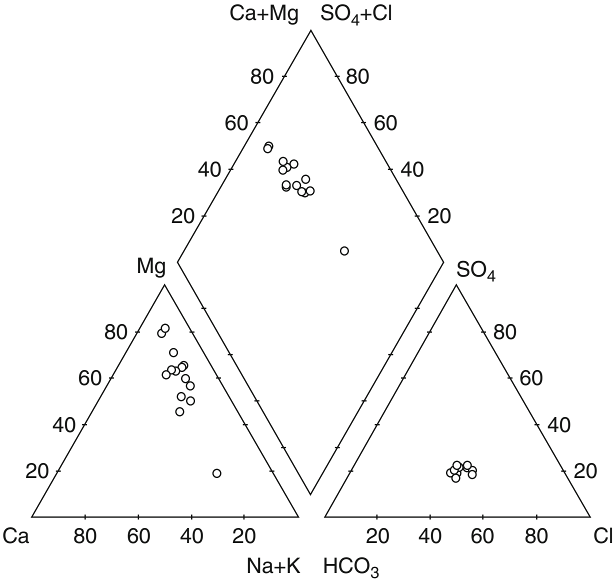

Fig. 8.5 Piper diagram: Groundwater samples from the ophiolite mountains of the United Arab Emirates. Well fields Haray, Lulaya and Wuraya, data from files of Ministry of Agriculture and Fisheries and Ministry of Agriculture and Water Resources, Dubai

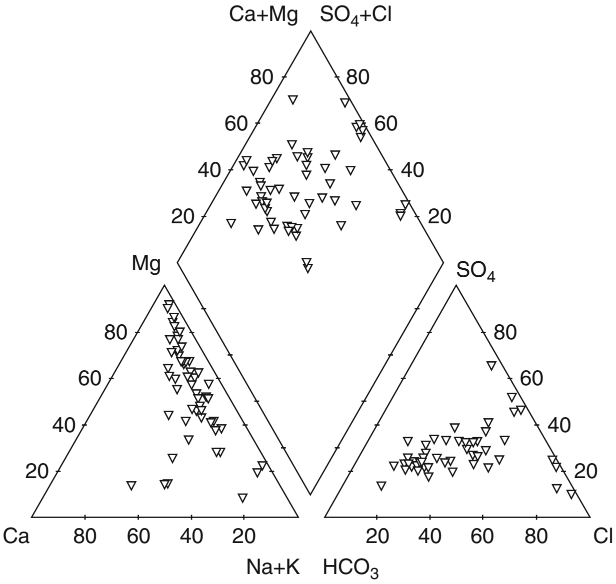

Fig. 8.6 Piper diagram: Groundwater samples from the ophiolite mountains of Oman (dolerite, gabbro, peridotite). Data from Dewandel et al. (2005)

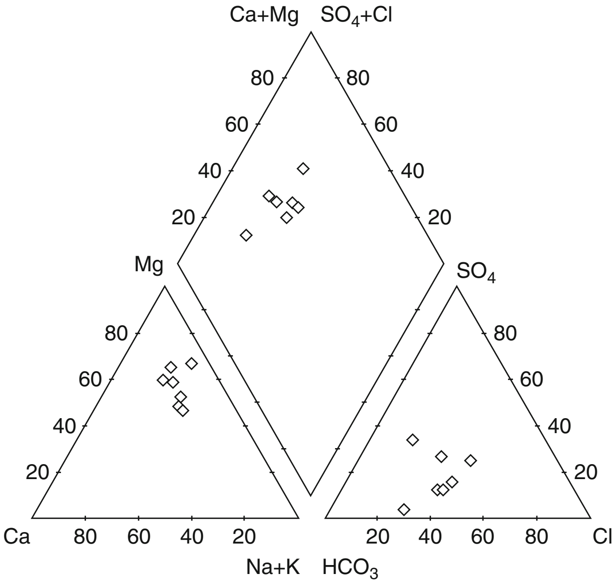

Fig. 8.7 Piper diagram: Falaj water from ophiolites in the United Arab Emirates. Data from Alsharhan et al. (2001)

shallow aquifer leads to the formation of secondary magnesite and abundance of magnesite veins of some millimetres to decimetres in thickness in the ultramafites.

Water discharging from falaj systems in the ophiolite mountains is prevailingly fresh water to slightly brackish water in some areas.

Falaj water in the United Arab Emirates draining fissured ophiolite rocks or overlying gravels is generally fresh water of Mg–HCO_3 type (Fig. 8.7) with EC values between 380 and 750 μS/cm. Components of alkaline groundwater from serpentinites are indicated in falaj water at several locations through pH values of up to 10.9 and up to 1,700 μS/cm elevated EC values.

Salinity of falaj water is generally low near the water divide in the mountain area and increases toward east and west with distance from the recharge area.

In the gravel plains at the coast and in the western foreland of the Oman mountains, EC values of falaj water increase to 1,250 and 1,850 μS/cm, respectively. Falaj water from the Hajar aquifer of the Khat area has EC values of 2,200–2,800 μS/cm. The Falaj Ain Soukhna near Al Ain, draining a Paleogene carbonate aquifer, has an EC value of 11,000 μS/cm.

8.3.3.2 Alkaline Deeper Groundwater

At many locations in the ophiolite mountains, highly alkaline brackish water springs emerge from ultramafic rocks. The spring water is Na–Cl water with elevated concentrations of Ca and OH and pH values of >9, up to 12.2. Most of the hyperalkaline springs have a low discharge and are located in the outcrop zone of ultramafic rocks between the partially serpentinized harzburgites and overlying ophiolite units.

The temperatures of 21–41°C of the brackish spring waters with EC values around 1,600 μS/cm suggest that the groundwater circulation ranges from near surface to around 700 m depth.

The hydrochemical characteristics of the hyperalkaline water are attributed to the impact of low temperature serpentinization of ophiolite rocks on circulating groundwater of meteoric origin. Several specific hydrogeologic conditions are responsible for the evolution of the hydrochemical composition of these waters.

Groundwater circulation is related to infrequent and irregular recharge pulses in an arid environment and slow movement in rocks with relatively low permeability. Accordingly, groundwater reacts during retention periods of several years to decades under closed conditions with the aquifer matrix. The initially acid to neutral Mg–HCO_3 water of the shallow ophiolite aquifer is altered through serpentinization/hydration processes at the contact of the water with the ophiolitic rocks: through silicate dissolution, Mg, Ca and OH are released into solution, pH rises and HCO_3 is converted to CO_3. With increasing alkalinity, dissolution of olivine and pyroxene phases result in the formation of serpentinite and an increase of Ca and OH in the water. Ca is derived from clinopyroxene.

During the serpentinization process, the water becomes progressively more reducing as ferrous iron is released from silicate minerals, and the oxidized dissolved solids SO_4 and NO_3 are reduced to HS and NO_2. Finally, the water attains an alkaline, highly reducing hydrochemical composition with high Ca and OH content.

The brackish nature of the water with elevated Na and Cl concentrations is attributed to the leaching of marine salts, which are dispersed in the ophiolitic rocks as remnants from the submarine phase before the uplift of the Oman mountains.

The discharge points of the hyperalkaline groundwaters are frequently accompanied by by-products of the serpentinization processes:

- Emerging hydrogen gas with minor amounts of methane and hydrocarbons
- $Ca(OH)_2$ and $Mg(OH)_2$ deposits as portlandite and amorphous gel

References. Abdulla and Durabi (1997), Al-Sayari and Zötl (1978), Dewandel et al. (2005), Faig (1990), Fritz et al. (1992), Matter et al. (2006), Neal and Stanger (1984), Rizk and El-Etr (1997), Rizk et al. (1997), Wagner (1996b), Wagner and Karanjac (1997).

8.4 Information from Isotope Data

8.4.1 Groundwater Age

A high percentage of groundwater extracted from the Hajar limestone aquifer of the Musandam peninsula appears to be old with varying admixtures of recently recharged groundwater. ^{3}H values show an impact of recent recharge at several locations in Wadi Dohareen and Sahawat well field (3.6–6.3 TU), Burairat well field (2.8–4.2 TU) and Wadi Bih (3.5–8.8 TU, tritium data from Gonfiantini 1992).

Indications of recent recharge according to ^{3}H data have been found in fresh water as well as in brackish water.

^{14}C values in the Hajar aquifer of the Musandam peninsula indicate generally high groundwater ages with 7.1 pmc in brackish water and 18.5 pmc in fresh water of Wadi Bih, and 9.5 pmc in brackish water of the Burairat well field. The age of these waters is more than 10,000 years, possibly several 10,000 years, but admixture of recent recharge has to be assumed from the ^{3}H values.

The ^{3}H values from the Khat area are generally low (0.8–2.6 TU), the groundwater appears to contain only minor components of recent recharge. ^{3}H values from Tawiyen boreholes south of Khat (6.7–7.2 TU) indicate significant recent recharge. From a corresponding ^{14}C value of 54 pmc, mixtures between old and recently recharged groundwater may be assumed.

The groundwaters of Jebel Akhdar are considered modern although the low ^{3}H values indicate retention periods of at least decades in extensive catchment areas.

8.4.2 Stable Isotopes of Oxygen and Hydrogen

8.4.2.1 Stable Isotopes in Precipitation and Runoff

Meteoric water lines for rainfall at Bahrain are stated by different authors as

$$\delta^2\mathrm{H} = 6.3 \times \delta^{18}\mathrm{O} + 11.4‰ \quad \text{and} \quad \delta^2\mathrm{H} = 4.9 \times \delta^{18}\mathrm{O} + 9.7‰.$$

Similar meteoric water lines have been deduced from data of stable isotopes in rainfall samples in Oman and the United Arab Emirates with gradients between 4.26 and 5.1 and d values of +8 to +9.7‰. For samples from rainfall events with more than 20 mm, the meteoric water line of northern Oman is

$$\delta^2\mathrm{H} = 7.5 \times \delta^{18}\mathrm{O} + 16.1‰.$$

In the United Arab Emirates, a trend has been observed that data of winter precipitation scatter around the Mediterranean Meteoric Water Line (d = +20‰), while stable isotopes of summer rains are more enriched with values plotting close to the Global Meteoric Water Line (d = +10‰).

The δ^{18}O/δ^2H relationship of rainfall in northern Oman is non-linear: samples with δ^{18}O values between −3 and −5‰ scatter around a meteoric water line with a slope of around 8, while samples with more enriched δ^{18}O between −3 and +8‰ tend to follow an evaporation line with a slope of around 5. The slope of around 5 found in sample sets of precipitation of the Oman mountains as well as in Bahrain is explained by an impact of evaporation during rainout, i.e. the rain drops are affected by evaporation during the fall of the droplets.

The variation of stable isotope values may be related to the seasonally varying origin of precipitation from two sources: the Mediterranean Sea and the Indian Ocean.

Samples of runoff in northern Oman scatter mainly around the more depleted part of the meteoric water line

$$\delta^2\mathrm{H} = 7.5 \times \delta^{18}\mathrm{O} + 16.1‰.$$

8.4.2.2 Stable Isotopes in Groundwater

Groundwater samples from the Hajar aquifer of the Musandam peninsula show a rather homogeneous cluster of $\delta^{18}O/\delta^2H$ values scattering close to the MMWL. $\delta^{18}O$ values of most samples are in a range between −3.3 and −3.8‰, the majority of d values is between +17 and +20‰. More negative $\delta^{18}O$ values reaching −4.26‰ and higher d values of up to +23‰ are found in some samples of Wadi Bih (Fig. 8.8).

The high deuterium excess in the groundwater may be attributed to recharge from moisture originating from nearby seas (Arabian Gulf, Gulf of Oman), and the scatter close to the Mediterranean Meteoric Water Line suggests that the recharge took place without evaporation of water drops.

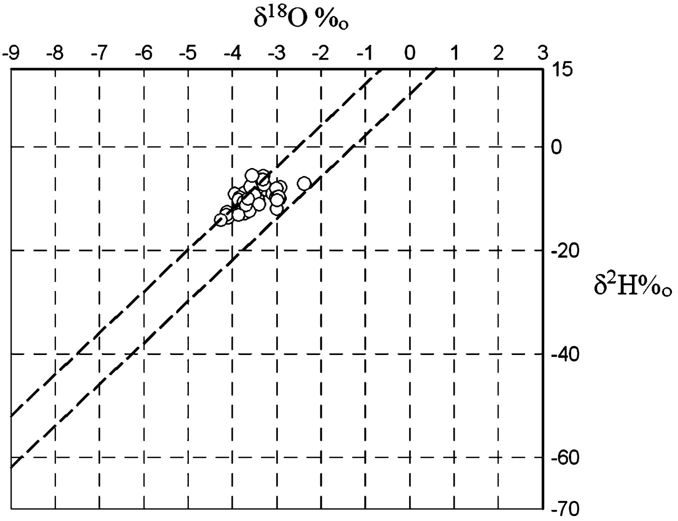

Fig. 8.8 $\delta^{18}O/\delta^2H$ diagram: Groundwater samples from the Hajar aquifer of the Musandam Peninsula in the United Arab Emirates. Data from Akiti et al. (1992), Gonfiantini and Akiti (1985), Kulaib (1991), Rizk et al. (2007), Wagner (1996b)

The distribution of stable isotope values may, in general, reflect the morphologic and recharge conditions. The generally depleted isotope composition of the groundwaters in the Musandam peninsula suggest that recharge occurs mainly at higher altitudes. For Wadi Bih, an average elevation of recharge zones of 1,450 m asl has been calculated, recharge probably occurs prevailingly in the higher ranges of the 1,050–2,090 m high mountain zones surrounding Wadi Bih with rapid recharge and infiltration in wadis steeply incised in the Hajar limestone massif.

The $\delta^{18}O/\delta^{2}H$ values of groundwater in the Khat area in the southwest of the Musandam peninsula are less negative than the values of groundwater in the main wadis of the Musandam mountain area. $\delta^{18}O$ values of groundwater in the Khat area vary from −2.9 to −3.1‰, d values from +12.1 to +15.8‰. The groundwater in the Khat area, discharging in thermal springs, appears to be related to a confined aquifer with recharge at relatively distant parts of the catchment at moderately high altitudes.

The $\delta^{18}O/\delta^{2}H$ values of the brackish groundwater of the Hajar aquifer of the Musandam peninsula indicate, that sea water is not the source of elevated salinity. "Only brine with salinity significantly greater than sea water could provide the observed solute distribution without perturbing the groundwater isotope signature. It appears there is a small water flux but large solute flux associated with the source of solutes. Most of the solutes appear to be derived from regional brine". "The solutes and the water are largely from different sources" (Rizk et al. 2007).

$\delta^{18}O$ values of most samples from the ophiolite mountains in the United Arab Emirates form a rather homogeneous cluster between −1.9 and −2.5‰ with d values scattering near the GMWL and varying from +9 to +14.5‰ (Fig. 8.9).

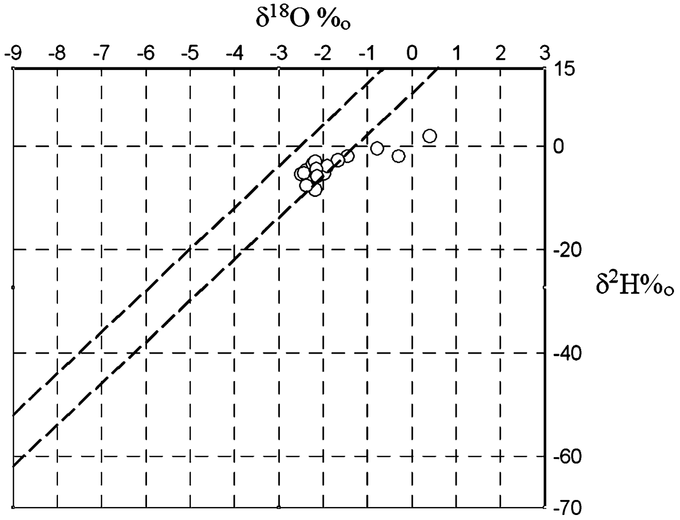

Fig. 8.9 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the ophiolite mountains in the United Arab Emirates. Data from files of Ministry of Agriculture and Fisheries and Ministry of Agriculture and Water Resources, Dubai

The $\delta^{18}O/\delta^{2}H$ values are significantly less depleted than values in the Hajar carbonate aquifer of the Musandam peninsula. The data reflect the recharge conditions in the ophiolite mountains at moderately high altitudes and in a not very pronounced topography, where evaporation effects are more intensive than in the high mountain areas. $\delta^{18}O/\delta^{2}H$ data at some locations of the ophiolite mountains are apparently influenced by local evaporation with $\delta^{18}O$ values enriched up to +0.4‰ and low d values between +5.8 and −0.5‰.

Groundwater with relatively depleted $\delta^{18}O$ and $\delta^{2}H$ values occurs in the Hajar carbonate aquifer in Jebel Hajar al Gharbi in a west–east belt across the northern catchments of Jebel Akhdar, Jebel Nakhl and the Saiq plateau with $\delta^{18}O$ values between −2 and −4.5‰ and d values around +14‰. The distribution of data shows a clear altitude effect: the most depleted $\delta^{18}O$ values of <−3‰ are restricted to the eastern part of Jebel Akhdar and to the upper catchments of the northward flowing wadis. $\delta^{18}O/\delta^{2}H$ values of groundwater samples from Jebel Hajar al Gharbi scatter around a meteoric water line

$\delta^{2}H = 5.1 \times \delta^{18}O + 3‰$ (Akhdar water line, Macumber et al. 1997),

indicating a consistent evaporation effect. The evaporative effect appears, however, less pronounced in the data set with $\delta^{18}O$ values of <−3‰, which with a d value around +14‰ resembles the composition of groundwater in parts of the Oman mountains in the United Arab Emirates; d values are, however, on average lower than d values of the Hajar aquifer of the Musandam peninsula.

Groundwater with depleted isotope values originating from high altitude recharge is also found in some springs and falaj msystems emerging at the mountain foot in Wadi Semail, but is not observed in springs along the southern flanks of Jebel Akhdar.

A plume of isotopically depleted (higher altitude) groundwater ($\delta^{2}H > 10$: $\delta^{18}O > 3$) emerges from the eastern parts of Jebel Akhdar and passes, through a gap in the ophiolitic "barrier", northwards across the lower catchment of the Wadi Al Maawil towards the coast near Barka. Apart from this stable isotope content, the presence of the plume is reflected in relatively high Ca/Mg ratios. The data indicate a pathway of groundwater from the limestone catchments of Jebel Akhdar onto the coastal plain.

On the southern flanks of the high mountain area of Jebel Akhdar toward interior Oman, stable isotope values of oxygen and hydrogen are less depleted with $\delta^{18}O$ values between −2.5 and −0.8‰ and show a significant evaporation effect.

In the ophiolite aquifer of the southern foothills of Jebel Akhdar, situated at 440–596 m asl, $\delta^{18}O$ values range from −0.6 to −1.4‰, $\delta^{18}O/\delta^{2}H$ values scatter around or below the GMWL with d values between +1.9 and +10.2‰. The stable isotope values, which are more enriched in comparison to values in the more northern ophiolite areas in the United Arab Emirates, indicate that recharge may be influenced by southern moisture sources.

$\delta^{18}O/\delta^{2}H$ values of alkaline springs in the Oman mountains tend to deviate from the ophiolite fresh water toward more enriched $\delta^{18}O$ values reaching up to +0.43‰ and relatively depleted $\delta^{2}H$ values. d values can be as low as −8.5‰ (Fig. 8.10). The deviations are probably caused by isotopic exchange between groundwater and

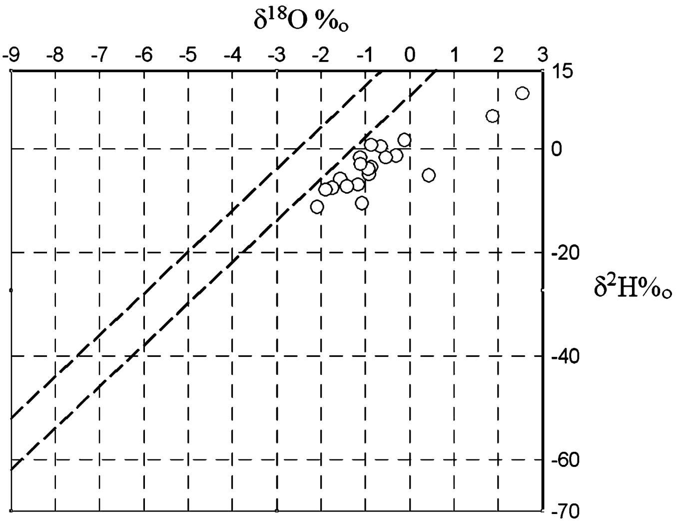

Fig. 8.10 $\delta^{18}O/\delta^2H$ diagram: Water samples from alkaline springs in the ophiolite mountains of Oman. Data from Neal and Stanger (without year)

hydrous phases of the serpentinite sequence. Ionic exchange with hydrous phases of the serpentinites, which have a δ^2H value of around −65‰ and $\delta^{18}O$ values of +7.84‰, leads to very negative δ^2H values in the groundwater until −11.2‰ and, accordingly, to low or even negative d values (Fig. 8.10).

References. Akiti et al. (1992), Al-Sayari and Zötl (1978), Gonfiantini (1992), Gonfiantini and Akiti (1985), Kulaib (1991), Macumber et al. (1997), Matter et al. (2006), Neal and Stanger (1984), Rizk et al. (1997, 2007), Wagner (1996b), Wagner and Geyh (1999).