Physical setting of the study area

Geology

The geologic situation of the Gulf region is basically the result of continuous sediment accumulation since Paleozoic times. The present structure was established during major tectonic processes in the Tertiary period. The Arabian Peninsula originally was attached to the African (Nubian) Shield. At the beginning of the Cambrian to the north and the east of the Arabian Peninsula a great sedimentary basin (Tethys) had developed. Throughout the Paleozoic, Mesozoic, and early Cenozoic times sediments, accumulated in this slowly sinking trough. In the wide epicontinental seas between the Tethys and the Arabian Peninsula, a relatively thin succession of almost flat lying Paleozoic, Mesozoic, and early Cenozoic strata was deposited (Chapman 1978). These strata spread widely over the eastern Arabian Peninsula. In the late Cretaceous, orogenic movements constituted the first stage of the Alpine orogeny. The second stage began in the late Tertiary, when the deformed rocks of the geosyncline started to rise leading to the formation of the Taurus, the Zagros mountains, and the Oman mountains. The Arabian Peninsula itself was little affected by this uplift except for being tilted towards the eastern Arabian Gulf region. There subsidence continued. In the middle Tertiary (25 Ma ago), when these events were at progress, the Arabian plate started to split away from the African Shield along the large rift system which extends from the Gulf of Aqaba and the Dead sea rift in the north to the Afar triangle in Ethiopia. There it diverges through the Gulf of Aden into the Arabian Sea and down the African mainland as the large African Rift Valley System in the south. The separated Arabian plate started moving northeastward with a slight counter-clockwise turn, sliding beneath the great Asian plate in Iran. The tensional forces along the rift lead to the formation of a graben structure (Red Sea depression) with a pronounced relief between the plateau and the floor of the rift. Magma rising up the faults covered large parts of the eastern Arabian Shield. This development continues until the present. The current Red Sea rift is estimated to be between 2 and 3 cm each year (Stanley 1994).

The Arabian Peninsula can be divided into two structural provinces. The Arabian Shield in the west is part of the Precambrian crustal plate, generally exposed except the parts which are covered by tertiary volcanic rock. The second structural province is the Arabian Shelf in the east which consists of the sedimentary sequences covering the plate.

The Arabian Shield

The Arabian Shield is an ancient land mass in the western part of the Arabian Peninsula, covering approximately one third of the Arabian Peninsula (fig. 3.1). It is a peneplain now sloping gently towards the north, northeast, and east and vanishes under a thin sedimentary cover in eastern Arabia. The Precambrian basement consists of the basement gneiss (mainly amphibolite facies), metamorphosed terrestrial sediments, and volcanic rocks of the greenschist facies and countless granitoid plutonic bodies. Long term terrestrial conditions eroded the Precambrian orogenes, forming a peneplain which was partly covered by extensive lava masses in the Tertiary period. Today about 15% of the shield are covered by volcanic rock (Child & Grainger 1990).

The Arabian Shelf

The Arabian Shelf lies to the east of the shield where it forms two thirds of the peninsula. Its foundation consists of the same Precambrian plate that makes up the shield. On top of this basement a series of continental and shallow water marine sediments accumulated, ranging from Cambrian to Pliocene age. These layers dip gently away from the shield into a number of deep basins (Chapman 1978). Thus the thickness of the sediment strata increases gradually from the west to the east where in the coastal lowlands 11,000 m are reached (Alsharhan & Nairn 1997). Beside the main Zagros Reverse Fault even 18,000 m of sediment has accumulated (Edgell 1996). Erosion exposed most of the sediments, forming a series of parallel strike escarpments facing westward, each capped with resistant limestone. These *cuestas* are exposed in a great curved belt along the eastern margin of the shield, reflecting the gently arched surface of the buried basement. Large parts of the basins in the southeast (Rub'al Khali), east (Gulf), and northeast (Nefud) are covered by quaternary sandy sediments. The Persian Gulf Basin is the largest basin with active salt tectonism in the world. The more than 900 km long Arabian/Persian Gulf is the present-day geosynclinal expression of the 2600 km long Persian Gulf Basin. The Persian Gulf Basin consists of a number of NW-SE trending, geotectonic units such as the Arabian Plattform and the zone of marginal troughs, including the Zagros Fold Belt, limited on the northeast by the Main Zagros Reverse Fault (Edgell 1996). The Basin is crossed by several N-S structures, expressed by the major Qatar-Kazerun lineament (Qatar Arch). These rejuvenated uplifts have existed for 650 Ma. The Halokinesis in the Arabian/Persian Gulf originates where major intersecting basement faults (e.g. the Qatar-Kazerun lineament) cut the buoyant salt beds of the different formations

(Edgell 1996). Diapiric oil fields as a result of salt tectonism account for 60% of the recoverable oil reserves of the Persian Gulf Basin (Edgell 1996).

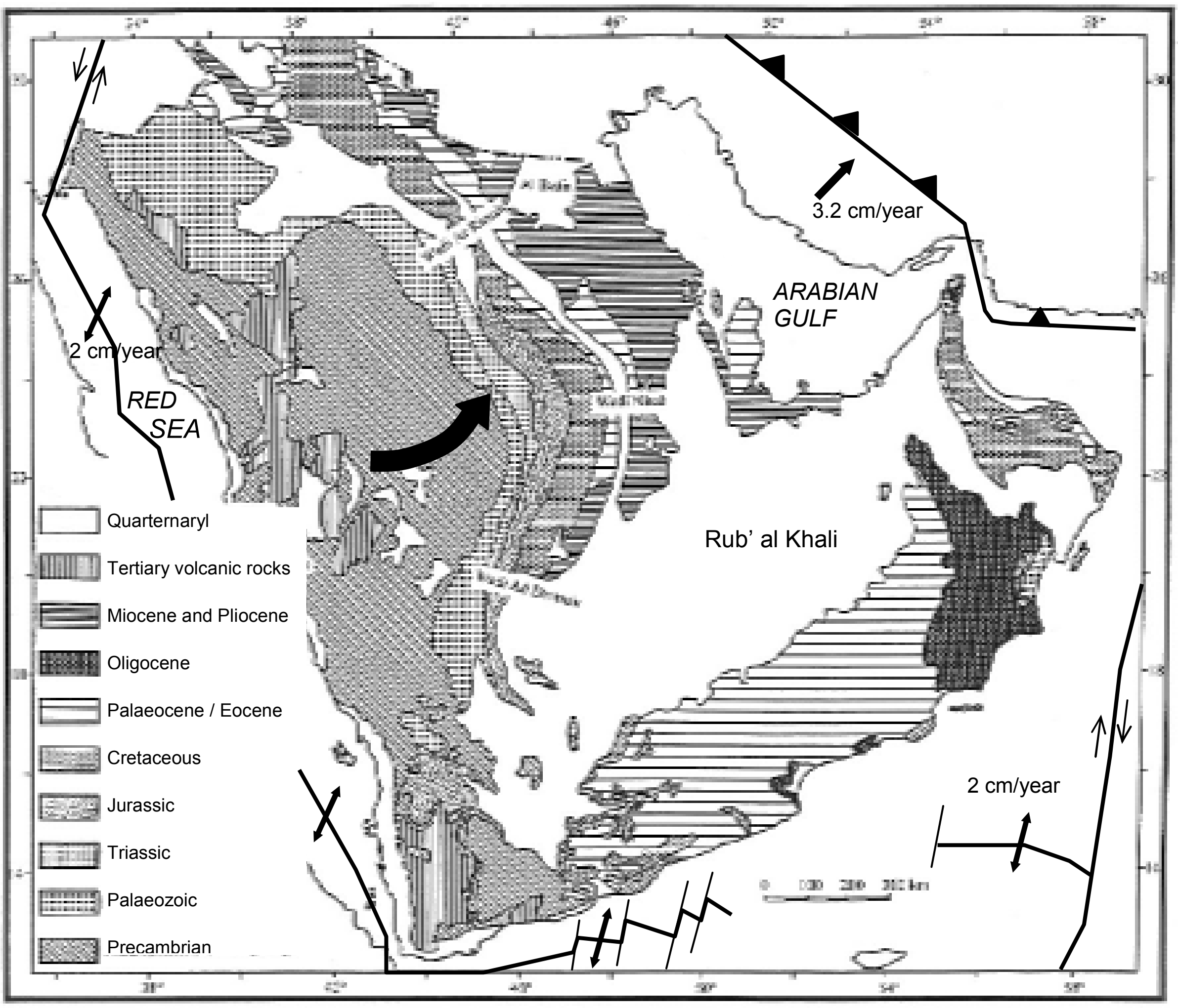

Fig. 3.1 Geology of the Arabian Peninsula and tectonic movements (after Chapman 1978 and Johnson 1998).

The Arabian Gulf coastal region

The southern part of the Mesopotamian depression includes the Arabian Gulf and a narrow coastal strip of the Arabian Peninsula. This coastal strip is the Arabian Gulf coastal region. The elevation of the coastal region rises gradually inland at a rate of about one metre per kilometre. The coastline is irregular, low, and sandy and the water has many shoals, so that tidal changes cause the waterfront to shift back and forth up to several kilometres. Sabkhat (salt flats) are common all along the coast from Kuwait to the southern end of the Arabian Gulf (Barth 2002). Along the northwestern shores north of Jubail, low rolling plains, covered with a thin mantle of sand, are characteristic. These sand sheets are mostly covered by a semi desert vegetation. Further to the north the "Northern Plains" southwest of Kuwait is characterised by a wide gravel plain. This triangular plain has its apex near Al Qaysumah and spreads towards the northeast almost to the Tigris and Euphrates valleys. It is a large alluvial fan of the Wadi Ar Rimah – Wadi Al Batin drainage system, which brought rock debris from the eastern crystalline uplands during one of the pluvials in the Pleistocene period. Reconstruction of the former river system which is partly covered by sand was recently possible by means of radar satellite analysis (Dabbagh et al. 1998). Most of Kuwait's surface consist of the Pleistocene alluvial sediments of the great "Arabian River" (El Baz & Al Sarawi 1996). South of Jubail is a wide belt of drifting sand that widens southward and merges with the sands of the Al Jafurah desert. Areas that are not covered by sand or sabkhat consist of Tertiary limestones. The relief is generally weak. The coastal lowlands are bordered by the As Summan Plateau in the west. The eastern edge of the late Tertiary As Summan plateau is a prominent escarpment indented by ancient stream valleys. In front of the escarpment, several buttes and mesas project prominently into the coastal lowlands. Near the northern limits of the Rub' al Khali, this escarpment fades out leaving a less distinct boundary.

The study area

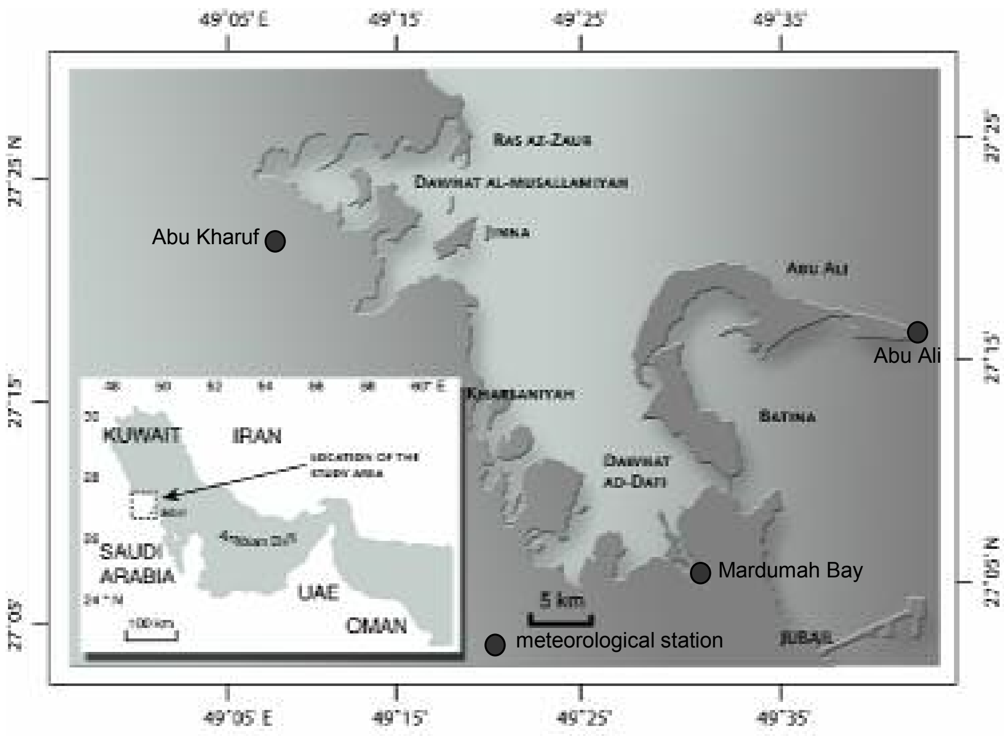

Fig. 3.2 Location of the study area and the meteorological stations discussed in chapter 3.2.2.

The study area is located at the Arabian Gulf coast, north of Jubail Industrial City and covers about 400 km of coast line (fig. 3.2). It belongs to central coastal lowlands of the Eastern Province of Saudi Arabia. The relief between Ras az-Zawr in the north of Musallamiyah Bay and Jubail in the south is weak, although some rocky exposures in the form of minor escarpments (5-20 m high) and small domes are quite common. These belong to the Miocene and Pliocene Hadrukh- and Dam formations and consist of sandy limestone, marl, gypsum, and beachrock formations (fig. 3.3).

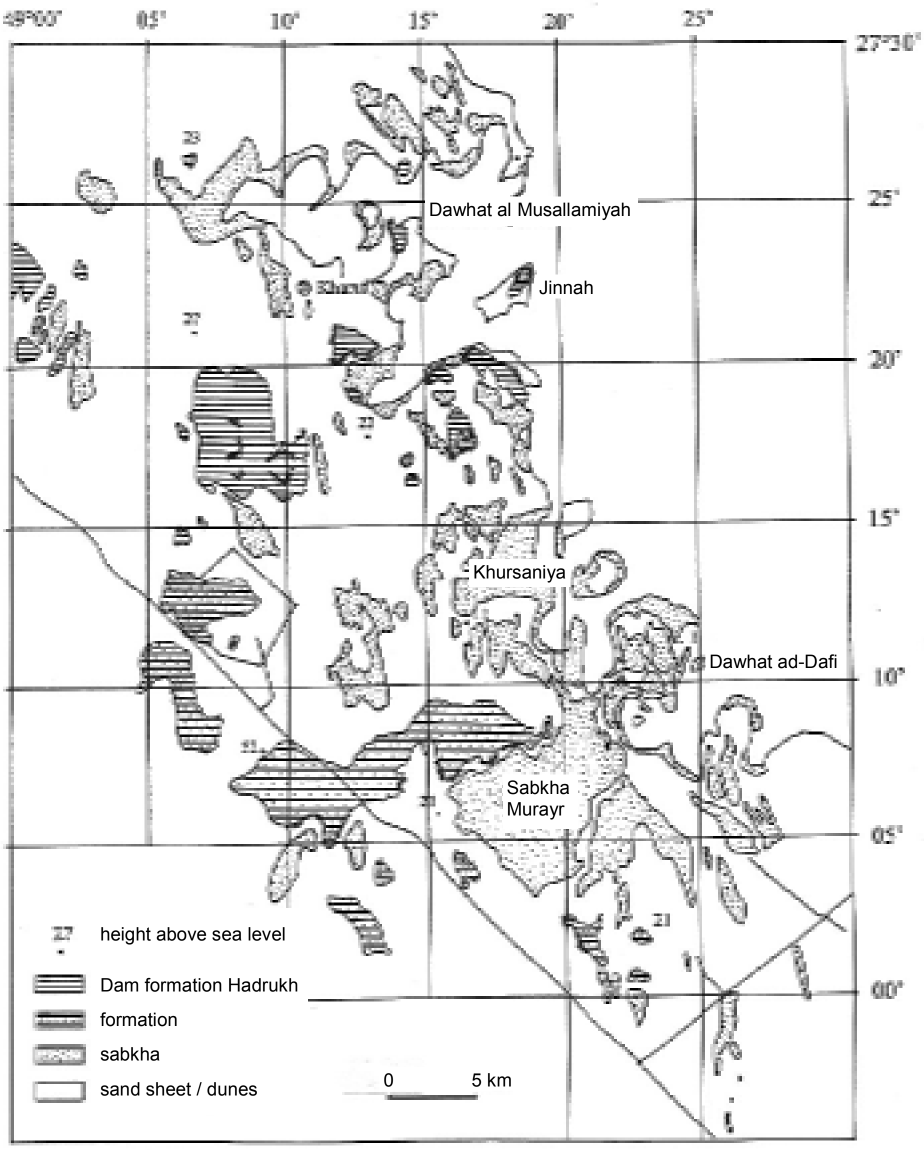

Fig. 3.3 Geology of the study area.

The outcrops of the Hadrukh formation occur in the western part of the study area. In the limestone of the Hadrukh formations chert and gypsum layers are prominent. The rocky outcrops in the northern part of the area under consideration belong to the Dam formation consisting of hard limey sandstone, marl, soft sandstone and beachrock with the typical fossils that are widespread in the region (*Cerithium, Hexaplex, Vermetus*). Occasionally remnants of former coastlines in the form of fossil cliffs and marine abrasion terraces can be found. Although the knowledge about the Pleistocene sea level fluctuations in the Arabian Gulf is modest, they were mentioned by a number of authors. Felber et al. (1978) found a series of 9 terrace levels reaching from the early Pleistocene to the Neolithic pluvial in the middle Holocene.

The largest part of the study area is covered by sand sheets and dunes. The sand sheets are flat sandy plains, mostly covered by scattered perennial grasses and herbs (vegetation cover ranges from 1 to 10%). The sands range from coarse to medium. In areas which have been positively identified as sand source areas by the existence of exposed root systems (Barth 1999, 2001b), the top layer (0.5-1 cm) consists of unimodal coarse sand (median: 1.5 mm), which are sometimes arranged in giant ripples. The clay and silt fraction is missing, owing to aeolian activity. The dunes, which are prominent in the northern part of the study area around Dawhat al-Musallamiyah, document a more arid period in the Holocene and Pleistocene when aeolian activity had a much higher morphological impact on the formation of the topography. Dominant are degenerated longitudinal dunes with their axis in NNW-SSE direction, thus forming a sequence of sand walls with undulated ridges, sometimes several hundred metres long. The depressions in between are often characterized by deflational processes. Most of the dunes are stabilized by a diffuse pattern of perennial grasses and herbs. Where vegetation cover is less than 2% (due to overgrazing), the dunes are reactivated. In the south as well as in the west of the study area, active sand dynamic is reflected in transverse barchanoid dunes without any vegetation cover and movement up to 3 m/yr (Siebert 2002).

A particular feature, typical for the western and southern Gulf coast, is the flat and wide spreading coastal sabkha. Penetrating up to 10 km inland they cover areas of more than 100 km^2. *Sabkha* is the Arabic term for flat salt-crusted desert. The local terminology of the Gulf region describes the extensive, barren, salt encrusted, and periodically flooded coastal flats as well as inland salt flats (Barth & Böer 2002). They consist basically of sand or finer unconsolidated substrate. Their surface is an equilibrium of deflation and aeolian sedimentation, controlled by the local shallow ground water level which is the lower limit of deflation.

Climate

General pattern of the Gulf region

The climate of the Gulf region is a typical desert and semi-desert climate, characterized by high summer temperatures and aridity throughout the year, due to its geographical situation within the subtropical high pressure belt. Descending air is adiabatically warmed as it looses altitude and consequently dried. This leads to an almost complete dispersal of cloud and an absence of rain, except when this pattern is disturbed by incursions from outside. These occur in the winter months between October and April. Thus, in the coastal lowlands of the Eastern Province of Saudi Arabia, rain is confined to this period. The *Trade Winds*, which are generally north-easterlies, become north to northwest winds as a result of locally dominant pressure patterns over the Gulf and the Asian land mass to the east. The surface circulation in the summer months is influenced by two pressure zones. First, the eastern north African high pressure centre, which – because of its clockwise turn – leads to northern currents over the Arabian Peninsula. Second, the thermal continental low pressure cell over the Asian land mass that reaches from the Indian subcontinent into the Arabian Gulf. It provides – because of its anti-clockwise turn – a northerly current on its western flank (fig. 3.4 A). Due to the southward shift of the global pressure belts in the winter months, atlantic cyclones breaking free from the sub-polar low pressure belt move eastward across the Mediterranean Sea and pass across the northern part of the Arabian Peninsula. These depressions are gradually dissipated as they move east or southeast across Arabia, and the probability of rain thus decreases to the southeast. South-eastern winds are the result of currents on the south-western flank of the continental Asian high pressure cell (fig. 3.4 B).

Precipitation in the Gulf region in not exclusively due to the influence of Mediterranean depressions. Recent studies by Steinkohl (2002) demonstrate that the formation of new low pressure centres in Iraq, west to the Zagros mountains is equally important. Thermal convection, as well as the influence of currents from Sudan and Ethiopia, are other precipitation sources (tab.3.1).

A

B

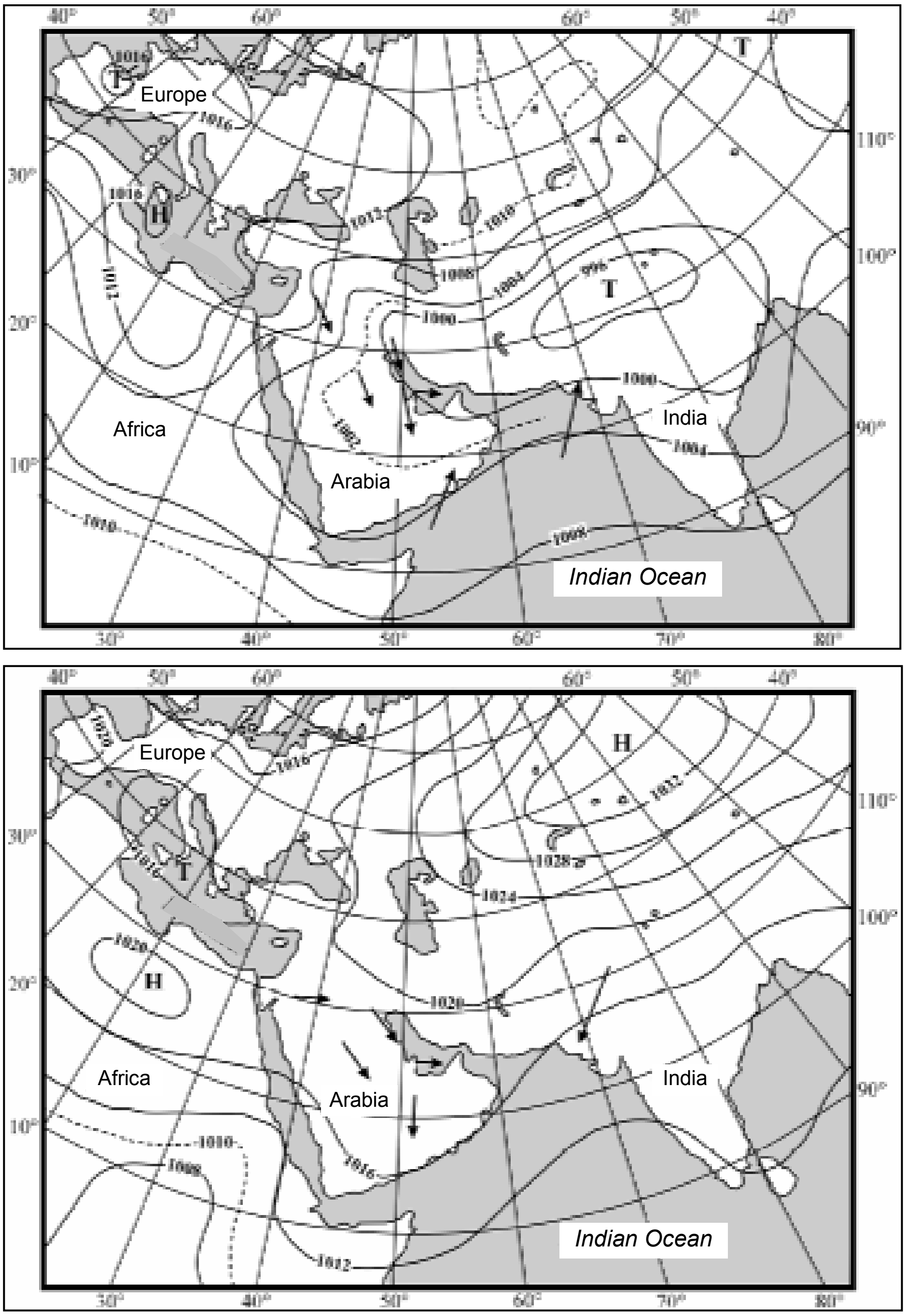

Fig. 3.4 Pressure zones influencing the Arabian Peninsula in July (A) and January (B) after Breed et al (1979). The low pressure trough above the Arabian Gulf in summer leads to strong northern and northwestern currents of the *Shamal*.

Tab. 3.1 Types and number of major precipitation events in the Eastern Province (Steinkohl 2002).

Precipitation type	1993/1994	1994/1995	2000/2001	Total
Mediterranean depressions	4	3	3	10
Formation of new low pressure cells	3	5	2	10
Convection	2	3	4	9
Currents from Sudan/Ethiopia	1	6	1	8
others	0	0	2	2

Climate in the study area

The climate in the study area is documented by the recordings of 3 meteorological stations distributed in a way that the terrestrial climate of the coastal lowlands (Abu Kharuf station), as well as the maritime Gulf climate (eastern Tipp of Abu Ali island), is recorded (fig. 3.2). The third station represents the climate of the intertidal areas within the shallow embayments of the dissected coast line at Mardumah Bay.

Temperature

Maximum and minimum temperatures of the coastal lowlands vary from more than 50°C in summer to 3°C in winter. In some inland areas even temperatures below 0°C were observed (Child & Grainger 1990). For the coastal region in the study area, the influence of the Arabian Gulf is reflected in less extreme values. Because of the shallowness of the Gulf (27.2% of the Gulf are less than 10 m deep (MEPA 1987)), and the restricted water exchange (see chapter 3.5) the amplitude of the water temperature (18-33°C) is higher than in other oceans. Therefore, the reduction of the air temperature amplitude in the coastal region is less compared with other maritime locations of similar latitudes. The mean annual temperatures of the three stations vary between 25.2°C at the inland station (Abu Kharuf) and 26.5°C at the maritime station (Abu Ali). Extreme values were 49.2°C and 4.1°C at Abu Kharuf and 44.3°C and 12.1°C at Abu Ali station. The amplitude (45.1°C) at Abu Kharuf is 12.9°C higher. This and the lower annual temperature, demonstrates the increasing continental character in only 5 km distance to the sea. The intertidal station at Mardumah Bay displays intermediate values (fig. 3.5 and 3.6).

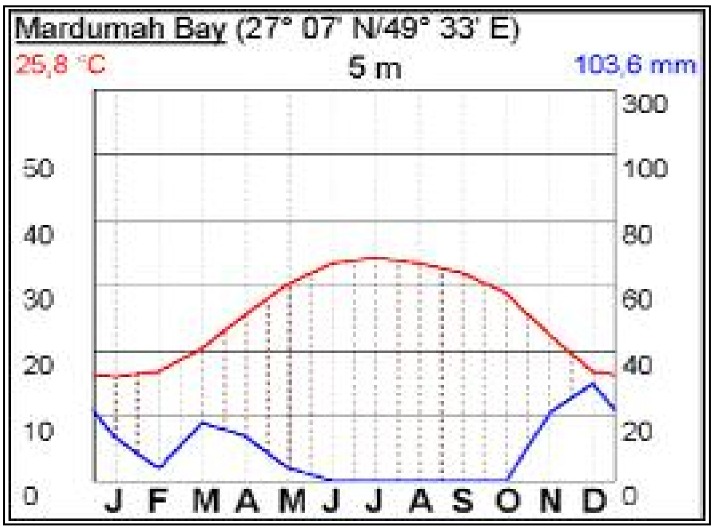

Fig. 3.5 Climatological diagram of the intertidal station Mardumah Bay (data of 4 years).

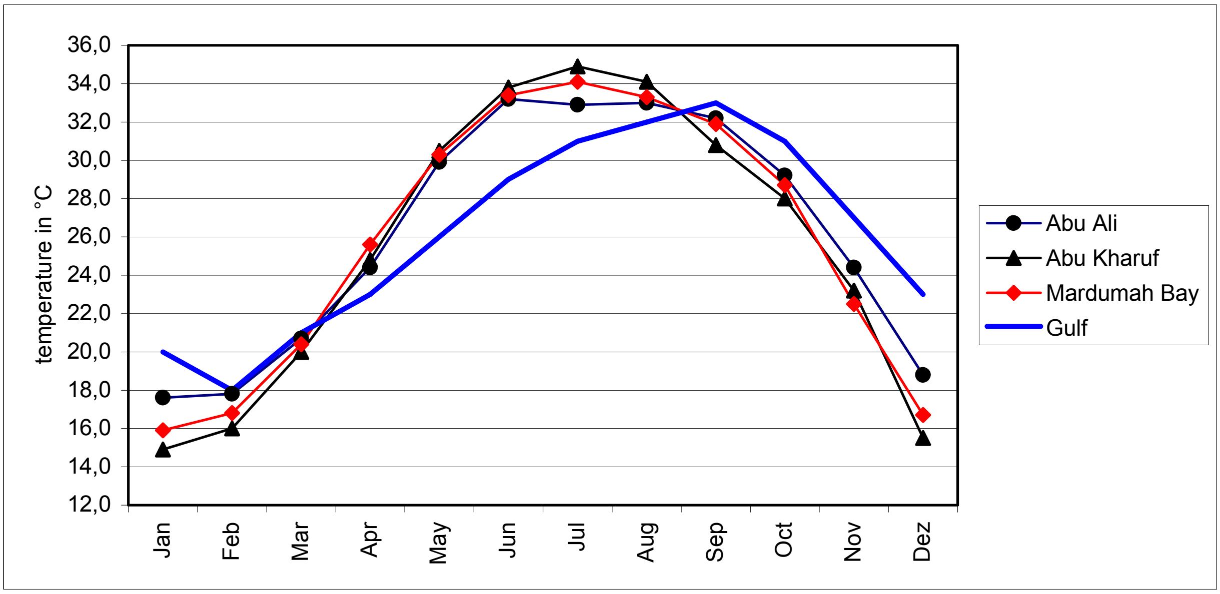

Fig. 3.6 Mean temperatures at the different meteorological stations within the study area. Gulf water temperatures after Hastenrath & Lamb (1979).

The smoothing effect even of the shallow Gulf waters are of major ecological importance to the intertidal fauna and flora. Both live close to the limits regarding the temperatures and salinities. Therefore, absolute summer temperatures more than 5°C lower and winter temperatures more than 6°C higher than in adjacent inland areas are much in the favor of both, plants and animals (fig. 3.7).

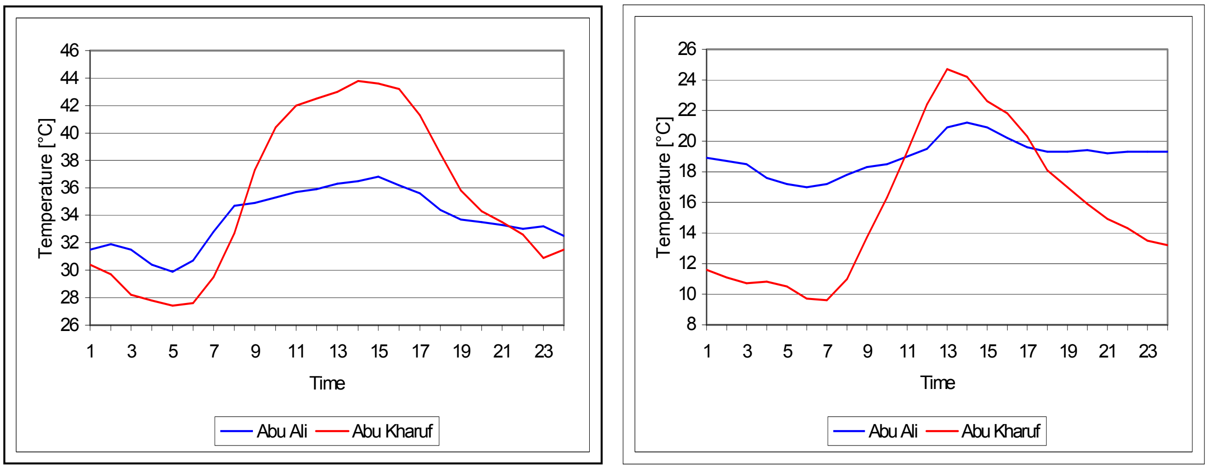

Fig. 3.7 Temperatures of a day in summer (25. August, 1994) and winter (18. January, 2001) at the maritime and coastal station. Note the difference in the amplitude between the coastal and inland station.

Relative humidity

The monthly mean values of the relative humidity vary between 56 and 78% on Abu Ali island and 31.1 and 72.1 at Abu Kharuf. Mardumah Bay again displays intermediate values between 47.5 and 75.6%. The higher values are reached during the winter period. Absolute values range between 13 and 100%. At the intertidal station Mardumah Bay, the relative humidity never drops below 20%. Figure 3.8 demonstrates the intermediate values of the intertidal station compared to Abu Ali and Abu Kharuf. The daily pattern is closely related to the temperature curve. Increasing temperatures decrease the relative humidity (fig. 3.9). During night time the relative humidity often reaches more than 90%, which leads to significant dew precipitation in the coastal region.

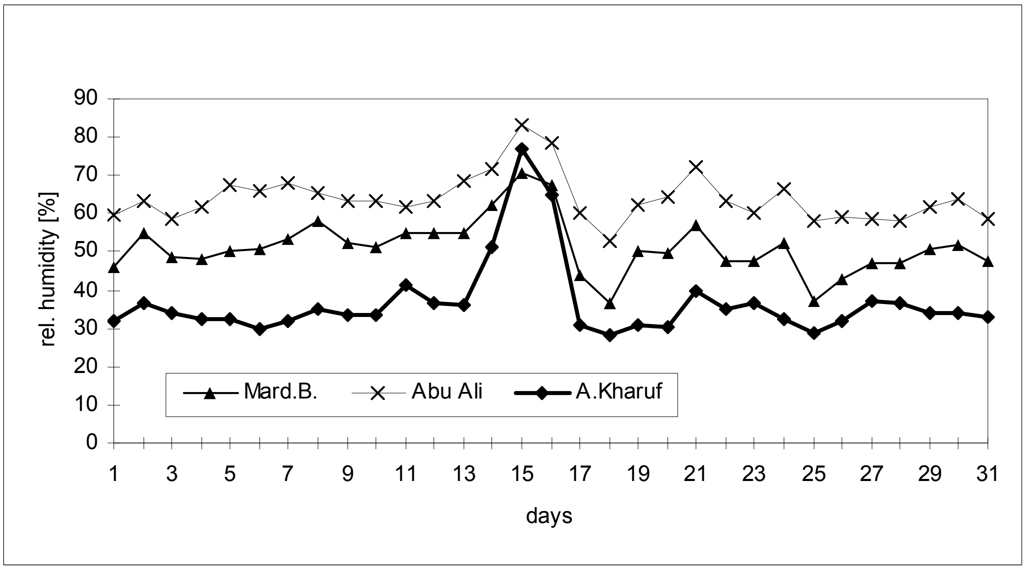

Fig. 3.8 Relative humidity at three stations in August 1994.

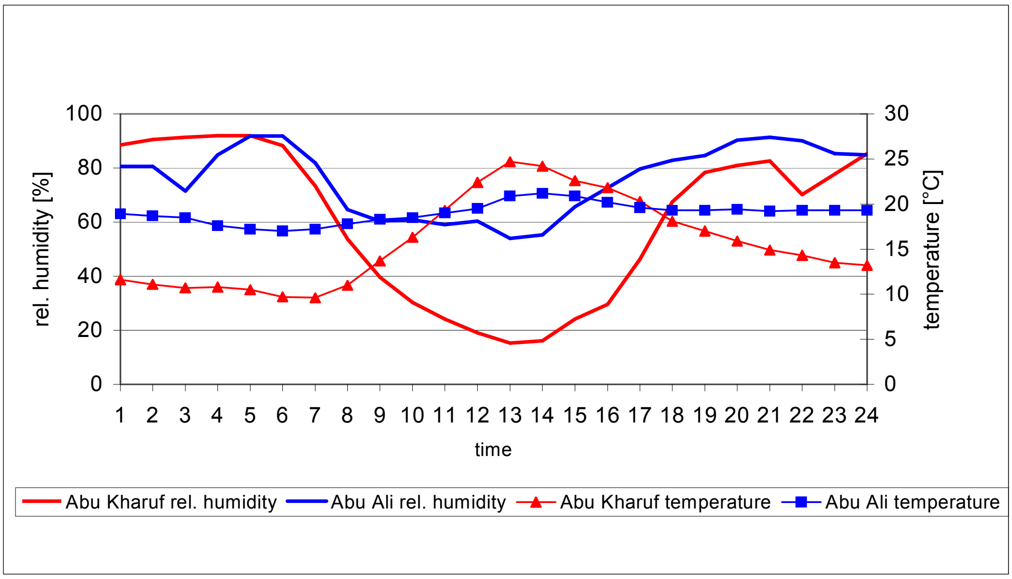

Fig. 3.9 Relative humidity at Abu Ali and Abu Kharuf in January (18.01.2001).

Dew precipitation

Dew is a frequent phenomenon at the coastal areas where it occurs at night with relatively higher values in winter than in summer. Dew measurements during the winter period 2000/2001 close to the intertidal, provided the highest values in January with 0.04 mm per night. November values are 0.021 mm in average. The significant loss of data is due to strong winds and rain events, both of which prevent dew precipitation. The measured total was between 0.27 and 1.1 mm each month (tab. 3.2). This may not seem significant, regarding the total amount of water provided by dew (probably not more than 7-8 mm/year), but the fact that this water is deposited almost every night on top of the plant leaves make it a very important factor in water supply, especially because the high variability of the rain events.

Tab. 3.2 Dew in the winter months between 2000 and 2001 (Jubail, 200m distance to the littoral fringe). The data loss is due to high winds or rain events, when dewfall would be minimal.

month	total	loss of data	mean amount of dew/night
	[mm]	days	[mm]
Nov	0,272	17	0,021
Dez	1,058	4	0,039
Jan	1,107	4	0,041
Feb	0,665	7	0,032
Mar	0,490	12	0,026
Apr	0,629	11	0,033

Precipitation

Precipitation in the Gulf region is confined to the winter months from October to early May. The annual rainfall at Dhahran over 39 years has ranged between extremes of 5 mm and 277 mm (Mandaville 1990). This extreme variability of rain is a typical phenomenon in desert regions. An other characteristic for desert rains is the intensity. Most of the total annual precipitation is delivered in a few torrential rainfalls. This is well documented by the example in figure 3.10. An the 12th of December, more than 50 mm fell at Mardumah Bay station, which is more than 60% of the long term total annual precipitation. Because such intensive rainfall is the result of convective thunderstorms, the rain distribution is very different locally. This is also well demonstrated by the December event on 1994 (fig. 3.10). In addition to the variability of the amount, there is also a strong local variability. Such events were also recorded in 1993 and in 2000 (Steinkohl 2002).

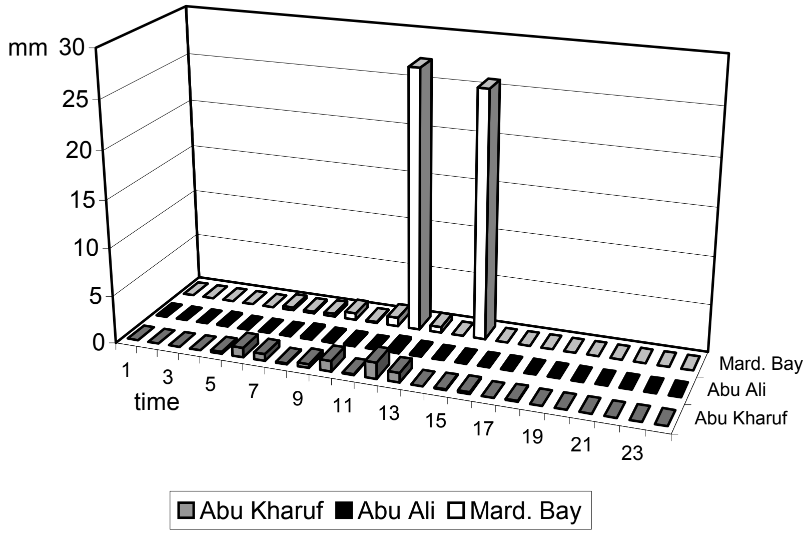

Fig. 3.10 Precipitation on the 11th of December 1994 at the three stations. Note the high local variability.

An other aspect which is very important for plant ecology is the number of precipitation events in a rain season and the timing of these rainfalls. For example at Abu Kharuf, 19 rain events were recorded in the 1993/94 rain season (tab. 3.3). In the following year, there were 44 rain events which allowed a much better development of annual and perennial plants. Success of germination after rain events depends not only on the amount of rain, but rather on the weather in the following days. Hot sunny days increase evaporation and desiccate the upper soil layer, thus, preventing many desert annuals from germination. Cloudy days and one or two other rain events in the following week on the other hand will lead to a flush of germinating annuals within a few weeks.

Tab. 3.3 Precipitation events per rain season at the three stations.

	Abu Kharuf	Abu Ali	Mardumah Bay
1993/1994	19	14	13
1994/1995	44	30	33
2000/2001	25	no data	30

Wind

The mean wind velocities measured in the study area between 3.5 and 6.9 m/sec are typical for the Eastern Province and even low compared to world standards. There is mostly a diurnal pattern with calm winds at night and maximum values during midday or early afternoon (fig. 3.11). At night, cooling creates a stable surface layer. The temperature inversion prevents vertical air exchange. As the sun rises, convection disturbs the inversion, probably supported by gravity waves at the surface of the inversion (Warren & Knott 1983). The unstable atmosphere promotes turbulent vertical air exchange, bringing high velocity upper winds down to the surface often causing gusts. Wind speeds usually continue to increase until the afternoon, driven largely by convection.

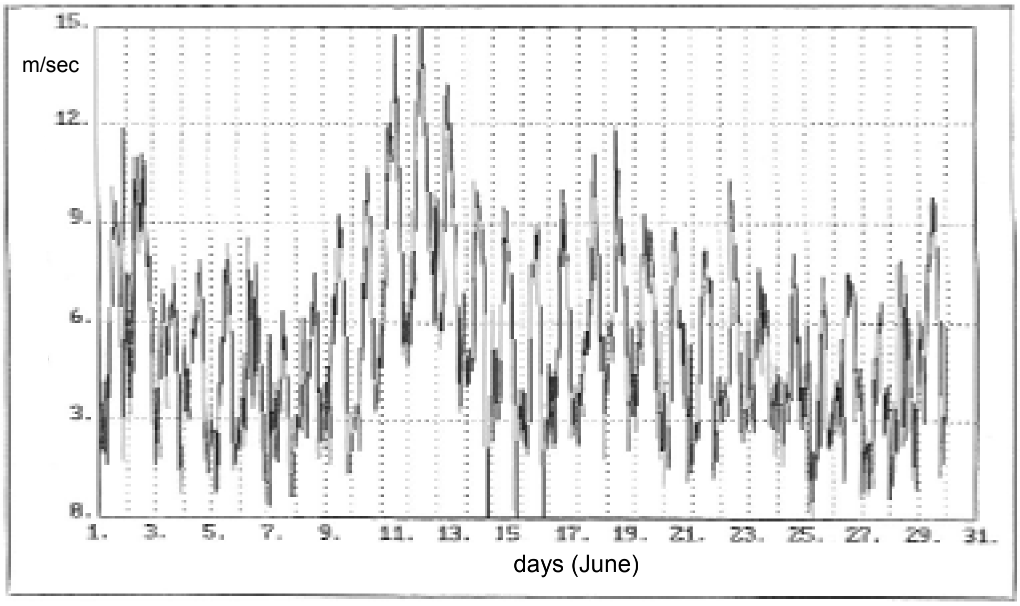

Fig. 3.11 Wind diagram for June 1995 (Abu Kharuf station) (Barth 2001b).

Although the monthly mean values between 3.5 and 5.1 m/sec at Mardumah Bay station (complete data in appendix 1, tab. 4) are low, the wind speeds at midday are frequently above 6 m/sec, which is enough to move sand at sparsely vegetated areas. Gusts reach much higher values often exceeding 12 m/sec. These winds significantly increase the desiccating power of the already dry and hot atmosphere, they have a powerful effect in modelling topography, particularly in dune sands, and directly affect the root stability of individual plants. In the course of one year 6 different wind regimes occur (Barth 2001b). This is: (1) a high energy Mediterranean north-west regime from November to February; (2) a bimodal cyclonic end-phase in March; (3) a moderate eastern spring phase in April; (4) a complex transition phase in May; (5) a high energy summer *Shamal* regime from June to August; (6) a low energy autumn phase in September and October. It is characteristic for the Eastern Province that all the high energy winds (winds above 6 m/sec and thus morphologically relevant - phase 1 and 5) come from north to northwesterly directions creating a wide unimodal wind regime with intermediate energy in the sense of Fryberger & Dean’s (1979) wind classification (fig. 3.12).

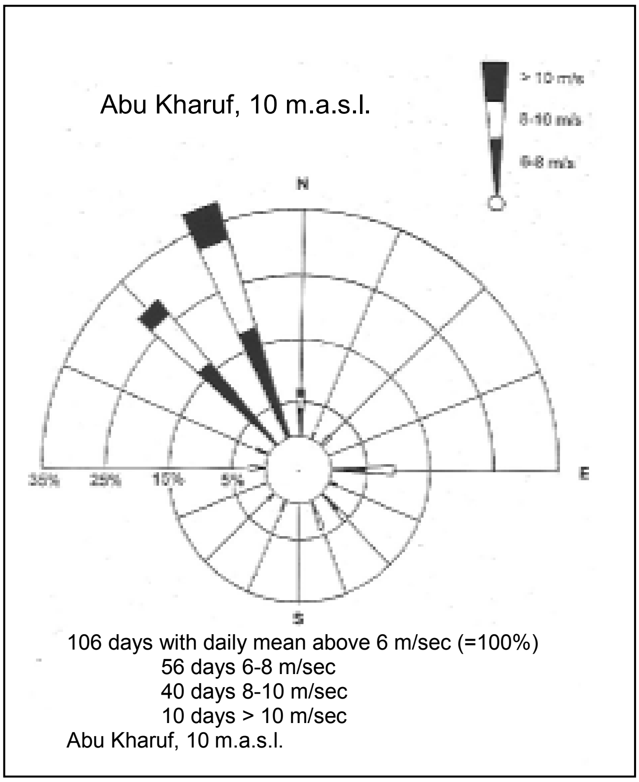

Fig. 3.12 Wind rose for the Abu Kharuf station (after Barth 2000).

Evaporation

High temperatures - especially in summer - , low relative humidity, and permanent wind (during daytime) result in extreme evapotranspiration rates. There is no reliable data available regarding the evapotranspiration in the Gulf region. Mean annual values of class-A pan measurements in Hofuf (50 km inland) are 2660 mm (*Saudi Arabian Ministry of Agriculture and Water Resources* 1980) which is about 42 times the annual precipitation. Towards the south and further inland evaporation increases. Mean values of class-A pan measurements in As Sulayyil at the western edge of the Rub'al Khali desert are 5250 mm (Mandaville 1990). But these values are certainly higher than the potential evapotranspiration, mostly due to the isolation effect of the water filled pan. Most measurement devices do not reflect the real evaporation values. By means of formulas and correction factors, the potential evapotranspiration can be estimated – but only for the climatic conditions that they were designed for. The problems of evaporation and evapotranspiration measurements is treated by several authors (e.g. Haude 1954, Besler 1972, Rosenberg et al. 1973, Henning & Henning 1984, Weischet 1995, DVWK 1996, Barth 1998, Obermüller 2002) and will not be discussed here. Regarding different calculation after Penman, Thornthwaite, Haude and Besler the potential evaporation in the Jubail coastal area is estimated to be between 2200 (Barth 1998) and 3500 mm (Obermüller 2002) per year.

Regarding the intertidal area which is regularly inundated the actual evaporation is near the potential evaporation. The upper intertidal, which is only periodically flooded shows only slightly less evaporation because of the permanent wet soil surface due to capillary force. Obermüller (2002) measured the actual evaporation in coastal sabkhat close to the intertidal north of Jubail. These data indicate an annual evaporation of 3500 mm. Therefore we can assume the same values for the intertidal during the times when the surface is not covered by sea water.

Hydrology

Low annual precipitation rates, high variability in quantity and locality, and high evaporation throughout the year result in a permanent water deficiency. The obvious result is the absence of perennial streams within the Arabian Peninsula. Even the Wadis in the western mountains display only periodical flows. The main water divide of the Arabian Peninsula runs along the highest ridges of the western mountains in north-south direction. The impermeable basement rocks (except some basalt flows) prevent infiltration and any substantial groundwater recharge. The overland flow, especially after torrential rains, is therefore high and has a powerful effect in modelling topography, particularly at the western side of the mountains with frequent knife edge ridges and deep canyons. In contrast to the western impermeable surface there are permeable sediment sequences with the enormous underground aquifers in the cuesta landscape of the Arabian shelf (fig. 3.13). Limestone sequences and some sandstones show excellent transmissibility and water bearing properties. The aquifers are sometimes divided by impermeable silt, clay or marl layers. The most important freshwater aquifer is the Paleocene Umm Er Radhuma formation, basically consisting of pure limestone. The outcropping curve is 50-100 km wide and extends from the Iraqi border to the Rub'al Khali. Because large parts of the outcropping Umm Er Radhuma formation are covered by dunes of the Ad Dhana desert, there is even some water replenishment in this formation. Studies by Dincer (1973) showed a replenishment of 2 mm per year, which would add approximately 30 million cubic metres of water each year only in the area that is covered by the Ad Dhana. The groundwater resources of the Arabian Peninsula can be divided in the underground aquifers (which are by far most important), the reservoirs within the gravels and unconsolidated substrates of the north-eastern part of the Peninsula, the groundwater within the wadi sediments (although their capacity varies with precipitation and size of the catchment area), and the groundwaters below the Tertiary basalt flows (also depending on precipitation). The groundwater of the eastern and central Rub' al Khali is a brine that follows a slight gradient towards the Arabian Gulf in unconfined aquifers close to the surface. Sabkha groundwater exists close to the surface in the coastal lowlands. It is a highly mineralised brine due to excessive evaporation. At the sabkha edges, usually some fresh or brackish water (seeping out of the dunes and sand sheets) occurs on top of the dense sabkha brine. The natural artesian wells in the largest oasis Al Hasa emerges from the Paleocene Umm Er Radhuma formation and the overlying Mio- and Pliocene layers. In the oasis Al Qatif south of Jubail, the groundwater emerges from the Hofuf, Dam and Hadrukh formations. There also seem to be connections between these and the lower Eocene Dammam formation and the Umm Er Radhuma formation. The groundwater of Bahrain, as well as countless submarine wells along the Gulf coast, belong to system of aquifers of Al Hasa and Al Qatif.

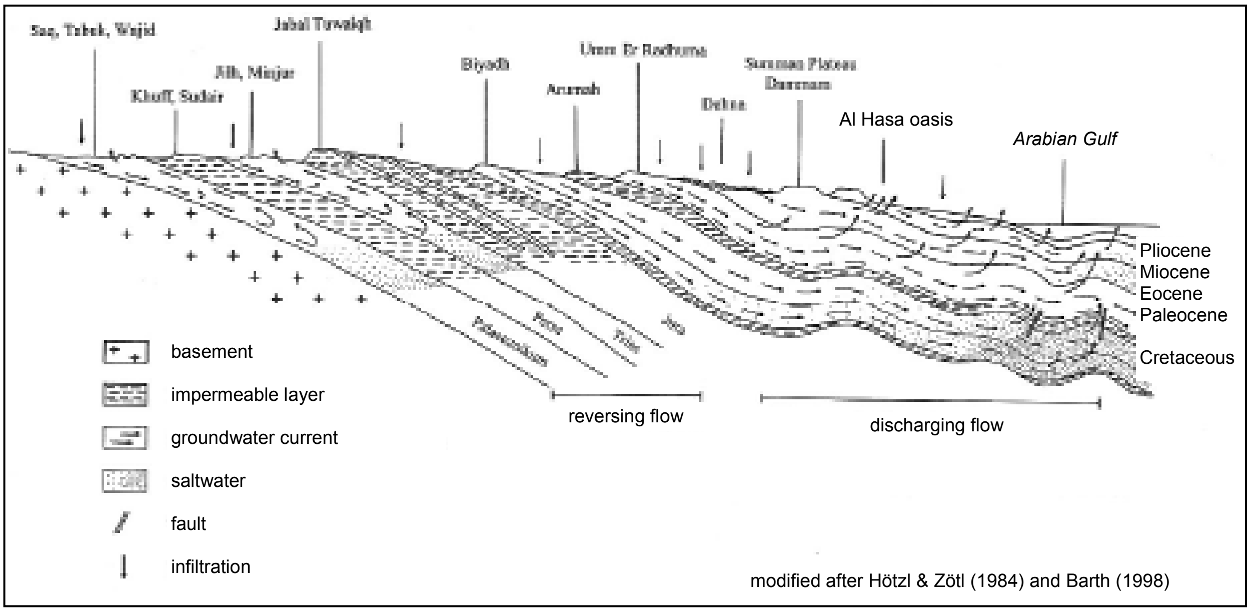

Fig. 3.13 Groundwater aquifers of the Arabian Peninsula.

Vegetation

The vegetation in desert and semi desert environments is basically determined by the availability of water. Where there is no additional surface or underground water input, the ground cover of the vegetation is directly proportional to the amount of precipitation (Klink & Mayer 1983). Therefore the semi desert coastal plains of the Gulf region are characterized rather by large patches of bare sand or rock between the plant individuals than by a dense vegetation cover. The harsh environmental factors - in the coastal and intertidal areas as well as at sabkha edges, salinity provides additional stress – are not only responsible for low ground cover rates but also for a low diversity of plant life.

The flora of the Gulf region mainly comprises thorny shrubs, therophytes, xerophytes, phraetophytes, halophytes, and some hydrophytes in the inundated intertidal ecosystems. Throughout eastern Arabia, summer is the unfavorable season for plant growth, leading to dormancy or the evasion of drought by the production of seeds. Therefore, the growth cycle for most plants begins in the autumn or winter period. Some perennial plants show a resumption of active growth as early as September, well before the arrival of the first rains (Mandaville 1990). This may be associated with the increase in atmospheric humidity which occurs at this season in the coastal areas. The arrival of the first winter rains often leads to a flush of germinating annuals within a few weeks. Along with the germination of annuals comes a resumption of new shoot and leave production by the perennials, many of which died back completely during the summer drought. Geographic areas of growth and reproduction of both annuals and perennials may be extremely patchy when rains come from small local storms (Mandaville 1990). A contrasting pattern is found in the saltbushes of the family Chenopodiaceae. These are in active vegetative growth during the summer period and most of them flower and fruit in October and November. Mandaville (1990) assumes in their pronounced winter die-back an ancestral adaptation to harsh winter conditions in an *Irano-Turanian* homeland to the north.

The floristic classification of the Middle East is strongly influenced by the work of Alexander Eig and Michael Zohary. They divide the Arabian Peninsula into the *Sudanean* region and the *Saharo-Arabian* region (Zohary 1973). Far to the north in Iraq and in the Iranian Zagros mountains there is the border of the *Irano-Turanian* region (fig 3.14). Due to the collection of new floristic data, Mandaville (1984) realigned the border between the Sahar-Arabian and Sudanian region basically on a consideration of the *Acacia*-dominated plant associations of central Arabia.

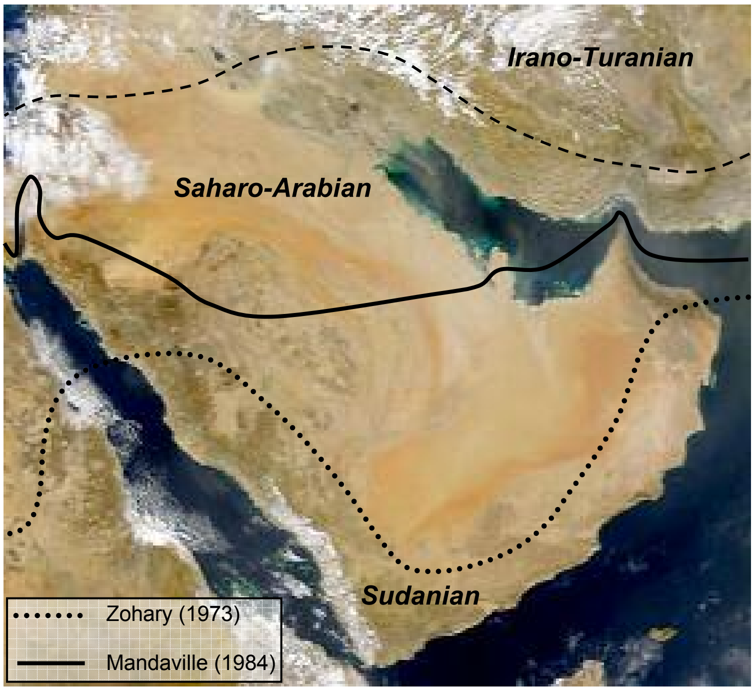

Fig. 3.14 Conventional floristic regions of the Arabian Peninsula and adjacent regions and the new defined boundary by Mandaville (1984). (Satellite image Orb View-2, 3-2-2000 VE Record ID:3240).

The border is additionally marked by the significant decrease of abundance and diversity of annuals - which is typical for the *Saharo-Arabian* deserts – towards the Rub'al Khali in the south. The diversity of desert annuals decreases from about 110 in the central coastal lowlands to less than 20 in the northern Rub' al Khali (Mandaville 1990).

In the study area, a systematic classification of the communities in the sense of Braun-Blanquet (1964) is only of limited use, because the most important desert plant communities (covering thousands of square kilometres of Eastern Arabia) are characterized by woody dominants of a single species. According to the dominant and co-dominant species in the study area, the following vegetation types are classified by Barth (1998):

1. *Calligonum*-type
2. *Panicum*-type
3. *Zygophyllum*-type
4. *Haloxylon/Calligonum*-type
5. *Rhanterium*-type
6. *Leptadenia*-type
7. *Lycium*-type
8. *Phoenix*-type

For the littoral fringe and lower supratidal, several species are important which may all be dominant in one or the other place. But still, most areas are dominated by one or two species comparable to the sandy habitats. There are the following important types of coastal vegetation:

1. *Halopeplis/Zygophyllum*-type (near sabkha edges)
2. *Seidlitzia*-type (especially on the offshore islands)
3. *Suaeda*-type (on coastal sands)
4. *Limoneum*-type (on silty coastal sands)
5. *Salsola*-type
6. *Sporobulus*-type

Within the intertidal four vegetation types occur:

1. *Halocnemum*-type
2. *Arthrocnemum*-type
3. *Avicennia*-type
4. *Salicornia*-type

Besides the availability of water and soil- and groundwater-salinity, the soil type (grain size distribution, mineral contents such as gypsum, calcium carbonate, quartz, and feldspar) determines the presence of certain vegetation types. Böer (1996) published results regarding the interdependences between plant communities and soil characteristics at the Saudi Arabian coast. Additional data was also provided by Barth (1998) for the area north of Jubail.

The Arabian Gulf

The Gulf is a sedimentary basin, about 1000 km long and between 200 and 300 km wide. The average depth is presently 35 m. The sea floor is dipping towards the east. The deepest areas are in front of the Iranian coast, reaching from 60 m to about 100 m at the entrance to the Strait of Hormuz. Thus, the whole Gulf lies within the photic zone. The shoreline at the Arabian side displays a gradual slope with a wide intertidal zone, compared to the steep and narrow shoreline at the Iranian side where the Zagros mountains rise more than 1000 m. As a consequence of the gradual topography and of the favourable environment to carbonate producing biota, the Gulf is a strongly sedimentary province with a dominating soft substrate benthos. Sediments of biogenic carbonates - mostly foraminifera - exist over much of the Gulf floor (Sheppard et al. 1992). Highest carbonate concentrations are to be found in the shallow waters of the western and southern Gulf (fig. 3.15). Within a depositional setting along the southern Gulf coast the offshore bank is progressively extending (Kendall et al. 2002). Terrestrial sediments are limited to the northwest where the waterway of the Shatt al Arab discharges into the Gulf, and the eastern Iranian shoreline where terrestrial fluvial sediments from the Zagros mountains occasionally are accumulated in the nearshore region. Offshore, underlying salt domes have forced upwards numerous islands and banks of hard substrate which are now colonized by corals.

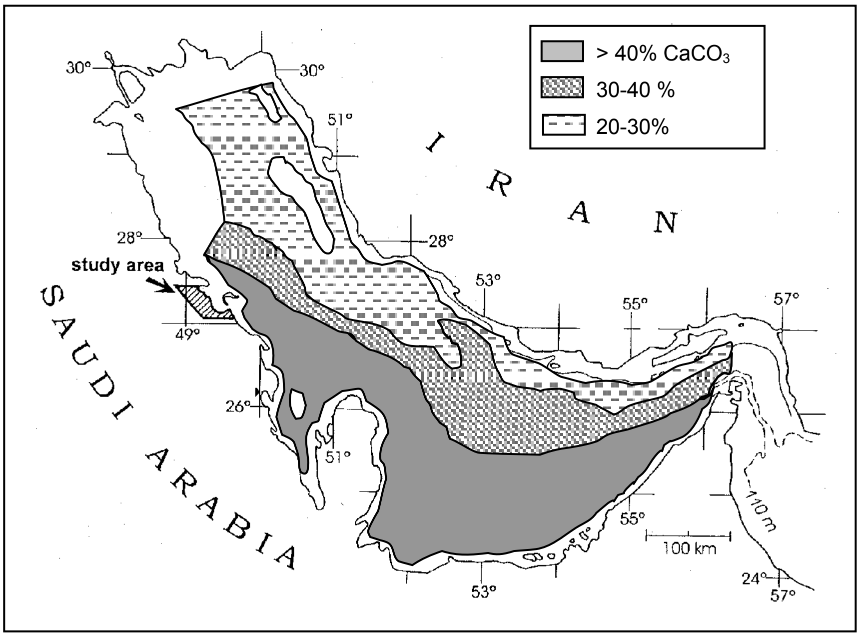

Fig. 3.15 Carbonate content of surface sediments in the Gulf (modified after Sheppard et al. 1992).

Sea level changes

Considerably lower sea levels and even complete evaporation of the Gulf occurred in the Pleistocene. The period between 110 ka BP and 30 ka BP was characterised by considerable sea level fluctuations within the range of 30 and 60 m below present lea level (Sheppard et al. 1992). These sea levels correspond to the depths of major wadis, especially at the Read Sea coast. After 30 ka BP the sea level fell rapidly to a minimum at about 17 ka BP. The values provided by various authors range between 120 and 150 m below present sea level. This implies that the Arabian Gulf was completely dry during that period. At about 15 ka BP global surface temperatures increased, which lead to the Holocene transgression. The rise in sea level commenced about 14 ka BP and proceeded rapidly to near present levels at about 6 ka BP. This transgression was especially pronounced during periods at 12 ka, 11 ka, 9.5 ka, 8.5 ka, and 7 ka BP (Teller et al. 2000, Glennie 1998) (fig. 3.16). The average horizontal transgression between 13 ka and 6 ka must have been 140 m/year, but during periods of intense sea level rise this distance increased to more than 1000 m (Teller et al. 2000). The transgression reached its maximum at about 6 ka BP. At that time the sea level was between 2.5 (Felber et al. 1978) and 3.5 m (Lambeck 1996) above the actual level.

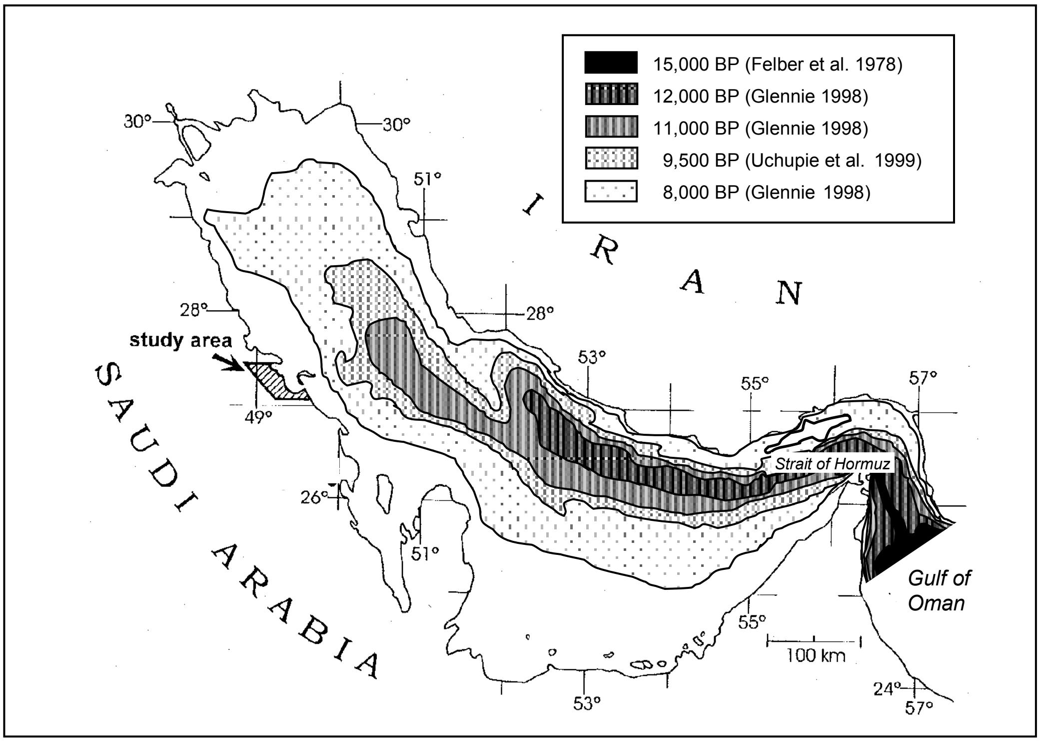

Fig. 3.16 Palaeogeographic map showing the Arabian Gulf during the post-glacial transgression (source: Barth 2001, Uchupi et al. 1999, Glennie 1998, Felber et al. 1978).

About the succeeding development there are different opinions. Felber et al. (1978) and Evans et al. (1969) state that the maximum sea level situation persisted for about 2000 years before regression started gradually. Kassler (1973) and Al-Asfour (1978) assert a considerable regression to 2 meters below the present sea level at 5000 BP and a following transgression back to the 6000 BP-level at 4000 BP. The later development was characterised by alternation of trans- and regression (fig. 2). Evans et al. (1969), Felber (1978), and Hötzl et al. (1984) as well as more recent studies (Alsharhan et al. 1995) promote the idea of a more gradual regression starting at 4000 BP and reaching today’s level at about 1000 BP (fig. 3.17).

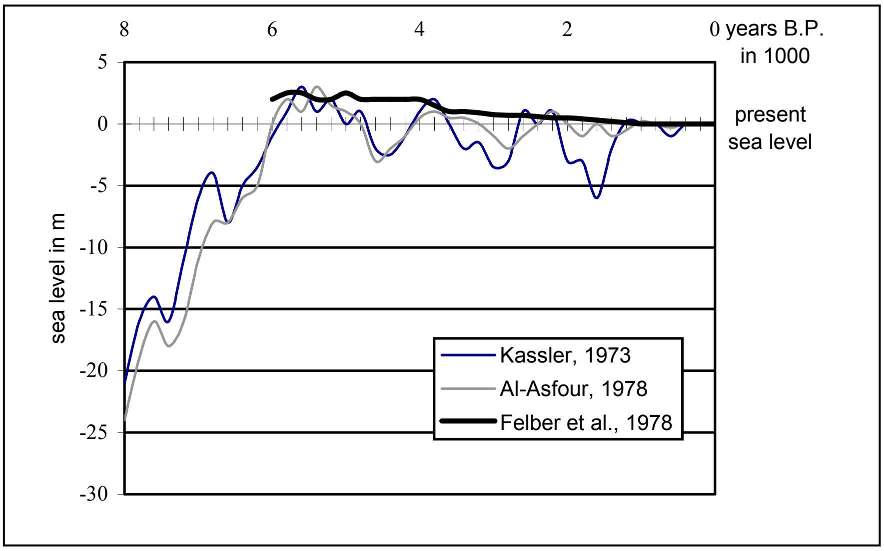

Fig. 3.17 Sea level changes of the Arabian Gulf during the last 8000 years (based on ^{14}C-dates of calcareous shells)(Barth 2001a).

But even later than 1000 BP the coastal geography at the western and southern Gulf coast experienced significant changes. Seaward progradation of carbonate intertidal flats in the UAE amounts up to 7 km during the last 4000 years (Kinsman 1964). Coastal marine sediments, found in a distance of more than 2 km from the present intertidal zone north of Jubail, provided ^{14}C dates (of cyanobacteria) of 700 BP. This implies an average progradation of more than 3 m/year (Barth 2001a). ^{14}C dates of cyanobacteria by Evans et al. (1969) in the Abu Dhabi sabkha indicate an average progradation rate of 1 m/year for the last 1000 years. Evans (2002) points out that the recent cyanobacterial mats lie slightly higher than the remains of older mats further inland. This may be due to local tectonics or some change in coastal morphology and the rate of supply of sediment, but there is also the possibility that it reflects a slight sea level rise (Evans 2002). Studies carried out by Al-Mansi (1992) may indicate a minimal rise of sea level in the Arabian Gulf of 2 to 3.8 cm between Ras Tanura and Saffaniya in the time period from 1980 to 1991.

Hydrographical influences

The marine environment of the Arabian Gulf along the Saudi Arabian shores is a unique ecosystem among the world's oceans. Primary determining factors are its restricted water exchange with the Arabian Sea, its high evaporation and low fresh water input, and its isolation (Hunter 1983).

Salinity and circulation

Fresh water enters the Arabian Gulf through the Strait of Hormuz at 36.5-37 ppt and circulates in a general counter-clockwise direction with northward currents along the Iranian shores and southward currents along the Saudi Arabian shores. With increasing distance from the Strait of Hormuz there is a general decrease in nutrients and increase in salinity because of excess of evaporation over fresh water input. The diluting influence of the Shatt al Arab at the northwest corner of the Gulf is evident throughout the year, but especially in winter when flow is greater (Sheppard et al. 1992). The dense saline water of the western Gulf (now 40 ppt) sinks towards the trough along the Iranian coast and is returned southward in greater depths. It exits the Arabian Gulf via the Strait of Hormuz as a deep water current, providing the driving force for the renewal of the Gulf water. In winter, temperature gradients increase the density flow, since water retained in the south cools more than the inflowing water. The total exchange rate of the Gulf water is estimated from 3-5 years (Sheppard et al. 1992). Going southward along the coast of Saudi Arabia, the salinity increases dramatically south from Al-Khobar where restricted water exchange in the Gulf of Salwah, due to the Peninsula of Qatar, promotes highly saline conditions. Salinities range between 38-42 ppt in the region north of Al-Khobar and 52-59 ppt in the open waters of the Gulf of Salwah (KFUPM/RI 1988). In the embayment system of the study area the sea water salinity in open waters range between 40 and 51 ppt and in coastal flats between 56 and 74 ppt. Tidal channels show salinities up to 78 ppt. Because salinity is a controlling factor for occurrence and abundance of organisms, the waters south of Al-Khobar display a less diverse plant and animal life (Coles & McCain 1989). Studies carried out by the KFUPM/RI (1988) showed, that salinity is the physical variable most highly correlated with changes in plankton abundance. Reef corals and many other major taxonomic groups are not found south of Tarut Bay, and the number of species and individuals of benthic infaunal organisms and zooplankton decrease significantly with increasing salinity (Cole & McCain 1989).

Tidal pattern

In the Arabian Gulf, the tidal pattern is complex and does not correlate with the tides of the Indian Ocean, although they are driven to some extent by the tidal forces propagating through the Strait of Hormuz. In the Gulf there are two amphidromic points where tidal range is zero (and around which tidal waves rotate). One is off the northern Saudi Arabian coast and the second off the UAE coast. The tidal regime in the central part is complex and basically semi diurnal (tidal cycle over 12 hours so that, on successive days, high and low tides occur approximately 1 hour later). However, in some areas of the Gulf there is only one daily, or diurnal, tide (fig. 3.17). Over most of the Gulf away from shore, tidal range is <0.6 m, but it rises to 1-2 m near land (Sheppard et al. 1992). Off Kuwait at the northern tip of the Gulf, spring tidal range reaches 2 m in the south and 4 m in the north (Jones 1986). Because of the barrier effect from a shallow reef complex between Qatar and Bahrain, the water in the Gulf of Salwah is more restricted than the width of its entrance suggests. Tidal ranges, which are about 1.2 m at the northern shores of Bahrain, are reduced to 0.5 m in the south of the Gulf of Salwah and its phase lags considerably (Sheppard et al. 1992).

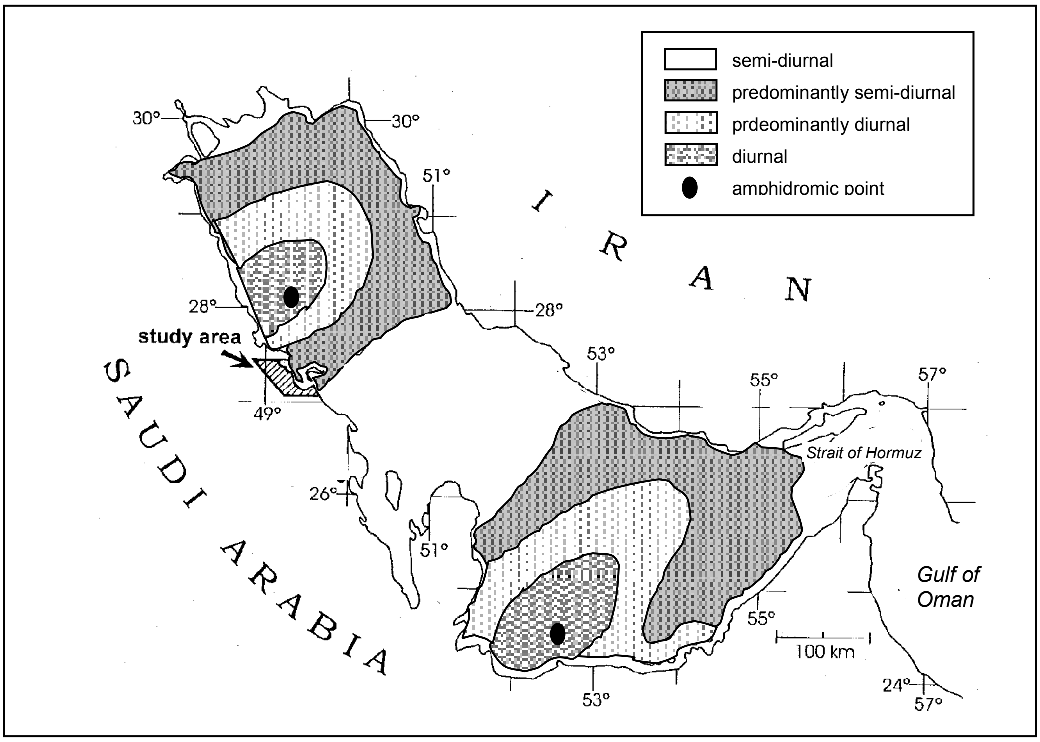

Fig. 3.17 Tides in the Arabian Gulf. Note the two amphidromic points around which the tidal wave rotates and where tidal amplitude is zero (data: Jones 1986).

In the study area the tides proceed from a mixed mainly semi-diurnal regime to a mixed mainly diurnal regime north of the study area (fig. 3.17). Thus, the study area is located at the northernmost limit of the effects emanating from the semi-diurnal amphidromic point situated at Abu Sa’fah (Jones et al. 1996). Mean spring tide range is approximately 1.5 m, whilst the neap tidal range is of about 0.8 m (Jones et al. 1994). Although the semi-diurnal pattern dominates, tides tend towards a mixed pattern during the spring tide period, with only one well defined high and low water cycle. It becomes more semi-diurnal with two well defined high and low water peaks towards the neap tide period. To some degree the diurnal pattern ameliorates the harsh environmental conditions for shallow and intertidal biota. In summer, high tides cover large parts of the intertidal zone during daytime when temperatures are extreme (above 45°C). In winter, when temperatures drop below 6°C, the high tide occurs at night (Jones et al. 1994). These conditions differ largely from the coast of central Saudi Arabia, Bahrain and Qatar where low tides commonly expose the gradually sloping intertidal region during daytime in summer. This results in significant differences regarding species diversity and abundance of intertidal biota.

Generally, the high tides in the study area are significantly higher in summer than in winter (fig. 3.18) (RCJY 1992). Additional changes in tidal levels are caused by the influence of wind. Strong onshore winds in shallow nearshore areas may push tidal waters up to 50 cm higher than normal. That is what happened several times in spring 1991 when exceptional high tides pushed the oil slick far into the upper intertidal zone until it reached the littoral fringe.

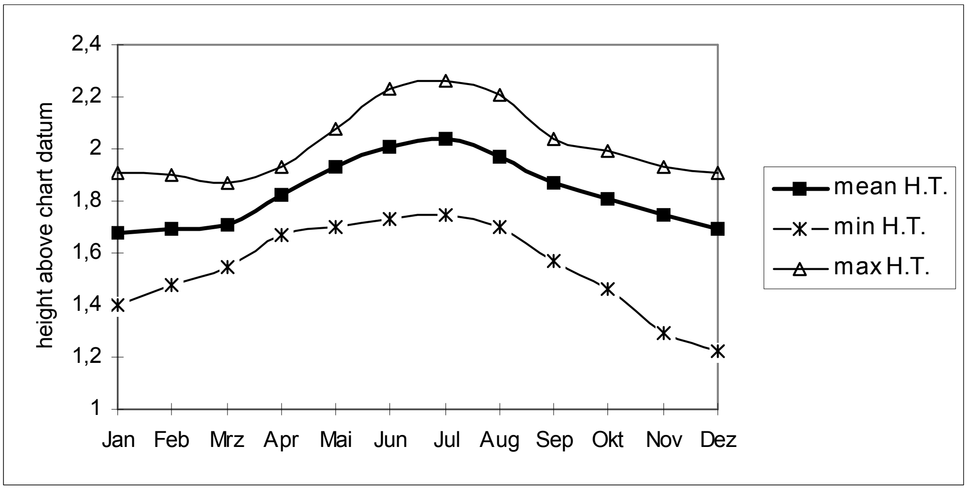

Fig. 3.18 Average height of high tides within the study area (data: RCJY 1992).

Temperature

The high temperature amplitudes are another controlling factor regarding the distribution of fauna and flora in the Arabian Gulf. Particularly at nearshore areas, where annual fluctuations of temperature exceed 20°C (16-36°C; compared to 17-34°C in open Gulf waters) (KFUPM/RI 1988), marine communities must withstand environmental conditions typical for tropical as well as for temperate regions. Thus, the species diversity is low. However, in shallow inshore areas with restricted circulation like Dawhat ad-Dafi, summer water temperatures can exceed 36°C and winter values may fall below 15°C (Jones et al. 1994). There is a general gradient from the northern towards the southern Gulf (fig. 3.19). The gradient is highest in winter when the difference between the open Gulf waters of Kuwait and the UAE is 8°C (fig. 3.19, January situation). Towards summer this gradient decreases to less than 2°C. In October, when the lower temperatures in the north are reflected in the sea surface temperature, the gradient increases again.

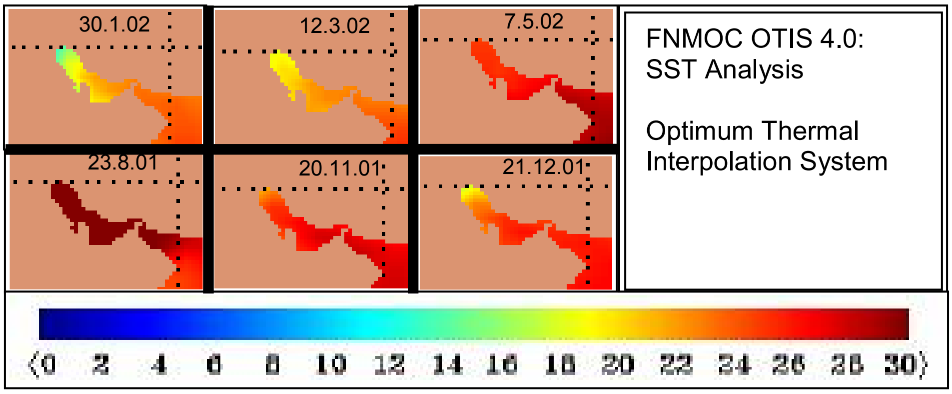

Fig. 3.19 Sea surface temperatures of the Arabian-Persian Gulf (source: FNMOC OTIS http://152.80.49.210/PUBLIC/).

Chemistry

The chemical environment in the Arabian Gulf is characterized by relatively low concentrations of nutrients (compared to other oceans), utilized in primary production by marine algae and higher plants. Because there is evidence of nutrient limitation, the true pelagic productivity in the Gulf is reduced. Thus, the Gulf can be considered to be one of the most productive bodies of water in the world regarding benthic production (Sheppard et al. 1992). In general, the concentrations of nutrients correlate negatively with the salinity. Phosphate, one of the most important nutrients, decreases rapidly south of Al-Khobar and with proximity to the shoreline (Cole & McCain 1989, fig. 3.20). This suggests rapid utilisation of phosphate and that it may be limiting to primary production. Silicate though - important as a structural component of phytoplanctonic diatoms and silicio-flagellates- generally shows high concentrations in the Gulf and significantly increasing values at the southern Saudi Arabian shores (fig. 3.21). According to Cole & McCain (1989), ammonia, turbidity, and suspended solids follow a similar pattern like silicate with values increasing with proximity to the shoreline and into the Gulf of Salwah. Nitrate and nitrite concentrations show no clear spatial distribution.

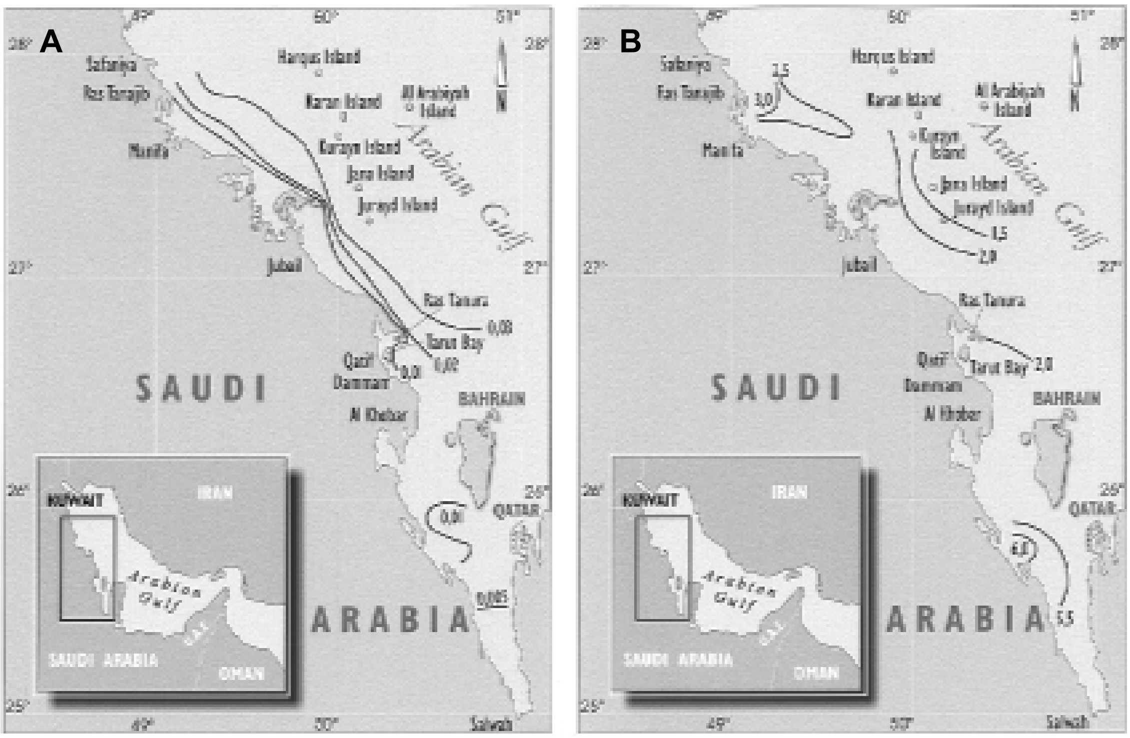

Fig. 3.20 A: Concentrations of anorganic phosphate in µg/l (source: KFUPM/RI 1988). B: Concentrations of silicate in µg/l (source: KFUPM/RI 1988).

Petroleum hydrocarbon pollution of the Arabian Gulf

The Arabian Gulf is the most affected sea in the world regarding hydrocarbon pollution (Cole & McCain 1989). The total annual oil spillage was estimated to range between 100,000 and 150,000 tonnes under normal circumstances prior to the first Gulf War (Golum & Brus 1980). The amount of spilled oil was certainly higher during hostile activities in the war. The largest war related event was the Nowruz oil spill in 1983. The estimated average post war oil pollution is between 150,000 tonnes (Krupp et al. 1996) and 160,000 tonnes per year (Höpner 1991).

The general pattern and level of petroleum hydrocarbon contamination in the Gulf water and sediments were subject of continuing investigations of the KFUPM-Research Institute for more than 10 years. The results are summarized in fig. 3.21. The highest hydrocarbon concentration in the seawater as well as in the sediments are concentrated around Ras Tanura and Ras Tanajib between Safaniya an Manifa (KFUPM/RI 1988). These are the major oil loading terminals and the principal producing oil field. Because of the high biodegradation potential (see chapter 5.1.2) of the Arabian Gulf, these values are not critical. Compared to other oil contaminated areas elsewhere in the world, where sediment concentrations have been reported as high as 6000 (Cole & McCain 1989), the Saudi Arabian values are low.

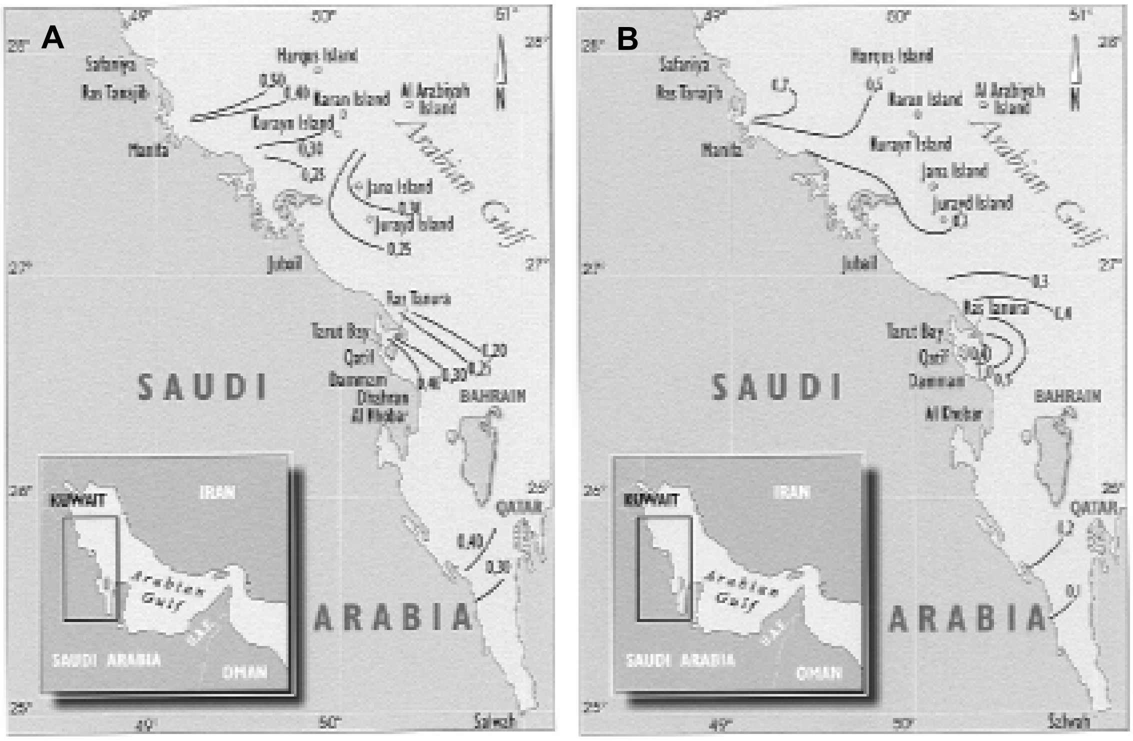

Fig. 3.21 A: Concentrations of petroleum hydrocarbons (ppb) in the Gulf water. B: Concentration of petroleum hydrocarbons in sediments (ppm) (source: KFUPM/RI 1988).

Due to the environmental factors in the Arabian Gulf (high evaporation and temperatures), volatile compounds in spilled oil are rapidly volatilised (see chapter 5.1.2). The residues are often tar balls drifting in the water or sinking to the bottom. Drifting tar is finally settled at the shoreline. Such beach tar accumulations reached up to 28.8 kg/m of beach front along the Saudi Arabian coast (KFUPM/RI 1988, Price 1987). Within the study area the highest concentrations are to be found on Abu Ali Island, where tar ball accumulation reach up to 8 kg/m and at sites where areas are covered by a closed tar layer (see chapter 6.4.1.2) more than 40 kg/m.

Ecosystem types

The main coastal ecosystem types are differentiated on the dominant substrate and vegetation type (see chapter 1.1.1). The coastal wetlands include salt marshes, mangroves, sabkha, sandy, and rocky beaches. Generally the muddy shores at the Saudi Arabian Gulf coast have a highly abundant intertidal community. Abundances of organisms larger than 0.2 mm in size reach up to 600,000 individuals per square metre, substantially greater than values previously reported for various areas elsewhere in the world (Cole & McCain 1989). Species diversity though are within the average of the range of world values. Abundance and diversity are controlled by the tidal level, salinity, and petroleum hydrocarbon concentration of the sediment substratum as well as the sediment characteristics. Generally, the greatest diversity and abundance occurs in the lower eulittoral of muddy shores (Jones et al. 1994). Elevated salinity favours the increase in a restricted number of salt tolerant species, resulting in a significantly lower species diversity with still high abundances (Cole & McCain 1989). The diversity of fauna generally decreases with the depth (Basson et al. 1981). This reflects a shortage of oxygen in the sediment, which is also displayed in a greyish or black colour of the substrate due to free sulphides. It results from the action of bacteria on organic matter in the absence of oxygen and indicates the presence of excess organic matter in the sediment as well as anaerobic conditions (Basson et al. 1981). This grey layer may occur between 1 cm (e.g. in tidal channels or pools) and 30 cm (e.g. within sandy substrate) below the sediment surface. The tidal flats which can be muddy, sandy, rocky, or mixed forms are the dominant intertidal environment along the Saudi Arabian Gulf coast. In terms of area Basson et al. (1981) estimate the extent of the Saudi Arabian tidal flats between 500 and 1000 km². In contrast the narrow strip of intertidal along the exposed sand and rock beaches is minimal.

Salt marshes

The salt marshes and adjacent muddy tidal flats are the most important type of intertidal environment along the Saudi Arabian Gulf coast. Salt marshes occur in bays and other sheltered locations where wave energy is low. Thus, the substrate mostly consists of mud or very fine sand. Due to the high productivity of the mudflats, excess organic matter is accumulated and trapped in the sediment. Degradation by bacteria provides an energy source for burrowing animals, especially meiofauna. Due to the slow oxygen flow into the interstitial spaces of the fine grained substrate, the organic matter can only partly be oxidized. This leads to a mostly anaerobic environment only a few centimetres below the surface, which is characterized by free sulphides – obvious because of the rotten egg smell of hydrogen sulphide.

Tidal mudflats are mostly characterized by a series of well defined zones, each occupied by a different community of organisms. Typical for salt marshes is the presence of halophytic plants in the upper eulittoral zone and additionally some flowering herbs and grasses, fringing the coast above the littoral fringe. Such salt marsh halophytes are prevalent along the Gulf coast and often forms the only coastal vegetation. Members of the Zygophyllaceae and Chenopodiaceae are the dominant salt marsh families. The typical vegetation zones (fig. 3.22) - controlled by tidal inundation, soil and groundwater salinity - are the cyanobacteria zone, the *Salicornia* zone, *Arthrocnemum* zone, *Halocnemum* zone, and landward of the littoral fringe follows the *Limonium – Suaeda – Seidlitzia – Halopeplis* zone.

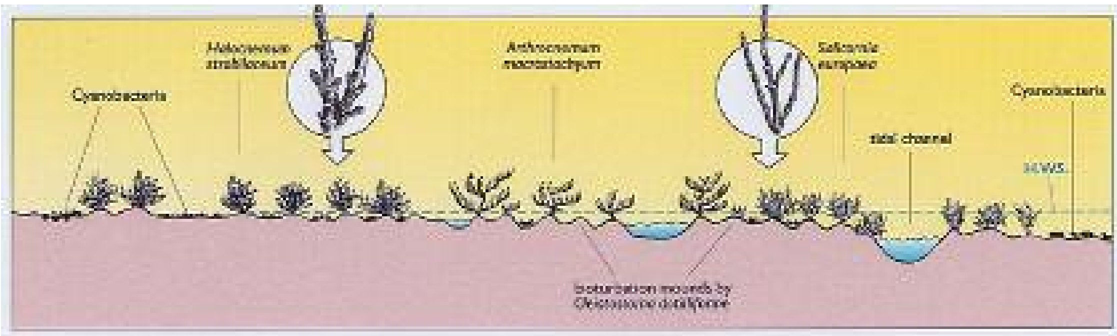

Fig. 3.22 Schematic profile of a salt marsh at the Gulf coast.

The most common invertebrates along the Saudi Arabian salt marshes include the crab *Cleistostoma dotilliforme* dominant in the upper eulittoral. This crab excavates burrows in the mud (up to 50 cm deep), and piles up the excavated material around the entrance, thus forming a distinctive mound or turret. These burrows occur at high densities of up to 40/m². An other crab that occurs virtually in all intertidal zones, *Metopograbsus messor,* is less abundant, does not build burrows, but seeks shelter in open burrows of other crabs. Cyanobacteria is distributed almost everywhere below the high water spring line, where bioturbation by crabs is limited. In tidal pools the oxygen concentration was significantly increased, due to the photosynthesis in the cyanobacterial mat (Basson et al. 1981). A variety of microscopic animals inhabit the cyanobacterial mats including gastropods, ostracods, nematodes, flatworms, copepods, and oligochaete worms. Larger animal life is usually absent where cyanobacterial mats are well established. Normal populations of the crab *Macrophthalmus depressus* and gastropods such as *Cerithium scabridum* and *Pirinella conica* keep the substrate constantly bioturbated and the mud surface churned up, preventing the cyanobacteria from forming a mat. Where a mat is established, crabs may have difficulties in tunnelling there and fail to become established. In the lower mid eulittoral and lower eulittoral zone, usually a zone of wet liquid mud is prominent. The upper portion of this region is occupied by a community dominated by several species of burrowing deposit feeding crabs. The most abundant of these is *Macrophthalmus depressus*. Densities may exceed 50 adults/m² (Basson et al. 1981). The lower eulittoral is dominated by the gastropod *Cerithidea cingulata* which may reach abundances of more than 2000/m². Salt marshes can be found almost continuously along the Saudi Arabian coast (MEPA 1992). During the MEPA survey (1992) salt marshes were recorded at 72% of the shores. However, the MEPA data is not sufficient to determine the precise linear extent along the Saudi Arabian coast, but certainly it is the most prominent ecosystem type at the western Gulf shores.

Mangroves

Mangroves, which are represented by a single species, *Avicennia marina*, are salt tolerant trees found from the mean high tide level down to the mid eulittoral. Often they occur in association with salt marsh halophytes, mainly *Arthrocnemum macrostachyum* and *Salicornia europaea*. The mangroves in the Gulf are poorly developed compared to their counterpart at the Red Sea because of the cold winter temperatures. They provide food and shelter to many small invertebrates, including commercially important shrimp and act as a nursery for many species of young fish. The mangrove stands occur only patchy at sheltered sites on waterlogged, soft anaerobic mud. The mangrove roots are only able to survive by means of pneumatophores which project above the ground and conduct oxygen to the buried portions of the root system. The species assemblages supported by mangroves are not very different from those of intertidal mudflats in salt marsh ecosystems (fig. 3.23). Nevertheless, they are treated as a separate ecosystem type, since the mangrove trees form a biotope that is very distinctive with special local cultural and ecological value.

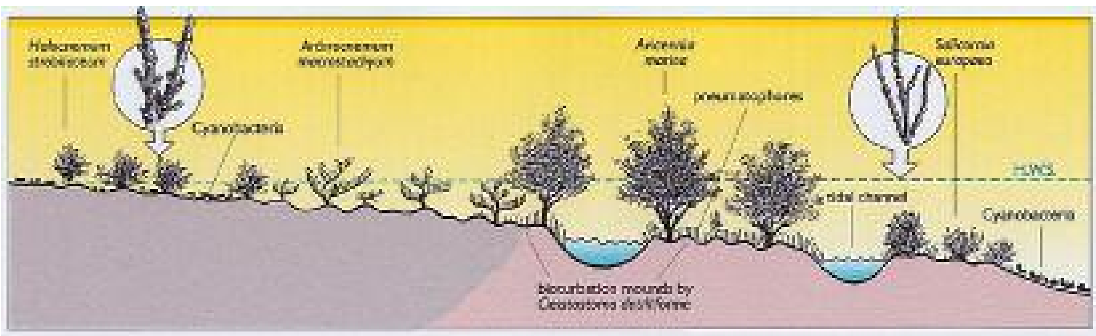

Fig. 3.23 Schematic profile of a mangrove habitat at the Gulf coast.

The most conspicuous invertebrates are again crabs whose burrows form a characteristic feature around mangroves and intertidal flats. Other common invertebrates associated with mangroves include barnacles (e.g. *Balanus* and *Euraphia*) on pneumatophores, various gastropods (*Cerithidae cingulata* and *Pirinella conica*), hermit crabs, and bivalves. Mangroves are of limited occurrence and can be only found on restricted small stands. The most northerly occurrence is within the study area north of Jubail. These stands belong to the most northern mangrove occurrences in the world. There is only one site at the Egypt Red Sea coast which is still further to the north. The southerly limit at the Saudi Arabian coast is just to the west of Dammam port (MEPA 1992). But there are also extensive mangroves stands in the UAE (e.g. Abu Dhabi Emirate). According to MEPA (1992), the linear extent of the mangroves is 12 km of the Saudi Arabian Gulf coastline, but this possibly is underestimated, because in the Dawhat ad-Dafi area there are already 6 km of coastline with mangrove stands.

Sabkha shores

Sabkha shores occur adjacent to sabkhat (low, evaporitic supratidal flats) without higher vegetation. High salt concentrations render the habitat unsuitable for growth of halophyte plants. Since coastal sabkhat are a common geomorphological feature along the Saudi Arabian Gulf coast, there are frequently intertidal areas which turn into sabkha on their landward side. Such intertidal areas are composed either of sandy or muddy substrate. They are not significantly different compared to the intertidal zone at sandy shores or salt marshes. The MEPA study (1992) found sabkha shores at 19% of the sites investigated.

Sandy shores

Sand beaches begin in the supratidal zone which is composed of beach dunes mostly vegetated by Halophytes such as *Suaeda maritima* or *Seidlitzia rosmarinus* and the beachgrass *Halophyrum mucronatum*. At higher energy sand shores, the ocypodid ghost crab, *Ocypode rodundata*, occurs frequently near the littoral fringe. It is especially conspicuous because of the large (up to 30 cm high) conical towers built by male crabs in the breeding season (mainly in spring) (photo 3.1A). Lower down the beach in the eulittoral, there are few signs of visible life. But beneath the sand, over 200 species of macroscopic animals have been recorded. On mixed sand-rock or sand-mudflats this number was even higher. Marine snails are the dominant group with 48 recorded species (Basson et al. 1981). Secondary with more than 20 species there are pelecypods (clams and cockles), polychaete worms, peracaridans (isopods and amphipods such as sandhoppers), and decapod Crustacea. Sand flats are prevalent in areas where wave or tidal energies are higher than those associated with mudflats. Outcrops of rock -mainly beachrock- may sometimes be found in the vicinity of sand flats. The small deposit-feeding crab, *Scopimera crabicauda*, particularly its burrows (often greater than 100/m² with typical feeding trench and piles of sand pellets – photo 3.1.B), is a conspicuous feature on the sand flats (MEPA 1992). Gastropods commonly found on sand flats include: *Cerithium scabridum, Cerithidea cingulata, Mitrella blanda,* and *Nassarius plicatus*. Other important invertebrates are polychaetae that occur beneath the intertidal sand. The lower tidal level is characterised by polychaetes and shells. Encrusting mats by cyanobacteria and diatoms are generally not well developed on sand flats. Sandy shores are very common along the Saudi Arabian Gulf coast. The linear extend is not known because it is hard to distinguish sand-mud and sand-rock flats without close inspection.

Photo 3.1 A: conical tower of the crab *Ocypode rodundata*. B: feeding trench and piles of sand pellets of the crab *Scopimera crabicauda*.

Rocky shores

This shore type consists principally of flat beachrock in sheets, often with a thin veneer (1-10 cm) of sand or sandy mud. On the landward side there may be a narrow sand beach or rock platforms building small cliffs between a few centimetres until nearly 20 m. The rocky shores in Saudi Arabia are not as productive as the other ecosystem types. The main reason is the heat and desiccation during low tide in summer which limits the growth of algae. Therefore the fauna is limited to animals which inhabit crevices, rock pools, holes, and the underside of boulders, or else are mobile forms capable of retreating to suitable shelter when tide is low (Basson et al. 1981). Permanently attached, sessile animals such as the barnacles (e.g. *Euraphia sp*., *Balanus amphitrite*), tube dwelling serpulid polychaetes (e.g. *Pomatoleios kraussii*) and bivalves (e.g. *Isogomon legumen, Brachidontes sp*.) mostly are plankton feeders and occur along the Saudi Arabian rocky shores, usually in crevices and on the underside of pieces of rock. They are either cemented to the rock, attached by a bundle of threads, or they live wedged into crevices in the rock. Some mussels even bore into the rock (e.g. *Lithophaga*). Tube worms and barnacles are usually found in dense clusters covering large parts of the rock where conditions are favourable. In contrast to the sessile forms are vagile animals, able to move about freely on the rock surface. The most important group in this category are the gastropods or snails (Basson et al. 1981). A majority of them are herbivorous and graze on algae and cyanobacteria. The dark or black colour, typical for intertidal rocks along the Gulf coast, is mostly due to the presence of cyanobacteria. Important grazing gastropods are *Nodolittorina subnodosa, Planaxis sulcatus, Cerithium scabridum, Mitrella blanda,* and the top shell *Trochus erythraeus*. A few common snails are carnivorous like *Thais sp*., feeding on sessile animals. Crabs are also an important group at rocky shores. The ubiquitous *Metopograpsus messor* is mostly herbivorous. Others such as *Thalamita admente* are predatory. Because rock beaches are highly stressed environments the structure and behaviour of their inhabitants are merked by traits enabling them to avoid or withstand the adverse conditions. Compared to other coastal biotopes, the exposed beaches are poor in both quantity and diversity of life (Basson et al. 1981). The linear extend of rock flats along the Saudi Arabian shores is about 240 km (MEPA 1992).