Lagoon Sediments of the Eastern Red Sea: Distribution Processes, Pathways and Patterns

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Abstract

The sedimentary characteristics of the lagoons along the Red Sea coast of Saudi Arabia are governed by the potential of the wadis (seasonal streams) to transport sediment, while the sediment distribution is influenced by the water current patterns that are mostly generated by the wind. Human interference and anthropogenic input are the two main issues that change the dynamics and morphology of the lagoons. The absence of permanent fluvial systems keeps the water transparent and helps coral growth, while the exchange of water between the lagoons and the Red Sea is restricted and leads to pollution in the lagoons. The sediment yield varies from north to south depending on the amounts of rainfall. The sediment veneer in the southern half of the Red Sea is mostly terrigenous because of relatively higher input from the wadis, whereas in the northern half where rainfall is low, the numerous wadis contribute terrigenous material in varying amounts. The central part is mainly devoid of terrigenous input where anthropogenic input prevails. The lagoons are mainly blanketed by carbonate of biogenic origin, and therefore the associated Red Sea environment is regarded as a carbonate-rich environment. Some wadis that drain directly into the Red Sea or into the lagoons are either dumping sites or are used as farm land, and lagoons close to major cities are being reclaimed and used as resorts. Although the coastal belt is still somewhat pristine, the health of the marine environment may deteriorate with excessive human interference and irresponsible actions.

Introduction

There are over twenty lagoons along the 1,800 km stretch of the Red Sea coast of Saudi Arabia. These lagoons, often referred to as *sharms, khors or khawrs*, are generally considered to be channels formed by erosion in the Late Pleistocene that were drowned by the post-glacial rise in sea level (Brown et al. 1989). Wadis (seasonal streams) directly drained these lagoons during the last glacial period when the sea level was lower by at least 140 m. An alternative view, proposed by Rabaa (1980), is that the lagoons are remnants of collapse features formed during post-warming (post-glacial?) emergence by selective dissolution of Miocene evaporite beds underlying the younger succession.

The lagoons are elongated, generally shallow and most have gently sloping shorelines and are connected to the Red Sea by a single or multiple channels with steeply dipping flanks. The channels were formed either naturally or are man-made, cutting through a series of barrier islands and reefs (barrier reef system) running parallel to the shoreline (Morley 1975) or raised coral reef terraces of Pleistocene age. However, some lagoons, especially in the northern Red Sea, have almost vertical slopes (reef walls) at the mouth down to 30 m depth composed entirely of coral beds.

The lagoons range in length from a few kilometres to over 20 km with depths ranging from a few metres to over 30 m (Fig. 1). The size and shape of lagoons and associated channels are dependent on the current velocity, wave energy and tidal range. Tides are of primary importance because they provide a periodic exchange of water through channels

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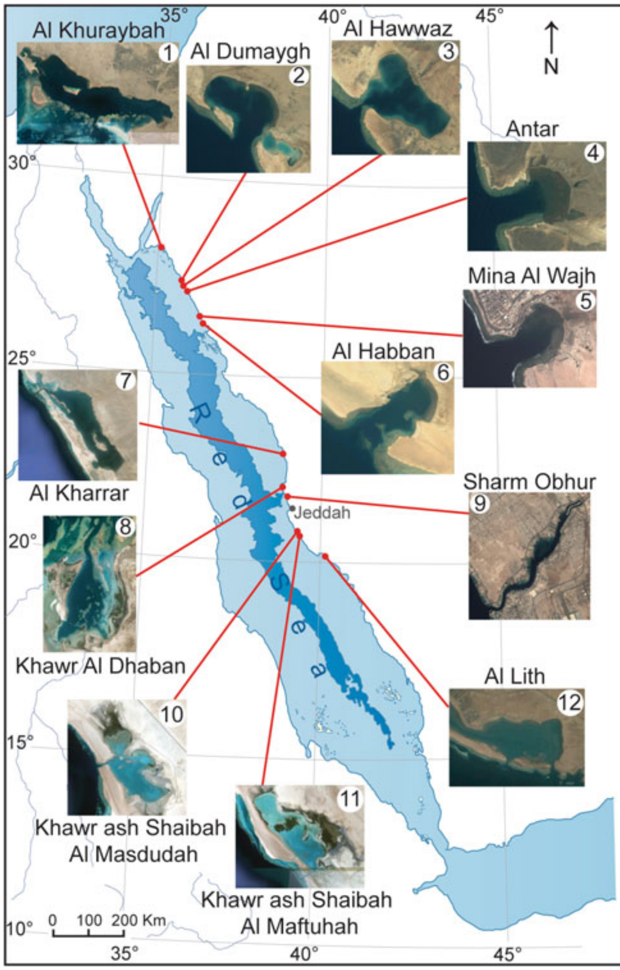

	Lagoon	Max. length (km)	Max. width (km)	Area (km²)	Entrance width (m)	Max. depth (m)
1		23.34	4.59	100	16; 36	25
2		1.57	0.71	0.70	25	33
3		1.26	0.65	0.70	2	22
4		0.81	0.40	0.35	24	15
5		0.73	0.43	0.33	28	22
6		1.26	0.50	0.72	42	14
7		18.00	4.86	71.44	150	14
8		6.59	3.58	13.17	37	12
9		11.00	1.20	5.60	250	35
10		4.70	2.46	7.85	14	45
11		8.05	2.70	15.87	9	3
12		6.46	2.83	16.48	58; 44	4

↗ entrance

Fig. 1 Location of the lagoons along the Red Sea coast of Saudi Arabia with their physical parameters

connecting the lagoons to the sea. Currents are usually weak inside the lagoons and are governed by the spring–neap tidal cycles and fluctuation in the water level (Albarakati and Ahmad 2012). Wind stress also plays a dominant but variable role in the process of sediment transport, depending on the strength of the local tides and wind speed (Sultan and Ahmad 1990; Ahmad and Sultan 1992), whereas the strength of the wave energy controls the shape of the lagoons. The margins of the lagoons are bounded by intertidal flats and sabkhas that extend to a few kilometres inland from the shoreline. In some places, elevated sandy berms separate the sabkhas from the lagoons where the low-lying areas are occasionally covered by shallow water during tidal cycles (El-Abd and Awad 1991).

There are over seventy-five wadis along the Red Sea coast of Saudi Arabia; some drain directly into the Red Sea, but some drain into lagoons creating contrasting dynamics in terms of sediment cover and water circulation pattern (Fig. 2). A summary of the drainage basins of selected wadis that are discussed in this chapter is presented in Table 1. Detrital sediments are transported into lagoons by wadis during sporadic rainfall and biogenic materials are either transported by tidal currents from the open sea or are locally produced. The sediment texture in these lagoons ranges from mud to muddy sand to gravel of both terrigenous and biogenic origin, the latter being dominant. Most locally produced skeletal remains of foraminiferal tests and carbonate materials of biogenic origin play a minimal role in understanding the sediment dynamics, whereas the lithogenic fractions of either aeolian or fluvial sources (transported by wadis), although in varying proportions, contribute to understanding sediment dispersal mechanisms, transport patterns and pathways.

Mangrove stands, especially *Avicennia marina*, are scattered on the islands and periphery of some lagoons and are populated by various bird and fish species endemic to the Red Sea. Various species of corals and benthic organisms control the character of sediment and the ecology of islands. Fish, shrimps, dolphins, crabs, dugongs and turtles congregate in the lagoons and use the sheltered environment for spawning,

Fig. 2 Selected wadis draining into the Red Sea coast of Saudi Arabia

while some lagoons have been used for fish and shrimp farming (e.g. Khor Al Ghallah). A few are used as recreational amenities especially those located near urban areas (e.g. Sharm Obhur), and some have been used for dumping partially treated sewage through pipelines, for example Al Shabab and Al Arbaeen lagoons (El-Sayed et al. 2011, 2013). Sewage disposal either in the lagoons or their vicinity has affected the corals and ecosystems of the Red Sea (Risk et al. 2009; Abu-Zied et al. 2012). Coastguard stations at the entrances and particularly boat docking facilities inside most lagoons cause the lagoons to undergo environmental stress resulting in loss to the marine community, and also greatly affecting the health of coral species. In addition, desalination plants have also impacted the coastal environments of the Red Sea of Saudi Arabia (Alharbi et al. 2012).

In general, the coastal waters and the transition between open water and land absorb much of the impact of human activities (Coakley and Rasul 2001), including ecotourism, whose links with science and the environment are often negligible (Crockett and Stow 2001). Increasing development and population density along shorelines have impacted marine environments resulting in severe changes in geomorphological and sedimentary character. Some coastal areas along the Red Sea are no exception to the severity of the impact on the sedimentary assemblages. Most lagoons are still not impacted, especially those located in areas where

Table 1 Lagoons and associated wadis along the Red Sea coast of Saudi Arabia

No.	Lagoon	Wadi (seasonal stream)	Area (km^2)	Length (km)	Slope (m/m) (overland slope)	Elevation (m.a.s.I)
1	Al Khuraybah	Wadi Al Lisan	97	22	0.0163	147
		Wadi Ifal	4,889	206	0.1888	2,335
		Wadi Abu Qusaybah	78	25	0.0196	141
		Wadi Al Mihasib	15	10	0.0395	154
		Wadi Aynunah	827	67	0.1993	1,368
		Sha'ip Qunaybi	26	13	0.0340	214
		Wadi Sharmah	1,958	163	0.1370	1,624
2	Al Dumaygh	Wadi Umm 'Ushsh	26	11	0.0800	274
3	Al Hawwaz	No Basin				
4	Antar	Wadi Antar	200	31	0.0915	415
5	Mina Al Wajh	Unknown	8	6	0.0247	36
		Wadi Kibra	54	22	0.0322	199
		Wadi Ash Shijnah	185	42	0.0419	255
		Sha'ib Umm Sidrah	73	22	0.0207	145
6	Al Habban	Sha'ib Hubaybin	24	11	0.0179	84
		Sha'ib Habban	34	20	0.0202	171
7	Al Kharrar	Unknown	14	10	0.0108	22
		Wadi Al Khariq	146	47	0.0361	202
		Wadi Murayyikh	32	15	0.0397	150
		Wadi Rahab	100	27	0.0330	176
		Wadi Al Khamas	371	65	0.0447	314
		Wadi Rabigh	4,739	212	0.0928	1,358
8	Khawr Al Dhaban	No Basin				
9	Sharm Obhur	Sha'ib Uimir	73	25	0.0279	132
		Wadi Murayyakh	141	29	0.0455	320
		Wadi Ghaya	92	Linked to open channel drainage system		
		Wadi Umm Al Hableen	46			
		Wadi Abhar	21			
		Wadi Daghabag	55			
		Wadi Braiman	64			
10	Khawr ash Shaibah Al Masdudah	Wadi Al Hashafat	388	67	0.0294	298
11	Khawr ash Shaibah Al Maftuhah	Unknown	120	37	0.0124	170
		Wadi Al Atwa'	213	45	0.0398	294
		Wadi Al Kharqah	736	92	0.0929	1,194
12	Khor Al Ghallah and Offshore Al Lith	Wadi Sayah	727	85	0.1282	1,551
		Wadi Markub	523	60	0.1198	454
		Wadi Marakh	112	22	0.0946	497
		Wadi Al Ghallah	597	78	0.1586	1,703
		Wadi Khariq Al Bir	169	26	0.0345	177
		Wadi Al Lith	3,157	174	0.2720	2,428

access is minimal. However, the physical and chemical characteristics of sediments have altered with time in areas where uncontrolled human intervention has occurred. Practices impacting the various sub-environments of the Red Sea are addressed by Davenport and Davenport (2006) and Gladstone et al. (2013).

Data Acquisition and Processing

Surficial sediment samples were obtained by either Ponar or Peterson grab samplers from the lagoons. The sediment samplers effectively sample the uppermost 15–30 cm of the bed sediment. On sediment recovery, the sediment colours were recorded and described directly in accordance with the Munsell Soil Chart. The number of samples obtained from each lagoon is presented in Table 2 and in the textural maps of all the lagoons. The procedure for grain size analysis involved pre-treatment and dispersion of the samples as described in British Standard 1377 (BSI 1975). Mechanical sieving and the results of the grain size analysis are presented as a textural classification is in accordance with the method adopted by Folk (1980). GRADISTAT particle size analysis software was used for calculating some particle size statistics (Blott and Pye 2001). Calcium carbonate ($CaCO_3$) was determined by gasometric methods using a 'calcimeter'. Total organic carbon (TOC) was determined by the wet oxidation method of Le Corre (1983).

A limited number of publications have described aspects of the sediments of the lagoons along the Red Sea coast of Saudi Arabia and recently detailed work on selected lagoons has been carried out by the Saudi Geological Survey. Among the 12 lagoons listed (Fig. 1), five have been studied in detail, representing the various sub-environments, either frequently used as resorts, drained by wadis, or with no association to wadis but instead industrially and anthropogenically impacted. A summary of some of these is presented here, and their physical, sedimentological, and hydrological parameters are listed in Table 2.

Sharm Obhur

Sharm Obhur is an elongated erosional lagoon that formed during the Pleistocene by tectonic faulting (Darwin 1962; Berry et al. 1966). The sharm cuts through coralline limestone and conforms to the end of a former fluvial valley inundated by the Red Sea. It forms the lower western part of the Red Sea coastal plain of the Tihama formation (Ali and Hossain 1988). Sharm Obhur has been studied by Dowidar et al. (1978), Behairy et al. (1983), El-Sabrouti (1983), El-Abd and Awad (1992a, b), Basaham and El-Shater (1994), Basaham et al. (2003), Fahmy and Saad (1996), El-Rayis and Eid (1997), Bantan and Rasul (2003), Al-Harbi and Khomayis (2005), Al-Farawati et al. (2008) and Rasul et al. (2009a). These authors present sedimentological data as well as temporal changes in the morphology, geology and sedimentology of the sharm.

Sharm Obhur has seen a remarkable transformation in its environmental setting as well as a series of geomorphological changes since the 1970s because of progressive urbanization of its coastal areas. The head of the sharm in the north was dredged over a kilometre to accommodate recreational facilities, while a bay-like feature at the mouth in the south was constructed that reduced the width of the mouth to about 250 m, leading to changes in water dynamics (Fig. 3). The water exchange between the sharm and the Red Sea has therefore been reduced and rejuvenation is minimized. The middle part of the sharm is the widest, but it has lost over 100 m to land reclamation between 1986 and 2000 and now is $\sim$1,200 m in width. During this time, the area of the Sharm decreased by about 800,000 m^2 representing an average annual loss of about 60,000 m^2 because of infilling (Basaham et al. 2006). This has therefore affected the morphology and composition of the bottom sediments. A concrete open channel system in the wadi leading to the head of the sharm was constructed recently to drain excess rain water to the sharm, which is only likely during heavy rainfall. Several wadis from the east flow towards the sharm and the water collected in the drainage system leads to the head of Sharm Obhur (Table 1).

The sharm is <1 m deep at the head in the north-east, while the thalweg is deep and narrow with a gradual increase in the depth to about 35 m downstream, with an abrupt fall to over 80 m about 100 m offshore (Fig. 3a). The abrupt fall is due to the lack of sediment supplied by Wadi Al Kura. The axis of the sharm is veneered with mixtures of detrital and biogenic fine-grained materials, where the indigenous biogenic marine sediments are locally produced, and detrital components were once transported by the dormant Wadi Al Kura. The sharm contains one of the highest amounts of detrital material compared to other sharms along the eastern Red Sea (Bantan and Rasul 2003). Although minor amounts of sediments are supplied by Wadi Al Kura, the sharm receives detrital sediments by wind, indicated by pitted quartz. The flanks are covered by coral reefs with variations in slope and are covered by varying amounts of very fine sediments. These are fringing-type reefs in which soft corals are abundant compared to branching corals. Among soft corals, *Xenia* and *Heteroxenia* are predominant, whereas in the Scleractinian corals, *Pocillopora* dominates followed by *Stylophora* species. In deeper waters, massive corals such as *Porites* hillocks are present. A considerable part of the reef system is occupied by the sponges of the Callyspongidae family (Jerald Wilson, personal communication). Some coral species are dead, although most survive the environmental stress. The coral reef exposures and the fringing reef pattern of the coastal area continue into the outer part of the sharm (Fahmy and Saad 1996).

The mouth of the sharm is tidally dominated with a current velocity of about 75 cm s^{-1} during spring tide. This is indicative of an inverse estuarine circulation pattern (Pritchard 1952; Nun Vaz et al. 1990). Recent studies show two layers of water flow through the entrance, with surface inflow from the Red Sea into the sharm and bottom outflow

Table 2 Summary of lagoons along the Red Sea coast of Saudi Arabia and their physical and sedimentological parameters

Lagoon	Area (km^2)	Total samples	Depth (m)	Sediment colour (Munsell Chart)	Sediment texture (Folk 1980)	Gravel avg (%)	Sand avg (%)	Mud avg (%)	Mean size (ϕ)	Sorting (ϕ)	Sand composition	$CaC0_3$ % (avg)	TOC % (avg)	Current velocity (cm s^{-1})
Al Khuraybah	24	159	25	2.5Y 6/3 light yellowish brown to GLEY 1 2.5/N black	Mud to muddy sand	2	36	62	2.16 (*fsd*) to 5.91 (*mst*)	0.16 (*vws*) to 2.68 (*vps*)	Dominated by terrigenous	3 to 89 (*71*)	0.17 to 0.98 (*0.37*)	45 (lagoon) to 110 (mouth)
Al Dumaygh	0.71	38	32 (22 at the mouth)	2.5 Y 4/4 olive brown to 5Y 2.5/1 black	Sandy mud to Gravelly sand	1	59	40	3.74 (*vfsd*) to 5.70 (*mst*)	0.16 (*vws*) to 2.17 (*vps*)	Dominated by biogenic in the northwest. Biogenic and terrigenous in the east	29 to 93 (*82*)	0.21 to 0.60 (*0.53*)	25
Al Hawwaz	0.68	37	49 (23 at the mouth)	2.5Y 5/2 greyish brown to GLEY 1 2.5/N black	Sandy mud to gravelly sand	3	67	30	3.71 (*vfsd*) to 5.70 (*mst*)	0.61 (*mws*) to 1.65 (*ps*)	Dominated by biogenic in the east. Biogenic and terrigenous in the north	30 to 92 (*79*)	0.12 to 0.37 (*0.26*)	43
Antar	0.35	12	26 (18 at the mouth	10YR 4/3 brown to 10YR 3/1 very dark grey	Sandy mud to sand	1	56	43	3.74 (*vfsd*) to 5.52 (*mst*)	0.16 (*vws*) to 1.46 (*ps*)	Dominated by terrigenous	13 to 81 (*68*)	0.27 to 1.16 (*0.85*)	No data
Mina Al Wajh	0.33	44	36 (28 at the mouth)	10YR 6/6 brownish yellow to GLEY 1 2.5/N black	Sandy mud to gravelly sand	1	81	18	3.72 (*vfsd*) to 5.73 (*mst*)	0.16 (*vws*) to 1.42 (*ps*)	Dominated by terrigenous and mostly stained	20 to 60 (*49*)	0.37 to 1.97 (0.99)	75
Al Habban	0.72	19	15 (10 from the mouth)	10YR 6/3 pale brown to GLEY 2 2.5/1 greenish black	Sandy mud to gravelly sand	1	54	45	3.70 (*vfsd*) to 5.71 (*mst*)	0.31 (*vws*) to 1.46 (*ps*)	Dominated by biogenic	19 to 86 (*77*)	0.11 to 0.41 (*0.22*)	No data
Al Kharrar	63	119	22	GLEY 1 8/1 (light greenish grey) to Gleyl 3/ (very dark grey)	Mud to gravelly sand	6	64	30	1.36 (*msd*) to 3.21 (*vfsd*)	0.30 (*vws*) to 1.60 (*ps*)	High biogenic in north and high terrigenous in south	2 to 93 (*59*)	0.29 to 2.5 (*0.97*)	18 to 100
Khawr Al Dhaban	16	28	12	10 YR 6/2 light brownish grey to 5 Y 4/1 dark grey	Sandy mud to gravelly muddy sand	3	43	54	1.40 (*msd*) to 2.30 (*fsd*)	1.31 (*ps*) to 0.79 (*ms*)	Dominated by biogenic	90 to 96 (*93*)	0.23 to 0.84 (*0.51*)	29

(continued)

Table 2 (continued)

Lagoon	Area (km^2)	Total samples	Depth (m)	Sediment colour (Munsell Chart)	Sediment texture (Folk 1980)	Gravel avg (%)	Sand avg (%)	Mud avg (%)	Mean size (ϕ)	Sorting (ϕ)	Sand composition	$CaCO_3$ % (avg)	TOC % (avg)	Current velocity (cm s^{-1})
Sharm Obhur (1986)	6	42	35	5 Y 8/1 white to 5 YR 4/3 reddish brown	Mud to gravelly sand	3	46	51	1.30 (*fsd*) to 3.55 (*fsd*)	0.37 (*ws*) to 3.44 (*vps*)	Dominated by terrigenous	40 to 45 (*40*)	0.4 to 0.6 (mud patch 0.9 %)	No data
Sharm Obhur (2003)	6	41	35	2.5Y 6/3 light yellowish brown to 5Y 5/3 olive	Mud to gravelly sand	2	24	74	2.23 (*fsd*) to 4.55 (*fsd*)	0.40 (*ws*) to 1.35 (*ps*)	Dominated by terrigenous	40 to 70 (*50*)	0.2 to 0.4 (mud patch 0.8 % highest 1.4 %)	25 to 80
Sharm Obhur (2009)	6	40	35	GLEY 1 3/1 5GY very dark greenish grey and 5 Y 6/2 light olive grey	Sandy mud to gravelly sand	3	42	55	2.29 (*fsd*) to 4.67 (*cst*)	0.68 (*ms*) to 1.76 (*ps*)	Biogenic and terrigenous	39 to 78 (*54*)	0.19 to 0.37 (*0.29*)	30 to 87
Sharm Obhur (2013)	6	42	35	2.5Y 5/2 greyish brown and 5Y > 2.5/1 black	Mud to gravelly muddy sand	4	44	52	2.90 (fsd) to 4.88 (cst)	0.73 (*ms*) to 2.15 (*vps*)	Terrigenous and biogenic	33 to 61 (*47*)	0.29 to 0.70 (mud patch 0.57 %)	25 to 75
Khawr ash Shaibah Al Masdudah (northern)	8.5	57	7 at the mouth av. 3.5 in the lagoon	10 YR 7/3 (very pale yellow to GLEY 1 3/ (very dark grey)	Gravelly mud to sandy mud	7	64	29	2.87 (fsd) to 0.86 (csd)	0.66 (*mws*) to 1.61 (*ps*)	Mostly biogenic	38 to 92 (*68*)	0.15 to 4.0 (*1.7*)	20 to 50 cm s^{-1} 45 avg at the mouth
Khawr ash Shaibah Al Maftuhah (southern)	7.5	85	15 at the mouth av. 4 in the lagoon	2.5 Y 8/3 (pale yellow to GLEY 1 3/1 (very dark grey)	Gravelly mud to sandy mud	4	60	36	3.42 (vfsd) to 2.87 (fsd)	0.58 (*mws*) to 1.42 (*ps*)	Mostly biogenic	36 to 92 (*75*)	1.08 to 4.95 (*1.92*)	20 to 50 cm s^{-1} 25 avg at the mouth
Khor Al Ghallah and offshore Al Lith	16	121	4 in the lagoon and 59 offshore	GLEY 1 10Y 6/1 greenish grey to GLEY 1 3/1 10Y very dark greenish grey, offshore 10YR 5/2 greyish brown	Mud to gravelly sand in the lagoon, gravelly muddy sand, dominated by sandy mud	1	42	57	0.52 (csd) to 4.24 (est)	0.16 (*vps*) to 1.88 (*ps*)	Mostly terrigenous in the lagoon. Mostly terrigenous in the southeast dominated by biogenic in the west	2 to 40 in the lagoon (3 % in the east). Over 70 % in the southwest offshore up to 40 % in the southeast shallow area.	0.1 to 0.5 in the lagoon. 0.3 to 0.7 offshore	29 at the mouth

* *csd* coarse sand, *msd* medium sand, *fsd* fine sand, *vfsd* very fine sand, *cst* coarse silt, *mst* medium silt
***vws* very well sorted, *mws* moderately well sorted, *ps* poorly sorted, *vps* very poorly sorted

Fig. 3 Sharm Obhur **a** depth increases abruptly at the mouth because of lack of sediment supply; **b** plastic chairs dumped into the sharm along with other anthropogenic material; **c** confluence of the sharm and Wadi Al Kura where barriers have been erected to retain debris; **d** land reclamation in progress; **e** dredging to increase the water depth for boats. The material is dumped into the deep water regardless of the environmental impact; **f** floaters (*in yellow*) deployed to restrict the effect of the sediment plume on the sharm, although the plume eventually disperses due to surface currents; **g** some coral species are not vulnerable to environmental stress and continue to thrive, and **h** seagrass and corals covered with algae show signs of high nutrient input from anthropogenic sources

into the Red Sea. However, in previous studies, three water layers were identified at the entrance: a surface water mass (upper 5 m of the water column) characterized by high temperature and salinity, an intermediate water mass of minimum salinity with a core at 10–20 m water depth, and a bottom (>20 m depth) water mass with maximum salinity. This hydrographic structure develops a two-layer flow, inflow of low-salinity water at both the surface and intermediate depths and outflow of high-salinity water at the bottom (El-Rayis and Eid 1997). Previous studies show that the evaporation rate ranges between 0.6 cm/day in May and 0.8 cm/day in February. The rate of water inflow ranges between 150 $m^3 s^{-1}$ (November) and 300 $m^3 s^{-1}$ (February), with the outflow ranging between 150 $m^3 s^{-1}$ (November) and 400 $m^3 s^{-1}$ (February) (El-Rayis and Eid 1997), although no recent data are available to substantiate water flow and evaporation rates. The surface water temperature ranges from 24.4 °C in winter to 32.2 °C in summer and increases gradually from the entrance to the head in the north (Basaham et al. 2006). The salinity ranges between 39.1 and 40.2 ‰ and follows a similar pattern to the water temperature (Ahmad and Sultan 1993). However, between 2006 and 2013, the average temperature ranged between 22 °C in winter to over 34 °C in summer, and the salinity averaged 39 and 41 ‰ at the entrance and head, respectively.

Discussion

Coastlines suffer changes over time because of their morphodynamic and sedimentary character, resulting in the spatial distribution of complex sedimentary assemblages

(Holland and Elmore 2008). In the last three decades, urbanization along the sharm has extensively modified the shoreline configuration and sediment characteristics. Recreational activities and domestic pollution have increased resulting in chaotic environmental changes (Fig. 3b). Wadi Al Kura, the old feeder stream or landward extension of the sharm, is presently an infill site and has been cut off by two bridges obstructing the supply of terrigenous material to the sharm. The head has been raised and barriers emplaced to stop debris transfer into the sharm, resulting in the cessation of sediment input (Fig. 3c). During the occasional rainfall, water from several wadis drains in channels to this wadi which may become inundated, but the raised bed at the confluence of the wadi and the sharm holds the water so that only during extreme rainfall does it spill over into the sharm.

Municipal and domestic waste and litter dumping as well as sports activities have caused extreme stress on the environment, especially on corals. The pollutants produced by either human activities or in situ by chemical reactions are likely to be retained by fine sediments. The reduction in width of the sharm and the restricted water exchange with the Red Sea, as well as the relatively weak bottom currents as shown by sediment texture, also lower water quality. Land reclamation is common (Fig. 3d), and dredging is used to increase water depth in front of the residential complexes and marinas to facilitate boat docking (Fig. 3e). Recently storm water has drained into the sharm through pipes, with floaters deployed to restrict sediment dispersal. Unfortunately, the effect of this input could not be controlled because of unsuitable technology (Fig. 3f).

Over 100 species of flora and fauna dwelling in the bottom water were identified between 1974 and 1979 by Bemert and Ormond (1981). Following land reclamation and increased urbanization, several species have been lost (Rifaat et al. 2001). The last decade has witnessed severe deterioration in the bottom environment, and many more species have disappeared (Basaham et al. 2003; Rasul and Qutub 2009). Recent dives in 2014 within and outside the sharm show a sharp decline in exotic species of corals and associated fauna. However, some corals survive under very harsh conditions and are resistant to the various environmental stresses (Fig. 3g). Seagrass beds are common in the northern part and at the mouth, indicating nutrient-rich water supporting their growth (Radwan Farawati, personal communication) possibly related to sewage and litter dumping and the restricted water exchange between the sharm and the Red Sea (Fig. 3h).

Sediment Characteristics

In order to track environmental changes, bottom sediment data from 1986, 2003, 2009, and 2013 are presented (Fig. 4). Significant alteration in the sediment's texture from coarse- to fine-grained through time and mineralogical compositional changes from detrital to biogenic origin have been observed due to cessation of fluvial input from Wadi Al Kura and an increase in human activities. The following sedimentological data show the various processes responsible for the changes over time.

Bottom Sediment Character (1986)

In 1986, the bottom sediment texture ranged between mud and gravelly sand but mostly consisted of muddy sand (Fig. 4a). Mud was present in small amounts close to the head of the sharm in a shallow and sheltered area, and a small elongated patch in the thalweg about 2 km from the sharm mouth covering an area of about 0.022 km^2. Muddy sand followed by sandy mud was supplied by Wadi Al Kura when the wadi directly fed the sharm, and the gravelly sand was mostly of biogenic origin (bioclastic debris). The sediments of the upper part of the sharm were mostly detrital, with relatively small amounts of associated biogenic sand. The sediments were poorly sorted, except in deep water, and the lower half, including the mouth, was moderately sorted. Very fine sands were better sorted at the thalweg, indicating that low-velocity currents were capable of sorting fine sediments.

Bottom Sediment Character (2003)

In 2003, the sediment texture ranged between mud and gravelly sand but was dominated by sandy mud (Fig. 4b). Gravelly muddy sand was present at the mouth, and a patch of mud about 2 km upstream had become much larger since 1986 and covers an area of about 0.127 km^2. The fine sediments at the mouth were re-suspended by strong tidal currents and transported upstream about 2 km during flooding, and during the turn of the tide before the ebb set in the suspended material settled. The sediment veneer had changed from coarse to fine with abundant mud. The sediments were mostly poorly sorted in shallow water due to their coarseness and moderately to well sorted in the deeper water and in the lower half of the sharm.

Bottom Sediment Character (2009)

In 2009, the sediment texture ranged between sandy mud and gravelly sand but was dominated by sandy mud (Fig. 4c). The abundant mud at about 2 km from the mouth in 1986 and 2003 disappeared (Fig. 4a–c). Abundant sand and mud was supplied by the wadi during heavy rainfall in 2009 resulting in major changes in the sediment distribution pattern. Sand of biogenic origin was well sorted at the mouth because of

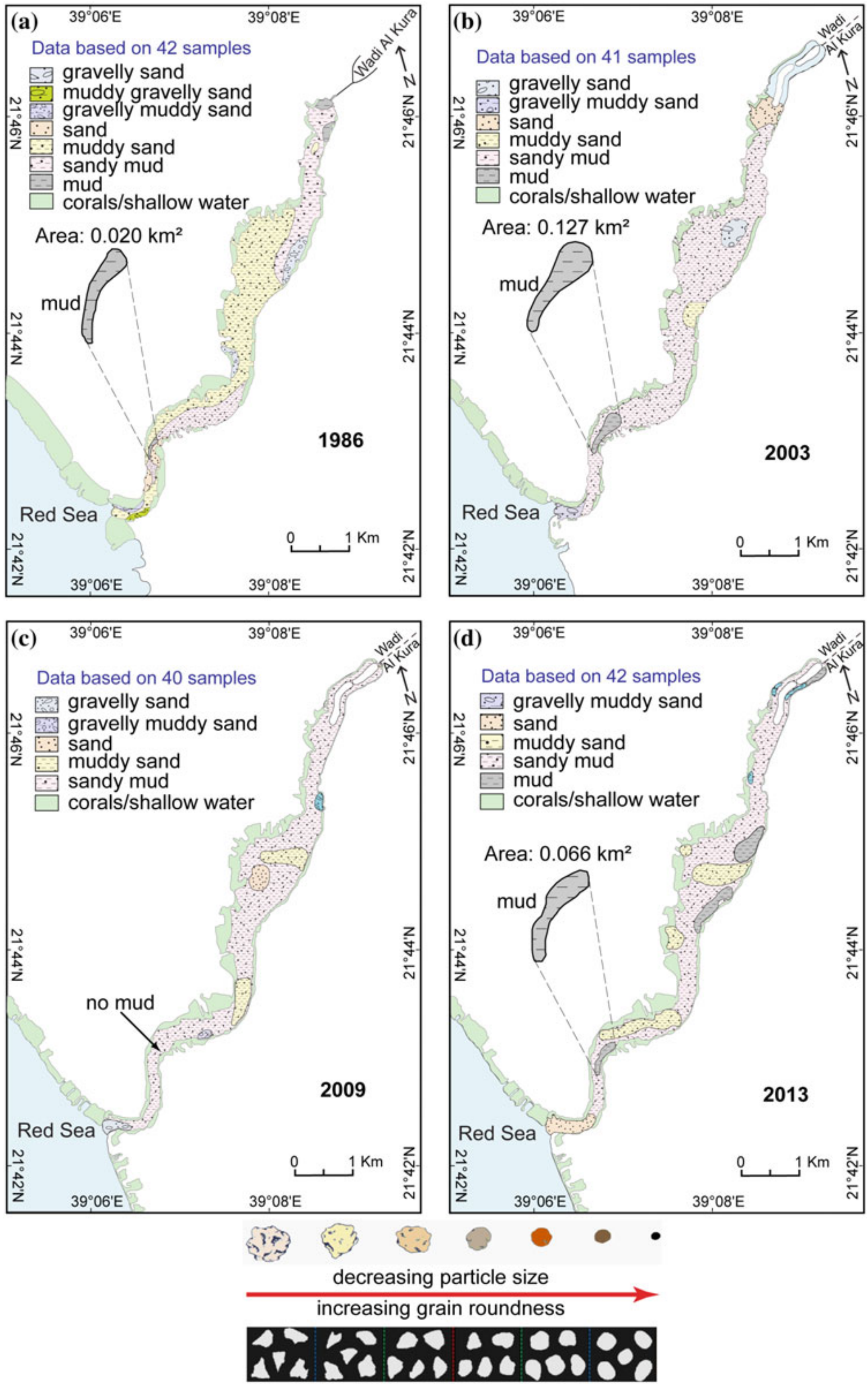

Fig. 4 Sediment distribution and variations in particle size in Sharm Obhur. The sediment veneer shows a fining trend over the last three decades. The textural classification is based on Folk (1980); **a** data are based on 42 sediment samples; **b** data are based on 41 sediment samples; **c** data are based on 40 sediment samples, and **d** data are based on 42 sediment samples

strong tidal currents. The sediments were mostly well sorted in shallow water, while sediments in deeper water in the mid to lower half and at the entrance of the sharm were moderately well sorted. The upper half was poorly to moderately well sorted because of the mixing of fine and coarse sediments of both detrital and biogenic origins.

Bottom Sediment Character (2013)

In 2013, the sediment texture ranged between mud and gravelly muddy sand but the bottom was covered mostly with sandy mud (Fig. 4d). Moderately to well-sorted sand was present at the mouth followed by sandy mud, and abundant mud about 2 km from the mouth covering an area of about 0.066 km^2. In addition, mud was also present at the head and on the central eastern flank. The mud on the eastern side is the recent product of the wadi, transported during rainfall in 2012, while the coarse fraction is of biogenic origin. Sediments are moderately sorted in shallow water, but elsewhere are poorly sorted, due to the flood of 2012 that transported debris and sediments of various sizes, as well as the increasing human influence through land reclamation or routing of storm and groundwater into the sharm via pipelines. The strongly deteriorating water transparency during the flood and groundwater dumping has caused the death of some coral species.

The sharm shows a fining trend in the sediment texture and is now covered mostly with sandy mud of detrital and biogenic origin in deeper waters, especially in the thalweg, while texture is coarse-grained and mostly biogenic in shallow water. The thalweg is 35 m deep and the bottom current is fairly weak facilitating sedimentation of fine-grained sediments under calm conditions with little reworking in the deeper water. The cohesive nature of the terrigenous sediment (wadi source) enhances sediment retention and even strong currents are unable to erode and re-suspend bottom sediment. The influence of reworking is also masked by biological aggregation and the degree of cohesiveness of the detrital sediments that are composed mostly of the clay mineral kaolinite, once supplied by Wadi Al Kura. The interference with natural conditions may lead to pollution and the finer-grained nature of the sediment veneer supports retention of pollutants and deterioration in aquatic life (Basaham et al. 2003). Activities such as jet skiing and movement of boats have greatly increased in recent years and are responsible for re-suspension of near-shore sediments and their transportation to deeper water. The coarse sediment appears to be contributed by coastal erosion and in situ production of biogenic material. The gradual coarsening of near-shore zone sediments is also caused by wave- and wind-generated currents and the energy generated by human activities. In near-shore areas where human influence is limited, the water transparency is higher and the sediments are well sorted. The mouth of the sharm was covered with muddy sand in 1986, gravelly muddy sand in 2003, gravelly sand in 2009, and sand in 2013, and the loss of gravel, but the presence of sand confirms a gradual decrease in the particle size of the sharm sediments. The coarse-grained well-sorted sands are the result of tidal currents that re-suspend fine sediments that are transported either upstream during flooding or to the open sea during ebbing. The limit of influence of the tidal currents is about 2 km from the mouth based on the pattern of mud deposition (Figs. 3 and 4d). However, the sediment at the mouth in 2013 indicates that the terrigenous sand is due to the rainfall of 2012 when sandy mud was transported to the sharm and the mud was lost to the Red Sea by winnowing. Since the sharm is in limited communication with the open sea and because the current velocity is controlled by the barrier (Fig. 3), sand settles out at the mouth and mud is winnowed away. The mouth of the sharm is not as dynamic as that of other sharms such as Al Kharrar lagoon (Rasul et al. 2010a) because of the present configuration of the sharm entrance. Moderately to well-sorted sand prevails at the mouth only because the bottom current of 0.75 $m\ s^{-1}$ is strong enough to winnow the fine material. A 3D model showing the sediment distribution process and pattern is presented in Fig. 5.

The head, south-eastern part and thalweg show better sorting. At the head, sorting is better because of excess aeolian material, and in the shallow water in the south-eastern half this is due to the effect of wind induced currents. Better sorting of non-cohesive sediments (biogenic origin) under weak current influence is observed. Where finer materials are cohesive, sorting values decrease because strong currents are required to sort the sediments. Where the near-shore sediments show deterioration in sorting, it confirms a multiple source from the fragmentation of corals and anthropogenic input. Although tidal currents tend to be strong at the mouth, the sediments are not very well sorted. The reasons sorting does not improve much are either because the currents are incapable of selective sorting or the current is so strong that fragmentation of the corals and biogenic materials contribute coarser materials to the sediment cover. The latter is probable because of the composition and appearance of the biogenic material which show polished surfaces caused by strong currents but have worn edges, indicating the influence of physical processes on the sedimentary materials. Prolonged exposure of the coral reefs and related organisms to agitated water conditions and mechanical destruction also supply significant sedimentary material to the sharm, but this is mostly confined to the lower end. The lesser degree of sorting is magnified by the addition of coarser material. Poor sorting is indicative of the transport history, hydraulic volatility of transporting agents and multiple sources and the composition of sediments in the sharm.

In general, $CaCO_3$ has increased in the sharm over time, especially at the lower end because of the absence of terrigenous input from Wadi Al Kura, and TOC has increased in the eastern and deep waters. Increased TOC is associated with fine and dark-coloured sediments in a reducing environment that tends to be most severe in stagnant and sheltered areas. $CaCO_3$ ranges between 11 % at the head and 73 % at the mouth, and TOC ranges between 0.2 % at the

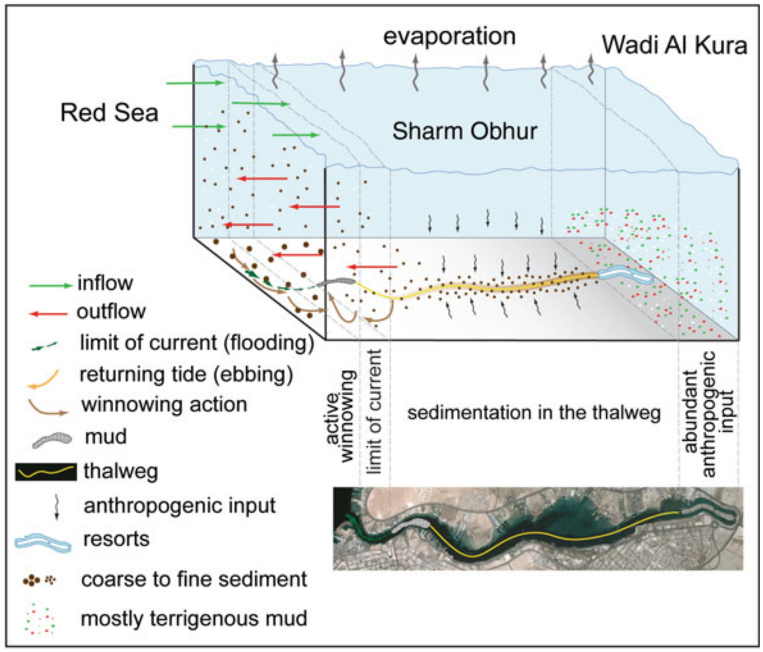

Fig. 5 3D model of the hydrological processes and sediment distribution pattern within Sharm Obhur

mouth to 1.6 % at the head. However, an area ~2 km from the mouth contains 1.2 % TOC due to abundant mud that tends to preserve organic matter well. North-westerly winds also transport debris in the south-easterly direction as a result of which anthropogenic material collects along the eastern shoreline and is further supplemented by human activity resulting in high amounts of TOC.

The chemical properties of dissolved seawater constituents [nutrients, faecal sterols and polyaromatic hydrocarbon (PAHs)] were recently investigated by Al-Farawati et al. (2008). High values of nutrients at the head of Sharm Obhur, in particular nitrite, nitrate and ammonium are attributed to its shallowness and restricted water circulation which enhances accumulation of nutrients, supplemented by additional sources through diffusion of nutrients from interstitial waters. As a result, Al-Farawati et al. (2008) suggest that reducing environments are most likely to develop at the head of the sharm in line with changes in the environment and anthropogenic input.

Present Status and Future Implications

Human interference has distinctly changed the configuration of Sharm Obhur. There is no set pattern of sediment distribution because of human activity at the margins of the sharm and lack of input from Wadi Al Kura. On the contrary, erratic activity has caused variations in the sedimentation pattern as reflected in the texture and sediment composition. The fining trend from abundant muddy sand in 1986 to sandy mud in 2013 may lead to retention of anthropogenic pollutants dumped in the sharm. Land reclamation at the sharm has greatly increased, justifying the need to study the environmental impact on the marine communities, namely the coral reefs and the exotic fish that have declined markedly over the last decade. It is also important to monitor the impact of runoff after heavy rainfall.

Shoaibah Lagoons: Khawr ash Shaibah Al Masdudah (Northern) and Khawr ash Shaibah Al Maftuhah (Southern)

The two hyper-saline lagoons, Khawr ash Shaibah Al Masdudah (northern) and Khawr ash Shaibah Al Maftuhah (southern), commonly referred to as the Shoaibah lagoons, have unique environmental conditions. Limited research has been carried out there by Meshal (1987), Sultan and Ahmad (1990), Ahmad and Sultan (1992), Gheith (1999), Al-Washmi and Gheith (2003), Hariri (2008), Rasul et al. (2010b), Al-Barakati (2010), Abu-Zied et al. (2011), Abu-Zied and Bantan (2013) and Al-Farawati et al. (2014). The lagoons were probably formed by erosion during a sub-pluvial to pluvial Pleistocene phase and were then submerged by the rise in sea level (Braithwaite 1987; Brown et al. 1989). On the western side, the lagoons are bounded by raised coral terraces of Pleistocene age (Marco Taviani, personal communication). No wadis flow into the lagoons, and therefore supply of detrital material is lacking. Most of the sediments are autochthonous carbonates with admixtures of aeolian quartz and evaporite minerals. Remnants of drainage channels of the dormant wadis are present, and small rainwater channels drain into the lagoons but do not play any role in flooding. The wadis that had an influence on the lagoons are listed in Table 1. The northern and southern lagoons are connected to the Red Sea through two separate narrow channels with water depths of 7 and 15 m, respectively (Fig. 6). The depth increases with distance towards the open sea and abruptly drops to over 50 m at the outer reach of the mouth. The northern lagoon has a wide tidally dominated channel, strong currents and unimpaired exchange of water with the open sea, while the southern lagoon has a long narrow channel where the tidal current is strong only until the mouth bends almost 90°, where the tidal current dissipates, reducing its impact on the lagoon and restricting water and sediment movement. The shape of the mouth, narrow entrance, shallow depth and strong currents govern sediment distribution. Shallow depths averaging 3.5 m, wind and tidal stirring are the main forces preventing the lagoons from developing stratification, resulting in a well-mixed body of water with high salinity and temperatures.

The two lagoons are separated by a paved road and connected by drainage pipes that are now buried under sediments (Fig. 6a). The northern lagoon has an elevation of about 6 m at the mouth and low-lying areas surround the lagoons (Fig. 6b, c). The sediment texture in the lagoons ranges between sandy mud to gravelly sand. Very coarse sediment dominates the entrance, and fine to coarse sediments mostly of biogenic origin form the surface sediments of the main lagoons. The biogenic materials are coral debris, coralline algae, molluscan shells, foraminifera, sponges and bryozoans in sand to gravel size fractions, and aeolian quartz in fine sand. The cyclical inundation of low-lying sabkhas by shallow water during flood tides and transfer of evaporite minerals (Fig. 6d) to the lagoon from the adjoining sabkhas during ebbing or rainfall are important in understanding the ecological consequences and sediment transport mechanisms. Carbonate is abundant in the form of calcite and aragonite, and High-Mg calcite indicates the carbonate is recent and formed under shallow water conditions. Halite, gypsum and dolomite are found in different proportions in the sabkhas surrounding the lagoons (Al-Washmi and Gheith 2003). The sediments of the northern lagoon are brown to grey in colour, and in the southern lagoon, the sediment colour ranges from yellow to grey (Table 2). Fine sediments are darker in colour with shades of grey, and the coarse sediments are lighter in colour with shades of yellowish brown to greyish brown. Dark-coloured sediments are found at the periphery of the lagoons and are related to the physico-chemical properties and not to external sediment sources. The coarse sediments including shells are stained grey to black because of the reducing environment and formation of authigenic pyrite. Stagnant conditions prevail inside the lagoons because of insufficient water exchange with the open sea, and a lack of rainfall causes hyper-saline conditions.

Mangrove (*Avicennia marina*) stands are scattered around the numerous small islands and margins of the lagoons and act as a source of nutrients to the flora and fauna, also initiating a reducing environment (Fig. 6e, f). Seagrass and macro-algae dominate the shallow parts of the lagoons (Abu-Zied et al. 2011). Gastropods and pelecypods are common and scattered on the tidal flats and in shallow waters. Benthic foraminiferal species that enable sea-level reconstruction have been reported from the lagoon (Abu-Zied and Bantan 2013). The Shoaibah region has suffered severe ecological changes in the past and is characterized by an intensely dry climate where only one wadi drains into the lagoon for a short period each year (Hötzl and Zötl 1978).

Discussion

Sediment colour plays an important role in discriminating various sub-environments in shallow water bodies such as the Shoaibah lagoons. Areas of dark grey sediment are quiescent reducing environments of deposition and stagnation where the currents are almost negligible and incapable of re-suspending and transporting sediments. The reducing environment is further enhanced by restricted water exchange between the Red Sea and the lagoons. Organic debris from mangrove and anthropogenic sources has a pungent smell and adds a dark tone to the sediment, associated with an increase in TOC (Fig. 6f), and is reflected in dark stained shells and coral debris.

The water exchange between the Red Sea and the two lagoons is greatly restricted because of the shape of the mouths where the current is strong, and flushing is restricted especially in the northern lagoon. Coarse sediments at the mouth of the lagoon are lighter in colour and well sorted with minor amounts of finer sediments because strong currents winnow and transport re-suspended sediments either inside the lagoon during flooding or to the open sea during ebbing. A bridge has been constructed recently over the mouth of the northern lagoon reducing the width of the channel to about 5 m, and hence, the exchange of the water between the lagoon and the open sea is minimal despite the strong currents that prevail because of the narrow channel (Fig. 6gi, ii, iii). The shallowness of the lagoons and meteorological forces keep the water agitated causing suspension of fine sediment, resulting in its transport to the lagoon margins by wind coupled with tidal currents. The permanent presence of suspended material in the lagoons affects water clarity. Although the seabed could be seen during Secchi Disk Disappearance Depth (SDDD) data collection, the water is murky due to suspended material. Water clarity increases with depth and increasing sediment size especially at the entrance, where strong tidal currents remove fine sediments and keep the water column free of suspended material, resulting in the

Fig. 6 Two Shoaibah lagoons with subenvironments: **a** rusted pipeline joining the two lagoons; pipelines are clogged with sediments restricting exchange of water between the two lagoons; water covers the shallow area during spring tide and high temperatures increase evaporation resulting in the formation of salt; **b** mouth of the lagoon during high tide. The cliff at the lagoon's entrance is about 6 m high and tapers off at the edge of the entrance; **c** periphery of the lagoon is flat, and so during high tide or strong winds, the sabkha is covered with water; **d** sabkha deposit where salt and gypsum are common; **e** mangrove stand and sabkha are inundated only during very high tide; **f** area inundated with water during tidal cycles. The mud is sticky, and organic debris creates a reducing environment; **g** (*i*) narrow mouth of the lagoon where the sides have coral reefs and the mouth widens; (*ii*) recently constructed bridge has narrowed the entrance to about 5 m and (*iii*) although the entrance has narrowed, the tidal currents show an increased velocity under the bridge where the channel has been deepened to give a smooth flow

highest water clarity. However, the shallow depth in the lagoons increases turbidity and results in a well-mixed body of water with extreme temperatures and salinities.

The flushing time of the lagoon is estimated to be 20 days with current velocities varying between 20 cm s^{-1} in December and 50 cm s^{-1} in July at the entrance (Alaa Barakati, personal communication). The tidal current can be observed in the entire lagoon, but the current velocity weakens as the mouth of the lagoon widens (Fig. 6gi). Strong tidal currents at the entrance play an important role in the redistribution of sediments, but the prevailing northerly and north-westerly winds influence the movement of water from the lagoon to the adjacent sabkhas, particularly during high winds. Previous studies in shallow water have demonstrated that wind-generated waves and their energy flux are important in initiating sediment transport at the entrance of most coastal lagoons (Ahmad et al 2002; Rasul et al. 2010b). Surface waves with periods from 1 to 30 s. are the most energetic waves that aid sediment redistribution in shallow water (Kinsman 1965).

The lagoons have two main sediment sources, biogenic and aeolian, that owe their distribution to transit and reworking processes. A third minor source is the evaporite deposits of the adjoining sabkhas. The sediment veneer ranges between gravelly sand and sandy mud but is dominated by biogenic muddy sand in both lagoons (Fig. 7). The coarse nature of the sediments is the result of constant fragmentation of reefal sediments and high production of molluscs and foraminifera in the lagoon. The northern lagoon is veneered mostly with sand in various size fractions, and gravel dominates the north-eastern side and at the mouth. Fine sediments of biogenic origin dominate the deep and central part of the lagoon. This shows that the current plays an important role in winnowing the fine sediment at the mouth, and the re-suspended mud is transported and deposited in the central part of the lagoon where the current is minimal allowing sediment to settle. The floor of the southern lagoon is also dominated by sand, but the relatively deeper water in the main lagoon is mainly veneered with biogenic mud. The gravel content is higher at the mouth of the lagoon but only at the confluence with the Red Sea, which shows the importance of wind and strong tidal currents that are strong but terminate where the mouth widens (Fig. 6). The coarser texture of the bottom material results from the removal of fine-grained sediment, particularly at the entrance, by the sifting action of strong tidal-, wind- and wave-generated currents (Fig. 7a).

Biogenic carbonate is abundant, followed by detrital and evaporite components. Erosion of reefs contributes most of the carbonate material to the lagoon, and the molluscs are typical products of a marine environment. The distribution of detrital material is mostly controlled by the hydrodynamics and by atmospheric dust brought in by the shamal (wind). The sand dunes in the Middle East are important contributors of aeolian input to the marine environment in the form of pitted quartz that dominates most lagoons. Relatively limited terrigenous material is also supplied to the lagoon by the adjacent coastal plain through the wadis during occasional flash floods (Al-Sayari and Zötl 1978).

Most shell fragments in the lagoons are stained black only on the outer surface (Fig. 7b–e). Similar staining on sediments has been reported in the Al Kharrar lagoon (Rasul et al. 2010a), at sabkhas on the Red Sea coast (Abou-Ouf and El-Shater 1993), on the Indus continental shelf and the Indus Fan sediments (Rasul 1992), the Arabian Gulf (Murray 1966) and the Bahamas (Illing 1954). Ancient and recent calcareous marine sediments stained grey or black with finely divided pyrite have been reported in pellety debris of carbonate sediments from the Middle East, Britain and other areas (Mixon and Pilkey 1976; Sugden 1966). Almost all types of pelitic material may become pyrite-stained. Debris such as ooids and hard shell fragments has staining only on the grain surface. In sedimentology, these blackened shells are regarded as important indicators of environment type (Cramp 1985; Rees 1988). Staining by pyrite is regarded as the end product of anaerobic bacterial activity. When sediment is buried under a pile of terrigenous material, a reducing environment develops due to consumption of oxygen and organic matter by bacteria. According to Sugden (1963), the aerobic bacterial activity, utilizing free oxygen, penetrates the surficial sediment layer. Some organic matter is oxidized and destroyed, and some is buried to depths where free oxygen decreases and then undergoes anaerobic bacterial decay to produce H_2S forming at first ferrous sulphide and subsequently pyrite. A high rate of sedimentation can result in the incomplete conversion to pyrite (Berner et al. 1979). However, a low input of organic matter and its consumption by both aerobic and anaerobic bacteria and low iron input limits pyrite formation (Fisher 1986). Pyrite formation in marine sediments depends upon the amount of iron minerals that are reactive with hydrogen sulphide, the presence of sulphate, and the amount of organic matter available for bacterial decomposition since the conversion of sulphate to hydrogen sulphide is biologically mediated (Berner 1970, 1982). The presence of iron in the sediment will stain grains brown-black during the oxidized state, and during burial and in a reducing environment, grains turn black resulting in iron sulphide in the form of pyrite. It is postulated that the black colour on shell fragments can change to brown when sediment from the reducing environment is exposed to an oxidizing environment by burrowing organisms, erosion or currents (Maiklem 1967). It has been shown experimentally that in a reducing environment, the blackening may occur in a matter of days (Mixon and Pilkey 1976). A pungent smell in sediment also indicates a reducing environment. However, Abou-Ouf and El-Shater (1993) concluded that blackening of shells is due to

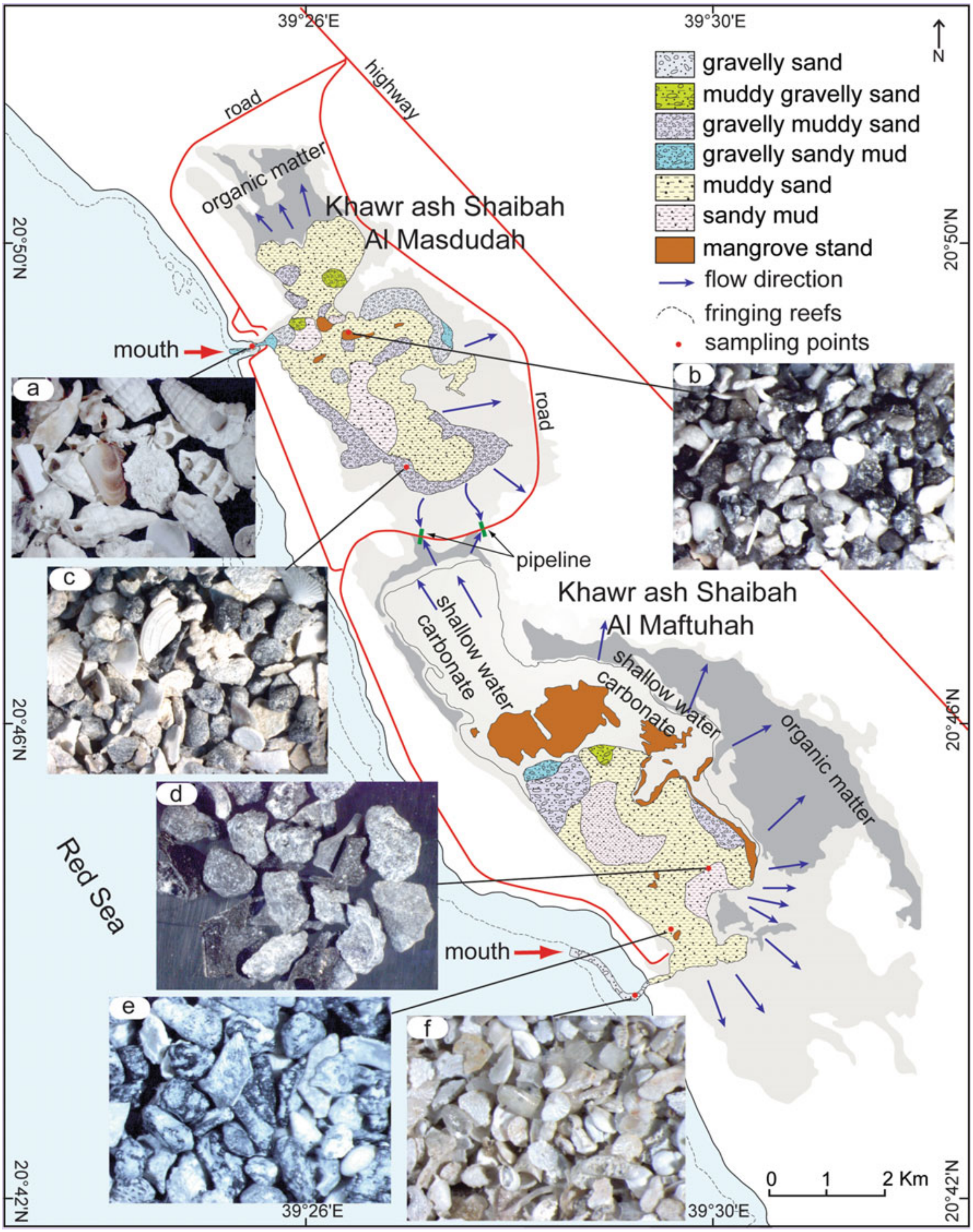

Fig. 7 Sediment distribution in the two Shoaibah lagoons: **a** recent gastropods have a fresh appearance, and the surfaces are polished by water movement; skeletal grain population (shell hash) consists primarily of more or less fragmented gastropod (cerithiids) and bivalve (e.g. *Brachidontes*) shells; **b** *grey to black* stained carbonate material in the vicinity of mangrove stand. Some fresh (*white*) carbonate material (gastropod shells and allochems) is recent and not influenced by a reducing environment; **c** stained and unstained grains indicating a mixed composition of sediment; skeletal component in gravel is dominated by fragmented bivalves, benthic macro-foraminifers and allochems; **d** *dark grey* sand size grains are the product of a reducing environment that gives rise to iron sulphide in the form of pyrite; **e** stained shells and carbonate debris have been severely affected by the reducing environment in the presence of high organic matter from the mangrove stands, and **f** recent biogenic material has a fresh appearance because it is influenced by tidal currents; skeletal component is rich in benthic foraminifers and subordinate ostracods

pyrite in iron-rich clays and sands from the coastal plain (Jado and Hötzl 1984; Jado et al. 1989) and not from the organic matter. In the southern lagoon, biogenic materials are more severely stained black compared to the northern lagoon. This could be due to a lack of exchange of the southern lagoon's water with the Red Sea due to the shape of the mouth and the availability of abundant organic debris from the mangrove stands.

The presence of halite in the sediment is the result of high evaporation and the hyper-saline water has a salinity of 54 %, although salinities of over 60 % have been recorded (Abu-Zied et al. 2011). The lagoons extend into a flat coastal plain that is covered by a few centimetres of saline water during flood tides. The north-north-westerly wind helps in the movement of shallow water over the sabkha. Air temperatures as high as 50 °C in the sabkha areas aid rapid evaporation, causing precipitation of evaporite minerals such as halite and formation of thin crusts and sand-sized halite crystals. Crystals of halite, gypsum and dolomite are abundant in the low-lying sabkhas and are occasionally transported to the lagoon by ebb tides (Fig. 6c).

The $CaCO_3$ content is higher in both the lagoons, especially at the mouths, and decreases gradually inside the lagoons (Table 2). The strong current at the entrances prevents terrigenous sediment from settling out and leaves coarse carbonate as lag deposits (Fig. 7a, f), where the sediment texture becomes coarser with an increase in carbonate content. $CaCO_3$ decreases into the lagoon, where the varying distribution is due to the influx of terrigenous material mostly of aeolian origin and evaporite minerals from the sabkhas diluting the carbonate. The biogenic sediments (shells and carbonates) are comminuted by current activity, thus initiating parturition of fine calcareous mud. Basins in reef-bound coasts without any significant runoff and high aridity are the most probable source of carbonate in the lagoon. Thus, grain size and grain characteristics are primarily controlled by in situ production of carbonate material. In the Red Sea, vigorously growing coral and the presence of fringing and barrier reefs play a very significant role in the high production of reefal and carbonate sediments.

Low values (<0.2 %) of TOC are recorded where the fine sediment is winnowed and lag material in the form of coarser carbonate fails to adsorb the organic material. The distribution of organic matter in general is somewhat higher (<2.5 %) than normal (1–2 %), and higher values are observed where finer sediments dominate and where $CaCO_3$ is low. In isolated areas, particularly close to the mangrove stands, coarse-textured sediment rich in carbonate material tends to show higher amounts since the mangrove supplies organic debris. There is a close relationship between TOC, sediment colour and texture, and a negative relationship between TOC and $CaCO_3$. In general, TOC is high and relates to stagnant conditions in both the lagoons and the high input of decomposing organic debris from the mangrove stands. The coarser sediments, mostly of biogenic origin, are stained grey-black because of the reducing environment confirming that high TOC and staining of shells are inter-related. In general, the fine sediments show high TOC compared to the coarse sediment rich in carbonate debris. The values are compatible with those reported by other workers in the Red Sea (El-Sayed and Hosny 1980; Behairy et al. 1983; Al-Washmi and Rasul 2003; Rasul et al. 2010b).

Dissolved nutrients such as reactive phosphate and nitrite are depleted in the lagoons, similar to the open water of the Red Sea, reflecting poor productivity (Rasul et al. 2010b). The speciation of phosphorus in the surface sediments, especially of the southern lagoon indicates the depositional environment, and apatitic phosphorus is the main form that possibly regulates reactive phosphate in the lagoon (Al-Farawati et al. 2014).

Present Status and Future Implications

Human interference has distinctly changed the configuration of the two Shoaibah lagoons, especially the northern lagoon where the construction of a bridge probably limits the exchange of water between the lagoon and the Red Sea. There is no input of fresh water from the wadis into these lagoons and therefore hyper-saline conditions prevail, and the increase in human activity in terms of boat docking and garbage disposal is on the increase and may lead to retention of anthropogenic pollutants, justifying the need to study the environmental impact on the lagoon.

Khor Al Ghallah and Offshore Al Lith

Khor Al Ghallah is a shallow lagoon fed by Wadi Al Ghallah that currently has limited sediment input because of intense human interference. The maximum depth of Khor Al Ghallah is about 4 m, and at the entrances to the lagoon on the western side between Jazirat Sharifah and Jazirat Sulab and on the eastern side of Jazirat Sulab water depths are 9 and 13 m, respectively (Fig. 8). The seabed off the city of Al Lith has numerous shoals and was at one-time fed by numerous wadis. Several wadis drain into the lagoon, the most important being Wadi Al Ghallah, while Wadi Rahman and Al Lith drain into the open sea and influence offshore sediment transport (Fig. 8; Table 1). The depth offshore increases gradually to 60 m in the south-west because of substantial sediment input, unlike other areas along the Red Sea where the depth increases abruptly because of a lack of sediment influx. During monsoonal rains, the wadis are flooded, passing through channels that drain into the Red Sea (Höltz and Zötl 1978). A number of studies have been carried out in the

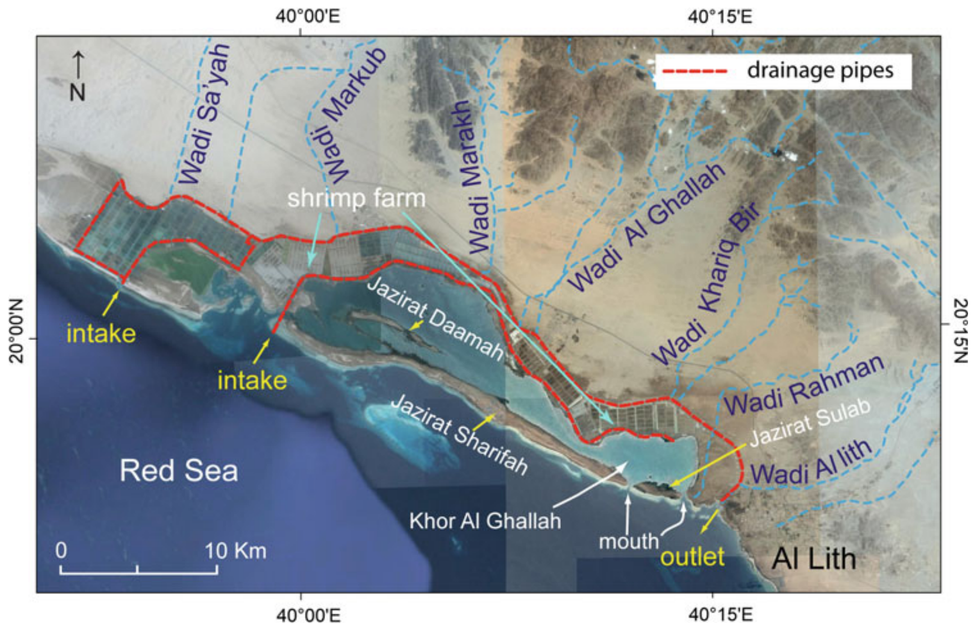

Fig. 8 Khor Al Ghallah and the wadis influencing the coastal and offshore areas

Al Lith region by Hadley and Fleck (1980), Hadley (1975, 1980), Prinz (1983), Pallister (1986), Tag (1986), Abou-Ouf et al. (1988), Heija and Shehata (1989), Tag et al. (1990), Basyoni (1997), Al-Washmi (2002), Al-Washmi et al. (2002), Rasul et al. (2009b).

The coastal zone of Al Lith is a low-lying area that is covered by sediments mostly of aeolian fluviatile marine origin, while shallow marine sediments on the tidal flats are composed of evaporite deposits (Al-Washmi 2002), including sands, clays and clastic carbonates. Geologically the area is part of the Arabian Shield, covered by detrital sediments of the Miocene Baid Formation that is about 30 m thick and composed of conglomerate, sandstone, limestone, marly argillite, chert and basalt, and the Pliocene Bat'Han Formation which is about 35 m thick consisting of conglomerate, sandstone and claystone (Hadley 1975, 1980; Hadley and Fleck 1980; Prinz 1983).

The lagoon is covered with dark-coloured mud to muddy sand, and the offshore area is veneered with sandy mud of terrigenous origin and relatively light-coloured gravelly biogenic sand (Fig. 9, Table 2). The distribution of detrital material is controlled by the local hydrodynamics, and the relative abundance is governed by the particle size and environment of deposition. Very fine sand dominates the lagoon and the offshore areas. The area is influenced by terrigenous input from several wadis draining the Khor Al Ghallah and the onshore area and through several channels connecting the lagoon with the open sea (Fig. 8). Based on the composition of the sand fractions, a model of sediment pathways is presented in Fig. 10.

Discussion

Based on the colour of the sediment in Khor Al Ghallah and offshore Al Lith, two facies have been identified, controlled primarily by provenance: (i) a dark-coloured facies related to terrigenous input, abundant in opaque heavy minerals (Fig. 10a, b) and (ii) a light-coloured facies related to biogenic material rich in carbonate with minor terrigenous influence (Fig. 10a–d). The dark and fine-grained sediments are mostly derived from wadis during occasional rainfall as shown by a relatively higher terrigenous input, where organic debris and iron-rich sediments induce local reducing environments with formation of pyrite, resulting in staining of the carbonate materials (Fig. 10e). Isolated patches of stained foraminifera and shell fragments with pyritic infilling are found in sheltered areas, especially at the foot of the shoals where dark sediments are common. Stained shells and coral debris are related to reducing conditions in quiescent hydrodynamic conditions (Figs. 9 and 10e).

The coarse well-sorted sand and gravel are due to the removal of fines, particularly at the western entrance of the lagoon between Jazirat Sharifah and Jazirat Sulab, by selective sorting generated by strong tidal currents. The fine sediments re-suspended by the current between Jazirat Sharifah and Jazirat Sulab and between Jazirat Sulab and the southern end of the lagoon are transported to the open sea by strong ebb tides that are further enhanced by the narrow channel. At the eastern entrance of the lagoon, the current is relatively weak and loss of sediment takes place when the

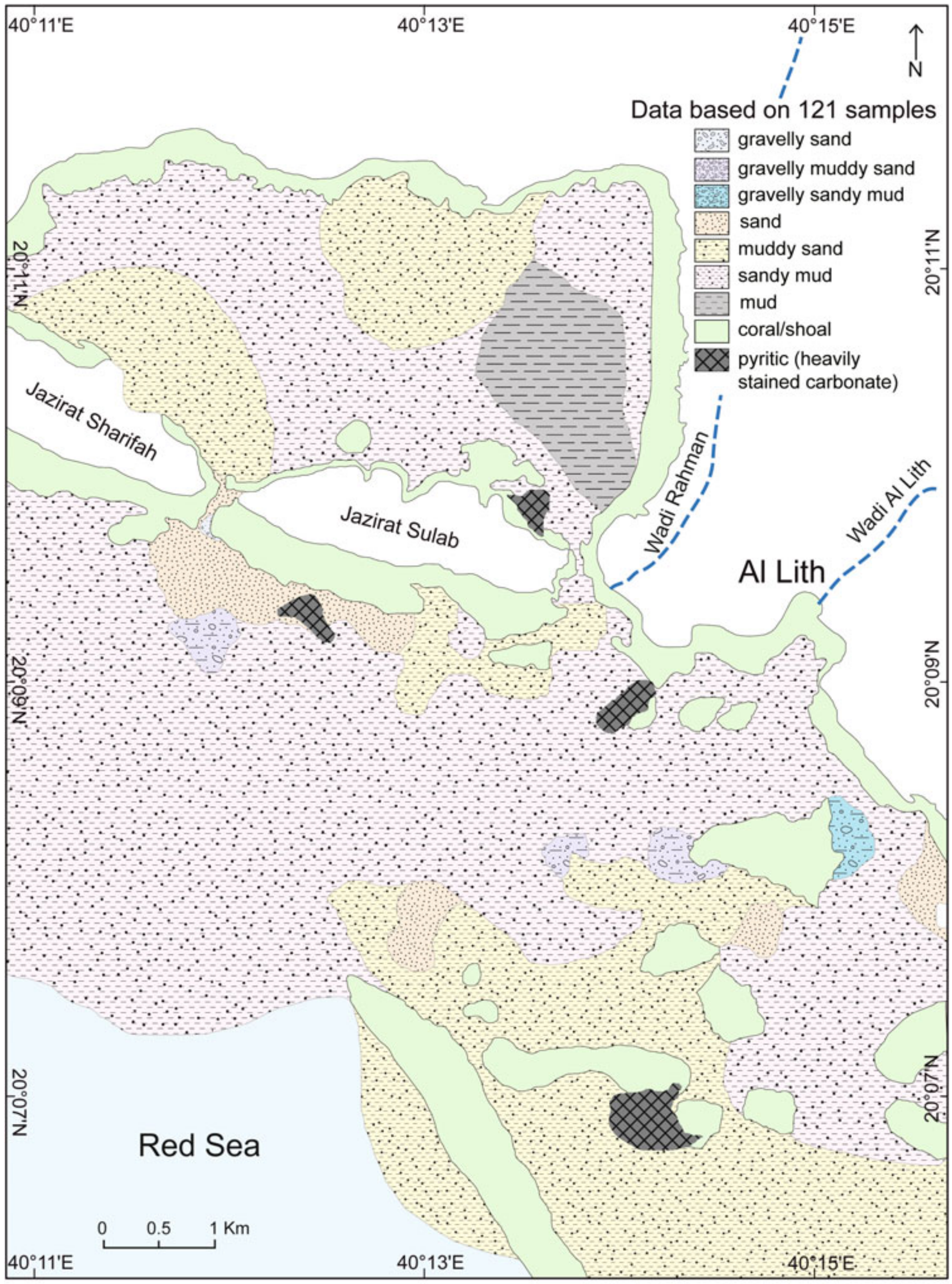

Fig. 9 Sediment distribution in the Al Ghallah lagoon and offshore Al Lith area. The textural classification is based on Folk (1980)

lagoon empties into the open sea. The north-north-westerly winds re-suspend fine sediments that are deposited either on the eastern side and at the margin of the lagoon under quiescent conditions, or are transported to the open water via the narrow channel. Two sedimentary environments are recognized based on the dispersal pattern: (i) a finer terrigenous environment in the south-east, and (ii) a coarser biogenic environment in the west (Fig. 10c, d). In the former, the terrigenous sediments supplied by wadis are dispersed southward (Fig. 10f), whereas the latter environment is veneered with recent biogenic material, and the distribution is governed by strong tidal currents (Fig. 10c, d, g). Sediments in the southern half of the lagoon are a mixture of terrigenous and carbonate materials, while almost pure bioclastic material dominates in the west, especially at the entrance between Jazirat Sharifah and Jazirat Sulab (Fig. 9).

Of the wadis draining into the lagoon, Wadi Al Ghallah is the most important and dominantly influences the sediment distribution. Once the sediment from the wadi enters the lagoon (average depth 2.5 m), the sediments are re-suspended and transported by the strong current generated by the northerly wind in an easterly direction, where sediments

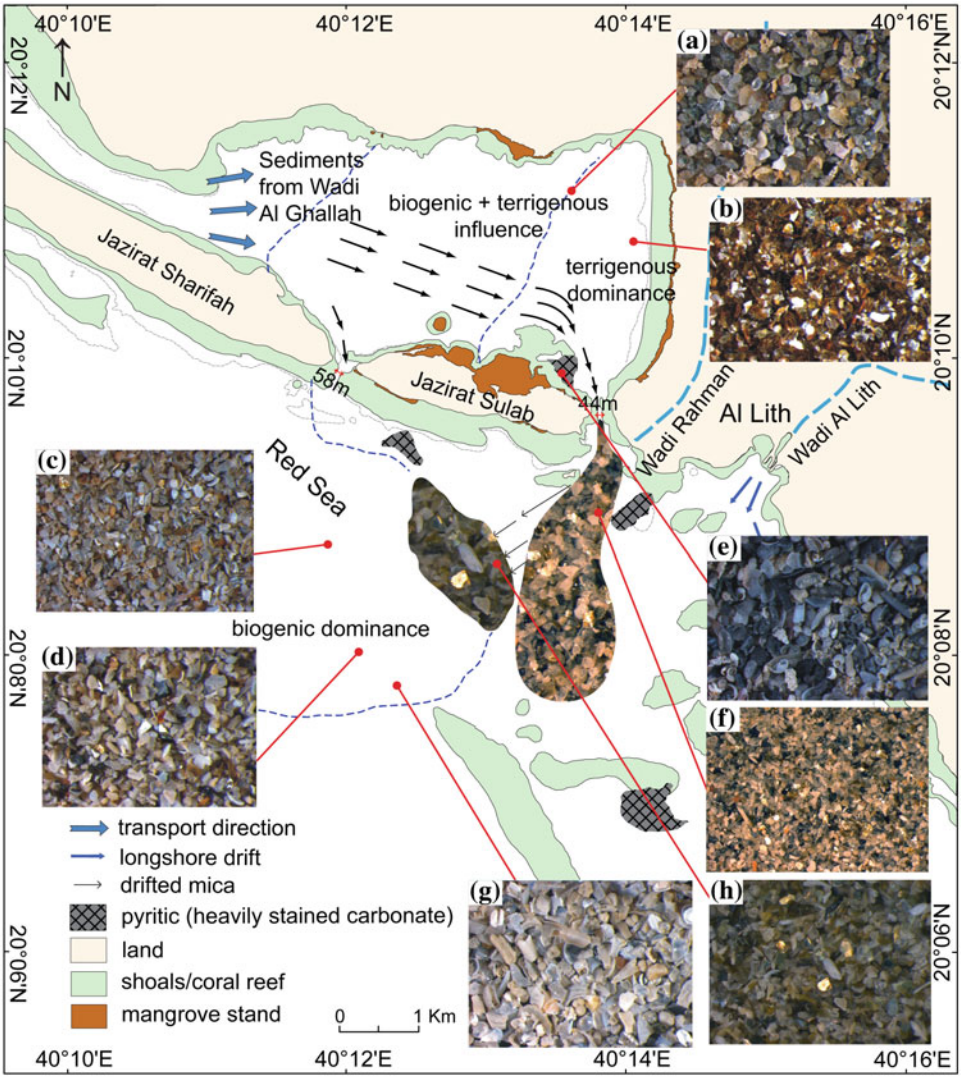

Fig. 10 Sediment dispersal pattern and pathways within the Al Ghallah lagoon and offshore Al Lith: **a** terrigenous material dominates the lagoon; skeletal component enriched in benthic formanifer tests (e.g. miliolids), subordinate benthic gastropods and pteropods with abundant pelagic material; **b** sediments are composed mostly of mica that settles out in a quiescent environment; also includes carbonate bioclasts; **c** carbonate bioclasts dominate; **d** biogenic (bioclasts) material dominates because of the diminishing input of terrigenous material; **e** sediments are stained grey to black because of a reducing environment; skeletal component dominated by benthic molluscs, subordinate ostracods, pteropods and carbonate bioclasts; **f** influence of terrigenous material. Heavy and light minerals are in abundance; skeletal component is dominated by benthic molluscs, subordinate ostracods, pteropods and other carbonate bioclasts including fragments of echinoid spines; **g** biogenic material dominates; skeletal assemblage composed of benthic foraminifers, planktonic foraminifers (e.g. globigerinids), pteropods, benthic gastropods, meroplanktonic stages of benthic bivalves, other bioclasts and higher pelagic input, and **h** abundant terrigenous material; carbonate bioclasts and some benthic foraminifers. However, mica is transported in suspension by surface currents and settles out, and incorporates with the biogenic material under the diminishing effect of current

enter the eastern part via a narrow channel. The re-suspended material also decreases water transparency to about 0.5 m. At the eastern part of the lagoon, the current diminishes appreciably causing deposition of terrigenous material from Wadi Al Ghallah. The terrigenous materials are also transported outside the lagoon in a southerly direction from the eastern opening into the open sea, where the shoals impede sediment transport. Surface currents play a major role in the distribution of mica transported offshore through Wadi Al Ghallah. During sediment transport, mica drifts in a westerly direction either because of the weaker current or with a change in wind direction. Mica mimics clay and stays in suspension for a long time until it settles out, as shown by the presence of mica with biogenic carbonate in the offshore area (Fig. 10h).

Sediments are also transported through secondary wadis present along the periphery of the lagoon. Although Wadi Rahman and Al Lith are important sources of lithogenic material, especially in the eastern part, they do not directly influence the sediment dynamics on the western side. The sediments brought into coastal zones by Wadi Rahman and Al Lith are transported in a south-easterly direction by littoral currents (Al-Washmi et al. 2002), where the dispersal pattern is controlled primarily by the prevailing current. The signature of aeolian quartz is somewhat meagre in the offshore area because the wadis reduce the aeolian influence. The Al Lith sabkhas are bounded on the east by aeolian deposits and are blocked from the Red Sea by coralline limestone (Basyoni 1997). Although the wadis transport most of the quartz, appreciable amounts of aeolian material are transported from the adjoining sabkhas and by severe sand storms that occasionally pass over the Red Sea area.

The lowest carbonate content is in the south-east and in the deeper waters in the south and is mostly derived from biogenic constituents, in places diluted by terrigenous carbonate material mostly derived from Wadi Rahman and Al Lith. The biogenic carbonate content increases with increasing grain size. The carbonate content increases in the western side because of the reduced dominance of terrigenous material (Fig. 9), and a reduction of biogenic material is also caused by climatic factors. The Al Lith area is at the approximate northern climatic limit of the area in south-western Saudi Arabia influenced by two monsoon seasons (NE and SW). The monsoonal wind and rain feed all the wadis substantially in the southern part of Saudi Arabia, and therefore input of terrigenous material plays an important role in diluting the carbonate veneer.

The lack of terrigenous material between the two islands is due to strong tidal currents at the entrance, resulting in fine terrigenous material from Wadi Al Ghallah being transported to the open sea. These currents prevent fine sediment from settling and leave coarse biogenic carbonate as lag deposits, as shown by the sediment texture that becomes coarser with increasing carbonate content. The low or absent carbonate content on the eastern side of the lagoon and in the open sea in the south is due to detrital input from Wadis Al Ghallah, Wadi Rahman and Al Lith. The influx of fluvial material from north to south is restricted to a point where the moving sediments run into the shoals, and the load is deposited.

In general, TOC is higher than normal (>2.0 %), compared to other areas in the Red Sea, and increases with decreasing grain size. In other words, low values are recorded at the northern end where the current winnows the fine sediment and lag material in the form of coarser carbonate fails to adsorb organic material. Most of the area is dominated by values ranging between 0.31 and 0.50 %, and higher values are found in only a few isolated areas, where coarse-textured sediments tend to show higher TOC. This is because the wadis drain through heavily vegetated areas and abundant plant debris supplies organic matter, whereas only scattered patches of vegetation occur on the beach. There is a close relationship between TOC, sediment colour and sediment texture and an inverse relationship between TOC and $CaCO_3$. In general, the finer sediments are richer in TOC compared to coarser sediments rich in carbonate material. However, the status of the lagoon and the influence of the wadis have recently changed due to shrimp farming. The configuration and environment of the lagoon and the influence of Wadi Al Ghallah have greatly altered, with changes in sediment transport pathways and depositional mechanisms in the lagoon and offshore areas (Fig. 8).

Present Status and Future Implications

Human interference has changed the general make-up of the lagoon especially after the construction of a shrimp farm that has retarded the draining of the lagoon by the numerous wadis. It is important that the health of the sediment veneer is studied because of the disposal of the waste water from the shrimp farm in the area. Fresh water input from the wadis into the lagoon is restricted, and therefore, the impact on the environment must be addressed.

Al Khuraybah Lagoon

The Al Khuraibah lagoon is one of the largest and deepest lagoons along the north-east Red Sea coast (Fig. 11, Tables 1 and 2). The geology of the area has been studied by Clark (1987) and the heavy mineral provenance by Nabhan et al. (2010). The Khuraybah region contains Proterozoic stratiform and highly folded volcanic, volcaniclastic and secondary epiclastic rocks of greenschist facies (Sahl 1981). Sedimentary rocks of Mesozoic and Cenozoic age encompass the eastern side of the lagoon. The southern part of the Al Khuraybah Formation consists of reefal limestone that extend along the coastal area, and the upper part of the Khuraibah region consists of limestone and sandstone that overlie the palaeo-relief extending northward and dipping gently under the sand and gravels of the Ifal plain (Nabhan et al. 2010). Part of the coastal Al Khuraybah area is composed of a reefal limestone platform covered by sand and mud. The lagoon is separated from the open water of the Red Sea by many convoluted shoals and coral reefs, and the entrance to the lagoon from the open sea for shallow-draft boats only is restricted to a couple of narrow channels that cut the shoals (coral reefs). The lagoon was once fed by several wadis, although some are now dormant and relict channels can be seen on satellite images (Fig. 12). Wadi Aynunah is one of the major wadis that supply the lagoon with eroded material from the mountains; this wadi is now populated and contains farms (Fig. 11a).

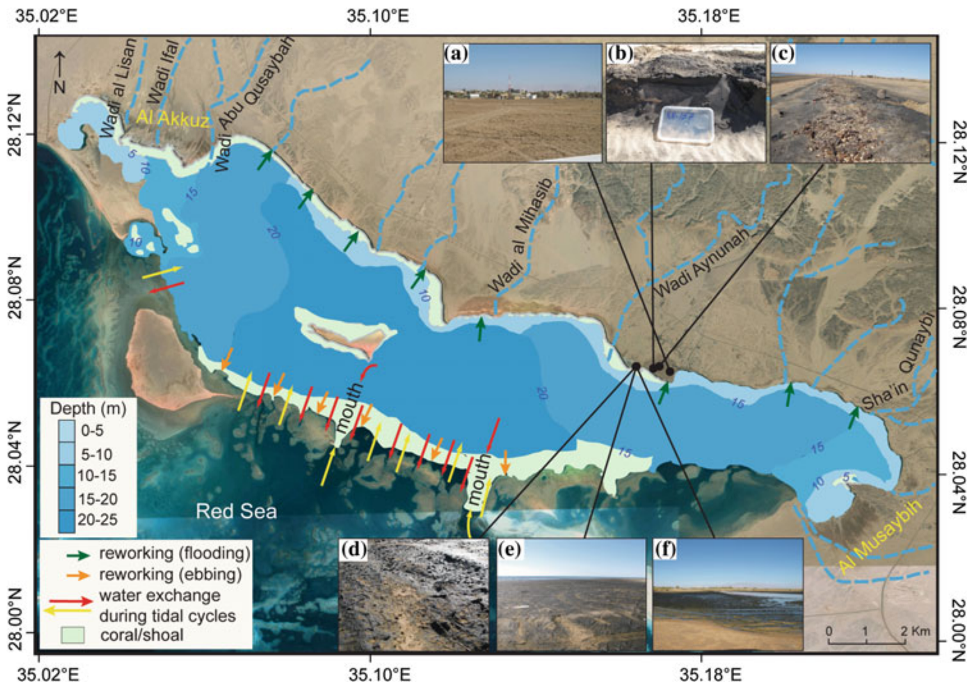

Fig. 11 Bathymetry of Al Khuraybah lagoon and model showing exchange of water between the Red Sea and the lagoon and the process of reworking during flood and ebb tides: **a** Wadi Aynunah, a major wadi supplies the lagoon with eroded material from the mountains, is now populated and used as farm land; **b**, **c** abundant sand size heavy minerals on the beach and intertidal zone consist mainly of biotite, magnetite and ilmenite, giving the sand a black appearance, and **e**, **f** high organic content and decomposed organic debris on the flat low-lying areas are inundated with water during tidal cycles

The lagoon is veneered with mud to muddy sand of both terrigenous and biogenic origin. The abundant mud in the central deeper part of the lagoon is mostly terrigenous, and carbonate is contributed by churning of the seabed sediment by trawling, making the carbonate material even finer (Fig. 12). The re-suspended sediment stays within the lagoon since there is no major outlet to the open sea, and sediment input from the wadis to force sediment out of the lagoon is almost completely absent, whereas in sheltered areas, terrigenous mud and sand are present (Fig. 13). Parts of the coast and shallower areas of the lagoon are veneered with lithogenic sandy mud, while carbonate dominates in other parts of the lagoon where the wadi influence is minimal. Staining of carbonate material is observed in areas where trawling activity is absent. There are well-sorted terrigenous materials, from gravels to cobbles, and wind-blown sand is common along the beach. There are abundant heavy minerals on the beach and offshore, and intertidal zone beach sands consist mainly of biotite, magnetite and ilmenite, giving the sand a black appearance (Fig. 11b, c). Biotite is abundant in the deeper and calmer areas.

In the western part of the lagoon, the sand is mostly of biogenic origin, supplied by fragmentation of reefal limestone and corals. The 0.9 m tidal range results in the transport of mud, and especially mica, in suspension to the open sea during ebbing, while carbonate material of biogenic origin settles at the foot of the coral reef system. During flooding, the water from the Red Sea reaches the lagoon by overspilling; this exchange of water makes the lagoon less saline (39 %) compared to other lagoons where the exchange of water is more limited. However, movement of sediment is restricted because of the shoals. The base of the shoals and Jazirat Umm Shujayrat Island are composed mostly of carbonate materials, and the western side is almost devoid of terrigenous material probably because the flow and transport direction is towards the south-east. Surprisingly, the lagoon lacks gravel-sized material of biogenic origin, indicating that the bulk of the material is from the wadis draining into the lagoon. The beach is covered by algal mats, especially where the influence of Wadi Aynunah was once significant and organic debris together with seagrass was transported to the lagoon and also deposited on the narrow beach in the vicinity of the mouth of Wadi Aynunah (Fig. 11d, e). High organic content and decomposed organic debris were noted on the flat low-lying areas that are inundated with water during spring tides (Fig. 11e, f). At present, pools of water are also stored in the Sharma area where salt is extracted after evaporation. The lagoon and low-lying areas are now

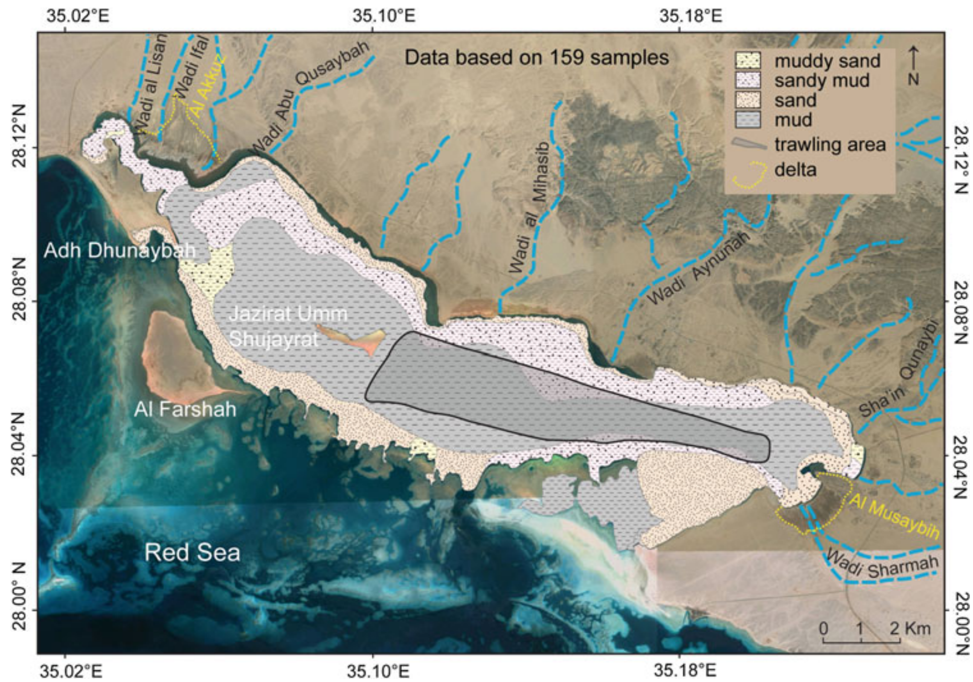

Fig. 12 Sediment distribution map and the wadis feeding the Al Khuraybah lagoon. The textural classification is based on Folk (1980)

fairly polluted by dumping of large amounts of shrimp waste. The composition of the Al Khuraybah lagoon is presented in Fig. 13a–o.

Present Status and Future Implications

The trawling activity has stopped in the lagoon, and therefore, the bed is not as in imbalance as before. Human activity such as salt extraction and boating activity is still common, but the environmental stress has minimized. The input of fresh water to the lagoon is still restricted because of farming practices and construction in the path of the wadi. This might have an impact on the lagoon, but at the present time, the status of the lagoon and the coastal belt is quite healthy.

Al Wajh Lagoons

The lagoons in the northern Red Sea are narrow incisions through coralline ridges extending for a few hundred metres and trending almost perpendicular to the coast. These are sometimes connected to a wadi system of varying dimensions (Table 1). Contemporary coral growth occurs in these lagoons at different depths and the entrance is always over 30 m in depth. At the entrances to these lagoons, the depth often increases abruptly by more than 60 m to a few hundred metres offshore. Five lagoons along the Al Wajh coast were sampled for sedimentological studies, and dives were conducted to study the distribution of corals.

The corals in the Al Wajh area are presently undergoing varying degrees of stress either through natural causes (wadis flushing, winds, currents) or human intervention that control their health and distribution patterns. All the dive sites have steep slopes down to 30 m depth with maximum water clarity, and coral colonies are shaped by the strong northerly wind and water currents. The corals studied were at 5 m water depth. The lagoons house fishing villages and are frequented by visitors, resulting in signs of deterioration in coral growth and health. Some species flourish under severe conditions, but others are vulnerable to slight changes in the environment. The configuration of the lagoons and types of bottom sediments are summarized in Figs. 14, 15, 16, 17, 18 and Table 2.

Al Dumaygh Lagoon

The lagoon is veneered with sandy mud and muddy sand with shoals where the corals are in good health. A coastguard facility is located within the lagoon. The north-western part of the lagoon shows raised coral reef terraces and the south-eastern part has small isolated mangrove stands of *Avicennia marina* and small budding shrubs. A small island separates the lagoon from the open water of the Red Sea, and a narrow 14 m channel allows limited exchange of water only during

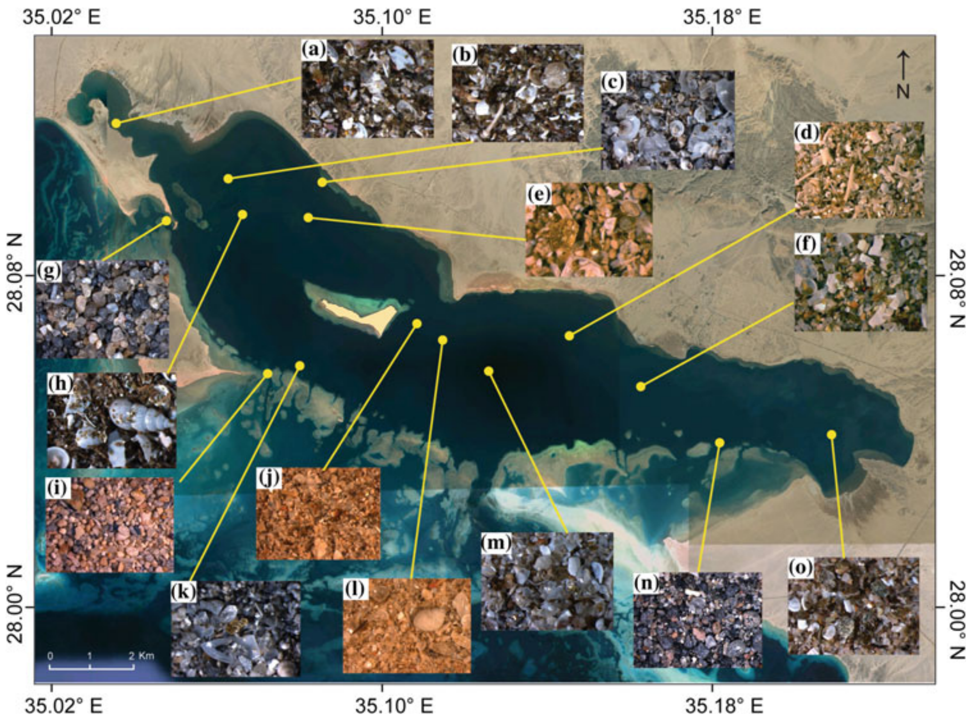

Fig. 13 Sediment composition of the Al Khuraybah lagoon. Terrigenous material composed of abundant mica, quartz, feldspars, magnetite and other opaque heavy minerals is from the numerous wadis draining into the lagoon, while carbonate material is mostly biogenic in nature: **a** mica is common; carbonate skeletal assemblage includes benthic foraminifers, echinoid spines, bivalve fragments and bioclasts; **b** mica is common; carbonate skeletal assemblage dominated by whole and fragmented benthic foraminifers, and bioclasts; **c** devoid of terrigenous material; carbonate skeletal assemblage dominated by whole or fragmented benthic gastropods, bivalves, subordinate echinoid spines and others; **d** mica and haematite and some magnetite; abundant carbonate skeletal assemblage dominated by echinoid spines, bivalves, ostracods, benthic forams and others; **e** mica and haematite present; carbonate skeletal assemblage includes bivalve shells and other bioclasts; **f** abundant mica; carbonate skeletal assemblage includes benthic gastropods, benthic foraminifers, bivalves and others; **g** abundant quartz, feldspars and undetermined stained grains; scarce carbonate skeletal assemblage composed of bioclasts; **h** abundant mica; coarse skeletal assemblage dominated by benthic microgastropods (e.g. *Finella*) and bivalve fragments; **i** some quartz, feldspars and stained material; abundant carbonate skeletal assemblage including fragmented gastropods, bivalves and bioclasts; **j** palimpsest sediments and carbonate skeletal assemblage including benthic foraminifers; **k** abundant mica and quartz; carbonate skeletal assemblage composed of bivalve fragments, benthic gastropods, benthic foraminifers and others; **l** devoid of terrigenous material; abundant carbonate skeletal assemblage including benthic gastropods, bivalves and bioclasts; **m** mica and feldspar present; scarce carbonate skeletal component with benthic foraminifers, echinoid spines and others; **n** opaque heavy minerals with quartz carbonate skeletal assemblage composed of bivalve fragments, benthic gastropods, echinoid spines and others and **o** abundant muscovite and biotite and quartz; rare carbonate skeletal component and bioclasts

high tide when low-lying areas are covered by shallow water. The sediment is mostly of biogenic origin, but aeolian quartz is abundant and eroded material from the raised terraces and fragmented shells are common because of human activity. The sediments are generally poorly sorted except at the entrance where the sediment is moderately well sorted because of strong tidal currents. Terrigenous material in the form of quartz, feldspars and some mica is transported to the lagoon by Wadi Umm Ushsh and its distribution is controlled by the large number of shoals. At 5 m water depth, the corals are healthy and comprise both hard and soft corals. There is a small fishing community, and some local pollution is present because of litter dumping by visitors and fishermen. Recently killed corals are common because of fishing activity, and dead corals make up 20 % of the total. Examples of the types of sediments and corals are presented in Fig. 14a–d.

Al Hawwaz Lagoon

Sandy mud dominates the bottom of this lagoon followed by muddy sand, but a few patches of gravelly sand of biogenic material occur. Shoals are common in the lagoon and control sediment transport. The narrow channel connecting the

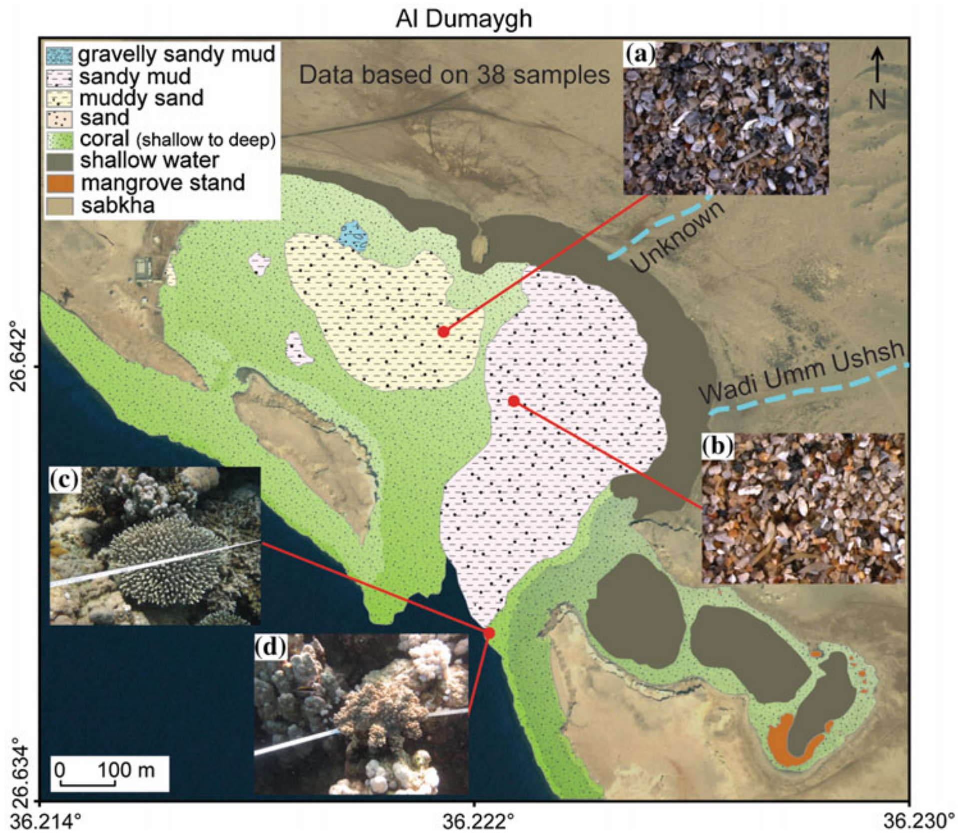

Fig. 14 Al Dumaygh lagoon **a** sediment mostly biogenic; **b** terrigenous material (product of Wadi Umm Ushsh); **c** Scleractinian corals Acropora in the foreground and Porites in the background, respectively, and **d** Alcyoniid and Xeniid soft corals in the foreground, scleractinian coral Porites in the background on the *left side*

lagoon with the Red Sea is not as dynamic as the other lagoons and no wadis flow into the lagoon. At the north-eastern end, there are raised coral terraces in which channels formed by rainfall supply terrigenous mud to the lagoon. The southern part of the lagoon is low-lying and during high tide, part of the surrounding area is inundated with water. A reducing environment stains the biogenic grains because of the restricted exchange of water. At 5 m water depth, corals are healthy and comprise both hard and soft corals. However, some have been impacted by human activities and have died. Examples of the types of sediments and corals are presented in Fig. 15a–d.

Antar Lagoon

This lagoon is fed by Wadi Antar, one of the larger wadis in the northern Red Sea coastal area (Table 1) and the wadi head is connected to numerous distributary channels. The lagoon bottom is veneered with sandy mud and muddy sand. Sand in the eastern part of the lagoon is mostly of terrigenous origin transported by Wadi Antar. Sediment at the entrance is moderately sorted because of current effects. During spring tide, the eastern part is inundated with water as it is flat and low lying and the angle of repose is nominal because of input from the wadi. Abundant mica, quartz and feldspars are contained in the lagoon sediments. At 5 m water depth, the corals are healthy and composed of both hard and soft species but are dominated by hard massive branching corals, some of which have been damaged by either strong waves or fishermen; dead corals make up 20 % of the total. It is an isolated lagoon with little or no influence from tourism. Examples of the types of sediments and corals are presented in Fig. 15a–d.

Mina Al Wajh Lagoon

The head of the lagoon is low-lying and numerous channels drain into the lagoon during rainfall. Wadi Ash Shijnah has a bigger basin, but Sha'ib Umm Sidrah with a smaller basin influences sediment distribution in the lagoon (Table 1). Because the area is flat, sea water inundates the sabkhas and channels during spring tides and transports terrigenous material, mostly in the fine fraction, to the lagoon during ebbing. Aeolian quartz, feldspars, calcite and opaque heavy minerals are abundant in the lagoon. The bottom sediment is mainly muddy sand of terrigenous origin with subordinate biogenic materials. The wide mouth of the lagoon is strongly influenced by wind- and wave-generated currents, supplemented by tidal effects. The sediment at the mouth is well sorted but contains over 60 % carbonate material made up

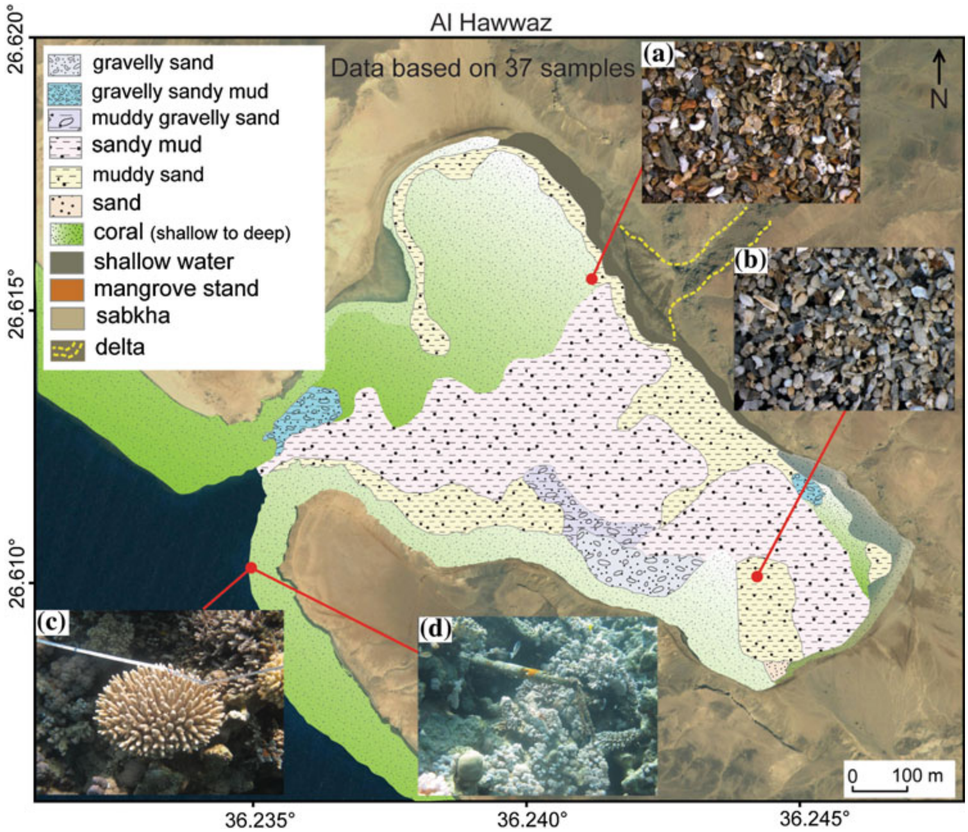

Fig. 15 Al Hawwaz lagoon **a** carbonate skeletal component includes benthic gastropods, benthic foraminifers (e.g. miliolids) and undetermined bioclasts with minor terrigenous influence from the adjoining hills; **b** carbonate skeletal component includes benthic foraminifers (e.g. miliolids) and undetermined bioclasts; sediments are stained black because of a reducing environment; **c** scleractinian coral Acropora in the foreground and Xeniid soft corals in the background on the *left*, and **d** mixed assemblages dominated by Xeniid soft corals Alcyoniid, a massive colony of the scleractinian coral genus *Goniastrea* in the foreground on the *left side*; fishermen in this area are the worst enemy of the corals, and natural factors are also of concern because the impact of sediments from the wadis on the lagoon and strong waves generated by northerly wind cause only the fittest species to survive

mostly of coral debris and shell fragments followed by terrigenous mud supplemented by aeolian quartz. At the head of the lagoon almost 80 % of the bottom sediment is composed of terrigenous material of Sha'ib Umm Sidrah origin. Staining of terrigenous grains and shell fragments is common, due to organic and anthropogenic input. The cohesive terrigenous mud adsorbs pollutants and organic material supporting the formation of a reducing environment. There is a coastguard office at the entrance to the lagoon as well as a fishing village, and the lagoon is frequently visited, resulting in some local pollution. At 5 m water depth, the corals are under stress and dead corals are common because of fishing and other activities. Waste water from the desalination plant located in the north is emptied into the Red Sea, with some impact on the lagoon, contributing to the demise of hard corals. Examples of the types of sediments and corals are presented in Fig. 17a–c.

Al Habban Lagoon

The north-eastern part of this lagoon is connected to a sabkha and residential complex. The two wadis draining into the lagoon do not influence the sediment distribution pattern. The eastern part is shallow, and a channel that drains into the lagoon brings in lithogenic material. The northern periphery is veneered with muddy sand of biogenic or aeolian material. The lagoon is veneered with sandy mud to muddy sand, and staining of biogenic material is locally observed. The walls of shoals/coral beds dip steeply on the north-western and south-western side. At the mouth, the depth increases abruptly, and the bed is mostly covered with muddy biogenic sand that is moderately sorted because of local water currents. At 5 m water depth, the corals are healthy and composed of both hard and soft corals. Some nearly dead

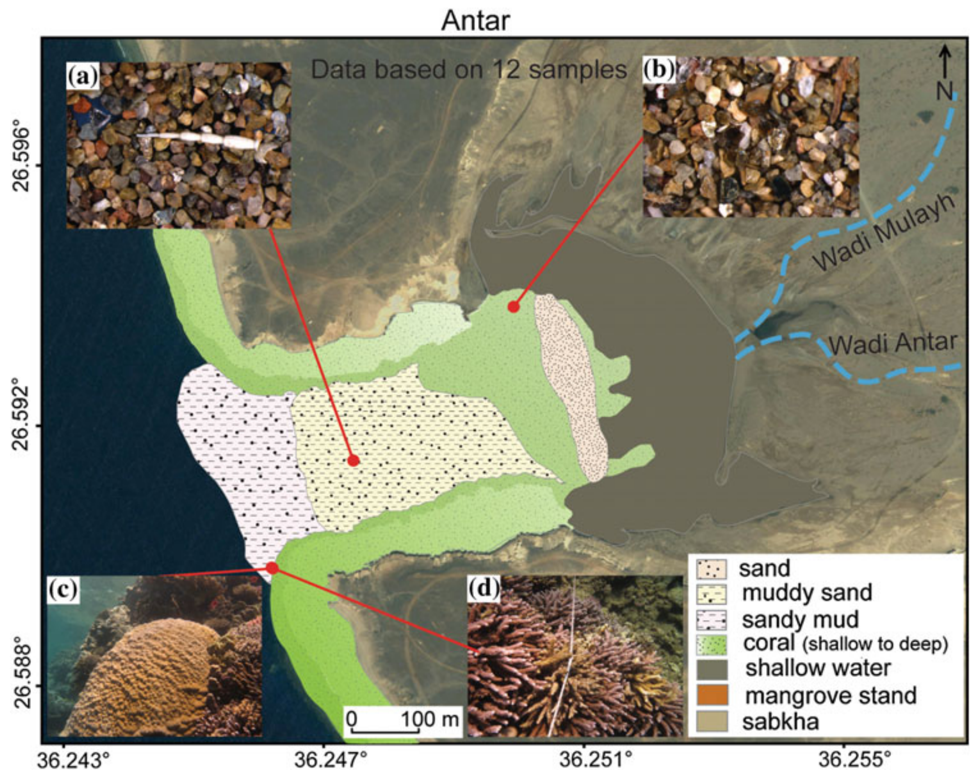

Fig. 16 Antar lagoon **a** carbonate skeletal component with benthic forams and other undetermined bioclasts and biosomes; biogenic material diluted by the sediments from Wadi Mulayh and Wadi Antar; **b** sparse carbonate skeletal component with undetermined bioclasts; biotite and muscovite are supplied by the wadis; **c** massive Porites scleractinian corals, and **d** branching Acropora scleractinian coral

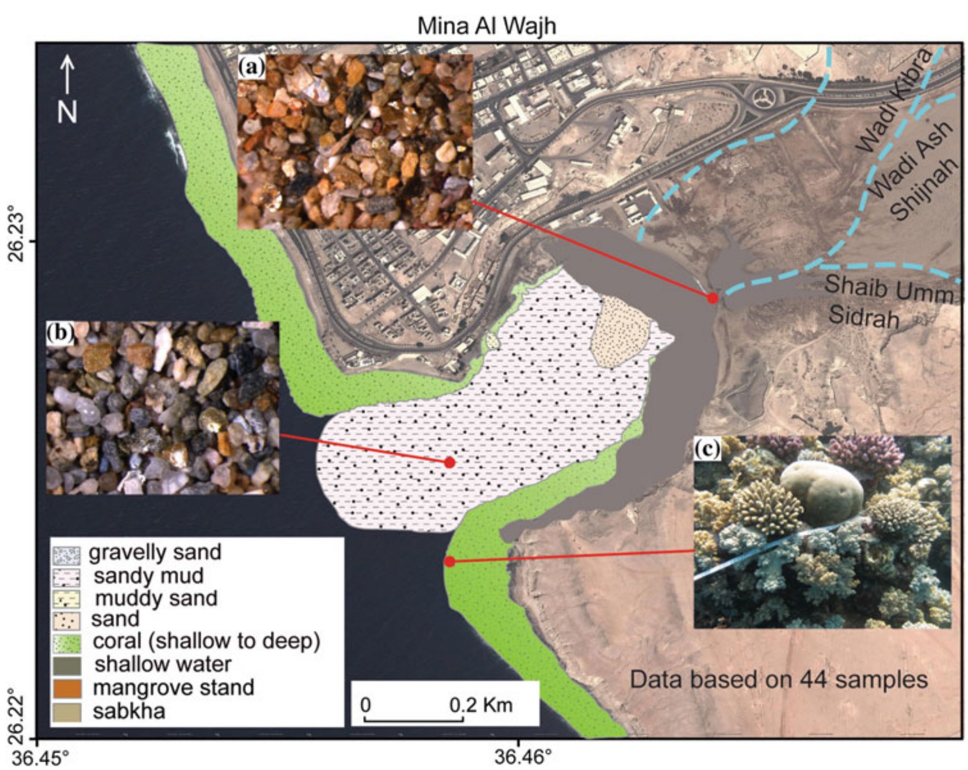

Fig. 17 Mina Al Wajh lagoon **a** sparse carbonate skeletal component with undetermined bioclasts; abundant input from the adjoining wadis; **b** sparse carbonate skeletal component with benthic forams and undetermined bioclasts; carbonate veneer diluted by the terrigenous input from the wadis; **c** *top half* shows digitate scleractinian corals Acropora (pale beige), and a massive Goniastrea, Alcyoniid soft corals at the *bottom half*

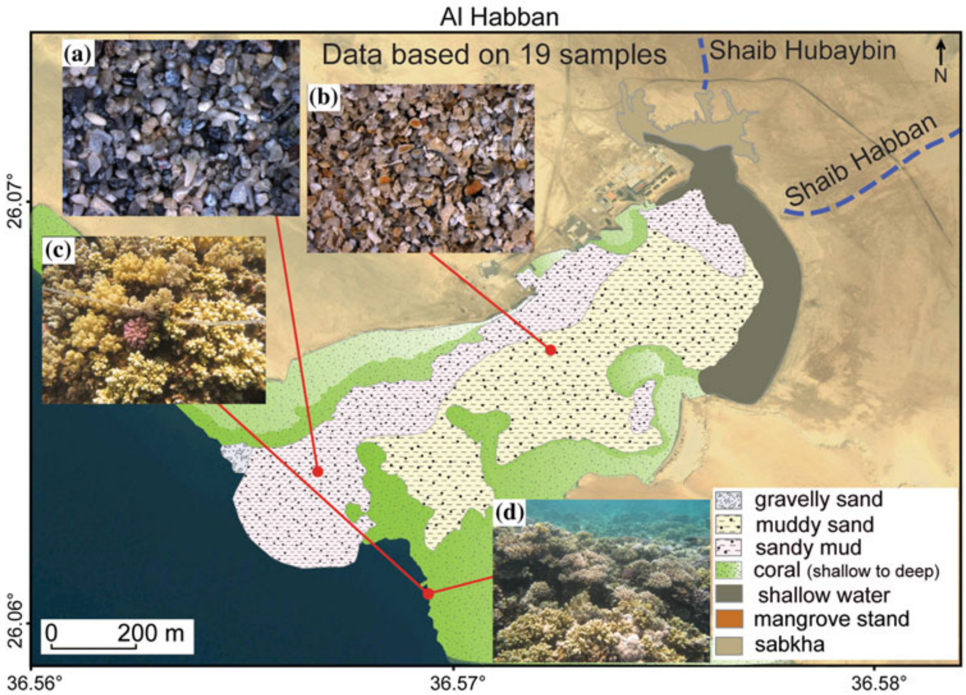

Fig. 18 Al Habban Lagoon **a** minor carbonate skeletal component, including benthic foraminifers and undetermined bioclasts; stained because of reducing environment; **b** carbonate skeletal component includes benthic foraminifers, benthic gastropods and undetermined bioclasts; **c** branching scleractinian coral Acropora (*on the right*) and Alcyoniid soft corals *on the left*) and a purple colony of pocilloporid scleractinian coral, and **d** digitate and branching Acropora and pocilloporid dominated benthic assemblage with some Xeniid soft corals; coral flourishes where human activity is minimal

coral areas have recovered after the removal of the coast-guard station brought about a change in the degree of stress. Examples of the types of sediments and corals are presented in Fig. 14a–d.

Al Kharrar Lagoon

The Al Kharrar lagoon is the second largest lagoon along the Red Sea coast of Saudi Arabia into which numerous wadis drain (Fig. 19, Table 1). Mud to gravelly sand of both terrigenous and biogenic origins veneer the bed of the lagoon (Fig. 20). Numerous studies have been carried out on the sedimentology, mineralogy and faunal assemblage of the Al Kharrar lagoon and its associated sabkhas (El-Abd and Awad 1991; Behairy et al. 1991; Abou-Ouf 1992, 1996; Gheith and Abou-Ouf 1994; Al-Washmi 1999; Al-Washmi and Rasul 2003; Basaham 2008; Rasul et al. 2010a). These include the processes responsible for the varied sediment cover and its relationship to the bathymetry and current patterns, including the role of wadis and sediment provenance in controlling the environment of deposition. A summary of the data is presented in Table 2.

The lagoon is connected to the Red Sea via a channel about 150 m wide, and although artificial connections using pipelines were installed for exchange of water during tidal cycles (Fig. 19a), these have become blocked by sediment and debris. In 2013, new openings were created to flush the nutrient-rich water to the Red Sea because of pollution concerns and excessive algal growth and seagrass in recent years.

The lagoon is bounded by inter-tidal flats and sabkhas in the south that are occasionally covered by shallow water extending about 3 km inland (Fig. 19b). Northerly winds influence the movement of water and sediments from the lagoon to the adjacent sabkhas in the south, particularly during spring tides, and southerly winds and ebb tides bring fine sediments into the lagoon, especially during occasional rainfall. Although tidal forcing is important at the mouth, transport inside the lagoon is essentially a wind-driven phenomenon. The shallow depth combined with the constricting effects of the channel decrease the tidal transport as

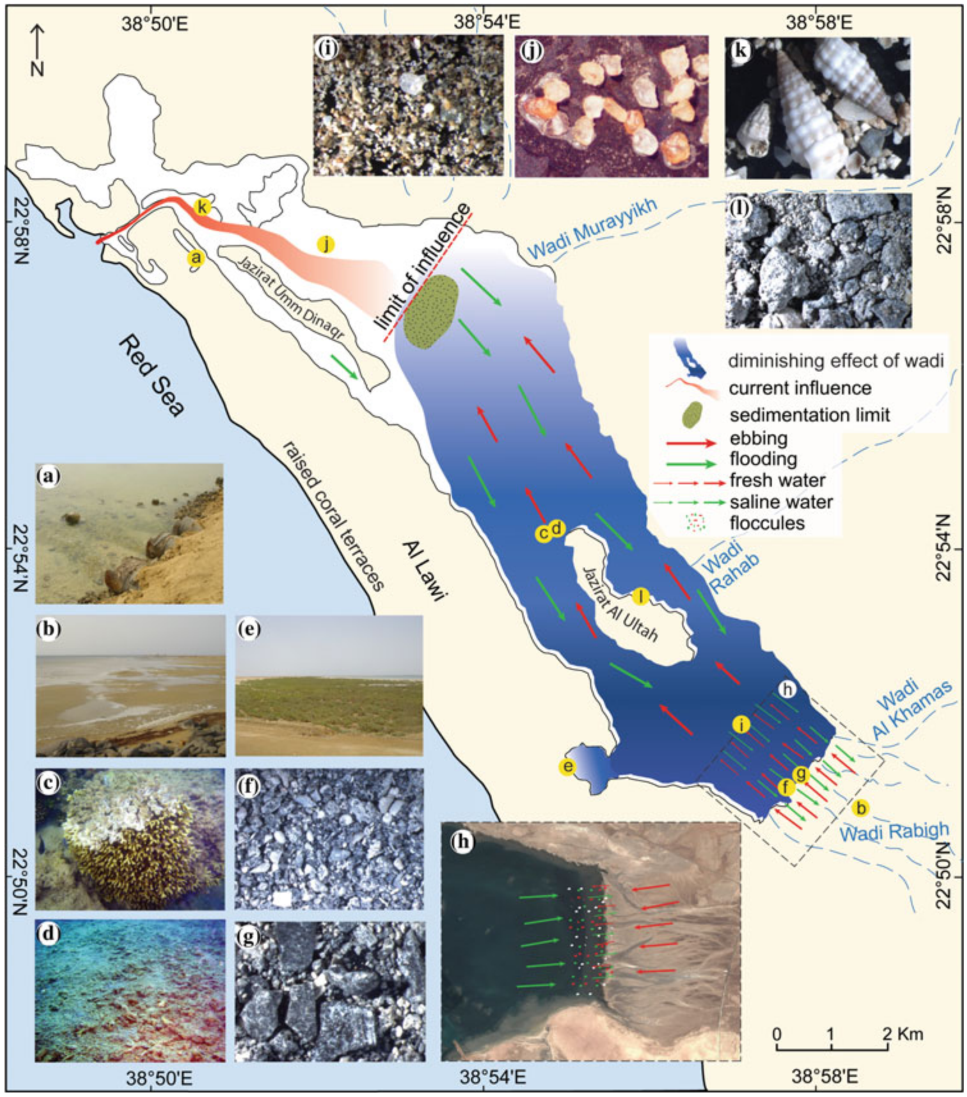

Fig. 19 Al Kharrar lagoon **a** pipeline that once exchanged water between the lagoon and the Red Sea; **b** during spring tides the water travels about 3 km inland, inundating the adjoining sabkhas; **c** coral covered with algae and fine sediments; **d** graveyard of corals resulting from human activities (anchoring, fishing and diving); **e** shrubs in the southern part of the lagoon thrive on nutrient-rich water and stagnant conditions; **f** and **g** shells and coral debris are stained brown to black in a reducing environment; **h** flocculation is initiated by the mixing of fresh and saline water; **i** mixture of aeolian and fluvial quartz; **j** aeolian quartz is common in the northern part of the lagoon where the influence of the wadi is limited; **k** gastropod shell (*Cerithium* sp.) a contemporary input from the Red Sea, and **l** remnant of reefal sediment (calcium carbonate)

distance from the mouth increases, so that wind becomes the primary transport mechanism inside the lagoon. Waves generated by strong local winds winnow fine sediments at the margin of the lagoon and transport sediment to deeper water.

The fine sediments are dark in colour with shades of grey, whereas the coarse sediments are lighter and brown to greyish brown. The sediment veneer mostly comprises coarse-grained sediment in the north and north-west and in shallower water. At the southern end and in deeper water, bottom sediments are dominated by fine-grained sediments. At the mouth, very coarse sand to gravelly sand of biogenic origin dominates because of strong tidal currents that winnow the sediments. Biogenic material is supplied to the lagoon by mechanical breakdown of shells and coral reefs, and by boring marine organisms. Additional biogenic material is supplied to the lagoon by the Red Sea, making the lagoon a poorly sorted environment. Mud to very fine sand of detrital origin is common in the south where the wadi fringes the lagoon.

Corals including *Sarcophyton* and *Poritessolida* and many more are common in the lagoon. Some corals are under stress because of re-suspension of sediments by strong currents, and because of this, coral growth is limited (Fig. 19c). Dead corals are covered with algae and very fine sediments accumulate on the corals following cessation of the currents (Fig. 19d). Human interference has also led to loss of coral reefs, but there are areas where the corals and marine life are in good health.

Mangrove (*Avicennia marina*) stands are scattered around the islands and at the margins, especially in the south, where seagrass also thrives where water from the wadis and lagoon meet. Stagnant conditions prevail at the south-western tip of the lagoon where there is some pollution and the nutrient-rich water supports growth of land shrubs and marine plants including algae and seagrass (Fig. 19e). Several species of

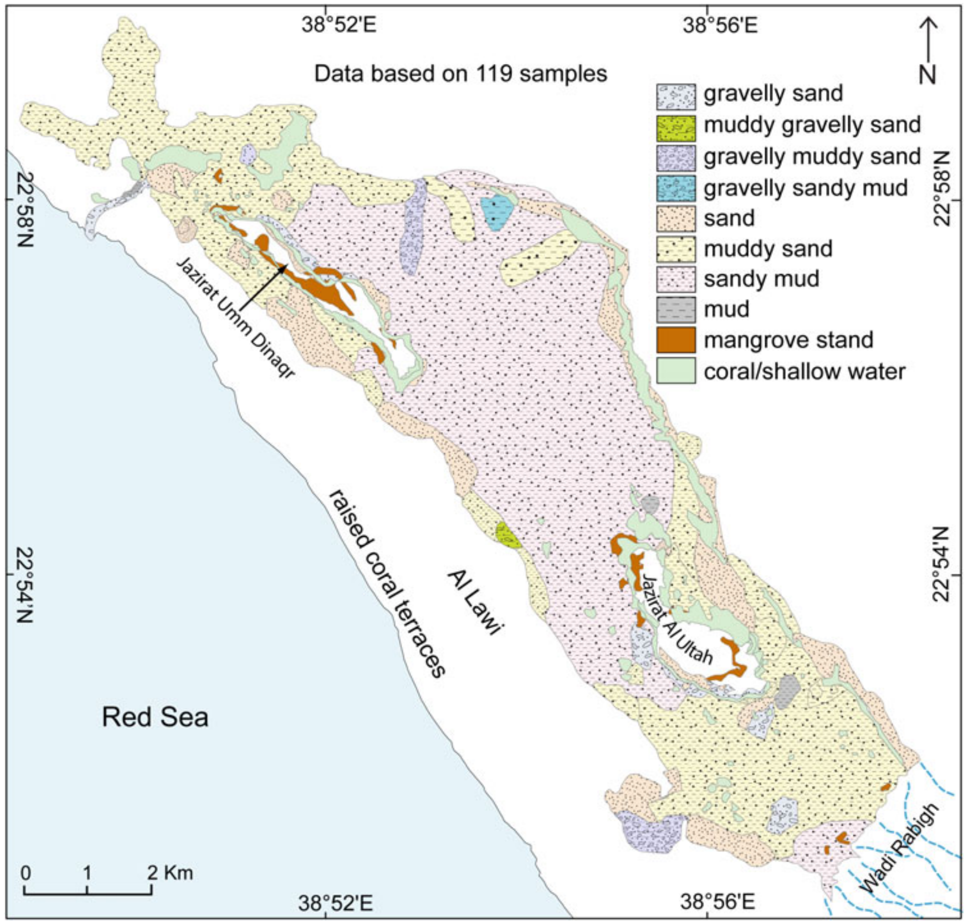

Fig. 20 Sediment distribution in the Al Kharrar lagoon; lagoon is mostly covered with sandy mud of both biogenic and detrital origins. Textural classification is based on Folk (1980)

macro-algae, including *Laurenica*, *Halimeda*, and *Sargassum*, and blue-green algae are present in the lagoon. Halophytes occur mainly in the south (Marine Studies Section 2000).

Discussion

Based on the sediment colour and particle size, two sedimentary environments are identified, controlled primarily by sediment source and physico-chemical properties: (i) a dark-coloured facies in the south, associated with fine terrigenous sediments, and (ii) a light-coloured facies in the north, associated with coarse biogenic sediment. Sandy mud dominates the middle and deeper parts of the lagoon, while muddy sand is common in the southern and northern parts (Fig. 20). The mixing and the coarse nature of the sediment results in poor sorting that is exacerbated by the presence of biogenic materials of varying grain size and grain fragmentation resulting in a bimodal-to-multimodal sediment distribution, especially near the islands where human access is frequent. Although aeolian materials are abundant and known to be very well sorted, the area comprises poorly sorted sediment because of mixing from multiple sources.

The mostly biogenic sediments are stained grey-black because of reducing environments close to the mangrove stands and in areas where stagnation prevails. High sedimentation favours a reducing environment in the presence of high productivity, as observed in the south, and the supply of organic debris by the mangrove stands, seagrass, algae and green foliage around the lagoon results in the dark colour, especially for fine sediments that are more prone to adsorption. The carbonate material is also stained grey-black as a result of the reducing environment that is enhanced by the organic debris. The dark or tarnished shell and coral debris are stained black only on the outer surface (Fig. 19f, g). Similar staining is common in the recent sediments of the Arabian Gulf (Murray 1966), the Bahamas (Illing1954) and the coastal sabkhas of the Red Sea (Abou-Ouf and El-Shater

1993), and in other lagoons along the Red Sea (Rasul et al. 2009a, b, 2010b, 2014).

The coarse light-coloured sediments reflect the removal of fine sediment, particularly at the entrance, by the sifting action of wind- and wave-generated currents and strong tides with velocities of around 1 m s^{-1}. The tidal current becomes stronger as it enters the mouth of the lagoon due to the constricting effect of the narrow channel (about 150 m wide) and diffuses as the entrance widens, resulting in the deposition of fine sediments (Fig. 19). The currents control the bathymetry at the entrance, as well as transporting fine sediments to the margins of the mouth where they settle out to form channel-levee-like structures. The re-suspended sediments at the entrance are also transported into the main lagoon, following the Red Sea saline water trail during flood tide, to be deposited in the deeper water in the lagoon (Fig. 19h). Some sediment is lost to the Red Sea during ebbing and is then transported to the south along the coast that parallels the lagoon (Rasul et al. 2014). During the rainy season when the wadis are most active, mixing of freshwater from the wadis and saline water from the Red Sea occurs, causing flocculation of fine sediments, especially in the south (Fig. 19h); this fine sedimentation is enhanced by the addition of the clay mineral kaolinite that is abundant in sedimentary deposits around the Red Sea and is transported into the lagoon by the wadis, especially through Wadi Rabigh (Rasul et al. 2010a).

Frequent dust storms over the Red Sea contribute a significant quantity of stained quartz of silt to fine sand grain size. The abundant biogenic material is derived from the attrition of corals by strong currents and human interference. Biogenic material dominates except in the south, where the detrital component is supplied to the lagoon via the numerous wadis originating to the south. Sediments brought into the lagoon are supplied by flash floods, wind (aeolian flux) and fragmentation of corals and shells (biogenic input). Since the lagoon is affected by strong tidal currents, the roundness of individual sediment grains, both detrital and biogenic, is important in understanding the effect of currents in governing sediment distribution patterns. Two dispersal pathways evolving from the wadis in the south and running in the north-westerly direction are controlled by ebb tides in general as well by rainfall (Fig. 19).

The degree of roundness of both aeolian and wadi-derived quartz differs significantly (Fig. 19i). The fine-grained aeolian quartz, due to tidal currents, is more rounded especially at the mouth (Fig. 19j), than the coarse-grained fluvial (mostly wadi-derived) quartz in the south that is relatively less rounded in the finer fraction but more rounded in the medium sand size fraction. This is due to movement during the tidal cycles, the shallow water and influence of the wadis. The relatively low roundness of the quartz transported by the wadis indicates that it is perhaps a single-cycle deposit derived from the parent metamorphic and igneous rocks. Both angular and subangular biogenic grains are present, and the low degree of roundness is attributed to constant breaking down by currents and boring by marine organisms. Whole shells and shell fragments are fresher in appearance in the north than in the south (Fig. 19k). The freshness and polished surfaces of shell fragments in the north are caused by constant agitation of water or their recent addition from the Red Sea, and the number of whole shells increases in the south because of reduced water agitation. The weak current does not have much influence on the attrition of biogenic grains nor is it capable of polishing their surfaces; hence, biogenic materials in the southern part of the lagoon are more intact and show a dull lustre.

In the Red Sea, vigorously growing coral, fringing reefs and barriers play a significant role in the very high production of carbonate and reefal sediments. $CaCO_3$ is contributed to the lagoon through the erosion of reefs by wave and current action, destruction of reefs by fishermen and nibbling of corals by fish (Fig. 19l). The source of the carbonate in the Al Kharrar lagoon is undoubtedly the reef system. Basins along reef-bound coasts with significant runoff and high aridity are the most probable source of carbonate material and the grain size, and its characteristics are primarily controlled by the in situ production of $CaCO_3$. A 3D model of the various environments and processes responsible for the sediment distribution in the lagoon is shown in Fig. 21.

The TOC is directly related to particle size and composition of the sediments and the nutrient-rich water in the lagoon. The lowest values of TOC are recorded at the northern end, where the fine sediments are winnowed, and lag material in the form of coarser carbonate fails to adsorb organic material. Higher values are in the south where fine sediments dominate and $CaCO_3$ is relatively low. The area close to the mangrove stands with coarse-textured sediment tends to show higher TOC, as observed in other lagoons, since the organic debris supplied by the mangrove and the fine sediment tends to adsorb TOC that that may be trapped by roots of the mangroves. There is a close relationship between TOC, sediment colour and texture and a negative correlation between TOC and $CaCO_3$.

In general, fine sediments are rich in TOC compared to coarse-grained sediments that contain abundant carbonate debris. Green-red algae in the nutrient-rich water also contribute significant amounts of organic matter to the environment. Dissolved reactive phosphate and nitrite are almost depleted, but there are high levels of dissolved ammonium. High concentrations of nitrite and ammonium in the western part of the lagoon suggest transformations between various forms of nitrogen compounds and may indicate the presence of a suboxic environment. The distribution of heavy metals in the surficial sediments of the lagoons shows the same

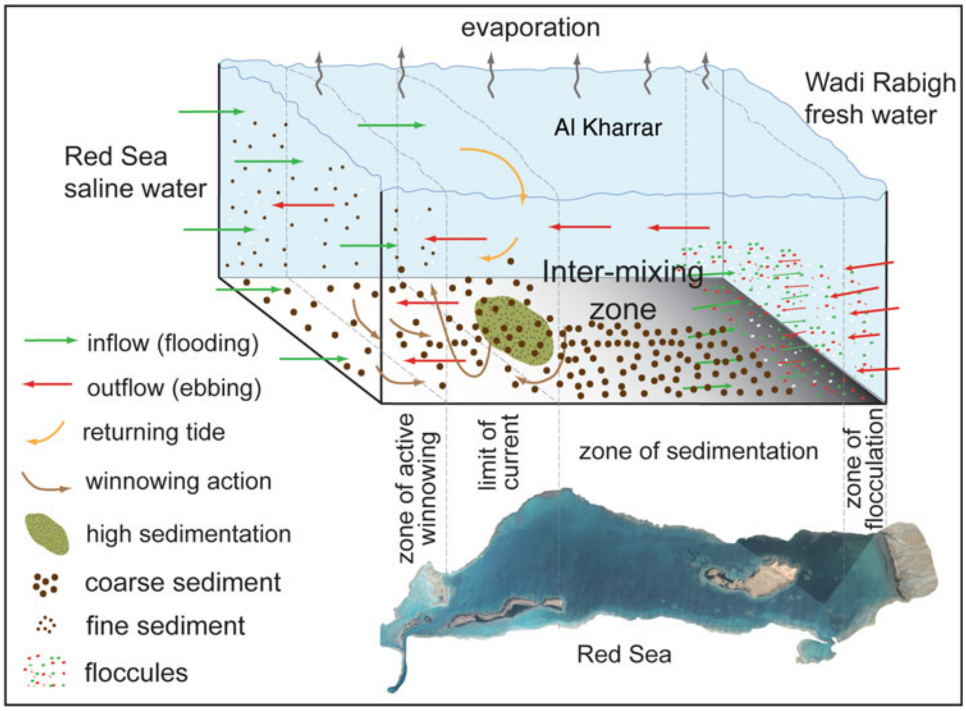

Fig. 21 3D model of the hydrological processes and sediment distribution in the Al Kharrar lagoon

pattern as TOC, with high levels in the southern part of the lagoon, indicating sources from sporadic rainfall (Rasul et al. 2010a).

Present Status and Future Implications

The water of the lagoon was exchanged with the Red Sea through multiple pipes in order to control pollution, but after the choking of the pipes with sediments and artificial materials, the quality of the water deteriorated leading to an increase in the algal bloom and seagrass. Several new openings and modifications made especially at the northern part of the lagoon in order to support an effective exchange of water. An assessment of the water quality and sediment veneer should be taken into consideration to avoid further deterioration.

Khawr Al Dhaban

Khawr Al Dhaban is an isolated shallow lagoon with a maximum depth of 10 m. The channel connecting it with the Red Sea is about 13 m deep with limited access because of numerous shoals and islands separating the lagoon from the Red Sea (Fig. 22). No wadis drain into the lagoon, but water is exchanged with the Red Sea over the shoals during tidal cycles. The sediment texture ranges between sandy mud and gravelly muddy sand, and in general, the veneer is poorly sorted because of weak currents. Sorting improves only marginally at the mouth because of a moderate average current velocity of 0.29 cm s^{-1}. Summer surface water temperatures as high as 34 °C and a salinity of 42 ‰ or even higher have been recorded reflecting the isolation of the lagoon from the Red Sea. The lagoon is veneered with very high carbonate content sediments, averaging 93 % $CaCO_3$ supplied mainly by the fringing reefs and shoals. The sediment fauna includes gastropods, foraminifera and pelecypods. The TOC averages 0.51 % in the bulk sediment but is much higher at 1.79 % in the fine fraction. A reducing environment prevails in the south-western side of the lagoon where the mangrove saplings are affected by water quality, and isolated mangrove stands supply organic debris to the lagoon (Fig. 22a, b). The sediment outside the lagoon in low-lying areas to the south that are inundated by the semi-diurnal tide shows TOC values of 5.6 %, much higher than in the main lagoon, as most of the mangrove debris is either transported or held there where it decomposes and enriches the sediment with organic matter. The southern area is flat, and during high tide, the surrounding area is inundated with a thin sheet of water. The movement of water between the lagoon and the shallow tidal zones transports sediments and organic material, as a result of which a few centimetres of alternating layers of yellowish brown carbonate material and dark rich organic sediments are observed (Fig. 22a, b). The dark-coloured sediment has a pungent smell indicating a reducing environment caused mainly by decomposition of organic debris. Stagnation prevails and organic matter is

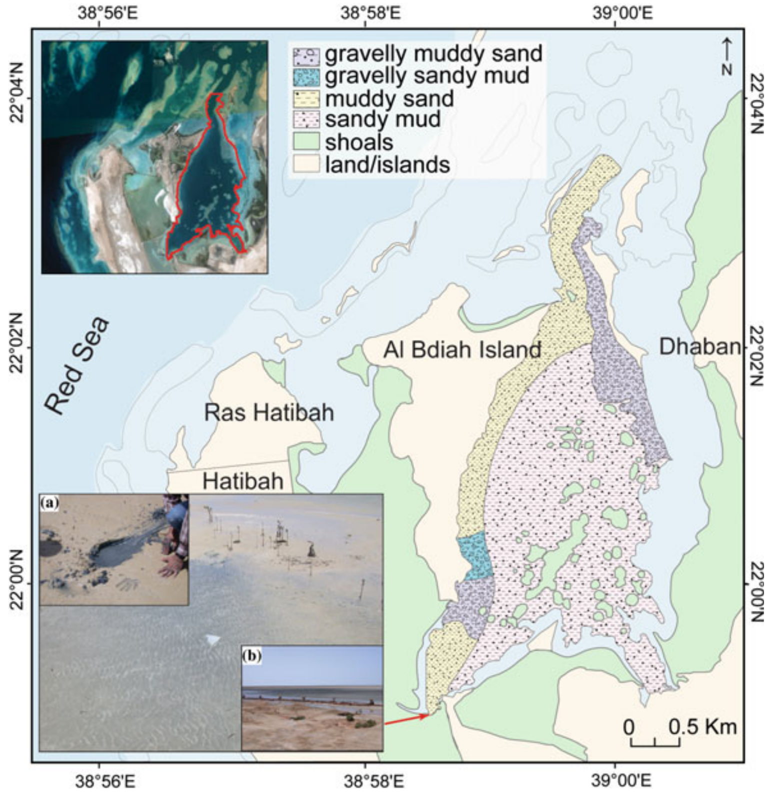

Fig. 22 Khawr Al Dhaban is an isolated body of water with restricted communication with the Red Sea; Shoals are mostly covered with <0.5 m of water, and only during spring tide does the water from the Red Sea move over the shoals to the lagoon. The restricted exchange of water results in a very high salinity of 42 ‰ in the lagoon; **a** sediment is reduced: a scrape shows the sediment is black below the surface. The alternate layering of dark and light-coloured sediments shows its cyclical (spatial and temporal) nature; **b** reducing environment is widespread in the area

incorporated into the sandy mud, augmenting the reduction process and leading to sediment staining.

Conclusion

The sediment transport mechanisms, patterns and pathways to the lagoons are controlled by sediment flux from the wadis, anthropogenic input from sewage treatment plants, aeolian transport and the degree of human intervention, and natural causes including biological productivity in the lagoons. Water currents generated by wind or tidal forcing play important roles in the distribution of sediment. Strong tidal currents affect only the mouth of a lagoon with limited influence on the main lagoon. The sediment composition and texture are also important when it comes to retention of pollutants because fine terrigenous material tends to hold the pollutants better than the biogenic component, and weak currents fail to winnow the floccules and organic-rich materials, resulting in a reduction in quality of the sediment veneer. The lagoon configurations differ significantly from north to south. In the north, the communication of the lagoons with the open sea is mostly through wide openings and the sediment composition is mainly a mixture of biogenic and terrigenous origins, while abundant aeolian material is supplied by dust storms. In the central part, the lagoons are dominated by biogenic material except where wadis drain into them. Here, the lagoons connect to open water through narrow openings, and sedimentation is controlled by strong tidal currents. The lagoons in the south are dominated by terrigenous materials supplied to the lagoons or offshore areas by active wadis. In some areas where the influence of wadis is strong, almost the entire lagoon bottom sediment veneer is lithogenic.

The lagoons in the urban areas have been sites of coastal development for decades, leading to pronounced changes in their morphodynamics, such as at Sharm Obhur. The Al Ghallah lagoon is the recent site of a large shrimp farm that has altered the environmental setting of the surrounding wadis and the lagoon itself. The Al Kharrar lagoon has experienced a bloom in seagrass and macro-algae because of the limited exchange of water with the Red Sea. The two Shoaibah lagoons, especially the northern one, have seen their mouths reduced in width, while Al Khuraybah lagoon has undergone trawling for shrimp for several years, and the wadis, especially Wadi Aynunah, have been used for farms and residences, resulting in a complete change in the environment. The lagoons in the Al Wajh area and Khawr Al Dhaban are less impacted by human activities. All the lagoons with limited human intervention are in near pristine condition. However, the growing trend of reclaiming land along the coastal belt of the Red Sea of Saudi Arabia is a cause for concern if adequate measures for addressing environmental impacts are ignored.

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