

# The Spatial Distribution Pattern of Surficial Sediment in Shiab Al-Kabeer, a Shoal in the Red Sea of Saudi Arabia

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## Abstract

A unique feature commonly referred to as a ‘*shoal*’, called Shiab Al-Kabeer, is located in the Red Sea offshore from Saudi Arabia. It is made up mainly of live and dead corals with over 90% calcium carbonate material largely contributed by the corals. Aeolian quartz from the adjacent deserts and fluvial material derived from numerous wadis during flood discharge make up a small part of the sediment veneer. The shoal is inhabited by various fauna and flora exclusive to the Red Sea. Bio-eroders such as grazers, borers and burrowers, especially some species of fish like parrotfish and shrimp-gobies, create cavities and holes in the shoal area, and generate new sediment by excavating the cavities, forming mounds on the sea bed. Apart from being an excellent ground for spawning, the shoal is also used for overnight dwelling by picnickers, as an anchorage for small boats, as a nesting ground for seabirds, and is an attractive site for marine tourism (SCUBA diving). The shoal undergoes a degree of stress either through human activities or natural processes. However, the clear and uncontaminated water keeps the sub-environment of the shoal healthy, although minor irreversible processes caused by contamination might be of some concern. Some coral debris, molluscs, and foraminiferal sand are stained black, because of precipitation of free pyrite in a reducing environment caused by weak currents and quiescent conditions, in the presence of plant and organic debris, mainly algae and sea-grass. The dynamics and shape of the shoal are controlled primarily by water currents generated either by wind or by tidal cycles, breaking waves and physical factors related to human activities.

## 1 Introduction

The Red Sea is an elongated body of water about 2000 km long with a maximum width of 355 km. It contains over a thousand islands, most of which have been named but remain unexplored due to inaccessibility. In addition, a large number of shoals with sizes ranging from a few metres across to several kilometres in length form part of the unique Red Sea environment. The Red Sea includes 3.8% of the world’s coral reefs (Sea Around Us 2007). The major Red Sea barrier reef is 400 km long and several kilometres wide, and located between 10 and 40 km off the coast of Saudi Arabia (Rasul et al. 2015). Most of the bays and lagoons along the Saudi Arabian side of the Red Sea are shallow and bordered by shallow fringing reefs. Many steep-sided patch reefs sit on the seabed platform, which starts at a depth of 30–60 m. Because of the absence of rivers and permanent streams, most terrigenous material inputs to the Red Sea take place only during heavy rainfall and flash floods through the wadis (seasonal streams). In arid coastal regions where riverine sediments are scarce or absent, aeolian material and carbonate materials form the major contribution to the marine sediments.

Islands and shoals associated with coral reefs are formed by various processes related to volcanic and tectonic activities. It is known that some islands are formed by hydrodynamic processes (e.g., barrier islands) and terrigenous sources (input) in deltaic and estuarine environments (Maul 1996). In tropical zones many islands are formed by coral reefs—a very common feature in the Red Sea. The Red Sea is regarded as one of the world’s richest seas in terms of its coral reef population. The reefs are more common in the north because of the favourable conditions for their growth as compared to the south. Dead corals that act as substrate (carbonate crust) are the building blocks for coral reefs. The cycle of building and destruction continues, resulting in the shoals made up of coral reefs. These contribute substantial amounts of carbonate debris to the Red Sea, especially by the

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breaking down of the reef system either by human activities or naturally, supplemented by biological productivity. The bases of the islands are associated mostly with shoal-like features that on the Saudi Arabian side of the Red Sea occur with relatively large dimensions (e.g., the Al-Wajh Bank area and the Al-Khuraybah lagoon). In the central Red Sea, about 24 km offshore from Jeddah, is the Shiab Al-Kabeer, where the shoal emerges during low tide. These shoals form excellent grounds for spawning and fishing, and are environmentally sensitive ecosystems with high carbonate content that is supplied to the area in the form of sediment by the reef system.

Detailed work on the shoals and islands is lacking, particularly with regard to the processes responsible for the transportation, distribution and dispersal pattern of sediments. Such data is not available, or if present, it is poorly integrated or too broad in scope to fully describe the system. The objectives of this study are to investigate the contemporary sedimentation processes, understand the sediment distribution pattern and determine the source and sediment transport mechanism in this carbonate-rich sub environment.

There has been limited research interest in the shoals and islands of the Red Sea because of the rocky nature and shallow water surrounding them making access to them very difficult. This is why most of these features have long remained unexplored, one of them being the Shiab Al-Kabeer. However, a few studies on the environmental aspects of the islands and shoals of the Red Sea (e.g., Ras Al-Qasabah, Al Wajh, and Yanbu areas in the north, and the Farasan Banks and Farasan Islands in the south), have been conducted by the Khaled bin Sultan Living Oceans Foundation (Bruckner et al. 2011, 2012). In 1997 and 1998, a semi-quantitative study related to the health of the coral reefs and water quality assessment at 79 sites in the Farasan Islands' Marine Protected Area was carried out by DeVantier and Pilcher (2000) and De Vantier et al. (2000). Detailed descriptions of the geology, physical environment, climate, hydrology, oceanography and habitats including the coral reefs of the Red Sea and wider Arabian Region have been presented by Fishelson (1971), Mergner (1971), Ormond et al. (1984), Behairy and Jaubert (1984), Edwards (1987), Crossland (1987), UNEP/IUCN (1988), Sheppard and Sheppard (1991), Behairy et al. (1992), Sheppard et al. (1992), Rowlands et al. (2014), Klaus (2015), Rasul (2015), Bruckner and Dempsey (2015), and Rowlands and Purkis (2015).

## 2 Study Area-Geographical Setting and Morphology

The Shiab Al-Kabeer is one of the many shoals in the Red Sea, and lies at latitude 21°42'15"N and longitude 38°50'15"E. It is ~24 km west of Sharm Obhur, toward the central

axis of the Red Sea dividing the Red Sea into Saudi Arabian and African waters (Fig. 1).

It is also known as "Abu Tair", referring to the marine birds such as the Brown Booby (*Sula leucogaster*) and white eyed gull (*Larus leucophthalmus*) that colonise the shoal. The surface area of the shoal is ~6.5 km<sup>2</sup>, with a width of 2.8 km, while the length of the coral patch facing the open sea toward the west is ~4 km, trending NNW–SSE.

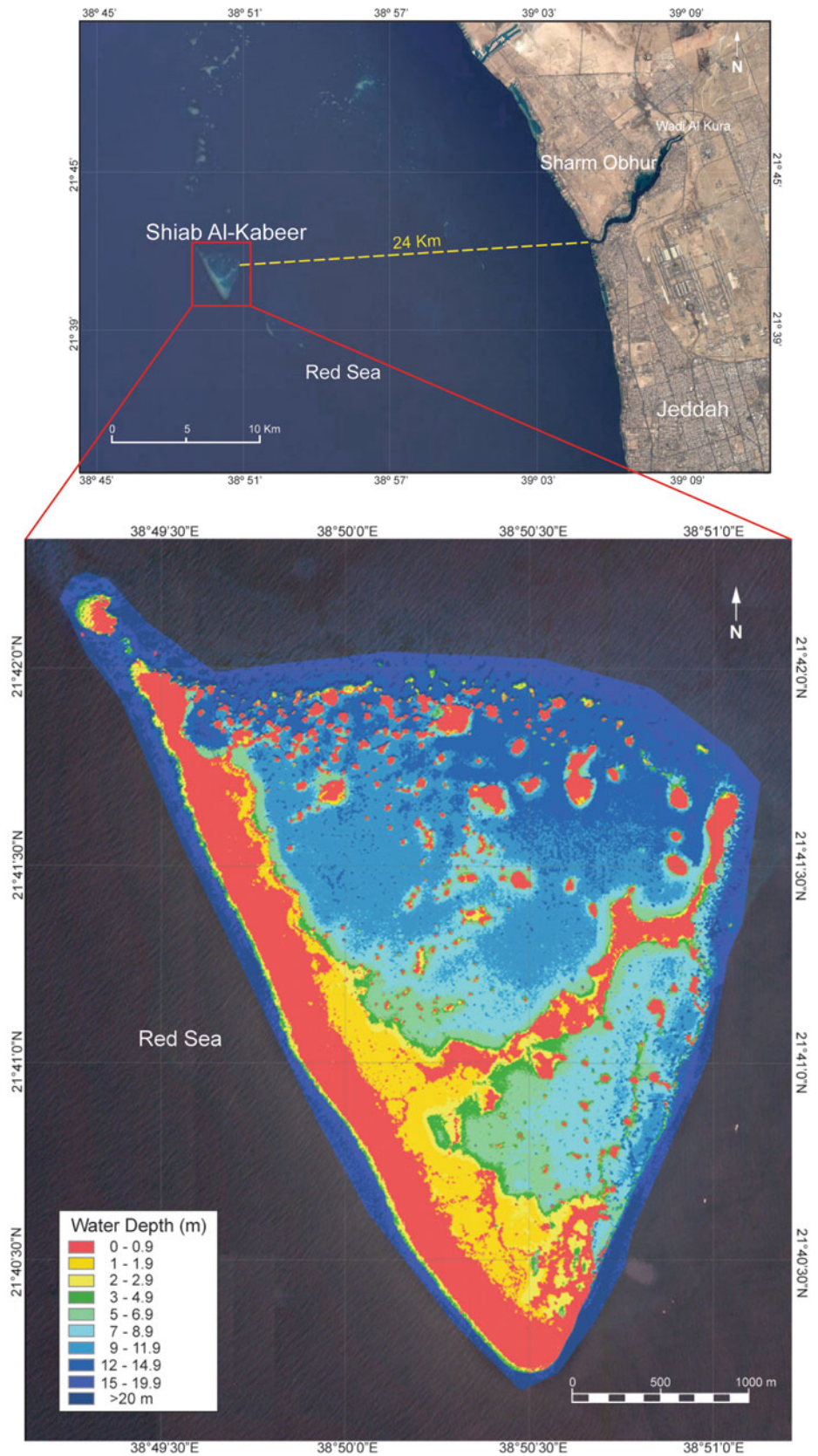
The Shiab Al-Kabeer has an average water depth of about 10 m and is surrounded by deep water, especially on the western side. The variation in the water depths within the sub environment is not as great as expected because of the numerous small shoals detached from the main shoal. However, the shoal facing the open sea to the west shows a greater and more abrupt fall where the direct actions of waves and currents create its elongated and solid appearance. The bathymetric map in Fig. 1 was produced in ArcGIS in conjunction with spot depth recordings during sediment sampling. The multi-spectral signature is based on reflectance from the seabed and geomorphological features extracted from satellite images.

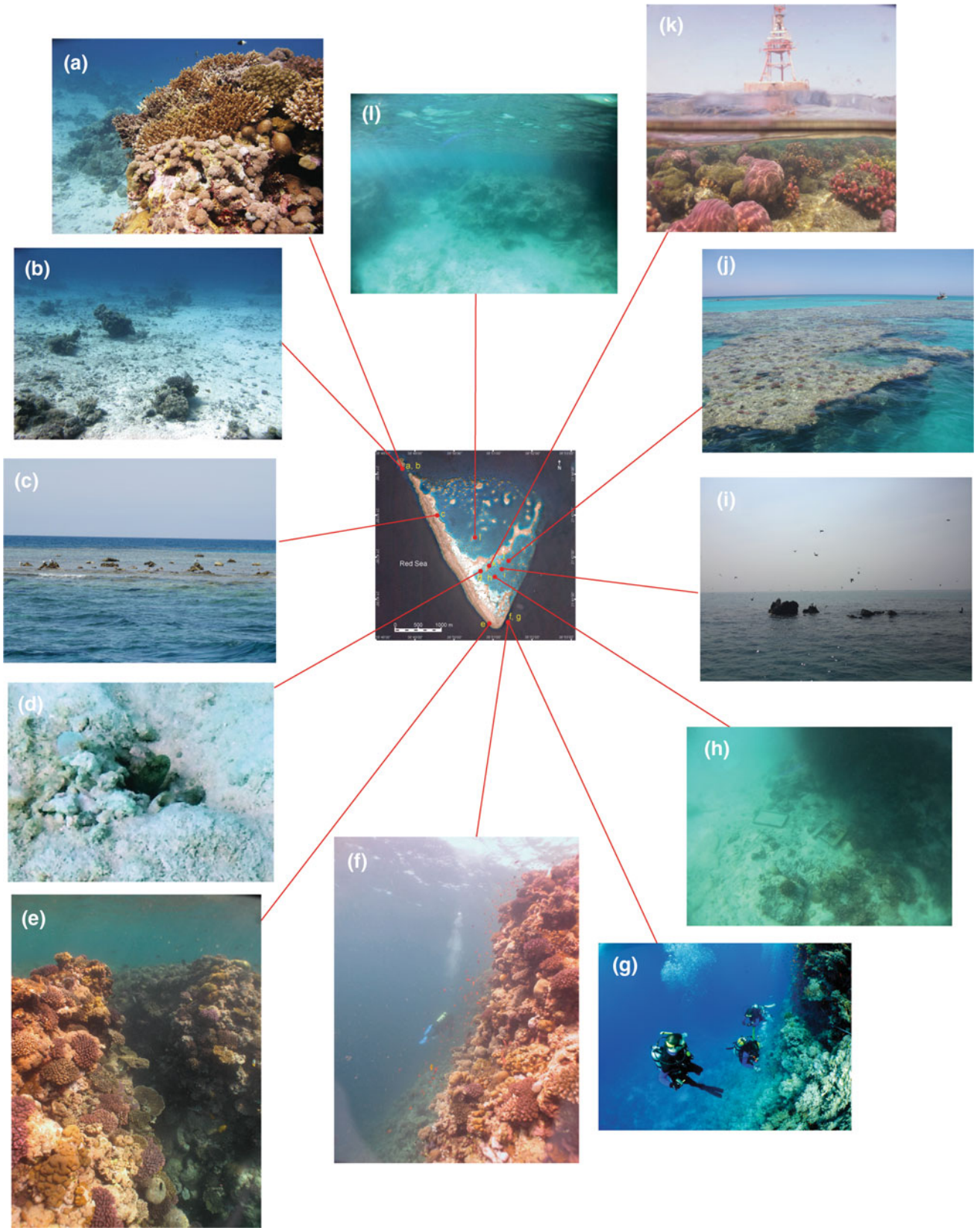
The geomorphological and seabed features associated with the shoals show the variations in the sub environment (Fig. 2a–l). Reef walls facing the open sea or drop-offs are steep and near vertical, with coral cover ranging from 10 to 70%. All coral forms are present, but mainly massive and foliose growth forms on exposed points. The coral community consists mainly of *Pocillopora* spp., *Favia* spp., and *Porites* spp. The space between coral colonies can be bare or occupied by macro-algae, coralline algae, and other species of soft coral. The area has isolated rubble accumulation along with sand at the foot of the numerous small shoals. The rubble and sand consolidate into a substrate and are colonized by stony and soft corals in a calm environment, whereas live coral cover is generally low due to the continual movement of sediment by bottom currents. Dead corals are covered with algae.

## 3 Materials and Methods

A total of fifty (50) surficial sediment samples were collected from the uppermost 15–30 cm of the seabed using a Van Veen grab sampler (Fig. 2). The samples were subjected to detailed grain-size analysis following the procedures outlined by Folk (1980). A Munsell Colour Chart was used to assign colour to the sediment veneer. During sediment sampling, turbidity in the water column was also determined by a standard Secchi disk, lowered from the shadow side of the boat to limit the effect of direct sunlight. A multi-parameter Hydrolab MS5 probe was used for collecting temperature, salinity and pH data from all the stations. Aanderaa RCM-9 and Valeport-106 current meters were

**Fig. 1** Location map of the Shiab Al-Kabeer 24 km due west from the mouth of Sharm Obhur. GIS based bathymetric map was produced by applying different wavelengths of the multispectral WV-2 bands





◀ **Fig. 2** **a** A colony of the stony coral *Goniastrea* sp. growing on top of dead coral substrate. Soft coral *Xenia* sp. and *Acropora* spp. are also common; **b** Shallow water (12 m) sand flat. In general, fine sediment is flushed by current and wave activity, allowing coral colonization, leading to a sparse coral community composed mainly of *Favia* spp., *Fungia* spp., *Acropora* spp., and *Xenia* spp. (soft coral); **c** exposed reef, commonly seen during low tide. Coral heads can be seen protruding from the water; **d** fish that prefers to live in burrows is seen peeping out from its home; **e** low-relief grooves run sporadically down the vertical

reef face; **f** reef wall on the southern tip; **g** water is extremely transparent because of lack of sediment supply; **h** garbage dumping by seafarers; **i** shoal during high tide. The rock like feature is exposed at all times; **j** carbonate crust and reef flats typically exposed during low tide, characterized by 1 cm thin veneer of sediment and macro-algae, *Pocillopora* spp.; **k** reef flat community at the back reef near the cemented base buoy used for navigational purposes; and **l** water clarity is reduced in shallow waters especially during spring tide and ebbing currents

deployed at various depths to obtain current velocities and direction. SCUBA diving was carried out to understand the flora and fauna inhabiting the area. A LEICA MZ 16A stereo-microscope with an attached high-resolution LEICA DFC 320 camera was used for studying the general composition, grain roundness and angularity of the coarse fractions. A TESCAN-VEGA 8 scanning electron microscope (SEM) was used to identify and image individual grains. Individual sand grains were stuck on conductive carbon tape stubs (standard sample holders). Each sample was gold-palladium coated using a Quorum coating machine to make the sample conductive. A Shimadzu 6000 X-ray diffractometer (XRD) with CuK $\alpha$  radiation, a voltage of 30 kV, and current of 10 mA was used for bulk mineralogy on finely powdered sediments at a scanning speed of 1°/min with an angle ranging from 2 to 60°. The relative abundance of individual minerals was determined by comparing their peak heights on 16 representative samples. An AC-280 Automated Calcimeter was used to determine calcium carbonate by treating the ground sediment samples with hydrochloric acid. The total organic carbon (TOC) was determined from sediment samples by the wet oxidation method adopted by Le Corre (1983), involving a chromic acid digestion, which was then back titrated with ferrous ammonium sulphate using diphenylamine as an indicator.

## 4 Results and Discussion

### 4.1 Surficial Sediment Characteristics

The sediment texture ranges between muddy sand and sandy gravel, dominated by gravelly sand with a few patches of other fractions (Table 1 and Fig. 3). Isolated and sheltered areas have coarse textured material along with a smaller proportion of biogenic carbonate mud. Gravel and sand, which are the product of coral disintegration by intruders, are the most common. The sediment veneer is comprised of 1–51% gravel with an average of 14%. Sand dominates the veneer ranging from 47 to 93% (average = 76%), whereas mud ranges from 1 to 46% (average = 10%).

Numerous attempts have been made in the past to identify sedimentary environments from grain-size parameters but

the results have been debatable (e.g., Mason and Folk 1958; Shepard and Young 1961; Schlee et al. 1964; Solohub and Klován 1970; Rasul et al. 2017). The use of bivariate plots (scattergrams) is based on the fact that the processes of (sand) transportation and deposition tend to produce sediments with a characteristic range of grain sizes, so the size parameters that define the sediment distribution are therefore often diagnostic of the environment. The inter-relationship of various statistical data from the study area did not help in discriminating the environment of deposition because of the carbonate-rich environment with a wide range of grain sizes. No distinct environments could be identified but a broad conclusion could be drawn in relation to the mixed source of sediments and erratic tidal and wind generated currents. However, the lack of terrigenous material and the abundant carbonate material produced by coral erosion and disintegration settle at the foot of the reefal system and therefore cannot be part of the sediment transport mechanism as perceived by many sedimentologists.

### 4.2 Sediment Colour and Staining

The sediment colour is important in understanding the history and process of sedimentation because it points to the sediment source(s), dispersal and distribution patterns, including any geochemical reactions that may have taken place in situ. Based on the Munsell colour chart the sediment colour ranged between 5Y 8/1/1 white and 10 YR 8/2/2 very pale brown. In general, the sediment colour has a lighter hue compared to other areas in the Red Sea (see Table 1 and Fig. 4). However, in places where the environment is less dynamic two coloured sediments are observed, darker in the bottom layer and lighter on the top (Fig. 5). The dark coloured sediment is due to the reducing conditions on the sea bottom instigated by the decay of organic debris.

Most of the area is covered by coarse grained, light coloured sediment derived from the corals inhabiting the shoal. However, in some fine sediments varying shades of gray are observed that could be related to sluggish conditions, and to anthropogenic input in the form of plant, sea-grass and algal debris whose decay enhances the process of

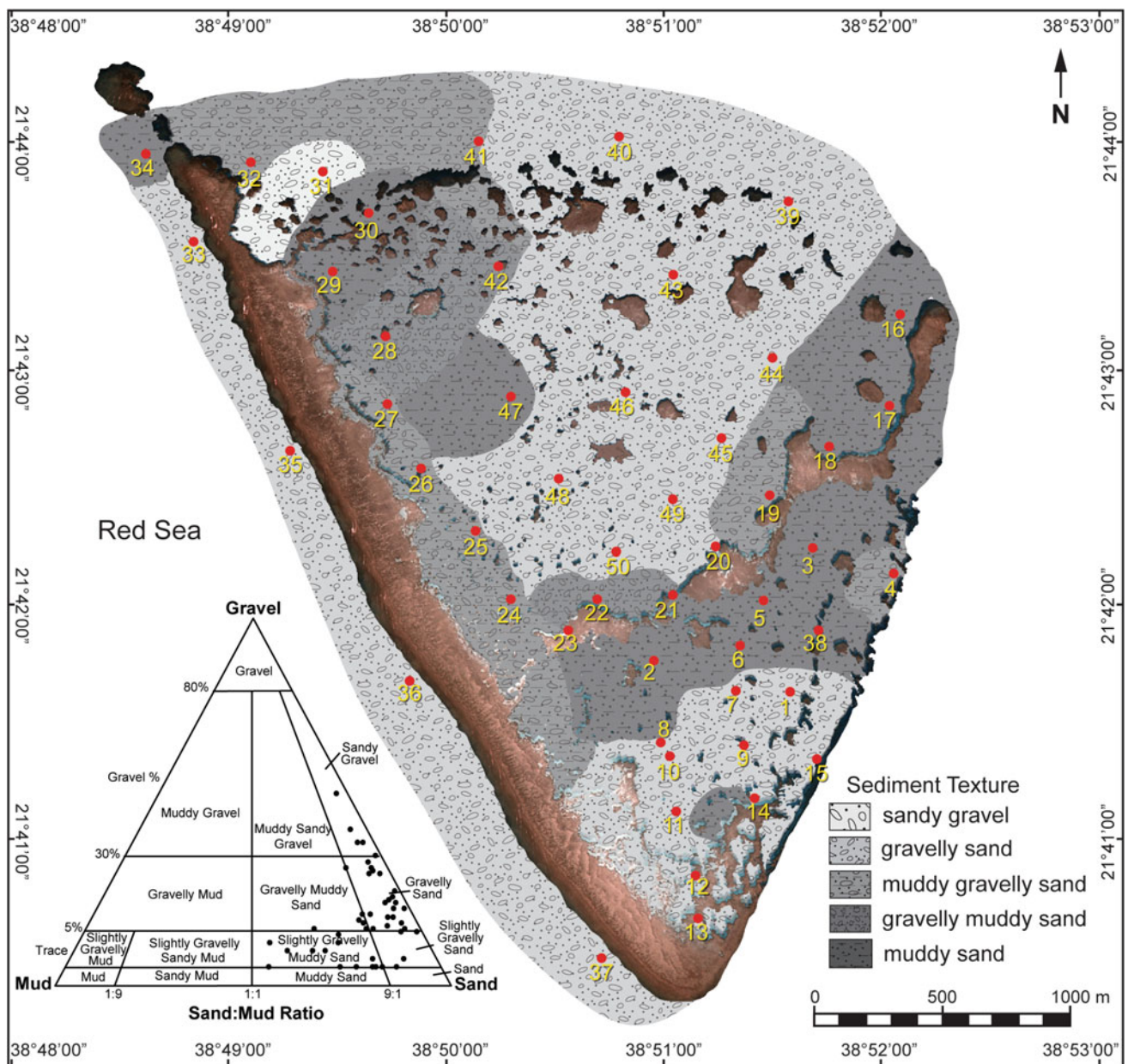
**Table 1** Sediment texture data based on various size fractions

Station	Water depth (m)	SDDD (m)	Gravel (%)	Sand (%)	Mud (%)	Sediment texture	Munsell colour
1	8.0	8.0	28	69	3	Gravelly sand	2.5Y 8/2/2 pale yellow
2	3.0	3.0	3	58	39	Muddy sand	5Y 8/2/2 pale yellow
3	8.3	8.3	2	85	13	Muddy sand	5Y 8/1/1 white
4	10.0	10.0	8	86	6	Muddy gravelly sand	2.5Y 8/2/2 pale yellow
5	7.9	7.9	3	70	27	Muddy sand	5Y 8/2/2 pale yellow
6	7.0	7.0	1	53	46	Muddy sand	5Y 8/2/2 pale yellow
7	7.4	7.4	30	67	3	Gravelly sand	5Y 8/2/2 pale yellow
8	6.6	6.6	4	74	22	Muddy sand	5Y 8/2/2 pale yellow
9	7.1	7.1	27	70	3	Gravelly sand	5Y 8/2/2 pale yellow
10	5.1	5.1	18	80	2	Gravelly sand	2.5Y 8/2/2 pale yellow
11	1.7	1.7	16	82	2	Gravelly sand	5Y 8/2/2 pale yellow
12	1.5	1.5	17	80	3	Gravelly sand	5Y 8/2/2 pale yellow
13	2.0	2.0	20	79	1	Gravelly sand	5Y 8/2/2 pale yellow
14	2.0	2.0	1	91	8	Muddy sand	5Y 8/2/2 pale yellow
15	7.0	7.0	40	57	3	Gravelly sand	5Y 8/2/2 pale yellow
16	12.5	11.0	1	85	14	Muddy sand	5Y 8/2/2 pale yellow
17	8.0	7.0	1	88	11	Muddy sand	5Y 8/2/2 pale yellow
18	6.6	6.6	10	78	12	Muddy gravelly sand	5Y 8/2/2 pale yellow
19	7.9	7.9	12	78	10	Muddy gravelly sand	5Y 8/2/2 pale yellow
20	8.5	7.0	11	85	4	Gravelly sand	5Y 8/1/1 white
21	5.6	5.6	7	82	11	Gravelly muddy sand	5Y 8/2/2 pale yellow
22	5.0	5.0	9	80	11	Gravelly muddy sand	5Y 8/2/2 pale yellow
23	1.5	1.5	10	78	12	Muddy gravelly sand	5Y 8/2/2 pale yellow
24	1.2	1.2	7	65	28	Muddy gravelly sand	5Y 8/2/2 pale yellow
25	2.8	2.8	28	64	8	Muddy gravelly sand	5Y 8/2/2 pale yellow
26	4.1	4.1	1	80	19	Muddy sand	5Y 8/2/2 pale yellow
27	5.8	5.8	11	84	5	Muddy gravelly sand	5Y 8/2/2 pale yellow
28	8.8	8.8	7	84	9	Gravelly muddy sand	5Y 8/2/2 pale yellow
29	6.2	6.2	1	75	24	Muddy sand	5Y 8/2/2 pale yellow
30	12.0	12.0	1	86	13	Muddy sand	2.5Y 8/2/2 pale yellow
31	14.5	14.5	51	47	2	Sandy gravel	5Y 8/2/2 pale yellow
32	13.0	13.0	7	90	3	Gravelly sand	2.5Y 8/2/2 pale yellow
33	18.7	18.7	6	93	1	Gravelly sand	2.5Y 8/2/2 pale yellow
34	25.0	25.0	2	92	6	Muddy sand	10YR 8/2/2 very pale brown
35	26.0	26.0	32	67	1	Gravelly sand	10YR 8/2/2 very pale brown
36	30.0	30.0	36	62	2	Gravelly sand	10YR 8/2/2 very pale brown
37	32.0	32.0	14	85	1	Gravelly sand	10YR 8/2/2 very pale brown
38	8.5	8.5	4	52	44	Muddy sand	2.5Y 8/2/2 pale yellow
39	14.8	14.8	26	70	4	Gravelly sand	2.5Y 8/2/2 pale yellow
40	17.2	17.2	16	80	4	Gravelly sand	2.5Y 8/2/2 pale yellow
41	16.8	16.8	12	80	8	Muddy gravelly sand	2.5Y 8/2/2 pale yellow
42	11.0	11.0	5	74	21	Gravelly muddy sand	5Y 8/1/1 white
43	11.5	9.0	18	80	2	Gravelly sand	5Y 8/2/2 pale yellow
44	11.0	9.0	36	61	3	Gravelly sand	5Y 8/2/2 pale yellow

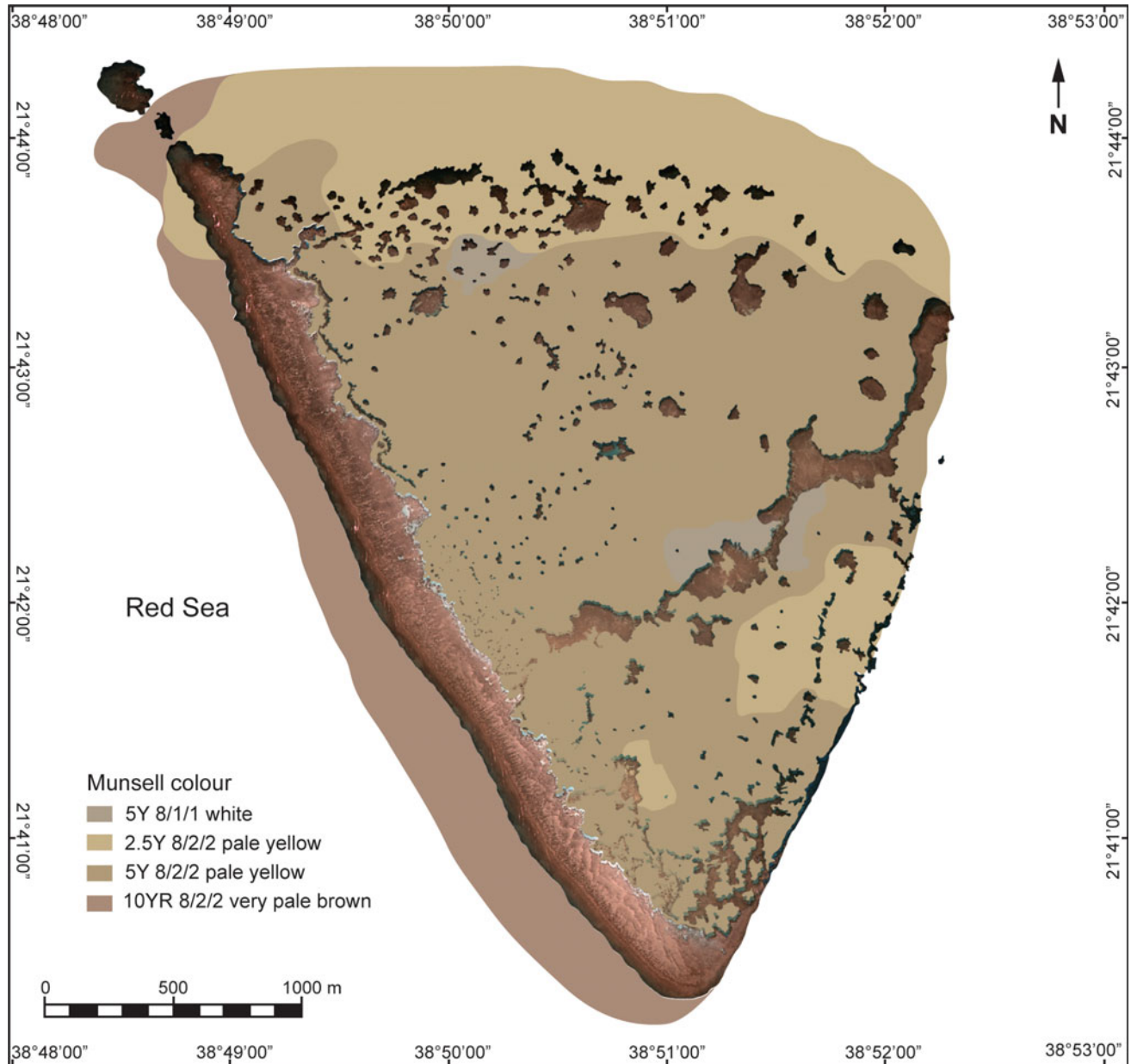
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**Table 1** (continued)

Station	Water depth (m)	SDDD (m)	Gravel (%)	Sand (%)	Mud (%)	Sediment texture	Munsell colour
45	11.0	8.5	26	72	2	Gravelly sand	5Y 8/2/2 pale yellow
46	8.3	7.0	17	80	3	Gravelly sand	5Y 8/2/2 pale yellow
47	10.0	9.0	3	66	31	Muddy gravelly sand	5Y 8/2/2 pale yellow
48	8.4	8.4	6	90	4	Gravelly sand	5Y 8/2/2 pale yellow
49	10.7	9.5	9	88	3	Gravelly sand	5Y 8/2/2 pale yellow
50	7.6	7.6	14	83	3	Gravelly sand	5Y 8/2/2 pale yellow
Min	1.2	1.2	1	47	1		
Max	32.0	32.0	51	93	46		
Avg	9.7	9.5	14	76	10		



**Fig. 3** Sediment distribution map based on the textural classification scheme proposed by Folk (1980)



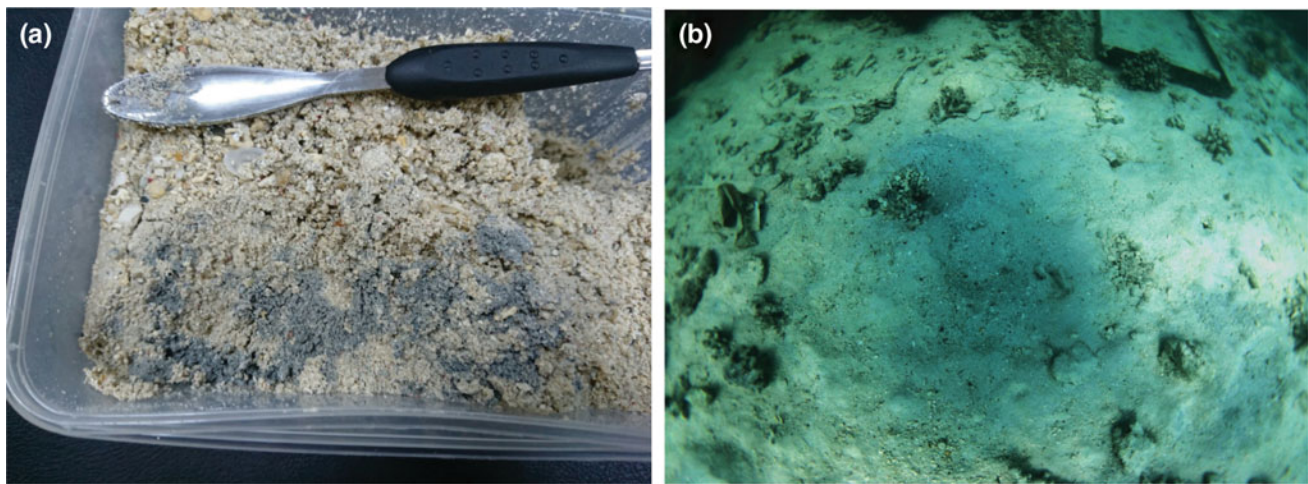
**Fig. 4** Sediment colour (top 30 cm) defined using the Munsell colour chart

reduction. The resulting loss of oxygen promotes the staining of the sediments (Rasul et al. 2017). It is worth noting that in the area where stagnant conditions prevail and sea-birds are present, the air has a disagreeable odour, mostly because of the tons of bird droppings. The relatively darker sediment in the shallow water, especially in the sheltered area on the southeastern side of the shoal, is where calmer conditions prevail because of the many small shoals that act as barriers to currents and water movement. The area of stained gray sediment could therefore be referred to as an environment of deposition where the effects of tide- wind- and wave-generated currents are limited, thus restricting

sediment movement and promoting the staining of the coral debris, shell fragments and forams.

Relatively older biogenic fragments are stained gray or are worn on the outer surface and sometimes on the inside as well. Similar staining is present in the many semi-enclosed bays and lagoons along the Red Sea as well as in many coastal and marine environments, especially where stagnation prevails (Rasul 2015; Rasul et al. 2017). Both ancient and recent calcareous marine sediments stained gray or black with finely divided pyrite have been reported in pellety debris of carbonate sediments from the Middle East, Britain and other areas (Rasul 2015; Sugden 1966). Once the





**Fig. 5** **a** The staining shows a reducing environment; top layer is lighter than the underlying layer. Although the composition of the sediment is the same, the colour is different because of a reducing

environment, and **b** a process that takes place in the presence of organic debris, staining under a thin veneer of recently contributed organic material in sheltered areas

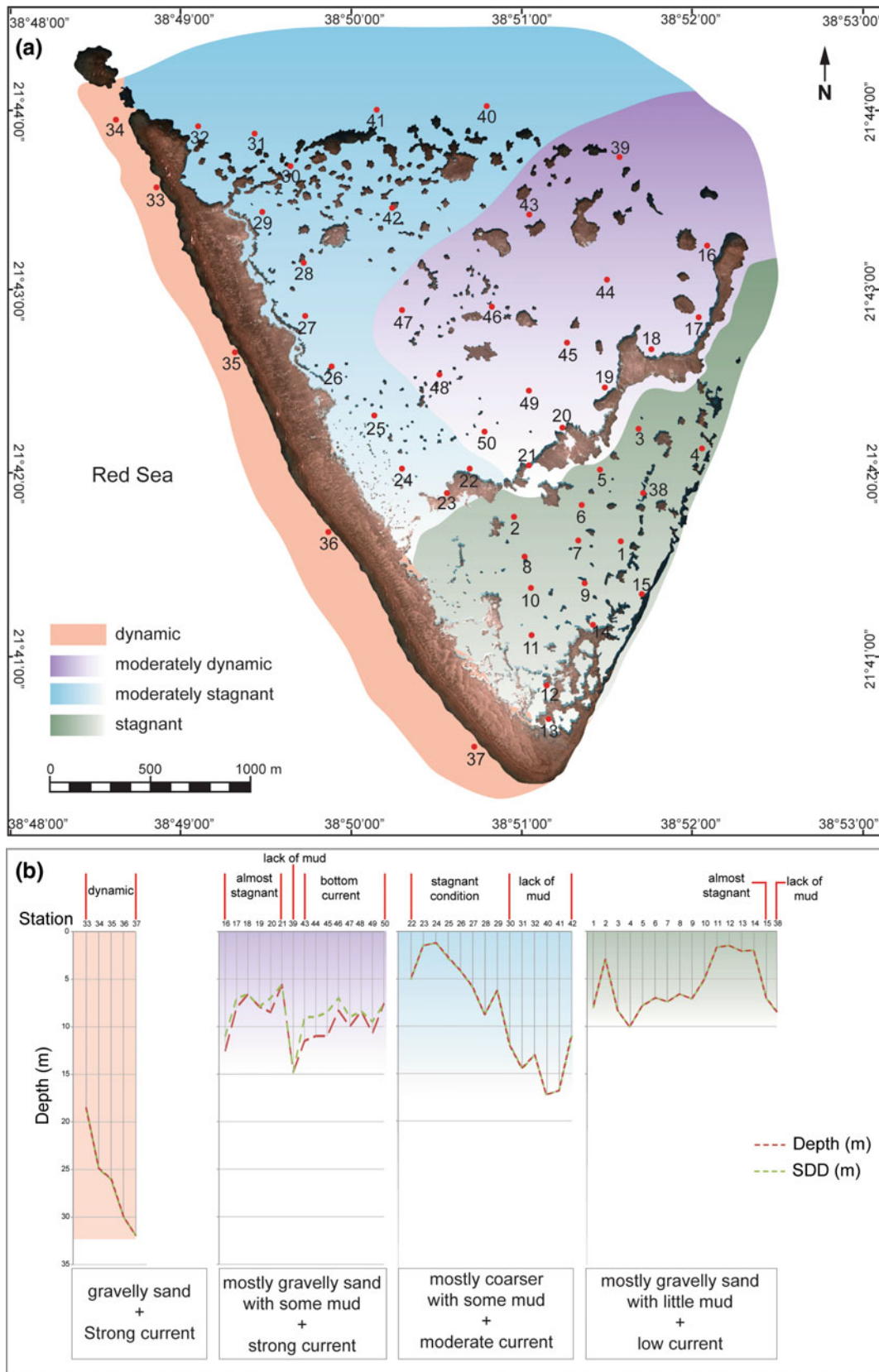
sediment is buried under the pile of either terrigenous or anthropogenic material in the form of organic debris, a reducing environment develops because of the consumption of oxygen and organic matter by bacteria during decay. Aerobic bacterial activity, utilizing dissolved oxygen, penetrates a surficial sediment layer from a few cm to tens of cm in thickness (Sugden 1963). Some organic matter is oxidized and destroyed and some gets buried to depths where free oxygen decreases and is then subjected to anaerobic bacterial decay that produces hydrogen sulphide. However, the black colour on the 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). The blackening or staining of shells may be due to the presence of pyrite in sediment from the coastal plain that contains iron-rich clays and sands (Jado and Hötzl 1984; Jado et al. 1989; Abou-Ouf and El-Shater 1993) and not from organic matter. The location of the shoal in an open environment of the Red Sea does not always promote a reducing environment because of the constant movement and mixing of water during tidal cycles and wind generated currents, but in the micro-environment within the shoal stagnant conditions prevail resulting in a reducing environment in places.

### 4.3 Water Transparency

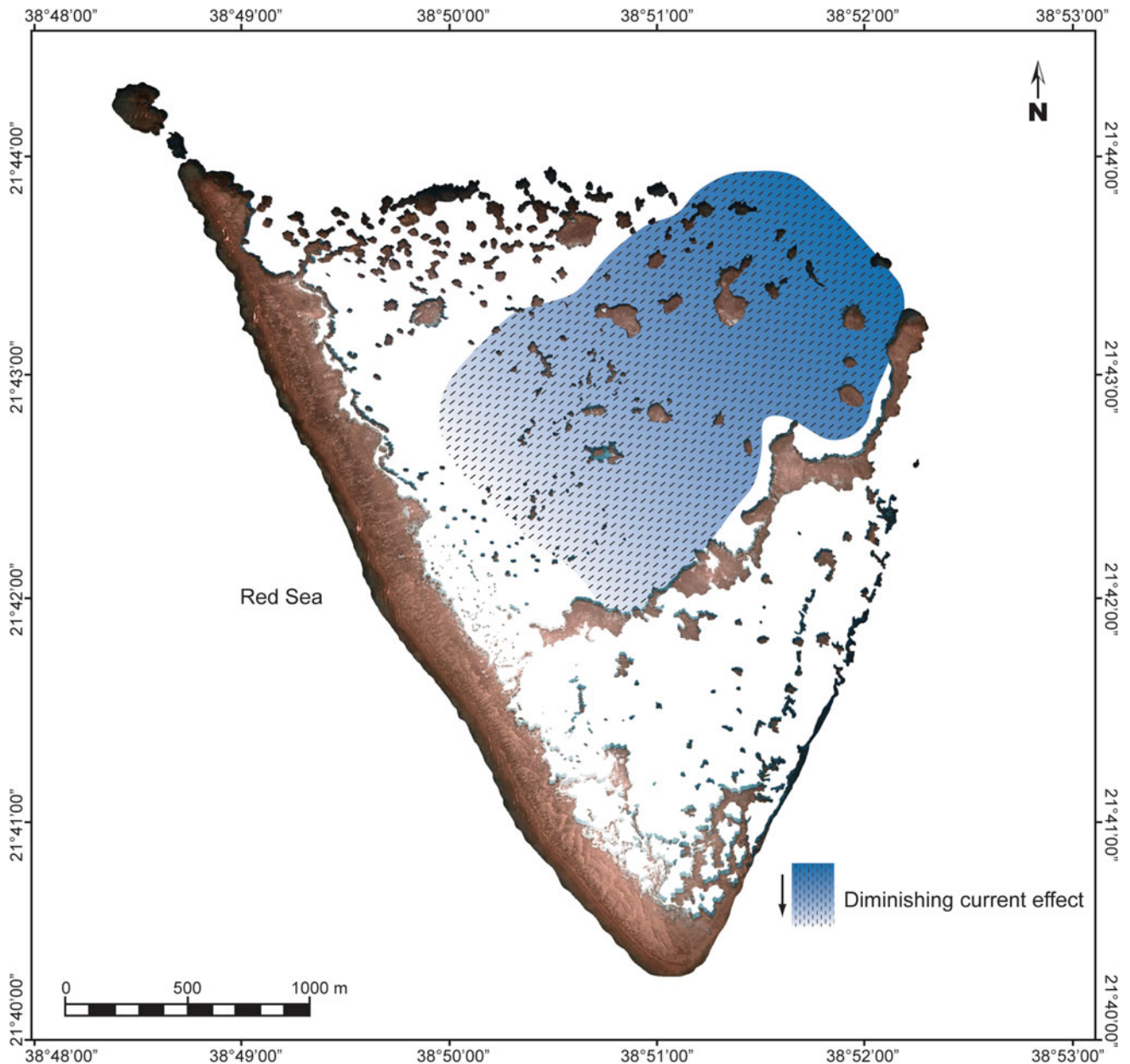
The dispersion of light in the water column and water transparency play an important role in understanding the effect of the local currents on the sediment veneer, including sediment colour, source, type and composition.

Apart from the water current, water depths also play an important role in the resuspension of bottom sediment (Rasul et al. 2017).

The Secchi Disk Disappearance Depth (SDDD) in the study area ranged between 1.20 and 32 m with an average of 9.45 m (see Table 1 and Fig. 6). The water clarity is exceptionally good and it seems that the local currents do not have an impact on the turbidity level because of a lack of terrigenous input even in shallow waters. SDDD and water depth are equal, indicating that the current in general fails to resuspend the bottom sediment. In addition, sediment supply to the area is negligible and therefore the clarity is good. The light colour of the carbonate material on the bottom also enhances the light reflection. Since the sediment veneer is important in defining the water clarity and turbidity level, the water clarity is directly related to the character of the seabed. In general, the SDDD is the same as the spot depths except at some stations, although the difference between the SDDD and spot depth does not exceed 1.5 m. The data show the probable influence of bottom currents on the resuspension of bottom sediment. However, the very poor sorting values of the bottom sediment show that the water currents are ineffective in disturbing the sediment veneer, resulting in an increase in water clarity that allows the fauna to colonise the area. The clarity of the water seems to be excellent because of the coarser texture of the seabed and the lack of input from the wadis. Since the seabed is coarser in nature and very little mud is present, the water is less turbid, allowing sunlight to penetrate through the water column much more effectively. However, where the bottom current is strong the calcareous fine materials are resuspended, resulting in a decrease in water clarity.



**Fig. 6** a Station locations and water transparency, and b the relationship between water depth, Secchi disk disappearance depth (SDD) and sediment type



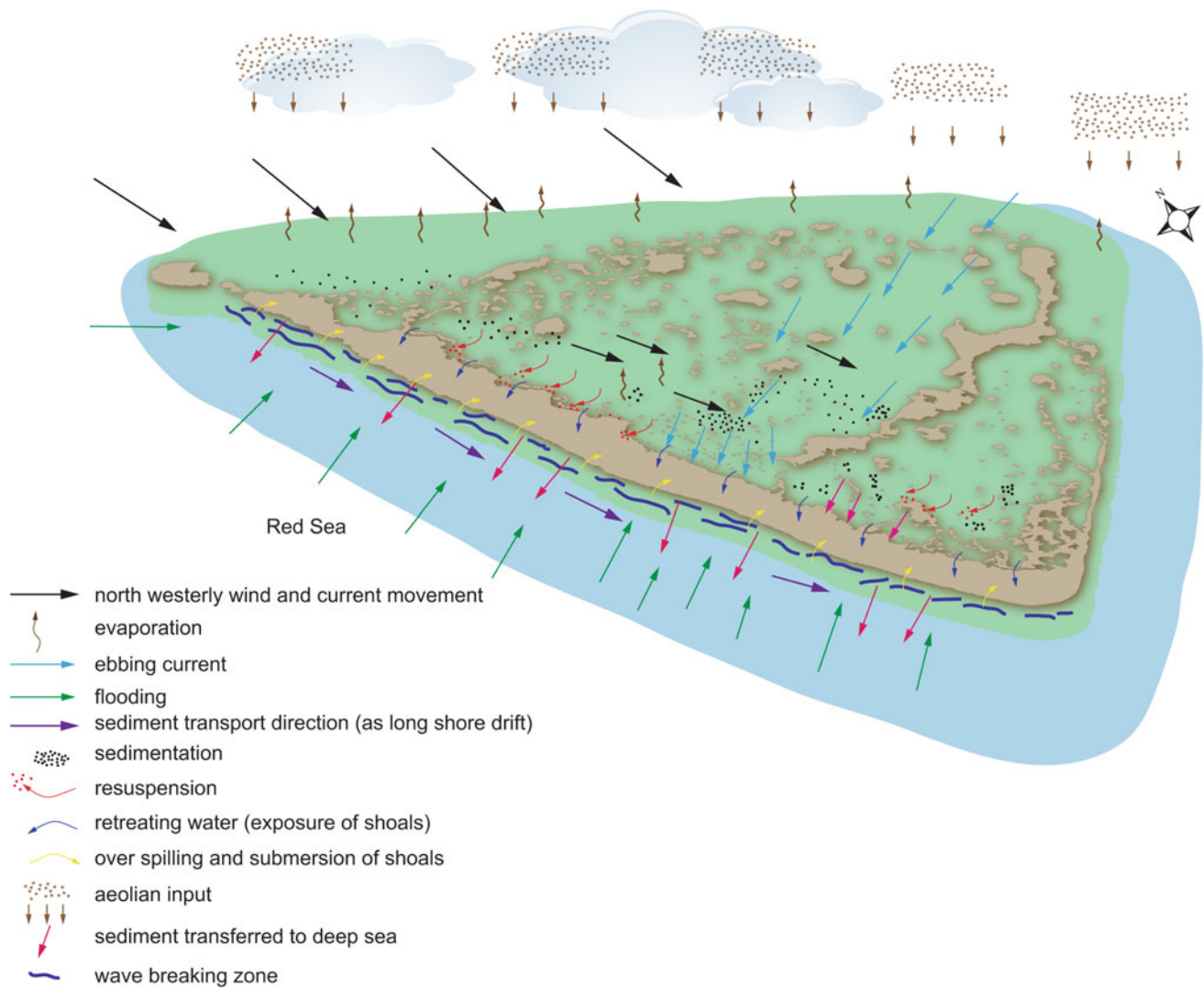
**Fig. 7** The diminishing effect of the current during ebbing. The energy of the current is checked and subsides after encountering the numerous shoals

#### 4.4 Water Current Measurement

Water currents are important in understanding the sediment transport pathways and patterns. Where the water depths were 7 and 36 m, the current meters were deployed at 5 and 18 m from the water surface respectively. The current velocities ranged between 3 and 47  $\text{cm s}^{-1}$  with an average of 21  $\text{cm s}^{-1}$ , mostly in the ESE direction and occasionally in the WSW. The current movement is mostly related to tidal cycles and to some extent is generated by the westerly wind. Weak, moderate to strong current velocities have been

observed, at times reaching a maximum of about 1  $\text{m s}^{-1}$  during flood tide on the eastern side of the shoal. In general, the water current is not strong in the area, and becomes weaker and gradually fades until the influence of currents ceases on reaching the numerous small shoals that act as barriers to sediment movement (Fig. 7).

Breaking waves and tidal currents are responsible for the erosion of the small-scale underwater features (coral reefs) and shoals. The coarser material in the area facing the open sea is attributed to the removal of fine sediment by the sifting action of the strong tide, wind and wave-generated currents



**Fig. 8** A 3D representation of Shiab Al-Kabeer depicting the sediment and water movement during tidal cycles and the effect of wave- and wind-generated currents in the movement of locally produced sediments

**Table 2** The degree of roundness of sedimentary grains

Station	Sediment texture	Sample type	Roundness/Angularity
1	Gravelly sand	Bimodal, very poorly sorted	Sub-angular
2	Muddy sand	Unimodal, poorly sorted	Angular
3	Muddy sand	Unimodal, moderately well sorted	Sub-angular
4	Muddy gravelly sand	Unimodal, moderately sorted	Sub-angular
5	Muddy sand	Unimodal, poorly sorted	Sub-angular
6	Muddy sand	Unimodal, poorly sorted	Sub-angular
7	Gravelly sand	Bimodal, very poorly sorted	Sub-angular
8	Muddy sand	Unimodal, moderately sorted	Very angular
9	Gravelly sand	Bimodal, very poorly sorted	Sub-angular
10	Gravelly sand	Bimodal, very poorly sorted	Angular
11	Gravelly sand	Bimodal, very poorly sorted	Angular
12	Gravelly sand	Bimodal, very poorly sorted	Angular
13	Gravelly sand	Bimodal, very poorly sorted	Angular
14	Muddy sand	Unimodal, well sorted	Sub-angular

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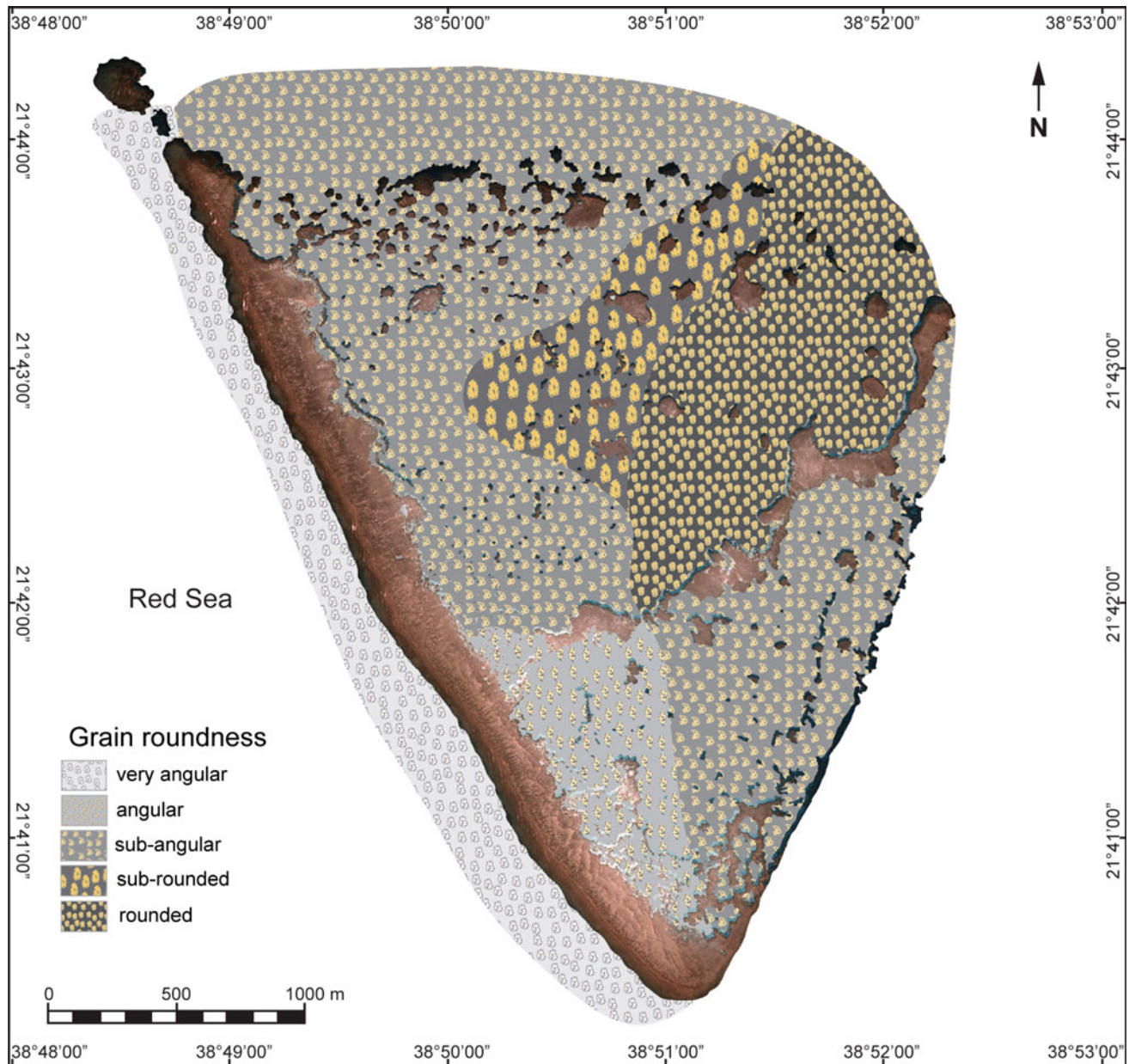
**Table 2** (continued)

Station	Sediment texture	Sample type	Roundness/Angularity
15	Gravelly sand	Bimodal, very poorly sorted	Sub-angular
16	Muddy sand	Unimodal, moderately well sorted	Rounded
17	Muddy sand	Unimodal, moderately well sorted	Rounded
18	Muddy gravelly sand	Unimodal, poorly sorted	Rounded
19	Muddy gravelly sand	Bimodal, poorly sorted	Rounded
20	Gravelly sand	Unimodal, moderately sorted	Rounded
21	Gravelly muddy sand	Unimodal, poorly sorted	Rounded
22	Gravelly muddy sand	Unimodal, poorly sorted	Sub-angular
23	Muddy gravelly sand	Unimodal, Poorly Sorted	Sub-angular
24	Muddy gravelly sand	Unimodal, poorly sorted	Sub-angular
25	Muddy gravelly sand	Bimodal, very poorly sorted	Sub-angular
26	Muddy sand	Unimodal, moderately sorted	Sub-angular
27	Muddy gravelly sand	Unimodal, moderately sorted	Sub-angular
28	Gravelly muddy sand	Unimodal, poorly sorted	Sub-angular
29	Muddy sand	Unimodal, moderately sorted	Sub-angular
30	Muddy sand	Unimodal, moderately well sorted	Sub-angular
31	Sandy gravel	Bimodal, very poorly sorted	Sub-angular
32	Gravelly sand	Unimodal, moderately sorted	Sub-angular
33	Gravelly sand	Unimodal, moderately sorted	Very angular
34	Muddy sand	Unimodal, very well sorted	Very angular
35	Gravelly sand	Bimodal, very poorly sorted	Very angular
36	Gravelly sand	Bimodal, very poorly sorted	Very angular
37	Gravelly sand	Bimodal, moderately sorted	Very angular
38	Muddy sand	Unimodal, poorly sorted	Sub-angular
39	Gravelly sand	Bimodal, very poorly sorted	Rounded
40	Gravelly sand	Bimodal, very poorly sorted	Sub-angular
41	Muddy gravelly sand	Bimodal, poorly sorted	Sub-angular
42	Gravelly muddy sand	Unimodal, poorly sorted	Sub-angular
43	Gravelly sand	Bimodal, very poorly sorted	Sub-rounded
44	Gravelly sand	Bimodal, very poorly sorted	Rounded
45	Gravelly sand	Bimodal, very poorly sorted	Rounded
46	Gravelly sand	Bimodal, very poorly sorted	Sub-rounded
47	Muddy gravelly sand	Unimodal, poorly sorted	Sub-rounded
48	Gravelly sand	Unimodal, moderately sorted	Sub-angular
49	Gravelly sand	Unimodal, moderately sorted	Rounded
50	Gravelly sand	Bimodal, moderately sorted	Sub-angular

(Fig. 8). The maximum movement of sediment due to wave action takes place just seaward of where waves break, as seen at the edge of the windward (west) side, where the sediment is coarse grained because fine sediments are removed and transported to deeper waters.

At high tide (as high as 30 cm), small waves may pass over the edge or top of the shoal, causing minor disturbance to bottom sediments, whereas waves or disturbance generated

during low tide (ebbing) are effective in resuspension because of stronger velocities than during flood tide. Therefore, the movement of sediment is governed primarily by the tidal cycle and, depending on the strength of the tide, either the sediments settle down within the shoal area or are transported offshore during ebbing. Granules may not be transported because of the weak energy, and remain as lag deposits, while mud is resuspended and transported to deeper water but may



**Fig. 9** The degree of roundness and angularity of grains in the study area

also settle down under low energy within the shoal. However, trapped granules could be transported to the deeper waters only when the water currents get stronger.

#### 4.5 Grain Morphology

Grain roundness and angularity are used in sedimentology for deciphering the severity of the mode of transportation, and the impact the grains undergo during their transit (Folk 1980). Roundness also relates to the distance and history of travel. The roundness of sediments on the shoal ranged between

angular to rounded. Well-rounded grains are absent, indicating either a low-energy environment or a short history of transportation (Table 2 and Fig. 9). The data presented are related mostly to biogenic material to investigate the effect of physical parameters, rather than source, in order to identify the cycle and history of transportation. Under normal circumstances, changes in grain size, angularity, sphericity and roundness are dependent on the environmental dynamic, the distance the grain has travelled, and the composition and strength of the individual grain.

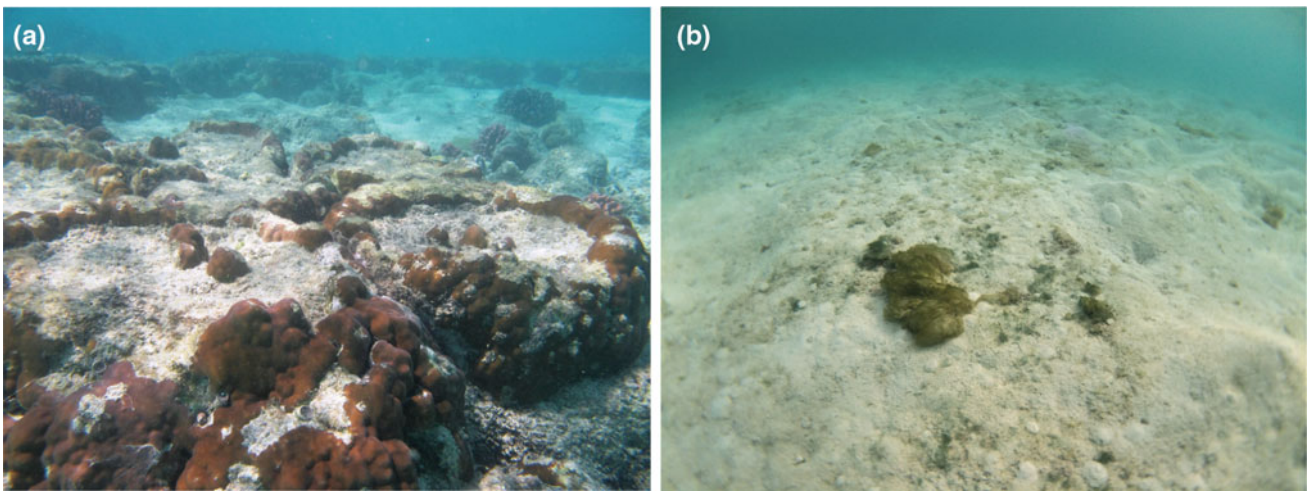
An admixture of angular, sub-angular and sub-rounded grains is observed. The low degree of roundness of the grain

is because of their being constantly broken up by strong currents and the boring of the substrate by the marine organisms that weaken and break the shells and corals, giving the grains their angularity. The whole shells and shell fragments are recent and fresh in appearance. The freshness and polished surface of shell fragments are from the constant agitation of water. The number of whole shells (intact) increases because of the restricted water agitation, especially because of the shoals present in the area. The weak water current does not have much impact on the breaking-up of biogenic grains nor is it capable of polishing the grain surface. This is one of the many reasons the biogenic materials are intact and dull brown in appearance. It is observed that the roundness and sorting decreases with diminishing current

velocity. Recently broken corals forming the debris are angular, whereas ones with dull lustre are sub-angular, indicating that with time the roundness increases because of the to and fro movement of grains by water currents.

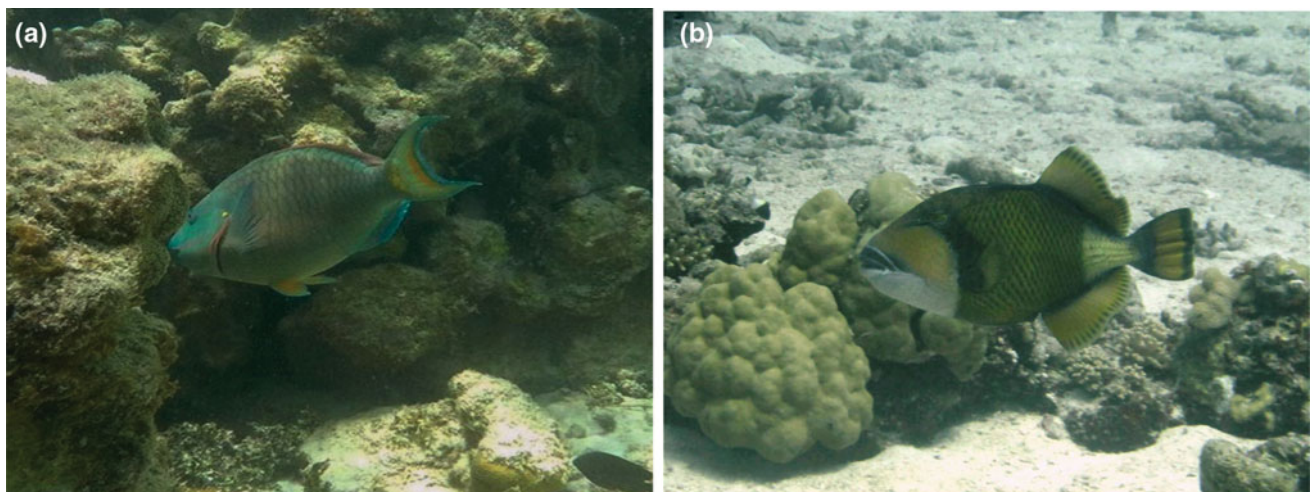
#### 4.6 Sediment Contributors

Sediment is contributed to the shoal by different means and sources, derived either locally or transported by wind or by wadis only during flash floods. The sediment can be biogenic or lithogenic in composition and the mechanism of sediment production can differ significantly for each type.



**Fig. 10** **a** Typical shallow reef-flat habitat that has ~1 cm thick cover of algae, and minor coral coverage; **b** Example of shallow lagoonal sand and mud; the clean fine sediment occasionally contains rubble and

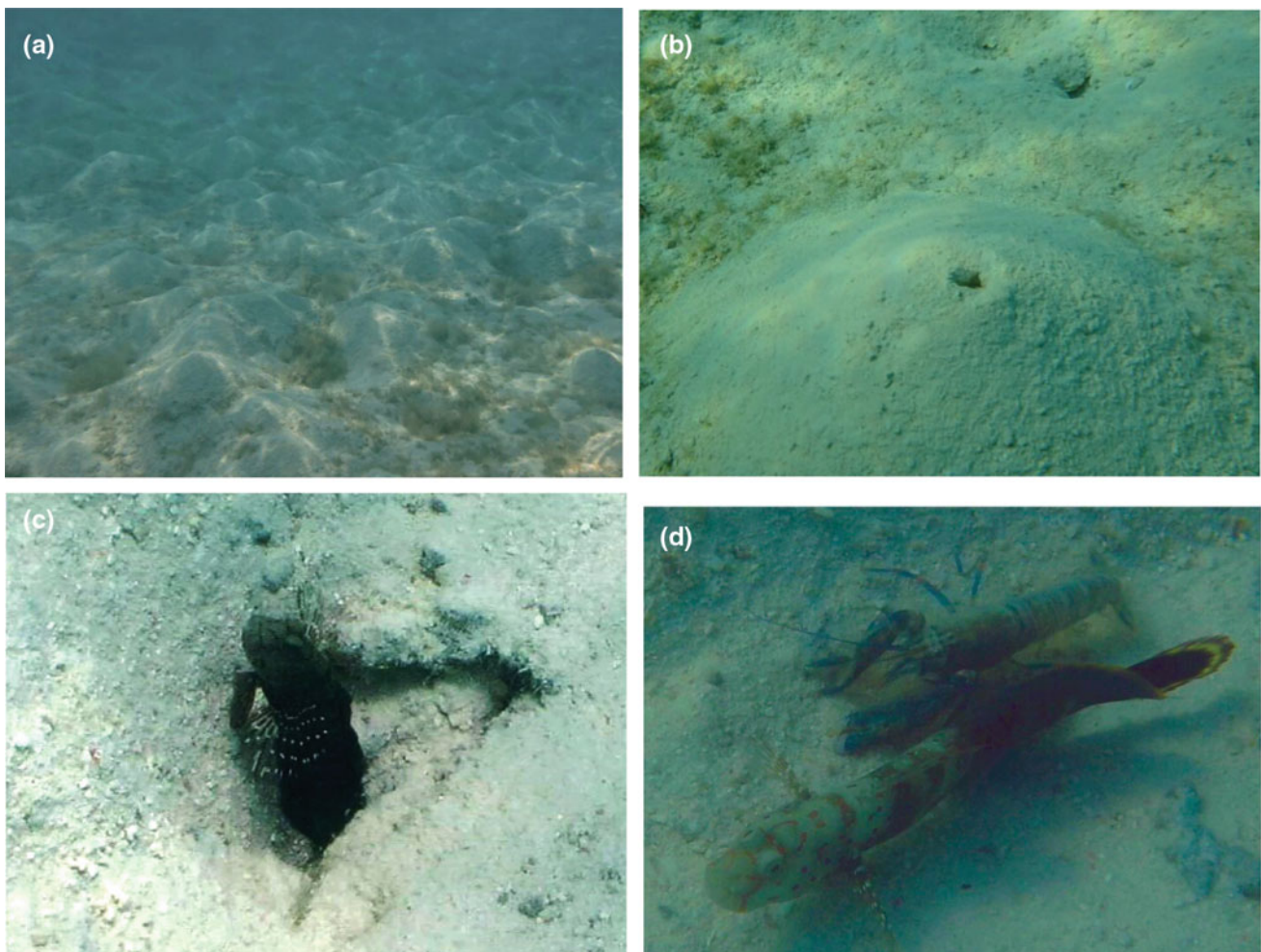
small broken coral heads; sand may be colonized by small patches of green–blue algae called Brown slime (*Schizothrix sigalcolica*), is a sign of stagnant conditions



**Fig. 11** Typical types of bio-erosion grazers; **a** Parrotfish nibble on hard corals, and **b** Surgeonfish (Acanthurids) scrape the coral surface with their sharp teeth

Biological processes involving the flora and fauna inhabiting the shoal are the principal contributors to the carbonate-rich environment where dead corals dominate. The contribution is from the bio-erosion of the coral reefs where marine organisms disintegrate the reefal system by chemical and physical processes. This bio-erosion plays two key roles; it creates new cavities in the reef, and produces new sediment by excavating the holes that are created by various marine fauna, especially parrotfish, shrimp-gobies and others capable of grinding the corals into small particles. The bio-eroders have been classified as grazers, borers, and burrowers by Dudley (2003), who defined the roles of each in supplying sediments, especially carbonate material. Grazers are organisms that feed and nibble on live corals, encrusting coralline algae, and on tufted, filamentous and endolithic algae growing on dead reef substrate (Fig. 10).

The most dramatic of the grazers are ones that attack the coral directly. Live corals are consumed by various species of worms, gastropods, sponges, nudibranchs, crabs, starfish and fish. Pufferfish (Tetradontids) are known to bite off and swallow the soft tips of growing coral, whereas surgeonfish (Acanthurids) scrape the coral surface with their teeth. The most important contributor is the parrotfish (Scarids) that feed mainly on soft algae growing on dead coral substrates and seldom on live corals (Fig. 11). When feeding on the encrusting layer on dead coral they remove part of the substrate beneath it, generating new sediment. Some species have been known to swallow mostly sand and recycle old reef sediment by ingesting. The pharyngeal mill of parrotfish, like the gizzard of surgeonfish, is known to grind fragments of carbonate material into tiny sizes. It is likely that some fine carbonate sediment is excreted in its original



**Fig. 12** **a** Cluster of burrows in a shallow lagoonal sand and mud environment, some areas covered with small patches of algae indicating a stagnant environment; **b** fine to coarse sand burrow construction known as a Symmetrical Mound, resulting from *Alpheus bellulus* shrimp boring activity; **c** fish known as Luther's shrimp-goby

(*Cyptocentrus lutheri*) inhabits expanses of fine to coarse sand in protected lagoons, and lives in burrows with the shrimps. It bores into the carbonate sediment with the help of *Alpheus bellulus* shrimp, as shown in **(d)**



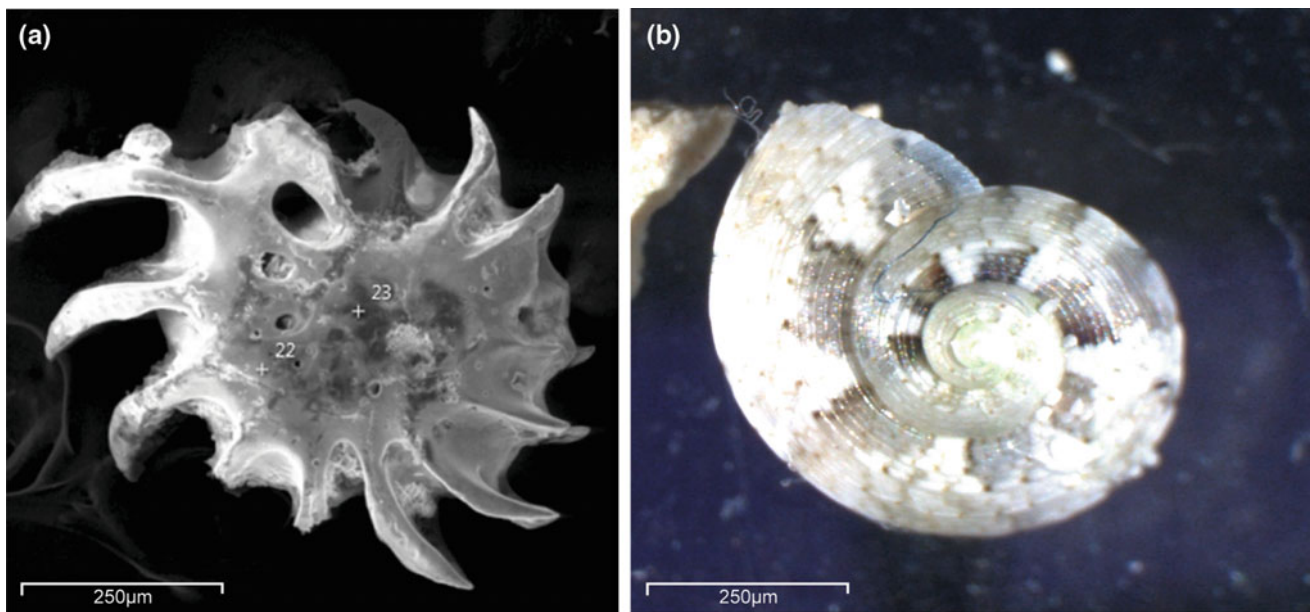
form whereas some particles dissolve while passing through the gut. Parrotfish can therefore be regarded as an important bio-eroder by generating new sediment as a result of nibbling on coral substrates, and by reducing the size of pre-existing sediments they ingest (Dudley 2003).

Many different plants and animals produce holes ranging in size from a few microns ( $\mu\text{m}$ ) to several centimetres by boring on the seabed (Rasul et al. 2017). However, holes between 1 and 5  $\mu\text{m}$  in diameter are known to be produced by bacteria and fungi. Boring activity of endolithic algae is well known. Green, red, and blue-green algae (cyanophyta bacteria) are also known to be capable of eroding carbonate substrates. The blue-green algae possess special boring filaments which produce cavities between 5 and 15  $\mu\text{m}$  in diameter. The micro-boring activity of algae, bacteria and fungi is believed to be accomplished through biochemical dissolution of the carbonate (Dudley 2003). Many examples have been observed in the marine environment, especially where the area is not dynamic.

Fish species such as Luther's shrimp-goby (*Cyptocentrus lutheri*) inhabit areas rich in fine to coarse sand in protected and sheltered environments like lagoons and bays, and live in burrows with the shrimp *Alpheus bellulus*. They make burrows by boring into the carbonate-rich sediment veneer with the assistance of shrimps. Mounds are created by the excavated sediments and are abandoned with time for unknown reasons. Once evacuated, the mounds become somewhat cemented and covered with algae (Fig. 12). Bioturbation seems to be quite active in areas where the bottom

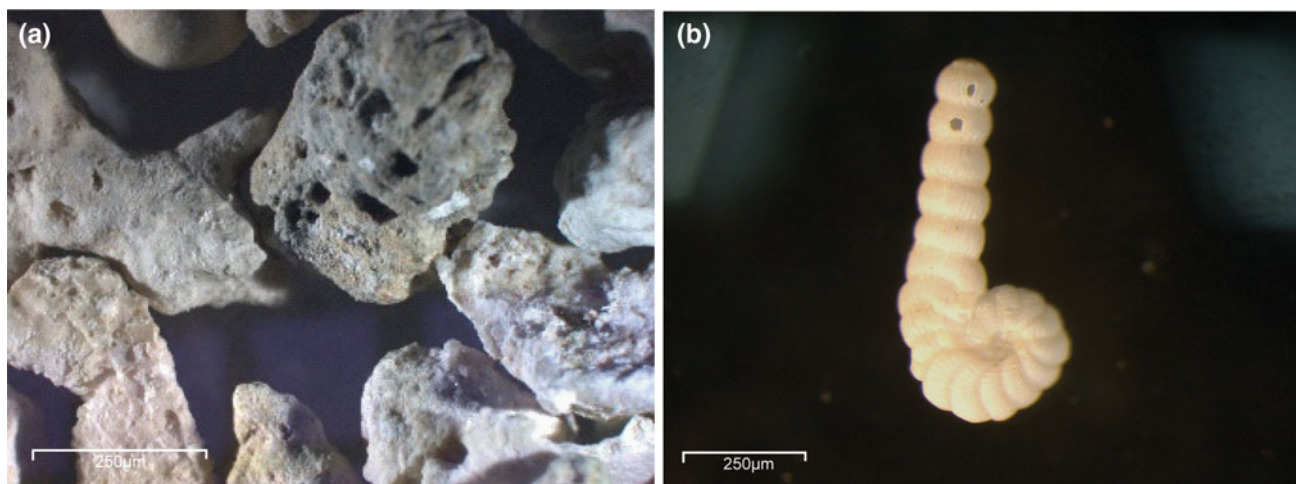
currents are not strong, making the calmer environment the best place to inhabit and to produce sediment. In order for the shrimp-gobies to house themselves or avoid being preyed upon, these two species make burrows in either hard ground or on loose sediment veneer. The dynamics of burrows are well known and documented. Karplus (1987) divided the concept of burrows into three; their structure, physical construction and their dynamics. All three are dependent on the species and the type of sediment (Cummins 1979; Karplus et al. 1974; Yanagisawa 1984). Some burrows may be shallow and branching while others could be short and deep. The morphologies of tunnel-like features, commonly referred to as burrows, are relatively consistent in all shrimp, and are used as homes to inhabit and to hide from predators. The floors are sandy as the shrimp excavates sand and the tops are rocky or filled in with coral debris to prevent collapse (Yanagisawa 1984). Farrow (1971) concluded that the physical characteristic of the sediment is critical in determining the structure and size of the burrows. When the substrate is hard and rocky, the holes are irregular, but when the substrate is muddy and soft, they are regular and dichotomously branching.

The process of bioturbation is quite common in the benthic marine environment. Apart from fish and shrimps, burrowing organisms such as worms and holothurians (sea cucumbers) take in fresh sediment at one end and excrete the processed sediment at the other. As the sediment passes through the gut not only is the organic matter removed but in some cases the sediment grains are also reduced in size due



**Fig. 13** **a** Broken benthic foraminifera (250  $\mu\text{m}$  medium sand), also altered by taphonomic processes such as breakage by currents, micro-borings by endolithic microorganisms and fungi, and dissolution

by low pH; **b** microgastropod (250  $\mu\text{m}$  medium sand) also altered and microbored by endolithic microorganisms and fungi, and dissolution by low pH



**Fig. 14** a Pitted carbonate grain (250  $\mu\text{m}$  medium sand), an indication of stagnant conditions, and b micro-borings by endolithic micro-organisms

to chemical dissolution or abrasion. Some organisms segregate sediments according to size, moving fine-grained material toward the surface (Dudley 2003). They are responsible for recycling the seabed and contribute sediments in different forms to the shoal in addition to the other sources.

Pitting observed on the surface of shells and forams could be related to algal growth (Rasul 1992, 2015; Rasul et al. 2017). The algae bore into the shell surface or wall and with time the algal filaments die and decay, leaving the trace of the boring. Algal boring is also observed on dead corals. However, the green and blue-green algae colonies within the pits could not be observed because of the hydrogen peroxide treatment to remove organic matter from the grains, leaving the boring visible. Shells may break because of strong currents and when the forams die the outer surface becomes weaker; therefore, they could be altered by taphonomic processes such as breakage by currents, microborings by endolithic micro-organisms, fungi and dissolution (Fig. 13). It is observed that where sediment input is absent or minimal boring or pitting takes place especially in calmer environments (Fig. 14).

#### 4.7 Sediment Composition

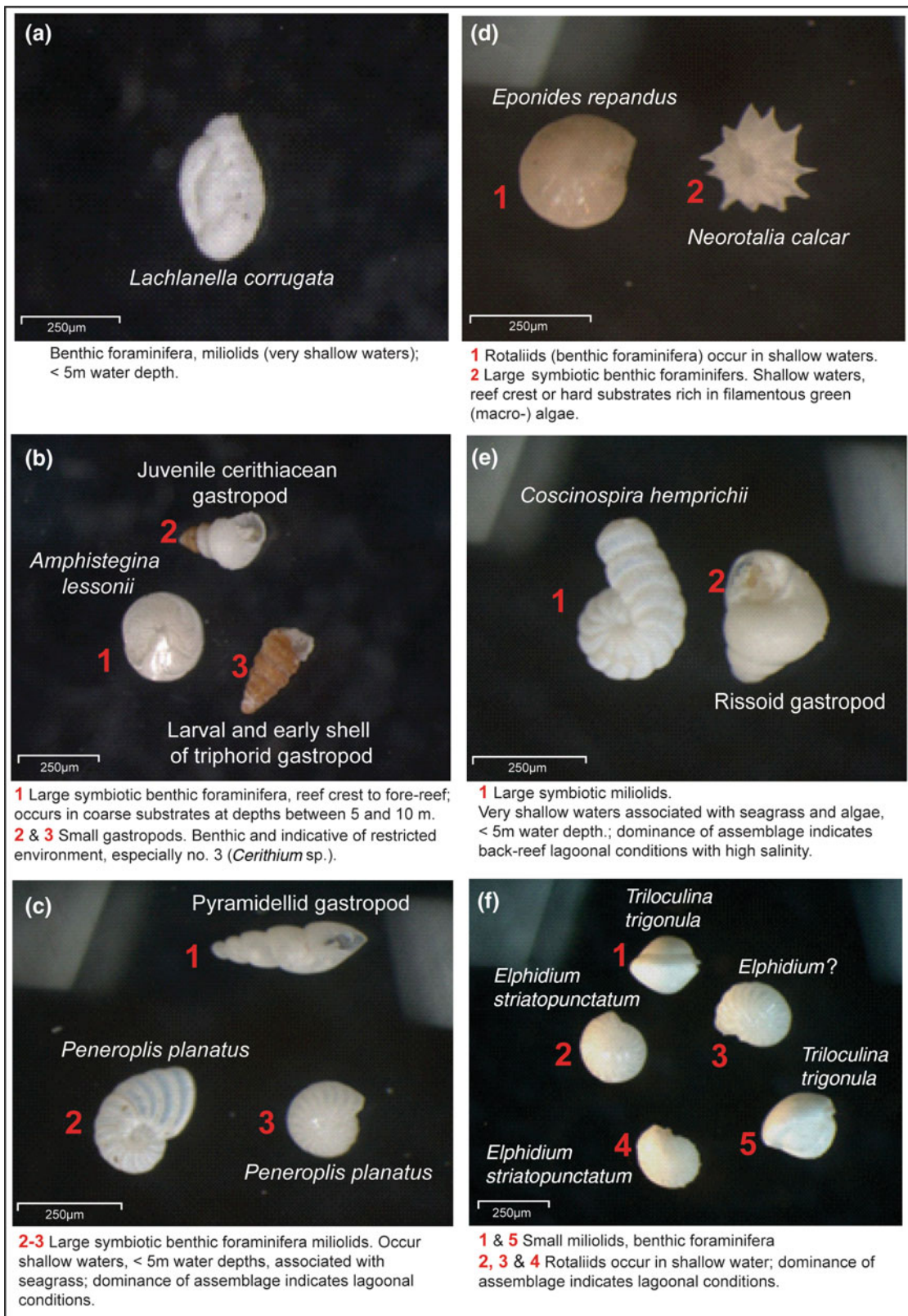
The shoal is veneered mostly with gastropods, forams (Fig. 15) and coral-reef debris (Fig. 16a) of biogenic origin (carbonate), followed by limited amounts of detrital material (Fig. 16b and c). Since no major wadis (seasonal streams) drain into the Red Sea, terrigenous input from the adjoining land by wadis is negligible and carbonate material dominates the sediment veneer. The distribution of detrital material is limited and controlled mostly by the hydrodynamics and by the atmospheric dust brought in by the shamal (wind). The

relative abundance is also governed by the particle size, and the environment of deposition, but the adjoining deserts contribute stained quartz to the area (Fig. 16d).

The destruction of reefs and shoals contributes most, if not all of the carbonate material to the study area. The supply and breakdown of reefs are either by wave and current actions, human activities and natural causes (weakening and breaking of the corals due to natural deterioration), and by boring marine organisms, including coralline algae, sponges and bryozoans that are related to high productivity in the Red Sea. The forams, gastropods and other shelly materials are the product of the typical marine environment of the Red Sea. A microscopic examination showed that most of the detrital materials consists of quartz, feldspars, and occasionally mica (biotite). The feldspars are fresh in appearance, while angular to sub-angular quartz grains, mostly of aeolian origin, are appreciably frosted. Relatively limited terrigenous material is supplied to the shoal, probably by Wadi Al-Kura or by wadis located north of Sharm Obhur. Since the veneer is made up of quartz, feldspars and mica, it is suggested that the probable source of these minerals, although in limited amounts, is from Wadi-Al Kura during the times when it was directly connected to the sharm, that is, before the construction of a bridge and barriers erected to control debris and garbage transport to the sharm. However, it is also possible that mica has drifted from the north (Rasul 2015; Rasul et al. 2009).

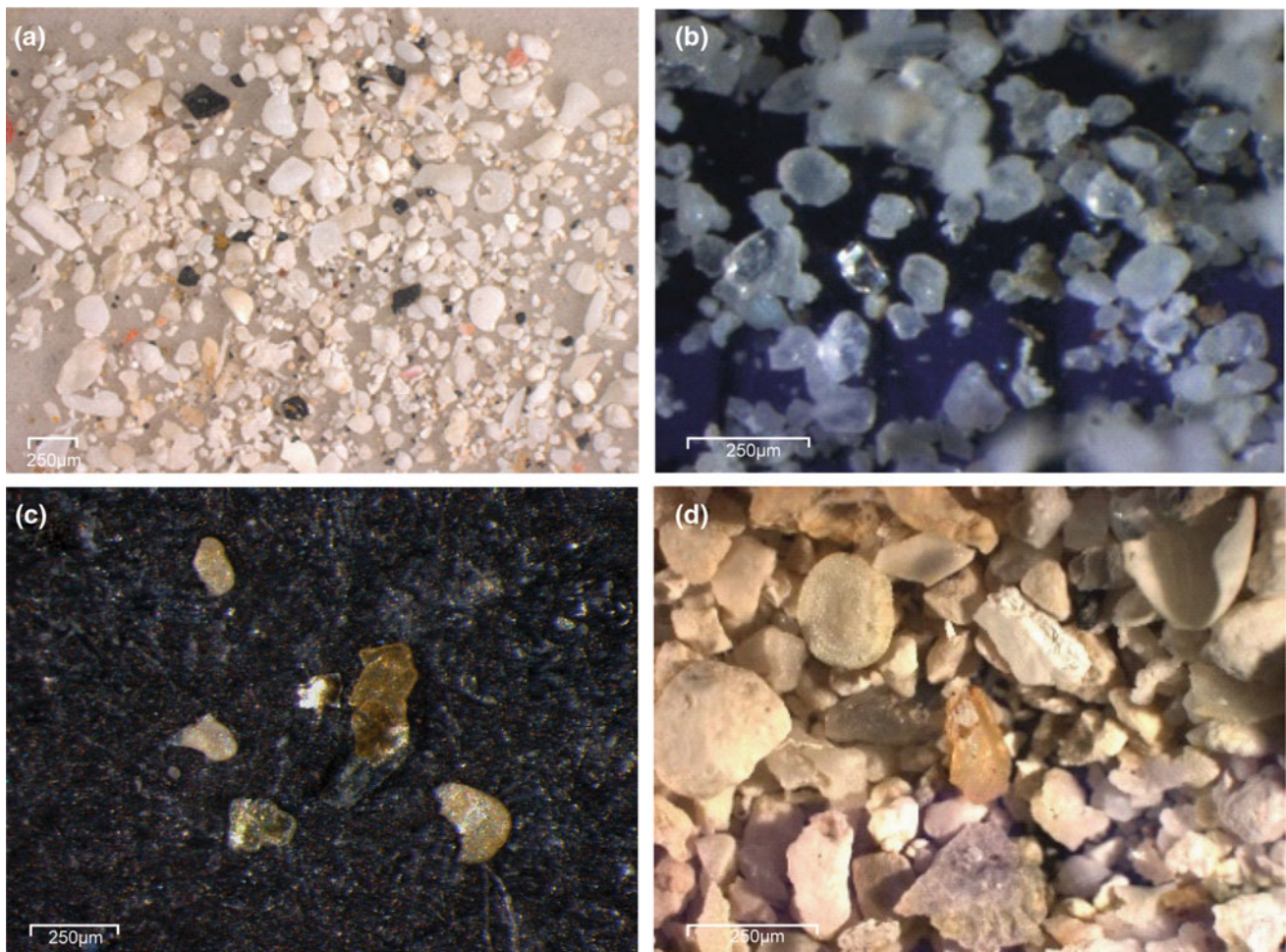
#### 4.8 Bulk Mineralogy

A total of sixteen representative samples were analysed and the following minerals were determined in order of abundance: aragonite, High-Mg calcite, quartz, feldspars, pyrite, dolomite and traces of halite and gypsum (Table 3 and Fig. 17). A few peaks were not taken into account because



These assemblages altogether indicate back-reef (back-reef lagoonal conditions) or intertidal-subtidal environments with water depths of < 5 m, and enriched in sea-grasses and algae dominated area.

**Fig. 15** The assemblages indicate back-reef lagoonal conditions or inter-tidal to sub-tidal environments at <5 m water depth. They flourish in areas where seagrass and algae dominate



**Fig. 16** **a** Typical shoal sample. Dark grains rich in carbon are associated with biogenic material. The brittle nature of the carbon material makes the grain break easily into small grains but it does not have a pre-determined source or association. **b** Mixture of quartz and feldspars. Some quartz is aeolian (wind blown), some may be

wadi-derived. **c** Biotite in a shallow quiescent environment. **d** Iron-stained quartz grain, a confirmation of aeolian input. Although wind-blown materials are commonly well-rounded, this quartz grain is sub-angular, indicating a short history of transportation

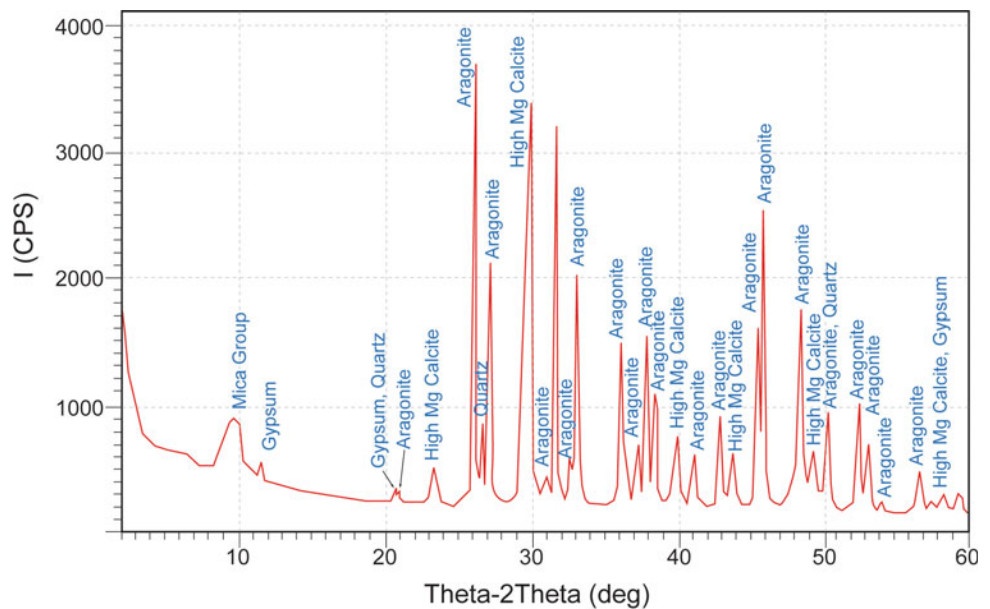
of the faint signal. Environmental conditions and the proportions of lithogenic and biological materials control the relative abundance of these minerals. Traces of halite (crystals developing from high evaporation rates) and gypsum were observed but the faint peak on the XRD diffractogram failed to show a distinct distribution pattern. Aragonite is produced originally from coral fragments, for example, *Helmina* sp., including inorganic carbonate precipitates, whereas High-Mg calcite and aragonite are produced from reefal sediments, coralline algae and mollusks (El-Sayed 1984). The abundance of aragonite and High Mg-calcite is probably derived from the coral fragments as observed by Friedman (1968) and Behairy and El-Sayed (1984). However, it is also suggested that the water flooding the sabkhas (supra-tidal deposits) is rapidly evaporated to an

extent that allows the precipitation of High Mg-calcite, dolomite and gypsum (Behairy et al. 1991), although dolomite was not present or identified. According to Levy (1977), dolomite is present in some sabkhas, including traces in the sabkha sediments of Wadi Al-Kura, where it forms diagenetically through the interaction between previously precipitated calcium carbonate and concentrated marine brines rich in magnesium. The dominance of aragonite and High-Mg calcite and limited pure calcite, and dolomite (not found on the shoal) is diagnostic of the Red Sea coastal sediments located in the subtropical region (Rasul et al. 2010; Bahafzalah and El-Askary 1981; Rao and Behairy 1986; Al-Washmi and Rasul 2003). The presence of some crystals of halite is the result of high evaporation and the hypersaline water.

**Table 3** Bulk minerals identified by X-ray diffractogram (XRD)

Station no.	Abundant	Moderate	Traces
4	Aragonite, High Mg–Calcite		Plagioclene, quartz
6	Aragonite, High Mg–Calcite		Clay minerals, mica, quartz, plagioclene
8	Aragonite, High Mg–Calcite		
14	Aragonite, High Mg–Calcite, quartz		
16	High Mg–Calcite, aragonite		Plagioclene, quartz
19	Aragonite, High Mg–Calcite		Plagioclene, feldspar
22	Aragonite, High Mg–Calcite		Plagioclene
26	Aragonite, High Mg–Calcite		Plagioclene, quartz
28	Aragonite, High Mg–Calcite		Quartz
29	High Mg–Calcite, aragonite		Low Mg–Calcite, quartz, gypsum
30	Aragonite, High Mg–Calcite		
34	High Mg–Calcite, aragonite		Clay minerals, mica?
36	Aragonite, High Mg–Calcite	Low Mg–Calcite	
38	High Mg–Calcite, aragonite	High Mg–Calcite, quartz, mica?	Gypsum, clay minerals
41	High Mg–Calcite, aragonite		
47	Aragonite, High Mg–Calcite		

**Fig. 17** X-ray diffractogram of Red Sea sediment showing various minerals identified by measuring the XRD peaks



### 4.9 Calcium Carbonate (CaCO<sub>3</sub>)

The calcium carbonate content ranges from 66% at station 33 to 99% at station 19, with an average of 83% (Table 4 and Fig. 18). The higher content is because carbonate is contributed mostly by the shoal and from biogenic materials

such as gastropods and foraminiferal sand. Basins in reef-bound coasts without any significant runoff and high aridity are the most probable source of carbonate material in the Red Sea. Therefore, the particle size and their characteristics are controlled primarily by the in situ production of carbonate material. In the Red Sea, the corals and presence

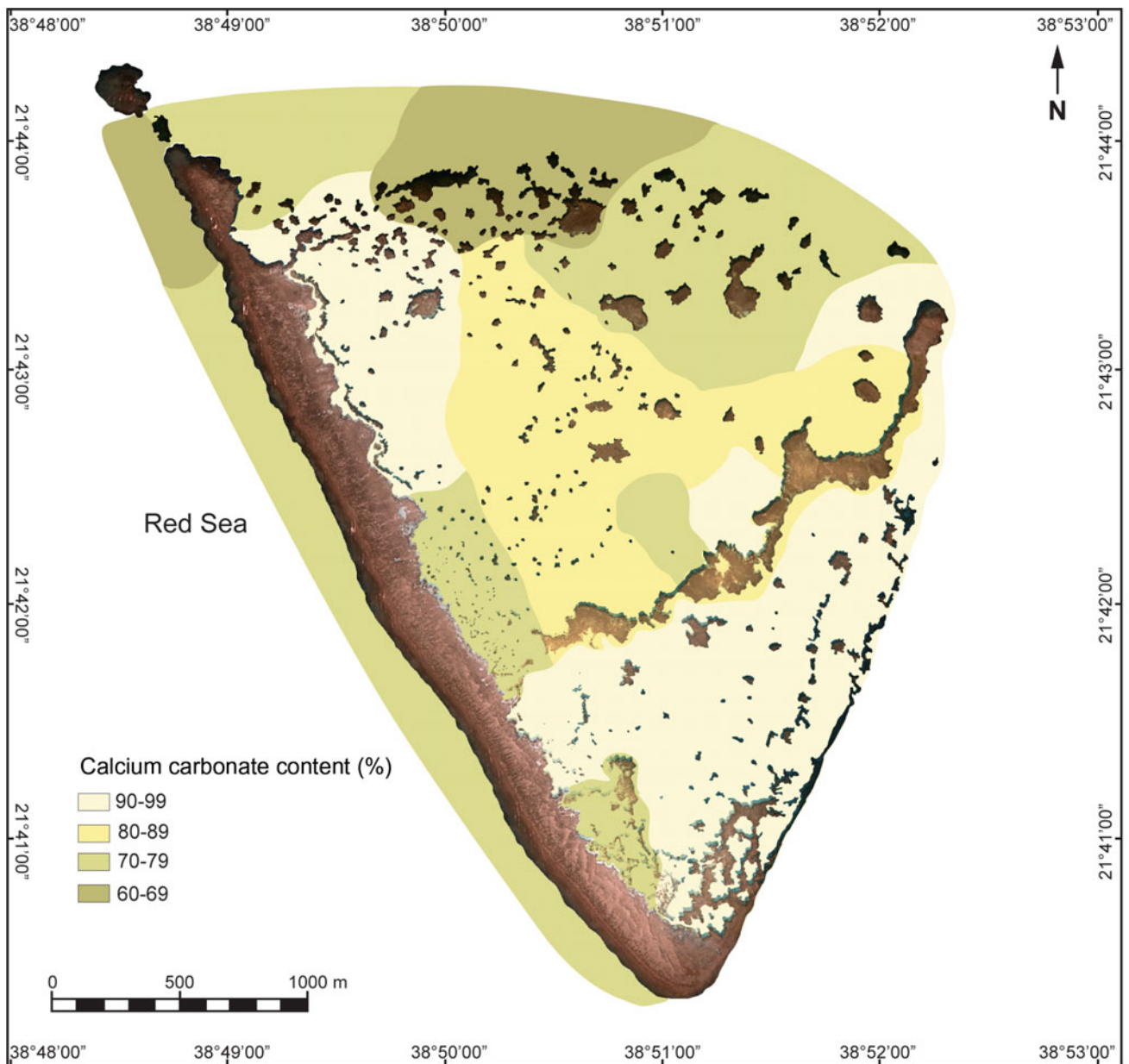
**Table 4** Calcium carbonate data obtained from an automated calcimeter

Station	Water depth (m)	Textural class (Folk 1980)	CaCO <sub>3</sub> (%)
1	8.00	Gravelly sand	91
2	3.00	Muddy sand	92
3	8.30	Muddy sand	88
4	10.00	Muddy gravelly sand	99
5	7.90	Muddy sand	88
6	7.00	Muddy sand	96
7	7.40	Gravelly sand	93
8	6.60	Muddy sand	96
9	7.10	Gravelly sand	91
10	5.10	Gravelly sand	90
11	1.70	Gravelly sand	74
12	1.50	Gravelly sand	75
13	2.00	Gravelly sand	92
14	2.00	Muddy sand	98
15	7.00	Gravelly sand	92
16	12.50	Muddy sand	95
17	8.00	Muddy sand	85
18	6.60	Muddy gravelly sand	87
19	7.90	Muddy gravelly sand	99
20	8.50	Gravelly sand	71
21	5.60	Gravelly muddy sand	88
22	5.00	Gravelly muddy sand	87
23	1.50	Muddy gravelly sand	70
24	1.20	Muddy gravelly sand	71
25	2.80	Muddy gravelly sand	72
26	4.10	Muddy sand	90
27	5.80	Muddy gravelly sand	92
28	8.80	Gravelly muddy sand	95
29	6.20	Muddy sand	91
30	12.00	Muddy sand	95
31	14.50	Sandy gravel	70
32	13.00	Gravelly sand	73
33	18.70	Gravelly sand	66
34	25.00	Muddy sand	68
35	26.00	Gravelly sand	72
36	30.00	Gravelly sand	75
37	32.00	Gravelly sand	75
38	8.50	Muddy sand	90
39	14.80	Gravelly sand	71
40	17.20	Gravelly sand	68
41	16.80	Muddy gravelly sand	67
42	11.00	Gravelly muddy sand	81
43	11.50	Gravelly sand	73
44	11.00	Gravelly sand	70

(continued)

**Table 4** (continued)

Station	Water depth (m)	Textural class (Folk 1980)	CaCO <sub>3</sub> (%)
45	11.00	Gravelly sand	86
46	8.30	Gravelly sand	86
47	10.00	Muddy gravelly sand	80
48	8.40	Gravelly sand	87
49	10.70	Gravelly sand	77
50	7.60	Gravelly sand	88
Min	1.2		66.0
Max	32.0		99.0
Avg	9.7		83.3



**Fig. 18** Distribution of calcium carbonate content in the surficial sediment from the study area

of fringing and barrier reefs play a significant role in the high production of reefal sediments. At present, the restricted flow of Wadi Al-Kura into Sharm Obhur (a creek) and numerous wadis to the north of the sharm mean that the neighbouring areas are not influenced by flash floods, and are rich in carbonate content. As expected the carbonate material over-shadows the limited terrigenous input from the past. The carbonate is supplied to the area by the erosion of reefs by wave and current action, break-up of reefs by fishermen and nibbling of the corals by fish. The percentage of calcium carbonate content contributed by each is undetermined but the source of the carbonate is undoubtedly the shoal itself. However, the biogenic components are further fragmented by human activity and pounded by wave action, especially that part of the shoal facing the open sea, causing the reef to break and thus initiating the production of fine calcareous material.

#### 4.10 Total Organic Carbon (TOC)

Of the 50 samples recovered, only six were selected for TOC analysis based on the sediment colour and grain size. Five showed minimal TOC values between 0.01 and 0.16%, while only one sample showed a very high percentage of TOC (3.12%; Table 5). This anomaly of 3.1% could be the product of bird droppings or from green algae or seagrass found in the area. This area is also very calm, the sediments are not greatly disturbed, and hence organic matter settles down and is incorporated into the veneer. In an environment where there is hardly any influence from fluvial input or organic sources, the TOC concentration is restricted or even absent. In general, the TOC is very low relative to various sub-environments in the Red Sea, because of the richness in carbonate material. It is important to note that the entire area contains light-coloured sediment. The perception that TOC is higher in fine sediments and lower in coarser and carbonate-rich material is not always valid, as shown in the preceding sections.

The distribution of TOC in general does not show any trend because of the remoteness of the area from the coast and lack of organic sources of supply. It is not possible to obtain a trend based on only 6 samples. However, the values

of TOC are not compatible with values reported by other workers in the Red Sea (El-Sayed and Hosny 1980; Behairy et al. 1983; Al-Washmi and Rasul 2003), nor are they present in fine sediments and related to sediment texture. The abundance in coarse-grained carbonate material is somewhat unusual but not abnormal. The higher values of TOC are related to weak currents, and to a sufficient supply of organic material from seagrass and algae, and including the droppings contributed by seabirds. The tendency of shells and forams to adsorb and absorb the organic material effectively has been observed in the shoal area. The degree of absorption is higher in species of forams and gastropods that have porous surfaces that result in the penetration of the nutrient-rich material, giving rise to algal growth (green-red algae) thus enhancing the process of reduction and contributing to TOC increase over time under stagnant conditions.

#### 5 Discernible Sediment Sources

Different compositions and sources of sediments have been identified in Shiab Al-Kabeer. The carbonate sediments of biological origin that dominate the shoal are locally produced by the flora and fauna inhabiting the shoal, including marine organisms such as algae growing on the reef itself. The sediment produced is deposited at the foot of the reef or transported short distances within the sub-environment by locally generated currents, especially during tidal cycles. However, water turbulence generated mostly by wind-generated currents and during spring tidal cycles plays an important role in resuspending the bottom sediments and transporting them to deeper waters.

Aeolian material in the form of stained quartz is transported from the desert by strong winds and deposited on the shoal during dust storms that pass over the Red Sea (Fig. 19e). Although other terrigenous components are scarce, drifted mica, fluvial quartz and feldspars are also contributed to the area either by the once-active Wadi Al-Kura located at the head of the sharm, or numerous wadis located to the north of Sharm Obhur. The numerous small wadis are not very active and therefore the input to the sea may be negligible and would be noticeable in the short term

**Table 5** Distribution of TOC in selected areas of the shoal

Station	Sediment texture	TOC (%)	Mud (%)
8	Muddy sand	3.12	39
28	Gravelly muddy sand	0.14	9
38	Muddy sand	0.12	44
40	Gravelly sand	0.03	4
42	Gravelly muddy sand	0.16	21
45	Gravelly sand	0.01	2





**Fig. 19** Probable modes of sediment input to the shoal. **a** Floaters (in yellow) deployed to restrict the effect of sediment plumes on the sharm, although the plume is eventually dispersed to the open sea by the surface current; **b** Dredging to increase the water depth for deep-keel boats to manoeuvre easily. The dredged material is dumped into the deeper water regardless of the environmental hazard or impact; **c** sediment plume from Sharm Obhur moving in a westerly direction. This event is after rainfall; **d** inadequately treated sewage and ground

water being discharged into the sea at the Corniche area. The murky water indicates the huge area under the threat of contamination; and **e** dust storm over the Red Sea area between Sharm Obhur and Shiab Al-Kabeer. The storm might influence the sediment distribution over the shoal and adjoining areas. Although dust storms are frequent over the Red Sea, the chance of finding aeolian quartz is low because of the constant carbonate input from the shoal

only. The groundwater that is discharged into the Red Sea, and the sediment plume that is generated during rainfall by the seasonal streams are possible contributors of sediments to the shoal (Fig. 19). However, because of the lack of terrigenous input it is very difficult to determine a single source for the veneer composition in the Red Sea and Shiab al-Kabeer.

## 6 Conclusion

The surface veneer rich in biogenic material in the form of shells, forams and abundant coral debris is relatively coarser, dark in colour and poorly sorted with little fine

sediment, which if present is in minor amounts and is calcareous in nature. This is related to weak currents where the environment is relatively stagnant, but coarse debris is contributed mostly by human activities and fine sediment by bio-erosion. Many fish species inhabiting the coral reefs and algae covering the dead corals in quiescent areas are exclusively responsible for the break-up of the carbonate crust or carbonate-rich rubble that constitute part of the sediment veneer of biogenic origin in the shoal area. Quartz, mica and feldspars make up the terrigenous input.

The area has mostly weak to moderate currents because the shoals have a significant role in controlling the movement of water and sediment. Staining, boring and pitting of

sediments are found in less dynamic areas. The sediment colour ranges from light yellow white to very pale brown, where darker sediments are related to the reducing environment and limited supply of terrigenous material. In general, the sediment on the shoal is contemporary and its distribution is controlled primarily by biological processes, physical erosion and how dynamic the area is in terms of wind-wave-generated currents, including the tidal current responsible for sediment transport.

Additional environmental and geological studies are warranted since investments related to tourism in many islands and shoals in the Saudi Arabian Red Sea are now being promoted.

**Acknowledgements** We wish to thank the Saudi Geological Survey for giving us the opportunity to use the data that were generated under the technical work program, and data used in a Master's thesis. We would also like to express our thanks to Dr. Marco Taviani and Dr. Ramadan Abu-Zeid in helping us in the identification of biogenic components. We also wish to extend our thanks to Drs. G. Owen, J. Coakley, N. Hashimi, G. Bailey, A. Khalik and A. Rushdi for reviewing the chapter. Many discussions with Dr. I. Stewart and his comments helped us tremendously in compiling this research. Louiesito Abalos is thanked for helping us in formatting the chapter. Special thanks to all the members of the Center for Marine Geology and colleagues at Saudi Geological Survey for helping us in the field and laboratory work.

## References

- Abou-Ouf MA, El Shater A (1993) Black benthic foraminifera in carbonate facies of a coastal sabkha, Saudi Arabian Red Sea coast. *J Fac Mar Sci King Abdulaziz Univ* 4:133–141
- Al-Washmi HA, Rasul NM (2003) Sedimentary processes of the Quaternary sediments of Al-Kharrar Lagoon, Red Sea, Saudi Arabia. *J Environ Sci Univ Mansoura Egypt* 26(1):273–296
- Bahafzalah AAK, El Askary MA (1981) Sedimentological and micropaleontological investigations of the beach sands around Jeddah, Saudi Arabia. *Bull Fac Earth Sci KAU* 4:25–42
- Behairy AKA, El-Sayed MKh (1984) Carbonate cements in modern Red Sea reef, north of Jeddah, Saudi Arabia. *Mar Geol* 58:443–450
- Behairy AKA, Jaubert J (eds) (1984) Ecology of a coral reef complex and of an inshore lagoon near Sharm Obhur, Red Sea, Saudi Arabia. Final Report, KAU. FMS/UN 163 p (unpublished)
- Behairy AKA, El-Rayis OA, Ibrahim AM (1983) Preliminary investigations of some heavy metals in water, sediments and plankton in Obhur Creek (eastern Red Sea). *J Fac Mar Sci King Abdulaziz Univ* 3:129–139
- Behairy AKA, Rao DNVN, El-Shater A (1991) A siliciclastic coastal sabkha, Red Sea Coast, Saudi Arabia. *J Fac Mar Sci King Abdulaziz Univ* 2:65–77
- Behairy AKA, Sheppard CRC, El-Sayed MK (1992) A review of the geology of coral reefs in the Red Sea. UNEP Regional Seas Reports and Studies No. 152, 39 p
- Bruckner A, Dempsey CA (2015) The status, threats, and resilience of reef-building corals of the Saudi Arabian Red Sea. In: Rasul NMA, Stewart ICF (eds) *The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin*. Springer Earth System Sciences, Berlin, pp 471–486
- Bruckner A, Rowlands G, Riegl B, Purkis S, Williams A, Renaud P (2011) Khaled bin Sultan Living Oceans Foundation atlas of Saudi Arabian Red Sea marine habitats. Panoramic Press, Phoenix, Arizona, 274 p
- Bruckner A, Rowlands G, Riegl B, Williams A, Renaud P (2012) Khaled bin Sultan living oceans foundation atlas of Saudi Arabian Red Sea marine habitats. Panoramic Press, 262 p
- Crossland CJ (1987) In situ release of mucus and DOC-lipid from the corals *Acropora variabilis* and *Stylophora pistillata* in different light regimes. *Coral Reefs* 6:35–42
- Cummins RA (1979) Ecology of gobiid fishes associated with alpheid shrimps at one tree reef. PhD thesis, University of Sydney, Sydney, Australia, 252 p
- De Vantier L, Pilcher N (2000) The status of coral reefs in Saudi Arabia. In: Global Coral Reef Monitoring Network (GCRMN)
- De Vantier L, Turak E, Al-Shaikh K, De'ath G (2000) Coral communities of the central-northern Saudi Arabian Red Sea. *Fauna Arab* 18:23–66
- Dudley WC (2003) Coral reef sedimentology. Kalakua Marine Education Center, University of Hawaii, Hilo, Hawaii. Marine Science Course 461
- Edwards FJ (1987) Climate and oceanography. In: Edwards AJ, Head SM (eds) *The Red Sea*. Pergamon Press, Oxford, pp 45–68
- El-Sayed SZ (1984) Productivity of the Antarctic waters—a reappraisal. In: Holm-Hansen O, Bolis L, Gilles R (eds) *Marine phytoplankton and productivity*. Springer, Berlin, pp 19–34
- El-Sayed MK, Hosny CF (1980) Sediments of the intertidal zone off Ghardaqa, Red Sea, Egypt. In: Proceedings of the symposium on coastal and marine environments of the Red Sea, Khartoum
- Farrow GE (1971) Back-reef and lagoonal environments of Aldabra atoll distinguished by their crustacean burrows. *Symp Zool Soc Lond* 28:455–500
- Fishelson I (1971) Ecology and distribution of the benthic fauna in the shallow waters of the Red Sea. *Mar Biol* 10:113–133
- Folk RL (1980) Petrology of sedimentary rocks. Hemphill's, Austin, Texas, 182 p
- Friedman G (1968) Geology and geochemistry of reefs carbonate sediments, and waters, Gulf of Aqaba (Elat), Red Sea. *J Sed Petrol* 38(2):895–919
- Jado AR, Hötzl H (1984) Quaternary period in Saudi Arabia. Springer, 361 p
- Jado AR, Hötzl, H, Boscher B (1989) Development of sedimentation along the Saudi Arabian Red Sea coast. *J Earth Sci King Abdulaziz Univ* 3:863–888
- Karplus I (1987) The association between gobiid fishes and burrowing alpheid shrimps. *Oceanogr Mar Biol Ann Rev* 25:507–562
- Karplus I, Szlep R, Tsumamal M (1974) The burrows of alpheid shrimp associated with gobiid fish in the northern Red Sea. *Mar Biol* 24:259–268
- Klaus R (2015) Coral reefs and communities of the central and southern Red Sea (Sudan, Eritrea, Djibouti, and Yemen). In: Rasul NMA, Stewart ICF (eds) *The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin*. Springer Earth System Sciences, Berlin, pp 409–451
- Le Corre (1983) Dosage du carbone organique particulaire. In: Aminot A, Chaussepeid M (eds) *Manuel des analyses chimiques en milieu marin*. CNEXO, France, pp 203–208
- Levy Y (1977) The origin and evolution of brine in coastal sabkhas, northern Sinai. *J Sediment Petrol* 47(1):451–462
- Maiklem WR (1967) Black and brown speckled foraminiferal sand from the southern part of the Great Barrier Reef. *J Sediment Petrol* 37:1023–1030
- Mason C, Folk RL (1958) Differentiation of beach dune and aeolian flat environment by size analysis, Mustang Island, Texas. *J Sediment Petrol* 28:211–226

- Maul GA (1996) Small islands: marine science and sustainable development. Coastal and Estuarine Studies, American Geophysical Union, Washington, DC, 467 p
- Mergner H (1971) Structure, ecology and zonation of Red Sea reefs. Symp Zool Soc Lond 28:141–161
- Ormond RFG, Shepherd AR, Price ARG, Pitts JR (1984) Report on the distribution of habitats and species in the Saudi Arabian Red Sea. No. 1. Kingdom of Saudi Arabia. IUCN/MEPA
- Rao DNVN, Behairy AKA (1986) Nature and composition of shore-zone sediments between Jeddah and Yanbu, eastern Red Sea. Mar Geol 70:287–305
- Rasul NMA (1992) Late Quaternary to present day coarse-grained sedimentation of the Indus fluvial-marine system. PhD thesis (unpublished), University of Wales, 248 p
- Rasul NM (2015) Lagoon sediments of the eastern Red Sea: distribution processes, pathways and patterns. In: Rasul NMA, Stewart ICF (eds) The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin. Springer Earth System Sciences, Berlin, pp 281–316
- Rasul N, Al-Nomani S, Al-Hazmi O, Widinly N, Qutub A, Bantan R (2009) Bathymetric survey in Sharm Obhur. Saudi Geological Survey Technical Report SGS-TR-2008-11, 15 p
- Rasul NMA, Abushosha M, Al-Hazmi O, Al-Nomani S, Bahareth F, Widinly N, Akbar A, Qutub AS, Farawati R (2010) Bathymetric survey and ground-truthing of the Al-Kharrar lagoon, Red Sea coast of Saudi Arabia. Saudi Geological Survey Technical Report SGS-TR-2008-8, 77 p
- Rasul NMA, Stewart ICF, Nawab ZA (2015) Introduction to the Red Sea: its origin, structure, and environment. In: Rasul NMA, Stewart ICF (eds) The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin. Springer Earth System Sciences, Berlin, pp 1–28
- Rasul NMA, Al-Kotob AN, Al-Nomani, S (2017) Geological and oceanographical studies of the coastal waters of Rabigh and Masturah regions, SGS Technical Report (submitted)
- Rowlands G, Purkis SJ (2015) The geomorphology of shallow water coral reef environments in the Red Sea. In: Rasul NMA, Stewart ICF (eds) The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin. Springer Earth System Sciences, Berlin, pp 395–408
- Rowlands G, Purkis SJ, Bruckner A (2014) Diversity in the geomorphology of shallow-water carbonate depositional systems in the Saudi Arabian Red Sea. Geomorphology. <https://doi.org/10.1016/j.geomorph.2014.03.014>
- Schlee J, Uchupi E, Trumbull JVA (1964) Statistical parameters of Cape Cod beach and eolian sands. US Geological Survey Professional Paper 501-D, pp D118–D122
- Sea Around Us (2007) A global database on marine fisheries and ecosystems. Fisheries Centre, University of British Columbia, Vancouver, Canada. [www.seararoundus.org/lme/SummaryInfo.aspx?LME=33](http://www.seararoundus.org/lme/SummaryInfo.aspx?LME=33)
- Shepard FP, Young R (1961) Distinguishing between beach and dune sands. J Sediment Petrol 31(2):196–214
- Sheppard CRC, Sheppard ALS (1991) Corals and coral communities of Arabia. Fauna of Saudi Arabia 12:3–170
- Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in the extreme tropical environments. Academic Press, The Netherlands
- Solohub JT, Klovan JE (1970) Evaluation of grain-size parameters in lacustrine environments. J Sediment Petrol 40:81–101
- Sugden W (1963) Some aspects of sedimentation in the Persian Gulf. J Sediment Petrol 33:355–364
- Sugden W (1966) Pyrite staining of pelley debris in carbonate sediments from the Middle East and elsewhere. Geol Mag 103:250–256
- UNEP/IUCN (1988) Coral reefs of the world. UNEP Regional Sea Directories and Bibliographies. IUCN, Gland, Switzerland and Cambridge, UK; UNEP, Nairobi, Kenya
- Yanagisawa Y (1984) Studies on the interspecific relationship between gobiid fish and snapping shrimp. 2. Life history and pair formation of snapping shrimp *Alpheus bellulus*. Publ Seto Mar Biol Lab 29:93–116