

Geochemistry and benthic foraminifera of the nearshore sediments from Yanbu to Al-Lith, eastern Red Sea coast, Saudi Arabia

Ramadan H. Abu-Zied^{1,3} · Mohammad S. B. Hariri²

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Abstract The nearshore waters and sediments along 500 km of the eastern Red Sea coast from Yanbu to Al-Lith were investigated in regard to environmental parameters (temperature, salinity, dissolved oxygen and pH), sediment grain size, organic matters, carbonates, metal concentrations (Fe, Mn, Zn, Cu, Cr, Pb, Ni and Co) and benthic foraminifera in order to document and give a broad view about the present environmental status of this shoreline area. The results showed that the studied nearshore sediments were mainly composed of biogenic sandy sediments with very low metal concentrations indicating an existence in a natural state. However, in the nearshore sediments of Jeddah coast, these metals became frequent showing the highest concentrations indicating urbanization activities. In the other hand, the organic matter showed no relations with these metals indicating its typical marine sources. The benthic foraminifera of these nearshore sediments were low due to modification by taphonomic processes and were visually (and by the CCA) divided into three faunal assemblages. The *Coscinospira hemprichii-Varidentella neostriatula* assemblage increased northwards, following the subtle northward increase of salinity, and this could be used as a high salinity indicator in the Red Sea fossil sediments. Whereas, the *Neorotalia calcar-Neoepionides bradyi*

assemblage increased southward, probably, as a result of a profusion of seagrasses and filamentous algae. The *Quinqueloculina seminula* assemblage showed no increase/decrease either towards the north or the south, indicating their tolerance for a wide range of environmental conditions and showing, however, their preferences to soft, muddy substrates.

Keywords Benthic foraminifera · Nearshore sediments · CCA · Metals · North gradient

Introduction

The shoreline and its associated coastal environments such as beaches, lagoons, mangroves, bays, inlets/sharms, estuaries, and lakes are very important for human to have a relaxable and enjoyable break and for the adjoining marine faunal and floral habitats to get fresh nutrients directly from freshwater influx into the sea or from the decomposition of organic matters of these environments during their water exchanges (e.g., Robertson et al. 1992; Alongi et al. 1998; Koch and Madden 2001; Prasad and Ramanathan 2008; Davidson-Arnott 2010; Cerda et al. 2013; Li et al. 2014). Prasad and Ramanathan (2008) concluded that the lagoonal mangroves supply considerable load of nutrients to the ocean than the river systems and regulate the global nutrient biogeochemical cycles. Moreover, these coastal environments provide shelters for spawning and nursery of many habitats; therefore, it's worth to keep these natural habitats safe (or make better management) from urbanization activities such as dredging, refilling, reclamation or pollution by industrial and municipal waste waters (e.g., Hunsaker and Carpenter 1990; Worm et al. 2006; Crooks et al. 2011; Cerda et al. 2013).

Many studies were carried out on the physical and chemical properties of some coastal lagoons of the study area

✉ Ramadan H. Abu-Zied
rabuzied@kau.edu.sa

¹ Marine Geology Department, Faculty of Marine Science, King Abdulaziz University, P.O. Box 80207, Jeddah 21589, Saudi Arabia

² Marine Biology Department, Faculty of Marine Science, King Abdulaziz University, P.O. Box 80207, Jeddah 21589, Saudi Arabia

³ Geology Department, Faculty of Science, Mansoura University, El-Mansoura 35516, Egypt

(Meshal 1987; El-Sayed 1987; Ahmad and Sultan 1992; Albarakati 2010, 2012; Abu-Zied et al. 2011a, b and 2013). The coastal marine lagoons/inlets of Jeddah City were investigated by many authors to determine the concentrations of heavy metals and nutrients from sewage effluents in the sediments and nearby waters (El-Rayis and Moammar 1998; Al-Aidaros and Ghazali 1998; Basaham 1998; El Sayed 2002a, b; El Sayed and Basaham 2004; Turki 2007; Abu-Zied et al. 2013). Abu-Zied et al. (2013) indicated that pollution of two coastal inlets (Jeddah City) by municipal wastewaters has led to disappearance of reefal benthic foraminifera (*Coscinospira hemprichii* and *Peneroplis planatus*) and their replacement by soft substrates species such as *Ammonia tepida* and *Quinqueloculina seminula*.

This study aims to document the present environmental status of the nearshore (shoreline) area that extends from Yanbu to Al-Lith and give a broad view about the geochemistry and benthic foraminiferal contents of their sediments in order to use these findings as a reference for the future monitoring.

The study area

The study area, located in the center of the eastern Red Sea coast (Saudi Arabia), is the nearshore sediments and waters that occur along the shoreline extending to about 500 km long from Yanbu to Al-Lith (Fig. 1). It lies between latitudes 20.1° to 24.3° N and longitudes 38° to 40.5° E. The architecture of the shoreline of this area from Yanbu to Al-Lith is irregularly shaped by many geomorphologic features such as bays, inlets/sharms, lagoons, and barrier (reefal) islands. Waves (and longshore currents) and high production of shallow water reefal communities in the Red Sea are also responsible for this irregularity due to redistribution of sediments by the first and build up of hard substrates (skeletons) by the latter leading to formation of shoals and reefal barrier islands. For example, in some places of the nearshore area where seagrasses and algae dominate, raised and hard substrates occur, and when these substrates have no epiphytes, soft to firm and low-lying substrates (subject to erosion) dominate. This may be as a result of trapping of sediments by these epiphytes and rapid deposition of CaCO_3 aftermath of the daily photosynthetic process of these epiphytes.

The study shoreline from Yanbu to Al-Lith generally opens directly to the sea bordering the landward side of tidal or reef flats that end foreshore by cliff of the fringing reefs or reef crests about 0.5–1.5 km away from the shoreline/beach. Backshore, the reefal limestone terraces and the Quaternary loose sediments/alluviums dominate the coastal plain throughout the studied shoreline attaining heights ranging from 0.5 to 5 m (Manaa 2011; Abu-Zied et al. 2013; Bantan et al. 2015). The coastal plain (~25-km wide) is dissected by several

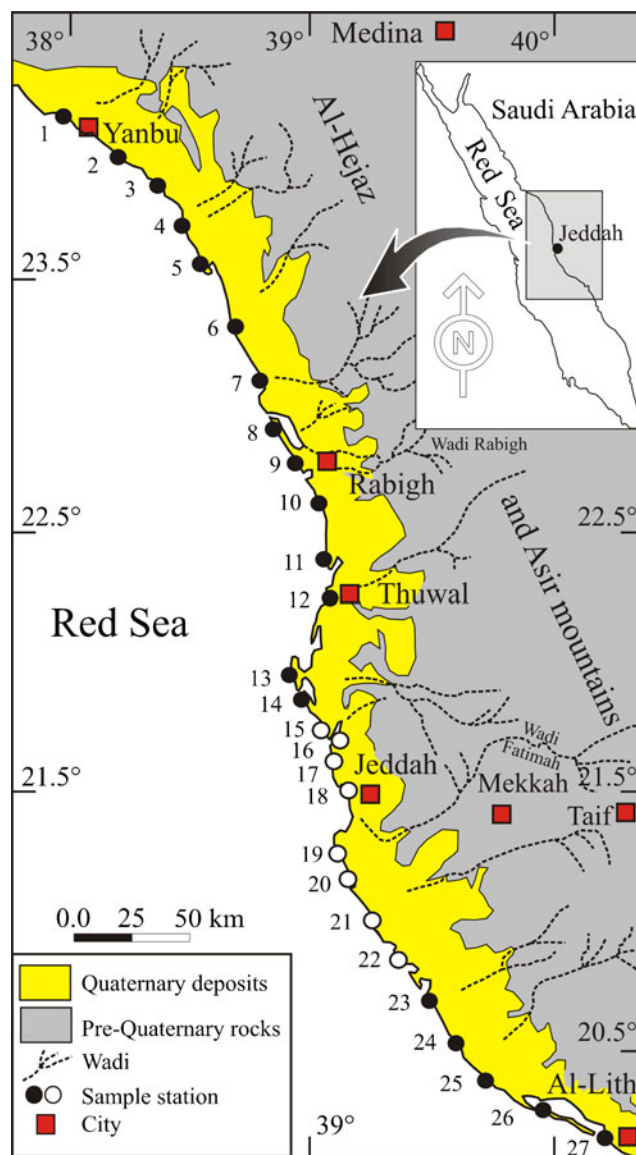


Fig. 1 Location map showing the studied stations as solid circles (Jeddah City stations as open circles). Lineation of wadies were traced from Google Earth 2015

wadies originating from the escarpment of the Al-Hejaz and Asir mountains and end with mouths at the eastern Red Sea shoreline or disappear in the alluvium of the coastal plain (Fig. 1). The raised reefal deposits are numerous and continuous along the shoreline, but away from the sea shoreline, they are covered by old alluvium and fan deposits derived from the nearby metamorphic and volcanic rocks of Al-Hejaz and Asir mountains (El-Sabrouti 1983). These reefal limestone terraces were formed during the late Pleistocene interglacial periods of sea-level highstand (Skipwith 1973; Plaziat et al. 2008; Manaa 2011; Bantan et al. 2015) and have been affected in some places by the Quaternary tectonic (Skipwith 1973). However, in the other places such as Rabigh and Jeddah, the late Pleistocene limestone terraces seem to be

unaffected by tectonics showing no uplift or faulting (Durgaprasada Rao et al. 1987; Manaa 2011; Bantan et al. 2015).

The study shoreline occurs under an arid, warm tropical climate with scarce rainfall of 63 mm/year (Edwards 1987), and no riverine inflow except some wadies (e.g., Rabigh and Fatimah) become active for a short period during the winter. Its northern part is bordered by the Tropic of Cancer (23.44° N).

Tides in the study area and Red Sea as a general are semi-diurnal and the tidal range is about 0.6 m at the northern part (Yanbu) of the study area and decreases southwards until approaching the nodal point at about 19° N, reaching 0.25 m at southern part of the study area (Morcos 1970; Albarakati 2012; Abu-Zied and Bantan 2013).

Materials and methods

Twenty-seven sediment samples were collected from the upper 2 cm of nearshore bottom sediments using a stainless steel scoop shovel. They were taken from close to shoreline extending from Yanbu to Al-Lith of about 500-km long (eastern Red Sea coast) and when water depth was around 0.7 m, during February 2014. After that, sediment samples were packed in plastic bags and transported to laboratory for geochemistry and faunal analyses. Their coordinates were determined by Garmin II GPS and listed with substrate types in Table 1.

The environmental parameters of the nearshore waters such as temperature, salinity, dissolved oxygen, and pH were measured, in situ, by YSI 556 Multi-parameter System (Table 1).

Sediment samples were partitioned into aliquots for sediment grain size and benthic foraminifera, organic matter, carbonate, and elemental analyses. An aliquot of sediment was dried in an oven at 50 °C for 24 h and then weighed to determine their total dry weight. Dried sediments were soaked in freshwater for about 24 h in order to disintegrate solidified aggregates. Wet sediments were washed over sieves of 2- and 0.063-mm mesh diameter. The residual fraction in each sieve was dried and weighed to determine its weight. Then, the percentages of >2 mm (gravel), 2–0.063 mm (sand), and <0.063 mm (mud) fractions were determined. The sand fraction was used for benthic foraminiferal analysis. It was split using a microsplits to reduce the amount of sediment and number of foraminifera to about 200 individuals. Individuals were identified using the following references: Loeblich and Tappan (1987), Haig (1988), Cimerman and Langer (1991), Sgarrella and Moncharmont-Zei (1993), Hottinger et al. (1993), Jones (1994), Yassini and Jones (1995), Abu-Zied et al. (2011a), and Abu-Zied and Bantan (2013). They were counted and presented as a total per gram and percentages of the total assemblages. Their census data are presented in the Appendix Table 3, and rare species that occur with only one

test in one station were lumped as miscellaneous. The key foraminiferal species are digitized by an OPTIKA camera attached to a Leica light microscope and displayed in Fig. 4.

Organic matter in sediments was determined by the loss-on-ignition (LOI) technique following Heiri et al. (2001) and Abu-Zied et al. (2011a), see Table 1. Carbonate was determined by using the WIKA calcimeter (accuracy ± 0.25 %), see Table 1. In this method, approximately 0.5 g of dry weight sediment was etched by 20 ml of 1 N (10 %) HCl inside the calcimeter, and then the reading of CO₂ pressure (PSI) was taken from pressure recorder after about 30 s of the start of the reaction. After that, the CO₃% was calculated by using the following equation: CO₃% = pressure reading (PSI) \times 100 / sample weight \times slope. Where the slope was determined from the curve produced by plotting the different weights (0.2, 0.4, 0.6, 0.8, and 1 g) of standard CaCO₃ against their calcimeter pressure reading (PSI).

The concentrations of major (Ca, Mg, Na and K) and trace (Fe, Mn, Zn, Cu, Cr, Pb, Ni, and Co) metals in studied near shoreline sediments were measured (Table 2) by VARIAN 720-ES ICP-Optical Emission Spectrometer (Inductively Coupled Plasma), Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University. An aliquot of bulk sediment sample was oven dried at 50 °C, ground using an agate pestle and mortar. Accurately weighed (0.25 g) subsamples were digested with hot concentrated nitric acid under reflux for 24 h. This digestion method is assumed to release the environmentally reactive portion of the metal from the sediment (i.e., adsorbed to or occluded within the hydrogenous and biogenic phases, which coat natural particles) leaving behind the silicate matrix (Basaham 1998; Clemente et al. 2008; Abu-Zied et al. 2013). The solution was then evaporated to near dryness and diluted to constant volume with 10 % hydrochloric acid. The concentrations of Ca, Mg, Na, K, Fe, Mn, Zn, Cu, Cr, Pb, Ni and Co were measured in dilute HCl acid solution using the ICP after calibration against standard curves of multi-element standard solution. The concentrations of Ca, Mg, Na and K are displayed in graphs as percentages, and the concentrations of Fe, Mn, Zn, Cu, Cr, Pb, Ni and Co are displayed in graphs as micrograms per gram, see Table 2.

Diversity indices of benthic foraminifera were performed using the PRIMER software (Clarke and Warwick 1994). All indices (simple diversity, *S*; species richness, *d*; Fisher's α index; Shannon-Wiener diversity index, *H*; species evenness, *J'*) were calculated by equations assigned by Buzas and Gibson (1969) and following Abu-Zied (2013).

Canonical correspondence analysis (CCA) was performed using the PAST software (Hammer et al. 2001). The CCA was used to show the relationship among benthic foraminiferal species (≥ 5 %), sediment grain size, environmental parameters (temperature, salinity, dissolved oxygen, and pH) and geochemical variables such as organic matter (LOI), carbonate

Table 1 Coordinates, environmental parameters (temperature, salinity, dissolved oxygen (mg/l), and pH), sediment grain sizes (%), organic matter (%), carbonate (%), environment, and substrate types of the studied stations along the shoreline from Yanbu to Al-Lith, collected during February 2014

Station	Latitude (° N)	Longitude (° E)	Temperature (°C)	Salinity (g/l)	Dissolved oxygen (mg/l)	pH	Gravel	Sand	Mud	Organic matter (%)	Carbonate (%)	Environment	Substrate
1	24.13775	37.95151	21.27	37.92	6.36	7.97	1.2	87.6	11.2	4.7	73	Open tidal flat, wide	Hard with filamentous green algae
2	23.98472	38.19201	24.89	37.93	6.73	8.14	21.3	74.1	4.6	1.0	2	Lagoonal tidal flat, mangroves	Sandy
3	23.87599	38.35914	32.7	39.72	6.6	8.06	7.0	91.5	1.5	1.3	74	Open tidal flat	Sandy
4	23.71719	38.4719	25.53	38.44	7.26	8.07	0.0	92.0	8.0	1.3	57	Open tidal flat	Soft to firm
5	23.56344	38.54753	26.65	38.23	7.14	8.1	0.0	95.7	4.3	5.0	86	Open tidal flat	Sandy
6	23.32939	38.69917	27.5	42.29	9.44	8.23	0.1	64.8	35.0	13.3	11	Lagoon with mangroves	Firm with algal mats
7	23.10146	38.80855	27.01	38.95	6.44	8.14	1.1	92.5	6.4	2.7	48	Open tidal flat, mangroves	Firm sand
8	22.93046	38.85617	26	37.77	6.89	8.08	8.9	89.2	1.9	4.3	97	Open tidal flat	White firm sand
9	22.7849	38.95784	26.34	37.85	6.96	8.12	30.4	66.5	3.1	5.0	97	Open tidal flat	Rocky with thin sandy layer
10	22.62739	39.04394	25.53	37.95	7.04	8.07	7.3	87.3	5.3	4.7	97	Open tidal flat	Rocky with thin sandy layer
11	22.41006	39.07589	26.07	37.89	6.91	8.08	0.1	87.9	12.0	2.3	74	Open tidal flat, wide	Firm sand, seagrasses, and algae
12	22.27128	39.08637	26.29	37.82	6.76	8.1	4.6	92.2	3.2	1.7	92	Open shore of lagoon, refilled	Firm sand
13	21.96267	38.94411	28.85	37.64	9.04	8.17	5.4	87.5	7.1	4.3	96	Back-reef tidal flat	Hard with algae
14	21.88295	38.97103	27.78	37.53	7.36	8.09	0.1	96.0	3.9	3.7	100	Open tidal flat	Sandy with seagrass remains
15	21.73247	39.07134	27.65	37.4	6.94	8.13	0.1	52.1	47.8	2.7	55	Small inlets	Soft
16	21.71693	39.10376	29.15	37.59	7.72	8.17	4.1	81.8	14.2	2.3	63	Small bay	soft
17	21.62678	39.10388	28.5	37.91	9.68	8.19	1.4	94.4	4.2	1.0	76	Open tidal flat, refilled	Firm sand, seagrasses, and algae
18	21.5126	39.16031	27.24	37.01	7.9	8.18	5.7	89.0	5.3	2.0	71	Small bay	Sandy mud with green algae
19	21.26769	39.12773	24.49	39.5	1.59	7.45	4.3	71.9	23.9	2.7	66	Mangroves	Soft blackish mud
20	21.15979	39.16933	24.14	37.78	6.59	8.04	0.1	96.2	3.7	4.7	39	Open tidal flat, algal mat	Soft with green algal mats
21	21.00223	39.27622	27.75	37.71	7.46	8.12	4.0	81.2	14.8	4.7	26	Open tidal flat	Soft with algae
22	20.8547	39.38896	29.31	37.47	8.82	8.21	1.9	94.4	3.7	4.7	66	Open tidal flat	Hard, thin sandy layer, seagrasses
23	20.69113	39.50793	29.24	37.55	9.08	8.19	8.4	72.3	19.3	2.0	89	Open tidal flat	Firm sand with seagrasses
24	20.52689	39.62288	28.36	37.39	7.03	8.04	2.7	86.8	10.5	5.7	94	Open tidal flat	Sandy with seagrass remains
25	20.3875	39.74174	26.68	37.64	6.33	8.04	0.1	94.5	5.3	3.3	18	Open tidal flat	Firm sandy with ripple marks
26	20.27279	39.98276	26.99	37.78	6.39	8.08	4.8	76.9	18.2	2.0	84	Sheltered reef flat	Firm sand with algae
27	20.15822	40.23266	28.39	37.92	6.7	8.04	7.9	89.5	2.6	3.0	92	Open tidal flat, wide	Silty sand

Table 2 Concentrations of the trace metals Fe, Mn, Zn, Cu, Cr, Pb, Ni and Co ($\mu\text{g/g}$) and the major metals Ca, Mg, Na and K (%) in the studied nearshore sediments of the stations from Yanbu to Al-Lith, collected during February 2014

Station	Fe	Mn	Zn	Cu	Cr	Pb	Ni	Cd	Ca	Mg	Na	K
1	7332	199	45.0	4.7	15.6	0	0.1	0	28.65	1.16	0.75	0.18
2	3725	87	42.6	8.0	4.5	0	0.0	0	1.64	0.45	0.25	0.21
3	2177	59	44.9	2.8	6.0	0	0.0	0	27.11	1.80	0.45	0.15
4	3	3	0.0	3.7	0.0	0	0.0	0	27.45	1.05	0.53	0.20
5	4	22	0.1	2.8	0.0	0	0.0	1.1	36.32	0.75	0.73	0.16
6	17,519	448	67.5	15.6	45.6	0	23.6	0	6.63	9.56	1.03	0.43
7	14,404	336	42.2	8.7	34.8	0	13.7	0	20.18	1.82	0.54	0.25
8	1294	32	19.9	5.5	8.8	0	3.8	0	42.14	1.85	0.63	0.21
9	2905	95	28.3	3.3	18.3	0	0.0	0	36.82	2.70	0.70	0.16
10	2416	62	21.3	5.3	19.6	0	0.0	0	41.25	1.87	0.77	0.20
11	9559	178	63.3	9.5	29.9	0	8.6	0	32.36	1.45	0.79	0.26
12	347	81	24.1	4.5	4.2	0	0.0	0	37.29	1.23	0.65	0.17
13	683	21	12.5	3.3	6.2	0	0.0	0	39.73	1.46	0.85	0.15
14	1625	30	74.1	6.6	12.7	0	0.0	0	39.92	1.11	0.98	0.16
15	42	131	68.8	16.9	1.4	0	27.1	0	23.46	2.68	0.99	0.31
16	20,000	361	83.6	48.9	44.7	7.8	13.2	0	34.22	1.59	0.87	0.19
17	10,890	192	80.8	18.2	34.0	0.0	4.9	0.21	33.22	2.15	1.00	0.20
18	13,415	222	87.8	32.3	25.7	3.7	2.2	0	36.20	1.27	0.83	0.19
19	19	188	60.6	9.1	4.9	5.2	6.4	0	36.10	2.05	1.91	0.27
20	17,490	376	133.9	14.8	49.4	0.0	8.3	0	21.61	1.45	0.92	0.19
21	20,000	339	93.2	24.4	40.2	1.2	10.8	0	14.52	1.37	1.38	0.31
22	12,673	289	57.2	11.8	35.2	0.0	2.8	0	26.37	1.57	0.63	0.17
23	4503	80	93.4	10.3	43.7	64.8	21.7	0	36.55	2.59	0.72	0.19
24	4205	72	34.2	7.7	9.8	26.2	0.0	0	40.56	1.88	0.54	0.16
25	12,332	322	50.8	6.0	18.2	0.0	0.0	0	13.28	1.32	0.69	0.21
26	5820	138	37.7	7.1	15.5	0	0.0	0	37.61	1.98	0.77	0.22
27	0	11	0	1.8	1.0	0	0.0	0	34.10	1.65	0.62	0.16

(CaCO_3), and metal concentrations (Ca, Mg, Na, K, Fe, Mn, Zn, Cu, Cr, Pb, Ni and Co).

Results

Environmental parameters

The water temperature near shoreline from Yanbu to Al-Lith showed a mean value of 27 ± 2 °C during February 2014 (Fig. 2). It was the lowest (21 °C) at the north, the Corniche of Yanbu (station 1) and the highest (33 °C) also at the north near the desalination plant of Yanbu, station 3 (Fig. 2). It is also delicately noted that the nearshore water temperature showed a subtle decrease as moving towards the north (Fig. 2).

The nearshore water salinity from Yanbu to Al-Lith showed a mean value of 38 ± 1 g/l, during February 2014 (Fig. 2). It was the lowest (37 g/l) at the station 18 (Al Hamra Corniche, Jeddah City) and the highest (42 g/l) at mangrove lagoonal area with rich algal mats, station 6 (Fig. 2). Same as

water temperature, the salinity showed a south-north gradient, but it increases as moving towards the north (Fig. 2).

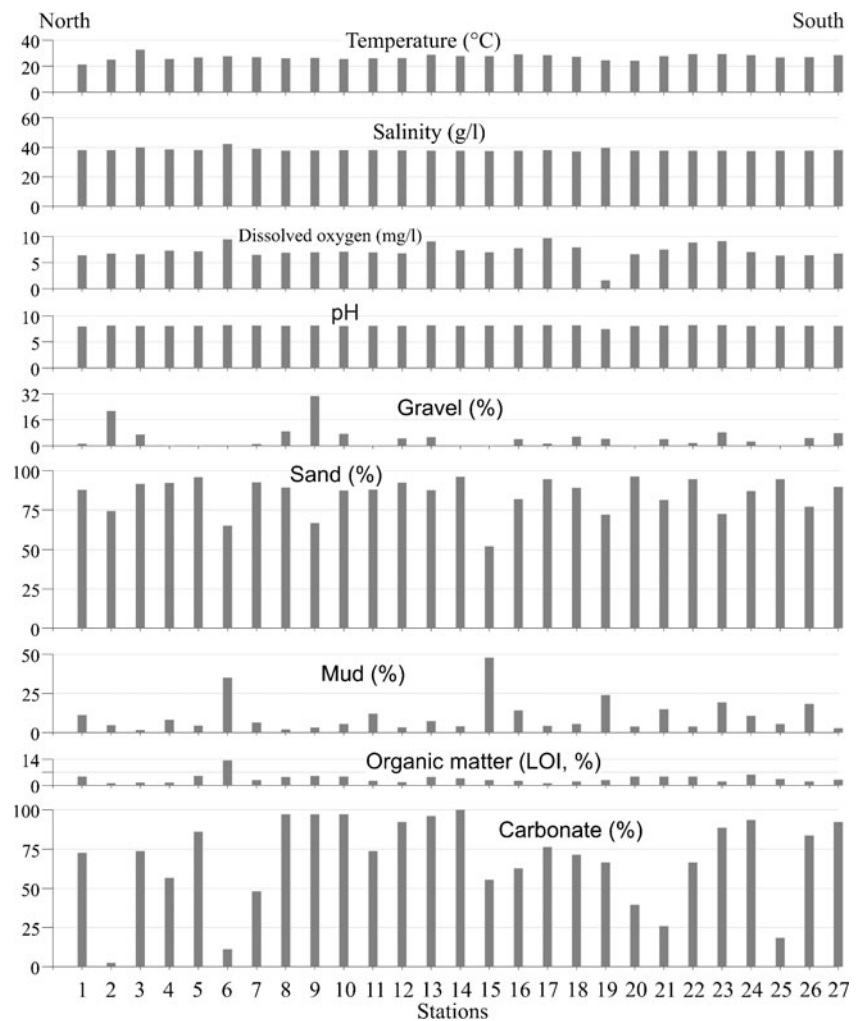
The dissolved oxygen of nearshore water of the study area was 7.2 ± 1.5 (mg/l), showing the lowest value (1.6 mg/l) at the station 19 where mangrove trees predominate and the highest value (9.7 mg/l) at the stations 6 and 17 where algal mats predominates (Fig. 2).

The pH of nearshore water from Yanbu to Al-Lith was 8.1 ± 0.1 , showing the lowest value (7.5) at the station 19 where mangrove trees predominate and the highest value (8.2) at the station 6 where algal mats predominates (Fig. 2).

Sediment grain size

The gravel fraction (>2 mm) in the studied nearshore sediments was very low showing a mean value of 5 % (± 7) and became undetectable at many stations (Fig. 2). It increased to the highest value (>15 %) at the stations 2 and 9 (Fig. 2). It is composed mainly of biogenic remains of corals and molluscs. The sand fraction (2–0.063 mm) was dominant sediment grain size reaching a mean of 85 % (± 11) of the total sediment dry

Fig. 2 Distribution of temperature, salinity, dissolved oxygen, pH, sediment grain sizes, organic matter, and carbonate in the studied stations along the shoreline from Yanbu to Al-Lith, collected during February 2014



weight (Fig. 2). It did not decrease below 50 % in all the studied shoreline sediments. However, it reached maxima up to 96 % of the total sediment dry weight at many stations (Fig. 2). It is composed mainly of biogenic remains of benthic foraminifera, corals, small molluscs, and calcareous algae. The mud fraction (<0.063 mm) was also very low in the studied shoreline sediments showing a mean value of 10 % (± 11) of the total sediment dry weight (Fig. 2). It increased to the highest values in sheltered areas of mangroves and embayments such as in the stations 6 (35 %), 15 (48 %), and 19 (24 %) (Fig. 2).

Organic matter and carbonate

The organic matter in the studied nearshore sediments was very low showing a mean of 3.5 % (± 2.4) (Fig. 2). It only increased to the highest value (13 %) in the sediments of the mangrove Station 6 (35 %). The carbonate (CaCO_3) was very high in the studied nearshore sediments displaying a mean of 68 % (± 28) and it reached maxima (>90 %) at many stations

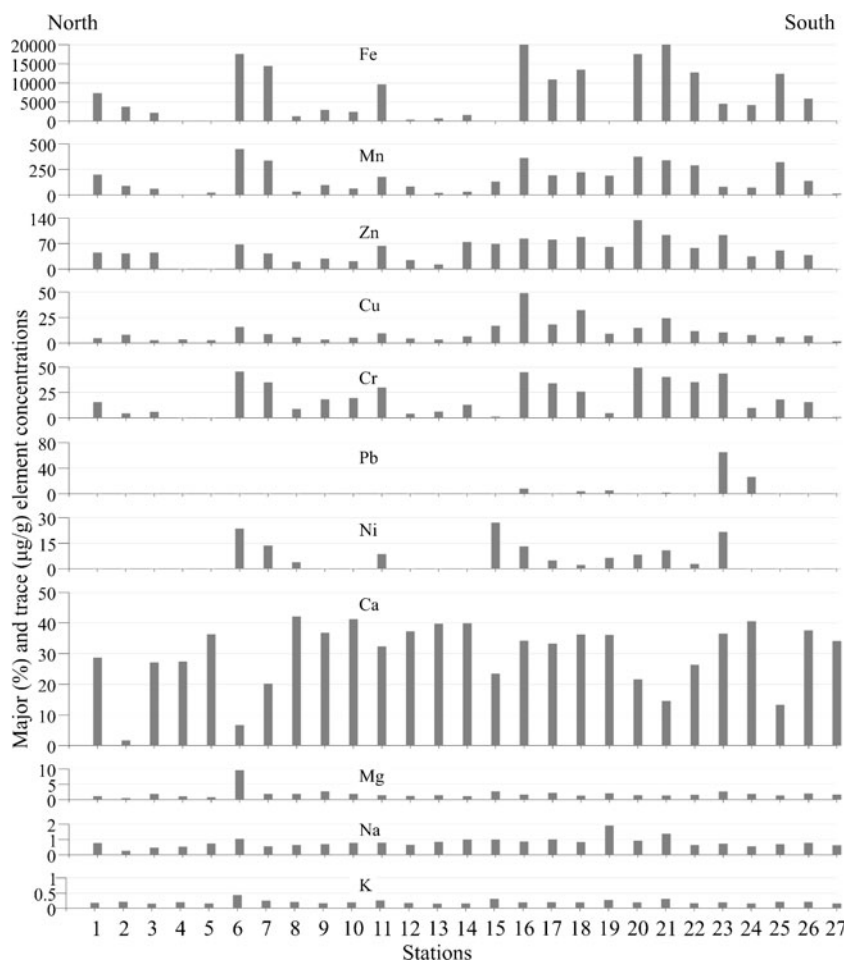
(Fig. 2). The carbonate decreased to low values at the stations 2, 6, and 25 (Fig. 2).

Metal concentration

Fe concentration in the studied nearshore sediments from Yanbu to Al-Lith was around 5000 $\mu\text{g/g}$ in most of the stations, but it has a mean of $\sim 7000 \pm 6900 \mu\text{g/g}$ (Fig. 3). It showed the highest concentrations in nearshore sediments of Jeddah coast, reaching values up to 20,000 $\mu\text{g/g}$ (Fig. 3). The concentrations of Mn and Zn are showing the same frequency distribution as that of Fe. They were around 125 ± 130 and $30 \pm 33 \mu\text{g/g}$ in most of the studied stations, but they have means of 160 and 50 $\mu\text{g/g}$, respectively (Fig. 3). They showed also the highest concentrations in nearshore sediments of Jeddah coast, reaching values more than 300 and 100 $\mu\text{g/g}$, respectively (Fig. 3).

Concentration of Cu in the studied nearshore sediments from Yanbu to Al-Lith was low showing a mean value of $11 \pm 10 \mu\text{g/g}$, and it remarkably increased (up to 50 $\mu\text{g/g}$) in the nearshore sediments of Jeddah coast (Fig. 3). Concentration of Cr showed a mean of $20 \pm 16 \mu\text{g/g}$; however, it became

Fig. 3 Distribution concentrations of the trace metals Fe, Mn, Zn, Cu, Cr, Pb, Ni and Co ($\mu\text{g/g}$) and the major metals Ca, Mg, Na, and K (%) in the studied stations from Yanbu to Al-Lith



more abundant and dominant (up to 50 $\mu\text{g/g}$) in the nearshore sediments of Jeddah coast (Fig. 3). Concentration of Pb was undetectable in the studied nearshore sediments from Yanbu to Al-Lith, but it only appeared in the nearshore sediments of Jeddah coast showing value up to 64 $\mu\text{g/g}$ (Fig. 3). Concentration of Ni was also undetectable in the sediments of most of the studied stations. It became more abundant and dominant ($>15 \mu\text{g/g}$) in the nearshore sediments of Jeddah coast (Fig. 3). Concentration of Co in the studied nearshore sediments from Yanbu to Al-Lith was undetectable (Table 2).

Concentrations of the major metals (Ca, Mg, Na, and K) were the highest in the studied nearshore sediments showing these mean values 30 ± 11 , 2 ± 1.5 , 0.8 ± 0.3 and 0.2 ± 0.1 %, respectively (Fig. 3).

Benthic foraminifera

In this study, 70 species of benthic foraminifera were recorded from nearshore sediments of Yanbu to Al-Lith; some of them (key species) were photographed by OPTIKA camera attached to a Leica light microscope and displayed in Fig. 4. All of them were considered when calculating the diversity indices. However, only 54 species were presented in the

Appendix Table 3 and the rest (16 rare species) were lumped as miscellaneous. For simplicity, the species (20 species) that contribute to more than 5 % of the total faunal assemblage are discussed and displayed in Figs. 6 and 7.

Benthic foraminiferal density showed a mean of 520 ± 460 (specimen/g) throughout the studied stations (Fig. 5). It increased to highest values (1500 specimen/g) in the stations 1, 14, and 24. It is noted that the faunal density increases towards the southern stations (Fig. 5). It was very low or disappeared from the sediments of station 2 and the mangrove station 6 (Fig. 5). The faunal diversities (S , d , Fisher’s α , H and J') also showed an increase towards the southern stations (Fig. 5). Overall, they have the following mean values in the studied stations: 24 ± 6.5 , 5 ± 1.4 , 10.8 ± 4.5 , 2.4 ± 0.5 and 0.8 ± 0.1 , respectively (Fig. 5).

The distribution abundance of the key foraminiferal species is displayed in Fig. 6. They could not be classified into groups by cluster technique due probably to occurrence of long distance between each station. However, they are well coordinated by the CCA into distinct assemblages (Fig. 7). Therefore, they were visually divided into three faunal assemblages (named according to the most dominant species) as follows: northward increased-assemblage (*C. hemprichii-Varidentella neostriatula*),

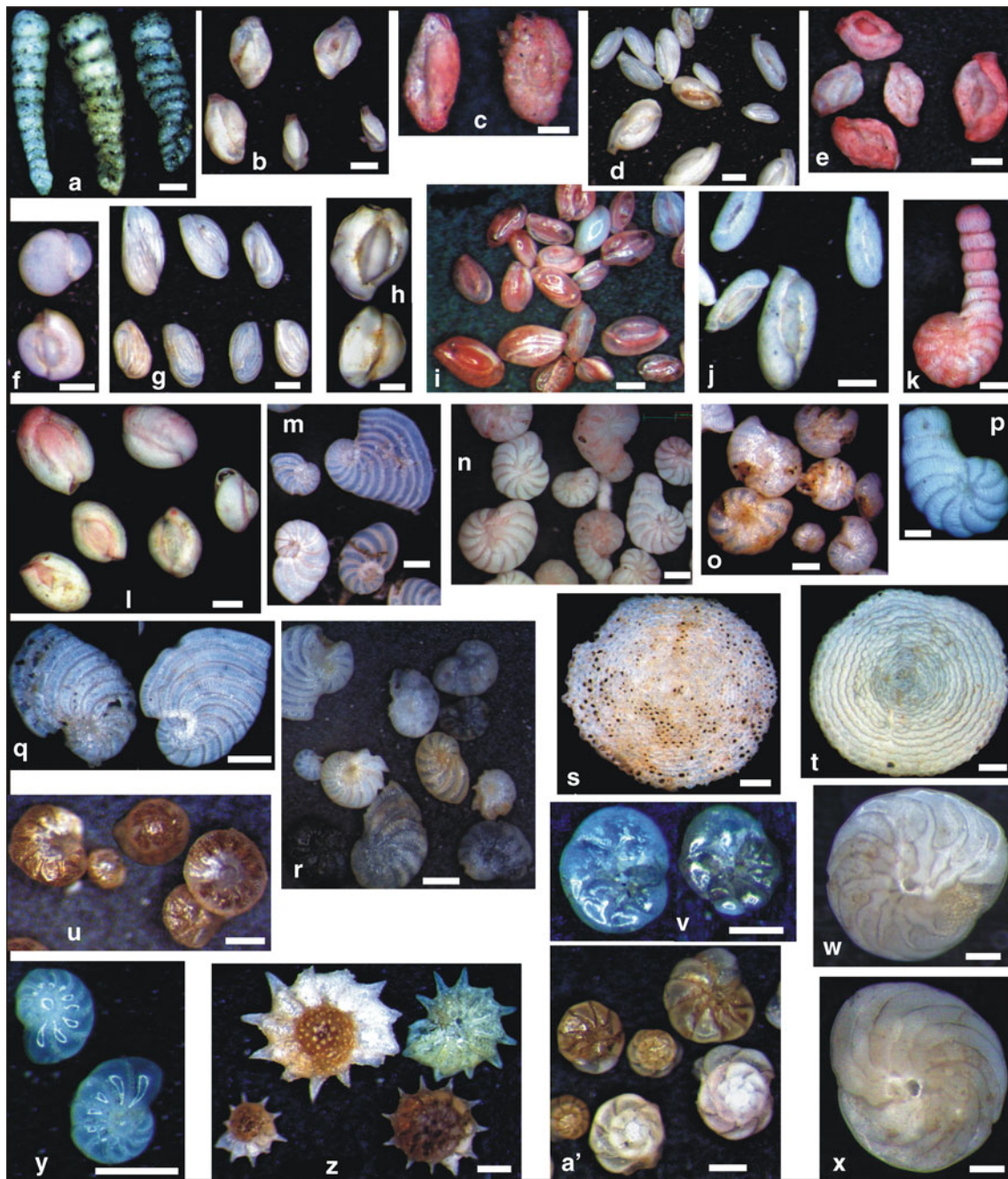


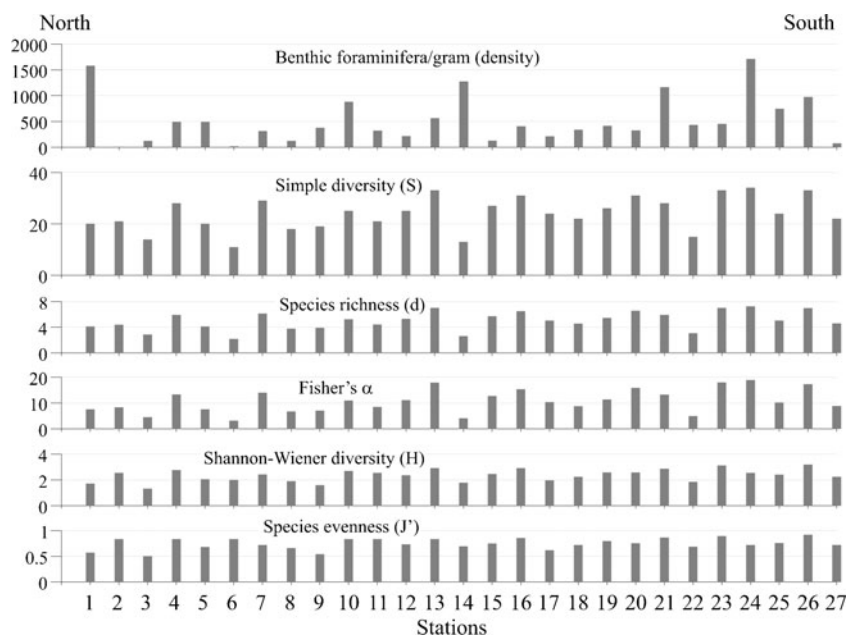
Fig. 4 Light microscope images of benthic foraminiferal species. **a** *Clavulina multicamerata* (Chapman): side views. **b** *Affinetrina quadrilateralis* (d'Orbigny): side views. **c** *Agglutinella compressa* (El-Nakhal): side views. **d** *Cycloforina carinatastriata*: side views. **e** *Lachlanella corrugata* (Collins): side views. **f** *Miliolinella labiosa* (d'Orbigny): side views. **g** *Quinqueloculina limbata* (d'Orbigny): side views. **h** *Quinqueloculina lamarckiana* (d'Orbigny): side views. **i** *Quinqueloculina seminula* (Linnaeus): side views. **j** *Quinqueloculina tropicalis* (Cushman): side views. **k, n, p** *Coscinospira hemprichii* (Ehrenberg): **k, n, p** side views of well-preserved specimens; **o** side views of broken and abraded specimen. **l** *Varidentella neostriatula*

(Thalman): side and apertural views. **m, q–r** *Peneroplis planatus* (Fichtel and Moll): **m** side views of well preserved specimens; **q–r** side views of broken and abraded specimens. **s–t** *Sorites orbiculus* (Forskål): **s** side view of abraded specimen; **t** side view of well-preserved specimen. **u** *Neoepionides bradyi* (Le Calvez): umbilical and dorsal views. **v** *Rosalina bradyi* (Cushman): umbilical views. **w–x** *Amphistegina lessonii* (d'Orbigny): **w** umbilical view; **x** dorsal view. **y** *Haynesina depressulus* (Walker and Jacob): umbilical views. **z** *Neorotalia calcar* (d'Orbigny): umbilical and dorsal views. **a'** *Ammonia tepida* (Cushman): umbilical and dorsal views. Scale bar = 200 μ m

southward increased-assemblage (*Neorotalia calcar-Neoepionides bradyi*) and no trend assemblage (*Q. seminula-P. planatus-Quinqueloculina limbata*).

The northward increased-assemblage is dominated by the *C. hemprichii-V. neostriatula* assemblages which are the most frequent species in the studied nearshore sediments of Yanbu

Fig. 5 Distribution abundances of benthic foraminiferal density (per gram of sediment dry weight) and diversity indices such as simple diversity (S), species richness (d), Fisher's α , Shannon-Wiener (H) and species evenness (J') in the studied stations from Yanbu to Al-Lith



to Al-Lith (Fig. 6). They gradually increased in their frequency abundances towards the northern stations reaching more than 50 % of the total faunal assemblages. They are associated with low-frequency abundances species such as *Quinqueloculina bicarinata* and *Elphidium striatopunctatum* that also showed the northward increase gradient (Fig. 6).

The southward increased-assemblage is dominated by the *N. calcar-N. bradyi* assemblages displaying the highest frequency abundances towards the southern stations (Fig. 6). They are associated with low-frequency abundances species such as *Quinqueloculina tropicalis*, *Amphistegina lessonii* and *Sorites orbiculus* that also showed the southward increase gradient (Fig. 6).

The no trend assemblage is dominated by *Q. seminula-P. planatus-Q. limbata* assemblages that are occurring in all the studied nearshore sediments of Yanbu to Al-Lith but showing no north-south gradient (no specific trends) as the above-mentioned assemblages (Fig. 6). They are associated with low frequency abundances species such as *Q. lamarckiana*, *A. tepida* and *Affinetrina quadrilateralis* (Fig. 6).

Correlation of faunal assemblages with the studied parameters

From the ordination plot of the CCA, it is noted that the main environmental parameters that affect the benthic foraminifera in the nearshore sediments of Yanbu to Al-Lith are sediment grain size (gravel and mud fractions) and organic matters (Fig. 7). The pH and dissolved oxygen also show a subordinate control (Fig. 7). The northward increased-assemblage (*C. hemprichii*, *V. neostriatula*, *Q. bicarinata* and

E. striatopunctatum) and *P. planatus* showed positive correlations with the organic matter, salinity, and carbonate (Fig. 7). On the other hand, they are inversely correlated with the gravel fraction and heavy metals such as Cr, Mn, Fe and Zn (Fig. 7). They also showed no relations with the environmental parameters such as pH, dissolved oxygen, temperature and mud-sand fraction. The southward increased-assemblage (*N. bradyi*, *A. lessonii* and *N. calcar*) showed opposite relationships with the northward increased-assemblage, showing positive correlations with the gravel fraction and heavy metals (e.g., Cr, Mn, Fe and Zn), inverse relationships with the organic matter, salinity, and carbonate, and no relations with the environmental parameters such as pH, dissolved oxygen, temperature and mud-sand fraction (Fig. 7).

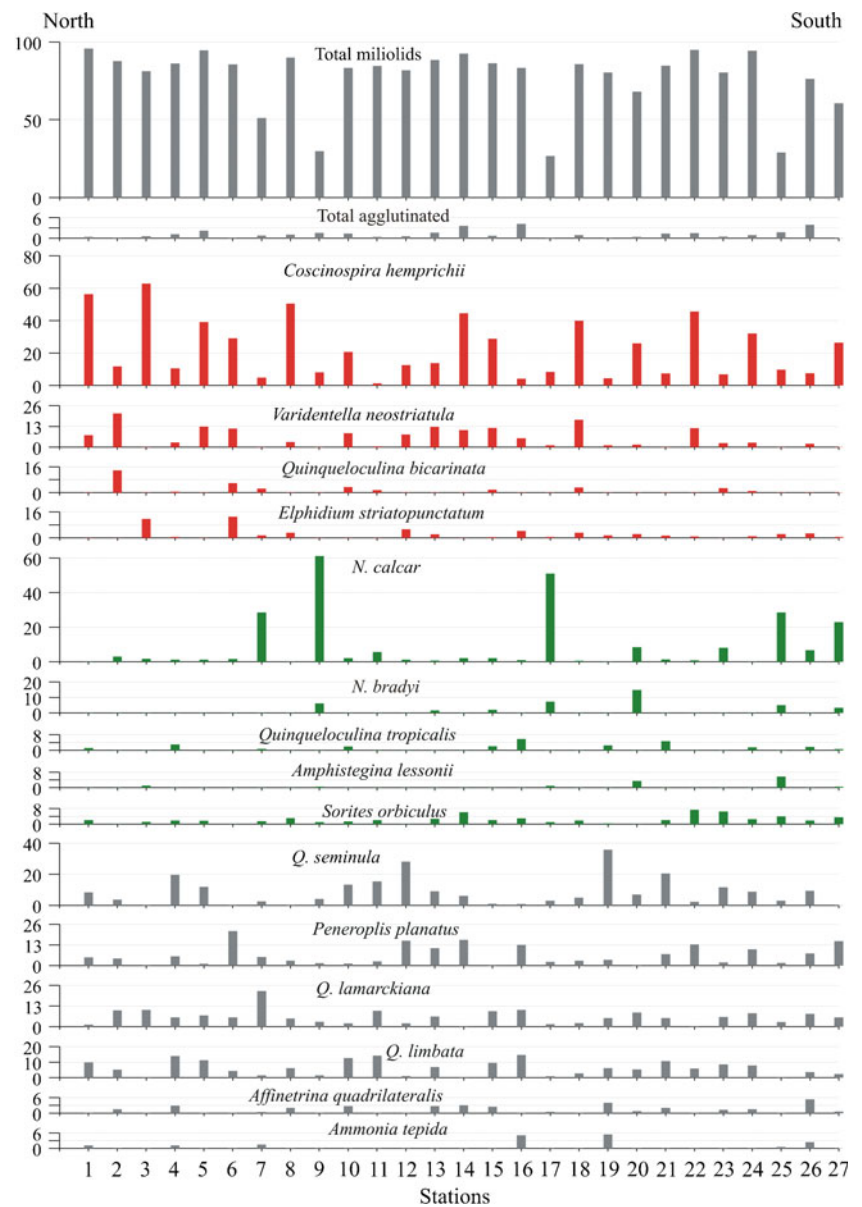
The metals such as Cr, Mn, Fe and Zn showed inverse correlations with the organic matter, mud and carbonate and their relationships with the pH, dissolved oxygen, temperature and sand fraction are negligible (Fig. 7). The trace metals such as Pb and Cu showed positive correlations with the muddy sediments and inverse correlations with the pH, dissolved oxygen, temperature and sandy sediments (Fig. 7). The major metals such as Na, K and Ca are positively correlated with the muddy sediments.

Discussion

Nearshore sediment characters and geochemistry

The nearshore sediments of Yanbu to Al-Lith (500 km long) are characterized by their sandy-type where the sand fraction constituted about 85 % of the total sediment dry weight and

Fig. 6 Relative abundances (%) of the key benthic foraminiferal species in the studied stations from Yanbu to Al-Lith



these are composed mainly of biogenic carbonate materials (68 %); also, mud and gravel grains were very low. This means that the nearshore sediments of the studied stations from Yanbu to Al-Lith subject to winnowing and wash-over by low-energy nearshore currents and waves and the detrital input by floods and wadies are minimal or absent at these stations. This was also reported by many authors (e.g., Morcos 1970; Abu-Zied 2013; Abu-Zied and Bantan 2013; Raitsos et al. 2015) that the Red Sea, in general, is characterized by its warm and dry climate throughout the year with scarce rainfall (63 mm/year) and no riverine inputs.

The metal constituents (specially the trace ones such as Fe, Mn, Zn, Cu, Cr and Pb) of the nearshore sediments of the studied stations were having very low concentrations, except

the nearshore sediments of Jeddah coastal line where their concentrations increased indicating human activities. The trace metal concentrations contrast between those of the Jeddah coastal line and the other stations may indicate that these nearshore sediments of the other stations are still under natural conditions and their content of trace metals can be used as a natural background for future monitoring. For example, the mean concentration values of the trace metals such as Fe, Mn, Zn, Cu and Cr are as follows: 7000, 125, 30, 11 and 20 $\mu\text{g/g}$, respectively, whereas Pb, Ni and Co were undetected in most of the studied stations; except in the nearshore sediments of Jeddah coastal stations, the metals Pb and Ni appeared displaying mean values of 4 and 5 $\mu\text{g/g}$, respectively. In the bottom sediments of heavily polluted two coastal inlets of

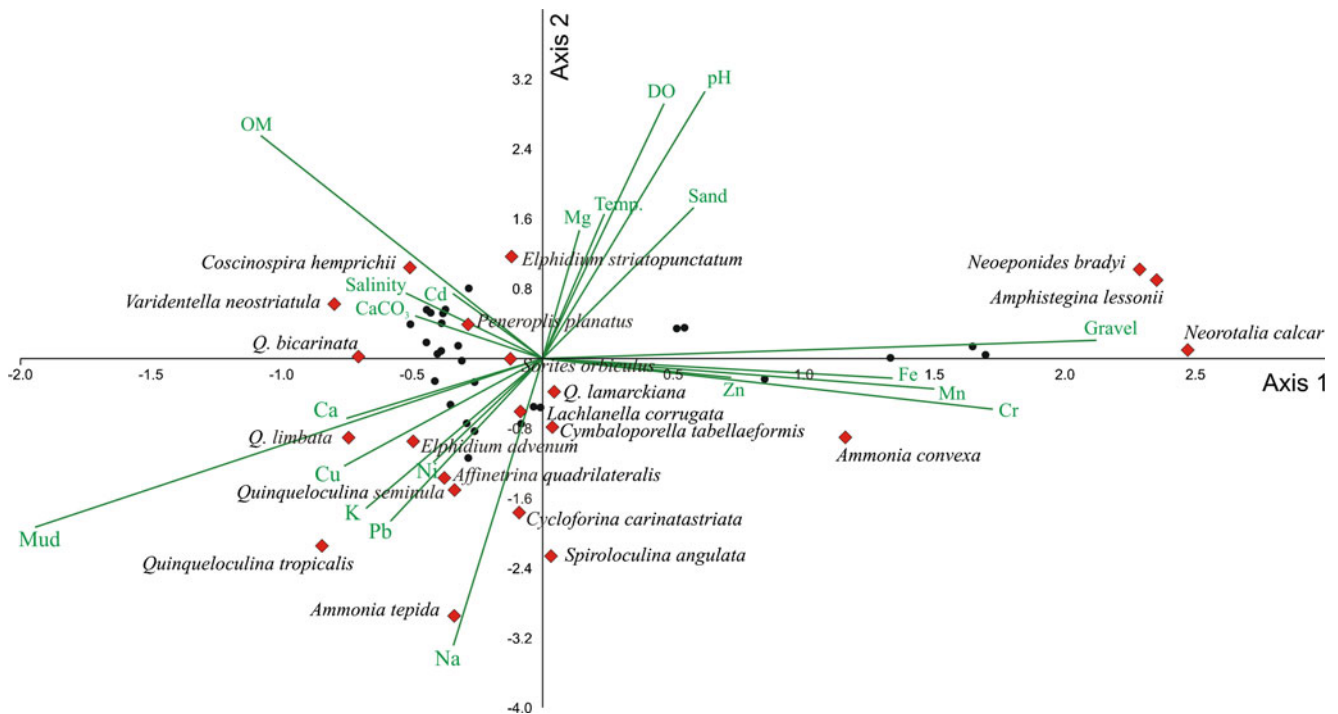


Fig. 7 Canonical correspondence analysis (CCA) showing the relationship of the key benthic foraminiferal species (red rhombus) with temperature, salinity, dissolved oxygen (DO), pH, sediment grain sizes,

organic matter (OM), carbonate (CaCO_3) and metals (Fe, Mn, Zn, Cu, Cr, Pb, Ni, Co, Ca, Mg, Na and K). Ordination of sample stations were also indicated by solid circle

Jeddah City, these trace metals (Zn, Cu, Cr, Pb and Ni) reached extreme concentrations such as 200, 80–120, 80, 60–90 and 50, respectively (Abu-Zied et al. 2013).

The concentration distributions of the trace metals in the nearshore sediments of the studied stations are likely to be governed mainly by sediment grain size and organic matters as indicated by the CCA (Fig. 7). The metals Fe, Mn, Cr and Zn were inversely correlated with organic matters and muddy sediments, whereas Cu, Ni and Pb were positively correlated with the muddy sediments. The opposite relationship between organic matter and the detrital metals such as Fe and Mn may indicate that it was mainly originated from marine sources as the decay of algae and seagrasses.

Benthic foraminifera and environmental parameters

The benthic foraminifera of the nearshore sediments of Yanbu to Al-Lith stations (500-km long) have low density and diversity of 520 specimens/g and 24 species, respectively. Most of these stations are located in open marine shorelines of flat reef conditions that mean that low-energy waves and currents play a considerable role in the distribution and composition of benthic foraminifera in these nearshore sediments. These environmental conditions enhance the effect of taphonomic processes such as breakage and abrasion after death leading to, for example, the depletion of thin-walled miliolid species as in the stations 9, 17, and 25, where *C. hemprichii* and *P. planatus* tests have shown many broken tests (Figs. 4 (O, R) and 5). In

some stations, the spines of *N. calcar* were also eroded due possibly to abrasion. Other taphonomic factors such as dissolution and microborings were witnessed in the *P. planatus* and *S. orbiculus* tests (Fig. 4 (Q, S)). These microborings may be attributed to endolithic microorganisms and fungi (Lobegeier 2002) that proliferate where the eater is calm (Cotter and Hallock 1988; Martin and Liddell 1991; Lobegeier 2002; Abu-Zied et al. 2011a). Similar results were recorded from the nearshore sediments of Farasan Islands (southern Red Sea) where the foraminiferal density was low (same as this study) in the nearshore sediments of the Jinabah Bay and Ras Farasan of open shorelines due to abrasion and breakage; and it was the highest (> 1500 tests/g) in the Khor As Sailah lagoon sediments that were modified by dissolution and bioerosion (Abu-Zied et al. 2011a).

It is also noted that the frequency abundance of faunal density and diversity increases towards the southern stations. This may indicate occurrence of favorable conditions with more foods such as microalgae at the southern stations than at the northern ones. It is known that the southern Red Sea is characterized by its nutrient-rich surface waters due to the entering of the surface water of the Indian Ocean through the Gulf of Aden, and this water as it moves towards the northern part of the Red Sea, it depletes in its nutrients (and in absence of freshwater inputs) leading to prevalence of oligotrophic conditions in the northern Red Sea (Murray and Johns 1997; Johns and Sofianos 2012; Triantafyllou et al. 2014; Raitsos et al. 2015). This latitudinal gradient in nutrients

as well as in salinity and temperature has impacted all faunal community in the Red Sea (Auras-Schudnagies et al. 1989; Edelman-Furstenberg et al. 2001; Siccha et al. 2009; Abu-Zied 2013; Kürten et al. 2014a, b).

The distribution abundance of faunal assemblages in the nearshore sediments of the studied stations has shown a south-north gradient. For example, the *C. hemprichii-V. neostriatula* assemblage increased northward, whereas the *N. calcar-N. bradyi* assemblage increased southward, and *Q. seminula-P. planatus-Q. limbata* assemblage has shown no preferable trend.

The *C. hemprichii* is an algal-symbiotic species and is being the dominant species (>40 % in many stations) in nearshore sediments of the studied stations. Its (and associates) increase towards the north is probably following the northward increase of salinity, displaying a positive correlation with salinity as indicated by CCA. It was found dominating the faunal assemblages in the hypersaline (>40‰) Shuaiba Lagoon (Abu-Zied and Bantan 2013). Therefore, the dominance of northward increased-assemblage (*C. hemprichii-V. neostriatula*) could be used as a high salinity indicator in the Red Sea fossil sediments that could be linked to periods of intense evaporation in the Red Sea region. This assemblage is also positively correlated with organic matters which were originated from the decay of algae and seagrasses that were discussed as preferable habitats for this assemblage (Haunold et al. 1997; Abu-Zied and Bantan 2013). Semeniuk (2001) studied the nearshore epiphytic foraminiferal populations along 1000 km of the Western Australian coast and indicated that the change in abundance of species showed a north-to-south gradient; however, this was related to local factors and changes in climate from subtropical semi-arid to subtropical humid.

The *N. calcar-N. bradyi* assemblage and the associated species (e.g., *Q. tropicalis*, *A. lessonii* and *S. orbiculus*) showed a southward increase. This could be related to profusion of epiphytes such as seagrasses and filamentous algae as a result of a fertility increase at the southern Red Sea (Bailey 2009; Raitsos et al. 2015). These epiphytes are essential habitats for proliferation of these faunal assemblages (Hohenegger 1994; Lobegeier 2002; Abu-Zied et al. 2011a; Abu-Zied and Bantan 2013). The *A. lessonii*, a symbiotic larger foraminifera, lives in transparent, shallow waters with depths ranging from 8 to 65 m in the Red Sea and preferring attachment to coarse substrates as indicated by the CCA (Reiss and Hottinger 1984; Haunold et al. 1997). Its frequent occurrences in the nearshore sediments (<1 m depth) of the southern stations may suggest that the tests of *A. lessonii* and their houses (like rock debris or coarse sediment particles) transported to shoreline sediments by action of waves and local currents. It is also possible that *A. lessonii* extends its depth ranges to more shallow depths to regulate light intensity for their endosymbiont photosynthesis (Leutenegger 1984; Hohenegger 1994).

The *Q. seminula-P. planatus-Q. limbata* assemblage occurred in all the studied nearshore sediments from Yanbu to Al-Lith, showing no increase/decrease towards either the north or the south. So, they are successful species tolerating a wide range of environmental conditions, but they did not, however, dominate the north-south increased assemblages. They (specially *Q. seminula*, *Q. limbata* and *A. tepida*) became frequent where soft, muddy sediments predominates as indicated by CCA (Abu-Zied et al. 2007 and 2013).

Conclusions

The nearshore waters and sediments at 27 stations along 500 km of the eastern Red Sea coast from Yanbu to Al-Lith yielded many faunal, sediment, and geochemical characters.

1. The water temperature, salinity, dissolved oxygen, and pH were shown with the following mean values: 27 °C, 38 g/l, 7.2 mg/l, and 8.1, respectively. However, the temperature and salinity showed a subtle decrease/increase indicating south-north gradients.
2. The studied nearshore sediments were mainly composed of biogenic carbonate materials reaching 68 % of the total sediment dry weight with very low amounts of organic matter and detrital materials.
3. Concentrations of trace metals Fe, Mn, Zn, Cu and Cr in the studied sediments were very low showing the following mean values: 7000, 125, 30, 11 and 20 µg/g, respectively, whereas Pb, Ni and Co were undetectable, except in the nearshore sediments of Jeddah coast they became frequent showing the highest concentrations indicating urbanization activities.
4. Three faunal assemblages were recognized in the studied nearshore sediments by visual observation and CCA. The *C. hemprichii-V. neostriatula* assemblage increased towards the north, following the northward increase of salinity, and this could be used as a high-salinity indicator in the Red Sea fossil sediments. The *N. calcar-N. bradyi* assemblage increased southward, probably, as a result of a profusion of seagrasses and filamentous algae. The *Q. seminula-P. planatus-Q. limbata* assemblage showed no increase/decrease either towards the north or the south, indicating their tolerance for a wide range of environmental conditions.

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Appendix

Table 3 Census data of benthic foraminiferal species (>5 %) in the bottom sediments of the studied stations along the shoreline from Yanbu to Al-Lith, collected during February 2014

Species	Station																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
<i>Affinetrina quadrilateralis</i>		2		5			1	2		4			5	6	7		1		11	2	3		3	5		18	1	
<i>Agglutinella compressa</i>				1						1	1		1			8		2			1		1			3		
<i>Ammonia convexa</i>		1		6	1		23			2		6	2			1		11	12		5			4	34		2	
<i>Ammonia tepida</i>	3			2			4									12			15						1	8		
<i>Amphistegina lessonii</i>			2						1								2			9					10		1	
<i>Clavulina multicamerata</i>	1			1	4		2	1	1			1	2	7	1	2					1	2		2	2		10	
<i>Coscinospira hemprichii</i>	143	16	113	18	73	20	13	50	16	31	3	24	26	88	84	10	17	89	12	68	11	62	17	106	17	25	46	
<i>Cycloforina carinatastriata</i>	2			10	1	1	1	2	3		10	1	1		11	13	2	1	7	3	1	1	16	4			26	
<i>Cycloforina contorta</i>					1	3		2		1			1							2			1	1	1	1	3	
<i>Cycloforina quinquecarinata</i>		4			1															7						5	3	
<i>Cymbaloporella tabellaeformis</i>	1	1	2			4	1		4	13	8	3	2	4	1	2	5	2	1		2	9	1			12	4	
<i>Elphidium advenum</i>								2		8	1																	
<i>Elphidium advenum</i>	3	6	2				1									3	5	5	8	2	2		4	3			1	
<i>Elphidium jenseni</i>				1			6								1												6	
<i>Elphidium striatopunctatum</i>			21	1		9	4	3				10	4		1	10	1	7	4	6	2	1		3	4	9	1	
<i>Elphidium williamsoni</i>	3	3	1		3					3			1		12				7		2		5	3			7	
<i>Haynesina depressula</i>																			4					1				
<i>Lachlanella corrugata</i>		3	5	2			1	2	8		38	4	7		2	4		6					1	4		1	5	
<i>Massilina gualtieriana</i>											9	1	2	1		2			1	2			4	5			6	
<i>Miliolinella labiosa</i>			1				1				2	1	5			3						3	3	3			6	1
<i>Neoeponides bradyi</i>									12				3		6		15				39					9	6	
<i>Neorotalia calcar</i>		4	3	2	2	1	78		121	3	14	2	1	4	6	2	105	1		22	2	1	20		50	22	40	
<i>Pararotalia sp.</i>							3	1									5								1		9	
<i>Parrellina milletti</i>		1	2	4			9		1	3	6	2	2		2	1	2	1	3	4	4		6	1		1	4	
<i>Parrina bradyi</i>	1				1													2						1				
<i>Peneroplis planatus</i>	13	6		10	2	15	15	3	3	2	7	30	21	32		31	5	7	10	1	11	18	5	34	3	26	27	
<i>Pseudomassilina reticulata</i>	2					1		1		5			1							1	2			2				
<i>Pseudotriloculina subgramulata</i>					1		3						2			3			7	1			5			4	1	
<i>Quinqueloculina bicarinata</i>		19		1		4	7			5	4				5			7					7	3				
<i>Quinqueloculina bosciana</i>	1	2		5	6					11		6			5	1	9	9	1	5			9	8			6	
<i>Quinqueloculina costata</i>				1												2			5	2			2	1			12	
<i>Quinqueloculina distorquata</i>										1		4	1														5	
<i>Quinqueloculina lamarekiana</i>	3	14	19	10	13	4	61	5	6	3	25	4	12		28	25	3	5	15	23	8		15	28	5	27	10	
<i>Quinqueloculina limbata</i>	25	7		24	21	3	4	6	3	19	36	2	13		28	35	2	6	17	14	16	8	21	26		12	4	
<i>Quinqueloculina seminula</i>	21	5		34	22		7		8	20	39	54	17	12	3	2	6	11	100	18	31	3	29	29	5		31	
	3			5			2			3					6	14			7		7			5		6	1	

Table 3 (continued)

Species	Station																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
<i>Quinqueloculina tropicalis</i>																												
<i>Roslaina bradyi</i>	1						2			2		3	2	1		8				2		3				4		
<i>Sigmoihauerina bradyi</i>															4				2			3						
<i>Sorites orbiculus</i>	5		2	3	3		4	3	2	2	5		5	12	6	7	2	4	1		3	10	16	8	7	6	6	
<i>Spiroloculina angulata</i>				4	2				2				1								8		5	1				
<i>Spiroloculina antillarum</i>	2		1				3			4	4	1	4	1	12	6	2	2		2		6		1		5	1	
<i>Spiroloculina communis</i>												1	2										4					
<i>Textularia agglutinans</i>									1						1											1		
<i>Triloculina bermudzi</i>	2									4											2		3	3				
<i>Triloculina fichteliana</i>				2	2						2			3	6	1	1	3		2	6		4			2		
<i>Triloculina inflata</i>	6						1						1			1						2			1			
<i>Triloculina serrulata</i>							4		1			1	1			2								4				
<i>Triloculina sp.</i>	1	2	2				1	2		2						15			2	4	1		2	4		8		
<i>Triloculina trigonula</i>	1							1							2			1	2		2				2	2		
<i>Trochulina dimidiata</i>	1			4																	2		1		1			
<i>Varidentella neostriatula</i>	19	29		5	24	8		3		13	1	15	24	21	35	13	2	38	3	4		16	6	9		7		
<i>Vertebrulina striata</i>							2				3	1	1			1			7	1	3		1	2	2	3	1	
Un-identified miliolids		6	4	7	3		8	7	4	5	17	9	9	7	15		10				11	5	1	13	14	3	2	4
Miscellaneous	1		2		1		1	1	4	2	2	8			7		7		9	9		1		7	8	4	1	
Total counted foraminifera	254	138	180	173	187	69	274	99	198	150	253	192	190	198	292	239	206	223	280	263	151	136	249	331	176	336	175	

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