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Morphological deformities of benthic foraminifera in response to nearshore pollution of the Red Sea, Egypt

R. El-Kahawy · M. El-Shafeiy · S. A. Helal ·
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Abstract The Red Sea encompasses a wide range of tropical marine habitats that are stressed due to anthropogenic activities. The main anthropogenic activities are hydrocarbon exploration and important trading harbors. This work aims to assess the influence of the Red Sea coastal heavy metal contamination on the marine meiofauna along three sites (Ras Gharib, Safaga, and Quseir). Eight heavy metal (Cu, Cd, Zn, Pb, Cr, Co, Ni, and Mn) contents are considered in four benthic foraminiferal species (*Elphidium striatopunctatum*, *Amphistegina lobifera*, *Amphisorus hemprichii*, and *Ammonia beccarii*). Quseir Harbor showed the highest level of pollution followed by Safaga and Ras Gharib sites. The analyzed benthic foraminiferal tests displayed noteworthy high concentrations of Cd, Zn, and Pb in Quseir Harbor which could be attributed to the anthropogenic activities in the nearshore areas. Some foraminiferal tests exhibited abnormalities in their apertures, coiling, and shape of chambers. A comparison between normal and deformed foraminiferal tests revealed that the deformed ones are highly contaminated with elevated heavy metal contents such as Fe, Mn, Ni, and Cd. Statistics in addition to geo-accumulation and pollution load indices reveal a whistling alarm for the Quseir harbor. The present data are necessary to improve conservation and management of the Red Sea ecosystem in the near future.

Keywords Benthic foraminifera · Test abnormalities · Heavy metals · Nearshore contamination · Red Sea · Egypt

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Introduction

A wide range of tropical marine habitats are typifying the Red Sea that provide economic and recreational value (Mohamed 2005). These habitats are probably stressed as a result of human activities. Moreover, the high evaporation rate in this arid to semi-arid region causes high water salinity that may exceed 40 (*PSU*) in the northern Red Sea (Badawi et al. 2005). Although the Red Sea had been considered for a long time as being relatively unpolluted (Mohamed 2005), threats are noticed nowadays due to increments in pollutants from phosphate mining, oil exploration, sewage, and landfill leachates over the last decades (El-Taher and Madkour 2014). Another environmental problem along the Red Sea coast is the anthropogenic contamination via chemicals such as heavy metals and organic matter that possibly cause eutrophication (Alve 1991).

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Benthic foraminifera usually are used as environmental bio-indicators owing to their high sensitivity to different types of pollution (Buosi et al. 2010). They show significant modifications in their test structures or changes in the composition of their assemblages. They are efficient in detecting environmental changes because of their wide distribution over marine environments, high taxonomic diversity, small sizes, high abundances, and short generation time (Murray 1991). The taxonomy, abundance, and distribution of the recent benthic foraminifera along the Red Sea coast from Egypt and Saudi Arabia were studied by several researchers (e.g., Reiss and Hottinger 1984; El-Halaby 1999; Madkour 2013; Youssef 2015). These studies investigated the effect of the natural parameters such as salinity and hydrodynamics of the water current on the benthic foraminiferal communities. Moreover, they revealed the influences of hypersaline water on the benthic foraminiferal deformities in the northern Red Sea. A species example is the *Sorites marginalis*, which displayed an abnormal morphological growing.

The present work focuses on three sites along the central Red Sea coast (Ras Gharib, Safaga, and Quseir; Fig. 1). The main objectives of the present study are

1. To identify the benthic foraminiferal assemblages in the studied sites.
2. To investigate the impacts of the natural stress-causing parameters (e.g., hypersalinity and hydrodynamics of water currents) as well as the anthropogenic sources of pollution using geochemical proxies.
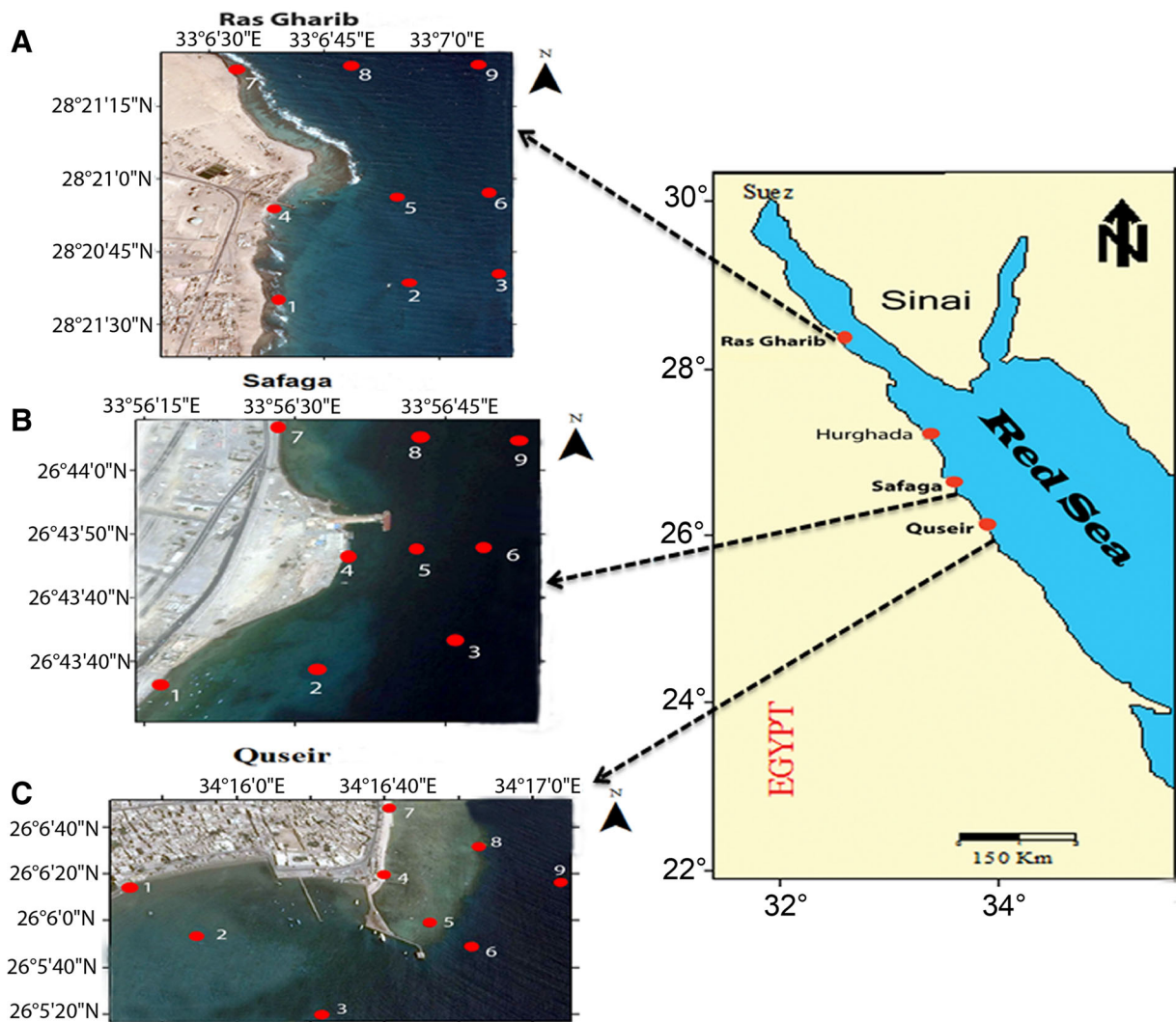

Fig. 1 Google Earth map shows the locations of the study area. Numbered red dots indicate locations of sediment stations

3. To figure out the linkage between foraminiferal test abnormalities and heavy metal contamination.

Study area

The study area encompasses three main sites along the Red Sea coast (Fig. 1). Ras Gharib is an active hydro-carbon exploration prospect with a clastic terrigenous supply resulting from the annual flash flooding (Hegazy and Effat 2010). Safaga is the most important seaport along the Red Sea coast of Egypt. Safaga hosts a tourist marina for fishing and tourism. Aside from the touristic activities, phosphate ore is exported out of Safaga via ships (Madkour 2013). Quseir is an active center for phosphorite mining industry in Egypt. In addition to the clastic supply from annual flash floods, the sewage sludge of Quseir city is discharged into the Red Sea (Appendix 1). The port water receives also fuel wastes owing to shipping activities.

Material and method

Sampling

The study areas were selected according to the type and degree of pollution. Thus, 27 recent sediment stations were collected by using a plastic coring tube of 25 cm in diameter and 10 cm in length. The stations from the three sites are coded as G (Ras Gharib), S (Safaga), and Q (Quseir) followed by the sample number. Bouchet et al. (2012) pointed out that three replicates are sufficient to determine a reliable representation of the dead benthic foraminiferal diversity at sample location. A solution of Rose Bengal dye with 70% ethanol was added to the sediments in the field to discriminate the living and dead organisms. Owing to the scarcity of the living benthic foraminifera in the samples, the statistical analyses of this study relied on the dead forms only. SCUBA (self-contained underwater breathing apparatus) diving was performed to collect offshore samples. Nine stations were sampled from each locality along three transects toward the open sea (Fig. 1a–c). We focused on the uppermost 5 cm of each sample that was possibly impacted by industrial and municipal activities. Salinity, pH, and water temperature of seawater were determined for each sample site using a Hydrolab

Surveyor-4 Instrument in July 2014 (Table 1). The water depth of each station was determined using an echo-sounder instrument, and ranged from 0.1 to 7.0 m.

Foraminiferal analysis

Fifty grams of sediments from the uppermost 5-cm sediment layer were collected from each station. This interval represents the more recent sediment, mostly tend to accumulate the contaminants released by modern pollution sources. Each sample was washed by distilled water and sieved over 63 μm to remove clay and silt. After sieving, it was dried at 80 °C; then, the residual was re-weighed to determine the mud fraction. The foraminiferal assemblages were identified according to the generic classification of Loeblich and Tappan (1988). The linkage between the density and diversity was assessed by diversity indices including foraminiferal density (FD; represented by number of specimens per 1 g), specific richness (S; number of species per sediment sample), and Shannon index. The latter is a diversity index that takes into account the number of individuals as well as the number of taxa (Shannon 1948). It varies from 0 for communities with only a single taxon to high values for communities with many taxa, each with few individuals.

$$H = -\Sigma(n_i/n)\ln(n_i/n).$$

All the previously mentioned indices were calculated using the Paleontological Statistics Program (PAST), version 2.17 (Hammer et al. 2009).

Furthermore, we considered the foraminiferal monitoring index (FMI) which equals the total number of abnormal species in each assemblage (Coccioni and Marsili 2005). Lastly, the foraminiferal abnormality index was calculated which is the percentage of the deformed fauna per each sample (Romano et al. 2009). The deformed specimens were imaged by scanning electron microscopy.

Geochemical analyses of sediments

The heavy metals in the sediment stations were measured at Acme Labs, Bureau, Canada. Aliquot of 0.5 g of fine sediments (63 μm) was analyzed using inductively coupled plasma-emission spectrometry (ICP-OES). The samples were digested in a Teflon vessel with a modified aqua regia solution (0.5 ml H_2O, 0.6 ml concentrated

HNO_3, and 1.8 ml concentrated HCl) for 2 h at 95 °C. The samples were cooled, diluted to 10 ml with de-ionized water, and then homogenized. The samples were then analyzed using a PerkinElmer OPTIMA 3000 Radial ICP-OES for the element suite. A standard matrix and a blank were run every 13 samples. A series of USGS geochemical standards were used as controls. The detection limits of the measured metals are Cu (1 mg/kg), Zn (1 mg/kg), Mn (2 mg/kg), Cd (0.5 mg/kg), As (2 mg/kg), Pb (3 mg/kg), Cr (1 mg/kg), Ni (1 mg/kg), Mo (1 mg/kg), P (0.001 mg/kg), Fe (0.01 mg/kg), and Co (1 mg/kg). The organic carbon was determined in each sample by weight loss method (Byers et al. 1987). The total carbonate content was determined by hydrochloric acid (2.5 N) attack and weight loss calculations (Gross 1971; Table 1).

Heavy metals in foraminiferal tests

The heavy metal concentrations were measured on three porcelaneous species and one hyaline species, namely *Elphidium striatopunctatum*, *Ammonia beccarii*, *Amphisorus hemprichii*, and *Amphistegina lobifera*. They were selected because they have the highest abundances and the largest numbers of deformed specimens in the all stations. From each site, the normal and deformed forms of the same species were picked up to be analyzed. Eight forms, four normal and four deformed, were picked from each site. Two hundred to 300 shells from each form were analyzed in one run. The tests were washed with sodium hypochlorite for 24 h then with distilled water. The shells were then dried at 60 °C and pulverized.

Table 1 Sample locations and descriptions of the studied sites

Station	Depth (m)	Salinity ‰	pH	T (°C)	TOC%	CaCO$_3$%	Location and description
Gl	0.4	41.31	7.7	20	2	59.18	To the south of Ras Gharib, sandy
G2	3	41.54	8.19	20.11	1.63	40.22	Down to the tidal flat, silty sand
G3	6	4145	8.21	20	2.61	59.28	Offshore to the open sea, silty sand
G4	0.6	40.91	7.71	20.12	2.49	62.09	In front of the harbor, biogenic sand
G5	4	41.42	8.12	20.71	2.11	37.6	Down to the tidal flat, silty sand
G6	7	41.53	8.08	20.32	2.7	64.52	Offshore to the open sea, silty sand
G7	03	41.12	7.4	20.91	2.11	37.6	To the north of the harbor, sandy
G8	3	41.61	8.33	20.52	2.72	38.11	Down to the tidal flat, silty, sand
G9	7	41.34	8.21	20.11	0.68	39.22	Offshore to the open sea, silty sand
S1	0.2	40.55	7.41	22.11	2.69	12.72	To the south of Safaga, coarse sand
S2	2	40.82	8.11	22.3	1.35	10.77	Down to the tidal flat, silty sand
S3	5	40.77	7.91	22	2.84	15.63	Offshore to the open sea, silty sand
S4	0.3	40.42	7.32	22.41	1.42	11.72	In front of the harbor, coarse sand
S5	1.5	40.73	8.09	22.6	1.56	7.02	Down to the tidal flat, silty sand
S6	4	40.71	7.78	22.33	2.47	21.25	Offshore to the open sea, silty sand
S7	0.1	40.27	7.29	22.9	0.93	12.6	To the north of the harbor, sandy
S8	1.75	40.92	8.01	22.6	1.45	6.01	Down to the tidal flat, silty sand
S9	5	40.87	7.91	22.22	4.07	18.34	Offshore to the open sea, silty sand
Q1	0.1	40.39	7.41	26.55	10.17	17.54	To the south of Quseir, silty sand
Q2	1	40.93	8.21	26.25	12.11	26.93	Down to the tidal flat, muddy sand
Q3	3	40.89	8.24	26.44	2.85	58.97	Offshore to open sea, muddy sand
Q4	0.2	40.52	7.45	26.31	3.03	76.28	In front of the harbor, biogenic sand
Q5	1.5	40.96	8.13	26.11	3.93	83.29	Close to shipping jetty, silty sand
Q6	4	40.93	7.86	26	2.93	56.78	Offshore to open set, muddy sand
Q7	0.2	40.62	7.62	26.6	2.95	75.22	To the north of the harbor, silty sand
Q8	1.78	40.99	7.97	26.44	4.1	80.29	Down to the tidal flat, muddy sand
Q9	3	40.88	7.84	26.21	2.85	58.97	Offshore to open sea, muddy sand

G Ras Gharib, *S* Safaga, *Q* Quseir

About 0.2 g of each sample was digested with a solution mixture (3 ml $HClO_4$ + 5 ml HNO_3 + 15 ml HF), and then, 50 ml HCl (1:1) was added. The stations were saved in 100-ml flasks, brought to volume with distilled H_2O, and measured using the instrument (Agilent 720 ICP-OES). Eight heavy metals were considered: Cu, Zn, Mn, Cd, Pb, Cr, Fe Ni, and Co. Other heavy metals were not detected, such as Mo, As, P, and B.

Statistical analyses

The relative abundance data of the foraminiferal species were standardized by means of z scores before hierarchical cluster analysis and squared Euclidean distances. Thereafter, hierarchical clustering was performed by applying Ward's method on the standardized data set. A Q mode (sample by sample) cluster analysis was used via Minitab v.16 to produce a dendrogram of stations and their species association. Another cluster analysis was used to produce a dendrogram classification of dominant species (R mode). Only species with at least one occurrence larger than 1% was included in the data matrix for the Q and R modes in the analyzed stations. Stations and species were grouped based on their degree of similarity using the Euclidean distance for Q and R modes. Moreover, the principal correspondence analysis was accomplished using SPSS v.19, to explore the clusters of elements and their linkage with the environmental factors.

A multivariate analysis was accompanied to figure out the inter-elemental relations. The correspondence factor and cluster analyses were applied here as well. They permit the projection of a large set of variables (stations and variables) into a reduced form. Reciprocally, each factor axis contributes to define the position of a given point relative to the center of the cloud of all projected points (Gabrié and Montaggioni 1982). The data matrix comprises 27 samples and 19 variables (Fig. 6).

Detrended correspondence analysis (DCA) was performed in order to choose applying either canonical correspondence analysis (CCA) or redundancy analysis (RDA). Canonical correspondence analysis (CCA) was conducted using CANOCO, v. 4.5 to investigate the community's linkage to abiotic parameters (e.g., Elshanawany et al. 2010). Environmental variables are represented on the CCA plot by arrows, which extend in both directions from the center. The arrows pinpoint to the direction of variation, and its length demonstrates the relative importance of each environmental variable. The angle between the environmental arrows is inversely proportional to the strength of their one another relationship. The perpendicular projection of species scores against these arrows infers the dominant environmental factors affecting species composition (e.g., Elshanawany et al. 2010). Moreover, geo-chemical index, contamination factor, and pollution load index are used here to assess the contamination level in order to obtain a wider idea on the heavy metal contamination.

Results

Hydrological features

During the field survey, the water temperature of the Red Sea was 20–26.6 °C. The water salinity varied between 40.3 and 41.6 *PSU* (Table 1), indicating a hypersaline water. The specific conductivity of the water ranged between 60 and 61.6 S/m (Table 1). The pH of the sampled stations was 7.29–8.33.

Environmental variables

Grain size distribution patterns

The bottom sediment facies are mainly muddy sand (more than 90% sand); however, Quseir site has highest silt and clay fractions comparative to Safaga and Ras Gharib (Appendix 2). The biogenic constituents of the sediments are produced mainly in the reefs (Reiss and Hottinger 1984). Ras Gharib typified by high percentage of coarse grain sediments on the beach stations excluding station G.3 (Appendix 2). The highest percentage of the fine particles (silt and clay) were observed around stations G.5 and G.7, representing up to 7.4 and 6.2%, respectively. Safaga site shows the same pattern as the pre-mentioned Ras Gharib, where the coastal beach stations displayed higher percent of the coarse-grained sediments except station S.7 (Appendix 2). The inner stations S.3, S.6, and S.5 are demonstrated by 11.3, 4.1, and 2.4% sand, respectively. Furthermore, Quseir site exhibits stations relatively enriched in the fine sediments compared to the rest of stations. They are Q.4, Q.5, Q.6, and Q.2, representing 9.3, 8.1, 5.1, and 5.0% sand, respectively (Appendix 2). Conversely, the stations enriched in the coarse sediments are Q.7, Q.9, Q.1, and Q.3, demonstrating 99.5, 99.1, 98.8, and 98.3% sand, respectively. They all have a high TOC% (up to 10.1% in Q.1), whereas the $CaCO_3$ behaves the other way around with TOC% (Table 1).

Total organic carbon and carbonate content

The quantity of organic matter in the samples increased at the mouth of the outfall and fluctuated in all stations. Ras Gharib and Safaga sites exhibit lower TOC% comparative to Quseir site. The lowest TOC% in Ras Gharib was observed in sample G.9 (0.7%), whereas the highest TOC% in Ras Gharib was recorded in G.8 (2.7%; Table 1). Station S.9 (TOC% 4.1%) represents the highest station in Safaga site, followed by S.3 (2.8%), averaging 2.1%. Station Q.2 (TOC% 12.1%) represents the highest station in Quseir and the entire three sites as well. Station Q.1 in Quseir site contains about 10% of the organic matter, whereas the entire site averaged 5% (Table 1).

The carbonate content in the sediment samples of Ras Gharib site ranges between 37.6% in station G.5 and 64.5% in station G.6 (Table 1). Safaga site suffers from depleted carbonate content. The lowest was observed in station S.8 (6.1%), whereas the highest was found in station S.6 (21.2%), averaging 12.9%. On the other hand, Quseir site shows a range of 17.5% in station Q.1 to 83.3% in station Q.2, averaging 45.2% (Table 1).

Heavy metal contents in the sediments

The data for heavy metal concentrations are shown in Table 2. Geochemical maps were designed to exhibit the spatial distribution patterns for elements in each site

Table 2 Heavy metal concentrations in the area of study with background references

Sample	P	Fe	Pb	Zn	Cu	Cd	Ni	Mn	Sr	As	B	Cr
G1	490	3700	3	7	186	0.6	1	75	3321	2	43	7
G2	510	3800	4	11	39	0.4	1	78	3262	2	41	7
G3	490	3700	3	7	1	0.3	1	75	3321	2	43	7
G4	230	1500	8	4	36	0.8	1	54	3302	3	34	2
G5	630	5800	15	15	81	0.4	2	89	3052	2	44	8
G6	340	2100	6	10	2	0.1	1	56	3347	2	47	4
G7	310	19,900	4	15	21	0.7	3	101	2715	3	31	18
G8	420	2800	3	6	1	0.5	1	77	2753	3	40	6
G9	1600	8400	3	21	6	0.6	22	150	395	3	22	27
S1	900	10,200	60	24	59	03	7	359	366	3	25	10
S2	940	8700	3	22	3	1.3	4	444	386	4	26	9
S3	790	5800	3	19	3	0.9	4	116	271	2	20	7
S4	480	4900	3	17	3	0.5	3	364	462	4	22	5
S5	520	4800	3	19	3	1.1	3	386	404	4	25	6
S6	790	6200	3	19	3	0.7	5	124	251	2	23	8
S7	270	3400	3	17	104	0.6	3	280	294	3	23	3
S8	550	5600	3	21	3	1.4	4	239	350	3	24	7
S9	770	6900	3	23	3	0.9	5	135	296	3	25	10
Q1	2240	10,300	14	49	17	1.9	25	150	303	7	21	28
Q2	3710	12,500	16	54	16	1.6	32	180	356	6	22	36
Q3	790	5800	3	19	3	0.6	4	116	271	2	20	7
Q4	53,000	6400	29	59	14	2.9	10	317	2531	15	244	30
Q5	51,000	5500	19	54	6	3.8	9	320	2401	12	253	32
Q6	4120	11,300	12	40	11	0.6	28	168	595,626	34		
Q7	1410	7900	6	20	7	1.7	22	148	502	4	23	25
Q8	1520	7900	3	20	5	0.9	22	149	471	4	25	25
Q9	1600	8400	3	21	6	0.5	22	150	395	3	22	27
Mansour et al. (2000)	116.7	6643.4	19.8	17.6	14	0.96	23.5	205.1	1800	–	–	–
El-Sorogy et al. (2006)	1104	527.75	3.13	5.32	0.65	0.5	1.88	91.7	–	–	–	–

(Appendix 3A-F). A high Fe content typifies the near-shore stations of Ras Gharib comparative to the open water stations. Such land-derived element ranges from 1500 mg/kg in station G.4 to 19,900 mg/kg in station G.7, averaging 5744.4 mg/kg (Table 2 and Appendix 3A). The Mn concentration is maximum in station S.7 (280 mg/kg); however, its minimum concentration was observed in station G.4 (54 mg/kg), averaging 84 mg/kg. The Ni concentration of sediments, however, ranges from 1 mg/kg in Ras Gharib to 32 mg/kg in station Q.2, averaging 6 mg/kg. Instead, Zn has a maximum of 59 mg/kg in Quseir area (station Q.4) and a minimum of 4 mg/kg in Ras Gharib area (station G.4; Table 2). Lead exhibits 3 mg/kg in most of Ras Gharib and Safaga stations, but station S.1 (60 mg/kg). Quseir area, however, displays elevated contribution of Pb in most stations (Table 2). Cadmium did not show elevated contribution in the studied stations, particularly in Ras Gharib and Safaga sites (Table 2). Its maximum contribution was recorded in Quseir site (3.8 mg/kg in station Q.5). Arsenic concentration is significantly low in Ras Gharib and Safaga stations (mainly 2–4 mg/kg). Higher contributions were observed in Quseir site particularly Q.4 (15 mg/kg) and Q.5 (12 mg/kg).

The spatial distribution of metals in the three studied sites infers that elements such as Fe, Cu, Pb, As, and Cd are enriched in the near-coast stations rather than the open water ones (Appendix 3A-F). On the other hand, elements such as P, Cr, Ni, Co, and Zn tend to be more accumulated in the inner stations instead. Noteworthy, the elements Pb, As, Zn, Mn, and Ni have significantly higher contents in Quseir site rather than Ras Gharib and Safaga sites (Table 2). Almost all of the collected stations exhibit abnormal enrichments in B (up to 253 mg/kg), Cu (up to 186 mg/kg), Cd (up to 3.8 mg/kg), Pb (up to 60 mg/kg), P (up to 53,000 mg/kg), As (up to 15 mg/kg), Fe (up to 19,900 mg/kg), and Ni (up to 32 mg/kg). The highly enriched heavy metal concentrations are found in the coastal stations of Quseir, especially those located in front of sewage pipes (Appendix 1). Safaga shows high Pb concentration around station S.1, and Ras Gharib exhibited abnormal concentration of Cu around G.1.

The correlations of Ni and other parameters show a positive significance with Fe, especially in Safaga area ($r = 0.86$, $p < 0.05$) and to some extent with sand % ($r = 0.4$, $p < 0.05$). Moreover, very good correlation coefficients were noticed between sand class with P ($r = 0.77$, $p < 0.05$), Co ($r = 0.87$, $p < 0.05$), and Cr ($r = 0.70$,

$p < 0.05$), whereas the silt class showed very good positive relation with only Cu ($r = 0.79$, $p < 0.05$). The clay class displayed very weak coefficients with all the metals ($r < 0.2$). Cu behavior in the studied areas was different, and its deposition is affected by different processes. It rendered a positive significant correlation between P and each of Fe ($r = 0.82$, $p < 0.05$), Zn ($r = 0.77$, $p < 0.05$), Ni ($r = 0.76$, $p < 0.05$), Cr ($r = 0.9$, $p < 0.05$), Co ($r = 0.71$, $p < 0.05$), and Al% ($r = 0.84$, $p < 0.05$) sand % ($r = 0.78$, $p < 0.05$), and to some extent TOC% ($r = 0.61$, $p < 0.05$). These parameters are well matched with the data of principal correspondence and cluster analyses, forming two main categories as in the shaded ellipsoids of the correspondence analysis or A and B clusters.

At Quseir site, significant positive correlations are obtained between P and each of Pb ($r = 0.81$, $p < 0.05$), Cd (r = 0.86, $p < 0.05$), As ($r = 0.93$, $p < 0.05$), Mn ($r = 0.98$, $p < 0.05$), and Hg ($r = 0.71$, $p < 0.05$). Positive significant correlations were also found with redox-sensitive metals like Cr, Ni, and Cu, as noticed from correspondence factor and cluster analyses (Fig. 8c). The silt proportions were observed to have strong correlation coefficient with some heavy and toxic metals such as Pb ($r = 0.78$, $p < 0.05$), Zn ($r = 0.70$, $p < 0.05$), and As ($r = 0.73$, $p < 0.05$). Correspondence and cluster analyses showed that the anthropogenic metals with silt facies form a category or cluster of significant positive correlation. Additionally, metals like Ni, Co, Fe, Al%, and TOC% form a category of significant positive correlation with each other in the opposed area to that of Al, Fe, Mn, and Zn (Fig. 8c). Similarly, the statistical analysis (correlation, cluster, and correspondence analyses) indicated a minor but consistent relation between the first and second category (cluster B and cluster A, respectively). These observations indicate an anthropogenic source of the first category to the marine sediments in the study area (Fig. 8c).

Heavy metal contents in foraminiferal species

The contents of heavy metals in the four concerned foraminiferal species, normal (N) and deformed (D), in the sampled sites are illustrated in Table 3. The metals can be classified into three categories. First group embraces Pb, Zn, and Cr that have a high tendency to be expressively accumulated into the deformed shells irrespective of species and sampling location sites (Table 3). Second encompasses Fe, Mn, Ni, and Cd that have a high tendency to be accumulated into the deformed tests as well; however, they

tend to be intensely more accumulated in the deformed shells of Quseir site (Table 3). Third is Co which did not show a substantial content changes in the deformed shells in most of the studied stations (Table 3).

Due to the very high content of Fe in the studied species, we constructed an individual box plot chart to observe its divergence (Fig. 2e). Its lowermost content (312 mg/kg) was noticed in normal shells of *A. beccarii* in Ras Gharib site. Normal shells of *E. striatopunctatum* tend to have around 608 mg/kg Fe concentration in Quseir site. The extreme Fe content (2020 mg/kg) was observed in deformed form of *A. hemprichii* in Safaga site (Fig. 2e).

Elphidium striatopunctatum displays a tendency to bio-accumulate some heavy metals with elevated concentration, for instance, Ni, Cr, and Mn (Fig. 2a). Some metals show doubled concentration in its deformed form than normal, such as Zn and Fe (up to 17 and 1040 mg/kg, respectively). *Amphisorus hemprichii* shows a probable bio-accumulation to Mn (up to 410 mg/kg; Table 3 and Fig. 2b). On the other hand, *A. beccarii* exhibits a significant manner of probable bio-accumulation to the metals Mn, Cr, Ni, Zn, and Pb (Fig. 2c). The highest contribution noticed for the pre-mentioned metals is 30, 15, 14, 21, and 14 (mg/kg), respectively. *Amphistigina lobifera* has a noticeably lesser extent of heavy metals, mainly Ni and Mn (Fig. 2d). They sometimes exhibit extreme contents of 93 mg/kg (Ni) and 43 mg/kg (Mn) (Fig. 2d). Although the Quseir site has the highest diversity and population density, it also has the highest percentage of morphological abnormalities of the foraminiferal tests and the highest heavy metal concentrations in their tests (Tables 3 and 5 (B)).

Table 3 Heavy metal concentrations in the foraminiferal test structures

Species	Cu	Pb	Ni	Co	Cd	Cr	Zn	Fe	Ma
Elphidium striato punctatum-N-G	6.4	8	5.4	1.3	0.1	6	6	460	11.2
Elphidium striato punctatum-D-G	6.2	11	5.7	1.4	0.2	11	17	1040	14.6
Ammonia beccarii-N-G	5.7	7	3.1	1.2	0.1	3	13	312	6.8
Ammonia beccarii-D-G	6.2	13	3.2	1.7	0.1	9	20	680	10.6
Amphisorus hemprichii-N-G	2.1	4	3	1.1	0.1	2	16	1008	68
Amphisorus hemprichii-D-G	8.4	10	3	1.1	0.2	12	16	1110	80
Amphistegina lobifera-N-G	2.2	3	8	1.1	0.1	2	9	326	1.6
Amphistegina lobifera-D-G	7.1	5	40	1.2	0.1	6	15	1020	6
Elphidium striato punctatum-N-S	3.1	10	4.3	1.2	0.1	5	8	560	21.8
Elphidium striato punctatum-D-S	7.2	15	4.7	1.4	0.1	8	15	1200	34.3
Ammonia beccarii-N-S	7.7	11	3.7	1.1	0.1	10	9	440	21.6
Ammonia beccarii-D-S	8.1	13	3.9	1.3	0.2	13	18	850	29.3
Amphisorus hemprichii-N-S	4.3	6	4	1.3	0.1	2.1	8	940	246
Amphisorus hemprichii-D-S	8.1	14	52	22	0.4	4.4	22	2020	410
Amphistegina lobifera-N-S	2.1	5	40	1.2	0.1	3.4	4	740	18
Amphistegina lobifera-D-S	4.3	8	92	1.6	0.1	4.8	9	740	42
Elphidium striato punctatum-N-Q	6.2	7	11	1.9	0.1	14	11	608	19.2
Elphidium striato punctatum-D-Q	7.1	16	17	2.1	0.7	19	23	1320	34.6
Ammonia beccarii-N-Q	6.6	8	10	2.2	0.2	11	12	640	18.6
Ammonia beccarii-D-Q	7.4	14	22	2.4	0.9	23	21	1240	31.1
Amphisorus hemprichii-N-Q	2.1	4	6	1.3	0.2	3.2	10	1280	58
Amphisorus hemprichii-D-Q	4.5	20	94	4.3	1.4	22	27	1414	60
Amphistegina lobifera-N-Q	1.7	2	16	1.4	0.1	2	3	640	22
Amphistegina lobifera-D-Q	3.9	12	26	2.1	0.4	11	14	1040	35.4

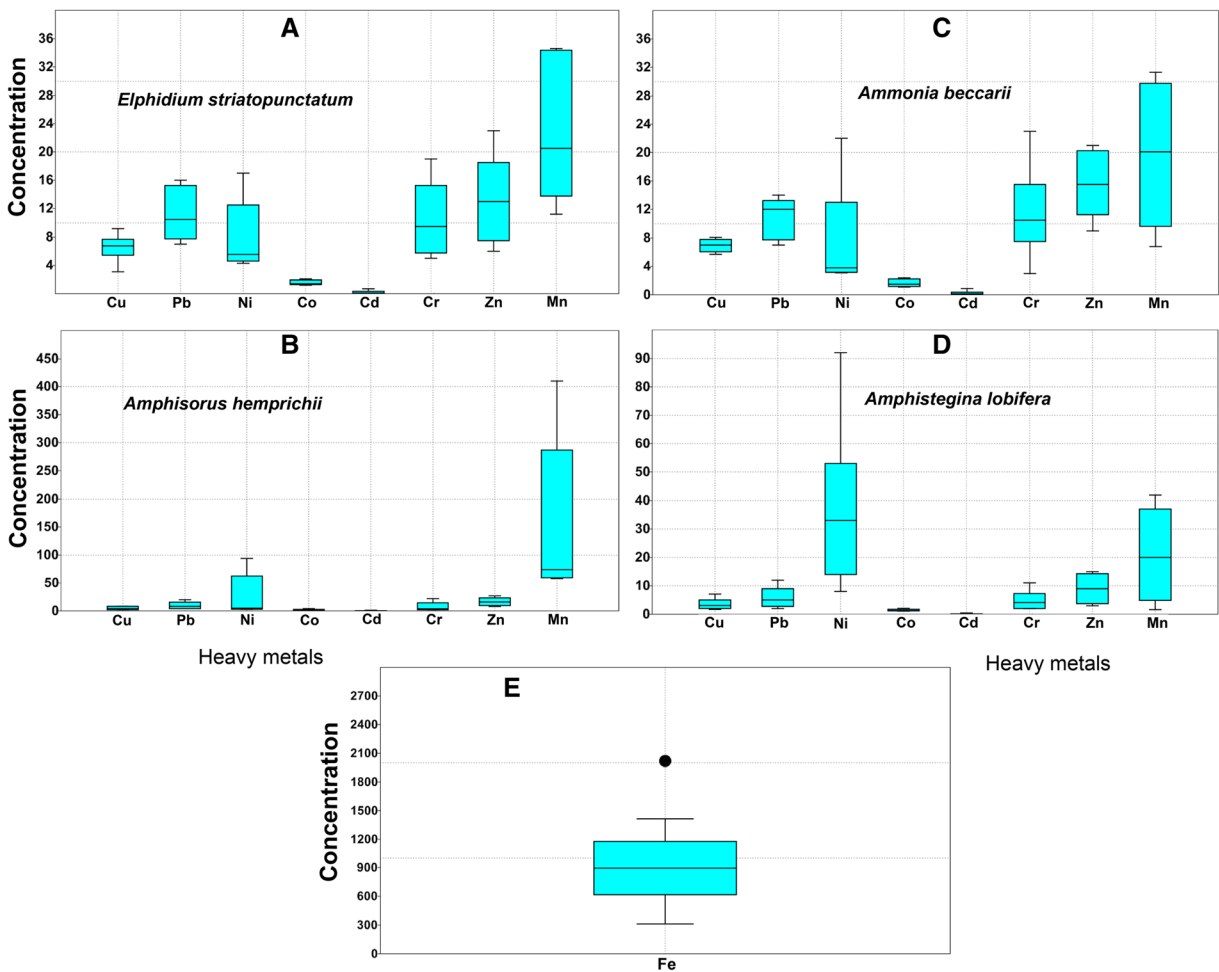*N* normal, *D* deformed, *G* Ras Gharib, *S* Safaga, *Q* Quseir

Fig. 2 Box plots for the heavy metals analyzed in the foraminiferal test structures

Benthic foraminifera

Thirty-four benthic foraminiferal species were iden-
tified, belonging to 20 genera, 16 families, and 3
suborders (Textularina, Rotalina, and Miliolina;
Appendix 4). *Amphistegina*, *Sorites*, *Calcarina*,
and *Peneroplis* are the main four constituting genera
in the three sites that reach 23.4, 14.0, 10.5, and
9.8%, respectively. Other common genera are *Am-
monia* (9.5%), *Triloculina* (7.6%), *Elphidium*
(6.8%), *Quinqueloculina* (5.9%), *Amphisorus* (5%),
Operculina (3.1%), and *Textularia* (2.6%). The fre-
quency of remaining genera is less than 1%
(Appendix 4).

Suborder Rotaliina forms the highest percentages
among the total foraminifera, representing 54% of

the assemblages in the study area (Appendix 4). It
is represented mainly by members of Rotaliidae
family. The most abundant species is *Amphistegina
lobifera*, constituting 13.3% of the total foraminif-
eral associations. This might be attributed to its
ability to colonize in polluted areas. Other major
species of this order are *Calcarina calcar* (10.5%),
Amphistegina lessonii (10.1%), and *Operculina
discoidalis* (3.1%). The suborder Miliolina is the
second most important component in the recorded
foraminiferal assemblages, comprising 43% of the
total foraminiferal assemblages in the area of study
(Table 4). The most abundant species in this sub-
order is *Sorites marginalis* (14%), followed by
Peneroplis spp. (9.8%), *Quinqueloculina* spp.
(5.9%), *Amphisorus hemprichii* (5%), *Triloculina*

oblonga (4%), and *Triloculina terqumiana* (3.2%). Since their shells degrade rapidly after death, the agglutinated species of suborder textulariina (3%; Appendix 4) were minor components of the documented assemblages in all harbors.

Amphistegina spp. is the most abundant taxon in all stations. It fluctuates from low values in the polluted stations in Ras Gharib harbor (specifically G.4 and G.7), and its ultimate value is in G.6 (up to 6%). It displays in Safaga site a very low relative abundance (< 1%) in all stations. Contrariwise, Quseir harbor shows the lowest relative abundance around stations Q.4 and Q.7, whereas the maximum abundance was observed in Q.6 (up to 14%; Fig. 3b).

The second most dominant taxon is *Sorites marginalis*. In Ras Gharib harbor, this species shows a very low abundance except G.6 and G.8. It instead

Table 4 List of percentages for the foraminiferal monitoring index (FMI) and foraminiferal abnormality index (FAI) in the three sites

A

Species	FMI%
Ammonia beccarii (Linne, 1758)	22.54
Amphisorus hemprichii Ehrenberg, 1839	17.12
Elphidium striato-punctatum (Fitchtel and Moll, 1798)	14.13
Peneroplis planatus (Fichtel and Moll, 1798)	13.44
Peneroplis pertusus (Forskal, 1775)	8.57
Coscinospira hemprichii Ehrenberg 1839	8.12
Operculina discoidalis Cushman, 1921	6.48
Calcarina calcar d'Orbigny, 1839	4.19
Quinqueloculina sp.	2.81
Spiroloculina sp.	2.6

B

Sample	FAI%	Sample	FAI%	Sample	FAI%
G.1	1.32	S.1	2.96	Q.1	3.32
G.2	0.48	S.2	0.8	Q.2	4.84
G.3	0	S.3	0	Q.3	1.2
G.4	0.4	S.4	1.88	Q.4	9.8
G.5	0.8	S.5	0	Q.5	8.04
G.6	0	S.6	0	Q.6	2.8
G.7	1.2	S.7	1.44	0.7	1.48
G.8	0	S.8	0.4	Q.8	0
G.9	0	S.9	0	Q.9	0

increases in Safaga stations where its pronounced peak is in station S.8 (up to 9%). Similarly, Quseir harbor sharply leaps up to 10% in Q.2 (Fig. 3a). The relative abundance of *C. calcar* fluctuates generally from low values in Safaga stations (< 1%) and moderate occurrences in Quseir stations (3%), and high relative abundance was recorded in Ras Gharib stations especially G.6 (23%; Fig. 3c). The distribution of *Peneroplis* spp. correlates well with that of *S. marginalis*. High relative abundances occur in the offshore stations of Safaga site where the highest is in S.8. The relative abundance of this species fluctuates all over Ras Gharib and Quseir stations (Fig. 3d). The relative abundance of *A. beccarii* is high in Quseir stations especially Q.2 (14%) and Q.3 (15%) (Fig. 3e). This species decreases in the relative abundance in Quseir stations such as Q.4, Q.7, and all the stations of both of Ras Gharib and Safaga sites (Fig. 3e). The relative abundance of *A. hemprichii* varies among all stations of the three sites. Ras Gharib stations showed little abundance (< 1%), whereas the abundance increases to about 5% in average in the Quseir stations. Apart, Safaga stations displayed fluctuated pattern except stations S.8 and S.9. Both of them jumped dramatically up to 15% (Fig. 3f).

In terms of the inter-relation between the specific richness and density, Ras Gharib site exhibits low numbers of Shannon index and density except station G.6 (Fig. 4). This station represent the highest number of individuals that reaches up to 12,800; however, the Shannon index of this station is not the highest. Additionally, station G.8, which revealed the highest Shannon index (2.3) at Ras Gharib, is the second most faunal-abundant station after G.6 (Fig. 4). The shallow stations such as G.1 and G.7 are regarded as the lowest stations in the diversity and density of fauna. On the other hand, Safaga site shows pattern to some extent different, where most stations are of moderate to high Shannon index and faunal density. The highest Shannon index and faunal density is for station S.8 (2.7 and 16,500, respectively). In the same context, Quseir stations are of more diversity and faunal density than Ras Gharib and Safaga sites. The highest station of Shannon diversity index is Q.4, where the Shannon index is 2.71. Noteworthy, this station has the lowest faunal density (14489) among Quseir stations.
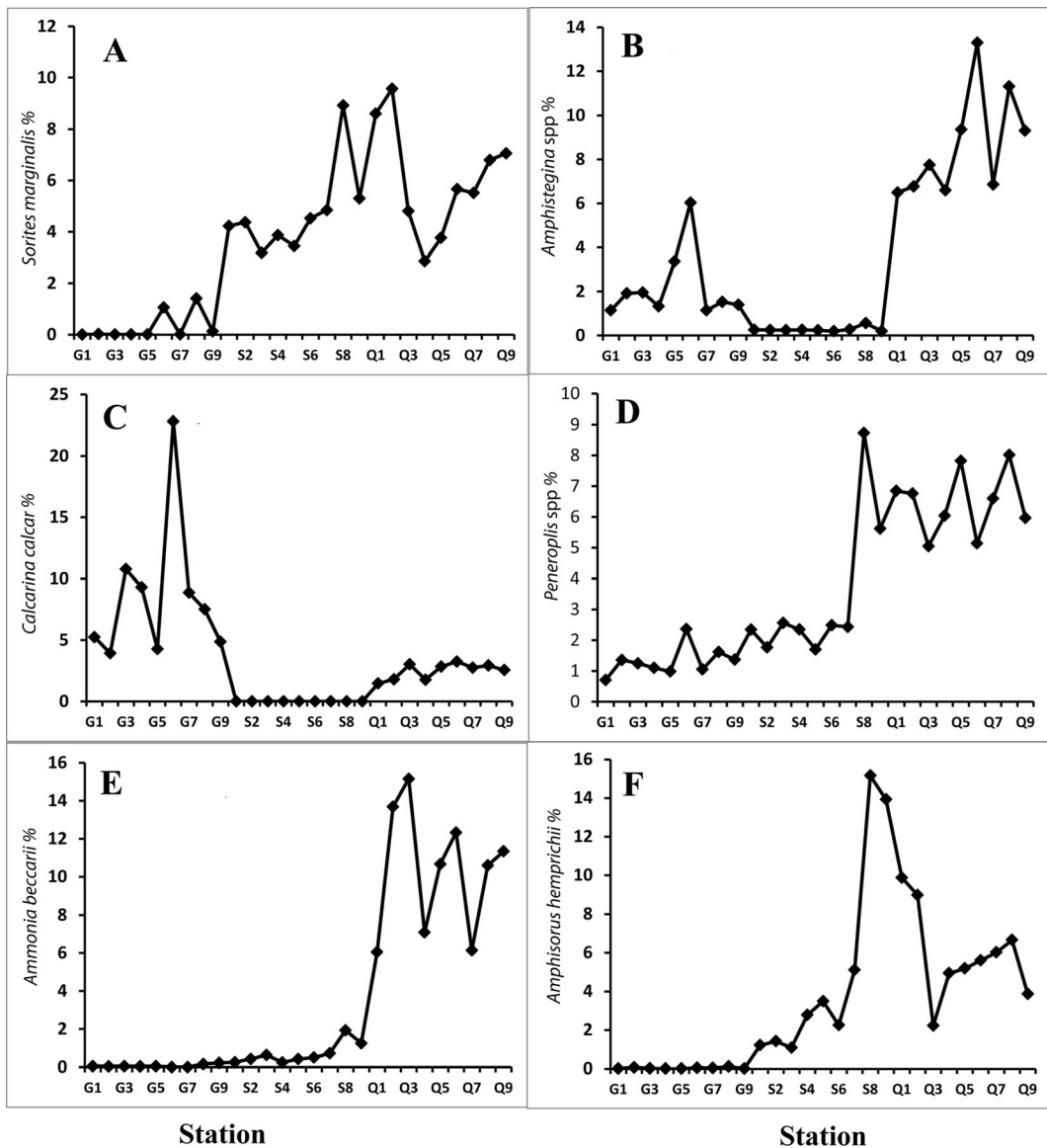
Fig. 3 Distribution pattern of the six most dominant foraminiferal species: *Sorites marginalis* (**a**), *Amphistegina* spp. (**b**), *Calcarina calcar* (**c**), *Peneroplis* spp. (**d**), *Ammonia beccarii* (**e**), and *Amphisorus hemprichii* (**f**)

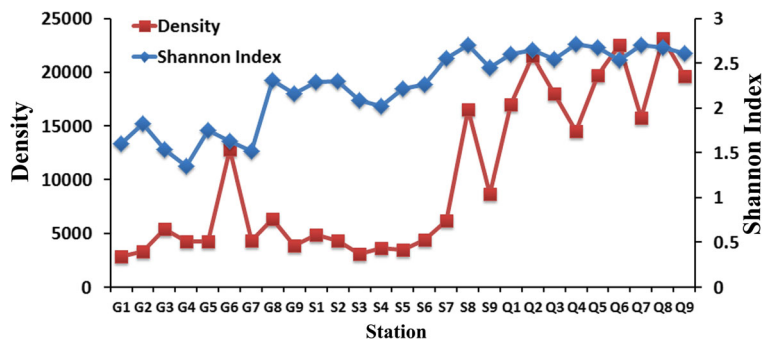**Fig. 4** Faunal diversity index and density of all stations in the three sites

Table 5 The calculated geo-accumulation index for the area of study, (A) Ras Gharib, (B) Safaga, and (C) Quseir sites, respectively

A			B			C		
Metal	I_{geo}	Contamination level	Metal	I_{geo}	Contamination level	Metal	I_{geo}	Contamination level
P	0.002	UP/MP	P	0.002	UP/MP	P	0.002	UP/MP
Fe	0.0002	UP/MP	Fe	0.0002	UP/MP	Fe	0.0002	UP/MP
Pb	0.074	UP/MP	Pb	0.07	UP/MP	Pb	0.1	UP/MP
Zn	0.023	UP/MP	Zn	0.03	UP/MP	Zn	0.035	UP/MP
Cu	0.053	UP/MP	Cu	0.04	UP/MP	Cu	0.044	UP/MP
Cd	− 1.019	UP	Cd	− 0.3	UP	Cd	0.3	UP/MP
Ni	0.0076	UP/MP	Ni	0.02	UP/MP	Ni	0.04	UP/MP
Mn	0.044	UP/MP	Mn	0.006	UP/MP	Mn	0.006	UP/MP
Co	0.01	UP/MP	Co	0.03	UP/MP	Co	0.05	UP/MP
As	0.083	UP/MP	As	0.1	UP/MP	As	0.16	UP/MP
B	0.034	UP/MP	B	0.03	UP/MP	B	0.035	UP/MP
Cr	0.021	UP/MP	Cr	0.02	UP/MP	Cr	0.034	UP/MP
Hg	− 4.15	UP	Hg	− 4.35	UP	Hg	− 1.88	UP

UP unpolluted, *MP* moderately polluted

Among the total of 34 identified species, 10 species show morphological abnormalities (Table 5 (A)). *Ammonia beccarii* shows the highest percentage of deformed specimens (22.8%), followed by *Sorites marginalis* (17.1%), *Elphidium striatopunctatum* (14.3%), *Peneroplis planatus* (13.4%), and *Peneroplis pertusus* (8.5%). The deformation in other species is listed in (Table 5). Ten species exhibited morphological deformation types in the three sites, comprising abnormal growth (Fig. 5).

The foraminiferal abnormality index (FAI) is calculated based on the number of the deformed specimens in the sample. In Ras Gharib site, station G.1 is the highest percentage of foraminiferal deformation (1.3%), followed by station G.7 and G.5 (1.2 and 0.8%, respectively; Table 5 (B)). Moreover, Safaga stations show higher percentages of deformed specimens than Ras Gharib stations. Station S.1 represents the most threatened one in Safaga site where the foraminiferal abnormality index reaches 2.9%, then S.4 (1.9%) and S.7 (1.4%; Table 5 (B)). The Quseir stations are considered the maximum percentages of deformed specimens in the three locations. The highest percentages of foraminiferal deformation in Quseir site are characterizing Q.4 (9.8%), followed by Q.5 (8.0%), then Q.2 (4.8%; Table 5 (B)).

Statistical analyses

Results of the cluster analysis

The cluster analysis (CA) revealed distinct clusters, characterized by different environmental implications, based on the absolute abundances of foraminiferal species. Q

Fig. 5 Types of abnormal foraminiferal tests recovered from the three sites: (1) abnormal growth as siamese twins and double apertures in *Peneroplis planatus*; (2) abnormal growth for the *P. planatus* where there is branching to be double apertures; (3) reduction in size for the last chambers of *P. planatus*; (4) abrasion the periphery of the test for *P. proteus*; (5) pitted surface and dissolutions for the *P. pertusus* test; (6) distortion due to compression of the test with aberrant chamber shape and size for *Coscinospira hemprichii*; (7) twisting the uniserial part of the *Coscinospira hemprichii* test; (8) abnormal growth of *Coscinospira hemprichii* with wrong direction of coiling in two directions; (9) complete distortion for *Operculina discoidalis* due to compressions; (10) twisting of *Elphidium striatopunctatum* from all directions; (11) and (12) reductions in sizes of the last chambers of *Elphidium striatopunctatum*; (13) aberrant chambers of *Quinqueloculina* sp. test, some specimens such as *Ammonia beccarii* exhibit more than one deformation type; (14) overdeveloped the last whorls with reduction in the chamber size of *Ammonia beccarii*; (15) reduction in chamber size of *A. beccarii* test; (16) abnormal growth and aberrant chambers of the last whorls for *Calcarina calcar* test; (17) abnormal growth with wrong direction of coiling in several directions for *Amphisorus hemprichii*; (18) complete distortion plus wrong direction of coiling in more than two directions of *A. hemprichii*; (19) wrong direction of coiling in two direction of *A. hemprichii*; (20) abnormal growth with wrong direction of coiling of *Spiroloculina* sp. test
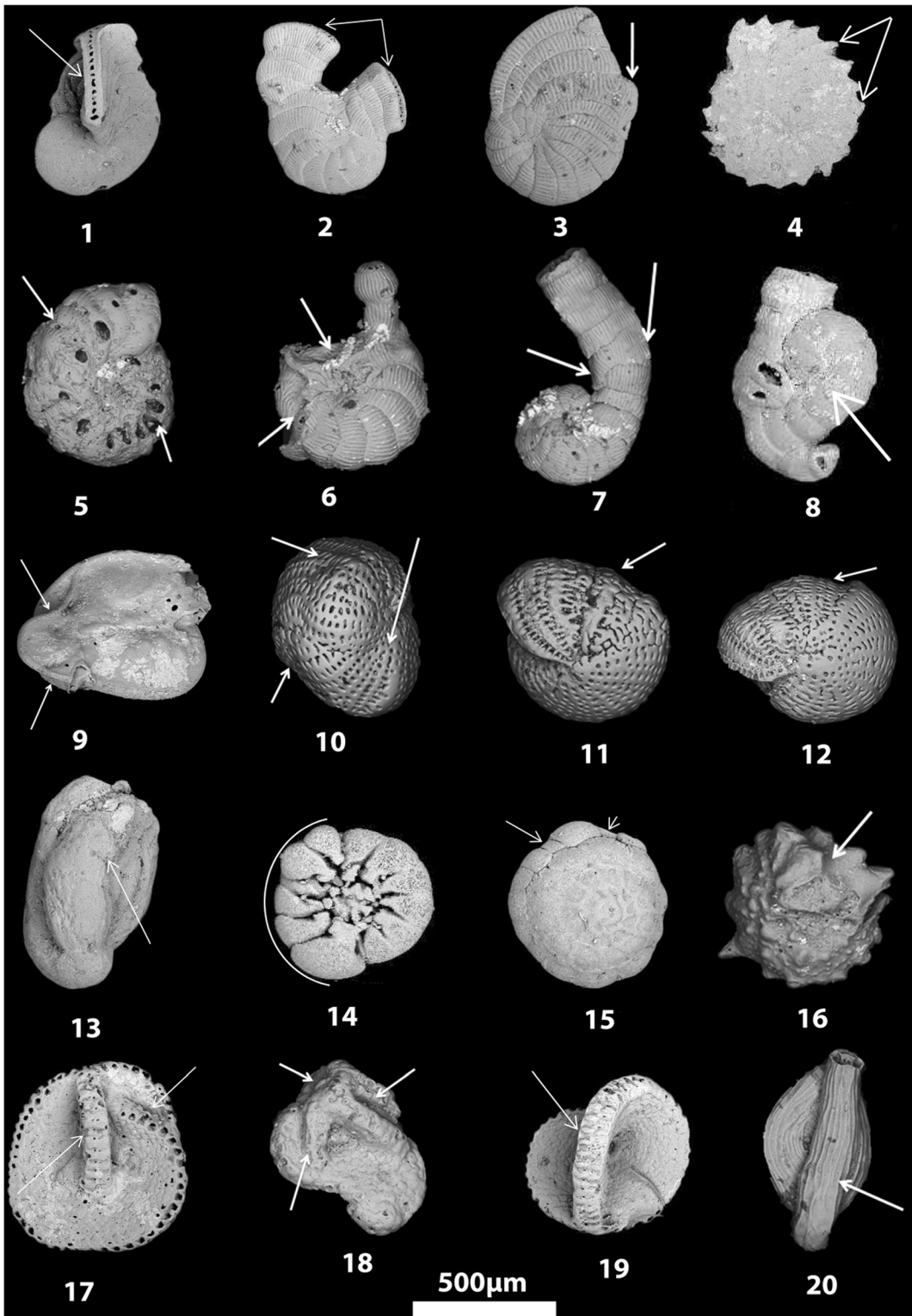
mode cluster analysis was performed to study the similarities between the stations. Stations are grouped into two main clusters (A and B) each with two sub-clusters (Fig. 6a). The two main clusters stand for the stations of each site separately as follows: A1 is grouping Quseir stations, A2 is grouping all Safaga stations, and B (B1 and B2) is enclosing all Ras Gharib stations. The clusters distributed based on their foraminiferal associations and their relative abundances (Appendix 5).

The first cluster (A) is well characterized by the main features of pollution. These features are enrichment of Pb, Zn, Fe, Ni, Cr, Cd, Mn, B, and TOC%, and sewage sludge from the pipes (Fig. 6a). Sub-cluster (A1) includes the extremely polluted stations of Quseir site (Q.4 and Q.5; Fig. 6a). These stations are mainly dominated by the species *A. beccarii*, *C. calcar*, *A. lessonii*, and *A. lobifera* (Fig. 6b). Sub-cluster (A2) comprises the comparatively more polluted stations of Safaga site (S.1 to S.9; Fig. 6a). These stations are located adjacent to pollution sources such as S.5. This sub-cluster has an assemblage dominated by *S. marginalis* (Fig. 6b).

Cluster (B) consists of two sub-clusters. Stations of Ras Gharib site G.2 and G.5 are grouped in sub-cluster (B1)

(Fig. 6a). This sub-cluster comprises foraminiferal assemblage characterizing shallow marine ecosystem. This assemblage includes *P. planatus*, *Q. limbata*, *Q. laevigata*, *T. terqumiana*, *T. oblonga*, *Elphidium* spp., and *O. discoidalis* (Fig. 6b). Aside, sub-cluster (B2) represents stations G.1, G.3, G.4, and G.6-G.9, where all mostly are influenced by pollution (Fig. 6a). These stations are located away from the direct influence of pollution. They are dominated by a foraminiferal assemblage comprising *A. hemprichii* and *P. pertusus* (Fig. 6b).

Canonical correspondence analysis

DCA revealed the length of the first gradient of 2.5 standard deviation unit, indicating a unimodal foraminiferal distribution in the area. Consequently, our data set can be presented and evaluated via CCA.

The first CCA axis explains 57.9% of the variation in the data set, whereas the second axis counts for 32% (Fig. 7). Ras Gharib site is poorer in species, whereas Safaga and Quseir sites are richer, but basically presenting distinct species. Axis 1 separates the stations based on pollution level into two groups (Fig. 7a). The first

Fig. 6 **a** Q mode. **b** R mode cluster analyses based on the recorded foraminiferal taxa in 27 variables (stations), using Ward's method for agglomeration
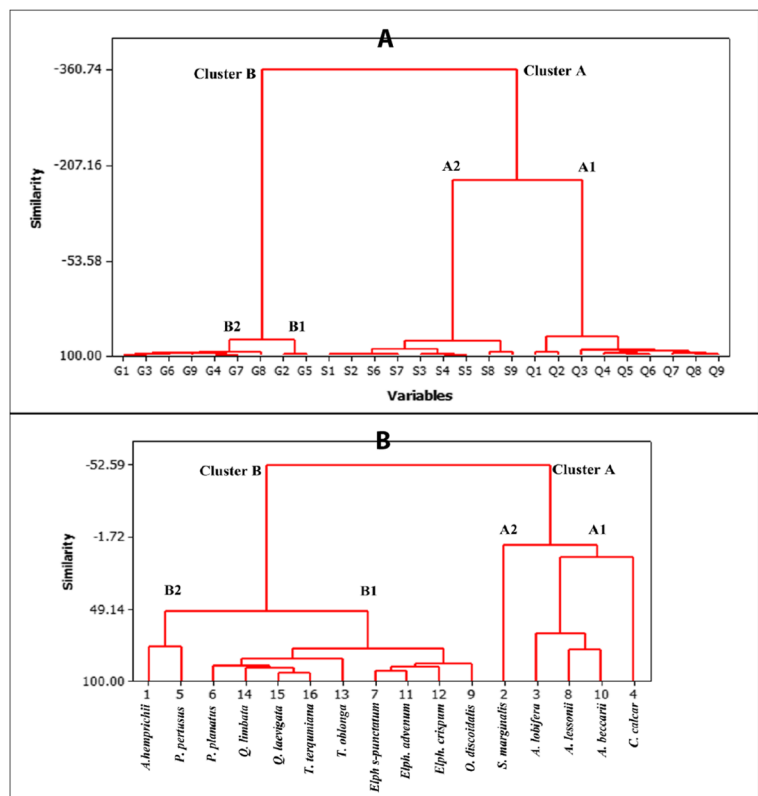
group is located on the negative side and includes the less polluted and offshore stations of the Quseir, Safaga, and Ras Gharib sites and their characteristic species. Another group is located on the positive side and consists of the polluted stations (mostly Safaga and Quseir stations) and their characteristic species. The highly polluted stations (Q.4 and Q.5 of Quseir site) are located in the lower part of the positive side of the first axis (Fig. 7a). Stations from other stressed stations (Q.1, Q.2, and Q.7 of Quseir and S.1, S.4, and S.7 of Safaga) are located also in the positive side. The less polluted stations are disseminated randomly in the negative side of such axis, including G.3, G.6, G.2, and G.8 of Ras Gharib site.

Axis 1 (Fig. 7b) separates species based on their relation with heavy metal. Accordingly, many foraminiferal species are located in the upper right corner where heavy metal concentrations, TOC, and pH are lowest, but Mn is the highest. These species include mainly *Quinqeloculina limbata*, *Triloculina oblonga*, *Triloculina terqumiana*, *Quinqeloculina laevigata*, *Peneroplis pertusus*, *Peneroplis planatus*, *Sorites marginalis*, and *Amphisorus hemprichii*. Few species plot in the lower right corner that are associated with high heavy metal concentrations, TOC, and silt content. These species include *Ammonia beccarii*, *Operculina discoidalis*, *Elphidium advenum*, and *Elphidium striatopunctatum* (Fig. 7b). Species that are located on

Fig. 7 Canonical correspondence analysis (CCA) biplot for relative abundance of foraminiferal species in surface sediment, together with the associated environmental variables. Station scores of 27 stations (**a**). Species scores of 18 foraminiferal taxa (**b**). Environmental vectors were omitted from **a** for clarity, but would be arranged as in **b**. Species abbreviations: A.bec: *Ammonia beccarii*, C.c: *Calcarina calcar*, A.lobifera: *Amphistegina lobifera*, A.less: *Amphistegina lessonii*, O.disc: *Operculina discoidalis*, El.s-p: *Elphidium. Striato-punctatum*, El.adv: *Elphidium advenum*, El.cr: *Elphidium crispum*, Q.mosh: *Quinqeloculina mosharrafi*, Q.laev: *Quinqeloculina laevigata*, Q.limb: *Quinqeloculina limbata*, S.marg: *Sorites marginalis*, A.hem: *Amphisorus hemprichii*, T.terq: *Triloculina terqumiana*, T.oblong: *Triloculina oblonga*, P.per: *Peneroplis pertusus*, P.plan *Peneroplis planatus*
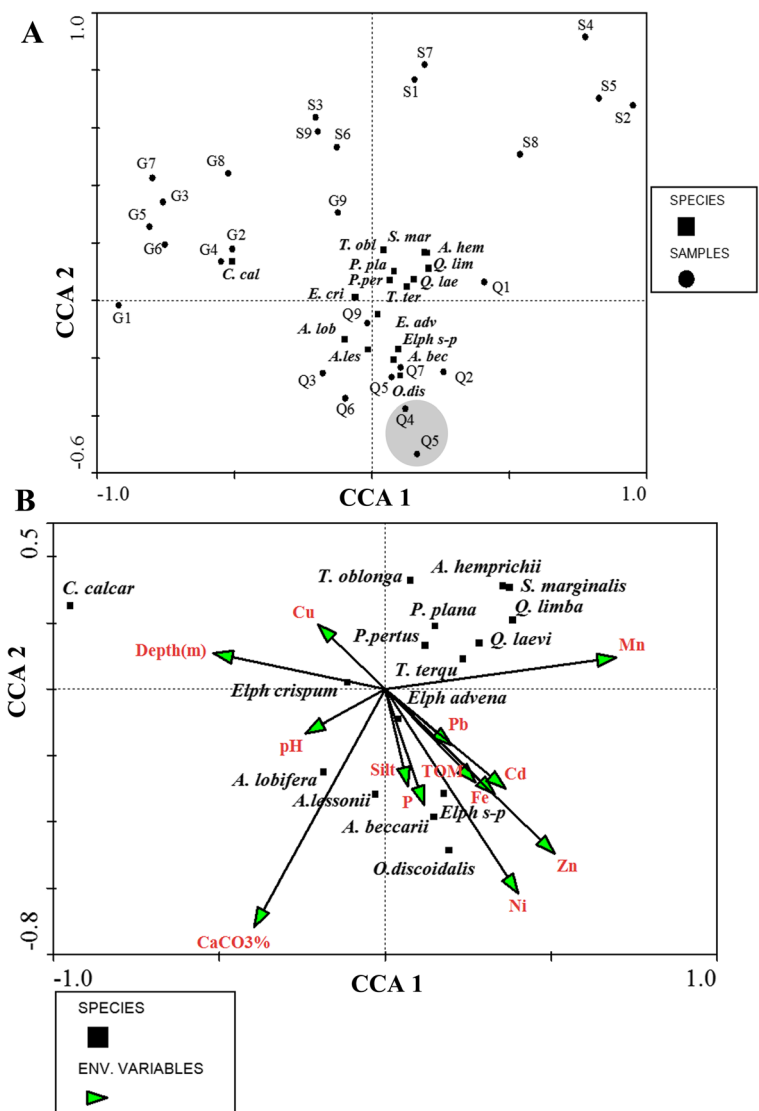
the lower left corner are mainly controlled by $CaCO_3\%$, Cu, pH, depth, and salinity. These species encompass *Calcarina calcar*, *Elphidium crispum*, *Amphistegina lobifera*, *and Amphistegina lessonii*. Along the second axis, a less prominent pattern of species and environmental variable was observed.

Discussion

Benthic foraminiferal distribution, diversity, density, and test deformation

Soritidae and Hauerinidae are two of the prevailing foraminiferal families in the study area. Their species exist with a high percentage that is consistent with warm and shallow coastal marine water (Madkour 2004). Suborder Miliolina occurred with a markedly high abundance (43.4%) which mirrors warm water bodies (< 20 °C; Youssef 2015). Suborder Rotalina is the most abundant, and the most abundant families are Amphisteginidae, Calcarinidae, Rotaliidae, and Elphidiidae. Their representative genera are *Amphistegina*, *Calcarina*, *Ammonia*, and *Elphidium*. Both *Amphistegina* and *Calcarina* show high abundances (23.4 and 10.5%, respectively), and the richest stations are G.5 and G.7 from Ras Gharib site. These species live on firm substrates (reefal and phytal), in warm water, at depth less than 30 m (*A. lessonii*), and less than 10 m (*A. lobifera*) (e.g., Haunold et al. 1997). The presence of *A. beccarii* with abundance 9.4% mirrors a stressful condition such as hypersalinity (Samir 2000). Moreover, its high percentage in Quseir site (station Q.3) confirms its ecologic tolerance in the muddy sand substrate and hypersaline warm shallow water.

The genus *Elphidium* displays a high abundance (6.8%) which reflects an active environment (Loeblich and Tappan 1988). For instance, station Q.4 is located nearby the harbor and demonstrated by biogenic sand, hypersaline warm water, and moderate content of total organic carbon. These ecological influences favor *Elphidium* spp., and therefore, they thrived in community.

To our knowledge, the published works on benthic foraminiferal bio-indicators have relied on the diversity and density as proxy for assessing the level of pollution (e.g., Du Châtelet et al. 2004; Bergin et al. 2006; Jayaraju et al. 2008; Debenay and Fernandez 2009; Frontalini et al. 2009). Bates and Spencer (1979) observed a decrease in the benthic foraminiferal diversity and density in the nearshore marginal marine regions,

whereas an increase was observed toward the open sea. The present study is in consistency and shows a resemblance with the documented results of Samir and El-Din (Samir and El-Din 2001; Fig. 4), concerning the importance of the specific richness as a bio-indicator for pollution assessment.

A different foraminiferal response was observed by Alve (1991). Intermediate faunal diversity with low faunal density was found in the area suffered from intense pollution. A poor community was observed in the polluted site, where there were few opportunists with high numbers (Murray 1973). Our data is well matched with a high diversity values in G.8 and S.8 in Ras Gharib and Safaga, respectively (Fig. 4). Quseir data show similar results to those discussed by Alve (1991) especially in Q.4 (Fig. 4). Thus, Q.4 may be a highly polluted station due to frequent ship activities around this station (Fig. 1), the presence of sewage pipes close to this station, and confirmed by high toxic metal contents (e.g., As, Cd, P, B, and Pb), as well as moderate to high organic matter contents.

The test abnormalities were suggested to be either due to natural causes (such as salinity and water currents that create abraded test peripheral), or general changes in the ecological conditions (e.g., Closs and Maderia 1968), or anthropogenic causes such as pollution (e.g., Geslin et al. 2002). Several authors attributed the malformations (test deformations) to mainly the natural factors (e.g., hypersalinity) irrespective to pollution. The chemistry of the present study deformed species shows an apparent heavy metal bio-accumulation. As long as the metal concentration increases in the foraminiferal tests up to critical values, the taxa would die and accordingly their number decreases. Another consequence suggests that the increased heavy metal concentrations may yield deformations in the test structures. Samir and El-Din (2001) reported that the compressed and/or twisted abnormal specimens are characterized by higher values of heavy metals. This study documented ten deformed species. In Quseir harbor, the dominant types of deformations are wrong coiling direction, Siamese twin, double/multiple apertures, aberrant chambers, compressed /distorted or twisted tests, and reduction in chamber sizes. These intensive deformations, which are the strongest among the three sites, are mostly due to anthropogenic influences. The analyzed normal and deformed foraminiferal species assured that the deformed forms, such as reduced chamber size, contain elevated concentration of heavy metals. In Safaga and Ras Gharib sites, however, the pitted test surface can be

attributed to bio-erosion from scavenging organisms. On the other hand, the braded peripheral tests are probably due to hydrodynamics of the water currents that are well known to be more strengthened at these sites.

Our results show that the signs of environmental pollution may be well maintained in the foraminiferal tests of some species. The heavy metals in the analyzed foraminiferal species displayed an enrichment of land-derived Fe concentrations in beach more than in open marine stations. Q.2 is of high Fe concentration, and consequently, the dominant shallow marine-tolerant *A. hemprichii* displayed a high affinity to the iron incorporation inside the test structure. The increased Pb concentrations in the deformed foraminiferal tests with respect to the normal tests of the same species can be interpreted as a contamination effect. It can be inferred that the bio-selectivity of Mn is high as long as its concentration and the residence time in the sediments were high too such as *A. hemprichii*, *E. striatopunctatum*, and *A. beccarii*. In the same context, the elevated Ni concentration in *A. lobifera* indicates its bio-accumulation tendency. However, Zn concentration is low in the shallow stations such as G.4 and G.8. The shallow marine-tolerant species displayed a high affinity to Zn accumulation in their tests such as *A. beccarii* and *E. striatopunctatum*.

Foraminifera as pollution bio-monitor

Two distinctive environments are recognized and their faunal community, based on the unevenness of the foraminiferal assemblages, their relationship with environmental conditions, and using the results of CA and CCA in addition:

Group 1:

This group occurred where the sediments are demonstrated by high TOC%, heavy metals, CaCO$_3$%, pH, and silt content. It is typified by dominant *E. striatopunctatum*, *Operculina discoidalis*, *Quinqueloculina* spp., *S. marginalis*, and *A. beccarii*. Abundant species in the polluted areas are likely to be tolerant (resistant or opportunistic) ones. The pollution sensitivity can be expressed by the absence of species (e.g., Yanko et al. 1998). *A. beccarii* is known to be dominant in the fine-grained sediment areas and tend to be sensitive to pollution (Samir and El-Din 2001). In temperate regions, *E. striatopunctatum* shows particular sensitivity to most kinds of contaminants (e.g., Bates and Spencer 1979). This observation is in accordance with the

results of the present study where *A. beccarii* decreases in the polluted stations such as Q.4 and Q.5. Moreover, these two stations have the highest foraminiferal abnormality index comparative to other stations.

Miliolids such as *A. hemprichii*, *Peneroplis* spp., *Coscinospira hemprichii*, *Quinqueloculina* sp., and *Spiroloculina* are sensitive to pollution as indicated by their high deformation percentages. These results are consistent to what noted by Rao and Rao (1979) and Samir and El-Din (2001). Although heavy metals have a major influence on foraminiferal distribution in the present study, other environmental factors should be regarded as well. Apart from the pollution level, *S. marginalis* is associated with coarse-grained sediments, high TOC%, and high salinity such as S.8 and Q.2 that accords well with the findings of Nour (2001).

Group 2:

The second group of foraminiferal species includes *Calcarina calcar*, *A. lobifera*, *Amphistegina lessonii*, *A. hemprichii*, *Peneroplis planatus*, *Peneroplis pertusus*, and *Elphidium crispum*. This group shows a high relative abundance in stations characterized by less pollution, coarser sediments, high salinity, and high CaCO$_3$%. The distribution of *Peneroplis pertusus* and *Peneroplis planatus* increases in the offshore area influenced by low turbulence. These species live as an epiphytic taxon on red algae (Reiss and Hottinger 1984) and require stable and low energy environments (Murray 1991). Additionally, *Peneroplis* spp. tends to flourish in warm waters and tolerates hypersaline environments (Murray 1970). Consequently, the deformed tests of these species may be due to environmental factors (mostly elevated salinities) rather than heavy metal accumulation. To conclude, the faunal assemblages of this group confirmed their increased abundance in areas of low heavy metal contents, as indicated by the cluster analysis and CCA diagrams.

Multivariate statistical analysis in relation to heavy metal clusters

Phosphorus has a vigorous control in trace metal scavenging and incorporation into sediments. Trace metals are first sorbed or precipitated on to P oxides, forming films or layers near the sediment surface (Duchart et al. 1973). The well-documented ability of these oxides to scavenge trace elements from solution makes this

process a likely reason for the high concentrations of the studied metals in sediment stations. In addition, P is an excellent marker for human sewage (due to detergents) and fertilizers. Consequently, higher concentrations probably are indicative of anthropogenic influences. The results of Pearson correlations indicate that Cr exhibits positive correlation with Mn ($r = 0.97$,

$p < 0.05$), which supports their similar spatial distribution pattern. Moreover, the relation between the sediment textural classes (sand, silt, and clay) and heavy metals show insignificant coefficients with sand and clay classes. On the other hand, the silt class shows positive correlations with some metals such as Fe ($r = 0.58$, $p < 0.05$), Pb ($r = 0.5$, $p < 0.05$), and Zn ($r = 0.53$,
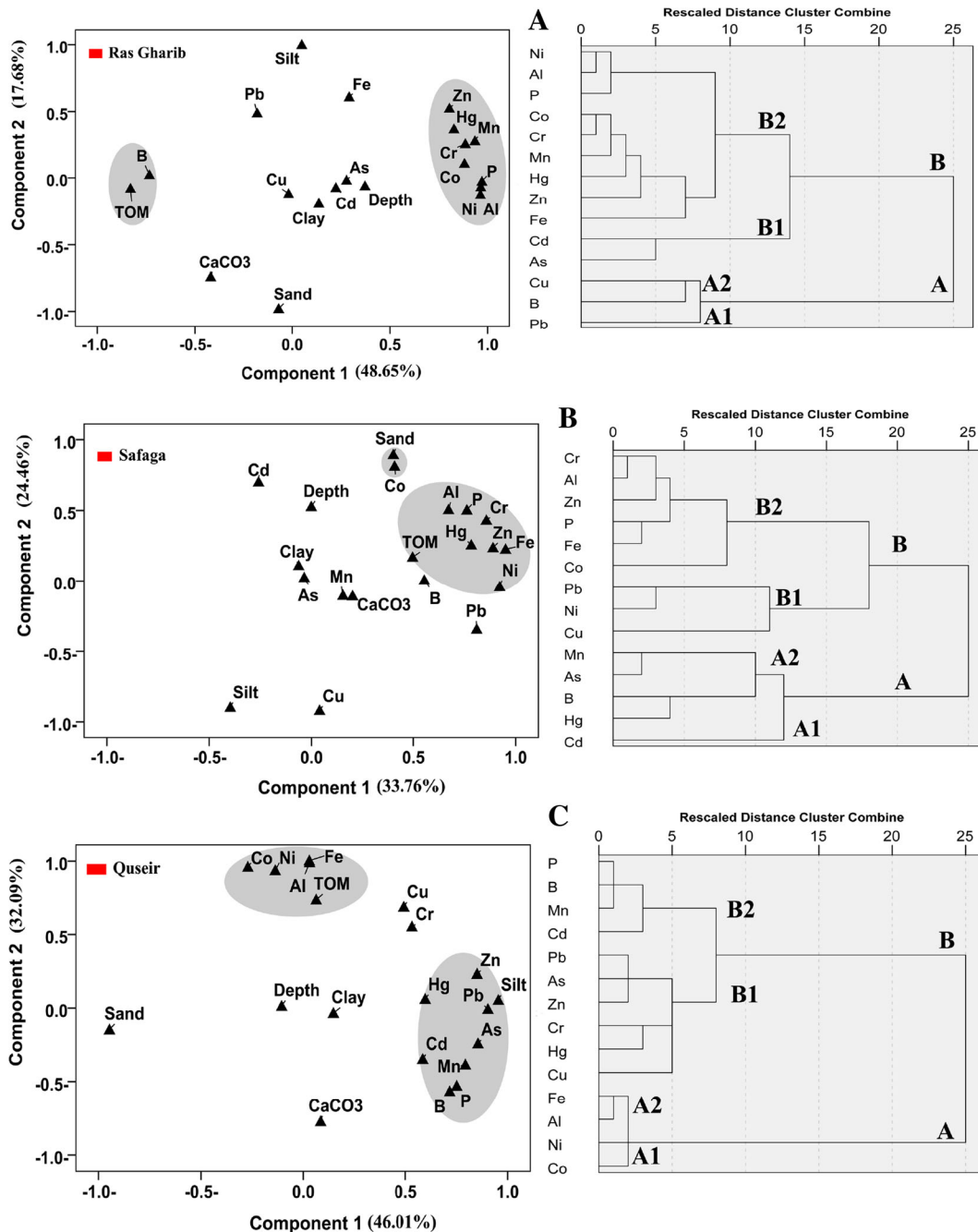

Fig. 8 Principal component analyses and cluster analysis of heavy metals in **a** Ras Gharib, **b** Safaga, and **c** Quseir sites

$p < 0.05$). Weak correlations were observed with Mn ($r = 0.31$, $p < 0.05$), Cr ($r = 0.27$, $p < 0.05$), Hg ($r = 0.37$, $p < 0.05$), and Co ($r = 0.1$, $p < 0.05$). Results of the correspondence analysis (Fig. 8a) agreed with these observations. The cluster analysis agreed with the results of the correspondence analysis, with two main clusters A and B. Sub-cluster B2 is compatible with either the positive significant correlation analysis or the correspondence analysis, whereas sub-clusters A1 and A2 represent the negative correlation as inferred from the correspondence analysis.

Assessment of metal pollution

The metal background concentrations in sediments are driven by weathering and unpolluted natural atmospheric deposition (Yang and Rose 2005). Metal increases in sediments due to pollution can be detached from its natural background, and passive tracer element can be used as proxies to assess the pollution level (Norton and Kahl 1991).

The geo-accumulation index (I_{geo}) is performed here to assess the pollution of metals in the sediment of the Red Sea coast. Geo-accumulation index was determined by the following equation according to Müller (1979) as

$$I_{geo} = \log_2 C_n/(1.5B_n),$$

where

C_n Measured concentration of heavy metal in the sediments.

B_n Geochemical background multiplied by the factor 1.5. This is used for the possible variations of the background data due to lithological variations.

Some stations have higher heavy metal contents than the average concentrations of Manosur et al. (2000) and El-Sorogy et al. (2006). Their contribution in Quseir samples are noticeably higher than what was documented by Manosur et al. (2000) and El-Sorogy et al. (2006). Generally speaking, a comparatively depleted contribution of the same metals was observed in Ras Gharib and Safaga sites than Manosur et al. (2000). However, their contribution is more or less similar to what El-Sorogy et al. (2006) found, for the same sites (Table 1). In the present work, the possibility of establishing the background level of the heavy metals is discussed with respect to the data obtained by Manosur et al. (2000). The indices of geo-accumulation of the heavy metals

obtained are given in Table 5. According to Müller (1979), I_{geo} classifies the pollution levels into six grades namely, unpolluted (grade 1, $I_{geo} < 0$), unpolluted to moderately polluted (grade 2, $0 < I_{geo} < 1$), moderately polluted (grade 3, $1 < I_{geo} < 2$), moderately to strongly polluted (grade 4, $3 < I_{geo} < 4$), highly polluted (grade 5, $4 < I_{geo} < 5$), and very highly polluted (grade 6, $I_{geo} > 5$).

I_{geo} grades for the study area sediments vary based on the metal and site (i.e., across metals and sites). In Ras Gharib site, Cd and Hg remain in grade < 0 (unpolluted) in all stations suggesting that the Ras Gharib area is within background values. I_{geo} for the rest of metals ranged from the unpolluted to moderately polluted grade (Table 5). In Safaga site, Pb and Cd attain grade 1 (unpolluted). I_{geo} shows most of the heavy metals in this site placing around grade 2. This suggests that the sediments of Safaga site are having background concentrations for Cd and Hg as well. In Quseir site, the average concentration of the heavy metals in each site shows that Hg remains in the unpolluted category, whereas the rest of our heavy metals are categorized in the unpolluted to moderately polluted grade.

Pollution load index (PLI) was computed according to Tomlinson et al. (1980) as follows:

$$PLI = (CF1 \times CF2 \times CF3 \times \ldots\ldots CF_n)^{1/n},$$

where CF refers to contamination factor and n refers to the number of metals investigated.

This index is a quick tool in order to compare the pollution status of different places (Adebowale et al. 2009). Results of the present study show that the contamination factor values in Ras Gharib, Safaga, and Quseir sites for most of the metals such as Mn, Fe, Zn Cu, and Ni are low (< 1; Table 6). Alternatively, the contamination factor values in Safaga and Quseir show higher values for P, Cd, and Hg (> 1; Table 6). This is mostly due to the influence of external discrete sources like industrial activities, agricultural runoff, sewage sludge, and other anthropogenic inputs. The values of pollution load index (Table 6) were found to be generally low (< 1) in the studied stations of Ras Gharib and Safaga sites. Quseir site, however, displays higher pollution load index (> 1) in stations Q.4, Q.5, Q.2, and Q.1. The difference in indices results can be attributed to the difference in sensitivity of these indices toward the sediment pollutants (e.g., Praveena et al. 2007). It is

Table 6 The calculated contamination factor and pollution load index

Metal	CF_G	CF_S	CF_Q
P	0.15	0.18	3.62
Fe	0.14	0.17	0.21
Pb	0.27	0.46	0.58
Zn	0.11	0.21	0.39
Cu	0.92	0.45	0.21
Cd	0.61	1.1	2.01
Ni	0.05	0.06	0.28
Mn	0.1	0.32	0.22
Co	0.07	0.1	0.15
As	0.24	0.31	0.65
B	0.38	0.24	0.73
Cr	0.1	0.08	0.3
Hg	0.66	0.54	1.5
Station	G	S	Q
St.1	0.77	0.88	*1.00*
St.2	0.81	*0.89*	*1.05*
St.3	0.77	0.80	0.80
St.4	0.77	0.82	*1.32*
St.5	0.86	0.82	*1.30*
St.6	*0.75*	0.85	0.99
St.7	0.83	*0.74*	0.93
St.8	0.81	0.83	0.96
St.9	*0.97*	0.85	0.97

St. station, *G* Ras Gharib, *S* Safaga, *Q* Quseir

Italic values at Ras Gharib and Safaga sites are representing the minimum and maximum PLI, whereas at Quseir site represent the highest four PLI values

noteworthy that the Red Sea coast is starting to face dangerous heavy metal pollution especially with, e.g., Hg, P, and Cd which results from increased rate of non-treatment industrial waste discharging into the Red Sea.

Conclusions

The environmental impacts on the foraminiferal assemblages were assessed here using 27 sediment stations collected from Ras Gharib, Safaga, and Quseir harbors. Thirty-four foraminiferal species belonging to 20 genera and three suborders (Miliolids, Rotalids, and Textularids) were detected. The families Amphisteginidae, Soritidae, Hauerinidae, and Peneroplidae were the major foraminiferal assemblages observed. Foraminiferal test deformities were detected such as compression and/or twisting, wrong direction of coiling, and multiple apertures. The chemical

analysis of four foraminiferal species revealed that the abnormal forms possess higher contribution of heavy metals. Enrichments of the analyzed metals in the foraminiferal test structures, particularly in Quseir site, show that the Red Sea ecosystem is influenced by anthropogenic activities.

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