

Natural and anthropogenic controls on sediment composition of an arid coastal environment: Sharm Obhur, Red Sea, Saudi Arabia

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Abstract The present study investigated the natural and anthropogenic processes that control the composition of the bottom sediments of Sharm Obhur, Red Sea. Mineralogical analysis using XRD indicated that the sediments consist of carbonate and non-carbonate minerals. Elemental interrelationships allowed differentiating two groups of elements of different sources and origin. Elements that are in the same group are positively correlated, while they correlate negatively with elements of the other group. The first group includes silicon, Al, Fe, Mn, Mg, vanadium (V), chromium (Cr), Co, Ni, Cu, and Zn, whereas the other group includes Ca, Sr, and CaCO₃. The highest concentration levels of the first group and the highest content of non-carbonate minerals were obtained from the sediments near the head of the sharm (zone A), whereas the sediments near the mouth of the sharm (zone B) yielded high concentrations of second group and carbonate minerals. Metal enrichment and contamination factors and pollution

load index were calculated. The values of these indices differentiate two groups of metals: lithogenic and non-lithogenic. Except for lead (Pb) at one sampling site, metals in zone A sediments are of lithogenic source, supplied to the sharm either naturally by aeolian transportation and through Wadi Al-Kuraa'a during rare but major floods or by human activities such as dumping and shore protection. Non-lithogenic Cr, Pb, V, and Mn were documented from some sampling sites in zone B, and their occurrences are related to waste disposal and fossil fuel combustion.

Keywords Red Sea · Arid environments · Environmental assessment · Heavy metal enrichment · Lithogenic and non-lithogenic metals

Introduction

Sediments play an important role for the transport and storage and possibly a potential source for many heavy metals (Förstner 1989). Geochemical analysis of sediments is a widely used method in environmental monitoring and assessment programs (Frignani et al. 1997; Morrison et al. 2010). Coastal sediments receive heavy metals through various natural and anthropogenic pathways (Radenac et al. 2001; Alagarsamy 2006; Buccolieri et al. 2006; Ahmed et al. 2011). Identification of the natural and anthropogenic sources of heavy metals is an important task in marine pollution research (Esen et al. 2010). Several geochemical approaches have been applied to distinguish the source and the degree of metal

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enrichment (Rubio et al. 2000; Esen et al. 2010; Ahmed et al. 2011; Heimbürger et al. 2012). Most of these studies were carried out on coastal sediments (estuarine and lagoons) of humid regions where land-derived detrital sediments via river inputs are significant (e.g., Caeiro et al. 2005; Tuncel et al. 2007; Ahmed et al. 2011; Esen et al. 2010).

The Red Sea coastal environments are characterized by a unique arid tropical ecosystem with surficial sediments consisting mainly of indigenous calcareous sediments of biogenic origin. They receive varying quantities of siliciclastic sediments via active wind transportation, occasionally active wadis, and by various human activities. This type of coastal systems has to be treated in regard to environmental pollution in a way different from those in humid settings.

Jeddah, the largest city on the eastern Red Sea Coast, has undergone a rapid rate of economic and social development, and therefore, a significant part of the coast has been subjected to extensive exploitation and heavy metal pollution (Badr et al. 2009). Considerable attention has been given to assess pollution along Jeddah City coastal zone (Basaham 1998; El-Rayis and Moammar 1998; El Sayed et al. 2002; Turki 2007; Badr et al. 2009; Pan et al. 2011; Abu-Zied et al. 2013). Sharm Obhur, the most prolific and the most popular recreation place in Jeddah, is of particular interest. Unplanned urbanization around Sharm Obhur neglecting environmental issues has produced hostile surficial conditions for many aquatic organisms and contaminated surficial sediments with hazardous and toxic heavy metals (Basaham et al. 2006).

The main objectives of the present study were to (1) gain insight into mineralogical and geochemical composition of the Sharm Obhur surficial sediments and their spatial distribution, (2) evaluate the controlling factors that affect the spatial distribution of heavy metals in Sharm Obhur surficial sediments, including possible anthropogenic influences, and (3) assess the present environmental status of Sharm Obhur.

Area of study

Sharm Obhur is a coastal inlet on the Red Sea Coast of Saudi Arabia, ~35 km to the north of Jeddah City center (Fig. 1). It extends inland for about 9.2 km between latitudes 21°42' and 21°47' N and longitudes 39°04' and 39°09' E with a maximum width of about 1.5 km. It has a general orientation of N35° E and connects to the Red

Sea at its southwestern end through a narrow mouth (~300 m wide). The sharm is shallow near its head (~1 m depth) and its depth increases gradually in the SW direction to reach a maximum depth of about 50 m near its mouth. The area has a hot arid tropical climate with surface water temperature varying from 26 to 28 °C in winter and from 30 to 31 °C in summer (Albarakati 2009). Rainfall is scarce and there is no perennial or ephemeral streams discharging into the sharm. The prevailing wind throughout the year is trending to N and NNW, only occasionally blowing from the S and SSE (Behairy et al. 1985). The salinity ranges between 39.1 and 40.2 and increases towards the NE terminal. The tidal range is negligible and the sharm is not subjected to strong waves (Ahmad and Sultan 1992).

The sharm has two sub-parallel shorelines. The eastern coast is heavily urbanized, thoroughly affected by human activities and occupied by restaurants, recreation sites, and marinas. It is protected against wave attack by huge basaltic blocks and in some places by concrete. The western coast on the other hand is less affected by human activities. The nearshore areas adjacent to the eastern shoreline are steeper and deeper than the nearshore areas adjacent to the western shoreline. The unplanned dumping and landfill processes have reduced the area of the sharm by about 800,000 m² between 1986 and 2000 (Basaham et al. 2006).

Material and methods

A total of 41 surficial sediments samples were collected from the Sharm Obhur using stainless grab sampler at water depths varying from 2 to 32 m. Fourteen samples were collected from the areas near the head of the sharm (zone A) and 27 samples were collected from the areas near the mouth of the sharm (zone B). The landmarks in the adjacent land areas to the sampling sites were recorded and all sampling sites were defined using global positioning system. The collected sediments were air dried at room temperature and subsequently sieved to determine the sand/mud content. Mineralogical and geochemical analyses were carried out on the mud fraction (<63 μm). Calcium carbonate (CaCO₃) content was determined by treating a known weight of dry sediment sample (~0.5 g) with an appropriate volume of cold 1 M HCl using a calcimeter (Basaham 2008). The geochemical analysis was carried out by a Rigaku RIX 2100 X-ray fluorescence

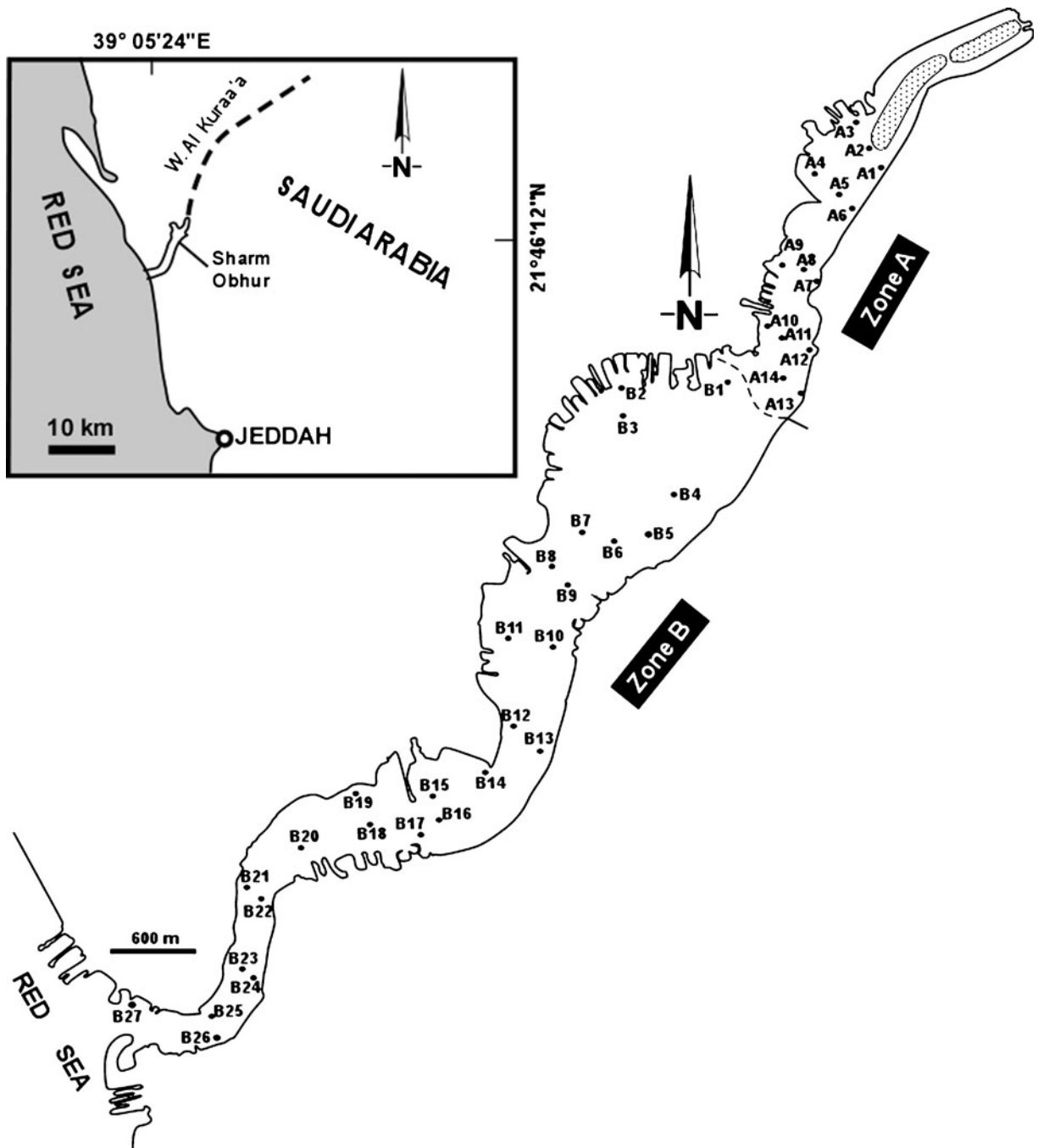


Fig. 1 Location map for the study area and sampling sites

spectrometer, equipped with Rh/W dual-anode X-ray tube. The analyses were performed under 50 kV and 50 mA accelerating voltage and tube current, respectively. Fused glass beads were prepared by mixing 1.8 g of powdered sample (dried to 110 °C for 4 h), 3.6 g of

spectroflux ($\text{Li}_2\text{B}_4\text{O}_7$ 20 %, LiBO_2 80 %, dried at 450 °C for 4 h), 0.54 g of oxidant LiNO_3 (dried at 110 °C for 4 h), and traces of LiI . The mixture is fused at 800 °C for 120 s and at 1,200 °C for 200 s, according to the method of Furuyama et al. (2001). The bulk

mineralogy of the mud fraction (<63 μm) was determined using X-ray diffraction analysis on 37 samples by powdered press techniques (Hardy and Tucker 1988). The relative abundance of minerals was determined using peak heights. The analysis was done by Rigaku RAD-I X-ray diffractometer (Cu $K\alpha$ radiation with 30 kV, 10 mA, and 2–40° (2θ)). The mineralogical and geochemical analyses were undertaken at the Department of Geosciences, Osaka City University, Japan.

Results

Sediment characteristics

The surficial sediments of Sharm Obhur are heterogeneous in composition and texture (Table 1). They consist of a mixture of autochthonous calcareous sediments of dominantly biogenic origin and allochthonous siliciclastic sediments. Texturally, the Sharm Obhur surficial sediments are classified as argillaceous sand to sandy mud. The mud content varied generally from 7 to 98 % with an average of 49 %. The lowest mud content was recorded from the samples which were collected from the nearshore areas (Table 1). The mud content in zone A sediments varied from 7 to 92 with an average of 52 %, whereas it ranged between 8 and 98 with an average of 50 % in the sediments of zone B. The CaCO_3 content in Sharm Obhur sediments varied generally from 14 to 82 %, with an average of 49 %. The sediments near the head of the sharm (zone A) yielded relatively low average CaCO_3 content (~31 %), whereas the CaCO_3 content in the sediments of the zone B ranged between 36 and 82 with an average of 58 % (Table 1). The CaCO_3 content increased gradually towards the western shoreline.

Mineralogical composition

The surficial sediments of Sharm Obhur consist of carbonate (calcite, aragonite, Mg-calcite, and strontianite) and non-carbonate minerals (quartz, phyllosilicates, hornblende, feldspars, and plagioclase). Traces of other minerals (dolomite, halite, anhydrite, and tremolite) were locally detected (Table 1). Carbonate minerals particularly calcite, aragonite, and Mg-calcite along with quartz are the most abundant minerals. Non-carbonate minerals are more abundant than carbonate minerals in the sediments of zone A. The content of non-carbonate minerals varied from 44 to 77 % with an average of ~64 %, whereas the

content of carbonate minerals ranged between 23 and 56 with an average of 36 %. The relative abundance of minerals in the sediments of zone A was as follows quartz > calcite > aragonite > phyllosilicates > hornblende > Mg-calcite > feldspars > plagioclase > strontianite. In sediments of zone B, the average carbonate mineral content (~52 %) was slightly higher than non-carbonate minerals (~48 %). Aragonite, quartz, calcite, Mg-calcite, phyllosilicates, and hornblende dominated the sediments of zone B (Fig. 3c–f). Feldspars, plagioclase, and strontianite were detected with low average contents (≤ 5 %) in the sediments of zone B.

Sediment geochemistry

Major elements

The concentration levels of major elements varied significantly within the area of study (Figs. 2 and 3). The concentrations levels of major elements except Ca in the sediments of zone A were higher than those in sediments of zone B (Table 1). The relative abundance of major elements in the sediments of zone A was in the order silicon (Si) > Ca > Al > Fe > Mg > Mn and in sediments of zone B in the order Ca > Si > Al > Fe > Mg > Mn (Fig. 2a–f). The spatial distribution of Ca showed that the concentration levels decreased towards the eastern shoreline (Fig. 2f). The concentrations of Ca ranged between 9.37 and 21.5 with an average of 14.2 % in the sediments of zone A and varied in sediments of zone B from 15.14 to 27.64 with an average of 22.35 %. On the other hand, the concentration levels of the other major elements decreased gradually towards the mouth of the sharm and the western shoreline (Fig. 2a–e). In sediments of zone A, Si varied from 11.45 to 21.45 (average ~17 %), Al from 3.56 to 6.8 (average 5.5 %), Fe from 2.8 to 5.64 (average 4.37 %), and Mg from 2.2 to 3.14 (average 2.8 %). In sediments of zone B, the average concentrations of Si, Al, Fe, and Mg were 9.39, 3.15, 2.33, and 2.2 %. The average concentrations of Mn in sediments of zones A and B were 674 and 358 $\mu\text{g/g}$, respectively.

Trace elements

Except for Sr, the concentration levels of trace elements in sediments of zone A were higher than those in sediments of zone B (Table 1). The relative abundance of trace

Table 1 The ranges and average values of the major and trace elements and the minerals in the sediments of Sharm Obhur. The X/Fe and X/Al ratios are documented for the sediments, the average chemical composition of deepest sediments, upper continental crust, average shale and basalt

	Zone A			Zone B			I	II	III	IV
	Min	Max	Mean	Min	Max	Mean				
Si, %	11.5	21.5	17	3.8	15.6	9.4				
Al, %	3.6	6.8	5.5	1.2	5	3.1				
Fe, %	2.8	5.6	4.4	0.9	4.1	2.3				
Mg, %	2.2	3.1	2.8	1.4	2.8	2.2				
Ca, %	9	22	14	15.1	27.6	22.4				
Mn, µg/g	542	929	675	155	542	359				
V, µg/g	107	201	143	39	144	78				
Cr, µg/g	84	204	135	31	115	70				
Co, µg/g	10	20	16	1	14	8				
Ni, µg/g	34	73	57	4	38	23				
Cu, µg/g	26	58	47	14	49	32				
Zn, µg/g	55	101	82	22	81	51				
Sr, µg/g	879	3,120	1,550	1,751	4,229	3,051				
Pb, µg/g	0.5	8.5	4.5	0.09	8.38	3.41				
CaCO ₃	14	53	31	36	82	58				
Mud, %	7	92	52	8	98	49				
Phyl, %	5	13	10	0	23	8				
Horn, %	5	19	9	0	20	8				
Qz, %	13	31	23	11	28	16				
Fel, %	0	16	6	0	11	5				
Plag, %	5	11	6	0	8	4				
Arag, %	5	14	9	8	39	19				
Calc, %	6	34	14	7	36	16				
MGC, %	0	13	7	0	25	14				
Str, %	3	7	5	0	6	4				
Others, %	5	16	11	0	13	6				
Si/Fe	3.5	4.2	3.9	3.11	4.87	4	3.95	9.8	5.8	8.5
Al/Fe	1.1	1.4	1.3	0.85	1.47	1.33	1.4	2.55	1.86	3.08
Mg/Fe	0.55	0.82	0.66	0.61	1.56	0.99	1	0.42	0.3	1.5
Ca/Fe	1.79	4.64	3.6	3.7	31.7	11.1	8.27	0.95	0.33	2.5
Si/Al	2.9	3.3	3.1	2.69	3.65	3.05	2.83	3.83	3.13	2.76
Fe/Al	0.71	0.92	0.79	0.68	1.17	0.76	0.71	0.39	0.54	0.32
Mg/Al	0.44	0.65	0.52	0.50	1.15	0.76	0.73	0.16	0.17	0.49
Ca/Al	1.38	6.05	2.84	3.01	23.31	8.69	5.91	0.37	0.18	0.81

Phyl phyllosilicates, *Horn* hornblende, *Qz* quartz, *Fel* feldspars, *Plag* plagioclase, *Arag* aragonite, *Cal* calcite, *MGC* Mg-calcite, *Str* strontianite, *I* average chemical composition of deepest sediments, *II* average composition of UCC (Taylor and McLennan, 1985), *III* average composition of shale (Turekian and Wedepohl, 1961), *IV* average composition of flood basalt (Kieffer et al., 2004)

elements in the sediments of zone A was in the order of Sr > vanadium (V) > chromium (Cr) > Zn > Ni > Cu > Co > lead (Pb) and in the sediments of zone B in the order

of Sr > V > Cr > Zn > Cu > Ni > Co > Pb. In addition, the concentration levels of trace elements decrease gradually towards the mouth of the sharm and the western shoreline

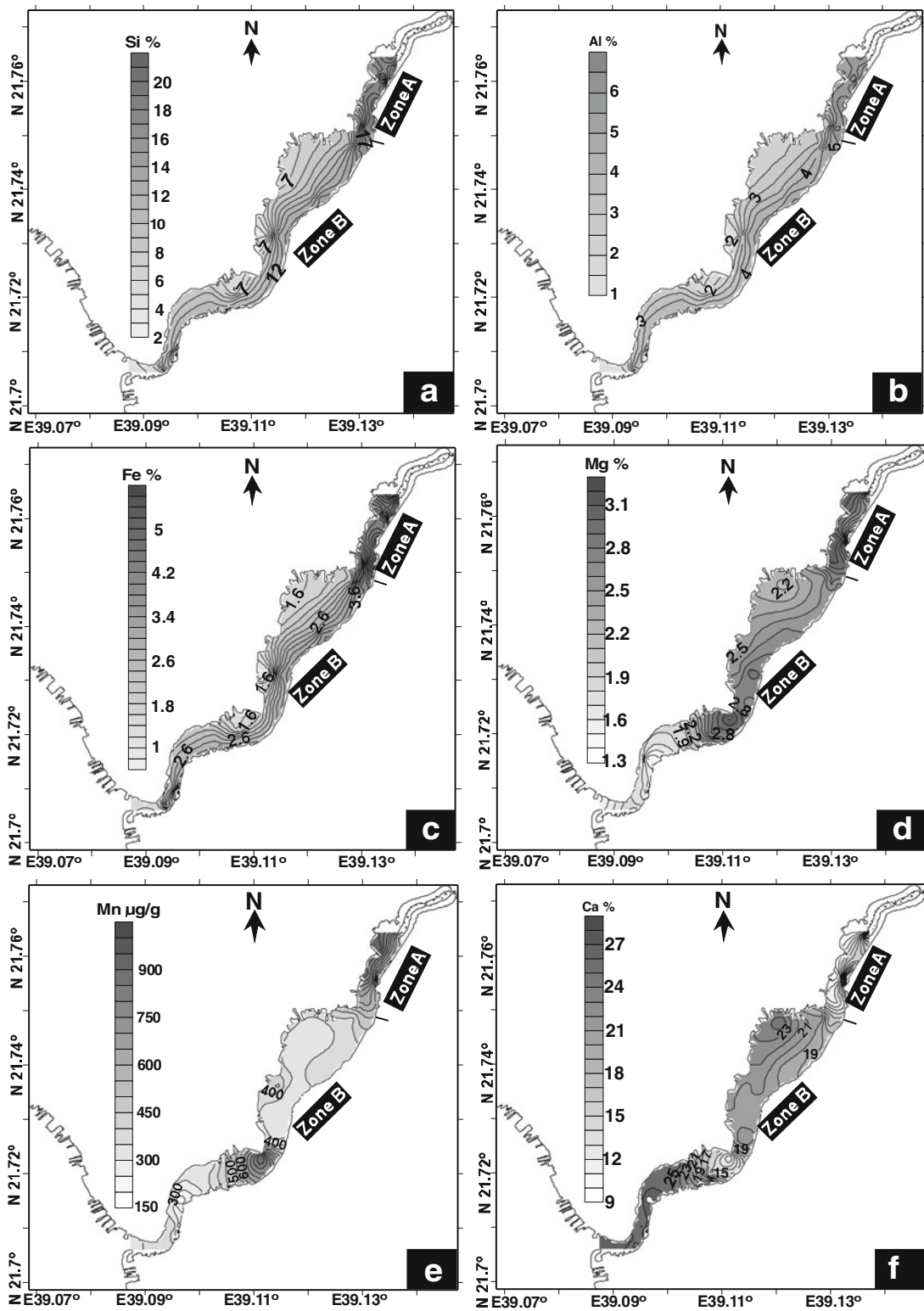


Fig. 2 Distribution of major elements Si (percent) (a), Al (percent) (b), Fe (percent) (c), Mg (percent) (d), Mn (micrograms per gram) (e), and Ca (percent) (f) in surficial sediments of Sharm Obhur

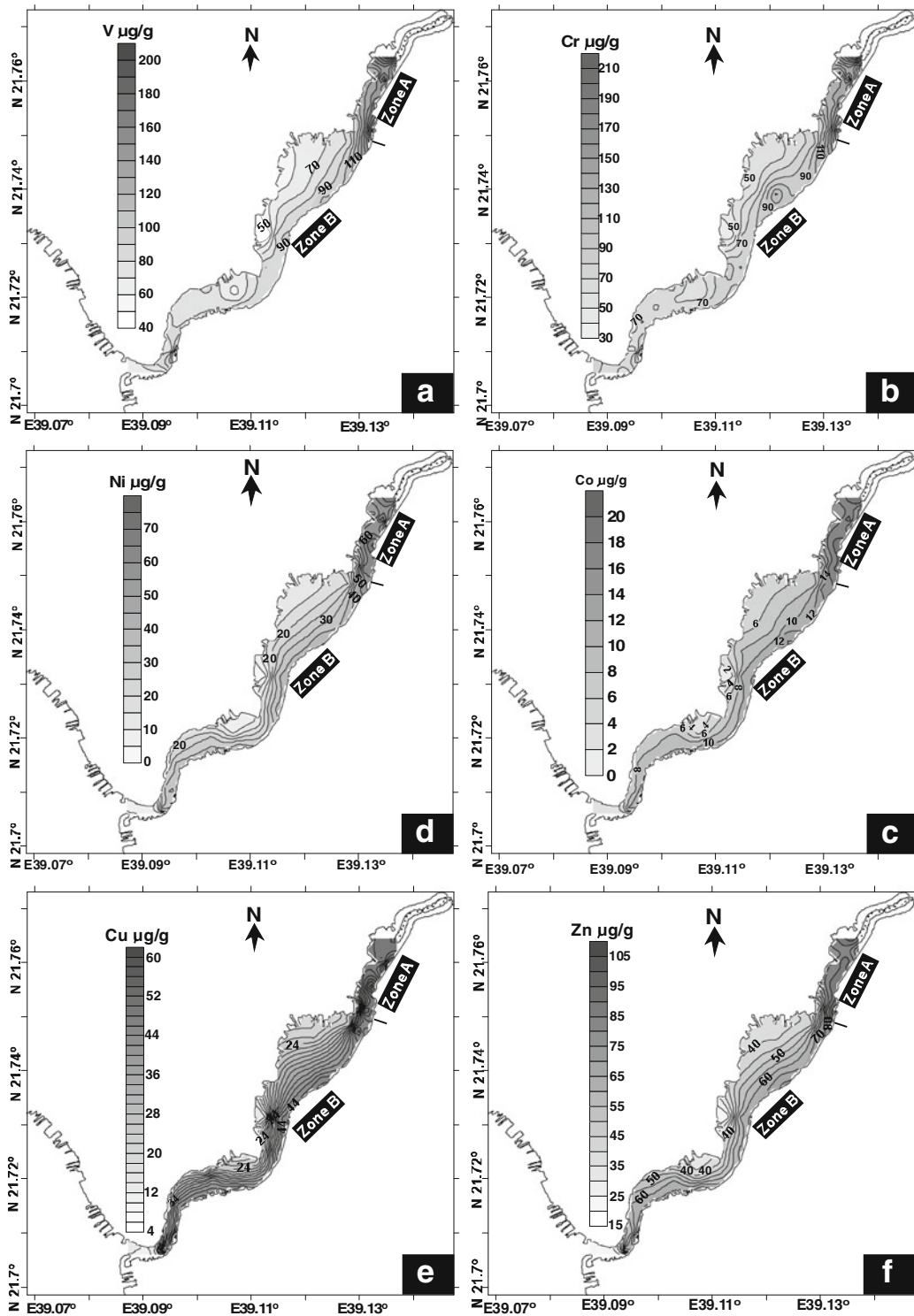


Fig. 3 Distribution of trace elements V (a), Cr (b), Co (c), Ni (d), Cu (e), Zn (f), Pb (g), and Sr (h) (micrograms per gram) in surficial sediments of Sharm Obhur

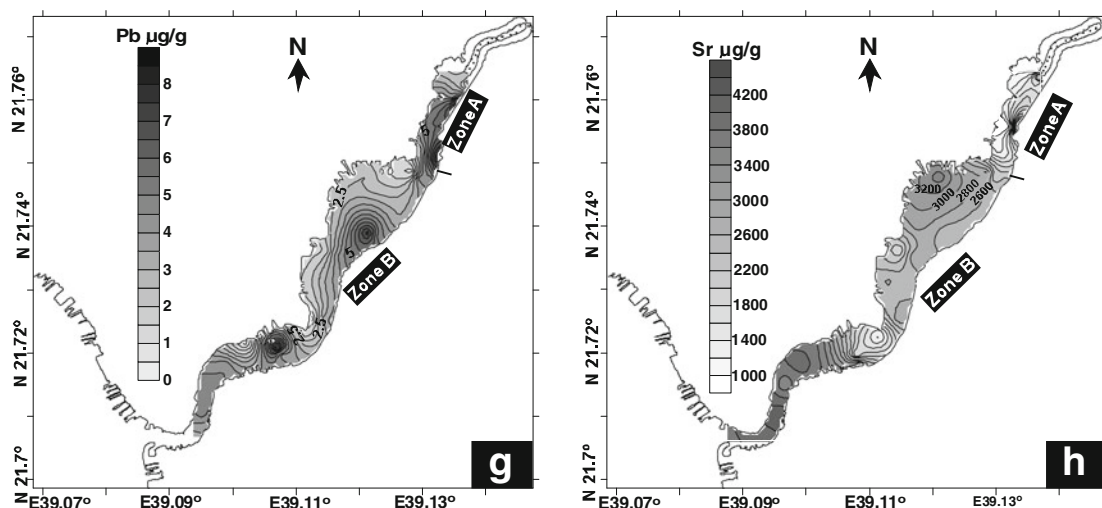


Fig. 3 (continued)

(Fig. 3a–h). In sediments of zone A, the minimum and maximum concentrations of trace elements were 106.6–200.9 $\mu\text{g/g}$ (V), 84–203.6 $\mu\text{g/g}$ (Cr), 9.8–20.4 $\mu\text{g/g}$ (Co), 26.3–57.6 $\mu\text{g/g}$ (Cu), 34–73.3 $\mu\text{g/g}$ (Ni), 54.8–100.8 $\mu\text{g/g}$ (Zn), 878.7–3,120 $\mu\text{g/g}$ (Sr), and 0.5–8.5 $\mu\text{g/g}$ (Pb). The sediments of zone B yielded relatively lower average concentrations for trace elements except for Sr. The average concentrations of V, Cr, Co, Ni, Cu, Zn, and Pb were 78, 70, 7.7, 23, 32, 51, and 3.4 $\mu\text{g/g}$. The average concentration of Sr was 3,051 $\mu\text{g/g}$.

Elemental interrelationships

The geochemical data in the present study were not normally distributed. The Spearman rank correlation (Rollinson 1993) was found to be more appropriate than a simple linear correlation (Preda and Cox 2005). Elemental interrelationships allowed differentiating two groups of elements of probably different origin and behavior (Table 2). The elements within the same group are positively correlated and negatively correlated with the elements of the other group. The elements of the first group include Si, Al, Fe, Mn, Mg, V, Cr, Co, Ni, Cu, and Zn, whereas the elements of the second group include CaCO_3 , Ca, and Sr. Lead (Pb) displayed insignificant positive correlation to the elements of the first group and correlates negatively with the elements of the second group. However, in sediments of zone B, Pb showed positive correlation (Spearman rank coefficient $r_s > 0.6$) with Cu and Zn.

Generally, in the surficial sediments of Sharm Obhur, CaCO_3 displayed strong positive correlation with Ca and Sr ($r_s > 0.85$). In the sediments of zone A, Si and Fe displayed strong positive correlation ($r_s > 0.8$) with Al, Mg, Mn, V, Cr, Co, Ni, and Zn and a strong positive correlation ($r_s > 0.8$) was observed between Al and Mg, Co, Ni, and Cu. On the other hand, Si, Al, and Fe correlated strongly ($r_s > 0.75$) with Mn, Mg, Co, Ni, Cu, and Zn in the sediments of zone B (Table 2). Cr significantly correlated with Mn and V ($r_s > 0.8$).

Environmental assessment

A typical task in environmental assessment is to distinguish the natural and anthropogenic sources of heavy metal enrichment. Environmental indices such as enrichment factor (EF; Hernandez et al. 2003), contamination factor (CF; Savvides et al. 1995; Pekey et al. 2004), and pollution load index (PLI; Tomlinson et al. 1980) are often employed. These indices were used successfully in the evaluation of heavy metal pollution in NE Greece (Nikolaidis et al. 2010). The central notion of these methods is to produce a numerical value either by metal normalization using a conservative element or by comparing the concentration levels of the metal in the sediments and in a suitable background. Evaluation of the source of metals and the degree of metal contamination depends on the choice of the normalizer and the appropriate background. Elements such as Al and Fe

Table 2 Correlation matrix for the geochemical data from Sharm Obhur

	Si	Al	Fe	Mn	Mg	Ca	CaCO ₃	V	Cr	Co	Ni	Cu	Zn	Sr	Pb
Si	1.00														
Al	0.92 ^b	1.00													
Fe	0.95 ^b	0.82 ^b	1.00												
Mn	0.88 ^b	0.67 ^b	0.93 ^b	1.00											
Mg	0.85 ^b	0.88 ^b	0.86 ^b	0.69 ^b	1.00										
Ca	-0.97 ^b	-0.97 ^b	-0.92 ^b	-0.79 ^b	-0.92 ^b	1.00									
CaCO ₃	-0.99 ^b	-0.93 ^b	-0.95 ^b	-0.85 ^b	-0.88 ^b	0.98 ^b	1.00								
V	0.91 ^b	0.72 ^b	0.96 ^b	0.97 ^b	0.78 ^b	-0.84 ^b	-0.89 ^b	1.00							
Cr	0.87 ^b	0.69 ^b	0.93 ^b	0.97 ^b	0.72 ^b	-0.80 ^b	-0.86 ^b	0.97 ^b	1.00						
Co	0.93 ^b	0.93 ^b	0.90 ^b	0.80 ^b	0.92 ^b	-0.96 ^b	-0.94 ^b	0.86 ^b	0.83 ^b	1.00					
Ni	0.96 ^b	0.96 ^b	0.89 ^b	0.80 ^b	0.91 ^b	-0.98 ^b	-0.97 ^b	0.83 ^b	0.80 ^b	0.96 ^b	1.00				
Cu	0.63 ^a	0.87 ^b	0.51	0.26	0.74 ^b	-0.75 ^b	-0.67 ^b	0.35	0.30	0.70 ^b	0.72 ^b	1.00			
Zn	0.90 ^b	0.76 ^b	0.93 ^b	0.86 ^b	0.76 ^b	-0.85 ^b	-0.87 ^b	0.88 ^b	0.83 ^b	0.84 ^b	0.82 ^b	0.44	1.00		
Sr	-0.87 ^b	-0.87 ^b	-0.82 ^b	-0.70 ^b	-0.83 ^b	0.90 ^b	0.88 ^b	-0.74 ^b	-0.67 ^b	-0.89 ^b	-0.90 ^b	-0.71 ^b	-0.72 ^b	1.00	
Pb	0.13	0.17	0.10	0.04	0.04	-0.13	-0.08	0.07	0.03	0.04	0.02	0.18	0.31	0.19	1.00
Si	1														
Al	0.98 ^b	1.00													
Fe	0.96 ^b	0.98 ^b	1.00												
Mn	0.80 ^b	0.72 ^b	0.76 ^b	1.00											
Mg	0.77 ^b	0.84 ^b	0.82 ^b	0.42 ^a	1.00										
Ca	-0.97 ^b	-0.99 ^b	-0.98 ^b	-0.70 ^b	-0.83 ^b	1.00									
CaCO ₃	-0.96 ^b	-0.98 ^b	-0.96 ^b	-0.72 ^b	-0.86 ^b	0.97 ^b	1.00								
V	0.73 ^b	0.65 ^b	0.73 ^b	0.91 ^b	0.41 ^a	-0.68 ^b	-0.66 ^b	1.00							
Cr	0.6 ^b	0.50 ^b	0.58 ^b	0.82 ^b	0.17	-0.54 ^b	-0.48 ^a	0.86 ^b	1.00						
Co	0.96 ^b	0.97 ^b	0.98 ^b	0.75 ^b	0.83 ^b	-0.97 ^b	-0.96 ^b	0.71 ^b	0.57 ^b	1.00					
Ni	0.91 ^b	0.93 ^b	0.93 ^b	0.67 ^b	0.90 ^b	-0.91 ^b	-0.95 ^b	0.58 ^b	0.40 ^a	0.93 ^b	1.00				
Cu	0.89 ^b	0.94 ^b	0.94 ^b	0.61 ^b	0.83 ^b	-0.93 ^b	-0.91 ^b	0.58 ^b	0.42 ^a	0.92 ^b	0.90 ^b	1.00			
Zn	0.85 ^b	0.89 ^b	0.93 ^b	0.70 ^b	0.79 ^b	-0.89 ^b	-0.87 ^b	0.68 ^b	0.56 ^b	0.90 ^b	0.87 ^b	0.93 ^b	1.00		
Sr	-0.84 ^b	-0.88 ^b	-0.89 ^b	-0.54 ^b	-0.82 ^b	0.89 ^b	0.86 ^b	-0.48 ^a	-0.34	-0.88 ^b	-0.85 ^b	-0.87 ^b	-0.83 ^b	1.00	
Pb	0.44 ^a	0.50 ^b	0.52 ^b	0.24	0.47 ^a	-0.51 ^b	-0.48 ^a	0.17	0.14	0.42 ^a	0.54 ^b	0.64 ^b	0.61 ^b	-0.40 ^a	1.00

^aCorrelation is significant at the 0.05 level

^bCorrelation is significant at the 0.01 level

and a combination of Al + Fe were tested to select the adequate normalizer. Iron was found to be the most appropriate normalizer. Iron exhibits significant correlation with most metals suggesting that Fe was the main geochemical carrier. Iron was successfully used as a normalizer for mineralogical composition in areas that are affected by contribution from mafic and ultramafic rocks as the Albanian coast (Prohic and Yuracic 1989), the Gulf of Iskenderun in Turkey (Ergin et al. 1996), and coastal sediments and soils near the Brazilian

Antarctic Station, King George Island (Santos et al. 2005). The predominance of a physical rather than a chemical weathering in such hot and arid regions does not favor the formation of clay minerals and hence decreases the importance of Al as a geochemical carrier for heavy metals.

To define the appropriate background, three reference materials such as average chemical composition of upper continental crust (UCC; Taylor and McLennan 1985), average shale (Turekian and

Wedepohl 1961), and the average chemical composition of a local reference material (deepest sediments; Abraham and Parker 2008) were tested (see Table 1). The mean X/Fe (where X refers to major element) ratios in the sediments of zones A and B are close to the ratio of the sediments of local reference material and differ significantly to UCC and average shale (Table 1). The mean Si/Fe ratios for the sediments of zones A and B (3.9 and 4, respectively) are close to the ratio of the internal reference material (3.95) and differ significantly for UCC (9.8) and average shale (5.8). Similarly, the Al/Fe ratio of 1.3 in the sediments of zones A and B is close to the Al/Fe ratio in internal reference material (1.4) and differ markedly from the Al/Fe ratio in UCC (2.55) and average shale (1.86). The mean Ca/Fe ratios for the sediments of zones A and B (3.6 and 11.1, respectively) are different but relatively closer to the Ca/Fe ratio for local reference material (8.27) and differ markedly from those in the UCC (0.95) and average shale (0.33). This suggests that the average chemical composition of deepest sediments is the appropriate background.

EF

The calculation of EF is a convenient method to determine the source of metals and the possible anthropogenic contribution. The enrichment factor for a metal in a sediment sample is calculated according to the equation:

$$EF_x = (X/Fe)_{\text{sediments}} / (X/Fe)_{\text{background}}$$

X refers to the concentration of the metal in the sediments and in the background. The average chemical composition of the local reference material (deepest sediments) was used as a geochemical background.

The enrichment factor values ≤ 1.5 indicate that the metal is impoverished relative to the background, whereas EF values > 1.5 indicate that the metal is enriched relative to the background, and a significant portion of the metal is provided by other, possibly anthropogenic sources (Nolting et al. 1999; Tuncel et al. 2007; Nikolaidis et al. 2010). The calculated EF values for Mn, V, Cr, Co, Ni, Cu, Zn, and Pb in the Sharm Obhur surficial sediments are given in Table 3 and their profiles are shown in Fig. 4.

Enrichment factors showed lower mean values for all metals ($EF < 1.5$). However, some sampling sites

displayed enrichment ($EF > 1.5$) for Mn, V, Cr, and Pb. The sediments of zone A were totally impoverished for metals except for Pb which showed a slight enrichment ($EF = 1.65$) in sample A6 (Table 3). In sediments of zone B, samples B6, B15, and B21 were enriched in Pb (EF values are 1.97, 4.36, and 1.15, respectively). V was slightly enriched in samples B11, B26, and B27 (EF values are 1.54, 1.52, and 1.53, respectively). Enrichment factor values of 1.76, 1.51, 1.6, and 2.03 were recorded for Cr in samples B6, B21, B26, and B27, respectively (Table 3). Sample B27 exhibited slight enrichment of Mn (EF value = 1.57).

The EF values for Co, Ni, Cu, and Zn were often less than 1.5 suggesting a natural (lithogenic) source of these metals in Sharm Obhur sediments. The major parts of Mn, V, and Cr Pb are of lithogenic origin. However, some sites with EF values > 1.5 indicate a possible anthropogenic contribution. Considering that all metal concentrations in the sediments (except for Mn, V, Cr, and Pb) are within or lower than the ranges in the background, it was difficult to assume a severe contamination problem in Sharm Obhur sediments. Metals which displayed profiles similar to Si (a measure for detrital influx) and EF values < 1.5 are commonly of lithogenic source. On the other hand, metals which had profiles different from Si and displayed EF values > 1.5 were considered to be of anthropogenic origin. The sampling sites that are enriched in Pb locate in the vicinity of the boat fuel station; oil leakage may stand behind the enrichment of the sediments with Pb. The steel scrapes that might contain alloying elements such as Cr, V, and Mn are probably source for enrichment of these metals near the mouth of the sharm.

CF

CF (Håkanson 1980; Pekey et al. 2004; Esen et al. 2010) is calculated to quantify the degree of metal contamination. Contamination factor represents the ratio between metal concentration (X) in the sediment and the background.

$$CF = (X)_{\text{sediments}} / (X)_{\text{background}}$$

The values of CF are classified as $CF < 1$ low contamination; $1 \leq CF < 3$ moderate contamination; $3 \leq CF < 6$ considerable contamination; and $CF \geq 6$ very high contamination.

The values of contamination factor are shown in Table 3 and their profiles are shown in Fig. 4. Sharm

Table 3 Values of enrichment and contamination factors and the pollution load index in Sharm Obhur sediments (EF values > 1.5 are shown in bold)

Sample no.	Mn		V		Cr		Co		Ni		Cu		Zn		Pb		PLI
	EF	CF	EF	CF	EF	CF	EF	CF	EF	CF	EF	CF	EF	CF	EF	CF	
A1	1.16	1.54	1.10	1.50	1.01	1.34	1.02	1.35	1.12	1.48	0.99	1.31	0.88	1.16	0.10	0.14	1.03
A2	1.09	1.98	1.1	2.00	1.20	2.19	1.16	2.12	1.21	2.21	0.73	1.34	0.79	1.44	0.42	0.77	1.67
A3	1.18	2.60	1.21	2.70	1.45	3.23	1.04	2.31	1.08	2.40	0.60	1.32	0.74	1.65	0.19	0.43	1.82
A4	1.07	1.50	1.09	1.60	1.14	1.63	1.08	1.54	1.14	1.63	0.90	1.28	0.94	1.34	0.76	1.09	1.44
A5	1.15	2.40	1.13	2.40	1.30	2.73	1.07	2.25	1.19	2.49	0.65	1.37	0.74	1.56	0.48	1.00	1.92
A6	1.20	1.50	1.20	1.50	1.22	1.57	1.07	1.38	0.91	1.16	0.64	0.82	1.11	1.42	1.65	2.12	1.40
A7	1.06	2.20	1.10	2.30	1.26	2.60	1.13	2.33	1.21	2.50	0.70	1.45	0.74	1.52	0.72	1.48	1.99
A8	0.95	1.76	1.00	1.80	1.11	2.04	1.14	2.10	1.26	2.33	0.84	1.54	0.83	1.52	0.83	1.53	1.81
A9	1.02	1.76	1.02	1.80	1.18	2.05	1.09	1.88	1.19	2.06	0.80	1.38	0.83	1.43	0.88	1.52	1.71
A10	1.38	1.54	1.29	1.40	1.45	1.61	1.01	1.13	1.07	1.19	0.63	0.70	0.85	0.95	0.88	0.98	1.15
A11	0.99	1.76	1.00	1.80	1.09	1.93	1.17	2.07	1.26	2.23	0.82	1.44	0.83	1.46	0.90	1.60	1.76
A12	1.25	2.60	1.27	2.70	1.45	3.05	0.98	2.07	0.99	2.08	0.58	1.22	0.82	1.74	1.11	2.34	2.15
A13	1.22	1.98	1.17	1.88	1.33	2.15	1.05	1.70	1.12	1.81	0.69	1.11	0.8	1.29	0.69	1.11	1.58
A14	0.98	1.54	1.01	1.60	1.16	1.82	1.11	1.74	0.99	1.55	0.86	1.36	0.82	1.29	0.80	1.25	1.50
B1	1.32	1.10	1.35	1.12	1.47	1.22	0.97	0.81	0.83	0.69	0.82	0.68	0.89	0.74	0.26	0.21	0.74
B2	1.34	0.88	1.33	0.87	1.41	0.92	0.90	0.59	0.65	0.43	0.84	0.55	1.02	0.67	1.07	0.70	0.68
B3	1.31	0.88	1.34	0.90	1.34	0.90	1.13	0.76	0.80	0.54	0.89	0.60	1.01	0.68	0.92	0.62	0.72
B4	1.05	1.32	1.00	1.26	1.09	1.37	1.03	1.30	0.93	1.17	0.87	1.10	0.88	1.10	0.66	0.83	1.17
B5	0.95	1.32	0.97	1.34	1.03	1.43	1.12	1.56	0.93	1.29	0.86	1.20	0.85	1.19	0.96	1.34	1.33
B6	1.06	1.10	0.98	1.02	1.76	1.83	0.95	0.98	1.01	1.05	1.03	1.07	1.04	1.07	1.97	2.04	1.22
B7	1.13	0.88	1.06	0.82	1.07	0.83	0.88	0.68	0.82	0.64	1.12	0.87	1.04	0.81	1.15	0.89	0.80
B8	1.02	0.88	1.06	0.91	1.10	0.95	1.00	0.86	0.88	0.76	0.93	0.81	0.97	0.84	0.50	0.43	0.79
B9	0.98	1.10	0.94	1.06	1.04	1.17	0.93	1.04	0.93	1.04	0.90	1.00	0.88	0.98	0.99	1.10	1.06
B10	0.94	1.10	1.01	1.17	0.98	1.14	1.04	1.21	0.97	1.13	0.95	1.11	0.88	1.03	0.74	0.87	1.09
B11	1.28	0.44	1.54	0.53	1.44	0.49	0.47	0.16	0.41	0.14	1.06	0.36	1.13	0.38	0.00	0.00	0.32
B12	1.27	1.10	1.42	1.22	1.62	1.40	0.94	0.81	0.74	0.64	0.77	0.66	0.90	0.78	0.07	0.06	0.65
B13	0.99	1.10	0.99	1.10	0.98	1.08	1.05	1.16	1.04	1.15	0.97	1.07	0.91	1.01	0.84	0.93	1.07
B14	1.47	1.10	1.46	1.09	1.67	1.24	1.06	0.79	0.49	0.37	0.83	0.62	0.93	0.69	0.47	0.35	0.71
B15	1.24	0.66	1.40	0.75	1.49	0.79	0.55	0.29	0.50	0.26	1.37	0.73	1.17	0.62	4.36	2.32	0.65
B16	0.96	0.88	0.96	0.88	1.02	0.93	0.96	0.87	0.87	0.80	0.99	0.90	0.93	0.85	1.11	1.01	0.89
B17	1.17	1.32	1.04	1.17	1.13	1.27	1.10	1.24	0.99	1.12	0.99	1.11	1.04	1.18	1.03	1.16	1.19
B18	0.92	0.88	1.04	0.99	0.97	0.93	1.02	0.97	0.98	0.94	1.06	1.01	1.08	1.03	0.66	0.63	0.91
B19	1.36	1.10	1.41	1.14	1.45	1.17	0.99	0.80	0.62	0.50	0.70	0.57	0.98	0.79	0.03	0.02	0.53
B20	0.92	0.88	1.0	0.96	0.97	0.93	0.93	0.89	0.90	0.86	1.07	1.02	1.01	0.97	1.27	1.22	0.96
B21	1.23	1.10	1.36	1.21	1.51	1.35	0.76	0.68	0.65	0.58	0.85	0.76	1.16	1.03	1.51	1.35	0.96
B22	0.88	0.88	1.00	0.99	0.93	0.93	0.97	0.97	1.03	1.03	1.09	1.09	1.06	1.05	1.27	1.27	1.02
B23	1.12	1.10	0.99	0.96	0.93	0.91	0.97	0.95	1.30	1.27	1.00	0.97	0.99	0.97	1.33	1.30	1.04
B24	0.94	1.54	1.18	1.93	1.11	1.82	0.91	1.48	0.68	1.10	0.80	1.30	0.86	1.40	0.67	1.09	1.43
B25	1.01	1.10	0.99	1.07	0.90	0.98	1.11	1.20	1.09	1.19	0.99	1.08	1.04	1.13	0.81	0.88	1.07
B26	1.57	0.88	1.52	0.85	1.60	0.90	0.56	0.31	0.40	0.22	0.77	0.43	0.74	0.41	0.00	0.00	0.50
B27	1.45	0.88	1.53	0.93	2.03	1.23	0.72	0.44	0.41	0.25	0.61	0.37	0.69	0.42	0.00	0.00	0.56

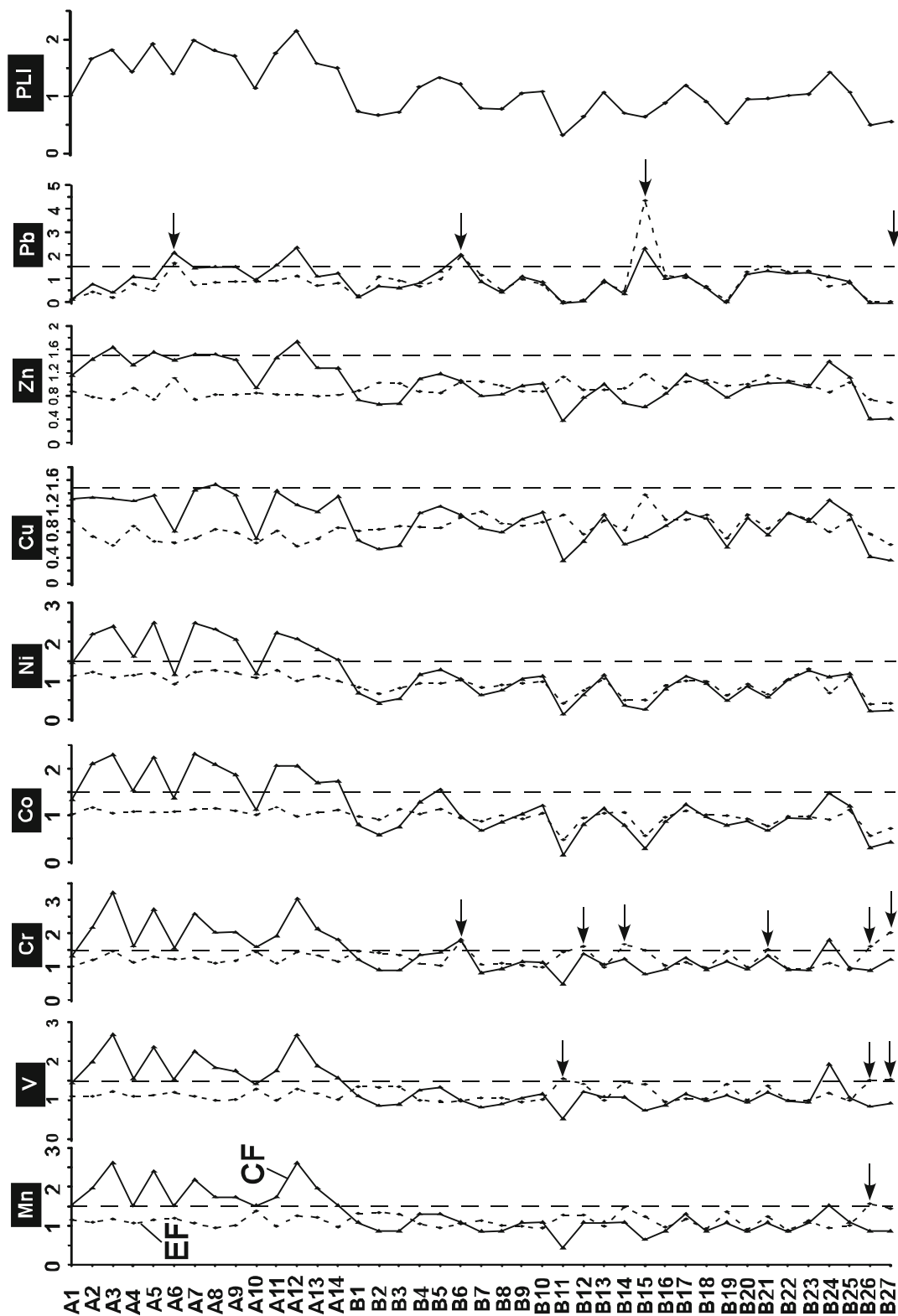


Fig. 4 Profiles of EF, CF, and PLI that were calculated for heavy metals in sediments of Sharm Obhur. *Black arrows* refer to the highest EF values (>1.5). Note the highest EF values for Pb correspond to the highest CF values

Obhur surficial sediments are classified as low to moderately contaminated; however, a single sampling site (A3) displays a considerable contamination with Cr (CF=3.23). The sediments of zone A are moderately contaminated with Mn, V, Cr, Co, and Ni ($1 \leq CF < 3$). About 86 and 64 % of the samples are moderately contaminated with Zn and Pb, respectively. The contamination factor values for the sediments of zone B are mostly less than unity indicating a low degree of contamination. About 45 % of the sampling sites in zone B fall in the class of low contamination ($CF < 1$) for Mn, V, and Cr, whereas 40 to 45 % of the samples are moderately contaminated with Ni, Cu, Zn, and Pb ($1 \leq CF < 3$). About 30 % of the sediments of zone B are moderately contaminated with Co ($1 \leq CF < 3$). Even not common for all metals, CF and EF for Pb are correlated, i.e., the highest EF and CF for Pb were obtained from the same samples (Fig. 4). This indicates that the source of Pb is probably anthropogenic.

PLI

PLI is calculated to assess the sediment quality (Tomlinson et al. 1980) according to the following equation:

$$PLI = (CF_1 \times CF_2 \times CF_3 \dots \times CF_n)^{(1/n)}$$

A PLI value of 0 indicates the absence of pollutants and PLI of 1 suggests the presence of pollutants, and when PLI is > 1 , it indicates the progressive deterioration of sediment quality (Tomlinson et al. 1980). The PLI values in the sharm sediments vary generally from 0.32 to 2.15 with an average of 1.13 (Table 3). The PLI values of zone A sediments are higher than their counterparts in zone B sediments (Fig. 4). They range in sediments of zone A from 1.02 to 2.15 with an average of 1.64, whereas in sediments of zone B, the PLI values range between 0.32 and 1.42 with an average of 0.89. About 56 % of the samples of zone B have PLI < 1 suggesting the absence of pollutants.

Discussion

Geochemical and mineralogical analyses of Sharm Obhur surficial sediments provide an excellent way to identify the source(s) of sediments and to quantify the impact of human activities. It is important to take into account the dominant climatic conditions and the

depositional setting of Sharm Obhur. Being located in an arid tropical zone, Sharm Obhur receives no direct riverine inputs, physical weathering in the surrounding land mass is more active than chemical weathering, and aeolian transportation is significant in such vegetationless areas. It is therefore expected that (1) the composition of surficial sediments is dominated by autochthonous calcareous sediments of biogenic origin and (2) the concentration levels of elements of lithogenic origin (e.g., Si, Al, and Fe) are low relative to their counterparts in siliciclastic coastal settings which commonly occur in humid regions. The sediments near the head (zone A) are relatively enriched in elements of lithogenic origin relative to those near the mouth (zone B).

Source of sediments

The mixed carbonate–siliciclastic composition of Sharm Obhur sediments reflects the spatial variation in the carbonate production and accumulation rates and the dilution effect by non-carbonate detrital influxes. Carbonate sediments are likely to be of biogenic origin, whereas non-carbonate ones were supplied partly by natural processes and partly by human activities. The significant positive correlation between $CaCO_3$, Ca, and Sr indicates that the large part of these elements is associated with calcareous skeletal remains. The high average contents of carbonate minerals (~52 %), $CaCO_3$ (~78 %), Ca (~22.35 %), and Sr (3050 $\mu g/g$) in the sediments of zone B particularly south of latitude N 21°45'6.2" indicate relatively high carbonate production and accumulation rates and low dilution effect. Aragonite, the most abundant carbonate mineral (average 19 %) in the sediments of zone B, is the major constituent in the skeleton of calcareous shelled organisms such as green algae, corals, and mollusks (Flügel 2004). The growth of corals in the area is enhanced by the scarcity of detrital input. On the other hand, the relatively low average contents of carbonate mineral (36 %), $CaCO_3$ (31 %), Ca (147 %), and Sr (1,550 $\mu g/g$) in the sediments of zone A are attributed to the significant dilution effect by non-carbonate detrital sediments. The area probably was or became inhospitable for coral growth as many dead corals were recorded (Basaham et al. 2006). Instead, the calcareous fraction contains foraminiferal and pelecypod shells; calcite (average; 14 %) is a major constituent of these shells (Flügel 2004).

The non-carbonate detrital sediments are supplied to the sharm by two processes: natural and anthropogenic. The natural processes include non-point aeolian supply and a point source through the occasionally active Wadi Al-Kuraa'a. The coastal plain of Jeddah is surrounded to the east by a series of Precambrian igneous and metamorphic rocks and Cenozoic volcanics. The weathered products of these rocks are transported to the sharm by the active wind transportation. Aeolian dusts deliver about $0.61 \text{ g/m}^2/\text{day}$ to the coastal area north of Jeddah, and the average concentrations of heavy metals in the dust are significantly high (Behairy et al. 1985). Although often inactive, Wadi Al-Kuraa'a supplies huge amounts of lithogenic sediments to the sharm during the rare but major catastrophic floods. The dilution effect is significant in the nearshore sediments at the mouth of Wadi Al-Kuraa'a. These sediments contain relatively low CaCO_3 , Ca, and Sr contents (19 %, 11 %, and $1092 \text{ }\mu\text{g/g}$, respectively) and relatively high contents of elements of lithogenic origin (e.g., Si and Al). Dumping, landfills, and shore protection by basalt blocks particularly near the eastern end are another source of non-carbonate sediments. The chemical composition of surficial sediments in zone A particularly the samples that are located adjacent to the eastern shoreline bears some similarity with the average chemical composition of basalt. The Si/Fe ratios in samples A6 and A12 are 3.6 and 3.5, respectively. The Al/Fe ratio in the two samples is 1.1. These ratios are close to the Si/Fe (3.11) and Al/Fe (1.07) ratios in flood basalt (Kieffer et al. 2004). Other samples that are located adjacent to the eastern shoreline yield slightly higher Si/Fe and Al/Fe ratios. The shoreline near these sampling sites is armored by concrete, not by basalt blocks.

Source of metal enrichment

Metals such as Mn, V, Cr, Co, Cu, Ni, Zn, and Pb are of major environmental concern. These metals in Sharm Obhur surficial sediments are classified here according to their source into lithogenic and non-lithogenic. Lithogenic metals refer to all metals that were formed by disintegration of a parent rock. They were then transported to the sharm either naturally by wind and inputs of Wadi Al-Kuraa'a or through anthropogenic activities. Lithogenic metals are supplied to the sharm by various human activities such as dumping/landfills and shore protection by basaltic

blocks. Non-lithogenic metals on the other hand include all artificial materials that were transported to the sharm mainly by human activities. These activities include waste disposal, contaminants left behind ship repair and painting, and fossil fuel combustion.

In sediments of zone A, Mn, V, Cr, Co, Ni, and Zn are of lithogenic origin. They display significant positive correlations ($r_s > 0.85$) with Si and Fe. Si is not involved in anthropogenic processes and is often used as a measure for terrigenous influx. The strong correlation with Fe indicates adsorption of metals on Fe oxyhydroxides which is a common phenomenon in marine sediments (Calvert, 1976). These metals are enriched relative to the background ($\text{CF} > 1$) however, the enrichment factor values are low ($\text{EF} < 1.5$). Pb is an exception as it is poorly correlated with Si and Fe suggesting a possible different source. It is recorded generally with low concentration levels ($< 10 \text{ }\mu\text{g/g}$) and EF values (< 1.5). A single sampling site (A6) yielded an EF value of 1.65 for Pb and this site is located in the vicinity of boat station. Fossil fuel combustion and painting activities are the possible sources for Pb at this site. Pb concentrations in clean coastal sediment are around $25 \text{ }\mu\text{g/g}$ or less (Bryan and Langston 1992) and the average Pb concentration in the studied sediments of zones A and B is less than $10 \text{ }\mu\text{g/g}$.

Metals in the sediments of zone B are mostly of lithogenic origin. However, non-lithogenic Mn, V, Cr, and Pb were identified from some sampling sites (see table). Though the relationships of these metals with Si and Fe are significant, they are lower compared to those in sediments of zone A. This suggests a possible contribution from non-lithogenic source particularly for Cr ($r_s \sim 0.58$). The source of Mn, V, and Cr is probably the steel pipes and litters left after the ship maintenance. The steel contains some alloying elements such as Cr, Mn, and V which are added as anticorrosive material to improve the quality of steel (Chen and Kandasamy 2008).

Cr is a relatively immobile element that is transported exclusively in the terrigenous component of sediment and therefore reflects the chemistry of their source (Taylor and McLennan 1985). It is used along with Ni as useful indicators for mafic–ultramafic source identification. Inputs from mafic and ultramafic sources would result in an enrichment of Cr and Ni (Garver and Scott 1995; Zimmermann et al. 2003). To differentiate the lithogenic and non-lithogenic Cr, the Cr/Ni ratios were

determined. This ratio has been proposed to identify the contribution from mafic–ultramafic source of these elements (Mason and Moore 1982; Amorosi et al. 2002; Amorosi and Sammartino 2007). When concentration levels are higher than 150 and 100 $\mu\text{g/g}$ for Cr and Ni, respectively, Cr/Ni ratios between 1.3 and 1.5 are diagnostic of ultramafic source rocks. On the other hand, Cr/Ni ratios around 2 or higher typify an input from mafic volcanic source (Garver and Scott 1995; Garver et al. 1996). The ratio was applied successfully in ancient pre-industrial deposits because anthropogenic contribution was absent. For recent sediments, this ratio must be used with utmost care because anthropogenic contribution of Cr or Ni may disturb this relationship. Significant proportions of Cr and Ni are possibly supplied to sediments of Sharm Obhur particularly in zone A from a mafic volcanic source. The Cr/Ni ratio in sediments of zone A varies from 1.85 to 3.14 (average 2.4) and from 1.54 to 10.49 (average 3.92) in the sediments of zones B. Although the Cr/Ni ratios in the majority of zone B sediments and few samples in zone A are extremely high, it cannot be related only to the contribution from mafic volcanic source, i.e., a contribution from anthropogenic source is plausible (Fig. 5). The highest Cr/Ni ratios (8.7 and 10.5) were obtained from samples B25 and B27 near the mouth of the sharm. These samples lack clay minerals and have low concentration levels of Cr, Ni, and Si. This indicates that the major part of Cr and Ni at these locations is non-lithogenous.

Current environmental status of Sharm Obhur

The concentration levels of metals in the present study are compared with polluted and unpolluted Red Sea coastal sediments, UCC, average shale, and other biogenic calcareous sediments elsewhere (Table 4). Though the metal enrichment cannot be precisely evaluated because of the variation of analytical procedures and the size fraction of the analyzed sediments, this method provides a quick and practical method for tracing progressive heavy metal enrichment.

The concentration levels of Mn, V, Cr, Ni, Cu, Zn, and Pb in zone A sediments are higher than their counterparts in most recent studies in Sharm Obhur (Basaham et al. 2006; Pan et al. 2011). Metals Mn, V, Cr, Ni, Cu, and Zn are enriched by values of 3, 1.3, 1.3, 2.3, 1.95, and 2, respectively, relative to those measured by Basaham et al. (2006). The sediments

of zone B are depleted for V, Cr, and Ni and slightly enriched for Cu and Zn. Metals Cu, Zn, and Pb in sediments of zone A are highly enriched compared to their recently recorded concentrations near the Sharm Obhur outlet (Pan et al. 2011). They are slightly enriched in sediments of zone B comparing to their concentrations near the sharm's inlet.

The concentrations levels of most metals in the sediments of zone A are higher than their counterparts in sediments along Jeddah coasts even the polluted ones (El Sayed et al. 2002; El Sayed and Basaham 2004; Abu-Zied et al. 2013). On the other hand, metal concentrations in sediments of zone B are slightly enriched or nearly close to the concentration level (Table. 4) in Red Sea coastal sediments (Basaham 2008; Badr et al. 2009). The concentration levels of Mn, V, Cr, Co, Ni, Cu, and Zn in the sediments of zone A are close to or slightly higher than their concentrations in average shale (Turekian and Wedepohl 1961) and UCC (Taylor and McLennan 1985), respectively. On the other hand, the concentrations of Mn, Co, and Ni in zone B sediments are slightly lower than their counterparts in UCC and average shale. The concentrations of V, Cr, Ni, and Cu in sediments of zone B are higher than their concentrations in UCC and lower than their concentrations in average shale.

The concentration levels of Mn, Ni, Cu, and Zn in the present study are compared with coastal calcareous sediments of coralline origin in Tutuila, American Samoa (Morrison et al. 2010). This area has a humid climate and the coastal sediments receive varying quantities of basaltic materials. The Aasu sampling site (15-4) relatively receives high content of basaltic materials compared to other sites. The concentration levels of Mn, Cu, and Zn in the sediments of zones A and B are higher than their concentrations in the coastal sediments of Tutuila, American Samoa even the one that receives high quantities of basaltic materials. The concentration of Ni in sediments of zone A is close to the one that receives high basaltic materials and higher than other sites.

In summary, the chemical characterization of Sharm Obhur bottom sediments showed that Sharm Obhur has remained a relatively clean environment in general despite some sites displaying considerable pollution with Cr, Pb, V, and Mn subsequent to accelerated anthropogenic activities in the sharm. The data from the present study should be considered as a baseline for monitoring chemical contaminants in the sharm region, an urban-impacted area in Jeddah.

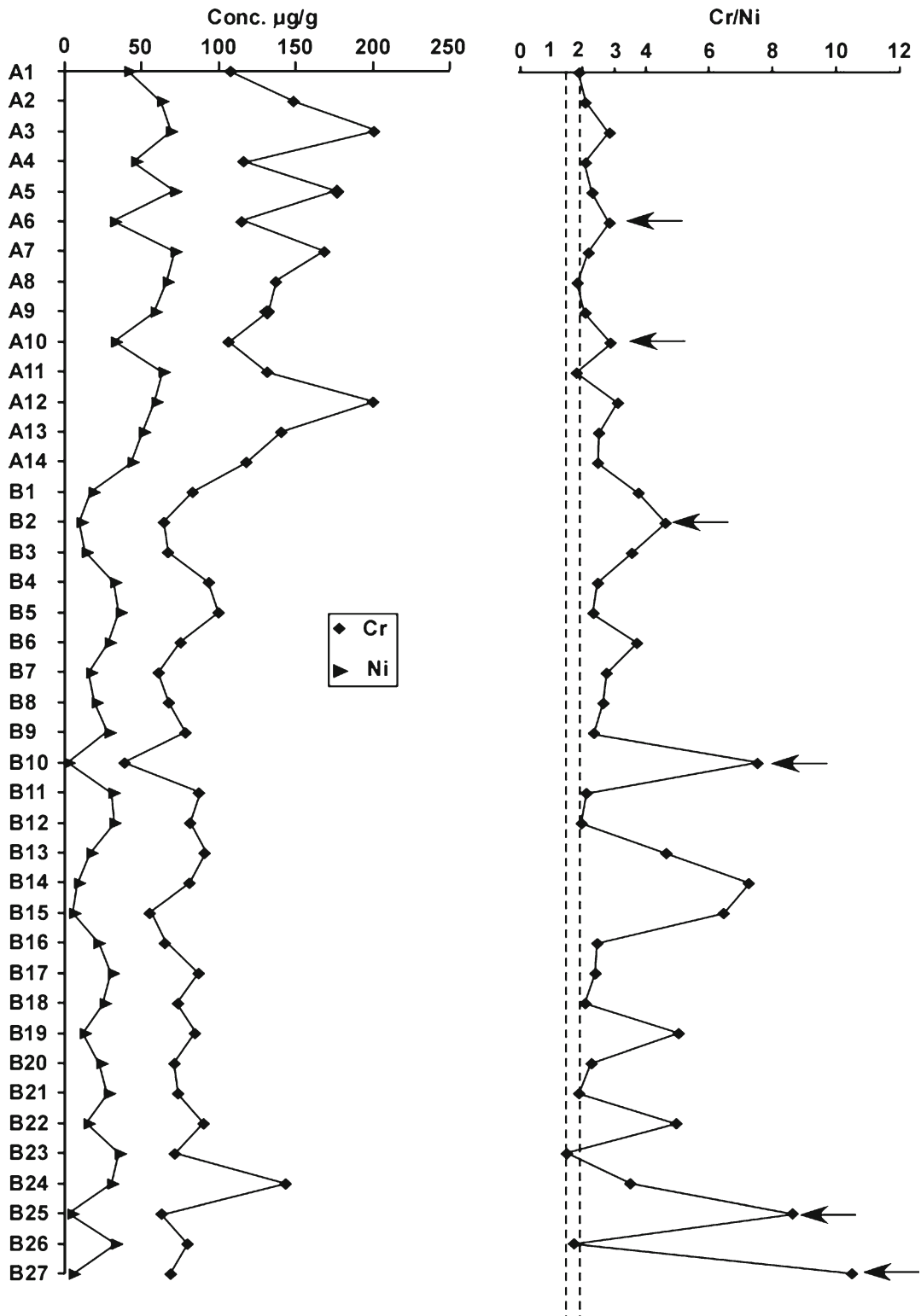


Fig. 5 Profile of Cr, Ni, and Cr/Ni ratio in the surficial sediments of Sharm Obhur. *Black arrows* refer to the sampling sites that yielded high Cr/Ni ratios and correspond to decreasing concentration values for Cr and Ni

Table 4 Mean concentrations and their ranges of metals in the sediments of Sharm Obhur compared with other areas along Red Sea, Gulf of Aqaba, upper continental crust, and average shale and other places

Ref.	Mn, µg/g	V, µg/g	Cr, µg/g	Co, µg/g	Ni, µg/g	Cu, µg/g	Zn, µg/g	Pb, µg/g
A	674 (542–929)	143 (105.6–220.9)	144 (84–203.6)	16 (9.9–20.4)	57 (34–73)	47 (26–57.6)	82 (54.8–100.7)	5 (0.5–8.5)
B	258 (154–542)	78 (39–143.6)	70 (31–115)	8 (1.4–13.7)	23 (4–38)	32 (13.6–48.6)	51 (22–81)	3 (0.08–8.38)
1	217	112	112		25	24	41	
2-1	139		60		48.7	58	118.9	
2-2	247		89.83		85.25	72.5	234.7	
3	50		12	4	26	7	41	
4	241					491	696	140
5-1	380	33	24		26	42	87	
5-2	560	71	51		35	31	56	
5-3	950	104	79		60	47	69	
6-1	169		33.8	23.4	7.4	9.6	26	3.8
6-2	148		31.52	20.15	4.25	7.57	21.47	3.78
6-3	181		29	7	16.6	56.8	340	3.6
6-4	136		35.43	18.43	34.3	377	423	201.3
6-5	31		24.4	18.6	3.8	7.2	16	3.4
7	8.7–39					1.3–25.1	5.3–30.6	
8	412	62	37	12	103	18	47	
9-1						0.69±0.09	10±0.6	0.93±0.15
9-2						18.48±0.45	45.5±1.5	5.79±0.18
10-1	34–205		13–23		68–85.5	17.5–24	52.7–76.4	80–99
10-2	56–251		13–26		79.7–80.5	17.4–25	41.4–63	82–93
10-3	181–413		22–91		79.2–90.8	18–25.8	55–94	75–84
11	53–655		15–186		19–76	7–27	31–260	83–225
12			1.12		0.43	0.03	0.42	4.07
13	610	60	35	10	20	25	71	20
14	850	130	90	19	50	45	95	20
15-1	82.2–136				16.2–22.3	2.31–26.8	6.7–25.1	
15-2	129–284				2.4–12.4	2.99–15.1	27.8–101	
15-3	208–267				27.4–31.6	5.25–9.23	24.1–34	
15-4	308–548				37.8–67.1	8.19–14.5	39.1–74.5	

Mean concentrations are shown in bold

A present study, zone A; B present study, zone B; 1 Basaham et al. (2006); 2 Abu-Zied et al. (2013); 2-1 Al-Arbaen Lagoon; 2-2 Al-Shabab lagoon; 3 Basaham (1998); 4 El-Sayed and Basaham (2004); 5 Basaham (2008); 5-1 carbonate rich; 5-2 mixed carbonate–siliciclastic; 5-3 siliciclastic; 6 El Sayed et al. (2002); 6-1 Northern Cornich; 6-2 Southern Cornich; 6-3 Al-Kaadah Al-Bahariyah; 6-4 Al-Arbaen Lagoon; 6-5 Al-Frusiyah; 7 Rifaat (1996); 8 Basaham (2008); 9 Pan et al. (2011); 9-1 Sharm Obhur outlet; 9-2 Sharm Obhur inlet; 10 Badr et al. (2009); 10-1 Jeddah; 10-2 Rabigh; 10-3 Yanbu; 11 Abu Hilal (1987); 12 Al-Najjar et al. (2011); 13 UCC (Taylor and McLennan 1985), 14 average shale (Turekian and Wedepohl 1961); 15 Morrison et al. (2010); 15-1 Masausi; 15-2 Loa; 15-3 Tafeu; 15-4 Aasu

Conclusions

Based on the spatial distribution of minerals and elements, Sharm Obhur is subdivided into two zones: A and B. Zone A covers the headward area north to the latitude 21°45'6.2" N, and zone B includes the area south of the latitude 21°45'6.2" N towards the mouth.

1. The non-carbonate lithogenic minerals are abundant in zone A, particularly near the eastern shoreline, whereas carbonate minerals are the most abundant in sediments of zone B.
2. Elemental interrelationships allow differentiating two groups of elements of different sources. Elements of the two groups are negatively correlated, whereas elements within the same group are positively

correlated. The elements of the first group include Si, Al, Fe, Mn, Mg, V, Cr, Co, Cu, Ni, and Zn, and the elements of the second group include CaCO₃, Ca, and Sr. Pb displays insignificant positive correlation with elements of the first group.

3. EF and CF values allowed identifying two types of metals: lithogenic and non-lithogenic elements. Lithogenic metals have low EF values (<1.5) and relatively high CF values (>1). Overall, PLI values for both zones A and B were low (≤ 2.15). Lithogenic metals are supplied to the sharm sediments by natural processes such as aeolian transportation and the supply from Wadi Al-Kuraa'a. They were also supplied by anthropogenic processes such as dumping and landfills and from the eroded basaltic blocks that have been used for shore protection. The concentration levels of lithogenic metals are enriched in sediments of zone A. However, they are generally much less toxic for organisms because they are chemically stable and biologically inactive. Non-lithogenic metals are mainly of anthropogenic sources that include fossil fuel combustion, disposal of ship steel scraps, and painting materials. The non-lithogenic metals, although less widely distributed, represent a threat to the biota.
4. The study showed that Sharm Obhur contains metal enrichments of lithogenic origin near the head but not of major contamination influence, whereas the anthropogenic source of metals is slightly to moderately contaminated with Cr, V, Pb, and Mn. The lack of severe pollution is attributed to the lack of major industrial activities in the vicinity of Sharm Obhur compared to other areas in Jeddah. Continuous monitoring and further investigation of the area are recommended to ascertain the long-term effects.

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