

**Mineralogical and  
chemical composition of  
the mud fraction from  
the surface sediments of  
Sharm Al-Kharrar, a Red  
Sea coastal lagoon**

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**Abstract**

Interaction between continental and marine end-members gives rise to the natural biogeochemical processes in Sharm Al-Kharrar, a lagoon in the arid Red Sea region. Twenty-nine surface sediment samples were collected from the area and their mud fraction analysed for grain size, OC, CaCO<sub>3</sub>, mineralogy and elemental composition. The mud fraction consisted of a mixture of siliciclastic/calcareous materials, dominated by silt size materials and characterised by low OC (average 0.71% ±0.13); CaCO<sub>3</sub> varied widely, with an average of 45% ±18. Concentrations of Al, Fe, Mn, Cu, Ni, Cr, V and Ba showed a wide range of variation throughout the Sharm. The results were normalised to Al and subjected to cluster analysis in order to examine the relations between the mineralogy and the elemental composition. The contents of Al, Fe, Mn, Cu, Ni, Cr, V and Ba appeared to be influenced by the mixing of the two end-members in addition to the physiochemical processes associated with the mixing between episodic freshwater flooding and seawater. Zn was the single element that showed a slight departure from the mixing model.

**1. Introduction**

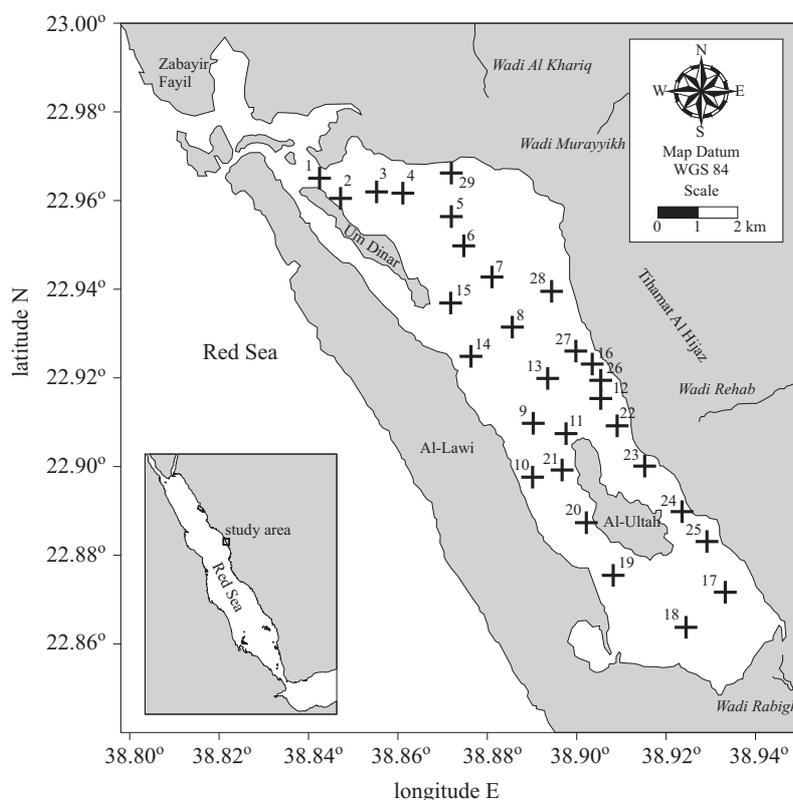
The Red Sea comprises a wide range of tropical marine habitats that are of great environmental significance and socioeconomic concern, including conservation, scientific research, economic and recreational purposes (Price et al. 1998). The coastal plain of Saudi Arabia known as Tihama is

The complete text of the paper is available at <http://www.iopan.gda.pl/oceanologia/>

characterised by young Tertiary and Quaternary deposits of continental or marine origin. The latter frequently form terraces of different elevation towards the shoreline. Other parts of the coast include steep cliffs of Precambrian basement (Dullo 1986). The plain is often cut through at the shelf edge by lagoons locally known as sharms (Brown et al. 1989). Sharms are the product of coastal plain flooding by a relative rise in sea level. Connecting the land and the open sea, they are dynamic and complex biogeochemical systems where the interaction of continental supply and marine contribution gives rise to multiple processes influencing the sedimentology and geochemistry of the sharms. Mud (silt and clay) in the marine environment is easily dispersed by currents and waves and may serve as good tracers for their sources. Inorganic and organic chemicals from different sources tend to concentrate in the mud fraction as particulate matter or be adsorbed onto particulate mineralogical particles; the composition of the mud fraction in the sea may be of environmental significance. Previously published works on Sharm Al-Kharrar bottom sediments and the associated sabkha focused on textural, mineralogical and foraminiferal studies, but no attention was given to geochemical composition (El Abd & Awad 1991, Behairy et al. 1991, Abou Ouf & El-Shater 1993, Gheith & Abou Ouf 1994, Abou Ouf 1996, Al-Washmi 1999, Abu Shanab 2000). The geochemical study of major and trace elements in the sharm shallow system, free of direct anthropogenic input, is useful for determining the nature of the biogeochemical processes and changes in the chemical characteristics of the sediments. The present work is of fundamental importance in an environmental study being carried out in connection with the protection of the continental shelf and coastal environments from terrestrial pollution and other sources of stress that may alter or affect the nature of the ecosystems. It provides data on the occurrence of some major and trace elements in the fine-grained mud fraction of sediments as well as the processes determining the natural level of these elements.

## 2. Study area

Sharm Al-Kharrar is a shallow (average depth 5 m), semi-enclosed marine coastal lagoon situated on the central part of the Red Sea coast of Saudi Arabia north-west of Rabigh. It extends inland, semi-parallel to the coastline, through reef limestone (approximately 17 km long) and is connected to the adjacent Red Sea at its north-western corner by a narrow, shallow channel (depth c. 14 m) (Figure 1). To the west the sharm is separated from the Red Sea by a small littoral reef limestone strand known as Al-Lawi, while on its southern and south-eastern coasts it is bordered by intertidal and supratidal sabkha flats, approximately 3 km



**Figure 1.** Map showing the study area and sampling stations of surface sediments in Sharm Al-Kharrar

wide. At some places, particularly the north-eastern part, an elevated sandy berm separates the sabkha from the lagoon where the low-lying areas are occasionally flooded (El-Abd & Awad 1991). The sharm is spotted with the reef limestone islands Al-Ultah and Um Dinar, which are  $> 5$  km apart. The islands, which arose as a result of Late-Pleistocene sea level fluctuations, are also fringed by scattered mangroves *Avicennia marina*, which both effectively reduce wave energy and promote the deposition of materials carried to the lagoon from fluvial wadi streams; the bottom sediments are thus enriched with biogenic carbonate deposits. Water exchange between the sharm and the neighbouring Red Sea is limited and governed by high velocity tidal currents that can attain  $1 \text{ m s}^{-1}$  at the entrance. During the flood tide in normal (dry) weather conditions relatively cold and low-salinity Red Sea water flows into the sharm, whereas during the ebb tide water of a higher temperature and higher salinity flows out of the sharm (Ahmed et al. 2002). The adjacent arid, flat, low-lying Tihamat Al Hijaz coastal plain (average width 30 km) extends from the shoreline and is

backed to the east by the Red Sea fringing mountains. The hinterland geology consists mainly of Late-Proterozoic metavolcanic, metasedimentary and plutonic rocks. Tertiary sedimentary rocks are capped by basaltic lava flows and Quaternary surficial cover. The Quaternary deposits of the plain are made up of reefal limestone, sabkha deposits, alluvial terraces and talus fans, aeolian sand deposits and alluvium. The climate is hot and humid with high rates of evaporation, and very low precipitation and runoff. The prevailing wind during most of the year is from the north and north-west. Rainfall is low, usually between 50–100 mm/year, mainly in winter. The major streams are intermittent, dry tributaries that form during the rainy season in the main wadis (i.e. valleys), like wadi Rabigh and wadi Rehab, and flow into the southern and south-eastern parts of the Sharm (Ramsay 1986).

### 3. Sample collection and analysis

Twenty-nine surface sediment samples were collected from the bottom of the sharm using a Van Veen grab (Figure 1). Samples were stored in sealed plastic bags and kept in ice boxes until returned to the laboratory. A representative portion of each air-dried bulk sample (approx. 50 g) was used to separate the mud fraction (silt plus clay) in order to minimise the grain size dependencies of element concentration in the sediments (Loring & Asmund 1996, Chen et al. 2000). The mud fraction ( $< 63 \mu\text{m}$ ) of the sample was separated by wet sieving through a  $63 \mu\text{m}$  sieve using doubly distilled water and then dried in a closed fan-assisted oven at  $40^\circ\text{C}$  to constant weight. Appropriate portions of the mud fraction were then taken for the determination of grain size and mineralogical and chemical composition. Silt and clay fractions were determined using a Shimadzu sald-3001 laser particle analyser. The sub-sample (c. 2 g) was suspended in 1 litre of doubly distilled water and pumped by a peristaltic pump into the cell scanned by the laser beam. Bulk mineralogical analyses were carried out on a number of randomly picked samples. The dried powdered sub-samples were analysed by X-ray diffraction (XRD) using a Shimadzu 6000 X-ray generator. Samples were scanned from  $2$  to  $60^\circ 2\theta$  at a speed of  $20^\circ/\text{minute}$  using a  $\text{Cu-K}\alpha$  radiation tube, Ni filter and a voltage of 30 kV and 20 mA. The relative proportions of the various minerals were determined by measuring the heights of the main reflections. Chemical analyses were carried out using dried powdered sub-samples. Calcium carbonate ( $\text{CaCO}_3$ ) concentrations were determined by treating a known weight of each sub-sample with an appropriate volume of cold dilute hydrochloric acid (1M HCl) using a Calcimeter. The organic carbon content (OC) was determined in the sub-samples by using a modification of

the wet dichromate-sulphuric acid oxidation method described by Le Core (1983). This method is based on the exothermic heating and oxidation of organic matter with 1N potassium dichromate acidified with concentrated sulphuric acid, followed by titration with 0.1N ferrous ammonium sulphate in the presence of ferroine as indicator. Concentrations of major and trace elements were determined after the complete digestion of the samples in hot HNO<sub>3</sub>/HF acid mixture and the leachate recovered in dilute HCl (Basaham & El Sayed 1998). Analyses of Al, Fe, V, Cr, Sr and Ba were carried out using an Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP/AES – Perkin Elmer 400), while Mn, Cu, Ni and Zn were measured on an Atomic Absorption Spectrophotometer (AAS – Varian, SpectrAA 250 plus). Analytical blanks were run in the same way as the samples and the concentrations determined using standard solutions prepared in 1M HCl. All the chemicals used were of Merck Suprapur quality, and pure water was of MilliQ grade. The accuracy and precision of the analyses were checked by the analysis of ten replicate samples of sediment reference materials NRCC (BSCC-1) and CCRMP (LKSD-4). Accuracies were within 15% of the certified values for Fe and Cr and better than 10% for the other elements. The precision, expressed as the relative standard deviation (RSD), was always better than 5% for the measured elements, except for Cr (7%) and Sr (12%).

### **3.1. Statistical procedures**

#### **3.1.1. Cluster analysis**

Multivariate cluster analysis was used to evaluate the hypothesis of the geographical separation of sampling stations in this study. All the measured parameters were used as variables to determine the number of groups of sampling stations into which the area should be divided. The dendrogram was created with the Average Linkage (between groups) method, and the similarity measure was the correlation coefficient.

#### **3.1.2. Element normalisation**

Geochemical normalisation using Al as a reference element was used in the present study to correct for variations resulting from variability in sediment type, and to identify anomalous contributions. To ascertain that statistical relationships were based on natural concentrations, data points outside the 95% confidence band were considered anomalous and removed to avoid the inclusion of element-enriched samples; the regression models were then repeated. The remaining points were considered as representing the normal/or background population of element concentrations.

## 4. Results and discussion

### 4.1. Grain size, organic carbon, calcium carbonate and mineralogy

The sediments of the sharm are a mixture of materials of marine and continental origin. The mud fraction (silt and clay) of the sharm superficial sediments is dominated by silty material (> 70%; 2–63  $\mu\text{m}$ ) with small amounts of clay size particles (20–30%; < 2  $\mu\text{m}$ ) (Table 1). Generally, the relative abundance of silt and clay is influenced by hydraulic sorting: coarse particles (silt) tend to concentrate in relatively shallow waters compared to the finer clay particles, which settle in deeper waters. Organic carbon (OC) concentrations in the sediments (Table 1) are relatively low (average 0.71%  $\pm$ 0.13) and practically constant all over the area. The low OC observed in the mud fraction may be attributed to the deposition of organic-poor siliciclastic terrigenous materials and/or the rapid degradation of the newly-formed, easily degradable organic matter. It has been reported (Behairy et al. 1982) that poor primary productivity in the central Red Sea coastal area is responsible for the low organic matter content of the

**Table 1.** The average and range of element concentrations together with grain-size,  $\text{CaCO}_3$  and OC in the mud fraction of the surface sediments

	Clay	Silt	$\text{CaCO}_3$	OC	Al	Fe	Sr
	[%]						
Overall average (n = 29)	24	76	45	0.71	3.69	5.37	0.37
SD	6	6	18	0.13	1.38	1.85	0.17
Min	< 1	63	7	0.55	1.44	2.14	0.04
Max	37	100	70	1.03	6.31	9.10	0.69
Metal/Al	–	–	–	–	–	1.45	0.01
Nearshore mud (Wedepohl 1960)	–	–	–	–	8.4	6.5	0.01
Metal/Al	–	–	–	–	–	0.77	0.001
	Mn	Cu	Zn <sup>†</sup>	Ni	Cr	V	Ba
	[ $\mu\text{g g}^{-1}$ ]						
Overall average (n = 29)	695	39	62	44	59	79	70
SD	264	12	12	18	26	31	19
Min	314	23	37	20	23	27	32
Max	1248	66	87	81	123	147	111
Metal/Al	188	10.56	16.51	11.92	15.98	21.40	18.97
Nearshore mud (Wedepohl 1960)	850	56	92	35	60	145	–
Metal/Al	101	6.66	10.95	4.16	7.14	17.26	–

<sup>†</sup> average value excluding carbonate sediment samples (n = 25).

coastal sediments in the area. However, the low concentrations of OC preserved in the surface sediments may also indicate the dominance of oxidising conditions, which may be due to permanent sediment reworking and a low sedimentation rate. The calcium carbonate ( $\text{CaCO}_3$ ) content in the sediments of the area is highly variable, ranging from 7 to 70% and averaging  $45\% \pm 18$  (Table 1). The  $\text{CaCO}_3$  in the shallow sharm sediments is predominantly of biogenic marine origin, although chemical and biochemical carbonate precipitation may be induced in the shallow, very saline and warm waters (Brewer & Dyrssen 1985, Evans 1988). On the other hand, the  $\text{CaCO}_3$  distribution may also vary as a result of mixing between different sedimentary material of varying composition, such as mixing between marine carbonate and terrestrial siliciclastic end-members.

Mineralogical data (Table 2) indicate that the mud fraction is composed of carbonate and non-carbonate siliciclastic detrital minerals. The minerals suite reflects the nature of the parent materials. The main carbonate minerals identified are aragonite (6–39%) and high-Mg calcite (6–29%). Calcite is a minor carbonate mineral present, representing approximately 10%. Aragonite is common in biogenic marine sediments. The siliciclastic detrital minerals are the erosion products of the igneous, metamorphic and sedimentary rocks that constitute the surface coverage of the adjacent land area. The erosion products are transported by intermittent surface water runoff and wind. These minerals are made up of quartz (12–40%), plagioclase feldspar (8–18%), chlorite (3–24%) and illite-mica, together with amphiboles present in different proportions ( $\approx 10\%$ ). The clay minerals in

**Table 2.** Bulk mineral composition in the mud fraction of the surface sediments [%]

Sample No.	Chlorite	Illite-Mica	Amphiboles	Quartz	Plagioclase	Aragonite	Calcite	Mg-calcite
2	6	3	–	12	14	37	–	28
4	9	5	4	17	15	26	9	15
17	3	–	–	14	8	39	7	29
19	17	8	4	31	15	10	7	8
20	15	6	3	38	16	8	7	7
21	24	8	4	37	13	–	7	6
22	13	5	3	40	14	6	7	12
23	14	6	3	37	13	8	7	12
24	14	8	4	33	18	8	6	9
25	14	6	3	30	12	14	9	12

the clay fraction (A. Gheith unpublished data) are composed predominantly of illite (49–85%), which forms under a wide variety of geological conditions and is largely terrigenous. Kaolinite represents between 16 and 32%, and is frequently detected where intense tropical and sub-tropical weathering conditions prevail; it is typically found in river systems where accelerated weathering under warm and wet conditions occurs. It is noteworthy that these two clay minerals tend to concentrate in relatively shallow nearshore settings, reflecting their strong tendency to flocculate in estuaries and mixing areas (Ghandour et al. 2003). Minor clay minerals present in some samples are chlorite (6–15%) and vermiculite (4–7%). Other rare clay minerals observed in a few samples are montmorillonite (6–14%) and mixed illite-montmorillonite (16–19%).

#### **4.2. Sedimentary processes**

Climatic factors and oceanographic processes interact to control the supply and distribution of sediment in the sharm. The plume of freshwater runoff draining the adjacent coastal plain is distinguished by its brownish colour owing to its high load of suspended matter, and is visible far to the north of the sharm inlet. During the rainy periods, the water circulation in the sharm can be described as an estuarine salt wedge circulation. Salinity measurements made a few days after a rainy period (Abu Shanab 2000) underlined the presence of a strong axial salinity gradient. At the head of the sharm, dilution reached about 80%. This dilution decreases northwards to c. 44% around Al-Ultah and 13% at Um Dinar islands. Only at the outlet was the normal Red Sea water salinity ( $\approx 39$  PSU) encountered. These particular hydrographic conditions, in addition to the tidal action, are responsible for the distribution and reworking of bottom sediments and mixing of marine carbonate and terrigenous materials. During the predominantly dry periods, aeolian transport of terrestrial materials is dominant, and the arid climate promotes physical weathering. The shallow depth of the sharm promotes sediment resuspension by wave and current action.

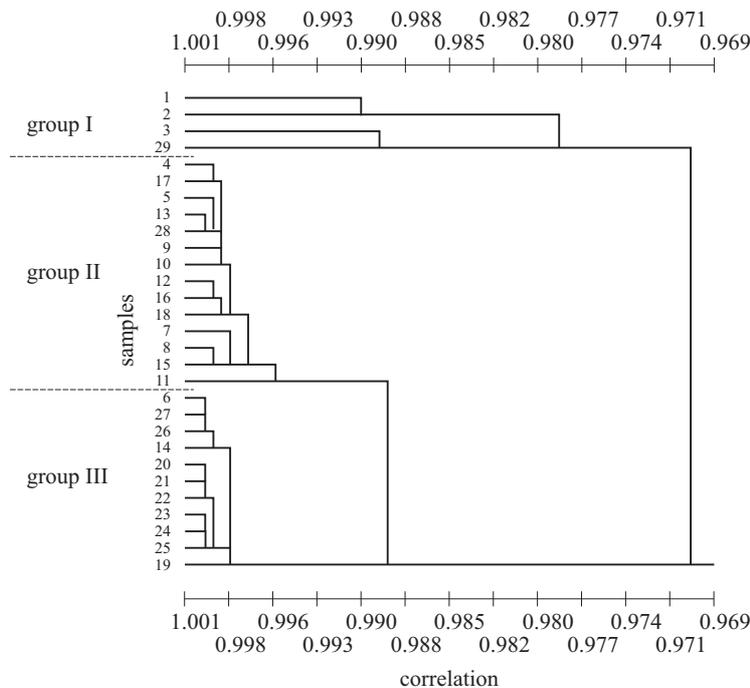
Mount (1984) proposed several different mixing modes that could lead to the development of mixed carbonate-siliciclastic deposits: punctuated mixing, facies mixing, in situ mixing and source mixing. The mixed siliciclastic-carbonate sediments on the sharm floor tends to develop during a punctuated mixing process.

#### **4.3. Sediment type**

Various methods have been used to identify mixed carbonate-siliciclastic sediments. Mount (1985) pointed out that carbonate sediments incor-

porating more than 10% terrigenous constituents are considered to be of a mixed carbonate-siliciclastic character. On the other hand, varied levels of  $\text{CaCO}_3$  content were proposed to identify the transition region between the terrigenous and carbonate provinces, commonly ranging from 25 to 75% (Hernandez Arana et al. 2005).

Multivariate cluster analysis was used to classify the sampling stations in this study according to their similarity (Figure 2). Based on the statistical clusters and  $\text{CaCO}_3$  values, three distinct types or groups of sediments were extracted (Table 3) and defined as: (i) a carbonate-dominant sediment type (four samples), characterised by more than 65%  $\text{CaCO}_3$  with slight admixtures of siliciclastic sediment and, (ii) a mixed carbonate-siliciclastic sediment type (thirteen samples) with a  $\text{CaCO}_3$  content in the range of 43 to 65% and (iii) a siliciclastic-dominant sediment type (twelve samples) with  $\text{CaCO}_3$  ranging from 7 to 53%.

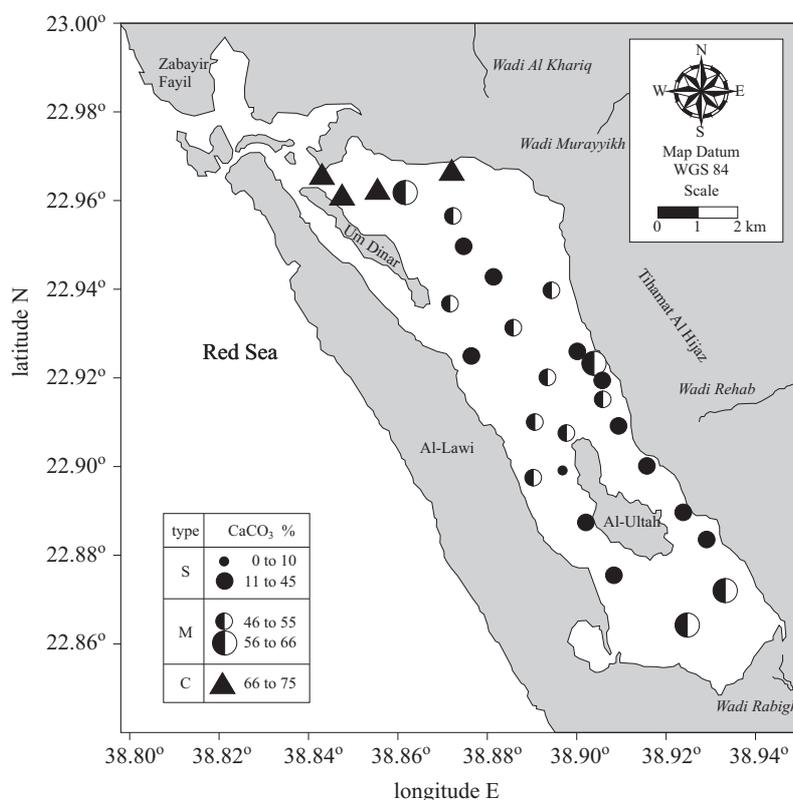


**Figure 2.** Classification of the sampling stations. Group I refers to carbonate sediment samples, group II to mixed siliciclastic-carbonate sediment samples, and group III to siliciclastic sediment samples

The spatial distribution of the sediment types is shown in Figure 3. The carbonate-dominated sediment type is predominant at the northern

**Table 3.** The average and range of element concentrations together with grain-size: CaCO<sub>3</sub> and OC in the various sediment types

Sediment type	Clay	Silt	CaCO <sub>3</sub>	OC	Al	Fe	Sr
	[%]						
Carbonate sediment:							
Average (n = 4)	20	80	68	0.66	1.76	2.54	0.55
SD	18	18	2	0.11	0.41	0.49	0.12
Min	< 1	63	66	0.55	1.44	2.14	0.41
Max	37	100	70	0.76	2.35	3.24	0.69
Metal/Al	–	–	–	–	–	1.46	0.32
Mixed siliciclastic-carbonate:							
Average (n = 13)	25	75	54	0.73	3.37	4.75	0.45
SD	4	4	7	0.16	1.00	0.78	0.09
Min	19	70	43	0.58	2.13	3.50	0.34
Max	30	82	65	1.03	5.37	6.05	0.62
Metal/Al	–	–	–	–	–	1.47	0.13
Siliciclastic sediment:							
Average (n = 12)	25	75	29	0.70	4.67	6.99	0.22
SD	4	4	14	0.09	1.10	1.34	0.12
Min	20	67	7	0.55	2.85	4.23	0.04
Max	33	80	53	0.85	6.31	9.10	0.38
Metal/Al	–	–	–	–	–	1.59	0.04
	Mn	Cu	Zn	Ni	Cr	V	Ba
	[ $\mu\text{g g}^{-1}$ ]						
Carbonate sediment:							
Average (n = 4)	379	42	87	26	24	33	36
SD	46	10	38	11	1	5	4
Min	314	30	41	20	23	27	32
Max	419	53	133	43	25	39	40
Metal/Al	221	24	48	15	14	20	21
Mixed siliciclastic-carbonate:							
Average (n = 13)	557	31	56	35	51	71	74
SD	87	5	10	7	14	11	14
Min	423	23	37	26	38	52	52
Max	741	40	75	51	87	90	111
Metal/Al	173	9	17	11	16	22	23
Siliciclastic sediment:							
Average (n = 12)	950	47	69	60	79	104	77
SD	197	12	10	15	24	29	16
Min	599	27	48	30	44	63	56
Max	1248	66	87	81	123	147	109
Metal/Al	221	11	16	14	18	24	17



**Figure 3.** Distribution of sediment types based on  $\text{CaCO}_3$  content. (S) – siliciclastic sediments; (M) – mixed siliciclastic-carbonate sediments; (C) – carbonate sediments. The size of the symbols represents the different contents of  $\text{CaCO}_3$  [%] (given in the inset)

extremity near the inlet, where maritime conditions prevail. Sediment samples consist mainly of marine biogenic carbonate with very little contribution from the terrestrial end-member. Strong tidal currents with speeds of about  $1 \text{ m s}^{-1}$  at the sharm entrance are responsible for the rewinnowing of sediment particles and the washing out of the fine particles. The mixed carbonate-siliciclastic sediment type marks the transition between the marine and terrestrial end-members. Its geographic distribution depends on the interaction between the supply of terrestrial materials and the acting transporting forces and will therefore vary according to the importance of the freshwater inflow and the tidal currents. The mixed sediment samples with carbonate content varying between 43 and  $\sim 55\%$  occupy the middle part of the sharm, north of Al-Ultah island. Two other samples taken south of Al-Ultah island were found to contain a relatively high carbonate content ( $\approx 65\%$ ). Increases in the carbonate content in these

samples may be related to local conditions, such as the washing out of fine terrigenous sediments seawards down the sharm by local currents. On the other hand, during the dry periods that prevail for most of the year, the fluvial wadi inflow into the sharm is minimal, and carbonate production and sedimentation continues. The siliciclastic sediment type indicative of a low-energy environment is dominant on the eastern and western sides of the Al-Ultah barrier island with some localised spots found in the area north of Al-Ultah. The shorelines of the island and the surrounding mangrove stands tend to reduce the current velocity and actively trap significant amounts of wadi-transported particles. This central island appears to play a significant role in the distribution of bottom sediments in the sharm and consequently affects the distribution of benthic fauna and flora.

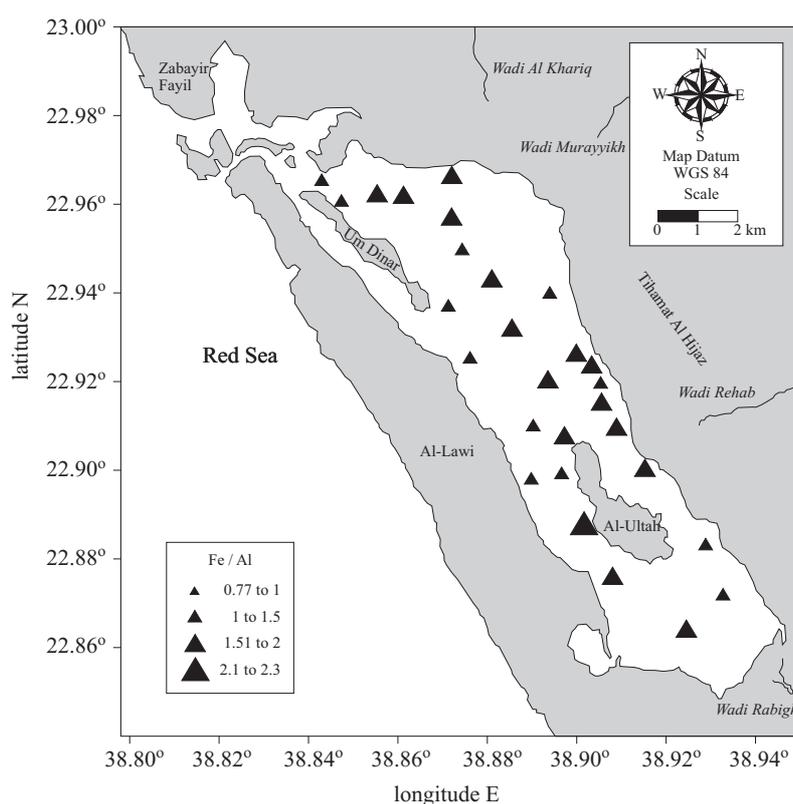
#### 4.4. Elemental composition

The concentrations of the major elements Al, Fe, Mn and the trace elements Cu, Zn, Ni, Cr, V, Ba and Sr vary widely (Table 1). In order to neutralise the effect of grain size and mineralogical fluctuations, results were normalised to Al (Calvert 1976). The V/Cr ratio has been used as a palaeo-oxygenation indicator (Ghandour et al. 2003). Values of V/Cr < 2 are considered indicative of oxic depositional conditions (Dill et al. 1988). The studied samples have a low OC and V/Cr values ranging between 0.81 and 1.60, which may indicate that sediments were deposited under oxidising conditions. The chemical composition of the sharm sediments is determined largely by the extent to which the carbonate and siliciclastic minerals are mixed together. Normalisation to Al demonstrates that in all the samples Fe, Mn, Cu, Ni, Cr, V and Ba constitute single geochemical populations, which are essentially contributed by the fine mud siliciclastic minerals. Sr is negatively correlated to Al ( $r = -0.62$ ) and seems to be of non-continental origin. Zn is the one element that does not correlate with Al. This may be due to its association with a particular mineral phase(s) or to post-depositional processes.

If it is accepted that Al and Fe are principally of terrestrial origin, and that Sr belongs to the marine carbonate end-member, the geographic distribution of these elements agrees with the distribution based on sediment mixing. In general, Al and Fe increase and Sr decreases with distance from the mouth of the wadi at the head of the sharm. This trend is supported by the average chemical composition of the three distinctly different types of the sediments obtained by the cluster analysis (Table 3). The carbonate-dominant sediment type at the sharm entrance is characterised by the highest concentrations of Sr and Zn and the lowest concentrations of Al, Fe, Mn, Ni, Cr, V and Ba. High Sr concentrations are common in

marine biogenic carbonates containing an appreciable aragonite content (Calvert 1976 and Basaham & El-Sayed 1998). Aragonite precipitated in warm shallow seas is likely to contain between 2500–9500  $\mu\text{g g}^{-1}$   $\text{Sr}^{2+}$  (Scoffin 1987). In contrast, the siliciclastic-dominant sediment type, prevailing in the vicinity of Al-Ultah island, is characterised by the lowest concentration of Sr and the highest concentrations of Al, Fe, Mn, Cu, Ni, Cr, V and Ba (Table 3). The mixed carbonate-siliciclastic sediment type shows intermediate concentrations of the elements relative to the other two sediment types. Their variability correlates with the changes in the proportions of the marine-carbonate dominant end-member and the terrestrial end-member.

The Fe/Al ratio may serve to trace the mixing of the marine biogenic sediments and the siliciclastic terrigenous materials. It appears from the distribution of the Fe/Al ratio (Figure 4) that the transport of terrestrial materials takes place mainly along the central channel of the sharm.



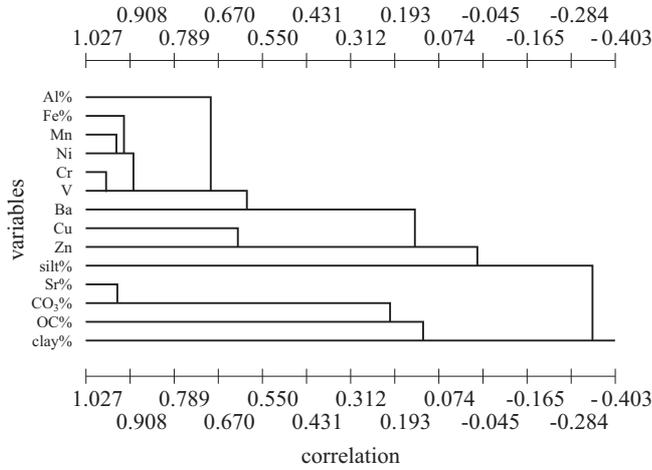
**Figure 4.** Distribution of the Fe/Al ratio in the mud fraction

Fe/Al ratios are relatively higher along its central axis than near its shores.

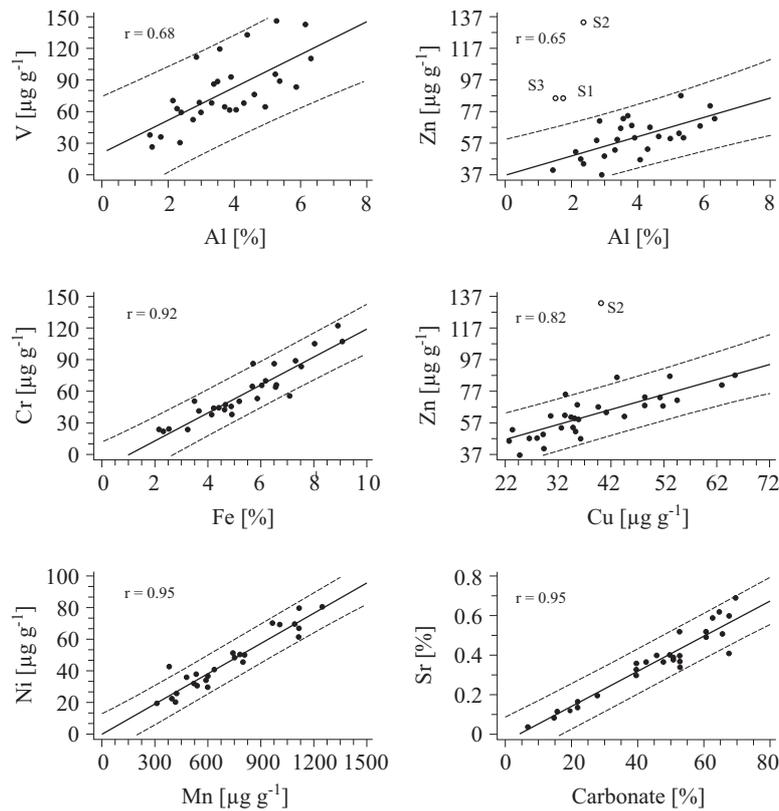
Direct comparison of element concentrations obtained in this study with other data reported elsewhere in the Red Sea, particularly on the Saudi coast, is difficult because of the different sediment types and textural incompatibility. Nevertheless, element concentrations can be compared to the element composition of the classical marine deposits. Average element concentrations are reported in Table 1 together with the shallow water nearshore mud treated as the boundary between the continental and marine influence (Wedepohl 1960). The sediments are similar in grain size but quantitatively different in their mineralogical composition; consequently, direct comparison would be biased. However, the element/Al ratio does allow comparison with the nearshore mud. The overall average element/Al ratios for Fe, Mn, Cu, Zn, Ni, Cr, V and Sr are higher in the sharm sediments than those of the nearshore mud (Table 1). This suggests that, besides lithogenic aluminosilicate minerals, other relevant non-lithogenic components could contribute to these elements in the sharm sediments. Mixing of fresh and seawater may provoke precipitation and co-precipitation of several trace elements such as Cu, Zn, Ni, Cr, V and Ba from solution and enhance their concentrations in the mud fraction.

#### **4.5. Element associations in sediments**

Elements may have varying preferential associations with respect to the chemical and mineralogical constituents of sediment. The degree of correlation between major and trace elements and other sediment constituents is often used to indicate the common origin and processes occurring in nature (Windom et al. 1989). To test the results obtained using Al normalisation, cluster analysis was used to investigate relationships between the ensembles of variables. The result differentiates five groups of associations among the variables (Figure 5). The first cluster involves the major elements Al, Fe, Mn and the trace elements Ni, Cr, V and Ba. These elements are associated with each other and indicate a common origin. Their concentrations, distribution and mobility are controlled largely by the deposition of inorganic aluminosilicate minerals, as well as other crystalline and/or amorphous Fe and Mn minerals characterised by a large specific surface area, and are intimately associated with the mud fraction. Fresh- and seawater mixing in the sharm certainly induces complex interactions between dissolved and particulate components, which may remove dissolved elements into different geochemical carrier-phases of suspended particles that will finally find their way to the bottom sediments. Al and Fe show strong covariance ( $r = 0.78$ ), and both are typical constituents of the suite



**Figure 5.** Classification of variables in the mud fractions



**Figure 6.** Selected scatter plots with a significant correlation coefficient in the mud fraction

of aluminosilicate minerals present in the mud samples. The mud fraction of the sediments contains varying proportions of silt and clay. Therefore, Al and Fe will also depend on clay minerals and other detrital minerals such as mica, chlorite, feldspar and amphiboles (Table 1). These detrital aluminosilicates partly control the geochemistry of the trace elements Ni, Cr, V and Ba. On the other hand, Ni, Cr, V and Ba correlate better with Fe and Mn than with Al, suggesting the preferential association of Ni, Cr, V and Ba with Fe-Mn, which commonly form mixed oxides and hydroxides (Figure 6). Hydrous oxides of iron and manganese may be transported directly by the freshwater inflow or may be deposited in situ from the water column, a process very common in estuarine environments (Forstner & Wittmann 1983, Slomp et al. 1997).

The average element to Al ratios in the three types of sediments (Table 3) shows that Fe is constant in the three different types of sediments, which indicates a common origin. Mn shows a large range of variability – depletion in the mixed siliciclastic-carbonate sediment type suggests some dissolution processes. Organic matter oxidation and the reduction of Mn oxides tend to be high near the sediment-water interface, resulting in the remobilisation of Mn and associated trace elements. V, Cr, Ni and Ba are the least soluble elements and show far less variability. The second cluster is formed by the trace elements Cu and Zn, which occur in association with the silt-sized fraction. In the absence of important human activities that may add these elements, their distribution is the product of natural sedimentological and geochemical processes. The average element to Al ratios for Zn and Cu (Table 3) show enrichment in the carbonate-dominant sediment type. However, it is worth indicating that Cu belongs to the normal geochemical populations, i.e. the fine-grained mud siliciclastic minerals, in all the 29 samples analyzed. In contrast, Zn provides a significantly positive linear correlation with the geochemical proxy Al for the entire siliciclastic and mixed siliciclastic-carbonate sediment samples ( $n = 25$ ). This suggests that with the exception of the carbonate sediment type, the Zn concentration in the analysed sediments represents the normal geochemical population and can be used as a reference for evaluating the extent of element enrichment or contamination in the coastal area. In contrast, in the carbonate sediment type close to the mouth of the sharm the same relationship does not hold – three samples (1, 2 and 3) deviated from the linear relationship with Al. This indicates that enrichment is possible even under anthropogenic-free conditions (Figure 6). However, the natural processes responsible for the Zn enrichment are not discernible.

The third group includes Sr and  $\text{CaCO}_3$ . Sr can substitute Ca in the marine biogenic carbonate sediment; because of the geochemical similarities

between Sr and Ca, the two elements are well correlated (Figure 6). The dependence of Sr on carbonate mineralogy probably reflects the existence of aragonite and high Mg-calcite as the main carbonate minerals in the mud fraction of the sharm sediments (Table 2). The fourth and fifth clusters of OC and clay do not appear to be determining factors; however, each forms a group of its own, which indicates that they have a different distribution process.

## 5. Conclusion

Sharm Al-Kharrar is a shallow coastal lagoon representing a natural environment and providing a unique study area free of direct anthropogenic input. The sediments in the sharm are mixed siliciclastic-carbonate sediments resulting from a complex interplay of climate and oceanographic processes. The prevailing arid conditions have given rise to extensive carbonate deposition, and the temporary rainy periods to freshwater wadi runoff and siliciclastic deposition. The mud fraction of the oxic surface sediments has developed as a result of the punctuated mixing of carbonate and siliciclastic (terrigenous) materials. The mud fraction in the sediments consists mainly of silt-sized particles and is characterised by a low OC and highly variable CaCO<sub>3</sub> content of marine biogenic origin. In this study, three types of sediments were distinguished: (i) carbonate-dominant, (ii) mixed carbonate-siliciclastic and (iii) siliciclastic-dominant. The elemental concentrations displayed a large range of variations that can be attributed mainly to the sediment types. In order to carry out an objective comparison, concentrations were normalised to Al. The contents of Al, Fe, Mn, Cu, Ni, Cr, V and Ba are influenced by terrigenous materials contributed mainly by the ephemeral fluvial wadi flow. Sr concentration is determined by the abundance of CaCO<sub>3</sub>. The concentrations of Al, Fe, Mn, Cu, Ni, Cr, V, Ba and Sr in the samples come from natural populations and may serve as background reference concentrations for further research activities in the Red Sea and as a monitor for determining unequivocally any future anthropogenic contamination.

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