Distribution and Behaviour of Some Heavy Metals in the Surface Sediments of Al-Arbaeen Lagoon, Jeddah, Red Sea Coast

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ABSTRACT. Analysis of surface sediments from Al-Arbaeen Lagoon shows that the sediments consist mainly of soft mud that is dark in colour, rich in organic matter, and associated with high concentrations of hydrogen sulphide. These characteristics indicate that the lagoon basin is a low energy, anoxic, sulphidic sedimentary environment.

The concentrations of Fe, Mn, Zn, Pb, Ni, Cr, Co, Cu and organic carbon are higher in the lagoon sediments than the background levels of these elements measured in remote unpolluted marine sediments This is due to the large input of anthropogenic waste into the lagoon.

Data indicate that the behaviour of Fe, Mn, Co and Cr are strongly influenced by redox reactions and seem to exist as sulphide minerals such as pyrite or are associated with iron sulphide minerals. Zn and Cu show a preferential association with the organic carbon. Ni and Pb do not show any definite association with different geochemical phases of the sediments.

Diagenetic remobilization of some metals and precipitation with iron sulphide minerals and organic carbon appear to be the possible mechanisms explaining the heterogeneous distribution of these metals produced by redox reactions in the lagoon's surface sediments.

Introduction

Al-Arbaeen Lagoon is a shallow (average depth about 4 m), tropical, anoxic, semi-enclosed basin. It is situated on the Red Sea coast of Jeddah, Saudi Arabia. It is surrounded by residential areas and is connected to the Red Sea through a mouth at its northwestern end. The lagoon is characterized by a two-layer estuarine circulation system, with restricted sub-surface sea water inflow and surface lagoon water outflow. The lagoon basin is divided into three sub-basins (inner, middle, and outer) due to the construction of concrete basements for two bridges cross the lagoon (Fig. 1). These struc-

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tures act as sills and therefore limit water exchange with the open sea to the upper 2 m surface layer. The inner and middle sub-basins host stagnant water mass at greater depths (greater than 2 m) until flushed completely or partially during particular hydrographic events (El-Rayis *et al.,* 1989). The lagoon is used as a dumping site for sewage and wastewaters, mainly of domestic origin, discharged from Jeddah sewage treatment plants. The limited circulation and the dumping of organic-rich wastes participate in creation of anoxic conditions within the lagoon system. Under these conditions the water body and sediments are enriched in organic matter, nutrient salts, heavy metals, and hydrogen sulphide compared with the adjacent oxic Red Sea water (El-Rayis *et al.,* 1989; El-Rayis, 1990).

The input of anthropogenic waste into the relatively deep inner sub-basin (depth range 2-8 m, average 4 m) far from communication with the sea, became inactive in October, 1990 (Ghazali, 1993). However, anoxia is still the main feature of the sub-basin. On the other hand, wastewater is still discharged into the middle sub-basin (depth range 2-5 m, average 3 m), (El-Rayis *et al.,* 1989; El-Rayis, 1990; Ghazali, 1993). Despite the dilution by a limited influx of oxic Red Sea water into this sub-basin, high organic matter input and hydrogen sulphide produced as a result of anaerobic oxidation of organic matter are sufficient to maintain the anoxic environment (El-Rayis *et al.,* 1989; El-Rayis, 1990). In the outer sub-basin, the surface water flowing out as a top 2 m depth surface layer mixes with materials discharged from a fish market and with the oxic Red Sea water. Generally, this area is shallow (depth range 2-5 m, average 4 m) and relatively sheltered and the texture of sediment, organic carbon content, and colour indicate prevailing reducing conditions.

Sediments are a large reservoir for many metals and are usually regarded as indicator of water quality (Förstner and Wittmann, 1983). They can act both as a sink and a possible source for metals for the environment. So far, little information on the heavy metal composition of Al-Arbaeen Lagoon sediments is available. The purpose of this paper is to investigate the distribution and the behaviour of Fe, Mn, Zn, Pb, Ni, Cr, Co, Cu and organic carbon in the anoxic surface sediment of the lagoon.

Materials and Methods

Twenty-three surface sediment samples were collected from the bottom of the lagoon using a grab sampler and immediately placed in sealed polythylene bags. Sampling stations have been selected to represent the three sub-basins (Fig. 1). Sediments collected are composed of soft mud, dark-gray to blackish in colour. Additionally, the mud fraction of eight unpolluted sediment samples, collected from Jeddah coastal area, was separated by sieving method and used to establish the background level of the metals analyzed.

Representative subsamples were oven dried at 40ºC, ground and used for bulk chemical analysis, carbonate and organic carbon determination and bulk mineralogical analysis. For the determination of heavy metals, accurately weighed subsamples were digested with hot concentrated nitric acid under reflux. The solution was then evaporated
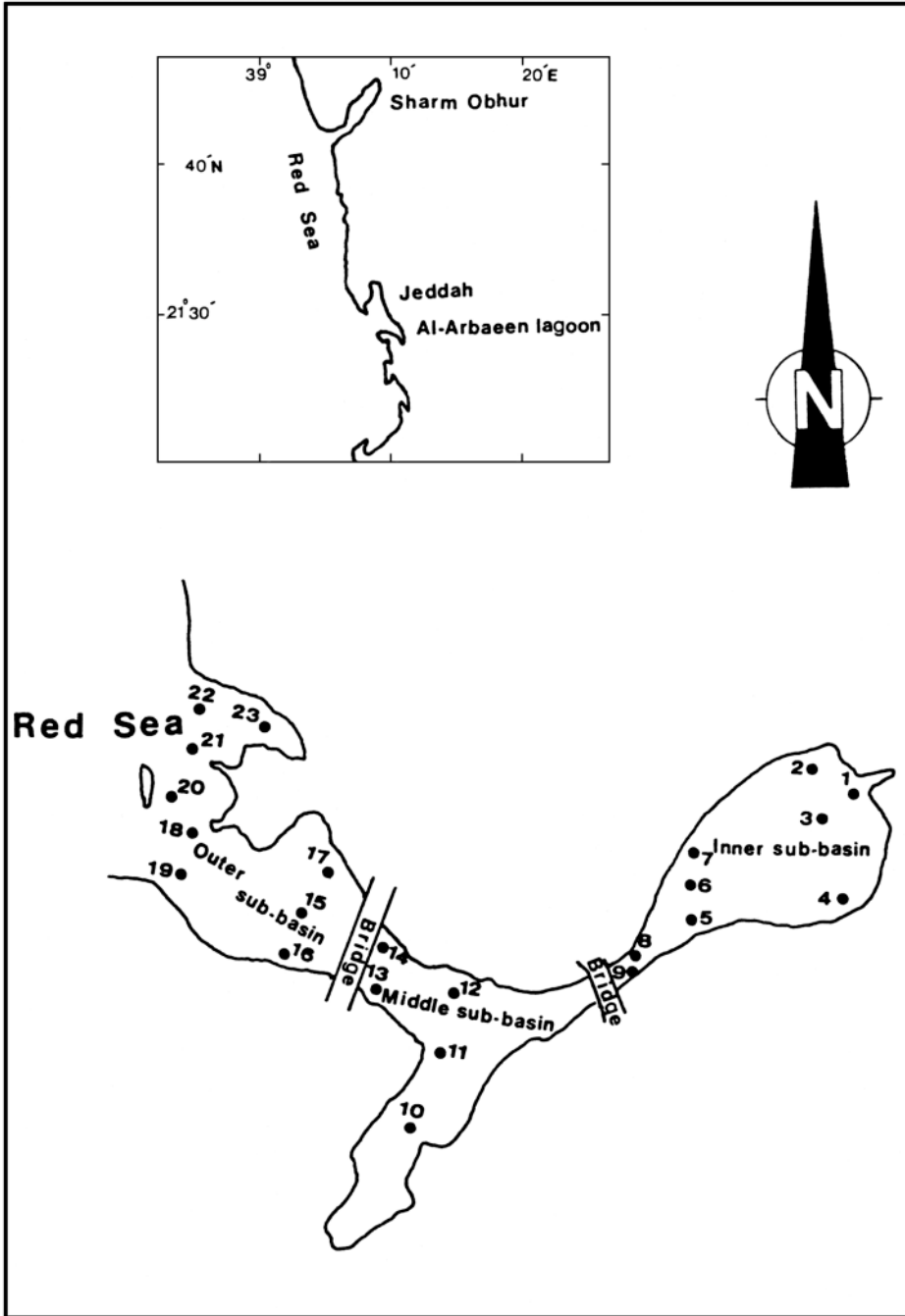
FIG. 1. Map showing location of samples, Al-Arbaeen Lagoon, Jeddah, Saudi Arabia (after Farsi, 1991).

to near dryness and diluted to constant volume with 10% hydrochloric acid. In using this method, it is assumed that the hydromorphic, or reactive portion of the metal in question is released into solution while the tightly held, clay lattice bound, portion of the metal is left behind. The concentrations of Fe, Mn, Cu, Cr, Co, Ni, Zn, and Pb were measured in the dilute HCl acid solution using Varian 250 plus flame atomic absorption spectrophotometer (AAS) fitted with D_2 background correction. The concentrations were obtained directly from the appropriate standard calibration curves. The coefficient of variation (CV%) for the trace metals in five replicate samples were as follows: Fe 2.3%, Mn 5.4%, Cu 4.8%, Zn 3.2%, Ni 9.8%, Cr 5.3%, Co 6.2% and Pb 4.1%.

Organic carbon (Org. C) was determined in the sediments by the wet oxidation method of Walkley and Black (1934). Calcium carbonate content was determined by treating the samples with 5% HCl. The weight of acid soluble material (CaCO$_3$) was expressed as a percentage of the total weight of the sample. Bulk mineralogical composition was performed on selected samples using X-ray diffraction (XRD).

Results and Discussion

Sediment Character and Depositional Environment

The analysed sediments are mud, rich in organic matter (average Org. C. content 8.9% ± 5.8), dark-gray to blackish in colour, and have high concentrations of H_2S. These characteristics reflect a low energy environment with high rate of supply and accumulation of organic matter resulting in the prevailing anoxic conditions. Organic matter is the driving force for early diagenesis in sediments. During early diagenesis the oxidation of organic matter in sediment proceeds through a general sequence of microbially mediated metabolic reactions involving oxygen, nitrate, manganese oxides, iron oxides and sulphate reduction to fermentation and methanic production (*e.g.* Froelich *et al.,* 1979; Berner, 1981). According to Berner (1981) environments corresponding to the processes leading to organic matter oxidation in sediments are oxic, anoxic non-sulphidic, anoxic-sulphidic and anoxic non-sulphidic methanic. In response to these diagenetic reactions, sediments show colour zonation; red or brown colour are attributed to oxidizing environments, while green, gray, or black colour are related to more reducing conditions (Lynn and Bonatti, 1965; Calvert, 1976; Lyle, 1983). Accordingly, the existence of H_2S in the Al-Arbaeen Lagoon water column provides evidence that the sequence of diagenetic reactions has reached the stage at which sulphate (SO_4^{2-}) is converted to sulphide (S^{2-}) ions, where the dark colour of the sediments is a function of the amount of organic matter and possibly iron-sulphide formation. El-Rayis (1990) reported that sediments deposited under anoxic water (euxinic) in al-Bankalah zone (*i.e.* the middle sub-basin in the present study) are sapropelic in character. The environmental conditions favourable to the formation of sapropel are typically found in truly anoxic basins characterized by the presence of H_2S and the sediments are commonly organic-rich and black in colour because of the presence of iron sulphides (Manheim, 1961; Calvert, 1976). The bulk mineralogy of the samples from the Al-Arbaeen Lagoon analysed by XRD, reveals the presence of detrital (quartz and plagioclase-feldspar), carbonate (aragonite, calcite and dolomite) and evaporite (gypsum and halite) minerals and

authigenic pyrite (Table 1). The terrigenous material is most probably derived from the neighbouring Red Sea coastal hills mainly by aeolian transport and during land filling operations to provide more space for development. Calcium carbonate minerals (aragonite and calcite) are largely present in the form of foraminiferal and other biogenic tests. These organisms drifted from the open sea with the sub-surface oxic Red Sea water inflow into the lagoon basin. Abo-Ouf and El-Shater (1991) indicated that the number of foraminifera is relatively higher in the sewage discharge areas (Al-Arbaeen Lagoon and south Corniche) compared to an unpolluted one. Sediments close to the discharge points are characterized by dead foraminifera tests. These authors pointed out that Al-Arbaeen Lagoon is devoid of living foraminifera but a few living species were present adjacent to the mixing zone. However, dolomite is recorded in the analysed sediments. Its formation within the lagoon anoxic, organic rich sediments is related to diagenesis. The presence of evaporite minerals can be attributed to the elevated evaporation rates, particularly during the summer, and the presence of high salinity water in the bottom layer of the lagoon. Pyrite is present as an authigenic mineral formed during the early chemical diagenesis in the lagoon anoxic bottom sediments. On the basis of the categories pointed out above it is apparent that the environment of Al-Arbaeen Lagoon can be classified as a low energy, anoxic "sulphidic" sedimentary basin.

TABLE 1. Relative percentages of minerals in Al-Arbaeen Lagoon surface sediments.

Sample no.	Aragonite	Calcite	Dolomite	Gypsum	Halite	Pyrite	Quartz	Plagioclase
3	6.7	15.6	–	23.4	7.8	4.5	33.4	8.6
6	8.6	17.1	–	11.4	10	4.3	40.5	8.1
9	6.6	11.8	–	11.8	7.9	5.3	41.3	15.3
13	–	21.7	–	–	11.1	3	48.1	16.1
14	6.1	16.5	–	–	8	3	40.1	26.3
15	5.5	7.9	–	36.7	24.5	2.9	18.4	4.1
18	14.2	35.9	4.9	–	3.1	2.6	18.9	20.4
20	11	37	–	–	13.2	5.8	20.7	12.3

Distribution and Behaviour of Heavy Metals in the Sediments

The concentrations, average and the range of heavy metals and organic carbon are listed in Table 2. Background levels from Jeddah unpolluted coastal sediments (mud fraction) are also given in Table 2 for comparison.

The average data (Table 2) show that the concentrations of Fe, Mn, Zn, Pb, Ni, Cr, Co, Cu and organic carbon are higher in the lagoon sediments than the background level measured in remote unpolluted areas. Dramatic enrichment is particularly noticed for Fe, Cu, and Zn as well as organic carbon which show enrichment factors of 5-90. All the other metals show relative enrichment factors varying between 1-5. This reveals that anthropogenic wastes released into the lagoon basin has considerably increased metal

and organic matter concentrations in the sediments. Similar conclusions have been reached by El-Rayis (1990) for al-Bankalah (middle sub-basin) anoxic sediments.

TABLE 2. Average and range concentrations of metals and organic carbon in the investigated sediments ($\mu g/g$) except for Fe and Org. C (%).

Location	Fe	Mn	Zn	Pb	Ni	Cr	Co	Cu	Org. C
Inner sub-basin	2.69	206	365	175	77	36	11	166	8.28
Range	(0.58 - 3.89)	(49 - 298)	(89 - 838)	(32 - 550)	(25 - 329)	(15 - 52)	(5 - 16)	(31- 335)	(0.34 - 17.93)
Middle sub-basin	2.43	150	733	198	29	33	9.4	474	13.85
Range	(1.14 - 3.45)	(66 - 231)	(233 - 1431)	(76 - 421)	(7 - 53)	(25 - 44)	(6 - 12)	(82 - 1038)	(6.97 - 25.56)
Outer sub-basin	1.57	157	223	57	15.44	29	8.66	118	6.74
Range	(0.86- 2.37)	(73 - 249)	(101 - 439)	(2 - 108)	(10 - 23)	(19 - 45)	(5 -11)	(39 - 298)	(3.76 - 11.62)
Unpolluted coast- al sediments	0.03	50	41	36	26	12	4.43	6.5	0.45
Range	(0.05 - 1.25)	(20 - 154)	(29 - 78)	(29 - 51)	(13 - 37)	(8 - 25)	(2.5 - 8.75)	(2.5 - 16.25)	(0.10 - 0.75)

The metal concentrations in the sediments of the three sub-basins indicate that characteristic differences are inherent to the area. In general the metal and organic carbon concentrations are higher in the inner and middle sub-basins than in the outer one. This is most probably due to the proximity of the first two sub-basins to the discharge points on one hand and, on the other hand, the dilution effect together with uncontaminated sediments transported along the coastal zone in the outer sub-basin. Slight differences are also observed between metal concentrations in the inner and middle sub-basins (Table 2). These could be attributed to differences in the composition of the effluents, reworking of bottom sediments, and/or even due to varying diagenetic processes.

It can be concluded that, under the prevailing anoxic conditions operative in Al-Arbaeen Lagoon, early diagenetic processes play an important role in the metal chemical changes (dissolution/precipitation). Therefore, the irregular distribution of heavy metals in the lagoon sediments can be largely attributed to these processes.

Metal Associations

Since the major portion of heavy metal and organic carbon content of the studied sediments is most likely contributed by the sewage and wastewater discharges, close correlation between the components should be expected in different parts of the area. This is true only if the distribution was governed by physical dispersive processes. However, this was not the case since atleast redox conditions and pH should vary considerably from one basin to the other. Therefore, the metal associations are modified according to the specific interaction of each of the metals under the prevailing environmental conditions. The correlation coefficients between metals and organic carbon in the lagoon sediments are presented in (Table 3a, b and c). Some of the most important scatter plots with linear regression curves are shown in (Fig. 2).

Fe, Mn, Co and Cr association

The behaviour of Fe and Mn is mostly controlled by their redox reactions, however, the kinetics of the redox processes are different (Stumm and Morgan, 1981). Under reducing conditions particulate Fe (III) and Mn (IV) are reduced and solubilized as Fe (II) and Mn (II) species. In the presence of excess H_2S, iron can be precipitated as mono-sulfides (such as mackinawite or amorphous FeS) or as pyrite (Jacobs *et al.,* 1985; Huerta-Diaz and Morse, 1992). During this dissolution/precipitation process, metals normally associated with the oxide phases or present as ions in solution, will co-precipitate with the iron sulphides in addition to the formation of their own insoluble sulphides.

In this study, concentrated nitric acid has been used for the digestion of sediment samples. This mineralization process will dissolve the fraction considered as labile with respect to dissolution/precipitation reaction processes. The remaining acid insoluble residue is normally composed of silicate and other resistant minerals. Mineralogical analysis has revealed the presence in the residue of quartz and plagioclase feldspar (Table 1). These detrital minerals are "inert materials" usually considered as trace metal-poor and act as diluents for trace metal carrier components (Martincic *et al.,* 1990). In Al-Arbaeen Lagoon Fe is expected to be found as sulphides and this is supported by the presence of pyrite in the XRD analyses (Table 1).

Co and Cr also undergo redox reactions, in oxidizing environments, the oxidation state of Co is (III) and Cr is found as Cr (VI), while in reducing environments, Co (II) and Cr (III) are the dominant species. Close association between Fe, Mn, and Co has been observed across the O_2/H_2S interface in the permanently anoxic Framvaren Fjord in Norway (Jacobs *et al.,* 1985) and in the Baltic anoxic water (Kremling, 1983). Co was also found associated with pyrite in a variety of reducing environments (Huerta-Diaz and Morse, 1992) however, Cr did not show the same association.

The results of this study indicate that Mn, Co, and Cr are significantly positive correlated with Fe in the sediments of the three sub-basins (Tables 3a,b,c and Fig. 2a,b,d,g and h). Such relationship is due to the absence of active oxide surface in this reducing environment and competition of H^+ ion (slightly acidic conditions are expected to develop as a result of the decomposition of the organic matter) for the surface adsorbing sites and the insignificance of the residual fraction. Precipitation of insoluble sulphides and co-precipitation of trace metals with pyrite are the most probable mechanisms for the incorporation of Mn, Co, and Cr in the sediments (Piper, 1971; Rasawell and Plant, 1980; Emerson *et al.,* 1983; Huerta-Diaz and Morse, 1992). It has been shown that the main factors affecting the incorporation of trace metals into pyrite phase in the reducing environments are the level of ΣH_2S, the concentration of reactive Fe and labile organic matter, and the magnitudes of sulphate reduction and sedimentation rates. The enhancement of the magnitude of these parameters favours the pyritization process of trace metals (Huerta-Diaz and Morse, 1992).

Cu and Zn association

Cu and Zn are positively correlated with each other and with organic carbon and negatively correlated with Fe and Mn in the sediments of the extremely anoxic inner and
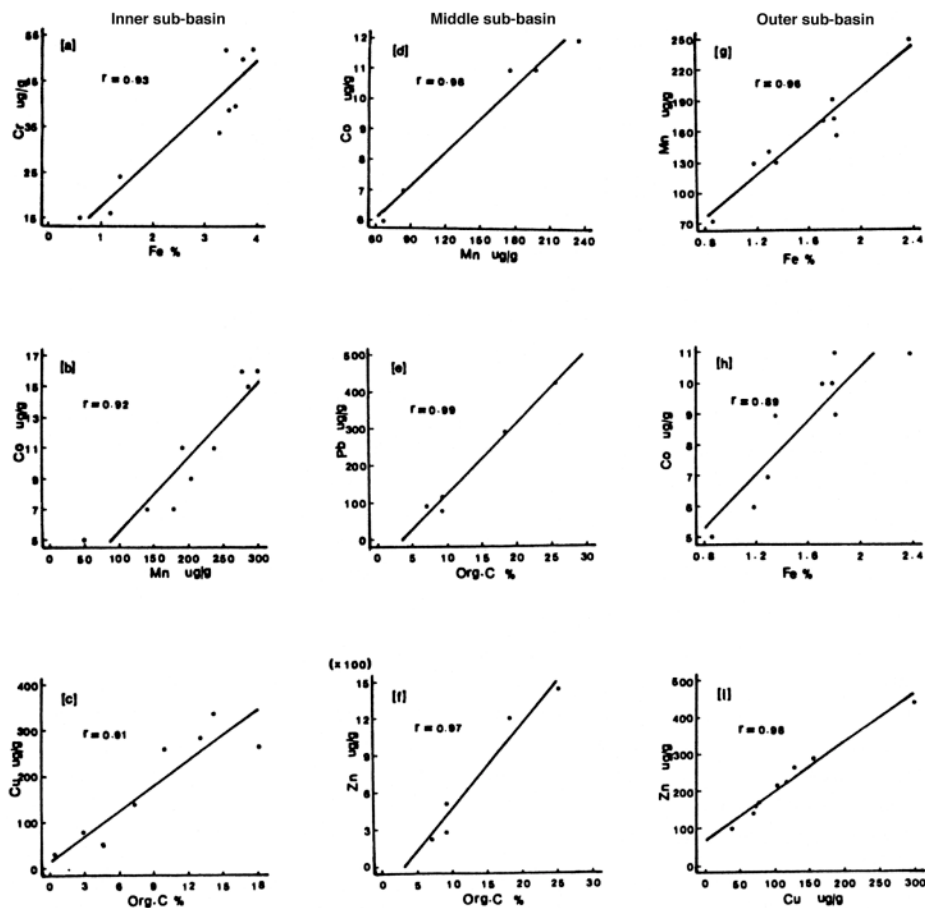
FIG. 2. Some of the important scatter plots with significant correlation coefficient in Al-Arbaeen lagoon surface sediments.

middle sub-basins (Tables 3a,b and Fig. 2c and f). The association between Cu and Zn and organic carbon in marine sediments is widely accepted (Brannon *et al.,* 1977; Angelidis and Gibbs, 1989; Mat *et al.,* 1994). Cu is the highest member of the Iriving-William series (Stumm and Morgan, 1981) forming co-ordination complexes of great stability. In this sulphidic environment and according to the solubility product of Cu and Zn sulphides, it is assumed that these sulphides will eventually precipitate even in the presence of FeS (Oakley *et al.,* 1980). However, Leckie and Nelson (1975) proposed the following mechanisms for the incorporation of trace metals in sulphidic deposits: (1) precipitation of pure metal sulphides; (2) solid solution formation of FeS and metal sulphides, and (3) adsorption of trace metals on FeS. The negative correlation between these two metals with Fe, mostly found as iron sulphide, indicates that none of these mechanisms are operating. It is supposed that due to the ability of Cu and Zn to form highly stable organic complexes and the presence of elevated concentrations of com-

plexing organic legand, both Cu and Zn are preferentially associated with organic matter. In an experimental study (Oakley *et al.,* 1980) using a model anaerobic sediment containing 2% humic acid, 20% clay, 78% sand, and 0.05% FeS-S, Cu was essentially distributed between FeS (~ 60%) and humic acid (~ 25%), while Zn was partitioned between clay (~ 50%) and humic acid (~ 25%). In the present study, organic carbon is of much greater importance and the sand fraction of the sediments is mostly composed of calcium carbonate, quartz and plagioclase feldspar. These minerals are reputed by their low adsorption capacity, due to their small specific surface area, and regarded as diluents for trace metals host materials (Martincic *et al.,* 1990). Therefore, the association of Cu and Zn with organic phase is expected in the lagoon bottom sediments.

TABLE 3a. Correlation coefficient matrix between metals and organic carbon in the inner sub-basin sediments.

	Fe	Mn	Cu	Zn	Ni	Cr	Co	Pb	Org. C
Mn	0.86								
Cu	– 0.69	– 0.67							
Zn	– 0.14	– 0.31	0.77						
Ni	0.30	0.23	– 0.31	– 0.09					
Cr	0.93	0.90	– 0.70	– 0.22	0.18				
Co	0.85	0.92	– 0.66	– 0.28	0.11	0.96			
Pb	0.32	0.15	0.30	0.75	– 0.11	0.30	0.21		
Org. C	– 0.62	– 0.53	0.91	0.76	– 0.37	– 0.54	– 0.50	0.36	
CaCO$_3$	– 0.67	– 0.78	0.19	– 0.21	0.11	– 0.78	– 0.81	– 0.60	– 0.01

r = 0.60; level of significance = 95%; n = 9.

TABLE 3b. Correlation coefficient matrix between metals and organic carbon in the middle sub-basin sediments.

	Fe	Mn	Cu	Zn	Ni	Cr	Co	Pb
Mn	0.65							
Cu	– 0.58	– 0.88						
Zn	– 0.57	– 0.86	0.99					
Ni	– 0.54	– 0.97	0.92	0.91				
Cr	0.72	0.86	– 0.58	– 0.55	– 0.74			
Co	0.75	0.98	– 0.91	– 0.90	– 0.96	0.83		
Pb	– 0.50	– 0.84	0.98	0.97	0.88	– 0.58	– 0.87	
Org. C	– 0.41	– 0.85	0.97	0.97	0.91	– 0.56	– 0.86	0.99

r = 0.75; level of significance = 95%; n = 5.

Table 3c. Correlation coefficient matrix between metals and organic carbon in the outer sub-basin sediments.

	Fe	Mn	Cu	Zn	Ni	Cr	Co	Pb	Org. C
Mn	0.96								
Cu	0.26	0.05							
Zn	0.24	0.03	0.98						
Ni	0.63	0.62	0.41	0.42					
Cr	0.78	0.84	0.23	0.22	0.63				
Co	0.89	0.84	0.08	0.06	0.44	0.50			
Pb	0.30	0.13	0.63	0.67	0.41	0.13	0.41		
Org. C	– 0.31	– 0.45	0.43	0.51	– 0.19	– 0.25	– 0.45	0.04	
CaCO₃	0.03	0.24	– 0.69	– 0.72	0.19	0.09	0.12	– 0.30	– 0.82

r = 0.60; level of significance = 95%; n = 9.

Ni and Pb association

These two metals do not show any definite association with the different geochemical phases. In the inner sub-basin sediments only Pb has positive correlation with Zn (Table 3a). In the middle sub-basin sediments Ni and Pb are highly inter-related and are associated with organic carbon (Table 3b; Fig. 2e). In the outer sub-basin sediments, Ni has positive correlation with Fe and Mn, and Pb correlates positively with Cu and Zn (Table 3c). Huerta-Diaz and Morse (1992) suggested that Ni is moderately incorporated into pyrite in anoxic environments, while the association of Pb with pyrite is insignificant. Jacobs *et al.* (1985) observed the unique solubility behaviour of Ni across the O_2/H_2S interface in the anoxic Framvaren Fjord and stated that the processes controlling the solubility of Ni appear to be largely independent of the redox state of the water even in intensively reducing waters. Several authors have found that these metals could be associated with the organic, sulphidic, and carbonate geochemical phases (Jacobs *et al.,* 1985; Pruysers *et al.,* 1991; Huerta-Diaz and Morse, 1992). Further examination of the sediments using more specific leaching technique is required to elucidate the geochemical sink of these metals in the area.

Conclusion

Waste water dumping has dramatically affected the environment in the Al-Arbaeen coastal lagoon. The water column is anoxic and enriched in H_2S, particularly in the bottom stagnant layer. Sediments are greatly enriched in organic matter and are anoxic-sulphidic. Some heavy metals in the surface sediments (Fe, Cu, Zn, and Pb) are enriched (with respect to the average concentrations encountered in the remote coastal area) by factors ranging from about 5 to 90 but for other metals enrichment factors are less and vary from 1 to 5.

Several metal associations are found in the lagoon sediments. These include metals of which the redox processes are important (Fe, Mn, Co and Cr) and seem to exist as sul

phide minerals or associated with iron sulphide minerals. Zn and Cu have been shown to be preferentially associated with the organic phase, particularly in the inner and middle sub-basins. Pb and Ni do not show any definite association with the different geochemical phases. Association of metals with the unstable sulphidic and organic phases indicates the reactivity of these metals. Any processes leading to redistribution of the sediments may result in the release of considerable amounts of these toxic metals into the lagoon environment.

Acknowledgements

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توزيـع وسلوك بعض العناصر الثقيـلة في الرواسب السطحية لبحيرة الأربعين – جـدة – ساحل البحر الأحمر

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المستخلص .   تبين من تحليل الرواسب السطحية التي جمعت من قاع بحيرة الأربعين أنها تتكون من وحل طرى ، داكن اللون ، غني بالمواد العضوية ، ينبعث منه غاز كبريتد الهيدروجين الكريهة الرائحة والسام . وتدل هذه الخواص على أن حوض البحيرة يتميز ببيئة ذات طاقة منخفضة وأن ظروف الاختزال بها ملائمة لترسيب الكبريتيدات .

إن تركيز كلا من الحديد – المنجنيز – الزنك – الرصاص – النيكل – الكروم – الكوبلت – النحاس – الكربون العضوي في رواسب البحيرة أعلى من تراكيز المستوى الطبيعي الذي تم قياسه في الرواسب البحرية الغير ملوثة ، ويعزي ذلك إلى صب الفضلات الآدمية في البحيرة .

تدل النتائج على أن سلوك كلا من الحديد – المنجنيز – الكوبلت – الكروم قد تأثر بشدة بتفاعلات الأكسدة والاختزال وعلى ما يبدو فإن تلك العناصر متواجدة في الرواسب على هيئة كبريتيدات أو مصاحبة لكبريتيدات الحديد ، بينما فضل الزنك والنحاس الارتباط بصحبة الكربون العضوي . أما النيكل والرصاص فلم يظهرا أي صحبة محددة مع النطاقات الجيوكيميائية المختلفة في الرواسب .

إن عملية تحرر بعض العناصر نتيجة للعمليات التحويرية ، وترسيب تلك العناصر مع كبريتيدات الحديد والكربون العضوي يبدو أنها العمليات المحتملة لتوضيح التوزيع الغير متجانس لهذه العناصر الناتج من تأثير تفاعلات جهد الأكسدة والاختزال في الرواسب السطحية للبحيرة .