Mineralogical and Chemical Composition of Dry Atmospheric Deposition on Jeddah City, Eastern Coast of the Red Sea

A.E. Rifaat, A.S. Basaham, M.H. El-Mamoney and M.A. El-Sayed

Faculty of Marine Sciences 80207, King Abdulaziz University, Jeddah 21589, KSA

Abstract. Atmospheric dust contains harmful minute-sized minerals that may cause a remarkable environment effect on marine life. The city of Jeddah expands drastically since the seventies and the dust content of harmful minerals increases. In this study fifty-two dust samples were collected at four locations using vertical dust trappers. Dust samples were analyzed for the major elements Al, Fe, Ca and Mg and the trace elements Mn, Cu, Zn, Cr, Ni, Pb and Cd. Some selected samples were analyzed for grain size distribution and mineralogical composition. Particles of the falling dust were mainly silty-sized and particle diameter increases in the direction of the prevailing wind indicating local mobilization. The mineralogical composition was dominated by quartz, plagioclase feldspars, calcite and gypsum. These minerals are widely present in the rock outcrops in the vicinity of the city. Results of major and trace elements show that trace elements particularly Cu and Zn were enriched in the dust particles relative to the continental crust. Applying factor analysis permitted the distinction of two dust populations, one originating from the crustal denudation and the other is constituted from anthropogenic particles. Mixing of the two components at varying degrees explains the variability of the chemical composition of the dust material.

Keywords: Dust, grain size, mineralogy, chemical composition, factor analysis, Red Sea.

Introduction

It has become apparent in the last few years that the atmospheric dust transport is significant environmental factor as it has the capability to move both natural and pollutant substances from the continents to both coastal and open sea areas (GESAMP, 1989; Duce et al., 1991; Guerzoni et al., 1997 and Migon et al., 2001). Some of these substances such as lead, cadmium, polyaromatic hydrocarbons and pesticides, when entering the oceans are potentially hazardous to the marine life. Others, such as compounds of nitrogen, phosphorus and iron, are nutrients and may enhance marine productivity (Guerzoni et al., 1997 and Migon et al., 2001). Several studies have related some marine problems such as pollution of the marine environment, over-blooming of phytoplankton, and coral diseases to aeolian dust deposition on the sea surface (Prospero and Nees, 1986, Muhs et al., 1990, Swap et al., 1992, Hughes, 1994, Smith et al., 1996, Done et al., 1996, Subba Rao et al., 1999 and Harvell et al., 1999). Atmospheric input might thus exert many different effects on the marine environment and it is necessary to evaluate the magnitude, the temporal and spatial variations of the atmospheric fluxes of these materials to both coastal and open waters.

The chemical and mineralogical composition and the fate of the atmospheric deposition on the Eastern Red Sea coast have not been sufficiently studied as revealed from the literature review. The present study aims to investigate the mineralogical and chemical composition of the atmospheric deposition in order to distinguish the possible source(s) of the dust material. Also, measuring the extent of the impact of locally generated dust particles on the average composition of the dust. The interaction of dust with surface seawater may have important ecological consequences.

Area of Study

The area of study extends from Latitude 21° 18' N to Latitude 21° 45' N covering a distance of ~50 km and representing the metropolitan area of Jeddah City (Fig. 1). The city of Jeddah occupies part of the narrow Tihama coastal plain extending from the mountain chain of the Arabian Shield to the eastern shoreline of the Red Sea. The area is characterized by an arid climate, scarce precipitation ($\approx 63 \text{ mm y}^{-1}$) and wind is mainly NNW (Morcos, 1970). Arid conditions enhance wind erosion and thus wind transport becomes significant in conveying the erosion products to the coastal and offshore water. Jeddah City is one of the most important urban agglomerations on the Eastern coast of the Red Sea. Since the seventies of the last century, the city witnessed vast demographic and

economic expansions. As a result, emanations from different industries, particularly refineries, and vehicles have increased greatly and a considerable part of these emanations is carried to the adjacent marine environment.

Materials and Methods

Wind Data and Dust Collection

The meteorological data are provided by KAIA (King Abdulaziz International Airport) station number 41024 located at 21° 42' 37" N, 39° 11' 12" E, at the elevation of 16.88 m above the mean sea level (Fig. 1). Thirteen months of wind data were obtained, from June 2002 until June 2003. The aeolian dust was collected at four locations (Fig. 1). At each location, four separate dust trappers (vertical dust flux type) were used to collect the falling dust. The set of plastic vials (dust trappers) was drawn from each location monthly. Table 1 shows the efficiency of the dust trappers at each sampling location during the period of collection.

Table 1. Efficiency of dust trappers at each	location during the period of sampling.

			Location		
		А	С	D	Е
June	2002	0.995	0.976	0.919	0.949
July	2002	0.996	0.899	0.920	0.869
August	2002	0.967	0.973	0.983	0.985
September	2002	0.989	0.972	0.988	0.909
October	2002	0.805	0.991	0.910	0.865
November	2002	0.962	0.991	0.987	0.747
December	2002	0.934	0.961	0.943	0.26*
January	2003	0.919	0.975	0.966	0.725
February	2003	0.978	0.966	0.965	0.867
March	2003	0.951	0.944	0.979	0.23*
April	2003	0.992	0.965	0.972	0.944
May	2003	0.972	0.984	0.963	0.820
June	2003	0.985	0.964	0.943	0.840
	Mean efficiency	0.957	0.966	0.957	0.952

* Results not included in calculation due to unknown error in sampling procedure.



Fig 1. The area of study and the locations of dust samples.

Grain Size Analysis

Selected dust samples were subjected to grain size analysis using a Shimadzu SALD-3001 Laser Particle Analyzer. The apparatus was

adjusted to measure the percentages of grain sizes in the range of 2000-0.100 μ m (-1 to 13 phi). Calculations of grain size statistical parameters were carried out using a home developed computer program (Rifaat, 2004). The program calculates the grain size parameters of Folk and Ward (1957), determines the sediment type according to the nomenclature of Shepard (1954) and plots the probability curves.

X-Ray Mineralogical Analysis

Representative powdered samples were emulsified with few drops of distilled water. The emulsion was smeared over a glass slide. The dry slide was placed in the X-Ray diffractometer (Shimadzu XRD 6000). The operating conditions are characterized by a scan angle from 2 to 60° 20, 40 kv, 40 mA, and 2°/min goniometer speed.

Metal Analysis

Powdered samples were subjected to complete dissolution using a nitric/hydrofluoric acid mixture (Basaham *et al.*, 1998). The acid was evaporated to near dryness and the residue was taken in 0.1 M HCl. Concentrations of Al, Fe, Ca, Mg, Mn, Cu, Zn, Cr, and Ni were determined using the atomic absorption spectrophotometer (Perkin Elmer Analyst 800, equipped with Zeman background correction). Lead and Cd were measured using the thermal atomization technique. The accuracy and precision of our results have been checked by analyzing ten replicates of the LKSD reference material supplied by CANMET, Canada and sample No. 287 of the reference marine sediment IAEA 356 supplied by IAEA Monaco. Precision was below 10% for all elements.

Results and Discussions

Wind Regime

Wind data showed that during the period from June until August 2002 the prevailing wind directions were north, northwest and west. September and October 2002 were characterized by the prevalence of the west-southwest and west wind directions. The period from November 2002 to January 2003 were dominated by the north and north-northeast wind. From February 2003 to June 2003, the wind directions were normally north and northwest (Fig. 2). Four dust storms blew over the study area on June 2002, March 2003, April 2003 and May 2003. During those months, the prevailing wind directions were N and NNE (Table 2) but during the days of dust storms, the wind direction was changed to the south and west components.



Fig. 2. Wind rose diagrams showing the frequency of wind directions.

Station	Date	Wind direction	Mean speed km/hr	Max. Speed km/hr	Cloud cover
41024	5-Jun-2002	NNW	14	34	48
41024	25-Mar-2003	S	18	18	64
41024	7-Apr-2003	SSW	7	23	43
41024	8-Apr-2003	SSW	8	21	55
41024	25-May-2003	WSW	5	24	67
41024	26-May-2003	W	5	24	67
41024	27-May-2003	SW	5	23	74

Table 2. Prevailing wind directions during the days of dust storms.

Grain Size Distribution

Table 3 presents the calculated statistical grain size parameter. It reveals that most of the collected dust samples fall in the silt size classes. The mean grain size of dust ranges from 3.63 phi (very fine sand) to 5.46 phi (medium silt) with the coarser types at location E. Figure 3 is a ternary diagram (Shepard, 1954) showing that at location C the dust is dominated by sandy silt types. The dust mean size increases in an E-W direction following the course of the prevailing wind (Fig. 3). The presence of coarser particles at the eastern extremity indicates that part of the aeolian dust particles are locally generated from the bordering mountains and that they may adhere to the area of production. Their transport away will be associated with storm events.



Fig. 3. Ternary diagram showing the types of collected dust at the four locations along Jeddah city (nomenclatures based on Shepard's 1954 classification).

SAMPLE	SAND%	SILT%	CLAY%	MEAN	ТҮРЕ	SORTING	ТҮРЕ
A0902	48.76	33.93	17.31	4.65	Coarse silt	2.15	Very poorly sorted
A1102	34.24	49.65	16.11	4.95	Coarse silt	1.96	Poorly sorted
C0802	23.04	55.42	21.54	5.46	Medium silt	1.9	Poorly sorted
C1202	27.52	55.49	16.98	5.16	Medium silt	1.89	Poorly sorted
D1202	42.71	45.65	11.64	4.5	Coarse silt	1.92	Poorly sorted
E0103	82.51	17.49	0	3.63	Very fine sand	0.52	Moderately well sorted
E0403	67.41	17.95	14.64	3.97	Very fine sand	2.34	Very poorly sorted
	SKEWNESS	ТҮРЕ	KURTOSIS	TYPE	SEDIMENT TYPE		
A0902	0.41	Strongly fine skewed	0.9	Platykurtic	SILTY SAND		
A1102	0.23	Fine skewed	1.03	Mesokurtic	SANDY SILT		
C0802	0.24	Fine skewed	0.94	Mesokurtic	SANDY SILT		
C1202	0.18	Fine skewed	1.03	Mesokurtic	SANDY SILT		
D1202	0.18	Fine skewed	1.08	Mesokurtic	SANDY SILT		
E0103	0.26	Fine skewed	1.26	Leptokurtic	SAND		
E0403	0.54	Strongly fine skewed	1.1	Mesokurtic	SILTY SAND		

Table 3. Statistical grain size parameters of dust samples in Jeddah city.

Dust Flux

The aeolian dust data showed that at location C (the western extremity of Jeddah close to the Red Sea coast), the collected dust was minimum during August 2002 (198.6 mg) and maximum during December 2002 (1491 mg). The daily dust flux at the same location varied from 13.9 mg da⁻¹ym⁻² (August 2002) to 99.3 mg day⁻¹m⁻² (December 2002). At location D, half way between the plain and the coast line, the minimum and maximum dust fluxes were also measured during the same time span respectively, however, dust flux was found to be 1.2 to 1.4 times higher at this station (Table 4). At location A, the monthly collected dust was minimum $(0.1194 \text{ mg da}^{-1}\text{ym}^{-2})$ during July 2002 and maximum $(1.5361 \text{ mg da}^{-1}\text{ym}^{-2})$ during November 2002. Location E, the closest to the coastal mountains, was different. The daily flux was much greater than the other locations showing a minimum of 99.3 mg day⁻¹m⁻² during June 2003 and a maximum of 1099 mg day⁻¹m⁻² during January 2003 (Table 4). The greater dust flux and its wide temporal variability at location E may be explained by its proximity to

the coastal mountains which could be a major local source of dust where the effect of wind can be neglected. This assumption is supported by grain size analysis which showed dominance of coarser dust grains at this location.

Comparing the quantities of dust collected during June 2002 and June 2003 (overlapping months), lead to the observation that at locations A, C, and D the amount of settling dust in June 2002 is much less than that of June 2003. On the other hand, the amount of dust collected at location E during June 2002 is 2.6 times compared to those collected during June 2003 (Table 4). Generally, location A is characterized by the lowest dust flux among the studied locations, while locations C and D displayed approximately comparable fluxes.

		Monthl	y Dust w	eight in g	grams	Daily D	ust settli	ng in gra	ıms	Daily Dust settling (dust flux rate) g/day/m ²			
		Locatio	n			Locatio	n			Location			
Month	Year	А	С	D	E	А	с	D	Е	А	С	D	Е
June*	2002	0.1255	0.5547	0.6752	3.4588	0.0040	0.0179	0.0218	0.1116	0.0092	0.0405	0.0493	0.2528
July	2002	0.1194	0.4643	1.0749	2.0007	0.0039	0.0150	0.0347	0.0645	0.0087	0.0339	0.0786	0.1462
August	2002	0.3798	0.1896	0.2669	2.2268	0.0123	0.0061	0.0086	0.0718	0.0278	0.0139	0.0195	0.1627
September	2002	0.1732	0.8723	1.4352	3.2132	0.0058	0.0291	0.0478	0.1071	0.0131	0.0659	0.1084	0.2427
October	2002	0.7088	0.6119	0.8352	3.1803	0.0229	0.0197	0.0269	0.1026	0.0518	0.0447	0.0610	0.2324
November	2002	1.5361	0.2775	0.4970	5.3940	0.0591	0.0107	0.0191	0.2075	0.1338	0.0242	0.0433	0.4700
December	2002	0.5367	1.4905	1.6783	8.9824	0.0158	0.0438	0.0494	0.2642	0.0358	0.0993	0.1118	0.5985
January	2003	0.2918	0.4617	0.7337	15.0323	0.0094	0.0149	0.0237	0.4849	0.0213	0.0337	0.0536	1.0986
February	2003	0.3762	0.7298	0.9609	5.0152	0.0125	0.0243	0.0320	0.1672	0.0284	0.0551	0.0726	0.3787
March*	2003	0.6674	1.0783	1.0744	7.2484	0.0238	0.0385	0.0384	0.2589	0.0540	0.0872	0.0869	0.5865
April*	2003	0.4020	0.8325	0.7200	2.1768	0.0122	0.0252	0.0218	0.0660	0.0276	0.0572	0.0494	0.1494
Mav*	2003	0.2272	0.4318	0.6021	1.4480	0.0073	0.0139	0.0194	0.0467	0.0166	0.0316	0.0440	0.1058
June	2003	0.7612	1.1356	1.1672	1.3146	0.0254	0.0379	0.0389	0.0438	0.0575	0.0858	0.0881	0.0993

*dust storm

In a previous study (Behairy *et al.*, 1985), the dust flux measured north of Jeddah (station C in the present study), during December 1981 to

May 1982, ranged between 23 mg day⁻¹m⁻² and 61 mg day⁻¹m⁻² with an average of 37 mg day⁻¹m⁻². This value is quite similar to the flux of the present study (52 mg day⁻¹m⁻²). Our monthly average dust flux varied between 37 mg day⁻¹m⁻² and 348 mg day⁻¹m⁻². These values are similar to those mentioned by Smith *et al.*, (1970) in Kansas, USA, Rabenhorst *et al.*, (1984) Texas, USA, Gile and Grossman, (1979), New Mexico, USA, Ganor and Mamane, (1982), Eastern Mediterranean, Herrmann, (1996), West Africa, McTainsh and Walker, (1982), North Africa, Swap *et al.*, (1992), Amazon, and Ramsperger *et al.*, (1998), Argentina (Table, 5). Derbyshire *et al.*, (1998) reported a dust flux value as high as 1.0 g/day/m² in Lanzhou China during heavily dust storms.

Location	Input (g/day/m ²)	Reference
Kansas, U.S.A.	0.055–0.25	Smith et al., 1970
Texas, U.S.A.	0.033	Rabenhorst et al., 1984
New Mexico, U.S.A.	0.027–0.162	Gile & Grossman, 1979
Eastern Mediterranean	0.055–0.11	Ganor & Mamane, 1982
West Africa	0.038-0.427	Herrmann, 1996
North Nigeria	0.271	McTainsh & Walker, 1982
Amazon	0.052	Swap et al., 1992
Argentina	0.101–0.214	Ramsperger et al., 1998
Jeddah, KSA	0.023-0.061	Behairy et al., 1985
Jeddah, KSA	0.0087-1.0986	Present study

Table 5. Comparison of dust deposition rates in a worldwide context.

Dust Mineralogy

Quartz (~54%) and plagioclase (~17%) are the dominant minerals in the investigated samples. Gypsum and calcite are present in most of samples in amounts averaging 12% and 10%, respectively. Occasional traces of halite, dolomite, amphibolies and kaolinite are identified in some collected dust samples (Table 6).

Sampl	Quart	Plagiocla	Calcit	Halit	Gypsu	Dolomi	Amphibol	Kaol
C0702	32.6	12.6	7.4	10.5	23.7	4.7	4.7	3.7
D0802	45.3	16.6	14.4		18.8	3.1	1.8	
E0403	74.8	7					18	
A0902	58.8	22.4	5.9		5.7		7.7	
C0802	56.6	12.2	7.9	10.6	9		3.7	
E0103	62.1	25.3	2.8	1.1	1.7		3.9	3.3
A1103	55.7	18	8.3		8.8		5.2	4.1
D1202	42.7	20	13.3		14		10	
C1202	55.7	18.6	19.1				3.3	3.3
Avera	53.8	17	9.9	7.4	11.7	3.9	6.5	3.6

Table 6. Percentages of minerals composing air-dust particles.

There are two main topographic features around Jeddah City; the coastal plain zone extending from the shoreline for about 10 km to the east and the eastern alluvia and outcrops (Behairy, 1980). The coastal plain consists of Quaternary coralline limestone, while the eastern area is rugged and is characterized by weathering products derived from the surrounding Precambrian mountains (Behairy et al., 1985). The outcropping Precambrian hills of igneous and metamorphic origins include granite, gneiss, andesite, diabase, rhyolite, andesite porphyry and greenstone in addition to some minor appearance of diorite, granodiorite and amphibole schist (Behairy et al., 1985). Shehata et al., (1998) reported that the mineralogical composition of sand dunes of southeast Jeddah is similar to that of the surrounding igneous, metamorphic and sedimentary rocks. According to Shehata et al., (1998), the dunes consist mainly of quartz, feldspars, biotite and hornblende in addition to minor amounts of chlorite, actinolite, sphene, zircon, epidote and opaque minerals. Gypsum was also present on the dune surface in the form of thin veneer. On the other hand, Behairy et al., (1985) found that kaolinite and montmorillonite separately constitute the clay mineral assemblage in the dust particles. Kaolinite was supposed to be the product of chemical weathering of feldspars under high humidity (humidity reaches more than 70% along the coastal plain). Gypsum, although reported among the mineral assemblage of the sand dune southeast of Jeddah (Shehata et al., 1998), its presence in most of the collected dust samples is probably related to sabkha areas in addition to its use in constructions and building restoration and decoration processes. These operations are responsible for releasing important quantities of gypsum to the atmosphere.

	Matal	1	Гa	Ľ	MG	Ma	2	75	<u>ځ</u>	NI:	ЧD	5
	INICIAL	R	LC	Ca	SIVI	TITAT	20	711	5		I U	
Location		g/gu	g/gu	g/gu	g/gn	g/gu	g/gn	g/gu	g/gn	g/gu	g/gu	ng/g
	Annual average	31438	40847	42644	12253	713	153	392	124	64	105	610
A	STDEV	18294	8385	19453	0662	119	74	106	21	18	76	220
	MAXI	63139	50280	67729	25880	879	308	572	164	83.6	74.7	1035
	MINI	742	25160	16760	3720	571	91	245	99	28.5	50.9	335
	Annual average	25449	35796	58266	13887	589	214.4	371	112	67	28	555
С	STDEV	16113	13453	20547	8964	112	189	254	37	18	16	199
	MAX	50420	59900	87944	27440	766	710	1070	174	101	51.9	1090
	MIN	5702	9800	18720	3640	438	72.8	147	64.2	43.6	5.5	310
	Annual average	38231	43669	63189	16332	720	109	424	118.9	81	86	499
D	STDEV	13692	4843	23133	6321	60	16	125	20	16	21	334
	MAX	55580	50800	113320	23960	820	140	653	166	104	114	280
	MIN	14694	31740	27660	5040	599	9.6	280	96.8	57.8	46.9	1494
	Annual average	30857	42594	40878	11215	647	72.4	157	66	41	35.7	204
Е	STDEV	18997	5798	16667	7498	97	16.5	56.7	21.1	16.3	14.5	61.7
	MAX	62740	55160	58160	22080	823	55.9	247	152	72.8	62.7	299
	MIN	3818	3800	5740	1080	493	102	81.4	72.8	12.4	17.3	112
	Overall average	31493	40727	51244	13422	667	137	336	114	63	64	476

Table 7. Statistical summary of the analytical results.

Al	Fe	Ca	Mg	Mn	Cu	Zn	Cr	Ni	Pb	Cd
D	D	D	D	D	С	D	А	D	А	А
А	Е	С	С	А	А	А	D	С	D	С
Е	А	А	А	Е	D	С	С	А	Е	D
С	С	Е	Е	С	Е	Е	Е	Е	С	Е

 Table 8. Classification of locations in a descending order according to the concentration of the different elements.

Chemical Composition

Elemental composition of dust particles shows a wide range of temporal and spatial variability (Table 7). The magnitude of such variability is different for each element. Major elements vary widely at station A where the RSD (relative standard deviation) varies from 40 to 50%. At the other stations, variations are narrower for the ensemble of the elements. Seasonal variability did not show any distinct pattern that could be attributed to a particular climatic event. Mn and other trace elements showed also no definite pattern. Mn is the element that showed the lower variability. The relative standard deviation for the four sampling stations varies between 8 and 19%. The other trace elements vary approximately in the same order of magnitude (Table 7). On annual basis, the relative abundance of the major elements was found to follow the following order: Ca> Fe> Al> Mg. This order was not strictly followed by Al and Fe at all locations. For trace elements, a clear and distinct order was observed for trace elements and the elements could be arranged in the following order: Mn> Zn> Cu> Cr>Ni=Pb>>Cd. The most pronounced feature of trace elements distribution is the fact that the average annual concentrations for all trace elements with the exception of that of Pb, are minimum at station E which is the most easterly station (Table 8). This location is characterized by the highest dust load which was supposed to have an appreciable fraction from local contribution. Reason behind this distinction may reside in the fact that particles forming the dust at this location are the coarsest. The massive dilution of the anthropogenic particles with particles of local origin having low trace element concentrations may be also considered as an acceptable explanation. Elevated concentrations of trace elements were recorded at stations situated near traffic axes (stations A &D).

Comparing the results of the present study with those given by Behairy *et al.*, (1985), the most pronounced observation is the significant lowering of Cd concentration. Behairy *et al.*, (1985) attributed the high Cd concentrations to the emission of particles rich in Cd from an old cement factory. Dismantlement of the factory in 1995 may explain the lowering of Cd in the dust particles at the present time.

Factor Analysis

Results of factor analysis show that elements in aeolian dust are controlled by two factors (Fig. 4): Factor 1 involves the association of aluminium, iron, calcium, magnesium, manganese, copper, zinc, lead, and cadmium. The explanation of this factor is that the distribution of positively associated metals is controlled by the amounts of aluminium silicate terrigenous material (Spencer et al., 1968) (probably of crustal and/or Saharan origin). Quartz is usually stained by iron, while plagioclase is essentially composed of Na-Ca-Al silicates with varying amounts of Fe, Zn, Pb, Cu and Mn as minor constituents (Spencer et al., 1968). Amphiboles are Ca-Mg-Al silicates with varying amounts of Fe and Cu as minor constituents. Calcite contains Cd in solid-solution with Ca in the crystal structure (Farely et al., 1985; Davis et al., 1987; Comans and Middelburg, 1987). This factor is entirely a mineralogical factor and represents the interaction of dust-forming minerals that control the metal concentrations in aeolian dust. On the other hand, Factor 2 is an association of Fe. Mn. Cu. Zn. Cr. Ni. Pb and Cd. It clearly delineates the existence of non-terrigenous source for these metals. Figure 4 shows the relationship between the two factors. It is clear that, Al, Ca and Mg are entirely contributed by a terrigenous source while Cr and Ni are completely controlled by non terrigenous source. Fe, Cu, Zn, Mn, Pb and Cd are contributed from both terrigenous and anthropogenic sources.



Fig. 4. Plot of the varimax rotated factor model of major and minor metals in eolian dust from Jeddah.

Enrichment Factor

The crustal enrichment factor method has been commonly used as a first step in attempting to evaluate the strength of contribution from crustal and non-crustal sources (Chester *et al.*, 1986; Gao *et al.*, 1992). The enrichment factor (EF) relative to any reference material is defined as:

 $EF_{reference, X} = (X/Y)_{dust} / (X/Y)_{reference}$

where X is the studied element and Y is the reference element, $(X/Y)_{dust}$ is the concentration ratio of X to Y in the dust sample, $(X/Y)_{reference}$ is the average concentration ratio of X to Y in the reference material.

The upper crust elemental composition was selected as reference to calculate the EF. This choice is based on the fact that the crustal material is widely used in the calculation of the EF and that its chemical composition is well known (Wedepohl, 1995; Gao *et al.*, 1992).

The annual averages of the EF at the different sampling locations are summarized in Table 9. The main features of the results are: 1) all the major constituents and Mn have an EF lower than 10 (2.29 to 8.86) confirming a dominant contribution of crustal material, 2) all the trace elements (except for Pb at location C and Cr at location D) have an EF higher than 10 indicating an important participation of non crustal material (probably contaminated soil and urban particles) in the dust population, 3) the most enriched elements are Cu and Zn, and 4) lead and cadmium are highly enriched at station A relative to the other sampling locations. Station A is located near major traffic arteries. Both Pb and Cd are liberated during fossil fuel burning and are largely contributed by vehicle exhaust. These features point out that the dust is composed of at least two populations having different composition that mix at varying proportions according to the geographic location and wind conditions.

Table 9. Average annual EF_{upper crust} for the major and minor elements at the different sampling locations.

Location	Fe	Ca	Mg	Mn	Cu	Zn	Cr	Ni	Pb	Cd
А	8.86	4.30	2.29	4.93	36.38	25.78	12.38	13.46	31.11	23.54
С	4.25	7.61	3.14	4.86	49.86	27.24	13.84	16.98	6.40	21.56
D	3.44	4.58	2.47	3.43	20.19	20.36	8.88	11.54	12.45	11.66
Е	7.39	5.56	2.8	6.6	27.86	17.19	16.44	12.47	12.93	10.58

Relative Participation of Non-Crustal Material

To quantify the man-mobilized fraction for each element, the excess fraction was calculated. The excess fraction represents the fraction of non-terrigenous origin and is given by the following formula:

 $X_s = 100/Me_{sample} X \{Me_{sample} - [Al_{sample} x (Me/Al)_{crust}]\}$

Where:

Xs is the fraction of element that is not of crustal origin,

Me_{sample} is the element concentration in the sample,

Al_{sample} is the concentration of Al in the sample,

(Me/Al)_{crust} is the element/aluminium ratio in the crust.

Results of the excess, non-terrigenous fraction, calculated using the upper crust elemental composition are summarized in Table 10. It is worthy mentioning that the crustal chemical composition was selected for the aforementioned reasons and not due to a confirmed proof that crustal material is the dominant component of our dust material. Therefore, results presented in Table 10 should be used with caution and numbers given should be considered as indicative of tendency rather than a real measure.

Location	Fe	Ca	Mg	Mn	Cu	Zn	Cr	Ni	Pb	Cd
А	70.9	71.8	50.8	70.5	95.9	94.6	88.6	85.1	91.9	92.6
С	73.0	83.5	67.4	72.2	97.3	948	89.6	90.2	71.0	93.9
D	65.8	76.5	57.6	64.2	93.3	93.5	85.0	88.0	89.7	88.2
Е	70.7	70.7	34.4	67.6	91.73	84.6	84.9	77.93	77.4	79.2

 Table 10. Average annual excess fraction (non-crustal) (%) for the major and minor elements at the different sampling locations.

It is not surprising that all the elements have an excess fraction even those that are supposed to have a dominant crustal origin. The formula for calculating the excess fraction is derived from the formula for the calculates of the EF, and it was noticed that even the crustal originating elements are slightly enriched relative to the crustal composition. However, the excess fraction for Fe, Ca, Mg and Mn are still greatly lower than those of trace elements. The excess iron may result from the iron oxides and iron stain on the surface of the quartz particles and probably as discrete iron oxide particles. Behairy *et al.*, (1985) detected

182

the mineral goethite in the dust samples, while Ca may be contributed by the mineral calcite where the latter does not interfere in the calculation. The elevated Mg excess fraction at station C may result from the contribution by sea salts as this station C is very close to the sea.

The high excess values calculated for Cu, Zn, Cr, Ni, Pb and Cd confirm the important participation of a non-crustal enrichment in these elements and mixing with the crustal component.

Elemental Flux

Results of flux calculations for the whole set of elements at the four sampling locations are presented in Table 11. Highly variable amounts of major and trace elements appear to be associated with the falling dust. High variability in the atmospheric flux of trace and major elements was also observed by Ridame *et al.* (1999) in their study on the atmospheric deposition of Al, Fe and trace elements in the northwestern Mediterranean. The element fluxes are apparently controlled by the quantity of the falling dust rather than by the concentration of elements. This is obvious at location E where dust flux is the highest while concentrations of the elements are the lowest.

Location	Al	Fe	Ca	Mg	Mn	Cu	Zn	Cr	Ni	Pb	Cd
А	542	783	622	231	11.5	2.22	6.29	1.91	1.03	1.48	8.79
	(753)	(733)	(568)	(359)	(11.3)	(1.93)	(6.55)	(1.61)	(0.89)	(1.28)	(8.51)
С	488	692	1124	263	11.8	3.78	7.05	2.18	1.31	0.54	10.33
	(451)	(451)	(594)	(227)	(6.5)	(2.99)	(5.18)	(1.34)	(0.67)	(0.39)	(4.08)
D	931	1070	1504	397	17.6	2.64	10.54	2.88	1.97	2.10	12.12
	(501)	(477)	(751)	(226)	(7.4)	(1.16)	(6.34)	(1.26)	(0.93)	(1.06)	(11.15)
Е	4629	5468	5418	1673	80.0	9.19	17.40	11.59	4.65	4.00	23.03
	(5753)	(4619)	(5094)	(2979)	(66.2)	(7.69)	(11.33	(7.78)	(3.77)	(2.59)	(16.42)

Table 11. Average annual flux (kg km⁻² y⁻¹, Cd is given in g km⁻² y⁻¹) of major and trace elements at the four sampling locations. (values between parantheses denote S.D.).

These fluxes do not represent the quantities that reach the marine environment. However, flux estimates at location C should give an approximate idea about the impact of aeolian dust on the coastal environment. The fluxes calculated at station C for Mn, Cu, Zn and Ni are slightly higher or comparable to fluxes calculated for the northwestern Mediterranean (Ridame et al., 1999). Meanwhile, fluxes of Pb and Cd estimated from the present study at location C are significantly lower than those for the northwestern Mediterranean (Table 12). Atmospheric particulates in northwestern Mediterranean are known to contain high concentrations of Pd (1113 μ g g⁻¹) and Cd (11.61 μ g g⁻¹) (Migon et al., 2001). On the contrary, fluxes of detrital elements Al and Fe are considerably higher in the study area. This is partly due to the greater solid flux due to the proximity of the continent as indicated by the presence of important dust particle in the size range of 40 to 50 µm. It is evident that atmospheric transport may supply important quantities of trace and major elements. Some of these elements are essential either as nutrients (e.g. P. N and Fe) or as essential for the constitution of some important molecules in marine organisms (e.g. Mg, Mn, Cu, Zn and Cr). Other elements are toxic (e.g. Pb and Cd). Atmospheric transport of trace elements is therefore an important process, particularly in the Red sea where land runoff is very scarce and episodic. It may significantly control the biogeochemistry of trace and major elements in the coastal environment.

Location	Al	Fe	Ca	Mg	Mn	Cu	Zn	Cr	Ni	Pb	Cd
NW Mediterranean (Migon <i>et al.</i> , 2001)	171	118			6.5	1.4	6.1		0.4	1.1	0.07
St. C Present study	488 (451)	692 (451)	1124 (594)	263 (227)	11.8 (6.5)	3.78 (2.99)	7.05 (5.18)	2.18 (1.34)	1.31 (0.67)	0.54 (0.39)	0.01 (0.004)

 Table 12. Comparison of trace and major element fluxes (kg km⁻² y⁻¹) from this study with fluxes calculated for the northwestern Mediterranean.

Conclusions

Chemical and mineralogical compositions of dry fallout on the coastal area of Jeddah show significant temporal and geographical variability, without exhibiting a distinct distribution pattern. Falling dust is enriched in trace elements Cu, Zn, Cr, Ni, Pb and Cd relative to the crustal composition. Dust has been shown to be composed of two populations. The first and most important is rich in Al and poor in trace elements. It consists of fine particles resulting from the erosion of crustal

and sedimentary materials. The other one is composed of material rich in trace elements and poor in Al and is most probably generated from local source. Irregular mixing of the two populations should account for the variabilities of the chemical and mineralogical composition of the dust particles. Cd concentration in the dust particles has significantly decreased with respect to values measured in 1985 probably due to the dismantlement of an old cement factory in 1995.

References

- Basaham, A. S., El-Sayed, M.A. and Geith, A.M. (1998) Sources and Distribution of Heavy Metals in the Coastal Area of Jeddah, Saudi Arabia, K.A.A.U., SRC, pp 60.
- Behairy, A.K.A. (1980) Clay and carbonate mineralogy of the reef sediments north of Jeddah, west coast of Saudi Arabia, *Bull. Fac. Sc. KAAU*, 4: 265-279.
- Behairy, A.K.A., El-Sayed, M.Kh. and Durgaprasada Rao, N.V.N. (1985) Aeolian dust in the coastal area north of Jeddah, Saudi Arabia, *J. Arid Environ.*, **8**: 89-98.
- Chester, R., Murphy, K. J. T., Towner, J. and Thomas, A. (1986) The partitioning of elements in crust-dominated marine aerosols, *Chemical Geol.*, **54**: 1-15.
- **Comans, R.N.J.** and **Middelburg, J.J.** (1987) Sorption of trace metals on calcite: Applicability of the surface precipitation model, *Geochim. Cosmochim. Acta*, **51**: 2587-2591.
- Davis, J.A., Fuller, C.C. and Cook, A.D. (1987) A model for trace metal sorption processes at the calcite surface: Adsorption of Cd²⁺ and subsequent solid solution formation. *Geochim. Cosmochim. Acta*, **51**: 1477-1490.
- Derbyshire, E., Meng, X. and Kemp, R.A. (1998) Provenance, transport and characteristics of modern aeolian dust in western Gansu Province, China, and interpretation of the Quaternary loess record. J. Arid Environ., 39: 397-516.
- Done, T.J., Ogden, J.C., Wiebe, W.J. and Rosen, R.R. (1996) Biodiversity and Ecosystem Function of Coral Reefs, Function Roles of Biodiversity: A global Perspective, Edited by Mooney, H.A., Cushman, J.H., Medina, E., Sala, O.E. and Schulze, E.D. John Wiley & Sons.
- Duce, R. A., Liss, P. S., Merill, J. T., Atlas, E. L., Buat-Menard, P., Hicks, B. B., Miller, J. M., Prospero, J. M., Arimoto, R., R. Church, T. M., Ellis, W., Galloway, J. N., Hansen, L., Jickells, T. D., Knap, A. H., Reinhardt, K. H., Schneider, B., Soudine, A., Tokos, J. J., Tsunogai, S., Wollast, R. and Zhou, M. (1991) The atmospheric input of trace species to the world ocean. *Global Biogeochemical Cycles*, 5: 193-259.
- Farely, K.J., Dzombak, D.A. and Morel, F.M.M. (1985) A surface precipitation model for sorption of cations on metal oxides, J. Colloid. Interface Sci., 106: 226-242.
- Folk, R.L. and Ward, W.C. (1957) Brazos River Bar: A study of the significance of grain-size parameters, *J. Sed. Petrol.*, **27**: 3-26.
- Ganor, E. and Mamane, Y. (1982) Transport of Saharan dust across the eastern Mediterranean, *Atmosph. Environ.*, 16: 581-587.
- Gao, Y., Arimoto, R., Duce, R. A., Lee, D. S. and Zhou, M. Y. (1992) Input of atmospheric trace elements and mineral matter to the yellow Sea during the spring of a low-dust year, J. *Geophys. Res.*, 97: 3767-3777.
- **GESAMP** (1989) The atmospheric input of trace species to the world ocean, *WMO Reports and Studies*, **38**: 111 p.

- Gile, L.H. and Grossman, R.B. (1979) *The Desert Project Soil Monograph*, Washington, DC: USDA Soil Conservation Service. 984 p.
- Guerzoni, S., Molinaroli, E. and Chester, R. (1997) Saharan dust input to the western Mediterranean Sea: depositional patters, geochemistry and sedimentological implications, *Deep Sea Res. II*, 44: 631-654.
- Harvell, C.D., Kim, K., Burkholder, J.M., Colwell, R.R., Epstein, P.R., Grimes, D.J., Hofmann, E.E., Lipp, E.K., Osterhaus, A.D.M.E., Overstreet, R.M., Porter, J.W., Smith, G.W. and Vasta, G.R. (1999) Emerging marine diseases - climate links and anthropogenic factors, *Science*, 285: 1505-1510.
- Herrmann, L. (1996) *Staubdeposition auf Boden West-Afrikas*, Stuttgart: Hohenheimer Bodenkundliche Hefte. 239 p.
- Hughes, T.P. (1994) Catastrophes, phase shifts, and large scale degradation of a Caribbean coral reef, *Science*, **265**: 1547-1551.
- McTainsh, G.H. and Walker, P.H. (1982). Nature and distribution of Harmattan dust. Zeitschrift f
 ür Geomorphologie N.F., 26: 417-435.
- Migon, C., Sandroni, V. and Béthoux, J.P. (2001) Atmospheric input of anthropogenic phosphorus to the northwest Mediterranean under oligotrophic conditions, *Mar. Environ. Res.*, 7: 1-14.
- Morcos, S. A. (1970) Physical and chemical oceanography of the Red Sea. Oceanogr., Mar. Biol. Ann. Rev., 8: 73-202.
- Muhs, D. R., Bush, C.A. and Stewart, K.G. (1990) Geochemical Evidence of Saharan Dust Parent Material for Soils Developed on Quaternary Limestones of Caribbean and Western Atlantic Islands, *Quater. Res.*, 33: 157-177.
- Prospero, J.M. and Nees, R.T. (1986) Impact of the North African drought and El Niño on mineral dust in the Barabados Trade Winds, *Nature*, 320: 735-738.
- Rabenhorst, M.C., Wilding, L.P. and Gardner, C.L. (1984) Airborn dusts in the Edwards Plateau, J. Soil Sc. Soc. Amer., 48: 621-627.
- Ramsperger, B., Peinemann, N. and Stahr, K. (1998) Deposition rates and characteristics of aeolian dust in the semi-arid and sub-humid regions of the Argentinean Pampa, J. Arid Environ., 39: 467-476.
- Ridame, C., Guieu, C. and Loye-Pilot, M.D. (1999) Trend in total atmospheric deposition fluxes of aluminium, iron, and trace metals in the northeastern Mediterranean over the past decade (1985-1997), *Geophys. Res.*, **104**: 30, 127-30, 138.
- Rifaat, A.E. (2004) A Program for the Computation of the Sediment Grain Size Statistical Parameters a Freeware (Created in 1992 and modified in 1996 and 2004), Marine Geology Lab., N.I.O.F., Alexandria, EGYPT.
- Shehata, W.M., Sabtan, A.A. and Ghazal, M.M. (1998) A study on sand dune forms southeast of Jeddah, Saudi Arabia, *J.KAU: Earth Sci.*, **10**: 91-103.
- Shepard, F.P., (1954). Nomenclature based on sand-silt-clay rations, J. Sed. Petrol., 24: 151-158.
- Smith, G.T., Ives, L.D., Nagelkerken, I.A. and Ritchie, K.B. (1996) Caribbean Sea fan mortalities, *Nature*, 383: 487.
- Smith, R.M., Twiss, P.C., Krauss, R.K. and Brown, M.J. (1970) Dust deposition in relation to site, season, and climatic variables, *Soil Sc. Soc. Amer.*, *Proceedings*, 34: 112-117.
- Spencer, D.W., Degens, E.T., and Kulbicki, G. (1968) Factors affecting element distributions in sediments. In: Origin and distribution of the elements, Ahrens, L.H. (edit.) *Inter. Series of Monographs in Earth Sciences*, Pergamon Press, 30: 981-998.

- Subba Rao D.V., Al-Yamani F. and Nageswara Rao C.V. (1999) Aeolian Dust Affects Phytoplankton in the waters off Kuwait, the Arabian Gulf, *Naturwissenschaften*, **86**(11): 525-529.
- Swap, R., Garstang, M., Greco, S., Talbot, R. and Kallberg, P. (1992) Saharan dust in the Amazon Basin, *Tellus*, 44B: 133–153.
- Wedephol, K. H. (1995) The composition of the continental crust, *Geochim. Cosmochim. Acta*, **59**: 1217-1232.

المكونات الكيميائية والمعدنية للغبار الجوي المتساقط على مدينة جدة – الساحل الشرقي للبحر الأحمر

أحمد السيد محمد رفعت، وعلي سعيد بسحم، ومحمد حمودة المأموني، ومحمد عبد الخالق السيد

كلية علوم البحار – جامعة الملك عبدالعزيز – جدة– المملكة العربية السعودية

المستخلص. تم جمع ٥٢ عينة من أربعة مواقع في مدينة جدة، على مدار ثلاثة عشر شهرًا، باستخدام مصائد غبار رأسية، وقد تم تحليل هذه العينات لمعرفة محتواها من العناصر السشائعة وهي: الألومنيوم، والحديد، والكالسيوم، والماغنيسيوم. والعناصر الشحيحة وهي: المنجنيز، والنحاس، والزنك، والكروم، والنيكل، والرصاص والكادميوم. اختيرت بعض العينات لمعرفة التحليل الحجمي لحبيبات الغبار والتركيب المعدني لها. وقد وجد أن أحجام عينات الغبار تنتمي إلى الغرين silt ، ويزداد حجم حبيبات الغبار مع الاتجاه السائد للرياح، مما يدل على وجود تأثيرات محلية. وأظهرت التحليلات المعدنية سيادة معادن الكوارتز، والبلاجيوكلاز، والكالسيت، والجبس، وهي الموجودة بوفرة في التكوينات الجبولوجية التي تحبط بمدينة جدة. كما أظهرت التحليلات الكيميائية زيادة تركيز ات العناصر الشحيحة، وخاصة النحاس، والزنك عن مثيلاتها الموجودة ف_ القـ شرة الأرضية: أوضحت المعالجات الإحصائية للنتائج، أن الغبار الجوى المتساقط على مدينة جدة يأتي من مصدرين أساسيين: أولهما تجوية التكوينات الجيولوجية المحيطة بجدة، والآخر، من تصاعد الأتربة. الناتجة عن الأنشطة البشرية، وهذا أدى إلى تباين نتائج التحل يلات الكبمبائبة لمكونات الغبار.