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Enrichment of desert soil elements in Takla Makan dust aerosol

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Abstract

During a Hungarian expedition in 1994 to arid regions of north-western China, atmospheric aerosol samples were collected in the Takla Makan Desert and on some sites in mountains surrounding the Tarim Basin. PIXE data obtained for the composition and enrichment factors of the regional aerosol clearly reflected that a heavy accumulation of salts has been formed in the closed inland basin. When compared to the regional soil composition data published by other authors, it turned out that S and Cl, showing high enrichment relative to average crust composition, are of soil origin.

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1. Introduction

An important source of the soil-derived component of atmospheric aerosol is wind erosion from desert regions; its annual average contribution to the global aerosol budget is considerable. Mineralogical and elemental analyses together with enrichment factor evaluation can well used to separate the influence of the most important source regions. In Asia Takla Makan Desert, Gobi Desert, Alashan Desert, and the upper drainage basin of Yellow River are the main source areas of yellow sand dust, which is regularly transported during so-called ''Kosa'' events towards Japan and the Pacific Ocean. They also contribute to the formation of Arctic haze [1,2].

Detailed investigations have been published in [3–6] on chemical composition, morphology and mineralogy of the soil of Asian desert areas. In other papers the yellow desert sand component of the atmospheric aerosol collected around Beijing [7,8], in different locations in Japan [9–14] and over the Pacific Ocean [15] was investigated and correlated to backward air trajectories for tracing long-range aerosol transport from selected Asian deserts as source sites. Recently, a new project has been proposed aiming at a broad scope investigation of the influence of aeolian dust outbreak from the continents on global climate through the aerosol load of the atmosphere [16].

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The aim of the present work was to characterize the local aerosol over the Takla Makan region. Such data may contribute to getting information on the enrichment of some soil-derived elements under the extreme geographical and climatic conditions of the desert area as well as on crust–air fractionation of crust derived elements. Furthermore, they may be important for the evaluation of desert dust influence on aerosol load in far away sampling areas connected to the source region by long-range aerosol transport; on one hand regional signatures (selected elemental ratios in local aerosol) can be used as tracers in such investigations; on the other hand their tracing power could be degraded by the ageing of the aerosol during transport time, a comparison of initial data with those found in the sampling region is essential.

2. Physical geography of the region, sampling sites

The Takla Makan Desert covers the Tarim Basin, which is surrounded by mountains of high relief. On the north it is separated by the Tian Shan Range from the Junggar Basin covered by the Gurbantunggut Desert. On the south and west

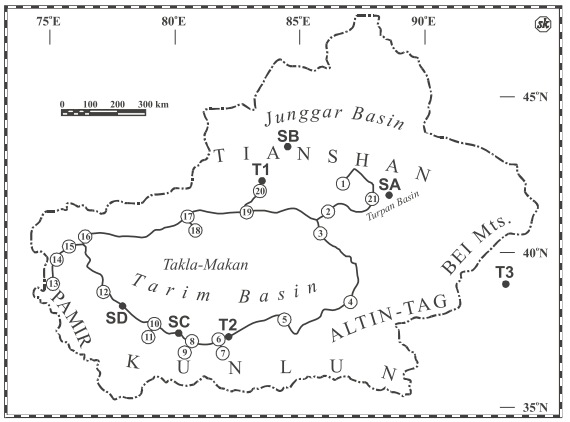

Fig. 1. Schematic presentation of the sampling sites used in the present work. Numbers refer to sites listed in Table 1. Notation T1, T2, T3 and SA, SB, SC, SD are soil sampling sites used in [3,4], respectively.

Table 1
Sampling schedule and local conditions of the sampling campaign

Site no.	Sampling date	Longitude (°E)	Latitude (°N)	Altitude (m)	Site description
1	12.06.1994	86°55′	43°10′	3370	Glacier no. 1 of Tian Shan (mountain)
2	16.06.1994	86°46′	41°55′	1048	Bosten Lake
3	17.06.1994	86°22′	41°23′	885	Yuli, Takla Makan (desert)
4[a]	18.06.1994	88°15′	39°05′	860	Ruoqiang, Takla Makan (desert)
5[a]	19.06.1994	85°35′	38°07′	1240	Qiemo, Takla Makan (desert)
6[a]	21.06.1994	82°50′	37°02′	1410	Minfeng, Takla Makan (desert)
7	22.06.1994	83°05′	36°39′	2150	Aryidake, Kunlun (mountain desert)
8[a]	23.06.1994	81°40′	36°49′	1390	Yutian, Takla Makan (desert)
9	24.06.1994	81°19′	36°40′	1720	Tulake, Takla Makan (desert)
10[a]	25.06.1994	79°59′	37°07′	1420	Hotan, Takla Makan (desert)
11	26.06.1994	79°55′	36°57′	2150	Yurungkas River, Takla Makan (desert)
12[a]	27.06.1994	77°47′	37°55′	1315	Yarkant, Takla Makan (desert)
13	30.06.1994	75°07′	37°51′	3010	Tashkurgan, Pamir (mountain)
14	01.07.1994	75°02′	38°29′	3595	Kara Kul Lake, Pamir (mountain)
15	02.07.1994	75°47′	39°02′	1900	Mayaz, Pamir (mountain desert)
16[a]	03.07.1994	75°39′	39°37′	1410	Kashgar, Takla Makan (desert)
17	04.07.1994	80°19′	41°16′	1180	Aksu, Takla Makan (desert)
18	05.07.1994	80°47′	40°39′	1085	Arlere Eku, Takla Makan (desert)
19	07.07.1994	82°57′	41°55′	1400	Du-ku, Tian Shan (mountain)
20	09.07.1994	83°14′	42°22′	2420	Dalong Chi, Tian Shan (mountain)
21[b]	10.07.1994	88°47′	42°39′	0	Toksun, Turpan Basin (lowland, desert)

[a] Limited visibility after a strong N–NE wind episode.
[b] Intense local traffic around rush hours.

the Tarim Basin is bordered by the Kunlun and Pamir ranges, respectively. Its climate is continental with scarce precipitation and a great variation in temperature. It is situated in the zone of middle-latitude westerlies, which rapidly convey vapour during extremely high temperatures. Dry winds of velocity exceeding 10 $m\,s^{-1}$ are frequent from late May to late June. The annual precipitation is only about 50 mm resulting in an arid climate. The vegetation of the ground surface is sparse. There are large areas of gravel and shifting dunes void of any vegetation.

The geochemical and mineralogical description of the desert soil has been given in [5,6,17]. For the aim of this work it is important to keep in mind that the Takla Makan is a closed basin without outlets for runoff and accumulating salts. Because of the dry climate and strong evaporation a heavy accumulation of salts mostly containing chlorides, sulphates or carbonates has formed in the basin. Rich supplies of oil, coal, iron and other ores can be found here, but the exploitation of the resources has not reached a high level as yet. Traffic and industrial activity are also low, the region is far away from major pollution sources and can be considered as a background area.

The atmospheric aerosol samples were collected in Takla Makan Desert and at some sampling sites in mountains Tian Shan, Pamir, and Kunlun surrounding the Tarim Basin by a Hungarian expedition in 1994 [17]. The sites and schedule of collecting our samples are shown in Fig. 1 and Table 1, respectively. In the figure, numbers refer to sampling sites listed in the table. Names of the sites are given in the form proposed for a consequent transcription of Chinese, Japanese and English notations in [18]. On sites 3, 19 and 21 one of the authors (L.M.) collected aerosol samples also in 1990 [19]. Notations T1, T2 and T3 in the figure indicate sites where local soil samples were collected from for elemental analysis in the work [3], while for soil analysis in [4] samples originated from sites SA, SB, SC and SD. The close coincidence of sampling sites of the different investigations with those of our campaign is explained by the limited availability of traffic lines, the majority of the sites are along the southern Silk Road used since ancient times.

3. Experimental

3.1. Sampling technique

Atmospheric aerosol samples were collected on nucleopore filters with pore size of 0.4 mm and diameter of 15 μm. The sampling was performed at 1.5 m height above ground level. The filter holder was connected to a vacuum pump, which operated at a flow rate of 20 $l\,min^{-1}$. The pump was equipped with an automatic timer and a gas meter, calibrated with an accuracy of ±2%. The sampling time was about 1.5–2 h during which an air volume 1–2 m^3 was sampled. The electric current to function the pump was supplied by an electric generator, the exhaust gases from the generator were conducted downwind with a tube. After sampling, the filters were placed into small plexiglass boxes and sealed carefully. The boxes were kept closed until analysis.

3.2. PIXE analyses

For particle induced X-ray emission analysis samples were irradiated by 2 MeV proton beam from a Van de Graaff accelerator. Details of the PIXE facility are given in [20]. The elements Al, Si, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Br and Ba were detected. A PIXE computer package named PIXYKLM [21] and its recent expansion PIXEKLM [22] were used for the spectrum evaluation. The typical irradiation time amounted to 20 min. The detection limits are 2–100 $ng\,m^{-3}$ depending on the elements. It was found that, except for bromine, blank values could practically be neglected. Data for bromine were omitted from further examinations.

4. Results and discussion

The elemental concentrations found in aerosol samples from sampling sites 1–21, are tabulated in Table 2 in units $ng\,m^{-3}$. For an enrichment factor evaluation, use was made of composition data for average Earth's crust [23] as well as for desert soil samples [3–6] collected in the region. The soil data used are given in Table 3, while in Table 4 shown

Table 2
Elemental concentrations in ng m^{-3} units given by PIXE analysis for sampling sites described in Table 1

	Site no.																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Al	337	482	3217	6925	4349	2642	1295	3368	2016	13,420	5168	28,520	1674	324	1728	3330	1443	96	1010	354	4604
Si	2176	2281	17,140	34,320	21,000	13,790	5506	16,350	10,730	74,160	23,350	1,71,300	7076	1170	6968	19,690	5605	831	4348	1428	21,730
S	516	439	1122	4034	2248	1544	485	1065	900	4021	2883	6966	624	280	757	1567	456	290	378	381	1261
Cl	108	71	1034	5056	2038	1500	465	939	856	8023	4820	4526	203	48	298	433	180	164	406	42	873
K	346	384	2727	5374	3532	2276	849	2489	1542	11,510	3820	26,610	1147	193	1143	3117	1074	193	851	219	3850
Ca	1020	1044	11,850	28,690	13,970	8350	3538	8937	6485	44,250	15,480	1,18,200	4405	529	3753	13,300	3697	665	2166	507	11,700
Sc	<20	<20	20	73	<20	<20	<20	<20	<20	230	38	699	<20	<20	<20	<20	<20	<20	<20	<20	33
Ti	41	39	364	745	703	298	116	345	220	1680	509	4427	151	23	141	393	117	9	107	27	511
V	4	6	14	<3	<3	15	5	21	10	38	10	152	9	3	9	16	7	3	7	3	17
Cr	5	9	39	53	75	32	8	52	26	353	52	492	11	8	10	41	12	9	8	10	23
Mn	17	19	107	189	106	81	40	99	59	310	136	718	59	10	51	115	56	12	32	13	123
Fe	605	563	4356	9576	5707	3542	1393	4332	2676	18,500	6497	49,700	1905	333	1780	4886	1553	231	1263	366	6333
Ni	<3	4	17	49	67	26		41	21	<3	29	<3	<3	4	<3	26	<3	4	<3	3	<3
Cu	125	45	245	624	374	226	81	255	166	1291	471	<3	12	6	45	187	62	28	209	38	<3
Zn	51	20	166	300	266	131	48	141	84	407	198	1596	114	16	70	203	67	14	92	13	<6
Ba	<15	16	43	<15	<15	<15	<15	87	<15	<15	<15	584	53	28	51	<15	30	23	40	42	<15

Average errors calculated from the errors of peak area, accumulated charge and detection solid angle amount to 5%.

Table 3
Elemental concentrations relative to iron in average Earth crust and Takla makan soil

Element	Earth crust	Takla makan soil						
	Average (Ref. [23])	SA Ref. [4]	SB Ref. [4]	SC Ref. [4]	SD Ref. [4]	T1 Ref. [3]	T2 Ref. [3]	T3 Ref. [3]
Al	1.6260	0.949	1.690	1.580	1.71	2.480	5.537	2.644
Si	5.5440	3.700	6.260	8.930	9.180	9.179	27.100	11.907
S	0.0104	0.370	0.024	0.035	0.029	0.007	<0.008	0.285
Cl	0.0063	0.810	0.022	0.066	0.073			
K	0.5180	0.335	0.652	0.765	0.772	0.586	1.182	0.829
Ca	0.7260	0.802	0.993	1.860	2.250	2.142	3.545	2.646
Sc	0.0001							
Ti	0.0088	0.093	0.080	0.089	0.100			
V	0.0030							
Cr	0.0040							
Mn	0.0200	0.023	0.022	0.027	0.024			
Fe	1	1	1	1	1	1	1	1
Ni	0.0016							
Cu	0.0014	0.0015	0.0006	0.0095	0.0013			
Zn	0.0026	0.0022	0.0018	0.0022	0.0021			
Ba	0.0050							

Table 4
Enrichment factors of elements averaged for groups of aerosol sampling sites

Soil sampling sites/ Aerosol sampling sites	Al	Si	S	Cl	K	Ca	V	Cr	Mn	Fe	Ni	Cu	Zn
SA	0.52	0.79	62.3	31.7	1.42	3.24	2.38	2.81	1.59	1.18	4.18	10.1	24.6
$\langle(1,2,3,21)\rangle$	*0.94*	*1.26*	*1.85*	*0.26*	*2.31*	*3.10*	–	–	*1.48*	*1.25*	–	*88.4*	*31.3*
$\langle(SC,SD)\rangle$	0.49	0.71	35.2	69.7	1.34	3.47	1.19	2.60	1.12	0.92	4.81	4.70	12.7
$\langle(4,5,6,7,8,9,10,11)\rangle$	*0.52*	*0.47*	*12.7*	*6.73*	*0.86*	*1.32*	–	–	*0.94*	*1.10*	–	*13.2*	*16.1*
SD	0.57	0.75	46.2	21.6	1.29	3.38	1.94	3.14	1.45	1.12	6.67	1.77	18.8
$\langle(12,13,14,15,16)\rangle$	*0.61*	*0.52*	*13.9*	*2.10*	*0.94*	*1.24*	–	–	*1.37*	*1.27*	–	*21.7*	*26.9*
SB	0.66	0.93	112	99.7	1.98	4.38	4.19	8.60	2.85	1.42	13.1	10.9	28.9
$\langle(17,18,19,20)\rangle$	*0.54*	*0.75*	*44.9*	*22.8*	*1.43*	*2.91*	–	–	*2.36*	*1.29*	–	*233*	*38.6*
Standard deviations	**11%**	**11%**	**39%**	**33%**	**13%**	**21%**	**36%**	**41%**	**23%**	**13%**	**31%**	**29%**	**22%**

are crust- and local soil-related enrichment factors averaged for groups of sampling sites defined in the first column of the table, in light-faced and italic character, respectively. From the data the following results have been obtained.

(i) It is clearly seen from Table 2 that silicon concentrations in sites 4, 5, 6, 8, 10, 12 and 16, situated along the southern Silk Road, are highly elevated with respect to similar data at other sampling sites. Samples were taken here after a heavy buran wind episode (wind erosion) of several days duration, which resulted in a limited visibility extending over a time period of many days. It is only the intensity of the soil erosion that varies with the meteorological conditions; relative concentrations of the elemental constituents remain nearly constant from site to site.

(ii) Similarly elevated silicon concentration was detected in site 21 in the absence of wind erosion. It is ascribed to intense local traffic around rush hours at this location. A remarkable similarity of the aerosol composition here to that observed in the above-mentioned sites indicates that the aerosol load, increased by the local traffic, is more a

consequence of the re-suspension of the deposited desert soil than the direct result of the emissions from the traffic.

(iii) The concentration ratios Si/Fe and Ca/Fe were found in [4] to be useful as regional signatures in tracing long-range transport of Asian desert dust in "Kosa" events. The respective concentration ratios $Si/Fe = 3.74 \pm 0.21$ and $Ca/Fe = 2.24 \pm 0.42$ obtained in the present work show remarkable independence of the locations of the sampling sites in the region, while they are much different from average crust data and from the ratios for other locations outside the Takla Makan region. Consequently, these regional signatures may be appropriate for tracing the aerosol from this source.

(iv) The Si/Al ratio 5.02 averaged over our 21 samples agrees within a 20% standard deviation with the average ratio 4.66 and 4.37 for the local soil samples SA, SB, SC, SD [4] and T1, T2, T3 [3], respectively, which means that no considerable crust–air fractionation [24] has been observed. A comparison of our data with those compiled in [24] is shown in Fig. 2. The upper strip represents typical composition of average rock and soil. The lower strip corresponds to clay minerals. All the symbols from our measurements are situated on the upper limit of the upper strip. This behaviour is in full agreement with the prediction of increased probability of high Si/Al aerosol ratios in natural high concentration areas such as deserts

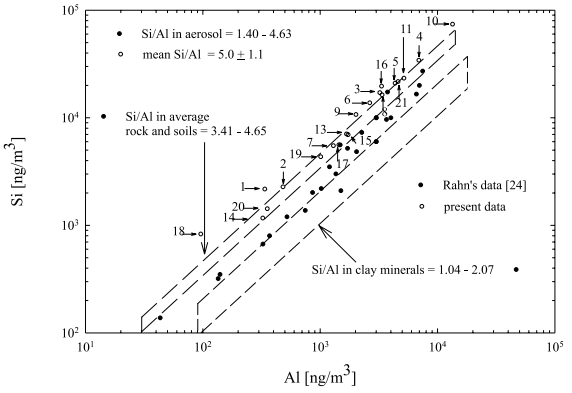

Fig. 2. Scatter diagram of Si and Al elemental concentration in aerosol. Hollow circles correspond to our data for sampling sites 1–21, while full dots show data compiled in [24].

[24]. The appearance of a similar increase has been pointed out in [25] in arid sites in Israel [26] following dust storms.

(v) To separate the effects of natural sources from those of anthropogenic emissions in the region and/or from the influence of inter-regional long-range transport of aerosol, enrichment factors have been deduced for individual samples. First we used average crust concentrations [23] for the characterization of soil component, and titanium has been selected as a soil-derived reference element. High enrichment factors obtained in this way for some elements normally considered as anthropogenic gave a quite unrealistic hint of the presence of strong non-natural sources in this remote area. Therefore, we next used local soil composition data published for sites SA, SB, SC and SD in [4]. Because of the lack of titanium data in soil analyses in [3], sites T1, T2 and T3 were excluded from this calculation. Soil compositions for sites SA, SB, SC and SD have been assigned to our aerosol sampling sites with some arbitrariness in taking prevailing wind directions and geographic locations into consideration. In Table 4, enrichment factors averaged for groups of aerosol sampling sites defined in the first column are presented for average crust and local soil composition in light-face and italics, respectively. Standard deviations are given in bold face.

(vi) Elements Al, Si, K, Ca, V, Cr, Mn, Fe are shown by both sets of enrichment factors to be soil derived, in most cases local soil based data lead to lower enrichment factors. The strong decrease of enrichment for S and Cl with local soil concentrations in place of average crust composition indicates the geochemical enrichment of these elements in the local soil of the closed arid basin. The enrichment factors for Cu and Zn in all sampling sites increase when changing from average crust to local soil, due to a decrease of about one order of magnitude of copper and zinc concentrations in the latter case, indicating that some anthropogenic sources of copper and zinc aerosol are involved. Limited experimental data, the lack of backward air trajectories and emission inventories did not permit us to assign the observed concentrations to distant sources. Besides it is not improbable that part of the observed Cu and Zn component comes

from the abrasion of metal parts of the electric generator. Such effects may be caused by the high level of sand and grit and desert aerosol and/or by normal mechanical erosion of the commutator segments and bronze carbon brushes.

5. Summary

Elemental concentrations and enrichment factors determined for Takla Makan Desert contributed new information on regional atmospheric dust conditions in this arid part of Asia which is an important aerosol source on global scale. A comparison of aerosol data with analysis of the regional soil indicated that high sulphur and chlorine contents of the regional aerosol are of natural origin, a consequence of the accumulation of salts in this arid closed basin. Both the Si/Fe and Ca/Fe elemental ratios of all sites cluster within narrow intervals, so they can be used in tracing long-range transport of Takla Makan aerosol. No considerable air–crust fractionation appears in Si/Al elemental ratio of the regional aerosol.

The results obtained in the present work can be of interest for the investigation of the atmospheric dust load transported to China, Japan and the Pacific Ocean during ''Kosa'' events. This phenomenon is attracting world-wide interest due to its direct environmental effects on the areas involved as well as to its possible influence on global aerosol chemistry and climate.

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