

**PIXE ANALYSIS OF ATMOSPHERIC AEROSOL PARTICLES
IN NORTH-WESTERN CHINA**

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Összefoglalás - Makra László második kínai terepi műszeres expedíciója során, 1994-ben 21 db aeroszol mintát gyűjtött Északnyugat-Kína arid és rendkívül ritkán lakott térségeiben. A mintákat PIXE-módszerrel analizáltuk. A tanulmány legfontosabb eredménye annak kimutatása, hogy a kén, a klór, a króm, a réz és a cink szignifikánsan földúsul az Északnyugat-Kína fölötti légköri aeroszolban. Bebizonyítottuk, hogy a kén és a klór talaj eredetű. A króm, a réz és a cink koncentrációi nem ismeretesek a helyi talajban. Mégis valószínűsítjük, hogy földúsulásuk a légköri aeroszolban, anomalikusan magas talajkoncentrációjukra vezethető vissza. A kén és a klór eredete Északnyugat-Kínában eltérő a Föld egyéb, hasonlóan száraz és gyéren lakott régióihoz képest.

Summary - Twenty-one aerosol samples were collected by László Makra in the air over arid regions of North-western China during a Hungarian expedition in 1994. The samples collected were analysed by PIE-method. The most important result of the study is, revealing highly enriched sulphur, chlorine, chromium, copper and zinc in the atmospheric aerosol over North-western China. It is clearly proved that sulphur and chlorine come from local soil. Concentration data of chromium, copper and zinc in local soil of North-western China are not available. However it is supposed that these elements come from local soil, as well. The origin of sulphur and chlorine here shows a difference from that of other similar lands of the Earth.

Key words: elemental composition, enrichment factor, non-crustal fraction, China, Inner Asia

INTRODUCTION

North-western China is the innermost part of Eurasia, which covers a vast expanse, accounting for more than 20 per cent of the total area of China. It is bordered by the Altay Mountains from North, by the Kunlun Mountains from South, by the Pamir from West and by the Altin Mountains from East. North-western China has a strong continental climate with scarce precipitation and a great variation in its range of temperature. It is

situated in middle-latitude westerlies, where both high and low pressures are active. The region is under the Mongolian high for most of the winter half-year. During this period the region is frequently invaded by the polar and arctic air masses. Influenced by strong radiation cooling of the ground surface, the climate in the winter is mainly dry and cold. In summer, as the region is located at the northern fringe of the continental low, the strong westerlies convey vapour quickly. Most of the exposed ground surface is then heated to extremely high temperatures. Due to the dynamical and thermodynamical influence of the air currents from the Qinghai-Tibetan Plateau, a high altitude tropical continental air mass forms over the Tarim Basin.

Deserts with gravel or sand cover vast areas. The largest one is the Takla Makan while the second largest desert is the Gurbantunggut which is found in the Junggar Basin.

The climate here is dry with little cloud cover and abundant sunshine. This is the most arid region in China, with aridity over 4. In the Tarim Basin the annual precipitation is only about 50 mm and the aridity is over 10 (*Domroes and Peng*, 1988). [The aridity is a quotient of the radiation balance and the precipitation amount for a given region and period. This quotient is in direct proportion to the dryness of climate and inversely proportional to the water supply. If the aridity is higher than 1, the climate is arid (the radiation balance would make it possible to evaporate more water than that, which is at disposal), while if it is below 1, the climate is humid (the precipitation amount is higher than the potential evaporation). Aridity over 4 represents extremely dry regions.]

The vegetation on the ground surface is sparse, the air is dry and dry winds blow frequently. Dry winds generally occur between April and August and often blow at a velocity exceeding 10 m s^{-1} from late May to late June. The plants generally do not cover more than 20 per cent of the ground surface and sometimes as little as 1 per cent, e.g. the southern slopes of the Tianshan Mountains. Even there are large areas of gravel and shifting dunes void of any vegetation mainly in the extremely arid Takla Makan Desert and the Qaidam Basin. 85 per cent of the Takla Makan is shifting by winds. This is the largest shifting sand desert in the world.

Soils in this region are grey-brown desert soil under the arid climate and aeolian sandy soil under the extremely arid climate. Under the influence of climate and vegetation the top of these desert soils contains little organic matter and there is no humus accumulation. It contains calcium carbonate in the upper layer and gypsum even in lower layers, too. There is a certain amount of salt in the soil, mostly sodium sulphate and sodium chloride. Because of the extreme aridity, the soil in the Tarim Basin also contains salt pans of chlorides, which are rarely found in desert soil in other parts of the world. The whole profile produces a medium or strong alkaline reaction (pH 8.0 to 10.0) (*Ren and Bao*, 1985).

The Junggar Basin is found north from the Tianshan Mountains and south from the Altay Mountains. It receives slightly more precipitation than the Tarim Basin. Consequently its margins are steppes and only its interior is desert.

The northern slopes of the Tianshan Mountains face to humid north-west current and receive much more precipitation than do the slopes at the same elevation in the Kunlun Mountains. The Tarim Basin south of the Tianshan Mountains is far drier than the Junggar Basin, and therefore the desert penetrates deep into the mountains here.

The characteristics of the southern fringe of the Tarim Basin (the northern slopes of the Kunlun Mountains) are the extreme aridity. E.g. in the middle section of the Kunlun Mountains desert vegetation with mountain brown desert soil can be found up to 3500 m above sea level.

The soil at the northern slopes of the Tianshan Mountains is grey-cinnamon forest soil, which produces a neutral to alkaline reaction with a pH value of between 7.0 and 8.0. The soil not only reflects some typical features in the formation of cinnamon soil (clayization and carbon accumulation) but also some in the formation of the grey forest soil (humus accumulation).

Most areas in North-western China are closed inland basins without outlets for the runoff and salts. Because the climate is dry and there is strong evaporation, a heavy accumulation of salts has formed in the basins over a long time. Solonchak is widespread and the salt content in this is very high. (Solonchak is a soil type, which is rich in soda. Its soil structure is homogenous. Its upper layer is the saltiest and on its surface there is salt efflorescence from place to place and time to time.) The surface layer of the solonchak contains 2-5 per cent salts, while the solonchak in southern Xinjiang (this is the Chinese name of the province of North-western China) and the Qaidam Basin contains from 10-20 per cent. Most of the solonchak in North-western China contains chlorides, sulphates or soda (*Ren and Bao, 1985*).

This region is very rich in mineral resources although geologic mapping has not been completed. Rich supplies of coal, iron and ores can be found, however oil is the most important. The exploitation of oil started in 1977 and by now North-western China has become the second region for oil production in China. Nevertheless, oil reserves in the Tarim Basin are as much as 12 billion tons, which are the largest ones in China and three times as much as those of the United States. The length of local rails is a mere 400 km and only parts of the highways are covered. Long-distance transportation is performed by lorries but local traffic, predominantly in the oases of the Tarim Basin, occurs by two-wheeled tumbrils drawn by donkeys. Local industry is developing faster in the last decade. Contrary to the present economic development, North-western China is far from major pollution sources and can be considered as a background region.

The elemental composition of atmospheric aerosol particles has been studied widely during the last three decades. Aerosols play an important role in the atmosphere, e.g. by modifying radiation transfer, cloud, fog and precipitation formations; even they influence human health. The reason of such measurements is estimating the environmental impact of the particles on local, regional and global scales. Among other things, samplings in the atmosphere far from human activities have been carried out under oceanic and continental conditions to investigate the global cycle of aerosols. In spite of these efforts (e.g. *Mészáros*, 1978; *Penkett et al.*, 1979; *Adams et al.*, 1980, 1983; *Winchester et al.*, 1981a, 1981b; *Morales et al.*, 1990;), the chemical composition of aerosol particles far from anthropogenic pollution sources over continents like Africa, South America and Asia is not well understood.

Although several papers have been published on the air pollution characteristics of urban and other inhabited regions of China (e.g. *Hu et al.*, 1987; *Ge et al.*, 1989; *Hashimoto et al.*, 1994; *Zelenka et al.*, 1994; *Fan et al.*, 1996; *Ning et al.*, 1996) nevertheless few information have been available from the aerosol in the air over Indonesia (e.g. *Zou and Hooper*, 1997) and in that over the vast regions of Asia. Elemental composition of atmospheric aerosols was analysed e.g. over Lake Baikal region (*Van Malderen et al.*, 1996); over Northern China (*Winchester et al.*, 1981a, 1981b; *Fan et al.*, 1996); in the Huangshan Mountain, Eastern China (*Xu et al.*, 1991); and on the Loess Plateau (*Zhang et al.*, 1993). However, relatively few papers have been published in the subject over the huge innermost regions of Asia, and North-western China (*Wang et al.*, 1987; *Winchester and Wang*, 1989; *Molnár et al.*, 1993b; *Hashimoto et al.*, 1994).

One of the frequently applied techniques of elemental analytics of atmospheric aerosols is the PIXE method. Possibilities of this procedure are discussed, among other papers, in comprehensive studies of *Koltay* (1990), furthermore *Maenhaut and Malmqvist* (1992). Authors of the present manuscript applied this technique, among other papers, in *Borbély-Kiss et al.* (1991, 1999), *Molnár et al.* (1993a, 1995) for qualification of regional aerosols. Technical details are given in these papers.

The aim of this paper is to present the results of aerosol samples collected in the air over North-western China (Xinjiang Province).

SAMPLING AND ANALYSIS

The geographical position and characteristics of the sampling sites are given in *Fig. 1-2* and *Table 1* (Samplings at sites No. 3., 19. and 21. were performed both in 1990 and 1994. These sites were written by bold letters.) All the sites are characteristic for

regional background conditions. This means that they are not influenced directly by local pollution sources.

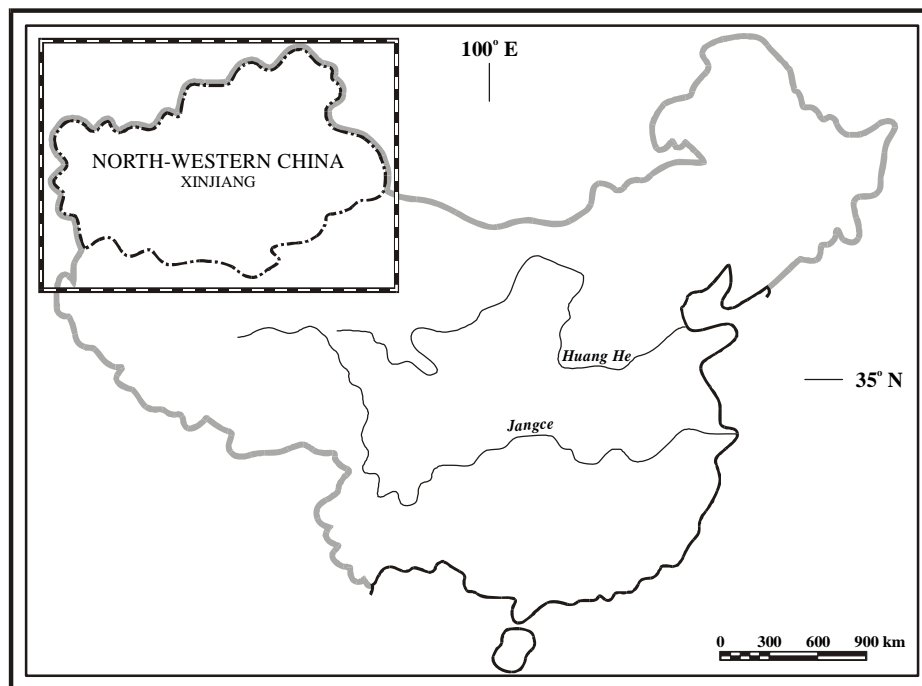


Fig. 1 Map of China with the position of North-western China

Atmospheric aerosol particles were collected in each case by means of Nuclepore polycarbonate filters with pore size of 0.4 μm . The sampling was performed at 1.5 m height. The filter holder was connected to a vacuum pump, which was operated at a flow rate of approximately 20 l min^{-1} . The pump was equipped with an automatic timer system and a gas meter. The gas meter was calibrated before the programme. On the basis of this calibration, the accuracy of volume measurements was $\pm 2\%$. The sampling time was about 1.5-2 hours during which at least 1 m^3 but not more than 2 m^3 of air 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. Thus, twenty-one aerosol samples were obtained in North-western China and seven samples in Indonesia. After samplings, the filters of 15 mm diameter were placed into small plexiglas boxes sealed carefully. The filters were kept in these boxes until their analysis in Hungary.

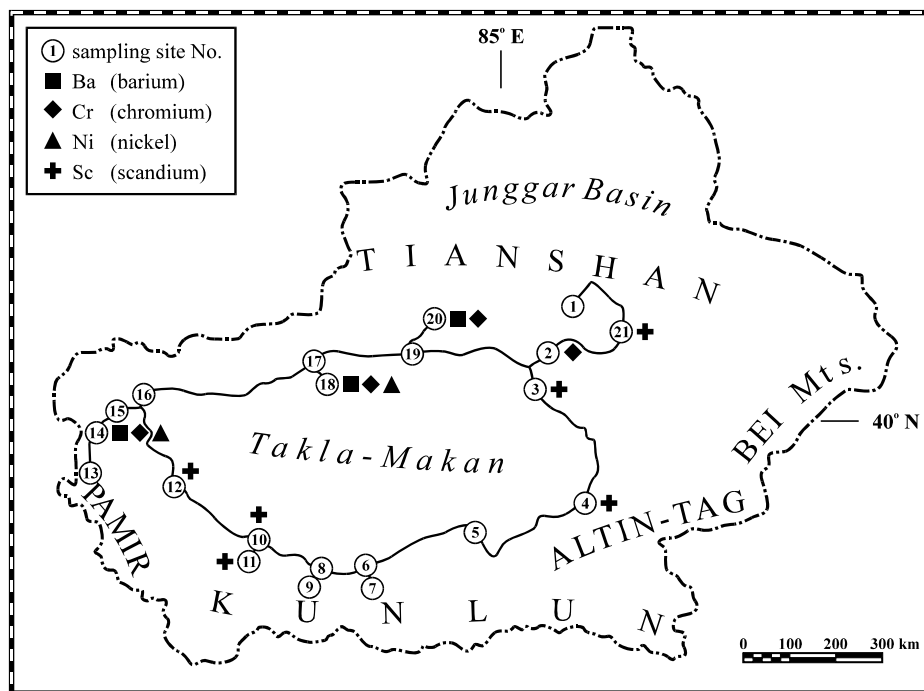


Fig. 2 Position of sampling sites in North-western China with spatial distribution of elements enriched over ten, excluding sulphur, chlorine, copper and zinc

The elemental composition was determined by particle induced X-ray emission (PIXE) method. The details of the procedure applied are described elsewhere (Koltay, 1988). Briefly, the samples were irradiated by 2 MeV proton beam supplied by the Van de Graaff nuclear accelerator of the Nuclear Research Institute of the Hungarian Academy of Sciences, Debrecen, Hungary. Nineteen elements (with atomic number 13 and over) were detected by this procedure: Al, Si, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Br and Ba. The detection limits are between 2-100 ng m⁻³ depending on the elements. The blank value for each element was carefully checked. It was found that, except for bromine, blanks could practically be neglected compared to measured concentrations. For this reason concentrations and enrichment factors for bromine were omitted from further examinations. The error of quantitative analysis was lower than 10 % as discussed in more details by Koltay (1988).

Table 1 Date of sampling; geographical positions and description of sampling sites, North-western China

Sample No.	Date	H (m)	φ (°N)	λ (°E)	Site description
1	12 June	3370	43° 10'	86° 55'	Glacier No.1. of Tianshan (mountain)
2	16 June	1048	41° 55'	86° 46'	Bosten-Lake
3	17 June	885	41° 23'	86° 22'	Yuli, Takla Makan (desert)
4	18 June	860	39° 05'	88° 15'	Ruoqiang, Takla Makan (desert)
5	19 June	1240	38° 07'	85° 35'	Qiemo, Takla Makan (desert)
6	21 June	1410	37° 02'	82° 50'	Minfeng, Takla Makan (desert)
7	22 June	2150	36° 39'	83° 05'	Aryidake, Kunlun (mountain desert)
8	23 June	1390	36° 49'	81° 40'	Yutian, Takla Makan (desert)
9	24 June	1720	36° 40'	81° 19'	Tulake, Takla Makan (desert)
10	25 June	1420	37° 07'	79° 59'	Hotan, Takla Makan (desert)
11	26 June	2150	36° 57'	79° 55'	Yurungkash River, Takla Makan (desert)
12	27 June	1315	37° 55'	77° 47'	Yarkant, Takla Makan (desert)
13	30 June	3010	37° 51'	75° 07'	Tashkurgan, Pamir (mountain)
14	01 July	3595	38° 29'	75° 02'	Kara Kul Lake, Pamir, (mountain)
15	02 July	1900	39° 02'	75° 47'	Mayaz, Pamir (mountain desert)
16	03 July	1410	39° 37'	75° 39'	Kashgar, Takla Makan (desert)
17	04 July	1180	41° 16'	80° 19'	Aksu, Takla Makan (desert)
18	05 July	1085	40° 39'	80° 47'	Arlere Eku, Takla Makan (desert)
19	07 July	1400	41° 55'	82° 57'	Du-ku, Tianshan (mountain)
20	09 July	2420	42° 22'	83° 14'	Dalong Chi, Tianshan (mountain)
21	10 July	0	42° 39'	88° 47'	Toksun, Turpani Basin (lowland, desert)

RESULTS AND DISCUSSION

The results of the analyses of samples are in *Table 2a-c*, where the absolute concentrations as well as the enrichment factors of 16 elements are shown. The enrichment of element X relative to average earth crust composition is given by the enrichment factor (EF)_{Ti}(X) defined as

$$EF_{Ti}(X) = (X/Ti)_{air} / (X/Ti)_{crust} \quad (1)$$

where Ti is used as a reference crust derived element (*Mason, 1966*), while (X/Ti)_{air} is a concentration ratio of an element X to that of Ti in atmospheric particulates and (X/Ti)_{crust} is a concentration ratio of an element X to that of Ti in crust. The use of titanium as reference element is due to the applied analytical method. At PIXE-analysis, the detection limit and the accuracy of the method depend on the atomic number of the given element.

The error of determining Al is bigger than that of Ti. Furthermore, Ti has less other (anthropogenic) sources than Al and Fe (e.g. Borbély-Kiss *et al.*, 1991).

We can see from the *Table 2a-c*. that relatively high concentrations were found for aluminum, silicon, sulfur, chlorine, potassium, calcium and iron at each sampling site. Aluminum, silicon, potassium, calcium, vanadium, manganese and iron have enrichment factors near to 1 proving their crustal origin. The concentration of the elements of soil origin is extremely high in particular for the samples No. 4, 10, 11 and 12. All these samples were collected at the southern part of the Takla Makan Desert, several days after dust storms. In the Tarim Basin, predominantly occupied by the Takla Makan Desert, winds are frequent and violent in the summer half-year. Following dust storms, dust particles get deposited in several days, while visibility is very weak and it seems as if there were fog around.

Table 2a Concentration (x : ng m^{-3}) and enrichment factor (EF) of different elements relative to average crust data, in the atmospheric aerosol over the regions of North-western China

	<i>Sample 1</i>		<i>Sample 2</i>		<i>Sample 3</i>		<i>Sample 4</i>		<i>Sample 5</i>		<i>Sample 6</i>		<i>Sample 7</i>	
	<i>x</i>	<i>EF</i>	<i>x</i>	<i>EF</i>	<i>x</i>	<i>EF</i>	<i>x</i>	<i>EF</i>	<i>x</i>	<i>EF</i>	<i>x</i>	<i>EF</i>	<i>x</i>	<i>EF</i>
Al	337	0.44	482	0.67	3217	0.48	6925	0.50	4349	0.33	2642	0.48	1295	0.60
Si	2176	0.84	2281	0.93	17140	0.75	34320	0.73	21000	0.48	13790	0.74	5506	0.75
S	516	212.9	439	190.5	1122	52.2	4034	91.5	2248	54.5	1544	87.9	485	70.7
Cl	108	89.1	71	61.6	1034	96.2	5056	229.5	2038	98.8	1500	170.8	465	135.6
K	346	1.4	384	1.7	2727	1.3	5374	1.2	3532	0.86	2276	1.3	849	1.2
Ca	1020	3	1044	3.2	11850	4	28690	4.7	13970	2.4	8350	3.4	3538	3.7
Sc	<20		<20		20	11	73	19.6	<20		<20		<20	
Ti	41	=1	39	=1	364	=1	745	=1	703	=1	298	=1	116	=1
V	4	3.2	6	5	14	1.3	<3		<3		15	1.6	5	1.4
Cr	5	5.4	9	10.2	39	4.7	53	3.1	75	4.7	32	4.7	8	3
Mn	17	1.9	19	2.3	107	1.4	189	1.2	106	0.70	81	1.3	40	1.6
Fe	605	1.3	563	1.3	4356	1.1	9576	1.1	5707	0.72	3542	1.05	1393	1.1
Ni	<3		4	6	17	2.7	49	3.9	67	5.6	26	5.1		
Cu	125	243.9	45	92.3	245	53.9	624	66.9	374	42.8	226	60.8	81	55.8
Zn	51	78.2	20	32.2	166	28.7	300	25.3	266	23.9	131	27.7	48	26
Ba	<15		16	4.2	43	1.2	<15		<15		<15		<15	

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Table 2b Concentration (x: ng m⁻³) and enrichment factor (EF) of different elements relative to average crust data, in the atmospheric aerosol over the regions of North-western China

	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7	
	x	EF	x	EF	x	EF	x	EF	x	EF	x	EF	x	EF
Al	3368	0.53	2016	0.50	13420	0.43	5168	0.55	28520	0.35	1674	0.60	324	0.76
Si	16350	0.75	10730	0.77	74160	0.70	23350	0.72	171300	0.61	7076	0.74	1170	0.81
S	1065	52.4	900	69.2	4021	40.2	2883	95.4	6966	26.8	624	69.8	280	206
Cl	939	92.5	856	131.7	8023	160.5	4820	318.9	4526	34.8	203	45.4	48	70.6
K	2489	1.2	1542	1.2	11510	1.2	3820	1.3	26610	1.03	1147	1.3	193	1.4
Ca	8937	3.2	6485	3.6	44250	3.2	15480	6	118200	3.3	4405	3.5	529	2.8
Sc	<20		<20		230	27.2	38	14.9	699	31.8	<20		<20	
Ti	345	=1	220	=1	1680	=1	509	=1	4427	=1	151	=1	23	=1
V	21	2	10	1.5	38	0.73	10	0.64	152	1.1	9	1.9	3	4.3
Cr	52	6.7	26	5.2	353	9.2	52	4.5	492	4.9	11	3.2	8	15.3
Mn	99	1.3	59	1.2	310	0.85	136	1.2	718	0.76	59	1.8	10	2
Fe	4332	1.1	2676	1.1	18500	0.96	6497	1.1	49700	0.99	1905	1.1	333	1.3
Ni	41	7	21	5.6	<3		29	3.3	<3		<3		4	10.2
Cu	255	59.3	166	60.4	1291	6.1	471	73.6	<3		12	6.3	6	20.9
Zn	141	25.8	84	24	407	15.1	198	24.3	1596	22.8	114	47.4	16	43.7
Ba	87	2.6	<15		<15		<15		584	3.9	52	3.6	28	12.6

Table 2c Concentration (x: ng m⁻³) and enrichment factor (EF) of different elements relative to average crust data, in the atmospheric aerosol over the regions of North-western China

	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7	
	x	EF	x	EF	x	EF	x	EF	x	EF	x	EF	x	EF
Al	1728	0.66	3330	0.46	1443	0.67	96	0.58	1010	0.51	354	0.71	4604	0.49
Si	6968	0.78	19690	0.80	5605	0.76	831	1.5	4348	0.64	1428	0.84	21730	0.67
S	757	90.8	1567	67.5	456	65.9	290	545.3	378	59.8	381	238.9	1261	41.7
Cl	298	71.5	433	37.3	180	52.1	164	616.8	406	128.4	42	52.7	873	57.8
K	1143	1.4	3117	1.3	1074	1.6	193	3.6	851	1.4	219	1.4	3850	1.3
Ca	3753	3.2	13300	4.1	3697	3.8	665	9	2166	2.5	507	2.3	11700	2.8
Sc	<20		<20		<20		<20		<20		<20		33	12.9
Ti	141	=1	393	=1	117	=1	9	=1	107	=1	27	=1	511	=1
V	9	2.1	16	1.3	7	1.9	3	10.9	7	2.1	3	3.6	17	1.1
Cr	10	3.1	41	4.6	12	4.5	9	44	8	3.3	10	16.3	23	2
Mn	51	1.7	115	1.4	56	2.2	12	6.2	32	1.4	13	2.2	123	1.1
Fe	1780	1.1	4886	1.1	1553	1.2	231	2.3	1263	1.04	366	1.2	6333	1.1
Ni	<3		26	3.9	<3		4	26.1	<3		3	6.5	<3	
Cu	45	25.5	187	38.1	62	42.4	28	248.9	209	156.2	38	112.6	<3	
Zn	70	31.2	203	32.5	67	36	14	97.8	92	54	13	30.3	<6	
Ba	51	3.7	<15		30	2.7	23	26.4	40	7.6	42	16.1	<15	

Sulphur and chlorine are enriched considerably at all sites. Enrichment factors of chlorine at sampling sites in the Takla Makan Desert are higher than those of sulphur; however, those for both are generally between 100 and 500. These elements are enriched presumably as a result of the disintegration of the surface. In more detail, it is proposed considering with caution the idea of the highly enriched sulphur and chlorine content of the air over North-western China, as follows. Because of the extreme aridity, soils in the Tarim Basin contain largely a certain amount of salt, mostly sodium sulphate and sodium chloride. Besides several lakes contain a lot of sodium chloride in the regions considered. Soils here largely contain gypsum not only in their upper layer but in their lower ones, as well. This is a particulate matter that contains both Ca and S ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). In deserts and semi-deserts [also at fringes of the mountains (Tianshan Mountains, Pamir, Kunlun Mountains) surrounding the Tarim Basin], gypsum frequently occurs as a result of the weathering of rocks of different composition. High enrichment factors of sulfur and chlorine at sampling sites at high mountains (sample numbers 1, 13 and 14) can be explained on the one hand by the composition of local soil different of that of average earth crust, and on the other hand by particulates transported by air currents from the arid regions of Inner Asia.

The above mentioned potential soil origin of S and Cl was investigated by using elemental concentrations of samples of local soil, which was collected in the Takla Makan Desert (Suzuki *et al.*, 1993). It was found that concentrations for sulfur and chlorine in samples of soil were at some cases by two orders of magnitude higher than those in the average crust (Mason, 1966) (Table 3).

From the equation (1) the connection between $\text{EF}_{\text{Fe, soil}}(\text{x})^1$ (enrichment factor of an element x to that of Fe relative to soil) and $\text{EF}_{\text{Fe, crust}}(\text{x})^2$ (enrichment factor of an element x to that of Fe relative to crust) is as follows:

$$\text{EF}_{\text{Fe, soil}}(\text{x})^1 = [(\text{x}/\text{Fe})_{\text{crust}}^2 / (\text{x}/\text{Fe})_{\text{soil}}^1] \cdot \text{EF}_{\text{Fe, crust}}(\text{x})^2 \quad (2)$$

¹ Suzuki *et al.* (1993)

² Mason (1966)

The quotient at the right hand side of the equation (2) is well below 1 (see Table 3). Consequently, enrichment factors (EFs) calculated relative to soil decrease considerably (Table 4a, 5a). In most cases, values of $\text{EF}_{\text{Fe, soil}}(\text{S})$ and $\text{EF}_{\text{Fe, soil}}(\text{Cl})$ are near (sometimes even below) 1, which clearly indicate the soil origin of sulfur and chlorine in the Takla Makan Desert (Table 4a). According to this result, enrichment factors of S and Cl in the Tarim Basin are proposed to be determined by not relative to the average crustal data (Mason, 1966) but by relative to the local soil (Suzuki *et al.*, 1993).

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Table 3 Elemental ratios of average crust¹ relative to those of local soil², North-western China

Sampling region*	$\left(\frac{c_S}{c_{Fe}}\right)_{crust^1}$	$\left(\frac{c_{Cl}}{c_{Fe}}\right)_{crust^1}$	$\left(\frac{c_{Cu}}{c_{Fe}}\right)_{crust^1}$	$\left(\frac{c_{Zn}}{c_{Fe}}\right)_{crust^1}$	$\left(\frac{c_K}{c_{Fe}}\right)_{crust^1}$	$\left(\frac{c_{Ca}}{c_{Fe}}\right)_{crust^1}$	$\left(\frac{c_{Mn}}{c_{Fe}}\right)_{crust^1}$
	$\left(\frac{c_S}{c_{Fe}}\right)_{soil^2}$	$\left(\frac{c_{Cl}}{c_{Fe}}\right)_{soil^2}$	$\left(\frac{c_{Cu}}{c_{Fe}}\right)_{soil^2}$	$\left(\frac{c_{Zn}}{c_{Fe}}\right)_{soil^2}$	$\left(\frac{c_K}{c_{Fe}}\right)_{soil^2}$	$\left(\frac{c_{Ca}}{c_{Fe}}\right)_{soil^2}$	$\left(\frac{c_{Mn}}{c_{Fe}}\right)_{soil^2}$
A	0.0141	0.0032	0.7333	0.6364	1.5463	0.9052	0.8261
B	0.2167	0.1182	1.8333	0.7778	0.7945	0.7311	0.8636
C	0.1486	0.0394	0.1158	0.6364	0.6852	0.3903	0.7037
D	0.1793	0.0356	0.8462	0.6667	0.6710	0.3227	0.7917

¹ Mason (1966)

² Suzuki et al. (1993)

* A and B sampling regions are found at the North-eastern part, while C and D at the south-western part of the Takla Makan Desert (Suzuki et al., 1993)

Table 4a Enrichment factors of S, Cl, Cu and Zn relative to local samples of soil¹, North-western China

Element*	Sample No.																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
S _A	2.31	2.11	0.70	1.14	1.06	1.18	0.94	0.66	0.91	0.59	1.20	0.38	0.89	2.28	1.15	0.87	0.80	3.39	0.81	2.81	0.54
S _B	35.54	32.49	10.73	17.55	16.41	18.16	14.51	10.24	14.01	9.06	18.49	5.84	13.65	35.04	17.72	13.36	12.23	52.31	12.47	43.37	8.30
S _C	24.37	22.28	7.36	12.04	11.25	12.45	9.95	7.02	9.61	6.21	12.68	4.00	9.36	24.02	12.15	9.16	8.39	35.87	8.55	29.74	5.69
S _D	29.41	26.89	8.88	14.53	13.58	15.03	12.01	8.48	11.60	7.49	15.30	4.83	11.30	28.99	14.66	11.06	10.13	43.29	10.32	35.90	6.87
Cl _A	0.22	0.16	0.29	0.65	0.44	0.52	0.41	0.27	0.39	0.54	0.92	0.11	0.13	0.18	0.21	0.11	0.14	0.88	0.40	0.14	0.17
Cl _B	8.11	5.73	10.79	24.00	16.23	19.25	15.17	9.85	14.54	19.71	6.27	4.14	4.84	6.55	7.61	4.03	5.27	32.27	14.61	5.22	6.27
Cl _C	2.70	1.91	3.60	8.00	5.41	6.42	5.06	3.28	4.85	6.57	11.24	1.38	1.61	2.18	2.54	1.34	1.76	10.76	4.87	1.74	2.09
Cl _D	2.45	1.73	3.25	7.23	4.89	5.80	4.57	2.97	4.38	5.94	10.16	1.25	1.46	1.97	2.29	1.21	1.59	9.73	4.40	1.57	1.89
Cu _A	137.7	53.29	37.50	43.44	43.69	42.50	38.77	39.24	41.36	46.52	48.33	-	4.20	12.01	16.85	25.52	26.62	80.80	110.3	69.22	-
Cu _B	344.4	133.2	93.74	108.6	109.2	106.3	96.91	98.11	103.4	116.3	120.8	-	10.50	30.03	42.13	63.79	66.54	202.0	275.8	173.0	-
Cu _C	21.75	8.41	5.92	6.86	6.90	6.72	6.12	6.20	6.53	7.35	7.63	-	0.66	1.90	2.66	4.03	4.20	12.76	17.42	10.93	-
Cu _D	158.9	61.48	43.26	50.13	50.41	49.08	44.73	45.28	47.72	53.68	55.77	-	4.85	13.86	19.45	29.44	30.71	93.24	127.2	79.87	-
Zn _A	38.32	16.15	17.32	15.66	21.19	16.81	15.66	14.79	14.27	10.00	13.85	14.60	27.20	21.84	17.88	18.89	19.61	27.55	33.11	16.15	-
Zn _B	46.83	19.74	21.17	17.40	25.89	20.55	19.14	18.08	17.49	12.22	16.93	17.84	33.25	26.69	21.85	23.08	23.97	33.67	40.47	19.73	-
Zn _C	38.32	16.15	17.32	15.66	21.19	16.81	15.66	14.79	14.27	10.00	13.85	14.60	27.20	21.84	17.88	18.89	19.61	27.55	33.11	16.15	-
Zn _D	40.14	16.92	18.15	14.92	22.19	17.61	16.41	15.50	14.95	10.48	14.51	15.29	28.50	22.88	18.73	19.78	20.54	28.86	34.69	16.91	-

¹ Suzuki et al. (1993)

* A, B C and D indices at the elements denote the sampling areas of the desert soils (A and B are found at the North-eastern part, while C and D at the south-western part of the Takla Makan Desert) (Suzuki et al., 1993)

Table 4b Non-crustal fractions of S, Cl, Cu and Zn relative to local samples of soil¹, North-western China, %

Element*	Sample No.																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
S _A	57	53	0	12	6	15	0	0	0	0	17	0	0	56	13	0	0	71	0	64	0
S _B	97	97	91	94	94	94	93	90	93	89	95	83	93	97	94	93	92	98	92	98	88
S _C	96	96	86	92	91	92	90	86	90	84	92	75	89	96	92	89	88	97	88	97	82
S _D	97	96	89	93	93	93	92	88	91	87	93	79	91	97	93	91	90	98	90	97	85
Cl _A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cl _B	88	93	91	96	94	95	93	90	93	95	84	76	79	85	87	75	81	97	93	81	84
Cl _C	63	48	72	87	82	84	80	70	79	85	91	28	38	54	61	25	43	91	79	43	52
Cl _D	59	42	69	86	80	83	78	66	77	83	90	20	32	49	56	17	37	90	77	36	47
Cu _A	99	98	97	98	98	98	97	97	98	98	98	-	76	92	94	96	96	99	99	99	-
Cu _B	100	99	99	99	99	99	99	99	99	99	99	-	90	97	98	98	98	100	100	99	-
Cu _C	95	88	83	85	86	85	84	84	85	86	87	-	0	47	62	75	76	92	94	91	-
Cu _D	99	98	98	98	98	98	98	98	98	98	98	-	79	93	95	97	97	99	99	99	-
Zn _A	97	94	94	94	95	94	94	93	93	90	93	93	96	95	94	95	95	96	97	94	-
Zn _B	98	95	95	94	96	95	95	94	94	92	96	94	97	96	95	96	96	97	98	95	-
Zn _C	97	94	94	94	95	94	94	93	93	90	93	93	96	95	94	95	95	96	97	94	-
Zn _D	98	94	94	93	95	94	94	94	93	90	93	93	96	96	95	95	95	97	97	94	-

¹ Suzuki et al. (1993)

* A, B C and D indexes at the elements denote the sampling areas of the desert soils (A and B are found at the North-eastern part, while C and D at the south-western part of the Takla Makan Desert) (Suzuki et al., 1993)

Table 5a Enrichment factors of K, Ca and Mn relative to local samples of soil¹, North-western China

Element	Sample No.																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
K _A	1.71	2.04	1.87	1.68	1.85	1.92	1.82	1.72	1.72	1.86	1.76	1.60	1.80	1.73	1.92	1.90	2.06	2.49	2.01	1.79	1.81
K _B	0.88	1.05	0.96	0.86	0.95	0.99	0.93	0.88	0.88	0.95	0.90	0.82	0.92	0.89	0.98	0.98	1.06	1.28	1.03	0.92	0.93
K _C	0.76	0.90	0.83	0.74	0.82	0.85	0.81	0.76	0.76	0.82	0.78	0.71	0.80	0.77	0.85	0.84	0.91	1.11	0.89	0.79	0.80
K _D	0.74	0.88	0.81	0.73	0.80	0.83	0.79	0.74	0.75	0.81	0.76	0.69	0.78	0.75	0.83	0.83	0.90	1.08	0.87	0.78	0.79
Ca _A	2.10	2.31	3.79	3.74	3.05	2.94	3.17	2.57	3.02	2.98	2.97	2.97	2.88	1.98	2.63	3.39	2.97	3.59	2.14	1.73	2.30
Ca _B	1.70	1.87	2.74	3.02	2.47	2.37	2.56	2.08	2.44	2.41	2.40	2.40	2.33	1.60	2.12	2.74	2.40	2.90	1.73	1.40	1.86
Ca _C	0.91	1.00	1.46	1.61	1.32	1.27	1.37	1.11	1.30	1.29	1.28	1.28	1.24	0.85	1.13	1.46	1.28	1.55	0.92	0.74	0.99
Ca _D	0.75	0.82	1.21	1.33	1.09	1.05	1.13	0.92	1.08	1.06	1.06	1.06	1.03	0.71	0.94	1.21	1.06	1.28	0.76	0.62	0.82
Mn _A	1.22	1.47	1.07	0.86	0.81	0.99	1.25	0.99	0.96	0.73	0.91	0.63	1.35	1.31	1.25	1.02	1.57	2.26	1.10	1.54	0.84
Mn _B	1.28	1.53	1.12	0.90	0.84	1.04	1.31	1.04	1.00	0.76	0.95	0.66	1.41	1.37	1.30	1.07	1.64	2.36	1.15	1.61	0.88
Mn _C	1.04	1.25	0.91	0.73	0.69	0.85	1.06	0.85	0.82	0.62	0.78	0.54	1.15	1.11	1.06	0.87	1.34	1.92	0.94	1.32	0.72
Mn _D	1.17	1.41	1.02	0.82	0.77	0.95	1.20	0.95	0.92	0.70	0.87	0.60	1.29	1.25	1.19	0.98	1.50	2.16	1.06	1.48	0.81

¹ Suzuki et al. (1993)

* A, B C and D indices at the elements denote the sampling areas of the desert soils (A and B are found at the North-eastern part, while C and D at the south-western part of the Takla Makan Desert) (Suzuki et al., 1993)

Table 5b Non-crustal fractions of K, Ca and Mn relative to local samples of soil¹, North-western China, %

Element	Sample No.																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
K _A	42	51	47	40	46	48	45	42	42	46	43	37	44	42	48	47	51	60	50	44	55
K _B	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	22	3	0	0
K _C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0
K _D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0
Ca _A	52	57	71	73	67	66	68	61	67	66	66	66	65	49	62	71	66	72	53	42	57
Ca _B	41	47	64	67	60	58	61	52	59	59	58	58	57	37	53	64	58	66	42	29	46
Ca _C	0	0	32	38	24	21	27	10	23	22	22	22	19	0	12	32	22	35	0	0	0
Ca _D	0	0	17	25	8	5	12	0	7	6	6	6	3	0	0	17	6	22	0	0	0
Mn _A	18	32	7	0	0	0	20	0	0	0	0	0	26	24	20	2	36	56	9	35	0
Mn _B	22	35	11	0	0	4	24	4	0	0	0	0	29	27	23	7	39	58	13	38	0
Mn _C	4	20	0	0	0	0	6	0	0	0	0	0	13	10	6	0	25	48	0	24	0
Mn _D	15	29	2	0	0	0	17	0	0	0	0	0	22	20	16	0	33	54	6	32	0

¹ Suzuki *et al.* (1993)

* A, B C and D indices at the elements denote the sampling areas of the desert soils (A and B are found at the North-eastern part, while C and D at the south-western part of the Takla Makan Desert) (Suzuki *et al.*, 1993)

Near the Great Wall, in the vicinity of Beijing, S and Cl with highest enrichment factors were analyzed by Winchester *et al.* (1981a, 1981b). Hashimoto *et al.* (1994) collected samples with high concentration of chlorine in Urumqi, Xinjiang. Sulfur concentration was found also high over Lake Baikal (Van Malderen *et al.*, 1996) and Xizang (Tibet) (Winchester and Wang, 1989). However, similar results were obtained in Sudan, Africa (Penkett *et al.*, 1979). Penkett and his co-workers attributed this finding to the disintegration of salt flats and to the evaporation of rainwater leaving a salt rich layer. High concentrations of S and Cl in the Namib Desert atmospheric aerosol content were confirmed by a marine contribution (Annegarn *et al.*, 1983).

The enrichment factors of copper and zinc counted relative to local samples of soil (Suzuki *et al.*, 1993), are also tabulated (Table 4a). Except for EF_{Fe}(Cu) calculated for the sampling region C (Suzuki *et al.*, 1993) EFs are well over 20 at most sampling sites. Presumably, these elements are mostly emitted by anthropogenic sources. Scandium, chromium, nickel and barium are the elements, which can be detected at some sites with high concentrations, with enrichment factors well over 10, relating at least partly to their non-crustal origin, while at other sites their EFs are below 10 or even cannot be traced at all. In order to reveal potential spatial connections, the mentioned elements were marked at their sites on the map if their EFs were higher than 10 (Fig. 2). According to this map, significant non-mineral sources for scandium can be detected partly at the south-western region, partly at the eastern—north-eastern region of the Tarim Basin. Chromium has significant concentrations in the northern part of the Tarim Basin. Nickel, as an element

mainly of non-crustal origin, can be measured with higher concentrations at the North-western part of the region. Barium can be ascribed to significant anthropogenic source at the southern fringe of the Tianshan Mountain (Fig. 2).

Enrichment factors of K, Ca and Mn, relative to local samples of soil (Suzuki *et al.*, 1993), were also calculated (Table 5a). Since in this case elemental concentrations in soil, with the exception of sampling region A for potassium, are also higher than those in the crust (Table 3), EFs of K, Ca and Mn decreased, respectively (Table 5a).

The $(c_x)^*$ fraction of the concentration of an element x, coming from non-crustal contribution, can be calculated by the following formula (Mason, 1966):

$$(c_x)^* = \frac{(c_x)_{air} - (c_{Ti})_{air} \cdot \left(\frac{c_x}{c_{Ti}}\right)_{crust}}{(c_x)_{air}}, \quad \text{where}$$

(3)

$(c_x)_{air}$: is the concentration of an element x in the air

$(c_{Ti})_{air}$: is the concentration of titanium in the air

$(c_x)_{crust}$: is the concentration of an element x in the crust

$(c_{Ti})_{crust}$: is the concentration of titanium in the crust.

The table of non-crustal fractions (Table 6) shows that an important part of potassium, vanadium, manganese and iron is released into the air from the Earth's crust. Potassium can have biological source. In spite of the fact that vanadium has a moderately high non-crustal fraction, we can conclude to its partial crustal origin. Manganese must be partly industry-orientated. Iron can be both of natural and anthropogenic origin. Mineral particles in North-western China contain high amount of Fe and can, therefore, be expected in the atmosphere. Their presence has also been reported in other desert areas, as well (Penkett, *et al.*, 1979; Annegarn *et al.*, 1983; Shattuck *et al.*, 1991). It is known on the other hand that ferrous metallurgy is a source of iron-rich particles, which might be of minor importance in our case, since heavy industry is only found in the region around Urumqi. Therefore, it is likely that the major part of iron is of natural origin. Quartz is one of the most widespread minerals in the Earth's crust. It is originated by weathering rocks, which might result in small particles easily dispersed into the atmosphere by winds. North-western China, with its deserts and steppes, arid and semi-arid regions, even with high mountains, surrounding the Tarim Basin, with slopes of which looking on to the basin and having practically no any vegetation, is one of the most important regions of the world where quartz is accumulated. Most of the Tarim Basin is covered by loose sandy soil, and shifting sand

covers predominant part of the Takla Makan Desert, inside the basin. Therefore, it is not surprising that quartz particles are commonly observed and they have a substantial fraction on the filters. High concentrations of quartz in soil samples of the Takla Makan Desert are confirmed by *Suzuki et al.*, 1993. At two-thirds of the samples, the concentration of silicon was at least one order of magnitude higher than that of the other elements (*Table 2a-c*). Another source of Si-rich particles is the combustion of coal in power plants as discussed by *Husein* (1986), furthermore *Flagan and Taylor* (1981). Enrichment of silicon at sampling site No. 18. and its moderately high non-crustal fraction might be traced back to an industrial background near the site. Though non-crustal ratio of calcium is relatively high, it is originated mostly from the crust. The case of vanadium is quite different. On the basis of its moderately high non-mineral fraction, measured at some sites, we can conclude to its partial non-crustal origin. As it is well known, its emission comes mostly from oil burning. For several elements (S, Cl, Sc, Cr, Ni, Cu, Zn) the non-mineral fraction, calculated on the basis of average crust concentrations, is over 80 per cent; even for some of them (S, Cl, Cu, Zn) it is between 95 and 100 per cent (*Table 6*). While nickel and copper can be connected to non-ferrous metallurgy, and nickel is also emitted by coal and oil combustion in power plants and industrial boilers, zinc is mainly emitted from iron-, steel- or ferro-alloys plants (*Pacyna*, 1984). Other sources of Zn are refuse incineration (*Mamame*, 1988) and tire wear (*Hopke*, 1985). In the lack of enlarged heavy industry in Xinjiang Province, moderately high non-crustal fractions of vanadium and manganese as well as those of nickel and especially copper and zinc might probably indicate enrichment of these elements in local soil. Scandium is rather enriched on the one hand at the south-western part, on the other hand at the north-eastern part of the Tarim Basin (*Table 2a-c, 6; Fig. 2*). This element might come mainly from oil burning. This hypothesis is to be confirmed by the fact that the two largest oil resources in the Tarim Basin can be found in the above-mentioned regions, and the scandium might come from their oil torches.

The enrichment factor for chromium was partly well over ten, but the sites for these concentrations are distributed at the northern part of the Tarim Basin. This indicates that chromium here is partly of non-crustal origin. These values are similar to those, which were measured over Hungary (*Borbély-Kiss et al.*, 1991; *Molnár et al.*, 1993a). This element was enriched at some regions, far from human settlements, as high as in the air over industrial areas. Chromium is regarded as an indicator of emission from the steel and iron industry. At the sites near Urumqi, concentration of Cr reflects the effect of the city which is an important centre of iron metallurgy. However, the only centre of iron and steel manufacturing in Xinjiang Province is hardly supposed to raise chromium concentrations thousands km away from Urumqi. It is also possible however, that chromium is of crustal origin (*Nriagu*, 1989a, 1989b) and its concentration in the soils of this area is higher than

its crustal average (Mason, 1966). This latter hypothesis is supported by the fact that the highest chromium concentration was found at the southern fringe of the Takla Makan Desert (Molnár *et al.*, 1993b). Chromium was detected in soil samples collected in the Takla Makan Desert but concentration data were not mentioned (Suzuki *et al.*, 1993). These data might confirm the above-mentioned hypothesis, according to which soils in the Tarim Basin are enriched in chromium relative to the crustal average.

Table 6 Non-crustal fractions of aerosol particles, relative to average crust data, %

Element	Sample No., North-western China																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Al	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Si	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0	0
S	100	99	98	99	98	99	99	99	99	98	99	96	99	100	99	99	98	100	98	100	98
Cl	99	98	99	100	99	99	99	99	99	99	100	97	98	99	99	97	98	100	99	98	98
K	29	41	23	17	0	23	17	17	17	17	23	3	23	29	29	23	37	72	29	29	23
Ca	67	69	75	79	58	71	73	69	72	69	83	70	71	64	69	76	74	89	60	57	64
Sc			92	95						96	93	97									92
Ti	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	69	80	23		52	37	29	50	33	0	0	9	47	77	52	23	47	91	52	72	9
Cr	62	90	79	68	79	79	67	85	81	89	78	80	69	93	68	78	78	98	70	94	50
Mn	47	57	29	17	0	23	37	23	17	0	17	0	44	50	41	29	55	84	29	55	9
Fe	23	23	9	9	0	9	9	9	9	0	9	0	9	23	9	9	17	57		17	9
Ni		83	63	74	82	80		86	82		70			90		74		96		85	
Cu	100	99	98	99	98	98	98	98	98	98	99		84	95	96	97	98	100	99	99	
Zn	99	97	98	96	96	96	96	96	96	93	96	96	98	98	97	97	97	99	98	97	
Ba		76	17									29	72	92	73		63	96	74	94	

The cases of sulfur and chlorine need a bit more attention. On the basis of their non-crustal fractions (96-100 per cent), they seem to be absolutely of non-mineral origin (Table 6). In order to understand why these enrichments occur in the two types of processes, it should be considered which one could be important in semiarid environments. In the first, case soluble salts are concentrated in the uppermost soil layers under conditions of alternating precipitation and evaporation and associated soil biological processes. The segregation of elements at the soil-air interface creates an opportunity for their preferential transfer to the atmosphere when dust is lifted. In the second case reactive acidic gaseous compounds, which are being present in the air from pollution or natural sources, attach to suspended basic dust particles. These might be subsequently deposited to the surface at rates that are controlled by aerosol mechanics. Chemical processes alone may drive soluble elements to the soil surface in alternating wet and dry conditions by capillary action. However, the process might be catalysed by algae and other desert flora that cover much of

the soil surface. Since high salinities are toxic to flora, the organisms pump out salt to counteract internal salinity build-up during their dehydration, and crystals might be formed on the surface. It is known that periods of high humidity, which can create a more favourable salinity environment for desert flora than dry periods, stimulate algae growth. According to *Wang et al.* (1987), the above-mentioned mechanism for salt accumulation at the soil surface might be biological, although chemical processes provide a driving force. Nevertheless, these processes are consequences, which are actually quite effective. The main climatological and geomorphological factors, which are reasonable for salt accumulation in the Tarim Basin, are the relief and its extreme climate. This basin is a vast inland region without outflow. In the summer, cloudiness is almost negligible; consequently, sunshine radiation is very high, which increases potential evaporation as well as aridity, since there is hardly any precipitation in this season here. As the Tarim Basin has no any outflow, salt has been accumulating. The connected biological and chemical processes accelerate this procedure. Since the air over North-western China is highly enriched with sulfur and chlorine, the dry deposition flux of these elements to the surface should be large, although balanced by an equal flux upward (*Wang et al.*, 1987). In the thinly populated Xinjiang Province it can hardly be imagined that anthropogenic sulfur emissions can lead to more than a modest additional dry deposition sulphate flux. High enrichment factors of S and Cl (*Table 2a-c*) are decreased considerably when calculating them relative to local samples of soil (*Table 4a*), however high non-crustal fractions of these elements (*Table 6*) calculated relative to local soils are decreased only slightly and non-mineral fractions of sulfur and chlorine are well over 80 % in several cases (*Table 4b*).

Non-crustal fractions relative to local samples of soil for S, Cl, Cu and Zn (*Table 4b*) furthermore those for K, Ca and Mn (*Table 5b*) are less than those relative to earth crust (*Table 6*). Even though those for Cu and Zn indicate an important effect of non-mineral origin. Higher non-crustal fractions might come partly from long distance transport; however, disintegration of the surface is more probable.

Our results were compared with those of other arid and semiarid regions in China (*Molnár et al.*, 1993b), Sudan (*Penkett et al.*, 1979) and Namibia (*Annegarn et al.*, 1983; *Eltayeb et al.*, 1993), respectively. According to the data in Sudan, when winds blow from Sahara, the concentrations of different elements are very high. This coincides well with our results for the Takla Makan Desert (see also *Molnár et al.*, 1993b). As a characteristic difference, the concentration of sulfur and chlorine as well as chromium is substantially lower in Sudan and the Namib Desert than in the Takla Makan. Further difference is that S and Cl is of marine origin in the Namib natural aerosol.

Results of the samplings measured at same three sites both in 1990 (*Molnár et al.*, 1993b) and in 1994 (present paper) were also compared (*Fig. 3a-c* and *Table 7*). [Bold letters indicate geographical positions and description of these three sampling sites (*Table*

7)]. The characteristic similarity of these three pairs of concentration series is that highly enriched sulfur and chlorine were detected equally in each site both in 1990 and in 1994. Furthermore, enrichment factors of elements of soil origin [Al, Si, K, Mn and Fe (with EF near unity)] are very similar in the two measuring periods. However, concentration data were significantly higher in 1994 at each site analyzed. Especially the absolute concentrations of copper and zinc, respectively were one order of magnitude higher in 1994 than in 1990. The total concentration of elements of crustal origin (Al, Si, K, Mn, Fe and further taking S, Cl and Ca into this group) reaches 95-99 per cent of that of the detected elements. This shows that soil controls almost exclusively the quantity of aerosol over the region. Phosphorus, cobalt and arsenic were only detected in 1990 but barium and scandium only in 1994 (Table 7). Latter results, considering high enrichment of these elements except for phosphorus, might suppose some changes in non-mineral emissions.

Table 7 Enrichment factors (EF) and concentration ratios of different elements in aerosol particles in North-western China

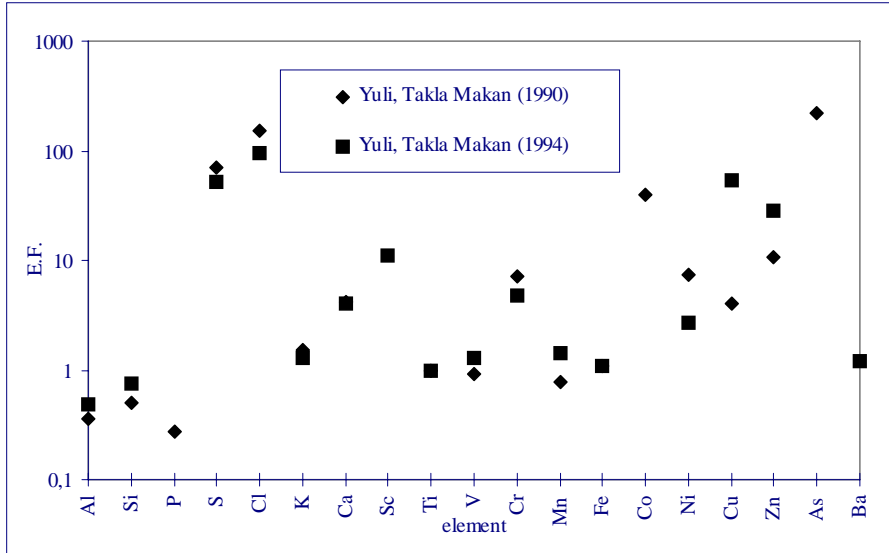
Element	Yuli, Takla Makan (desert)			Toksun, Turpani Basin (lowland, desert)			Du-ku, Tianshan (mountain)		
	EF 1990 ¹	EF 1994 ²	$\frac{(c_x)_{1994}^3}{(c_x)_{1990}}$	EF 1990 ¹	EF 1994 ²	$\frac{(c_x)_{1994}^3}{(c_x)_{1990}}$	EF 1990 ¹	EF 1994 ²	$\frac{(c_x)_{1994}^3}{(c_x)_{1990}}$
Al	0.36	0.48	3.2	0.50	0.49	23.5	0.34	0.51	6.6
Si	0.50	0.75	3.6	0.54	0.67	30.5	0.43	0.64	6.6
P	0.27			1.2			1		
S	69.8	52.2	1.8	131.2	41.7	7.7	86.7	59.8	3.1
Cl	150.2	96.2	1.6	123.7	57.8	11.3	79.2	128.4	7.2
K	1.5	1.3	2.1	1.4	1.3	22.1	0.99	1.4	6.1
Ca	4.2	4	2.3	2.7	2.8	24.7	3.4	2.5	3.2
Sc		11			12.9				
Ti	=1	=1	2.4	=1	=1	24.2	=1	=1	4.5
V	0.92	1.3	3.3	2	1.1	13.1	2.2	2.1	5.4
Cr	7.1	4.7	1.6	17.1	2	2.8	12.6	3.3	1.2
Mn	0.78	1.4	4.2	1.2	1.1	21.8	0.62	1.4	9.9
Fe	1.1	1.1	2.3	1.5	1.1	18.2	1.2	1.04	4
Co	39.4			26.7			28.2		
Ni	7.5	2.7	0.9	5.2			2.7		
Cu	4.1	53.9	31.5	3.7			4.6	156.2	151.4
Zn	10.8	28.7	6.4	10.5			6.5	54	36.9
As	219.8			231.7			270.9		
Ba		1.2						3.9	

¹ Molnár et al. (1993)

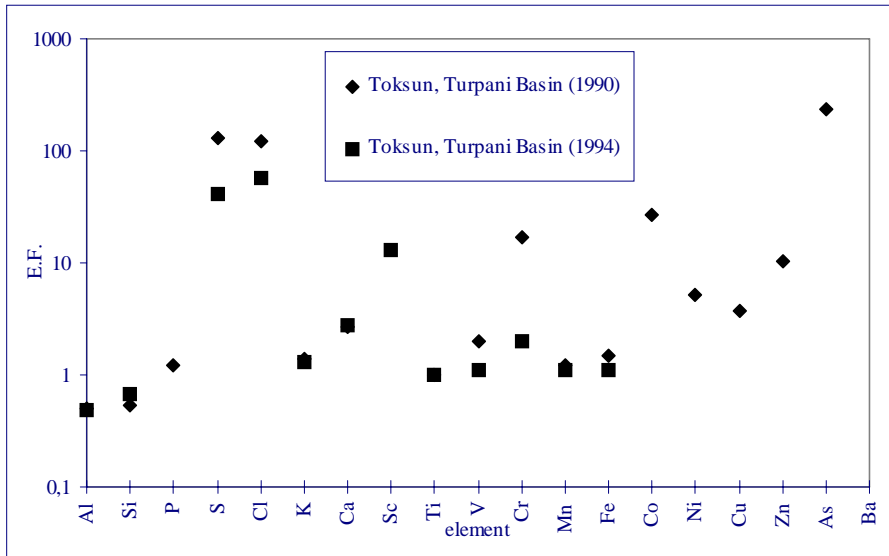
² Present paper

³ concentration of an element x measured in 1994 (present paper) relative to that measured in 1990 (Molnár et al., 1993)

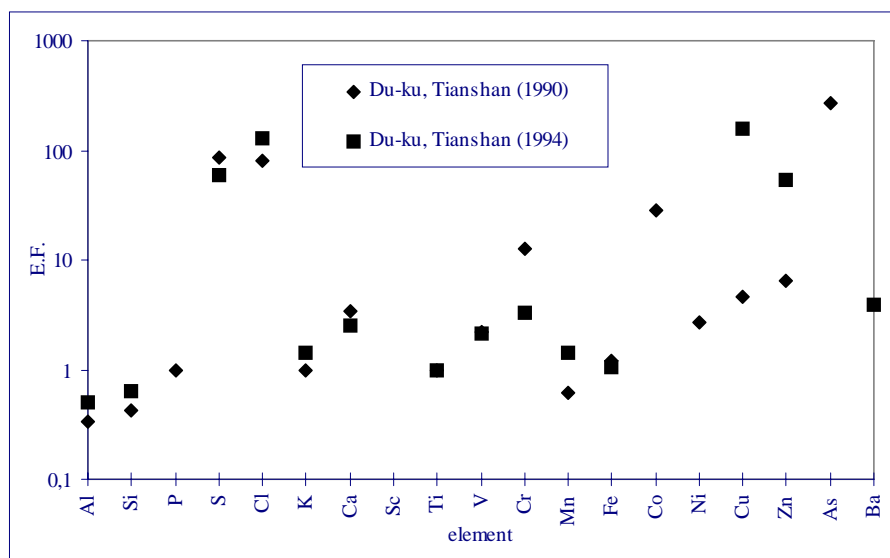
Pixe analysis of atmospheric aerosol particles in North-western China



3a Enrichment factors of 19 elements at Yuli, Takla Makan Desert



3b Enrichment factors of 19 elements at Toksun, Turpani Basin



3c Enrichment factors of 19 elements at Du-ku, Tianshan Mts.

CONCLUSION

According to our results the absolute concentrations of S and Cl are surprisingly high in the Tarim Basin comparing to desertic regions in Africa. Besides the level of chromium is also very high. Those of Wang *et al.* (1987) and Winchester and Wang (1989) confirmed these results for sulfur and chlorine. Both papers show high sulfur concentration over North-western China and Xizang (Tibet). The sulfur content over Xizang is only relatively high; compared to that over Xinjiang it is nearly one order of magnitude lower. Sulfur and chlorine is enriched in Northern China (Winchester *et al.*, 1981a, 1981b), sulfur and chromium in the Lake Baikal region (Van Malderen *et al.*, 1996). [Sulfur content is also high in Chinese cities, which can be explained by coal burning. However, it is out of our field, since we study and compare (in China) only atmospheric aerosols of background regions without local anthropogenic sources.] The concentration of aerosols might change with seasons. In the winter, they probably get accumulated, while in the summer they are deluted. The examination of the seasonal change of the elemental concentration is the task of further research. Several papers of this kind of analysis have been published for urban

areas of China with expressed seasonal change in concentrations (e.g. *Ning et al.*, 1996; *Hashimoto et al.*, 1994).

As a conclusion, the extremely high concentrations of S, Cl and the moderately high ones of Cr over North-western China, taking into account the surrounding large thinly populated regions, might not come from local anthropogenic sources. Local soil is highly enriched with sulfur and chlorine (ratios of these elements of local soil relative to those of crust are well over 1). Consequently enrichment factors of these elements relative to local samples of soil are near (at some cases below) 1. Therefore, it is clearly proved that the source of highly enriched sulfur and chlorine in atmospheric aerosols in North-western China is exclusively the local soil which is also highly enriched with salts. Concentration data of chromium in local soil are not available. Thus, enriched chromium in atmospheric aerosol particles can not be explained directly. However, it is presumed that Cr is also of soil origin. Enrichment factors of Cu and Zn even relative to local soil are well over ten. Hence, their non-crustal fractions are generally well over 80 % which assumes their mostly non-mineral origin. However, there are no industrial sites over the vast territories of North-western China. There are insufficient concentration data of copper and zinc in local soil; nevertheless, it is supposed that these elements also come from local soil.

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