Elemental tracers for Chinese source dust*

ZHANG Xiaoye (张小曳), ZHANG Guangyu (张光宇), ZHU Guanghua (朱光华)**,
ZHANG Deer (张德二)***, AN Zhisheng (安芷生),
CHEN Tuo (陈 拓) and HUANG Xiangping (黄湘萍)

(Xi'an Laboratory of Loess & Quaternary Geology, Chinese Academy of Sciences, Xi'an 710054, China)

Received March 1, 1996

Abstract The mass-particle size distributions of 10 dust-carrying elements in aerosol particles were determined for 12 sites in desert regions of northern China. The desert dust is proved to be of origin of eolian loess deposited on the Loess Plateau. Their transport to the loess was mainly attributable to the non-dust storm processes under the interglacial climate condition. The impact of dust storm on the accumulation of the loess increased in the glacial stage. On the basis of the signatures of 4 dust elements (Al, Fe, Mg and Sc), Chinese dust is believed to have 3 major desert sources (northwestern deserts, northern high dust deserts and northern low dust deserts). With a chemical element balance model, an elemental tracer system is established to proportion the export of China-source dust.

Keywords: Chinese deserts, mineral dust, atmospheric trace elements, elemental tracer.

The mineral dust particles with stability in chemistry are widely considered as a good indicator for atmospheric movement. The dust particles originating from arid and semi-arid regions of China were proved to be a major component in the atmosphere over mid-latitude (25° — 40°) of the Northern Hemisphere[1, 2]. However, sources of the dust were not accurately known, even some sub-source regions like the Loess Plateau were also considered as source regions. Many other reports further ascertained that the actual origin of Chinese dust is the Chinese major desert areas. For example, Liu (1965) and Lu (1974) mentioned that the accumulation of Chinese loess was attributable to the contributions of the deserts[3, 4]. Through synoptic-climate studies on historical "dust shower" in China, Zhang (1984) pointed out that the Chinese dust was derived from the deserts of China, not from the Loess Plateau[5]. By intercomparsion of contributions from "local" deserts and "remote" sources, Zhang (1996) demonstrated that the major sources of the mineral dust inputted to the Loess Plateau were the desert regions in northern China during the last glacial cycle[6].

With the elemental mass-size distributions (MSDs) of the atmospheric aerosol particles

* Project supported by the National Natural Science Foundation of China.

** Institute of Low Energy Nuclear Physics, Beijing Normal University, Beijing 100875, China.

*** Laboratory of Climate Research, National Meteorological Bureau, Beijing 100081, China.

over the major deserts of China, the specific objectives of the studies reported here are: (1) to determine whether or not there are still distinguishable source regions in Chinese deserts; (2) to define the distributions of the sources; (3) to establish an elemental tracer system for Chinese source dust.

1 Materials and methods

The 120 sets of ground-based, size-separated aerosol particle samples (8 stages) were collected at 12 Chinese desert sites in spring of 1994. Of total samples 9 were collected under dust storm (DS) conditions. Single orifice, 8-stage, Battelle-type cascade impactors (PIXE International Corporation, Tallahassee, Florida) were used for sampling. Sampling intervals generally range from 5 to 10 h. The flow rates were approximately 1 L · min^{-1}, thus providing 8 particle-fractions: <0.25, 0.25 — 0.5, 0.5 — 1, 1 — 2, 2 — 4, 4 — 8, 8 — 16 and >16 (μm in diameter). The sampling sites are described respectively as (figure 1).

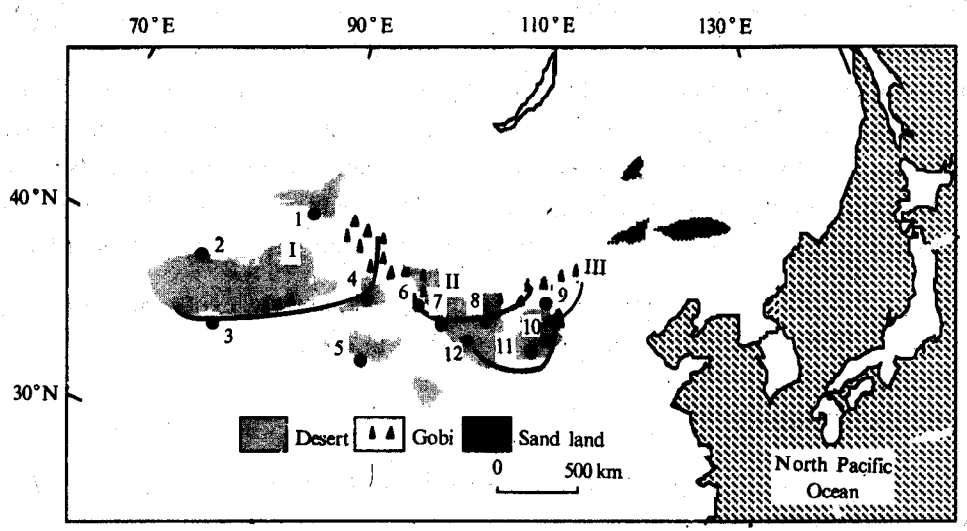

Fig. 1. Aerosol sampling locations in Chinese desert regions and source distribution (I, II, III) for Chinese dust. 1, FK; 2, Aksu; 3, Qira; 4, DH; 5, Golmud; 6, JYG; 7, HQ; 8, Jartai; 9, Dalad Qi; 10, YL; 11, DB; 12, MQ. I, Northwestern deserts; II, northern high dust deserts; III, northern low dust deserts.

Of sampling stations in Xinjiang, Fukang (FK, 44° 17′N, 88° 7′E) is at the southern margin of Gurbantunggut Desert. It is about 76 km north of Urumqi City. Aksu (41° 22′ N, 80° 43′E) is at the northern part of Taklimakan Desert. Sampling station was set up at a water balance observatory, nearly 90 km southeast of Aksu City. Qira station (37° 6′N, 82° 34′E) is located at Desert Observatory of the Chinese Academy of Sciences in the southern margin of Taklimakan Desert, about 100 km east of Hotan City. In Golmud (36° 52′N, 95° 54′E) the aerosol samples were collected at the Tibetan Plateau Excursion

Base of the Chinese Academy of Sciences, in the northern part of deserts in Qaidam Basin. Dunhuang site (DH, 40° 16′N, 94° 10′E) is located at a meteorological station about 16 km northwest to the Dunhuang City (Gansu Province) in Kumutage Desert. Jiayuguan (JYG, 40° 38′N, 98° 31′E) and Heiquan (HQ, 40° 26′N, 100° 16′E) are situated at the southwestern and southern margins of Badain Juran, the largest desert in Inner Mongolia. Jartai (40° 34′N, 106° 34′E) is located in Ulan Buh Desert. Dalad Qi (40° 53′N, 110° 5′E) is in another desert named Hobq in Inner Mongolia. We also collected aerosol samples at Minqin (MQ, 39° 17′N, 103° 10′E) in southern part of Tengger Desert. In Mu Us Desert we assigned two sampling sations. Yulin (YL, 38° 37′N, 109° 46′E) and Dingbian (DB, 37° 37′N, 107° 34′E) are in the middle and the southwest part of the desert, respectively.

We also obtained 4 dustfall samples on 1984-03-14—15, 1984-04-19—20, 1984-04-25—26 at Lanzhou (provided by Li Shangcheng), and 1990-04-24—26 at Beijing, respectively.

The aerosol samples were analyzed using a proton induced X-ray emission (PIXE) method. The PIXE analyses were performed using the 2.5 MeV protons with a 50 nA beam current produced by a 2×1.7 mV tandem accelerator at Beijing Normal University. Using these procedures we were able to determine the concentrations ($\mu g \cdot m^{-3}$) of 10 elements: Al, Ca, Fe, K, Mg, Mn, Sc, Si, Sr and Ti. The concentrations of the elements were determined also by PIXE in 20 aliquots of a standard reference material from National Bureau of Chemical Exploration Analysis, China[7]. The quality control and quality assurance tests showed that the analyses for the elements were within 20% of the standards.

The dustfull samples were analyzed using inductively coupled plasma mass spectrometry. The analysis procedure was described in reference [6].

2 Results and discussion

2.1 Origins and concentrations of the atmospheric trace elments

The mean concentrations of 10 elements of non-dust storm (N-DS) and DS aerosol samples over the desert regions are summarized as the sum of the data for the eight individual cascade impactor filters in tables 1 and 2, respectively. The concentrations of Al, Fe, K, Mg, Mn, Sc, Sr and Ti in bulk aerosol particles resemble the pattern of the concentrations of the average crustal rock[8]; those of Ca and Mn are slightly higher, but smaller than 5, which suggests that the concentrations of the ten elements were dominated by dust-carrying aerosol particles. This was demonstrated by a calculation of enrichment factors relative to crustal rock using Si as the reference element ($EF_{crust}=(X/Si)_{air}/(X/Si)_{crust}$) (data omitted).

Mean concentration of Ca in the atmosphere over the deserts is 3.2 times as high

Table 1 Arithmetic mean concentrations of trace elements in bulk aerosol particle samples over Chinese deserts during non-dust storm periods from 1994-04 to 1994-06

Element	Unit	Taklimakan Desert		Gurbantunggut Desert	Kumutage Desert	Badain Juran Desert		Ulan Buh Desert	Hobq Desert	Mu Us Desert		Tengger Desert	Deserts in Qaidam Basin
		Aksu (n=9)	Qira (n=9)	FK (n=15)	DH (n=7)	JYG (n=6)	HQ (n=7)	Jartai (n=6)	Dalad Qi (n=8)	YL (n=10)	DB (n=10)	MQ (n=9)	Golmud (n=15)
Al	$\mu g \cdot m^{-3}$	23	30	13	20	18	18	20	17	25	30	16	15
Ca	$\mu g \cdot m^{-3}$	51	74	22	32	35	27	34	28	37	59	22	27
Fe	$\mu g \cdot m^{-3}$	22	35	6.2	14	11	12	15	9.1	12	28	5.7	9.7
K	$\mu g \cdot m^{-3}$	13	20	5.6	8.8	5.7	7.7	9.8	6.1	8.4	17	4.6	6.1
Mg	$\mu g \cdot m^{-3}$	6.7	6.9	5.0	4.0	5.0	7.4	7.0	4.6	7.2	6.7	4.2	4.7
Mn	$\mu g \cdot m^{-3}$	0.78	1.1	0.41	0.67	0.67	0.66	0.77	0.56	0.88	1.2	0.47	0.45
Sc	$ng \cdot m^{-3}$	6.0	7.7	4.2	4.9	5.8	5.7	6.8	5.7	8.8	9.3	5.5	4.3
Si	$\mu g \cdot m^{-3}$	110	140	46	72	54	74	92	61	88	140	46	57
Sr	$ng \cdot m^{-3}$	110	93	62	47	110	69	110	95	120	130	81	82
Ti	$\mu g \cdot m^{-3}$	2.7	3.8	1.3	2.0	1.6	2.1	2.5	1.7	2.6	4.0	1.4	1.5

Table 2 Concentrations of trace elements in bulk aerosol particle samples over Chinese deserts during dust storm periods

Element	Unit	Qira 32# (1994-05-24)	Qira 35# (1994-05-24)	Qira 40# (1994-05-25)	Qira 39# (1994-05-25)	Aksu 51# (1994-05-31)	Aksu 52# (1994-05-31)	Aksu 48# (1994-05-31)	JYG (1994-05-01)	Jartai (1994-05-15)
Al	$\mu g \cdot m^{-3}$	55	38	64	41	40	28	76	20	30
Ca	$\mu g \cdot m^{-3}$	160	120	210	140	110	77	200	39	73
Fe	$\mu g \cdot m^{-3}$	78	59	100	67	43	36	120	13	48
K	$\mu g \cdot m^{-3}$	43	32	54	35	25	20	60	7.4	30
Mg	$\mu g \cdot m^{-3}$	4.2	2.1	4.6	4.0	5.2	4.9	12	8.9	3.8
Mn	$\mu g \cdot m^{-3}$	2.2	1.8	3.3	2.0	1.4	1.2	3.2	0.66	1.7
Sc	$ng \cdot m^{-3}$	15	11	19	12	12	7.7	16	5.9	11
Si	$\mu g \cdot m^{-3}$	310	240	380	240	210	150	420	71	170
Sr	$\mu g \cdot m^{-3}$	0.36	0.18	0.15	0.19	0.20	0.06	0.09	0.05	0.23
Ti	$\mu g \cdot m^{-3}$	8.1	6.3	11	6.8	5.2	4	11	1.9	6.2

as that of the crustal rock. By comparing the eight main kinds of surface soils from northern to southern China[7], one can see that the concentration of Ca in loess is also about 1.4 times as high as that of the crustal materials[8], showing that the eolian loess bears the characteristics of the mineral dust and originated from the Chinese deserts.

Although the concentrations of the dust elements were all higher in DS conditions than in "clear" stages, the highest concentrations were not found for all the elements in the same DS sample (tables 1 and 2), implying that the proportions of the dust elements might vary in different Chinese desert sources.

Of all the dust elements Si has the highest concentration. At the southern margin of Taklimakan Desert (Qira) the concentration of Si reaches $380\,\mu g \cdot m^{-3}$, and at the northern margin (Aksu) was $420\,\mu g \cdot m^{-3}$. We averaged the concentration for every element at each sampling site and summed the concentrations for ten elements. The two highest values were $410\,\mu g \cdot m^{-3}$ at Qira and $310\,\mu g \cdot m^{-3}$ at Aksu, suggesting that the dust loading over Taklimakan Desert was the largest among the deserts. The two lowest (100 and $120\,\mu g \cdot m^{-3}$) occurred over southern margins of Gurbantunggut (FK) and the deserts in Qaidam Basin (Golmud); they were even lower than that in loess region[9]. This is why we do not take the data of these deserts into consideration in our tracer system.

2.2 Mass-size distribution (MSD) of dust-carrying Al

One can model the particle size distributions of atmospheric dust as the sum of three modes, each being characterized by a log-normal distribution with size ranges of about 20—200, 2—20 and 0.04—1 μm[11]. Dust particles were deposited in each stage of a cascade impactor according to the curves of impaction efficiency; as a dust-carrying element, therefore, Al can be considered to exist in continuous granulometric distributions. On the basis of the correlation coefficients of the least-square linear regressions, the log-normal fitting of MSDs for Al were satisfactory at a probability for chance occurrence of $p<0.05$ for 120 size distributions; in most cases $p<0.02$. The standard deviations of the distributions were generally smaller than 2. On the basis of the fitted MSDs, we obtained the mass percentages of 3 particle-size modes for DS and N-DS samples and calculated the frequency distributions of the percentage for each mode. We also calculated the frequency distributions of percentages for 39 last glacial loess and 22 interglacial paleosol from Luochuan loess section in the center of the Loess Plateau. All the results are summarized in table 3.

The mode values of N-DS desert dust in 3 particle-size ranges are compatible with that of the last interglacial paleosols. The DS dust particles are consistent with that of the last glacial loess samples. This consistence demonstrates that the deserts in northern China are major sources for mineral dust input to the loess. Moreover, it suggests that the transport of the desert dust to the loess is mainly attributable to the non-dust storm

Table 3 Mode values of percentages on 3 particle-size ranges for the dust particles in Chinese deserts and center of the Loess Plateau

	Mode (%)		
	>20 μm	2—20 μm	<1 μm
Non-dust storm aerosols, Chinese deserts (n[a)]=112)	6.5	58	33
S1 paleosol, Luochuan[b)] (n=22)	7.8	57	34
Dust storm aerosols, Chinese deserts (n=9)	22	54	22
L1 loess (No LISS1 samples), Luochuan[b)] (n=39)	30	47	24

a) Sample number; b) data from reference [9].

processes during the interglacial climate condition. The impact of dust storm on the accumulation of the loess increased during the glacial stage.

2.3 Elemental tracer system for mineral dust

To resolve the mixed pollution aerosol into source components, a chemical element balance (CEB) model is commonly used. It is essentially a weighted multiple-linear regression to estimate the contributions of various sources to an ambient aerosol[12]:

$$C_i=\sum_{j=1}^{p} X_{ij}S_j, \tag{1}$$

where C_i is the concentration of ith element in an ambient sample, X_{ij} is the corresponding data of ith element in jth source signature; S_j is the derived strength of jth source signature; p is the assumed number of source signatures. The used CEB model is modified to constrain S_j to values greater than zero[13].

For a successful elemental tracer system of mineral dust, several requirements should be met, namely, the elements should be crust derived, evenly sampled and accurately measured, stably and homogeneously emitted in each region. Furthermore, the derived source signatures should be distinct and stable during dust transport[13].

2.4 Elemental signatures for Chinese desert sources

Chinese desert dust is composed of various elements; no true tracer, or special elements unique to specific source regions. However, it is reasonable to expect the proportions of at least some elements to vary with source areas because different areas have different mixes of the minerals. Due to the anthropogenic influence on K, Mn and Sr in the atmosphere over the Loess Plateau[10], and the absence of the data for Si, Ti and high postdepositional impact on Ca in the used data set of the loess[9], when applying CEB to trace the transport of Chinese dust, we limited the known chemical signature to 4 dust elements (Al, Fe, Mg, Sc).

Here the proposed chemical signature consists of 4 elemental ratios to Al. Ratios are used to normalize various effects, such as the strength of dust emission in different

time, dispersion and removal during the transport. Al is used in the denominator because it is a general dust found at similar concentrations in the diverse desert regions and hence will not bias the ratios toward any particular regions.

To eliminate the effects of dust transport among the desert sites, the signatures were calculated based on the mode concentrations of frequency distribution. The data for individual desert sites are given in table 4.

Table 4 Elemental signatures for dust particles in Chinese desert regions, and for dustfall samples in Lanzhou and Beijing

Site and region	Fe/Al	Mg/Al	Sc/Al ($\times 10^{-4}$)	n[a]
		Individual desert site (mode value)		
Aksu	0.84	0.25	2.6	12
Qira	1.2	0.16	2.9	13
DH	0.57	0.16	2.5	7
JYG	0.65	0.30	3.4	7
Jartai	0.60	0.32	3.5	7
HQ	0.70	0.31	3.2	7
MQ	0.35	0.22	3.5	9
DB	0.78	0.20	3.1	10
YL	0.25	0.17	3.7	10
Dalad Qi	0.53	0.23	3.4	8
		Desert sources (geometric mean)		
Source I[b]	0.83	0.19	2.7	32
Source II[c]	0.65	0.31	3.4	21
Source III[d]	0.44	0.20	3.4	37
		Individual site, four DS events		
DS-A, Lanzhou				
1984-03-14— 15	1.1	0.41	4.7	1
DS-B, Lanzhou				
1984-04-19— 20	0.68	0.30	2.8	1
DS-C, Beijing				
1990-04-24— 26	0.51	0.18	8.2	1
DS-D, Lanzhou				
1984-04-25— 26	0.75	0.36	4.0	1

a) Sample number; b) mean of Aksu, Qira and DH data; c) mean of JYG, Jartai and HQ data; d) mean of MQ DB, YL and Dalad Qi data.

The signatures of Qira, Aksu and DH are grouped by using cluster analysis; their geometric mean is considered to be representative of the source signature for northwestern deserts, called source I. The data of JYG, HQ and Jartai are gathered, called northern high dust deserts (source II). Others are put together and called northern low dust desert (source III) (fig. 1 and table 4).

2.5 Distinctness of the source signatures and stability of the signature during transport

The two major requirements for a successful source tracer system are distinctness of

source signatures and stability of the signature during transport. From a test of Fisher's Protected Least Significant Difference, one can see that the significant differences for the signatures do exist among the three dust sources (table 5), which suggests that there are three major source regions (I, II, III) in Chinese desert areas.

Table 5 Test of Fisher's Protected Least Significant Differences for elemental signatures between the Chinese desert sources[a)]

Desert source	Mean difference	p-value
Source I vs. Source II	0.01	0.000 6
Source I vs. Source III	0.09	0.006
Source II vs. Source III	0.08	0.001

a) Significance level: 5%.

An elemental data set also records a nearly 400-km transport of Chinese dust directly from a desert site (Shapotou) to a site at southern margin of the Loess Plateau (Xi'an) during a DS event (called DS-E). This provides us with a way to evaluate stability of the signature during transport[10, 14]. The elemental ratio changes for bulk sample at the desert and the loess sites are shown in table 6. Changes for every tracer element at each site are also summarized in the table by assuming the coarse particles are removed more rapidly than the fine ones based on the cascade impactor data[10]. The similarities between each ratio for the bulk dust at the desert and loess sites positively suggest that the chosen signature is recognizable at least when dust was transported about 400 km from the desert source. Furthermore, the stabilities of the ratio for every tracer element remained at least before particles larger than 2 μm in diameter were removed. These results reveal that the

Table 6 Stability test of elemental signature for bulk samples and the rest fractions in the consequential removal-steps during a direct transport of Chinese dust from a desert site to a loess site in a DS event

	X/Al					
	Bulk	<16 μm	<8 μm	<4 μm	<2 μm	<1 μm
	Desert site, Shapotou, DS-E, 1990-04-10					
Al	1.0	1.0	1.0	1.0	1.0	1.0
Fe	0.78	0.70	0.72	0.76	0.61	0.84
Mg	0.42	0.42	0.43	0.45	0.40	0.37
Sc ($\times 10^{-4}$)	0.71	1.3	2.0	2.7	6.0	2.4
	Loess site, Xi'an, DS-E, av., 1990-04-11,					
Al	1.0	1.0	1.0	1.0	1.0	1.0
Fe	0.85	0.86	0.86	1.0	1.2	1.9
Mg	0.47	0.42	0.44	0.42	0.31	0.24
Sc ($\times 10^{-4}$)	1.1	1.3	1.6	2.4	4.3	7.0

signature is fairly stable with high tracing capacity for a long-range transport of dust.

2.6 Four-element tracer system for Chinese source dust

With the verified signatures for the three sources and that of the dustfall in four DS events, called DS-A, B, C and D (table 4), we obtained the contributions of dust from every source to each DS-fallout using CEB, and compared them with a careful meteorological diagnosis for the origins of each DS event[15] (table 7).

Table 7 Comparison of source contributions to trace elements for dustfall particles during 4 DS events from tracer system with major source identification from meteorological diagnosis[15]

Source strength	Source contribution	Al	Fe	Mg	Sc	Mean	Meteor. diagnosis for major source
	DS-2						
1.0	% Source I	100	75	46	57	70	Deserts in Xinjiang, especially Taklimakan Desert
	% Source II						
	% Source III						
	% Others					30	
	DS-3						
0.12	% Source I	12	15	7.6	12	11	Gobi, Badain Juran,
0.88	% Source II	88	84	91	110	92	Tengger, Ulan Buh, Hobq,
	% Source III						Mu Us Deserts in Inner
	% Others						Mongolia
	DS-4						
0.19	% Source I	19	31	20	6.3	19	*ditto*
	% Source II						
0.81	% Source III	81	70	90	34	69	
	% Others					12	
	DS-5						
0.24	% Source I	24	27	13	16	20	Deserts in Xinjiang
0.76	% Source II	76	66	65	65	68	and Inner Mongolia
	% Source III						
	% Others					12	

The mean contributions to the four tracer elements from the three source regions for each DS event exhibit no difference from the determination of the meteorological source diagnosis (table 7), which demonstrates that the four-element tracer system works well. If one accurately measured the concentrations of Al, Fe, Mg and Sc for atmospheric aerosol or eolian loess in receptor areas, he is able to use our tracer system to proportion the exports of Chinese source dust.

Acknowledgement The authors thank the staff of Aksu Water Balance Observatory of the Chinese Academy of Sciences, Qira Desert Observatory of the Chinese Academy of Sciences, Tibetan Plateau Excursion Base of the Chinese Academy of Sciences, Shapotou Desert Observatory of the Chinese Academy of Sciences. Thanks are especially due to Li Shangcheng and Jiang Baoming for their kind help and logistical support. This work was also supported by grants from Shapotou Desert Observatory, the Chinese Academy of

Sciences and Laboratory of Climate Research, National Meteorological Bureau.

References

1 Uematsu, M., Duce, R. A., Prospero, J. M. *et al.*, Transport of mineral aerosol from Asia over the North Pacific Ocean, *J. Geophys. Res*, 1985, 88: 5343.

2 Prospero, J. M., Uematsu, M., Savoie, D. L., Mineral aerosol transport to the Pacific Ocean, *Chemical Oceanography. Academic*, San Diego, Ca., 1989, (10): 188.

3 Liu, T. S., *The Loess Deposits of China* (in Chinese), Beijing: Science Press, 1965.

4 Lu, Y. C., Wen, Q. Z., Huang, B. J. *et al.*, A preliminary discussion on the source of loessic materials in China—A study of the surface textures of silt quartz grains by transmission electron microscope, *Geochimica* (in Chinese), 1976, (1): 47.

5 Zhang, D. E., Synoptic-climatic studies of dust fall in China since the historic times, *Science in China*, Ser. B., 1984, 27(8): 825.

6 Zhang, X. Y., Shen, Z., Zhang, G. *et al.*, Remote mineral aerosol in Westerlies and their contributions to the Chinese Loess, *Science in China*, Ser. D, 1996, 39(1): 67.

7 GSS., *Preparation of Geochemical Standard Reference Samples* (GSR1-6, GSS1-8, GSD9-12), National Bureau of Chemical Exploration Analysis, China, 1984.

8 Taylor. S. R., Abundance of chemical elements in the continental crust: a new table, *Geochim. Cosmochim. Acta*, 1964, 28: 1273.

9 Zhang, X. Y., Arimoto, R., An, Z. *et al.*, Late Quaternary records of the atmospheric input of eolian dust to the center of the Chinese Loess Plateau, *Quat. Res.*, 1994, 41: 35.

10 Zhang, X. Y., Arimoto, R., An, Z. *et al.*, Atmospheric trace elements over source regions for Chinese dust: concentrations, sources and atmospheric deposition on the Loess Plateau, *Atmos. Envir.* 1993, 27A(13): 2051.

11 Patterson, C. C., Gillette, D. A., Commonalities in measured size distributions for aerosols having a soil-derived component, *J. Geophys. Res.*, 1977, 82: 2074.

12 Williamson, H. J., Dubose, D. A., *Users Manual for Chemical Mass Balance Model*; *Receptor Model Technical Series*, U. S. Environmental Protection Agency: Research Trignle Park, NC, 1983, Vol III, EPA-450/4-83-014.

13 Lowenthal, D. H., Wunschel, K. R., Rahn, K. A., Tests of regional elemental tracers of pollution aerosols, I. Distinctness of regional signatures, stability during transport and empirical validation, *Environmental Science & Technology*, 1988, 22: 413.

14 Zhang, X. Y., An Z., Liu, T. *et al.*, Study on three dust storms in China-source characterization of atmospheric trace element and transport process of mineral aerosol particles, *Chinese Science Bulletin*, 1992, 37(11): 940.

15 Zhang. D. E., Wang, J. H., Preliminary studies on atmospheric circulation and synoptic-dynamic conditions for dustfall processes, *Loess, Quaternary Geology, Global Change* (in Chinese), Beijing: Science Press, 1995, 151—157.