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Aerosol Particles from Dried Salt-Lakes and Saline Soils Carried on Dust Storms over Beijing

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ABSTRACT

Characteristics of individual particles from a super dust storm (DS) on 20 March 2002, and those of non dust storm aerosols for Beijing (NDS) and Duolun (DL) (a desert area) are determined using a variety of methods. In China, typically the source of aerosols in dust storms is thought to be deserts with aluminosilicates being the main constituent particles; however, this does not reflect a complete analysis with our evidence indicating potential alternate dust sources along the storm's transport path. Individual particle analysis of aerosols collected from a super dust storm on 20 March 2002 in Beijing shows that among all the 14 elements measured, only S and Cl have remarkable positive correlation. 82.5% of all particles measured contained both S and Cl, and the relative mass percentage of S and Cl in these particles is much higher than the average of all particles. 62.0% of all particles contained S, Cl, and Na, in which the concentration of Na is 1.4 times higher than average. PMF (Positive Matrix Factorization) analysis indicates that NaCl and Na_2SO_4 are major components of these particles with S and Cl showing significant positive correlation. Moreover, SO_4^{2-} and Cl^- also show significant positive correlation in bulk aerosol analysis. XPS (X-ray Photoelectron Spectroscopy) analysis of the surface of aerosols demonstrates that concentrations of Na and S on particles from the dust storm are higher than those from non-dust storm particles in Beijing and also for particles from. It is very likely that particles enriched with S, Cl, and Na is from the surface soils of dried salt-lakes and saline soils enriched with chloride and sulfate. This evidence demonstrates that besides deserts, surface soils from dry salt-lakes and saline soils of arid and semi-arid areas are also sources of particulates in dust storms over Beijing.

Key words: Dust storm, Individual particle analysis, Correlation of S/Cl, Salt lake and saline soil

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1. INTRODUCTION

Dust storms, which arise in desert and loess areas of northwestern China and sweep over the major cities of Northern China, such as Beijing, each spring, have become increasingly intense over the past few years (Cyranoski 2003). Dusts driven by strong westerly winds accompanying cold fronts are transported long distances to Korea, Japan, the Pacific Ocean, and even as far as North America (Duce et al. 1983; Gao et al. 1992; Mori et al. 2002 etc.). About half of the dust from deserts in China and Asia is finally deposited in seas near China and the remote Pacific Ocean (Arimoto et al. 1996; Zhang et al. 1997). The loose loess in

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arid and semi-arid areas in northwestern China and Inner Mongolia is the main source of dust in China's storms. Yuan et al. (2006) collected soil samples at various land surfaces in Central Inner Mongolia. These were resuspended using a dry powder atomizer in an enclosure chamber to identify the origin of Asian sands for tracing them as they traveled downwind. Zhang et al. (2003) and Zhuang et al. (2001, 2003) studied the physicochemical characteristics of dust storms and their impacts on global climate during long-range transport in China in 2000, 2001, and 2002. Wang et al. (2004) discussed transport pathways and sources of PM10 pollution in Beijing during spring 2001, 2002, and 2003 and found that the pathways and sources of polluting aerosols are associated with Asian dust emissions. Recently Zhuang et al. (1992, 2003) further demonstrated the mechanism of coupling and feedback between iron and sulfur in air-sea exchange and concluded that transport in dust storms is an important path in global biogeochemical cycles.

Many scientists have paid a good deal of attention to the characterization of bulk aerosols in dust storms (Zhuang et al. 2001; Sun et al. 2004, etc.), while few have carried out individual particle analysis, which can give much more information on heterogeneous reactions, morphometrics, and transformation during long-range transport. A difficulty with analysis of bulk aerosols is that it does not different particles from different sources. Yet, individual particle analysis can provide useful information on the original source and chemical transformation of chemical species during long-range transport. Gao and Anderson (2001) analyzed single aerosol particles (using automated SEM) collected from Beijing, Qingdao, and Waliguan during April 1999 and revealed that the particulate matter of each region are complex, heterogeneous mixtures of soil dust with anthropogenic particles from various sources. Using image analysis Whittaker et al. (2003) found that particles in dust storm samples of PM10 at Beijing are a mixture of soot, smelter pollutants, loess and gypsum. Shi et al. (2003) also distinguished particles collected over Beijing to be soot, fly ash, and minerals by using image analysis. Zhang et al. (2000, 2003) reported that single particles from both dust storm and non dust storm samples collected from Qingdao, a costal city, were coated by sulfate and nitrate.

Here we report new findings based on individual particle analysis in addition to XPS, IC analysis for aerosol samples collected from a super dust storm over Beijing. The results demonstrate that besides deserts, particulate matter was generated from the surface soils of dry salt-lakes and the saline soils of arid and semi-arid areas.

2. EXPERIMENTAL SECTION

2.1 Sampling of Aerosol Particles

Samples were collected on 20 March 2002 when a super dust storm (DS) covered Beijing (39.9 N, 116.4 E) accompanied by strong winds of ~10 m s^{-1}. Sampling was conducted at between 15:30 - 19:50, just after the dust peaked. Two TSP samples were also collected on non dust storm days: one from Beijing (designated as "NDS", sampled at 8:30 - 10:30 on 25 July 2002, clear weather), and the other from Duolun (designated as "DL", 42.2 N, 116.4 E, sampled at 12:06 - 17:40 on 19 April 2002, clear weather). DS and NDS were taken on the roof of the Science and Technology Building of Beijing Normal University, twelve stories (~40 m) above the ground. DL was collected on the roof of a three-story building at Duolun Middle School. Aerosol samples were collected on Nuclepore polycarbonate membrane filters of 0.6- m pore size and 90-mm diameter with a medium-volume sampler (model: TSP/PM$_{10}$/PM$_{2.5}$-2; flow rate: 77.59 L min^{-1}) manufactured by Beijing Geological Instrument-Dickel Co., Ltd. The aerosols samples for ion chromatographic (IC) analysis were collected on a Whatman4l filter membrane (Whatman Co., UK). Sample filters were put in a polyethylene plastic bag immediately after sampling. After weighing (Sartorius 2004MP Electronic balance, 0.01 mg) under constant temperature and humidity, the samples were refrigerated for later analysis. All procedures were strictly monitored to avoid any possible contamination.

2.2 Individual Particles Analysis

Individual particles were analyzed with a HITACHI X650 Scanning Electron Microscope (SEM) coupled with an energy-dispersive X-ray microanalyzer (EDX) following EDX 9100's procedures. The operating conditions were set to 20-kV (accelerating voltage) and 40-pA (beam current) with spectral acquisition time of 60 - 100 s. A 1-cm^2 piece of the filter was mounted on a stub and coated with a thin graphite film by heating and sputtering. We randomly selected several areas on the filter with relatively low particle density and analyzed all the particles in these areas for 14 elements. Carbon and oxygen were not considered because they were too abundant in the polycarbonate filters. The intensities of the characteristic X-ray lines of each element were converted into their corresponding atomic fractions by the standard ZAF correction method - The method calculates the effects of atomic number (Z), absorption (A), and characteristic (and sometimes continuum) fluorescence (F), separately. The abundance of each oxide in the particles was determined with the standardized oxide method for EDX, which assumes that each element (except Cl) exists as an oxide and sums the 14 abundances of the elements to 100%. Geometry effects that arise from the finite size of micro particles introduce a systematic error, but this error has little effect on the characterization of particle types (Gao and Anderson 2001). In all, we measured 565 single particles from DS, 419 from NDS, and 498 from DL. Details of the method used are given in Yuan et al. 2004.

2.3 Ion Chromatographic (IC) Analysis

SO_4^{2-} and Cl^- were analyzed for the samples collected during the dust storm with a Dionex 600 IC system that consists of an anion separation column (Dionex Ionpac AS11), a guard column (Dionex Ionpac AG11), a self-regenerating suppressed conductivity detector (Dionex Ionpac ED50), and a gradient pump (Dionex Ionpac GP50). Peaknet 6 software was used for chromatographic data processing. The filters were extracted in an ultrasonic cleaner and filtered through 0.45- m microporous membranes (25 mm), and the extracts were then injected into the IC with polypropylene syringes (Yuan et al. 2003).

2.4 X-Ray Photoelectron Spectroscopy (XPS) Analysis

The surface composition and structure of the aerosols was measured using XPS (PHI 5000C ESCA System, 14 kV, 250 W, 93.9 eV, exciton, AlK a, scanning range for acquiring spectroscopy, 0 - 1200 eV, Perkin Elmer Company, USA). The minute spectroscopies of 10 elements (C_{1s}, O_{1s}, Na_{1s}, Mg_{2p}, Al_{2p}, Si_{2p}, S_{2p}, Ca_{2p}, Mn_{2p}, and Fe_{2p}) were acquired. A special software (PHI-MATLAB) was used for data analysis. The binding energy of polluted C1s (284.8 eV) was used in calibration to confirm the binding energy of all other elements.

The relative concentrations of atoms are calculated by the following formula (Boudevilie et al. 1979):

$$\frac{n_i}{n_j} = \frac{I_i}{I_j} \cdot \frac{\sigma_i}{\sigma_j} \cdot \left(\frac{E_{kj}}{E_{ki}}\right)^{1/2} \qquad (1)$$

Where n is the atom number over the aerosol surface, I is the intensity of XPS, σ is the area of the element in some energy level, and E_k is the kinetic energy of the photoelectron. Details of the method are given in Zhang et al. (2005).

2.5 PMF Factor Analysis

Positive Matrix Factorization (PMF) was developed by P. Paatero of the Department of Physics, University of Helsinki, Finland, and marketed jointly by YP-Teekniika K Y Company and the university's Department of Physics. It was first applied to environmental data by Juntto and Paatero (1994). Many works have shown it to be an effective and novel method for source apportionment of aerosol particles (Huang et al. 1999). PMF is a powerful tool that can work without original source information, provide all the nonnegative loadings of the elements in matrix, and optimize results by adjusting the standard deviation of each data point. Suppose X is a matrix with n m, where n is the number of samples and m is the number of chemical components, including all ions, elements and organisms. Then X can be divided into GF + E, where G is the matrix of n p, and F is the matrix of p m with p being the number of main pollution sources. E is a matrix defined as follows:

$$e_{ij} = x_{ij} - \sum_{h=1}^{p} g_{ih} f_{hj} \qquad Q = \sum_{i=1}^{m} \sum_{j=1}^{n} (e_{ij} / h_{ij} s_{ij})^2 \qquad (2)$$

where S_{ij} is the standard deviation. The restriction condition is that the elements in G and F are all nonnegative. E can acquire optimized results and confirmed G and F by comparing Q values. Usually F is considered a load matrix and G the figure matrix of the sources.

3. RESULTS AND DISCUSSION

3.1 General Descriptions

The mass fraction and the number fraction [the ratio of the number of particles, in which the element of interest was detected, to the total number of particles measured, also called number frequency (see below)] of each element in the samples of DS, DL, and NDS were reported in Yuan et al. 2006. The results show that: (1) the major elements, including Al, Si, P, S, and Ca were abundant in single particles of DS, DL, and NDS, whose number fractions were close to 100%; (2) Both Si and Al are dominant in the particles of DS and DL, and the sum of Si and Al accounted for ~65% of the total; whereas, greater numbers of S, P, and Cl were found in NDS, the sum of these three elements contributed 35% of the total; (3) Na and Mg in NDS were highest among the three samples, indicating that Na and Mg in NDS were partly from pollution; whereas, K was greater in DS and DL than in NDS, indicating that more K was from dust, as with Si and Al; (4) Cu in DL had an extremely high number frequency (96.8%), revealing there must be a special source of Cu nearby. Fan et al. (1996) reported the number frequencies of Mg, K, Ca, and Fe in dust storm particles collected in April 1991 in Beijing were all above 62%, results which were similar to this study. However, in this study we found very high number frequencies of S (99.5%) and Cl (82.5%) in DS; these values were much higher than that of S (14%) and Cl (0%) in the dust storm of 1991.

3.2 Composition and Size Distribution of Individual Particles

The highest recorded TSP hourly concentration was 10.90 mg m^{-3} for the DS period of 20 March 2002. This was 36 times higher than TSP concentration recorded during the non-DS. The 12 hr-averaged $PM_{2.5}$ concentrations also reached 1.39 mg m^{-3} (Sun et al. 2004). The size distribution and the morphology of the particles (morphology varies with particle size) were measured with SEM images of single particles. Particle sizes ranged from ~0.3 to ~20 μm. The median sizes were ~1.3 μm for DS particles, ~0.8 μm for NDS particles, and 1.2 μm for DL particles. For DS particles, > 80% were < 2.5 μm, which is respirable.

The average relative mass percentages of SO_3 and Cl in DS particles were 6.42% and 0.57% with the highest proportions of 97.39% and 11.43%, respectively. The percentage of (S+Cl)-containing particles constituting the total particles measured was 82.5%; the average relative mass percents of SO_3 and Cl were 6.70% and 0.58%, respectively, which were higher than the overall (n = 565) averages (2.6% and 0.42%, respectively). The (S+Cl+Na)-containing particles represented 62.0% of the total particles measured; the relative mass percent of Na was 6.10%, and 1.4 times that of the overall mean (4.36%). These results showed that the three elements Na, S, and Cl were enriched in some DS particles. The proportion of Na-containing particles with relative mass percent of > 15% in the DS sample was 1.24% of the total, which is 5 times higher than that (0.24%) in the NDS sample from Beijing. The relative mass percent of Na in the DL particles was 1.54%, which is lower than that (4.36%) in the DS sample from Beijing. The size of those S-enriched particles with a relative mass percent of 15% S was < 1.0 μm, indicating that these S-enriched fine particles were mostly from secondary pollutants. In contrast, (S+Cl)-containing particle size was > 1.0 μm. This indicates that those particles were mostly primary and their sources were likely the same though not from deserts, in which Si dominates the coarse particles. The PMF analysis showed that the major components in the (Na+S+Cl)-rich particles were Na_2SO_4 and NaCl, and the number of these particles was 9% of total particles. We have identified (Na+S+Cl)-containing particles from the spectrum of the EDX analysis and the SEM images, as shown in Fig. 1a. Additionally, the common particles in the DS samples are aluminosilicate particles enriched in Si, Al, and Ca, as indicated in Fig. 1b. These results demonstrate that particles that were enriched by a combination of S, Cl, and Na during DS were likely not from deserts.

3.3 Correlation Analysis of the Elements in Individual Particles

Table 1 lists the result of correlation analysis by STATISTICA®. Surprisingly, among the 14 elements measured

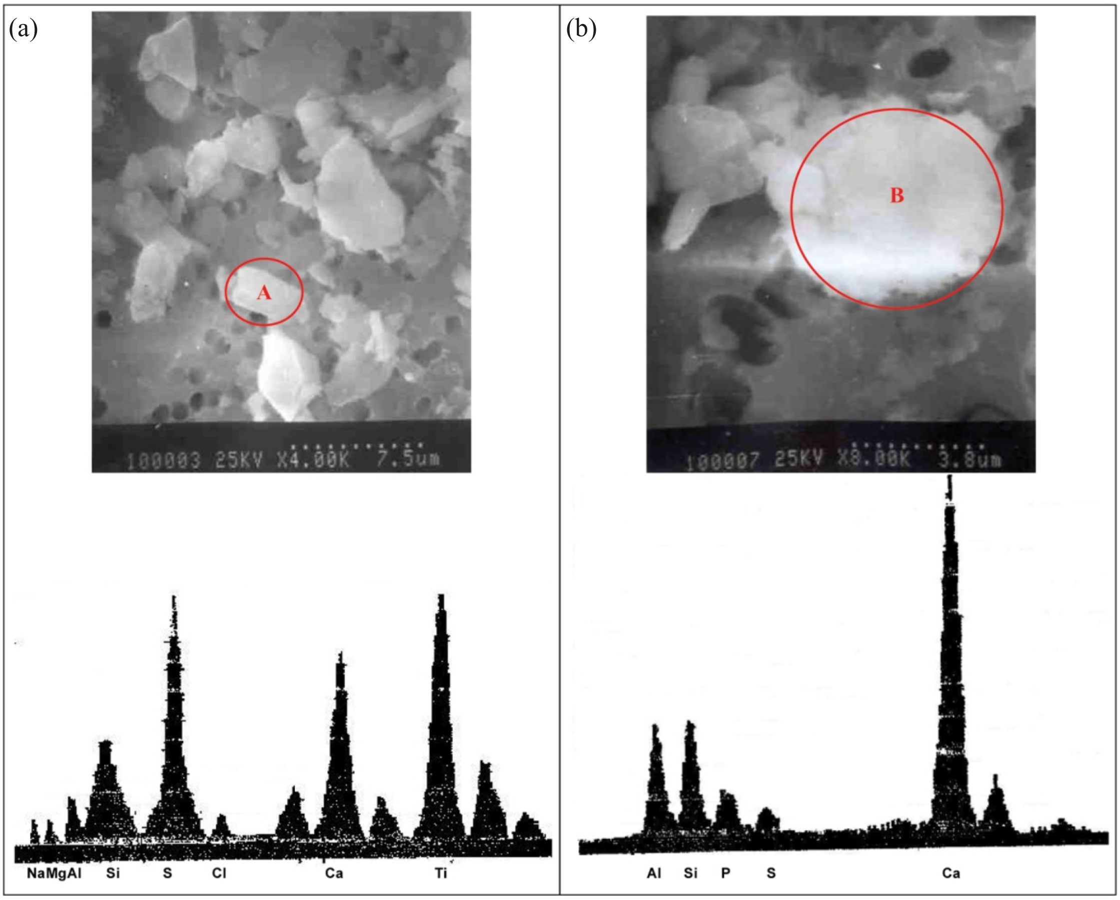

Fig. 1. Spectrum of a certain individual particle of duststorm aerosol by EDX: (a) S- and Cl-rich particle; (b) common dust particle.

Table 1. Correlation of relative mass percentage of elements in particles of the dust storm.

Dust storm in Beijing										
Wt%	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**Cl**	**K_2O**	**CaO**	**Fe_2O_3**
Na_2O	1.00									
MgO	0.27	1.00								
Al_2O_3	0.09	0.30	1.00							
SiO_2	-0.26	-0.44	-0.16	1.00						
P_2O_5	-0.37	-0.30	-0.28	-0.13	1.00					
SO_3	-0.20	-0.34	-0.45	-0.33	0.49	1.00				
Cl	-0.20	-0.24	-0.33	-0.28	0.41	**0.75**	1.00			
K_2O	-0.17	-0.10	0.29	0.07	-0.30	-0.13	-0.05	1.00		
CaO	0.10	0.19	-0.22	-0.44	-0.09	-0.08	-0.08	-0.16	1.00	
Fe_2O_3	0.10	0.32	0.12	-0.22	-0.38	-0.29	-0.23	0.05	-0.08	1.00

as individual particles in DS, only one pair of elements, S with Cl, show good correlation (the correlation coefficient being 0.75, = 0.05, $p << 0.01$). Correlation coefficients are only 0.53 in NDS samples and 0.07 in DL samples, respectively. It is clear that aerosol particles in DS are different to those particles of NDS and both DS and NDS particles are different again to the non-dust particles of DL, although the desert of Duolun, Inner Mongolia was considered to be a major source of aerosols for dust storms over Beijing. It must be noted that individual particle analysis is different to bulk aerosol analysis. The concentrations of crustal elements, such as Si, Al, and Fe, normally show positive correlation in bulk aerosol samples collected at different times and sites; whereas, the results from individual particle analysis do not show such a relationship (Yuan et al. 2006). Individual particle analysis gives information regarding an individual particle from a large number of particles in an aerosol sample; this does not present information regarding bulk analysis. Figure 2 shows a marked positive correlation between Cl and S in individual dust particles with an average ratio Cl/SO_3 of 0.09, which is close to the world average ratio for soil [0.06, from Bowen (1966)]. However, the ratio of Cl/Al_2O_3 was ten times that of world soil. This sole correlation of Cl with S and the high ratio of Cl/Al_2O_3 imply that Cl and S might come from an identical source where the soil has been enriched with both S and Cl. It is well known that dry salty lakes and saline soils in Inner Mongolia, which contain both Na_2SO_4 and NaCl (Yang 1996), lay on the path of dust storms, thus, dust storms would very likely pick up these particles here. The high correlation between Cl and S in dust storm particles suggests that these saline soils could be a source of particulates for dust storms (Yuan et al. 2006). This analysis can also explain why a number of dust particles containing Na, S, and Cl of crustal origins were found over Qingdao before passing across the ocean (Zhang et al. 2003).

3.4 Ternary Plots Analysis

Ternary plots (Yuan et al. 2004) of three major components [clay and quartz (Al_2O_3, SiO_2, etc.), calcite ($CaCO_3$, CaO), and salts (sulfate, phosphate, chloride)] of single particles revealed that Na_2SO_4 and NaCl might be externally/internally mixed in the DS particles. Yuan et al. (2006) proved that the $CaCO_3$, CaO, $CaSO_4$, and salts, i.e., sulfate and phosphate plus chloride, such as $(NH_4, Na)_x(SO_4, Cl, PO_4)_y$, mixed with clay and quartz in those particles.

3.5 Compositions and Correlations of the Soluble Ions

Figure 3 shows the concentrations of the SO_4^{2-} and Cl^- in

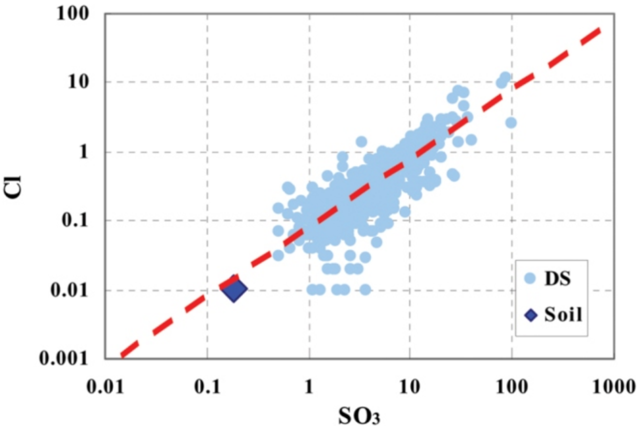

Fig. 2. Relationship between SO_3 and Cl in individual particles of the duststorm aerosol.

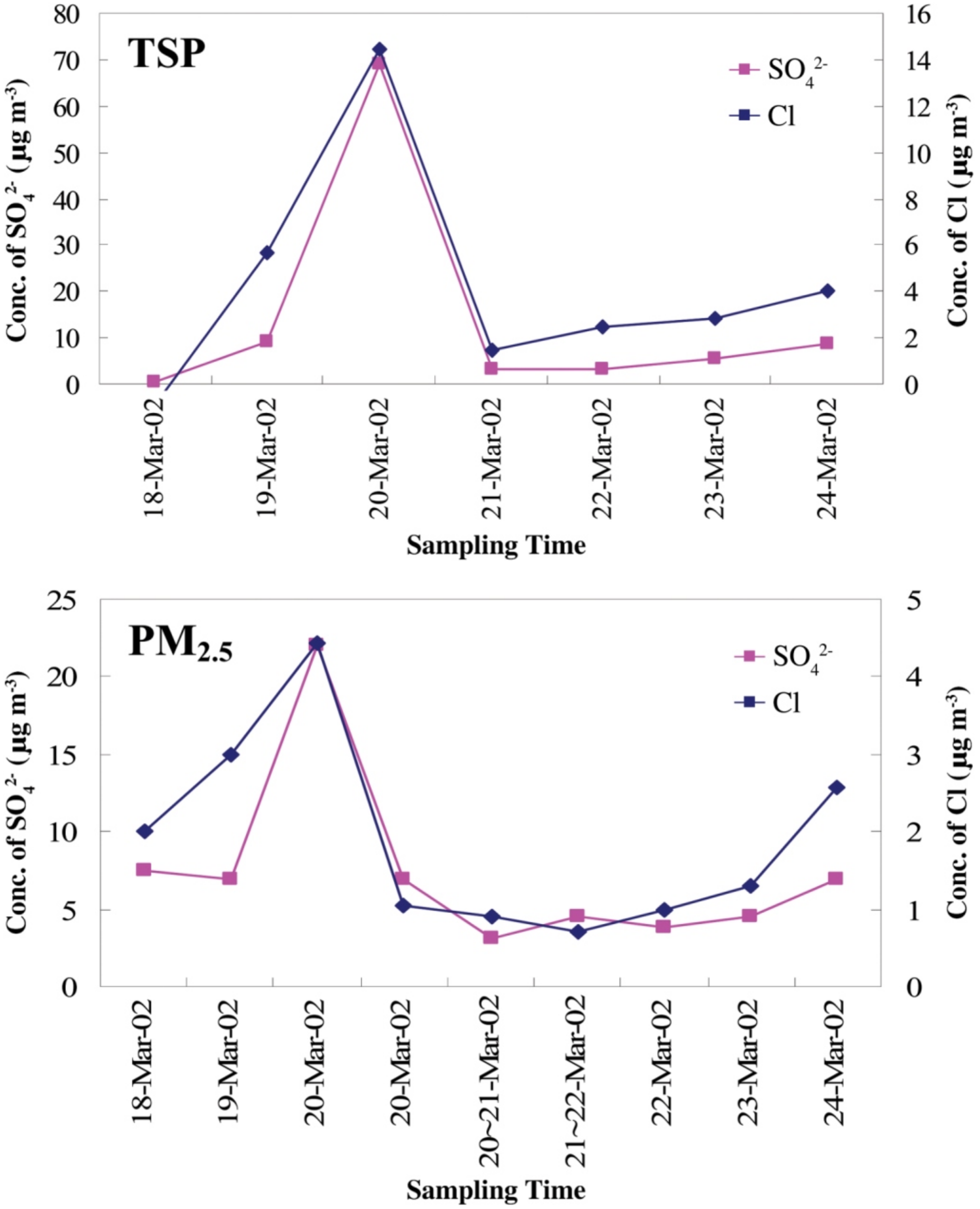

Fig. 3. Variations of SO_4^{2-} and Cl^- in TSP and $PM_{2.5}$ samples.

the TSP and $PM_{2.5}$ samples collected during DS. The concentrations of the SO_4^{2-} and Cl^- tracked each other. The average concentrations of SO_4^{2-} and Cl^- during DS are 1.95 and 0.48 mg g^{-1}, respectively. These results are 27 and 8 times those of DL (SO_4^{2-} 0.07 mg g^{-1}, Cl^- 0.06 mg g^{-1}). It has been reported that concentrations of SO_4^{2-} and Cl^- in typical salty soils in North China are 1.4 and 1.5 mg g^{-1} (Jiang and Zhang 2001). Comparing all these results, it is clear that there are more S and Cl in the individual particles of DS, implying that there must be other sources than deserts generating these particles, such as saline soil enriched with S and Cl components.

Figure 4 illustrates concentrations and correlation of SO_4^{2-} and Cl^- of six aerosol samples collected sequentially during DS. The sampling times were: 10:20 - 12:20, 12:22 - 14:22, 14:25 - 16:25, 16:25 - 18:25, 18:25 - 20:25, and 20:25 - 22:25. The figure shows a very positive correlation (R^2 = 0.9908) between SO_4^{2-} and Cl^- in these samples. Beijing is an inland city, and wind direction on the day of the storm was from the northwest or north at more than 10 m s^{-1}. Cl^- could not have come from the sea, which is located to east or southeast. Given the positive relationship between results for individual particle analyses and IC analysis for S and Cl and the prevailing winds during DS, it is likely that S and CL share a common source somewhere on the path of the dust storm to the northwest or north of Beijing.

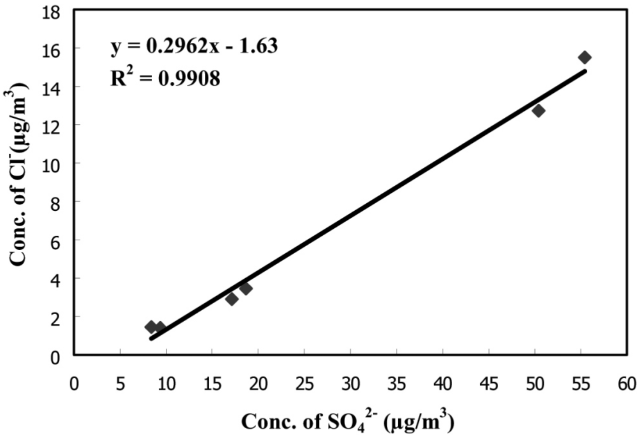

Fig. 4. Liner regression of SO_4^{2-} and Cl^- in dust storm day, 20 March 2002.

3.6 PMF Factor Analysis of the Elements in Individual Particles

The results of the 565 individual particles collected during DS, 419 particles of NDS, and 498 particles of DL have been analyzed by PMF2, which has been successful in getting source appointments of aerosol particles in Hong Kong, Thailand, and Spain, etc. (Huang et al. 1999; Lee et al. 1999; Predes et al. 1999; Jiang and Zhang 2001). The result of PMF analysis show that S and Na are of the same factors (55% SO_3, 41% Na_2O, and 36% P_2O_5), indicating that Na_2SO_4 was a major component of sulfates in the dust aerosols. The results from graphic technique analysis based on the SEM data also demonstrate that Na_2SO_4 is the main contributor to this factor in dust aerosol particles (Yuan et al. 2004). According to graphic analysis of individual particles, $(NH_4)x\ SO_4$ existed in dust aerosols, though in small numbers, thus giving Na_2SO_4 as the major sulfate. Cl, Na, and Mg are of the same factor for the samples of DS, in which the ratio of Cl/Na is 5. This is quite different to its ratio in seawater (1.8), which is normally based on the existence of both NaCl and $MgCl_2$. As previously discussed northwesterlies or northlies prevailed during DS, making it impossible for sea salts to be a factor in the particulate matter of DS and suggesting that particles enriched with Na and Cl were sourced from saltpans and saline soils in northwest and northern China. This is further evidenced by the main components of soils from saltpans and saline soils being rock salt (NaCl) and Glauber's salt (Na_2SO_4) (Xu 1993).

3.7 Surface Analysis by XPS

The XPS (X-ray photoelectron spectroscopy) analysis is an excellent method for studying particle surface structure and composition. Table 2 lists XPS results of samples collected during DS. The relative mass concentration percentage of Na on the surface was 0.30% in particles from DS, 0.27% for NDS and 0.18% for DL, indicating greater Na enrichment of DS particles. This result again confirms that there must have been an alternate source for Na on the storm's path as it traveled toward Beijing. XPS results also reveal the relative mass concentration percentage of S on the surface to be 0.80% for DS particles, a result higher than that for both NDS and DL samples (0.39%). Similarly, these results along with those of SEM and PMF analyses indicate another source besides the desert as being responsible for S, Na, and CL levels in DS particles.

3.8 Source of Those Particles Enriched with S, Cl, and Na

Okada and Kai (2004) analyzed soil samples collected at Qira in the Taklamakan Desert by EDX and found that 'Cl-rich' and 'Na-rich' particles were detected in approximately 10% of total particles. The backward trajectory from 500 m above Qira at the time of sampling showed that the air parcel did not arrive from over oceanic areas within the previous five days. The presence of atmospheric halite particles in the Taklamakan Desert was reported by Molnár et al. (1993) and Yabuki et al. (1998, 2002). Hence, 'Cl-rich' and 'Na-rich' particles were suggested to be mainly composed of halite. The 'Na-rich' particles contained S as the second most abundant element, excluding Cl. A 'S-dominant' particle was isolated from the two samples. This particle was evaporated upon irradiation with an electron beam, leading the researchers to conclude that it was composed of sulfate not originating from a mineral source; however, they did not explore further the possible sources of those particles containing S, Cl, and Na.

For DS two possible paths existed for the storm's approach: north and northwest (Ren et al. 2003). Figure 5 shows that all kinds of chloride-sulphate saline soils exist in the transport pathway of DS. Strong wind could have carried these particles enriched with S and Cl and transported them to Beijing. The saline soils cover an area of about 763.01 10^4 hm^2 in Inner Mongolia, these account for 21% of China's total (3630.53 10^4 hm^2) (Fan and Ma 2001). There are also a great number of salt lakes in Inner Mongolia (Li et al. 1990; Xu 1993). The A'LaShan salt lake area to the north and northwest of Beijing is one of four major salt lake areas in Inner Mongolia, and it lies on the dust transport path to Beijing. Because of continual drought in recent years, there are many saltpans in these salt-lake areas. The main components of the saltpans are rock salt (NaCl) and Glauber's salt ($Na_2SO_4 \bullet 10H_2O$) providing an abundant source of S and Cl enriched particles. An earlier study (Wang et al. 1987) of aerosol composition in the drylands of northern China reported the composition of aerosols collected at a site (see Fig. 5) located on Tianchi Mountain, east of Urumqi, to be strongly enriched with both S and Cl. They attributed this enrichment to uppermost soil layers being enriched with S

Table 2. Surface analysis of dust aerosol by XPS.

Sampling time	Sampling function area	S%	Na%
2002.3.20, 15:00 - 18:00	Beijing dust storm	0.802	0.302
2002.4.19, 12:00 - 17:00	Inner Mongolia non-dust	0.397	0.187
2002.4.26, 08:00 - 12:00	Beijing non-dust	0.983	0.271

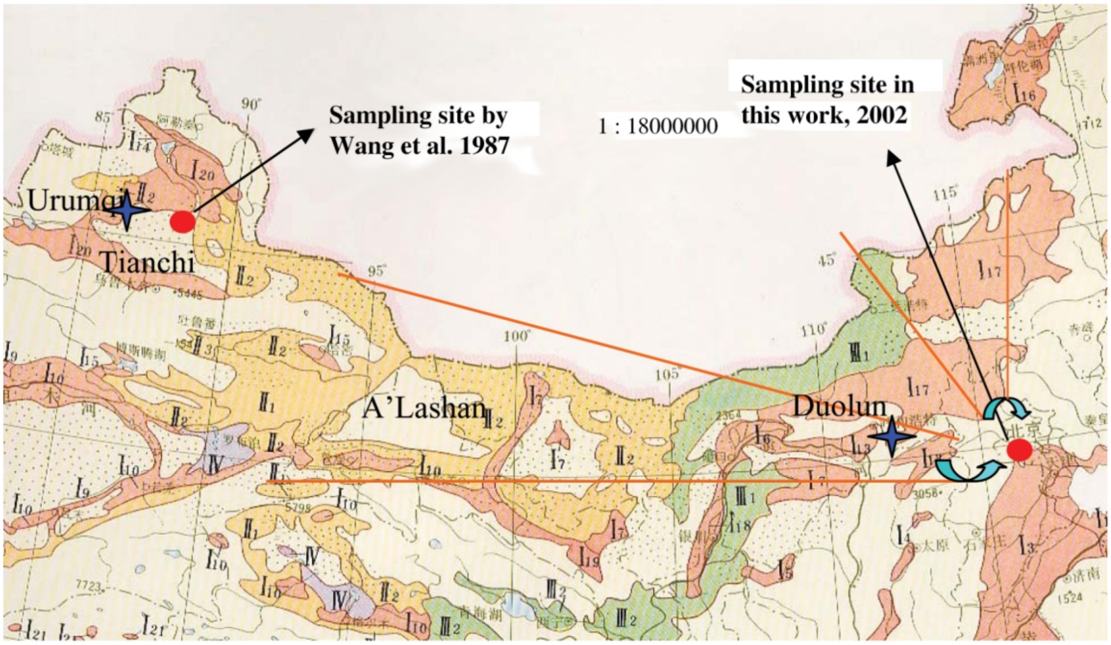

Fig. 5. Distribution of saline soils over Inner Mongolia, China.

Note: 1. two areas with red line mean that two path (North-west path and North path) for dust to Beijing.

2. I$_1$, *I_2, and II_1 mean different types saline soil in China.*

and Cl in this area. It's worth noting that there are many saline soils around this sampling site, 45 53'N, 88 07'E, such as I_2, I_{14}, and I_{20} in Fig. 5. These soils are typically enriched with sulfate and chloride. Thus, for this early study, strong wind could have raised surface saline soils during their sampling period giving such results. Thus, our study along and this earlier study both show that besides deserts, surface soils of dry salt-lakes and saline soils in arid and semi-arid areas can provide particulate matter for dust storms.

4. CONCLUSIONS

(1) Individual particle analysis of aerosols collected from a super dust storm on 20 March 2002 in Beijing showed that among all the 14 elements measured, only S and Cl had remarkable positive correlation.

(2) PMF analysis indicated that NaCl and Na_2SO_4 were major components of these particles, in which S and Cl showed significant positive correlation.

(3) The evidence that S and Cl in this dust storm were highly related indicates that dried salt-lake and saline soils over northern and northwest China might have contribute to the dust storm's origins.

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