

¹⁴C AND ¹⁰Be IN DUST DEPOSITED DURING THE STORM OF 16–17 APRIL 2006 IN BEIJING

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ABSTRACT. The concentrations of ¹⁰Be and ¹⁴C and values of δ¹³C in samples collected during a major dust storm in Beijing on 16–17 April 2006 were studied. The ¹⁰Be concentrations ranged from 1.69 × 10⁸ to 2.07 × 10⁸ atom/g, ¹⁴C ages for black carbon (BC) ranged from 3001 to 5181 yr BP and for total inorganic carbon (TIC) from 8464 to 9119 yr BP, and δ¹³C values for BC ranged from –23.15‰ to –23.80‰ and for TIC from –5.39‰ to –5.98‰. A comparison of BC content and δ¹³C value between the dust, surface soil in the dust source region, and aerosols in Beijing indicated that BC in the dust deposited in Beijing is significantly incorporated by aerosol BC during the dust transportation. Based on the ¹⁴C ages of BC, the proportion of fossil-fuel-derived BC was 0.35–0.49 of the total. In contrast to BC, the TIC deposited in Beijing can be firmly related to the source area and δ¹³C was not significantly modified during its transportation. According to the ¹⁴C ages of TIC, the proportion of the secondary carbonate in the dust was from 0.63 to 0.70. The results confirm that ¹⁴C of TIC is another useful tracer to indicate the source region of dust besides the content and δ¹³C value of TIC from the arid and semi-arid regions of China.

INTRODUCTION

Asian dust originating from the arid and semi-arid areas of northwestern China causes serious social and economic problems as it increases dust concentration and significantly reduces visibility in the atmosphere (Kwon et al. 2002; Kim and Kim 2003). About 800 Tg of Chinese dust is emitted annually into the atmosphere, of which 70% is transported eastward and deposited over East Asia (Zhang et al. 1997). When dust is transported, it brings new pollutants as aerosols to the local atmosphere. It also transfers a great amount of dust containing various trace elements and nutrient elements to the ocean ecosystem (In and Park 2003; Uematsn et al. 2003; Lim and Chun 2006). During dust transportation, the soil dust or dust in aerosol from downwind areas would also be incorporated. Therefore, it is important to characterize and distinguish between the components of dust and identify their respective source types and the sequence of their incorporation into the load (Chen et al. 2008). Analysis of the physical and chemical compositions of dust provides not only the evidence of the type of source for the dust and its area of origin, but also basic data that help to evaluate the influence of dust on the environment (Uematsn et al. 2003; Cao et al. 2005; Wang et al. 2005).

On 16–17 April 2006, a dust storm arrived in Beijing, causing the deposition of ~330,000 tons of dust, which was several times higher than the amount usually deposited during dust storms in Beijing (Zhang et al. 2008). The meteorological satellites NOAA-17 and NOAA-16 monitored the process: a clear band of dust appeared in Alashan and Bayannao'er on the Sino-Mongolian border at 11:22 AM, April 16, then, at 3:12 PM, an accelerated eastward movement of the dust was observed. There were 2 distinct dust zones: 1) the northern side moved eastward, covering the northeast Alxa, Bayannao'er, Ordos, Baotou, Wulanchabu, and Xilin Gol Leagues, which are Inner Mongolian subdivisions; 2) the other zone on the southern side was newly generated dust from the Mu Us Desert, which mainly affected NW Shaanxi Province in China (Figure 1a). The continuously eastward shift of the northern dust brought large dust storms to Beijing, Tianjin, northern Shanxi, Henan, and Shandong provinces, and the northern Bohai Sea region at 7:02 AM, April 17 (Figure 1b).

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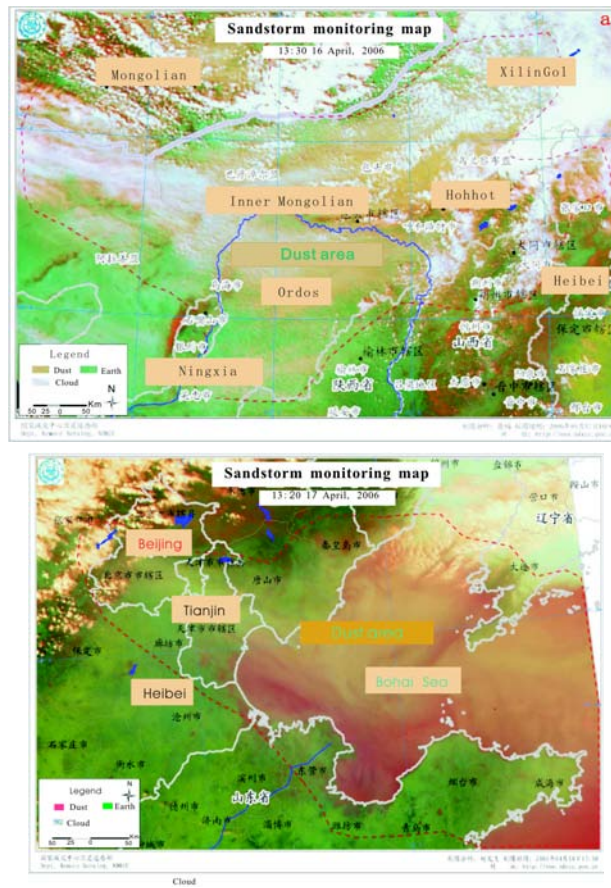


Figure 1 a) Formation of the dust in northwestern and northern parts of China monitored by the NOAA-17 meteorological satellite on 16 April 2006. b) The satellite map of the eastward transition of the dust to the Beijing, Tianjing, and Bohai areas on 17 April 2006.

Professor Tunsheng Liu at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), organized a comprehensive study on the dust deposited in Beijing during this storm (Liu et al. 2006). The physical properties and the chemical compositions of the dust were analyzed by different scientific groups (Liu et al. 2006; Han et al. 2007; Shen et al. 2007; Zhang et al. 2008). We obtained 12 dust samples to analyze the ^{10}Be and ^{14}C concentrations and $\delta^{13}\text{C}$ values in different fractions of the dust. Based on the results, we discuss whether these results could be used as indicators for the primary source region of the dust and the influences due to subsequent incorporation from other sources during transportation of the dust.

SAMPLING AND METHOD

Sampling

Dust samples were collected around Beijing ($39^{\circ}48'\sim 39^{\circ}58'\text{N}$; $116^{\circ}15'\sim 116^{\circ}31'\text{E}$) on 17–18 April 2006 by the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS). All the samples were collected on cleaned stainless steel discs fixed on roofs of cars except one fixed on a

bicycle shed. To minimize dust produced by human activities, all the selected sampling sites were far from expressways and construction sites. The detailed sampling distribution is given by Liu et al. (2006). In total, 27 dust samples about 1 g in weight for each sample were collected. For comparison, another dust sample was collected on 2 April 2007 in Ningbo (29°52'N; 121°33'E) using the same method by our group.

Analytical Methods

Sample Preparation and ¹⁰Be Measurements

Sample preparation was carried out in the State Key Laboratory of Isotope Geochemistry, CAS, in Guangzhou. The dust samples were first dried in a vacuum freeze-drier (ALPHA 1-2LDplus) in order to ground them easily to 200 mesh. About 0.5 g of dust was weighed out and placed in a 100-mL plastic beaker, to which 1 mg of ⁹Be carrier solution was added. Organic matter was removed by leaching with the mixture of 30% H₂O₂ and 6 mL 6 mol/L HCl for 24 hr (Shen et al. 1992). The leachates were separated by centrifugation, and the insoluble material was leached with 6 mL 6 mol/L HCl for 12 hr and separated by centrifugation. The insoluble residues were then freeze-dried in preparation for accelerator mass spectrometry (AMS) ¹⁴C analysis. Solutions from the 2 leaches above were mixed and dried by heating. The dried residues were dissolved by adding 1 mol/L HCl. Be, Al, Fe, and Mn ions in the solution were deposited by adjusting the pH of the solution to 8 by adding NaOH solution. Then, a 4 mol/L NaOH solution was added to the sample solution, and the pH of the solution was adjusted to 14, in order to precipitate Fe and Mn, which can then be separated by centrifugation.

The pH of the solution was then adjusted to 2.5 by adding 0.5 mol/L HCl. At the same time, EDTA solution was added into the solution to mask Al³⁺ in the solution. Subsequently, the solution was adjusted to pH 8 by adding NaOH solution to precipitate out Be(OH)₂. The precipitated Be(OH)₂ was again dissolved in HCl. The impurities in the solution were separated by passing the solution through a cation-exchange resin that was finally washed 10 times with 10 mL 1M HCl. We then collected the effluent solution in which Be was concentrated and adjusted the pH value of the effluent to 8 so that Be(OH)₂ was precipitated out. The Be(OH)₂ precipitate was separated by centrifugation and washed several times with deionized water. Then, the Be(OH)₂ precipitate was combusted into BeO powder at 900 °C. The BeO powder was mixed with niobium powder at a 1:1 weight ratio to make the BeO target for AMS measurement (Suter et al. 1984; Shen 1986; Shen et al. 1992). ¹⁰Be was measured by a 6MV tandem accelerator mass spectrometer with a sensitivity of 6 × 10⁻¹⁵ at Peking University. SRM-4325 ⁹Be/¹⁰Be from the National Institute of Standards and Technology (NIST) was used as a standard (Liu et al. 2007).

¹³C and ¹⁴C Measurements

The procedures of sample preparations for AMS ¹⁴C and δ¹³C measurements were carried out at the AMS ¹⁴C laboratory in the State Key Laboratory of Isotope Geochemistry, CAS, in Guangzhou. The carbon in the residues separated from the chemical pretreatment of ¹⁰Be mentioned above was extracted for isotopic analysis. Because the total inorganic carbon (TIC) in the residues had been acid-hydrolyzed, and the organic carbon had been oxidized by peroxide (30% H₂O₂) during the pretreatment, the carbon left in the residue was mostly black carbon (BC) (Smith et al. 1975). The residues with silver and excess granular CuO in quartz tubes were first evacuated under vacuum at 1.0 × 10⁻³ Torr for 12 hr. The residues were then combusted to convert BC into CO₂ gas at 860 °C for 2 hr after the tubes were sealed. The combusted tube was cracked open in a vacuum system in which the CO₂ gas was extracted and purified. The pressure of the purified CO₂ was measured in a known volume, and then the gas was divided into 2 portions with 1 portion containing ~1 mg C for

graphitization using the method reported by Xu et al. (2007), and the other portion for stable carbon isotope analysis (Shen et al. 2001).

The other portion of the ~0.5-g dust sample was weighted out and placed into a tube with a branch filled with purified H₃PO₄ (~100%). After the tube was pumped to vacuum, the dust sample was mixed with the H₃PO₄ to release the CO₂ gas. The gas was purified and divided into 2 portions for both ¹⁴C and ¹³C isotopic analyses using the method described above.

Graphite targets were measured by the compact AMS system in the State Key Laboratory of Nuclear Physics and Technology, Peking University, at a precision of 3‰. Oxalic acid standard I and II (NBS OXI and OXII) were both used as standards (Liu et al. 2007). $\delta^{13}\text{C}$ values were obtained using a Finnigan MAT-251 isotopic ratio mass spectrometer with a precision of $\pm 0.2\text{‰}$ in the State Key Laboratory of Loess and Quaternary Geology, CAS in Xi'an. Results are reported as $\delta^{13}\text{C}$ in ‰ with respect to the International Pee Dee Belemnite (PDB) standard.

RESULTS AND DISCUSSION

Contents of BC and TIC, $\delta^{13}\text{C}$ values and ¹⁴C ages of BC and TIC, and ¹⁰Be concentrations in the dust in 12 samples from Beijing and 1 from Ningbo are given in Table 1.

Table 1 Contents, $\delta^{13}\text{C}$ values, and ¹⁴C ages of TIC and BC, and total organic carbon content (TOC) and ¹⁰Be concentration in the dust in Beijing and Ningbo (f_m = fraction modern).

Sample nr	TOC ^a (%)	TIC				BC					¹⁰ Be ($\times 10^8$ atom/g)
		TIC ^a (%)	$\delta^{13}\text{C}^a$ (‰)	¹⁴ C age (yr BP)	f_m	BC (%)	$\delta^{13}\text{C}$ (‰)	¹⁴ C age (yr BP)	f_c	d^b	
ZLJJ001	2.38	0.93	-5.95	8604 ± 27	0.34	1.00	-23.46	4932 ± 31	0.51	0.34	1.72 ± 0.09
ZLJJ003	1.83	1.36	-5.83	8845 ± 29	0.33	1.12	-23.25	4024 ± 38	0.57	0.33	1.75 ± 0.06
ZLJJ006	2.18	1.22	-5.97	8976 ± 32	0.33	1.44	-23.80	3645 ± 37	0.60	0.33	1.86 ± 0.08
ZLJJ009	2.11	1.33	-5.96	8709 ± 30	0.34	1.26	-23.43	4102 ± 53	0.57	0.34	1.83 ± 0.09
ZLJJ010	2.16	1.15	-5.97	8464 ± 32	0.35	1.15	-23.15	3001 ± 28	0.65	0.35	1.80 ± 0.10
ZLJJ014	1.97	1.16	-5.98	8673 ± 31	0.34	1.02	-23.50	5181 ± 33	0.49	0.34	1.77 ± 0.11
ZLJJ015	2.01	1.23	-5.96	8647 ± 33	0.34	1.20	-23.69	3657 ± 36	0.60	0.34	2.07 ± 0.09
ZLJJ016	2.00	1.35	-5.63	8828 ± 31	0.33	1.30	-23.67	4078 ± 30	0.57	0.33	1.78 ± 0.13
ZLJJ019	1.98	1.34	-5.80	9119 ± 31	0.32	1.23	-23.45	4840 ± 51	0.52	0.32	1.66 ± 0.10
ZLJJ021	2.35	0.99	-5.60	9252 ± 32	0.32	1.28	-23.70	4253 ± 31	0.56	0.32	2.06 ± 0.12
ZLJJ024	2.43	1.22	-5.39	9276 ± 31	0.32	1.26	-23.48	3756 ± 32	0.59	0.32	1.69 ± 0.13
ZLJJ027	2.08	1.24	-5.48	8622 ± 28	0.34	1.17	-23.45	3545 ± 46	0.61	0.34	1.80 ± 0.12
Ningbo		ND				4.13	-24.89	4277 ± 36		0.55	12.50 ± 0.64

^aProvided by Zhang Song.

^b d is the ratio of the content of secondary carbonate to TIC.

Distribution of ¹³C and ¹⁴C in the Dust in Beijing

Black carbon (BC) originates from the incomplete combustion of biomass, fossil fuel, waste, and forest fire (Bond et al. 2004). It is widely distributed in the soil, atmosphere, water, sediments, rocks, and even in glaciers (Chylek et al. 1992; Bird et al. 1999; Zhou et al. 2007). Methods to detect BC include optical, thermal oxidation (TO), chemical thermal oxidation (CTO), rock pyrolysis (RE), and multi-element scanning thermal analysis (MESTA), but all these methods have problems in the separation and quantification of black carbon (Currie et al. 2002), because BC is a complex component that is mainly composed of charcoal and black carbon (Lim et al. 1996).

¹⁴C and ¹⁰Be in Dust

As shown in Table 1, the contents of BC in the dust samples ranged from 1.00% to 1.44%, and the δ¹³C values of BC varied between -23.15‰ and -23.80‰ (Figure 2). The meteorological satellite map indicated that the source region of the dust sampled in Beijing this time was middle Mongolia and midwestern Inner Mongolia where there is a large area of saline soils from dried salt lakes (Zhang et al. 2008). The organic carbon (OC) content of these soils ranges between 2.50‰ and 4.92‰ (Chen et al. 2003), which is very similar to the OC content of ~5.00‰ in loess (Wen 1989). We know that BC is a part of the components in OC, thus the content of BC should be lower than OC content in same sample. Since dust was considered to be the source material of loess, the BC content in soils in middle Mongolia and midwestern Inner Mongolia should be close to that in loess (Liu and Ding 1998; Liu et al. 2007). As shown in Table 2, the BC content in loess was usually <0.5‰ as suggested by the loess from Lingtai and Weinan (Yang et al. 2001; Zhou et al. 2007). The obviously higher BC content in the dust in Beijing likely indicated a strong incorporation of BC from aerosols during the transportation. Annual observation in Beijing showed that the BC content in aerosol ranges from 0.6% to 2.8% in the city and from 0.12% to 1.90% in surrounding regions (Tang et al. 2013). Assuming that BC content in the surface soil from the dust source region ranges from 0.50‰ to 5.00‰, the proportion of aerosol source BC would be as high as 50% to 96% of total BC in the dust. BC prefers to be absorbed in finer particulates (Chen et al. 1997). Grain-size distribution analysis had shown that the proportion of fine grains (<50 μm) in the dust was more than 90% (Liu et al. 2006). It is therefore assumed that BC in the aerosol would be absorbed by the fine dust grains when the dust storm moved to Beijing and this mixture was then deposited.

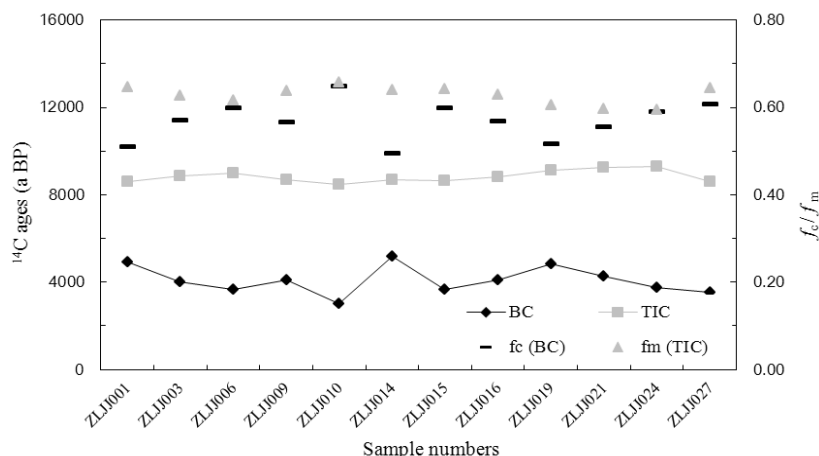


Figure 2 Content and δ¹³C value of BC in dust, aerosol, and surface soil in the dust source region

Table 2 Comparison of the content and δ¹³C value of BC and TIC, and ¹⁰Be concentration in different material.

Materials	BC		TIC		¹⁰ Be
	Content (%)	δ ¹³ C (‰)	Content (%)	δ ¹³ C (‰)	Content (×10 ⁸ atom/g)
Dust ^a	1.00~1.44	-23.15 ~ -23.80	0.93~1.36	-5.95 ~ -5.98	1.69~2.07
Original site surface soils	~ <0.5 ^{b,c}	-21‰ ~ -24‰ (OC) ^{b,d} -12‰ ~ -21‰ (EC) ^{b,e}	0.53~4.68 ^f	-5.58 ~ -8.35 ^e	1.40~2.80 ^{b,g}
Aerosols	0.55~2.77 ^h	-25.17 ~ -25.02 ⁱ	0.41~0.83 ^j	-6.50 ~ -9.30 ^k	

^aThis work; ^bData from loess; ^cWen (1989); ^dLiu (1998); ^eYang et al. (2001); ^fWang et al. (2005); ^gShen et al. (1987); ^hTang et al. (2013); ⁱCao et al. (2011); ^jZhang et al. (2002); ^kδ¹³C value of carbonate in surface soil of Beijing, unreported.

The $\delta^{13}\text{C}$ values also suggested that BC in the dust had been mixed. As mentioned above, dust was considered to be the source material of loess; the $\delta^{13}\text{C}$ value of BC in the dust should therefore be close to those in the loess (Liu et al. 2007). Research on loess profiles from Heimugou in Luochuan and Yangguo in Weinan showed a distinct difference in $\delta^{13}\text{C}$ value of OC and EC, which ranged from -21‰ to -24‰ and -12‰ to -21‰ , respectively (Liu and Ding 1998; Yang et al. 2001). As illustrated in Figure 2, the $\delta^{13}\text{C}$ value of BC is obviously more negative than the minimum $\delta^{13}\text{C}$ values of EC in the loess. An earlier investigation showed that the average $\delta^{13}\text{C}$ values of OC and EC fraction of $\text{PM}_{2.5}$ in Beijing were -25.17‰ and -25.02‰ (Cao et al. 2011). However, in different studies in Xi'an and Changchun, China, the $\delta^{13}\text{C}$ values of OC and EC fraction of $\text{PM}_{2.5}$ were less negative, ranging from -23.08‰ to -23.61‰ (Cao et al. 2011). The negative shift of $\delta^{13}\text{C}$ of BC in Beijing dust can be attributed to the mixture of the BC from aerosols, which contain both biogenic BC and fossil fuel source BC that has significantly lower ^{13}C and ^{14}C contents (Levin et al. 2003).

Due to the incorporation of fossil fuel sourced BC that had no ^{14}C from aerosols, the ^{14}C ages of BC in the dust were apparently old, ranging from 5181 to 3001 yr BP (Figure 3). Following the calculation of Levin and Heshaimer (2000): $f_c = f_m/1.06$, $f_f = 1 - f_c$, where f_c , f_m , f_f and 1.06 represent "fraction contemporary," "fraction modern" (measured), "fossil fuel carbon" and atmospheric ^{14}C level in f_m in 2006, respectively, f_c and f_f of BC were calculated to range between 0.51 to 0.65 and 0.35 to 0.49, respectively. Yang et al. (2005) reported a range of 0.33–0.50 of f_c of OC in $\text{PM}_{2.5}$ during 1999–2000 in Beijing. In contrast, f_c of OC in aerosol from Lhasa where the level of human activities was lower showed greater values varying between 0.70 and 0.38 (Huang et al. 2010). The relative stable and intermediate f_c value in the dust is consistent with more than a half of the BC being derived from aerosols during the dust transportation.

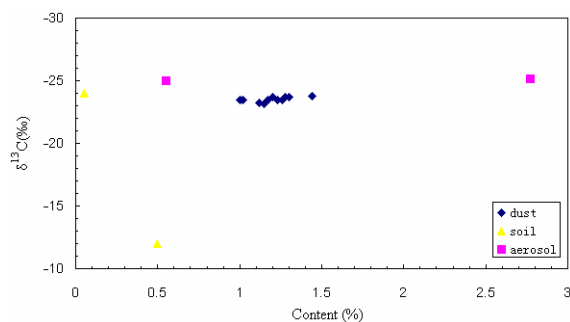


Figure 3 ^{14}C ages and f_c of BC and TIC in the dust

In contrast to BC that has been strongly influenced by the addition of BC in aerosol, TIC in the dust seems to have been little affected. As illustrated in Table 1, the TIC content in the dust ranged from 0.93% to 1.36%, and the $\delta^{13}\text{C}$ values varied between -5.39‰ and -5.98‰ . Both indicators showed stable characteristics (Figure 4). A former investigation of the content and $\delta^{13}\text{C}$ values of carbonates in the surface soil from source regions of the dust in China indicated that in the source region of the dust sampled in Beijing in this study the carbonate content was about 0.53% to 4.68%, and the $\delta^{13}\text{C}$ value was about -5.58‰ to -8.35‰ (Wang et al. 2005). Observation on the carbonate content in the total suspended particles (TSP) under normal meteorological conditions showed a content range of 0.41% to 0.83% in Beijing. However, when the dust storm arrived, the content reached to 1.80% in dust (Zhang and Dong 2002). Therefore, the TIC content in the dust mainly originated from the source region of dust. Previous studies in Changchun and Xi'an city in China indicated that the $\delta^{13}\text{C}$ values of the carbonates in the aerosol were close to that in the local surface soils (Cao et al. 2004;

Chen et al. 2008). The carbonate in surface soil of Beijing showed a variation between -6.50‰ and -9.30‰ in $\delta^{13}\text{C}$ value (Song Zhang, personal communication). Therefore, there is a distinct difference in $\delta^{13}\text{C}$ value between the carbonate fraction of surface soil in Beijing and the dust deposited during the sand storm, -5.98‰ to -5.39‰ (Table 1).

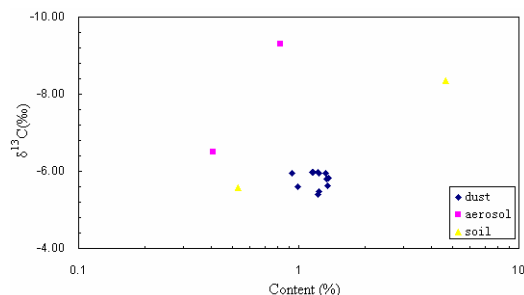


Figure 4 Content and $\delta^{13}\text{C}$ value of BC in dust, aerosol, and surface soil in dust source region.

Both TIC content and $\delta^{13}\text{C}$ values suggest there are no obvious influences of aerosol and the local soil on the TIC composition in the dust deposited during the storm. Observations in Xi'an have confirmed the close relationship between the TIC content and $\delta^{13}\text{C}$ value in dust and the surface soil in the dust-source region (Cao et al. 2004). The $\delta^{13}\text{C}$ value of carbonate in the dust deposited in Xi'an showed significantly closer range of $\delta^{13}\text{C}$ value from -1.4‰ to -4.2‰ to these in the dust source regions rather than that in the local aerosol ranging from -7.50‰ to -9.30‰ . In summary, our results support the former suggestion that both the TIC content and $\delta^{13}\text{C}$ value could be useful indicators for tracing the source regions of the dust (Zhang et al. 2002; Cao et al. 2004; Wang et al. 2005).

Proportion of the Secondary Carbonate in the Dust

Carbonate phases are widespread in the topsoil, particularly in the regions with annual precipitation of <750 mm, while it is rare in regions with annual precipitation >1000 mm (Liu et al. 2007). It can be divided into primary carbonates derived from the weathered ancient primary carbonate minerals occurring in limestone and dolostone, which have no ¹⁴C, and secondary carbonates generated from the exchange of the CO₂ gas with the primary carbon, which has the similar ¹⁴C concentration to that in exchanged CO₂ gas (Cerling et al. 1989). According to Cerling et al. (1989), the primary carbonate can be redissolved to form bicarbonate in the presence of soil water. The content of the secondary carbonate is tightly controlled with the local hydrothermal conditions (Cerling 1984).

As listed in Table 1 and shown in Figure 3, the ¹⁴C ages of TIC range from 8460 to 9120 yr BP, suggesting a mixture of the primary carbonate and secondary carbonate as explained below. As the dust mainly originated from the surface dried salt-lake saline soils in the dust source region (Chen et al. 2008), the secondary carbonate in the dust would mostly originate as that the primary carbonate is dissolved as bicarbonate and then bicarbonate mixed with modern ¹⁴CO₂ from the atmosphere, which would result in 50% modern material (Cerling et al. 1989). Therefore, the ratio of secondary carbonate to TIC (d) in the dust could be regarded as $d = 2 \times f_m$ noted above. As illustrated in Figure 3, d ranged from 0.63 to 0.70 in the dust in Beijing. For the source region of the dust this time, the surface soil water content is determined by the annual precipitation. The higher the annual precipitation, the bigger the secondary carbonate content probably is.

The annual mean precipitation in Inner Mongolia decreases generally from north to south from 410 to 58 mm per year (Bao et al. 2012). Investigations on the TIC content and $\delta^{13}\text{C}$ value in the surface soils from dust source regions shows that both TIC content and $\delta^{13}\text{C}$ value of TIC usually decreases with increasing annual precipitation in dust source regions (Wang et al. 2005). That means d together with TIC content and $\delta^{13}\text{C}$ value in dust from different source regions could be different. Therefore, investigating the secondary carbonate content in dust could be helpful to identify the source region. Traditional methods such as microscopic observation and $\delta^{13}\text{C}$ method have limitations in differentiating the secondary and primary carbonate in dust. For microscopic observation, the ratio of the relative content of secondary carbonate to primary carbonate is estimated, and usually associated with great error (Wen et al. 1989). The $\delta^{13}\text{C}$ method was found to be useful in loess profiles rather than in dust (Ning et al. 2006). The ^{13}C method is useful for determining the content of secondary carbonate content in dust and thus to help identify the source region.

^{10}Be in the Dust in Beijing and Ningbo

^{10}Be is produced in the atmosphere. It is absorbed onto aerosol and is deposited on the Earth's surface with both dust and precipitation. As the deposition of ^{10}Be is closely related with the air mass movement and dust transportation, ^{10}Be is an excellent tracer to indicate dust processes (Shen et al. 1987). As illustrated in Figure 5, the ^{10}Be concentration in the dust in Beijing ranged from 1.69 to 2.07×10^8 atom/g with an average value of 1.82×10^8 atom/g. The concentration was more than an order of magnitude higher than that in the Gobi Desert, which had been previously measured to be from 0.5 to 4.5×10^6 atom/g (Lü et al. 2010). The ^{10}Be concentration in the Beijing dust was closer to that in loess, which had a range between 1.4 and 2.8×10^8 atom/g rather than to that in paleosols ranging from 2.7 to 4.5×10^8 atom/g (Shen et al. 1987; Beer et al. 1993; Heller et al. 1993; Gu et al. 1996, 1997).

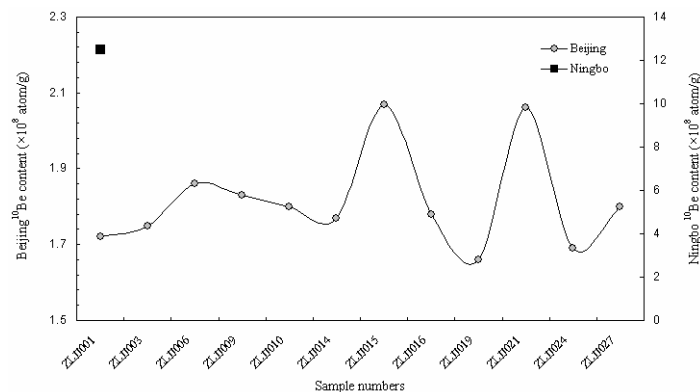


Figure 5 Distribution of ^{10}Be concentration in the dust in Beijing and Ningbo. The dust sample from Ningbo was collected on 3 April 2007.

In contrast, the ^{10}Be concentration in the dust in Ningbo was 1.25×10^9 atom/g, which is higher by 1 order of magnitude than that in Beijing. The large difference can be attributed to a longer transportation distance or differences between source regions of the dust. Lal (2007) investigated the ^{10}Be concentration in the eolian dust in Miami ($25^{\circ}47'16''\text{N}$; $80^{\circ}13'78''\text{W}$), and the result showed a similar value of $(2.12 \pm 0.036) \times 10^9$ atom/g with that of Ningbo. ^{10}Be absorbed on aerosol particles may have incorporated into the dust and show a similar trend as BC. In the course of transportation of dust, the grain size of the particulates tend to become finer with increasing distance of transporta-

tion. Furthermore, the dust at Ningbo has a more negative $\delta^{13}\text{C}$ of BC value of about -24.89‰ , approximately by 1‰ in comparison with Beijing. The content of BC in the dust in Ningbo was 4.13%, approximately 3–4 times higher than that in Beijing. The ^{14}C age of BC was 4277 ± 66 yr BP, older than most ^{14}C ages of BC in the dust in Beijing. These differences probably reflect an increasing impact on the dust composition from aerosols during the longer distance of transportation of dust to Ningbo than to Beijing.

CONCLUSION

Black carbon (BC) deposited during the dust storm in Beijing on 16–17 April 2006 has been enriched by incorporation of the BC in the aerosol during its transportation from its source area in Mongolia. This enrichment changed the characteristics inherited from its original source area in Mongolia. It significantly increased the BC content, and modified its $\delta^{13}\text{C}$ values and ^{14}C ages. Therefore, BC is not suitable to be used as a tracer to indicate the dust source regions in China. The ^{10}Be content in the dust was also found to be influenced during the transportation. However, carbonate in the dust could be a useful indicator to confirm the dust source regions. The present study shows that the carbonate content and $\delta^{13}\text{C}$ value in the dust were firmly related to the source region. ^{13}C of carbonate in the dust has proven to be another useful indicator for the source region of the dust in the arid and semi-arid regions of China.

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REFERENCES

- Bao G, Wu Q, Alatenguya, Bao YH. 2012. Changes in temperature and precipitation during past 30 years in Inner Mongolia. *Journal of Inner Mongolia Normal University* 41(6):668–74. In Chinese with English abstract.
- Beer J, Shen CD, Heller F, Liu TS, Bonani G, Beate D, Suter M, Kubik PW. 1993. ^{10}Be and magnetic susceptibility in Chinese loess. *Geophysical Research Letters* 20(1):57–60.
- Bird MI, Veenendaal E, Moyo C, Veenendaal EM, Lloyd J, Frost P. 1999. Stability of elemental carbon in a savanna soil. *Global Biogeochemical Cycles* 13(4):923–32.
- Bond TC, Streets DG, Yarber KF. 2004. A technology-based global inventory of black and organic carbon emission from combustion. *Journal of Geophysical Research Atmospheres* 109: D14203, doi:10.1029/2003JD003697.
- Cao JJ, Chow JC, Tao J, Lee SC, Watson JG, Ho KF, Wang GH, Zhu CS, Han YM. 2011. Stable carbon isotopes in aerosols from Chinese cities: influence of fossil fuels. *Atmospheric Environment* 45(6):1359–63.
- Cao JJ, Lee SC, Zhang XY, Chow JC, An ZS, Ho KF, Watson JG, Fung K, Wang YQ, Shen ZX. 2005. Characterization of airborne carbonate over a site near Asian dust source regions during spring 2002 and its climatic and environmental significance. *Journal of Geophysical Research* 110: D03203, doi:10.1029/2004JD005244.
- Cao JJ, Wang YQ, Zhang XY, Lee SC, Ho KF, Cao YN, Li Y. 2004. Analysis of carbon isotopes in airborne carbonate and implications for aeolian sources. *Chinese Science Bulletin* 49(15):1637–41.
- Cerling TE. 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. *Earth and Planetary Science Letters* 71(2):229–40.
- Cerling TE, Quade J, Wang Y, Bowman JR. 1989. Carbon isotope in soils and palaeosols as ecology and palaeoecology indicators. *Nature* 341(6238):138–9.
- Chen B, Kitagawa H, Jie DM, Hu K, Lim J. 2008. Dust transport from northeastern China inferred from carbon isotopes of atmospheric dust carbonate. *Atmospheric Environment* 42(19):4790–6.
- Chen QM, Wang SQ, Yu G. 2003. Spatial characteristics of soil organic carbon and nitrogen in Inner Mongolia. *Chinese Journal of Applied Ecology* 14(5):699–704.
- Chen S, Liao S, Jian W. 1997. Particle size distribution of aerosol carbons in ambient air. *Environment International B* 23(4):475–88.
- Chylek P, Johnson B, Wu H. 1992. Black carbon concen-

- tration in a Greenland dye-3 ice core. *Geophysical Research Letters* 19(19):1951–3.
- Currie LA, Benner BA, Kessler JD. 2002. A critical evaluation of inter laboratory data on total elemental, and isotopic carbon in the carbonaceous particle reference material, NIST SRM 1649a. *Journal of Research of the National Institute of Standards and Technology* 107(3):279–98.
- Gu ZY, Lal D, Liu TS, Southon J, Caffee MW, Guo ZT, Chen MY. 1996. Five million year ^{10}Be record in Chinese loess and red-clay: Climate and weathering relationships. *Earth and Planetary Science Letters* 144(1–2):273–87.
- Gu ZY, Lal D, Liu TS, Guo ZT, Southon J, Caffee MW. 1997. Weathering histories of Chinese loess deposits based on uranium and thorium series nuclides and cosmogenic ^{10}Be . *Geochimica et Cosmochimica Acta* 61(24):5221–31.
- Han TL, Lin JX, Wang Y, Zheng BY, Song HL, Liu JY, Jiang GM, Shi PJ, Zhang J. 2007. Nature and control of dust storms in the Beijing-Tianjin region, China—a case study of the dust storm in Beijing on April 16, 2006. *Geological Bulletin of China* 26(2):117–27. In Chinese with English abstract.
- Heller F, Shen CD, Beer J, Liu XM, Liu TS, Bronger A, Suter M, Bonani G. 1993. Quantitative estimates of pedogenic ferromagnetic mineral formation in Chinese loess and palaeoclimatic implications. *Earth and Planetary Science Letters* 114(2–3):385–90.
- Huang J, Kang SC, Shen CD, Cong ZY, Liu KX, Wang W, Liu LC. 2010. Seasonal variations and sources of ambient fossil and biogenic-derived carbonaceous aerosols based on ^{14}C measurements in Lhasa, Tibet. *Atmosphere Research* 96(4):553–9.
- In HJ, Park SU. 2003. The soil particle size dependent emission parameterization for an Asian dust (Yellow Sand) observed in Korea in April 2002. *Atmospheric Environment* 37(33):4625–36.
- Kim KH, Kim MY. 2003. The effects of Asian dust on particulate matter fractionation in Seoul, Korea during spring of 2001. *Chemosphere* 51(8):707–21.
- Kwon HJ, Cho SH, Chun Y, Lagarde F, Pershgen G. 2002. Effects of the Asian dust events on daily mortality in Seoul, Korea. *Environmental Research A* 90(1):1–5.
- Lal D. 2007. Recycling of cosmogenic nuclides after their removal from the atmosphere; special case of appreciable transport of ^{10}Be to polar regions by aeolian dust. *Earth and Planetary Science Letters* 264(1–2):177–87.
- Levin I, Hesshaimer V. 2000. Radiocarbon—a unique tracer of global carbon cycle dynamics. *Radiocarbon* 42(1):69–80.
- Levin I, Kromer B, Schmidt M, Sartorius H. 2003. A novel approach for independent budgeting of fossil fuel CO_2 over Europe by $^{14}\text{CO}_2$ observations. *Geophysical Research Letters* 30(23):2194, doi:10.1029/2003GL018477.
- Lim B, Cachier H. 1996. Determination of black carbon by chemical oxidation and thermal treatment in recent marine and lake sediments and Cretaceous-Tertiary clays. *Chemical Geology* 131(1–4):143–54.
- Lim JY, Chun Y. 2006. The characteristics of Asian dust events in northeast Asia during the springtime from 1993 to 2004. *Global and Planetary Change* 52(1–4):231–47.
- Liu K, Ding X, Fu D, Pan Y, Wu X, Guo Z, Zhou L. 2007. A new compact AMS system at Peking University. *Nuclear Instruments and Methods in Physics Research B* 259(1):23–6.
- Liu T, Ding Z. 1998. Chinese loess and the paleomonsoon. *Annual Review of Earth and Planetary Science* 26:111–45.
- Liu T, Han JM, Zhang D, Qin XG, Zhang S, Jin CS, Liu P, Jiang WL. 2006. Falling dust and deposition in anthropogene I: preliminary analyses of the dust in Beijing on April 16–17, 2006. *Quaternary Sciences* 26(4):628–33. In Chinese with English abstract.
- Lü YW, Gu ZY, Aldanhan Ala, Zhang HC, Possnert G, Lei GL. 2010. ^{10}Be in quartz gravel from the Gobi Desert and evolutionary history of alluvial sedimentation in the Ejina Basin, Inner Mongolia, China. *Chinese Science Bulletin* 55(33):3802–9.
- Ning YF, Liu WG, An ZS. 2006. Variation of soil $\delta\Delta^{13}\text{C}$ values in Xifeng loess-paleosol sequence and its paleoenvironmental implication. *Chinese Science Bulletin* 51(11):1350–4.
- Shen CD. 1986. Beryllium-10 in Chinese loess [PhD thesis]. Universität Bern.
- Shen CD, Beer J, Liu T S, Oeschger H, Bonani G, Suter M, Wölfli W. 1992. ^{10}Be in Chinese loess. *Earth and Planetary Science Letters* 109 (1–2):169–77.
- Shen CD, Ding P, Wang N, Han J, Zhang S, Liu K, Ding X, Fu D. 2007. Distribution of cosmogenic ^{14}C and ^{10}Be of fall dust in Beijing on April 16–17, 2006. *Quaternary Sciences* 27(6):919–33. In Chinese with English abstract.
- Shen CD, Liu TS, Beer J, Oeschger H, Bonani G, Suter M, Wölfli W. 1987. ^{10}Be in Chinese loess. In: Liu TS, editor. *Aspects of Loess Research*. Beijing: China Ocean Press. p 277–82.
- Shen CD, Yi WX, Sun YM, Xing CP, Yang Y, Yuan C, Li Z, Peng SL, An ZS, Liu TS. 2001. Distribution of ^{14}C and ^{13}C in forest soils of Dinghushan Biosphere Reserve. *Radiocarbon* 43(2B):671–8.
- Smith DM, Griffin JJ, Goldberg ED. 1975. Spectrometric method for quantitative-determination of elemental carbon. *Analytical Chemistry* 47(2):233–8.
- Suter M, Balzer R, Bonani G, Hofmann H, Morenzoni E, Nessi M, Wölfli W. 1984. Precision measurements of ^{14}C in AMS—some results and prospects. *Nuclear Instruments and Methods in Physics Research B* 5(2):117–22.
- Tang Y, Han GL, Xu ZF. 2013. Black carbon in the atmo-

- spheric dust of Beijing City and its north area. *Acta Scientiae Circumstantiae* 33(2):332–8. In Chinese with English abstract.
- Uematsn M, Wang ZF, Uno I. 2003. Atmospheric input of mineral dust to the western North Pacific region based on direct measurements and a regional chemical transport model. *Geophysical Research Letters* 30(6): 1342.
- Wang YQ, Cao JJ, Zhang XY, Shen ZX, Mei ZX. 2004. Carbonate content and carbon and oxygen isotopic composition of surface soil in the dust source regions of China. *Marine Geology & Quaternary Geology* 24(1):113–17. In Chinese with English abstract.
- Wang YQ, Zhang XY, Arimoto R, Cao JJ, Shen ZX. 2005. Characteristics of carbonate content and carbon and oxygen isotopic composition of northern China soil and dust aerosol and its application to tracing dust sources. *Atmospheric Environment* 39(14):2631–42.
- Wen QZ. 1989. *Geochemical Research on Chinese Loess*. Beijing: Science Press. p 115–44. In Chinese.
- Xu XM, Trumbore SE, Zheng SH, Southon JR, McDuffee KE, Luttgen M, Liu JC. 2007. Modifying a sealed tube zinc reduction method for preparation of AMS graphite targets: reducing background and attaining high precision. *Nuclear Instruments and Methods in Physics Research B* 259(1):320–9.
- Zhang S, Heller F, Jin CS, Liu P, Qin XG, Liu TS. 2008. Grain size distribution and magnetic characteristics of dust fall in Beijing on April 17, 2006. *Quaternary Sciences* 28(2):354–62.
- Yang F, He K, Chen X, Cha L, Cadle SH, Chan T, Mulawa PA. 2005. One-year record of organic and elemental carbon in fine particles in downtown Beijing and Shanghai. *Atmospheric Chemistry and Physics* 5: 1449–57.
- Yang Y, Shen CD, Yi WX, Sun YM, Liu TS. 2001. The elemental carbon record in Weinan loess section since the last 21ka. *Chinese Science Bulletin* 46(18):1541–4.
- Zhang S, Heller F, Jin CS, Liu P, Qin XG, Liu TS. 2008. Grain size distribution and magnetic characteristics of dust fall in Beijing on April 17, 2006. *Quaternary Sciences* 28(2):354–62. In Chinese with English abstract.
- Zhang T, Dong XH. 2002. Carbonate carbon measurement in sand storm and dust storm source identification. *Environmental monitoring in China* 18(2):11–4.
- Zhang XY, Arimoto R, An ZS. 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *Journal of Geophysical Research* 102(D23):28,041–47.
- Zhou B, Shen CD, Sun WD, Yang Y, Sun YB, An ZS. 2007. Elemental carbon record of paleofire history on the Chinese Loess Plateau during the last 420 ka and its response to environmental and climate changes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252(3–4):617–25.