Global and Planetary Change 67 (2009) 186–192

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Element composition of dust from a shallow Dunde ice core, Northern China

Guangjian Wu [a,*], Chenglong Zhang [a], Shaopeng Gao [a], Tandong Yao [a,b], Lide Tian [a], Dunsheng Xia [c]

[a] Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China
[b] State Key Laboratory of Cryospheric Science, CAREERI, Chinese Academy of Sciences. Lanzhou 730000, China
[c] Key Laboratory of Desert and Desertification, CAREERI, Chinese Academy of Science, Lanzhou 730000, China

ARTICLE INFO

Article history:
Received 24 July 2008
Accepted 12 February 2009
Available online 28 February 2009

Keywords:
Asian dust
Dunde ice core
element composition
Tibetan Plateau

ABSTRACT

The Dunde ice cap (38°06'N, 96°24'E, with a summit of 5325 m) is situated at the centre of the northern Chinese deserts and receives dust from these regions. Here, we present the trace and rare earth element (REE) compositions of dust extracted from a shallow ice core from the Dunde ice cap, which provide a framework to trace the source of Dunde dust. Trace and REE parameters of Dunde dust show characteristics of a typical eolian deposit, with an average La/Th ratio of 2.6, a Th/U ratio of 3.7, and a strong negative Eu anomaly (0.61). The dirty layers in the ice core section have the same element characteristics as in the clear layers, indicating that the dust in Dunde is well-mixed and has a stable composition. Trace element and REE ratio plots show that Dunde dust has a similar composition to the finer fraction materials in the Taklimakan desert, suggesting that the Tarim Basin might be an important source for Dunde dust under the present circulation, but not favoring a material contribution from Badain Jaran. Our results reveal distinct differences in composition between Dunde dust and Chinese loess materials, which suggests that they have different sources.

1. Introduction

The Asian continent contains vast arid and semi-arid regions. These regions, including the deserts in northern China and Gobi in southern Mongolia, are important dust source areas in the Northern Hemisphere and contribute an amount of dust eastward to East Asia (Zhang et al., 1997), the North Pacific (Rea et al., 1998), and Greenland (Biscaye et al., 1997; Bory et al., 2003). Recently, interesting and controversial opinions on the source of Chinese loess have arisen. Many researchers have studied the surface material across the Chinese Loess Plateau (CLP) and arid areas in northern China and have provided numerous basic data for regional geochemistry. Using Sr–Nd isotopic ratios and finer-grained quartz ESR signals, they argued that the Gobi in southern Mongolia and the sandy deserts of Northern China (primarily Badain Jaran and Tengger), rather than the Tarim Basin (Taklimakan) in western China, are the major sources of the CLP material (Sun, 2002; Chen et al., 2007; Sun et al., 2008).

Glaciers on the Tibetan Plateau, with a high altitude and proximity to those Asian dust emission areas, receive dust carried by high level Westerlies (>5000 m) from remote source areas, and from local circulations from the nearby environment. The Dunde ice cap, which lies in the western Qilian Shan Mountains, between Taklimakan and the CLP, can provide valuable information on the properties of dust in northern China (Fig. 1). Previous papers on the Dunde ice cap and ice core records have provided comprehensive understanding of environmental change on the northern Tibetan Plateau (Thompson et al., 1988, 1989; Yao and Thompson, 1992). Atmospheric dust history was also reconstructed for the Holocene (Thompson et al., 1989), especially for recent centuries (Davis, 2002; Yang et al., 2006). However, detailed geochemical analysis of dust in Dunde and other ice cores over the Tibetan Plateau has seldom been done since the first ice core was drilled about 30 years ago. This greatly limits our understanding of the properties of Asian dust and its climatic implications.

Various studies have demonstrated that trace element and REE analysis can be a useful tool for investigating sources of eolian deposits in northern China, such as loess (Jahn et al., 2001; Ding et al., 2001; Sun, 2002) and desert sand (Honda et al., 2004; Yang et al., 2007a,b). Most of the work on the geochemical characterization of dust in ice cores has been done on polar ice samples (e.g. Biscaye et al., 1997; Bory et al., 2003; Delmonte et al., 2008). In this paper, we present the elemental composition, mainly trace elements and REEs, of dust extracted from a shallow Dunde ice core in the western Qilian Shan in order to provide a better constraint on atmospheric dust properties and reveal their provenances in northern China.

2. Environmental setting, sampling, and measurement

2.1. Geographic and climatological setting

The Dunde ice cap (38°06'N, 96°24'E) is located in the western Qilian Shan and is surrounded by the huge deserts of northern China,

* Corresponding author. Tel.: +86 10 62849399; fax: +86 10 62849886.
E-mail address: wugj@itpcas.ac.cn (G. Wu).

0921-8181/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2009.02.003

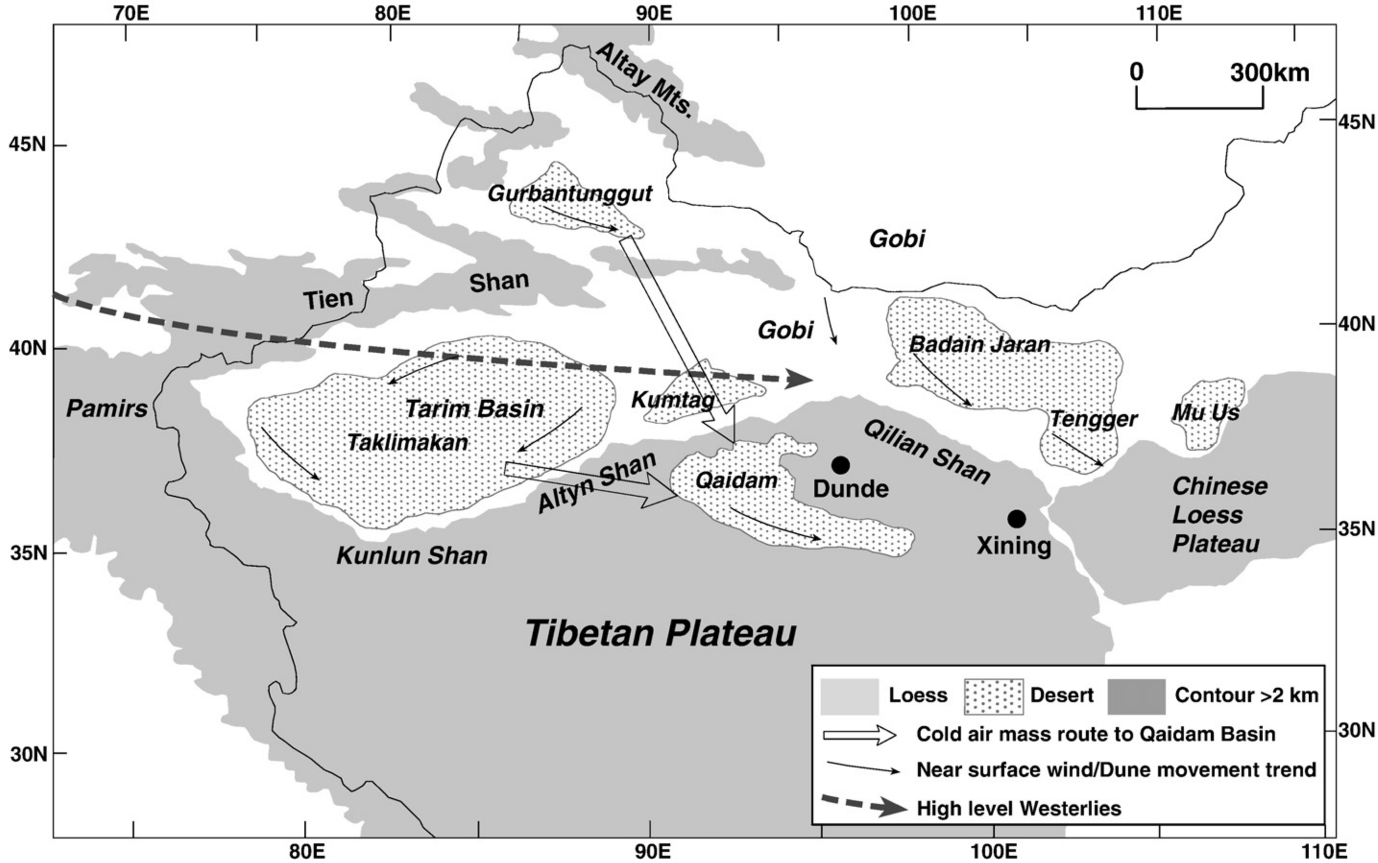

Fig. 1. Sketch map of Dunde ice cap location, and the mountains and deserts in northwest China.

with the Badain Jaran to the northeast, Gobi and Kumtag to the north, Taklimakan to the west, and Qaidam Basin to the south (Fig. 1). This relatively large ice cap has a summit elevation of 5325 m and a total area of 60 km^2. The ice cap is about 140 m thick and the underlying bedrock is flat. Over the past two decades, many studies have been carried out on the ice core record of Dunde (e.g. Thompson et al., 1988, 1989). The dry season dust concentrations in the Dunde ice core are up to 15 to 20 times those in the summer (Davis, 2002). The prevailing high level Westerlies and near-surface winds carry amounts of dust from peripheral arid and semi-arid environments to Dunde. According to modern meteorological data, the dust storm events in northern China mostly occur during spring. In the Qaidam Basin, frequent dust storm events are found to occur during spring (March to May, 54% of the annual total), while there are very few during the period July to December. Two main types of cold air route, including the northwest and the west type, are found for frequent dust storms in the Qaidam Basin. The west route comes from the Pamirs and then moves across the Altyn Shan to the western part of the Qaidam Basin. The northwest route comes from north Tien Shan and moves southward to Qaidam across the Altyn Shan. It is the northwest route that is the more important one, responsible for dust storms in the Qaidam Basin (Gouriduojie, 2003).

2.2. Sample collection

In October 2002, five shallow ice cores (named DD1 to DD5, respectively) were recovered near the site that was drilled before in the Dunde ice cap (Thompson et al., 1989). The half-section of the 9.52 m DD1 ice core was cut and grouped into 18 successive sub-sections (named DD1-01 to DD1-18, respectively) at intervals of 26–101 cm. The outer part of each sub-section, between 1.5–2.0 cm, was scraped away using a stainless-steel scalpel under a class 1000 clean cabinet in a cold room (−5 °C). The inner part of each ice core slice was then put into acid pre-cleaned HDPE bottles for storage. All samples were melted at room temperature and immediately filtered using LCR hydrophilic PTFE membrane filters (Millipore Corporation) of 47 mm diameter and with a pore size of 0.45 µm. Therefore, all dust particles of diameter greater than 0.45 µm were collected on the filters. The filtration was completed in a class 1000 clean room. Blank filters were filtered using ultra-pure water (Milli-Q Element, Millipore Corporation) to determine the background. We also collected two surface snow samples, using 1000 ml acid pre-cleaned HDPE bottles, at the Dunde ice cap (38°05.7'N, 96°26.6'E, 5160 m) on 2 October 2005. They were kept frozen from the field to the laboratory and filtered using the same procedure as for the ice core samples.

2.3. Analytical method

The filters were dissolved with ultra-pure HNO_3–HF at 150–190 °C in PTFE screw-top bombs. After digestion, the dust on the filters was totally dissolved. Quantitative elemental analyses of the samples were performed using ICP–MS (Thermo X-7, Thermo-Elemental Corporation). The measurement accuracy for a Chinese national reference material (GSS-8, loess from Luochuan, CLP) is found to be better than $\pm 10\%$ for major elements and better than $\pm 11\%$ for REEs. Only U (17%) shows a notable uncertainty (Wu et al., 2009). Duplicate analytical precision is better than 2% for measuring major elements, Rb, Sr, Th, and U. For REEs, the precision is better than 6%, except for Tb, which shows a relatively lower precision of 16%. Tb and Tm had the greatest uncertainties in the REE measurement, as pointed out by previous researchers (e.g. Henderson and Pankhurst, 1984).

Three samples (DD1-12, DD1-17 and DD1-18) in the digestion procedure failed due to the non-tightening of a screwed cap of the

PTFE bomb. Therefore, a total of 15 DD1 ice core and two surface snow samples (Snow 1 and Snow 2) are discussed in this study. The laboratory blank filters were also digested and measured following the same procedures as for the dust samples, and showed very low concentrations. The blank background values were subtracted from the measured results. We weighed the dust mass collected on the filters (except for the two snow samples) before they were digested, in order to calculate the absolute abundance of these trace elements.

3. Results and discussion

3.1. Profile for tracing elements

When using the REE as tracing elements, possible contamination should be checked and removed. We checked the enrichment factor (EF) values ($EF = (X/Al)_{sample} / (X/Al)_{crust}$) for some trace and all the rare earth elements to estimate possible anthropogenic pollution, which can distort the abundance and pattern of REEs in dust particles and add uncertainties for source tracing. In the DD1 ice core, Th and U have EF values less than 2, and the EF for REEs varies from 1.26 (Ce) to 1.75 (Gd). These results show that the elements are not contaminated by human activities and are of predominantly natural origin.

The results of ICP–MS measurement of element abundance are listed in Table 1. Our results show that the average Al abundance is about 6.5%, compared to 8% in the average upper continental crust (UCC) (Taylor and McLennan, 1995). The total dust concentrations in the shallow DD1 ice core range from 20 to 243 mg per kg ice. The weighed dust mass and the measured Al concentration show high similarities in their profiles along the depth. Through the ice core, the crustal element Al has absolute concentrations varying largely from 1.44 to 18.87 mg per kg ice, while the composition exhibits a small variability within narrow ranges. The compositions of the two surface snow samples resemble the compositions of the ice core samples (Table 1).

The strata features of the DD1 ice core are very simple. The shallow Dunde ice cores predominantly contain bubbled ice with some intercalated dirty layers and firn layers (Fig. 1). We have measured the ice density for the DD3 ice core. The density of the DD3 ice core varies from 0.80 to 0.89 g cm^{-3} in the upper part of 0–11 m. The average annual accumulation rate between 1963 and 1987 was about 420 mm ice equivalent in the Dunde ice core (Thompson et al., 1989). If the average accumulation rate during the period 1963–1987 is assumed to be characteristic of the DD1 ice core, the age of the DD1 ice core is expected to be no greater than about 20 years. What is interesting is the possible seasonal variation in composition of the dust that is trapped in the Dunde ice cap. This seasonality in composition, if it does exist, could reflect different seasonal circulation modes. Unfortunately, due to the large sampling intervals (26–101 cm, which are greater than the seasonal or annual layer thickness) for dust samples in this study, there are limits on further discussion of possible seasonal to annual variations in dust composition. However, the low resolution sampling has no substantial impact on the average elemental composition of the dust. Several visible dirty layers were found in the ice core section (Fig. 2). Samples that contain dirty layers, such as DD1-01 and DD1-02, show no significant differences from those samples entirely containing relatively clear layers. This indicates that dust deposited in the storm season, though its concentration and grain size are greater, is not significantly different in composition from that deposited in non-dust storm seasons. No systematic correlation is found between dust concentration and composition in the DD1 ice core samples, indicating that the dust supplied to the Dunde ice cap was well-mixed during transport under the present climate.

3.2. REE distribution pattern and trace element parameters

REEs are useful tools for investigating eolian sediment properties and provenance, due to their characteristics are mainly controlled by

Table 1
The dust weight and trace element abundance of dust from the DD1 ice core and snow samples.

Sample	Depth (m)	Ice wt. (kg)	Dust (mg)	Al (%)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Th (ppm)	U (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Hf (ppm)
DD1-01	0–0.58	0.364	88.29	7.78	38.45	74.75	8.75	32.71	6.44	1.28	6.33	0.89	5.33	1.08	3.16	0.45	2.93	0.44	14.30	3.85	136.58	138.59	191.40	5.35
DD1-02	0.58–0.89	0.318	67.40	7.40	38.87	78.40	8.90	33.25	6.64	1.31	6.38	0.90	5.36	1.08	3.17	0.45	2.89	0.44	12.41	3.25	131.17	140.53	185.45	5.08
DD1-03	0.89–1.30	0.362	17.56	5.56	30.11	61.92	7.01	25.95	5.17	0.90	4.88	0.67	3.95	0.80	2.31	0.33	2.12	0.31	13.90	3.36	108.83	163.73	112.87	3.21
DD1-04	1.30–1.86	0.4586	19.76	7.15	37.17	74.72	8.43	31.35	6.16	1.22	6.08	0.83	4.85	0.96	2.80	0.41	2.57	0.39	14.00	4.01	129.81	127.48	161.34	4.43
DD1-05	1.86–2.12	0.334	64.30	7.20	37.01	74.66	8.41	31.35	6.15	1.23	6.11	0.84	5.11	1.04	3.02	0.43	2.78	0.42	11.81	3.15	126.64	145.85	197.50	5.29
DD1-06	2.12–3.13	0.430	24.43	6.87	34.54	69.48	7.91	29.56	5.90	1.18	5.71	0.81	4.86	0.96	2.87	0.41	2.61	0.40	13.41	3.51	124.89	147.77	164.59	4.52
DD1-07	3.13–3.88	0.312	18.18	5.01	23.96	48.83	5.54	20.51	4.14	0.82	4.03	0.57	3.44	0.68	2.02	0.29	1.88	0.28	9.26	2.51	92.57	103.41	109.46	3.05
DD1-08	3.88–4.35	0.248	7.42	4.82	25.01	50.27	5.70	21.38	4.26	0.82	4.18	0.60	3.49	0.70	2.00	0.29	1.83	0.28	11.54	3.20	91.23	83.57	92.27	2.64
DD1-09	4.35–5.13	0.428	26.56	6.62	33.16	66.62	7.62	28.50	5.68	1.10	5.54	0.77	4.69	0.93	2.67	0.39	2.52	0.38	11.70	3.07	118.41	167.02	160.20	4.38
DD1-10	5.13–5.67	0.336	15.39	4.82	23.22	46.54	5.32	19.71	3.88	0.81	3.92	0.55	3.27	0.67	1.95	0.27	1.79	0.27	9.44	2.76	90.32	94.48	113.00	3.12
DD1-11	5.67–6.23	0.350	14.48	6.31	33.56	69.57	7.67	28.30	5.68	1.11	5.58	0.79	4.69	0.96	2.76	0.39	2.58	0.39	10.91	2.82	115.88	135.15	153.66	4.14
DD1-13	6.60–7.06	0.520	52.74	7.47	33.82	67.91	7.65	28.57	5.55	1.16	5.56	0.79	4.61	0.93	2.72	0.39	2.54	0.38	12.70	3.45	137.64	143.86	138.74	3.87
DD1-14	7.06–7.57	0.6768	18.45	5.55	26.47	53.24	6.01	22.55	4.47	0.89	4.40	0.62	3.68	0.75	2.17	0.31	1.99	0.30	11.35	3.13	103.31	226.61	115.77	3.17
DD1-15	7.57–8.22	1.106	21.88	7.76	37.98	76.66	8.71	32.54	6.49	1.27	6.20	0.87	5.10	1.02	2.99	0.43	2.74	0.42	14.26	3.63	141.45	166.87	154.98	4.28
DD1-16	8.22–8.80	0.612	19.85	7.23	35.89	72.56	8.26	30.68	6.12	1.18	5.96	0.83	4.90	0.99	2.89	0.42	2.66	0.41	13.86	3.43	132.54	171.74	146.10	4.04
Snow 1		0.336			34.46	71.02	7.87	29.35	6.02	1.20	5.99	0.85	5.37	1.10	3.18	0.46	2.86	0.44	12.55	3.67	136.65	146.19	178.98	4.95
Snow 2		0.354			35.80	70.08	8.06	29.96	5.92	1.14	5.65	0.81	4.82	0.96	2.83	0.41	2.62	0.40	14.14	3.73	130.51	139.60	154.19	4.20

Note: Element abundances for Snow 1 and Snow 2 are calculated by using Al (7% to the total, average of the DD1 ice core dust samples) as the reference element. The result of DD1-12, DD1-17, and DD1-18 is not presented due to the experiment failures.

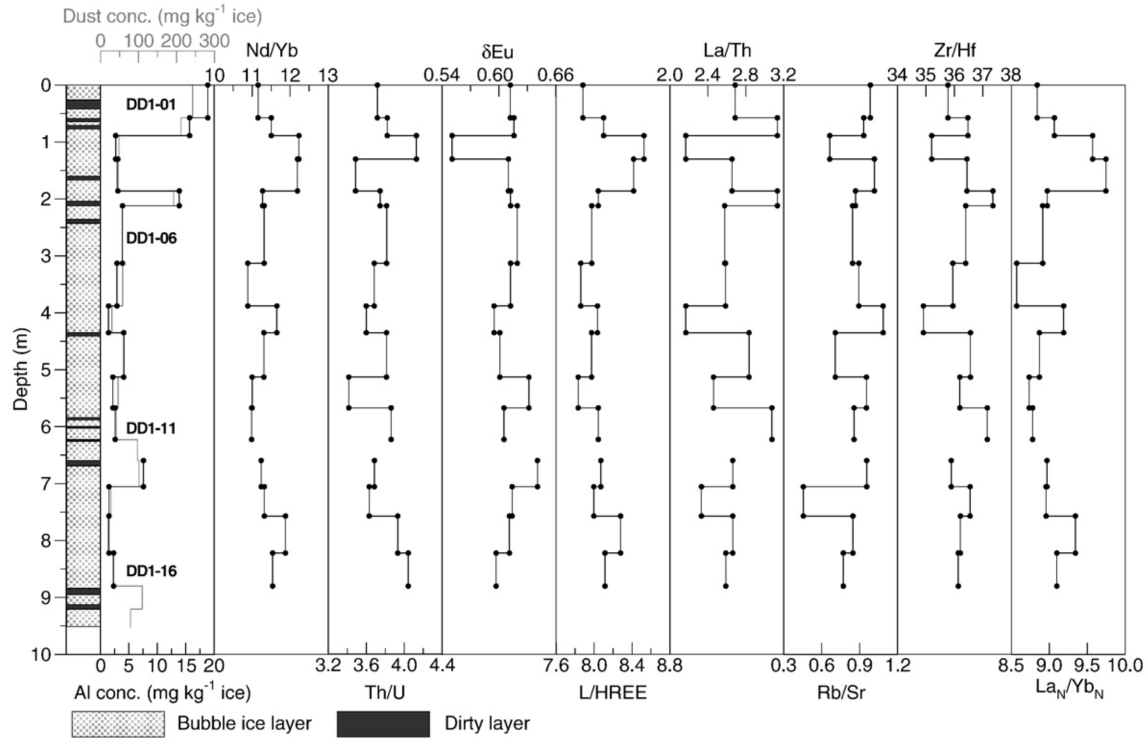

Fig. 2. Profiles of element composition for the DD1 ice core.

provenance rather than diagenesis and due to the least soluble of the trace elements and less mobility during weathering (Taylor and McLennan, 1995). The Dunde dust has REE chondrite-normalized distribution patterns (Fig. 3) with relative enrichment in light REE (LREE, including La, Ce, Pr, Nd, Sm, and Eu) and a slight depletion of the heavy REE (HREE, including Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), as shown in Fig. 3. Although dust concentrations vary largely between samples, those with high dust concentrations (with dirty layers, such as DD1-01 and DD1-05) have similar REE patterns to those with low dust concentrations (such as DD1-08 and DD1-14). This finding also supports the stable composition along the DD1 ice core.

Previous work indicated that although Eu fractionation relative to other REEs is unlikely to occur, and only strong enrichment of plagioclase could substantially modify δEu ($=Eu_N/(Sm_N{*}Gd_N)^{1/2}$) ratios, variation could be utilized to reflect the different characteristics of source rocks (provenance effect). All the REE compositions of Dunde dust are uniformly characterized by a strong negative Eu anomaly (δEu averaging 0.61 and varying from 0.55 to 0.64), and are identical to those in surface snow samples (Fig. 4). Trace element characteristics show that Dunde dust is a typical eolian deposit of surface soil material.

The ratios between trace elements are used to characterize the dust properties and trace Asian eolian deposits (e.g. Jahn et al., 2001; Ding et al., 2001). REE and Th in superficial processes exhibit similar behavior, and the average La/Th ratio of 2.8 in fine-grained sediments gives an independent estimate of the UCC composition (Taylor and McLennan, 1995). The La/Th ratios of Dunde dust average 2.63 (ranging between 2.17 and 3.13), which is very similar to the UCC and Chinese loess (L1)-paleosol (S1) (La/Th = 2.8) (Ding et al., 2001). All Dunde samples showed identical Th/U ratios (averaging 3.73 and ranging from 3.33 to 4.13) to those in the UCC and loess–paleosol (3.8).

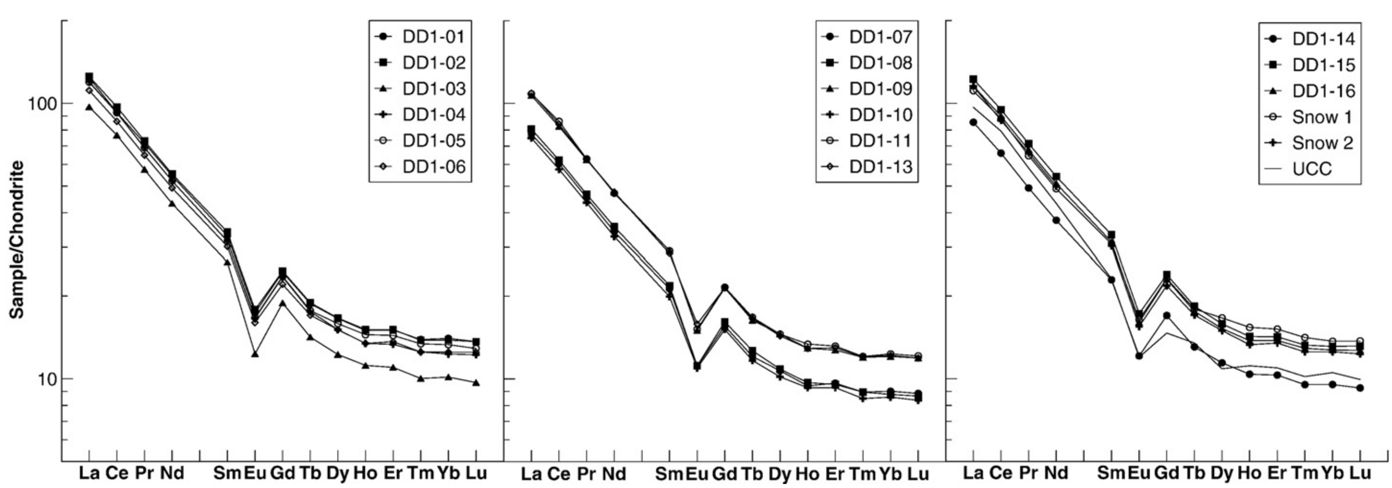

Fig. 3. Chondrite-normalized REE patterns for DD1 ice core/snow samples and UCC (Taylor and McLennan, 1995).

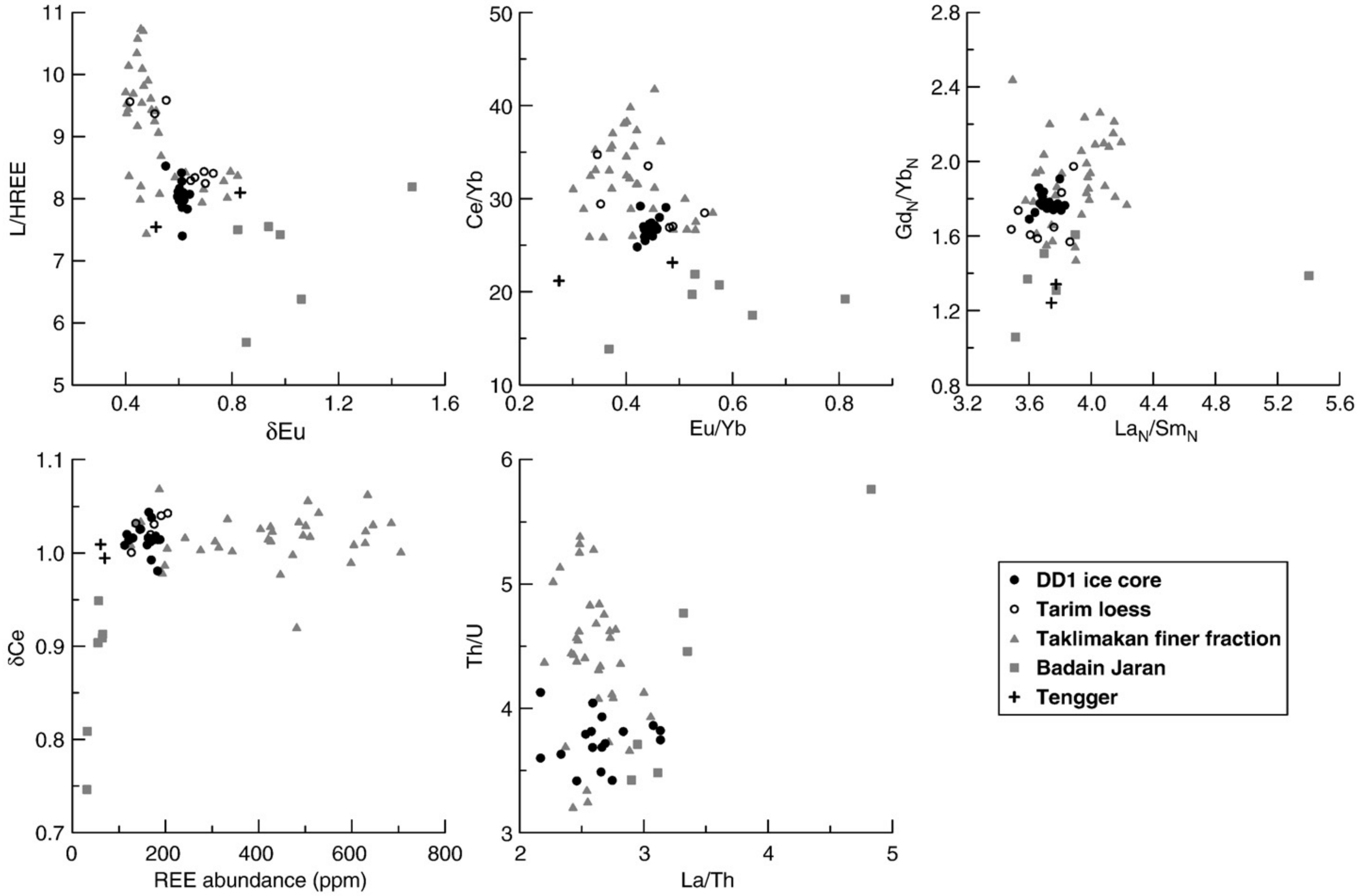

Fig. 4. Trace element and REE parameters for dust samples from Dunde dust, Taklimakan finer fraction of eolian sediment (Yang et al., 2007a), Tarim Basin loess (Honda et al., 2004), Tengger (Honda et al., 2004) and Badain Jaran eolian sediment (Yang et al., 2007b).

3.3. Possible source areas

Identifying a geochemical fingerprint is possible only if different source areas can be clearly discriminated by their geochemical signatures. The trace and REE element ratios used in the study show that these indices are of distinguishable regional differences. Being close to the Dunde ice cap, the western Qaidam Basin is the proximal source area for Dunde dust. The fine fractions (<0.053 mm, mainly silts) of eolian sediment in Taklimakan are more homogenized in REE composition (Yang et al., 2007a). Element composition of these finer fraction (which can serve as the long-range transport dust particles) in the Taklimakan sediment is similar to that of Dunde dust, suggesting that the Tarim Basin might be an important dust source area for Dunde. The mechanism is as follows: frequent dust storm events during spring entrain and lift the finer fraction of Taklimakan material up to a level higher than the Altyn Shan, and this material is then transported by the Westerlies eastward to the western Qilian Shan. Although the reason for the high REE abundance in Taklimakan finer fraction material is not clear, the loess deposits around the Tarim Basin (Honda et al., 2004) show no anomalies in REE abundance and have the same abundance as Dunde. The dust contribution at Dunde also comes from the northwest by near-surface winds (especially north-westerly), such as the Kumtag and southwestern Gobi, as shown by the cold air front pathways (Fig. 1).

REE data was examined from other potential dust source areas, such as Badain Jaran and Tengger, whose dust material shows some similarities in Th/U ratios to Dunde. However, the Badain Jaran sand materials (Yang et al., 2007b) have much lower REE abundances (about only a quarter of that in Dunde dust), greater La/Th ratios (2.90–4.83), lower Ce/Yb and Gd_N/Yb_N ratios, lower L/HREE ratios, especially the less negative or even positive Eu anomaly (0.85–1.48) and negative Ce anomaly ($\delta Ce = Ce_N / (La_N * Pr_N)^{1/2}$, 0.75–0.95), compared to Dunde dust. The Tengger materials (Honda et al., 2004) show similar elemental features (e.g., Ce/Yb, Gd_N/Yb_N, and REE abundance) to Badain Jaran sand but display the different composition to Dunde dust, such as the lower Gd_N/Yb_N ratios (Fig. 4). However, only two samples are available from Tengger Desert and therefore there might be some uncertainties in the comparison.

It might be possible that a mixture of Taklimakan and Badain Jaran desert material contributes to the Dunde dust, as shown in Fig. 4. However, even if this mixture exists, the contribution from Badain Jaran might be less important because (in addition to the compositional evidence) of the following reason: the Gansu (Hexi) Corridor, north of the Qilian Shan, is a main pathway (eastward) for dust storms in Northern China. Derbyshire et al. (1998) concluded that the huge piedmont alluvial fans along the northern Qilian Shan constituted a major contribution to loess deposits in the western CLP. Modern atmospheric circulations, with high-level prevailing Westerlies and north-westerly near-surface wind, contradict this possibility. The high Qilian Shan (elevation over 5000 m) is a large obstacle to dust transport from Baidan Jaran/Tengger southward to the Qaidam Basin. Plots of monthly average frequency for 72 h back-trajectories by the Hysplit model (Draxler and Rolph, 2003) between 2000 and 2007 show that during July to September, the air masses hitting Dunde come from the east and south, while during October to May (the dust storm season period), the air masses come from the west (see the Appendix). Although the Hysplit model shows that air masses can come from the east, the dust from the eastern deserts is expected to have contributed only a small amount to Dunde dust. Precipitation at Delingha, the closest meteorological station to Dunde, most frequently occurs during June to August (about 60% of the annual total). With regard to Dunde snowfall, currently 70% to 80% comes from the southeast monsoon during the summer (Thompson et al., 2005). Therefore, during summer the precipitation will decrease the atmospheric dust by scavenging. The observed data in the Dunde ice core also support the conclusion that, during the dry season, dust concentrations range up to 15–20 times those in the summer (Davis, 2002). Due to the size of the sampling intervals, a more detailed seasonal variation in the dust composition is limited and therefore the interpretation of the minor contribution from Badain Jaran and Tengger to Dunde remains tentative.

3.4. Comparison with Chinese loess materials

The Qaidam Basin provides material to Dunde dust and the loess deposit at Xining, which is 800 km east of Dunde and at the western margin of the CLP. A previous study revealed that the provenance of Xining loess was probably the arid regions to the west and northwest, such as the Qaidam Basin and inland of the Tibetan Plateau surface (Li and Nie, 1999). Dunde dust has the majority of its mass distribution concentrated within a modal grain size of 4–12 µm, which is finer than loess grains in Xining (with mean diameter of 30 µm). Although the impact of grain size on the composition cannot be ignored, the compositional differences between Dunde dust and Xining loess imply their provenances are dissimilar.

Here we plot the parameters (element ratios) in order to present more clearly the similarities and differences in element compositions of Dunde dust and Chinese loess material (Fig. 5), including those at Xining (Jahn et al., 2001) and the CLP (Ding et al., 2001). The Dunde dust displays a smaller range of these parameters than the loess materials. Some similarities can be found, including the L/HREE, Ce/Yb, and La/Th ratios. These suggest that there might be some common sources for them. However, there are notable differences in trace element parameters between the various samples, and these indicate different provenances. The Dunde dust has lower δEu values but higher Rb/Sr ratios than those from the Xining and CLP samples, and an intermediate value in Eu/Yb and Th/U ratios between the Xining and CLP materials. The Dunde dust shows more similarities with Xining loess than with CLP material, suggesting that Dunde and Xining have more compatible sources than the CLP, whose materials mainly come from the Badain Jaran, Tengger, and southern Mongolian Gobi (Sun, 2002; Sun et al., 2008). Based on the element composition, Dunde dust most likely comes from the Taklimakan, western Qaidam Basin, Kumtag, and southwestern Gobi.

Recently, debates on the Chinese loess provenance have arisen (Sun, 2002; Honda et al., 2004; Chen et al., 2007; Sun et al., 2008). There is an influential hypothesis, as presented by Sun (2002), that the finer part of dust material originating in the Tarim Basin was carried by high level Westerlies and deposited in the far North Pacific, while the coarser part would be deposited on the northern flank of Kunlun Shan and not contribute to Chinese loess. However, the similarity between the Dunde and Tarim disputes this hypothesis. The Dunde dust displays similar compositional characteristics to the finer fraction of Taklimakan in the REE and trace elements, implying that the material from Tarim Basin could reach to the Qilian Shan.

Scanning electron microscope examination of dust particles from the underlying dirty ice that deposited at bottom of Dunde ice core showed that the size distributions and morphologies were similar to

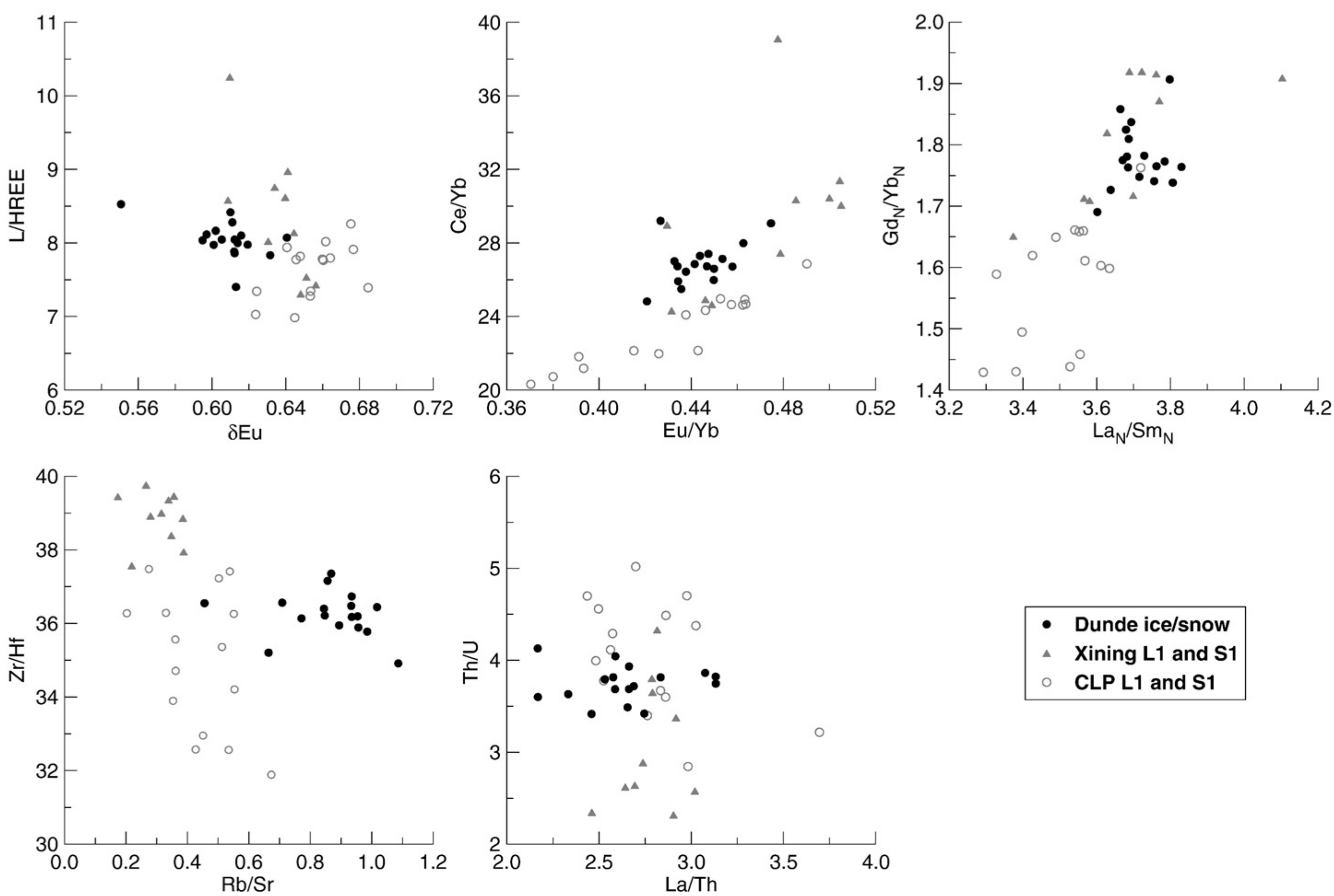

Fig. 5. Plots of L/HREE vs. *d*Eu, Ce/Yb vs. Eu/Yb, Gd_N/Yb_N vs. La_N/Sm_N, and La/Th vs. Th/U for Dunde dust, loess material in Xining (Jahn et al., 2001), and across the CLP (Ding et al., 2001).

those of loess particles near Xining (Thompson et al., 1988). However, uncertainties might arise if only compared by morphology of dust particle. Our results show that Dunde dust differs from the Xining loess in composition. However, comparison of present Dunde dust with Quaternary loess material may cause some uncertainties. The transport mechanisms of the present might differ from those during the last glacial–interglacial cycle, due to the different climatic regime. Sun et al. (2008) have found that the dominant source of fine-grained particles in CLP material varied significantly from southern Mongolia during cold periods to northern China during warm periods. When significant changes did occur in the source areas and circulations during the last glacial–interglacial cycles, this compositional comparison between Dunde dust and Chinese loess material may be compromised. Our results suggest that under the modern climate, the Westerlies predominate and there is no substantial contribution to Dunde dust from the Eastern Chinese deserts, such as the Badain Jaran and Tengger, by other circulations. Furthermore, these results provide a potential implication for paleoclimate reconstruction (specifically variations in air mass movement) from long ice core records on the Tibetan Plateau.

4. Conclusion

This paper presents the element composition of present day atmospheric dust trapped in a shallow Dunde ice core and surface snow. Trace and REE elements show little variation in composition through the ice core and consequently suggest a stable provenance under the present circulation. The Dunde dust exhibits a much closer similarity in composition to Taklimakan finer materials, especially the loess deposit around the Tarim Basin, than to the Badain Jaran/Tengger desert deposits. Dunde receives remote and long-distance dust transported from the western Gobi and Chinese deserts, most likely from the western Qaidam Basin, Kumtag, and Taklimakan. The contribution of Badain Jaran and Tengger material to Dunde dust might be only a minor one or less likely to happen. The Dunde dust exhibits different compositional characteristics from Chinese loess deposits at Xining and the CLP, indicating that they have different provenances, although some common source areas might exist.

Acknowledgements

We are grateful to two anonymous reviewers for valuable comments and Ms. G. Hodgson for improving the text. This work is supported by the National Natural Science Foundation of China (Grant No. 40871046, 40671043) and National Basic Research Program of China (Grant No. 2005CB422004).

References

Biscaye, P.E., Grousset, F.E., Revel, M., Van der Gasst, S., Zielinski, G.A., Vaars, A., Kukla, G., 1997. Asian provenance of glacial dust (stage 2) in the Greenland Ice Sheet Project 2 Ice Core, Summit, Greenland. J. Geophys. Res. 102 (C12), 26765–26781.

Bory, A.J.M., Biscaye, P.E., Grousset, F.E., 2003. Two distinct seasonal Asian source regions for mineral dust deposited in the Greenland (NorthGRIP). Geophys. Res. Lett. 30 (4). doi:10.1029/2002GL016446.

Chen, J., Li, G.J., Yang, J.D., Rao, W.B., Lu, H.Y., Balsam, W., Sun, Y.B., Ji, J.F., 2007. Nd and Sr isotopic characteristics of Chinese deserts: implications for the provenances of Asian dust. Geochim. Cosmochim. Acta 71, 3904–3914.

Davis, M.E., 2002. Climatic Interpretations of Eolian Dust Records from Low-Latitude, High-Altitude Ice Cores. Ph. D. Thesis, Ohio State University.

Delmonte, B., Andersson, P.S., Hansson, M., Schöberg, H., Petit, J.R., Basile-Doelsch, I., Maggi, V., 2008. Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): provenance during glacial ages over the last 800 kyr. Geophys. Res. Lett. 35. doi:10.1029/2008GL033382.

Derbyshire, E., Meng, X., Kemp, R., 1998. Provenance, transport and characteristics of modern aeolian dust in western Gansu Province, China, and interpretation of the Quaternary loess record. J. Arid Environ. 39, 497–516.

Ding, Z.L., Sun, J.M., Yang, S.L., Liu, T.S., 2001. Geochemistry of the Pliocene red clay formation in the Chinese Loess Plateau and implications for its origin, source provenance and paleoclimate change. Geochim. Cosmochim. Acta 65, 901–913.

Draxler, R.R., Rolph, G.D., 2003. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory). NOAA Air Resources Laboratory, Silver Spring, MD. Model Access Via NOAA ARL READY Website (http://www.arl.noaa.gov/ready/hysplit4.html).

Gouriduojie, 2003. The sandstorm weather characteristics in Qaidam Basin and its forecasting. Meteorol. Sci. Technol. 31 (2), 84–87 (in Chinese).

Henderson, P., Pankhurst, R.J., 1984. Analytical chemistry. In: Henderson, P. (Ed.), Rare Earth Element Geochemistry. Elsevier, New York, pp. 467–499.

Honda, M., Yabuki, S., Shimizu, H., 2004. Geochemical and isotopic studies of aeolian sediments in China. Sedimentology 51, 211–230.

Jahn, B., Gallet, S., Han, J., 2001. Geochemistry of the Xining, Xifeng and Jixian sections, Loess Plateau of China: eolian dust provenance and paleosol evolution during the last 140 ka. Chem. Geol. 178, 71–94.

Li, Z., Nie, S.R., 1999. Loess deposit at Xining and its provenance. J. Earth Sci. 24 (6), 1–3 (in Chinese).

Rea, D.K., Snoeckx, H., Joseph, L.H., 1998. Late Cenozoic eolian deposition in the North Pacific: Asian drying, Tibetan uplift, and cooling of the northern hemisphere. Paleoceanography 13 (3), 215–224.

Sun, J.M., 2002. Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. Earth Planet. Sci. Lett. 203, 845–859.

Sun, Y.B., Tada, R., Chen, J., Liu, Q.S., Toyoda, S., Tani, A., Ji, J.F., Isozaki, Y., 2008. Tracing the provenance of fine-grained dust deposited on the central Chinese Loess Plateau. Geophys. Res. Lett. 35. doi:10.1029/2007GL031672.

Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of the continental crust. Rev. Geophys. 33, 241–265.

Thompson, L.G., Mosley-Thompson, E., Wu, X., Xie, Z., 1988. Wisconsin/Wurm Glacial Stage Ice in the Subtropical Dunde Ice Cap, China. GeoJournal 17 (4), 517–523.

Thompson, L.G., Thompson, E.M., Davis, M.E., Bolzan, J.F., Dai, J., Yao, T., Gundestrup, N., Wu, X., Klein, L., Xie, Z., 1989. Holocene–Late Pleistocene climatic ice core records form the Qinghai–Tibetan Plateau. Science 246, 474–477.

Thompson, L.G., Davis, M.E., Mosley-Thompson, E., Lin, P.-N., Henderson, K.A., Mashiotta, T.A., 2005. Tropical ice core records: evidence for asynchronous glaciation on Milankovitch timescales. J. Quatern. Sci. 20 (7–8), 723–733.

Wu, G.J., Xu, B.Q., Zhang, C.L., Gao, S.P., Yao, T.D., 2009. Geochemistry of dust aerosol over the Eastern Pamirs. Geochim. Cosmochim. Acta 73, 977–989.

Yang, M.X., Yao, T.D., Wang, H.J., 2006. Microparticle content records of the Dunde ice core and dust storms in northwestern China. J. Asian Earth Sci. 27, 223–229.

Yang, X.P., Zhu, B.Q., White, P.D., 2007a. Provenance of aeolian sediment in the Taklamakan Desert of western China, inferred from REE and major-elemental data. Quatern. Inter. 175, 71–85.

Yang, X.P., Liu, Y.S., Li, C.Z., Song, Y.L., Zhu, H.P., Jin, X.D., 2007b. Rare earth elements of aeolian deposits in Northern China and their implications for determining the provenance of dust storms in Beijing. Geomorphology 87, 365–377.

Yao, T.D., Thompson, L.G., 1992. Trends and features of climatic changes in the past 5000 years recorded by the Dunde ice core. Ann. Glaciol. 16, 21–24.

Zhang, X.Y., Arimoto, R., An, Z.S., 1997. Dust emission from Chinese desert sources linked to variation in atmospheric circulation. J. Geophys. Res. 102, 28041–28047.