Global and Planetary Change 127 (2015) 12–21

Contents lists available at ScienceDirect

Global and Planetary Change

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

Geochemical characteristics of insoluble dust as a tracer in an ice core from Miaoergou Glacier, east Tien Shan

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ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form 22 December 2014
Accepted 18 January 2015
Available online 23 January 2015

Keywords:
Tienshan ice core
Insoluble dust
Rare earth elements
Sr–Nd isotopic ratios
Asian deserts
Loess

ABSTRACT

An ice core was extracted from Miaoergou Glacier, east Tien Shan, China. Concentrations of the rare earth elements (REEs) and Sr–Nd isotopic ratios were measured in insoluble dust sampled from the core. The ratios of REEs in insoluble dust were found to have characteristics typical of aeolian deposition, similar to those of sand and loess from Taklamakan. This suggests that the Taklamakan Desert might be an important source of dust reaching the Miaoergou Glacier. Sr ($^{87}Sr/^{86}Sr$ average 0.718014 and range 0.717025 to 0.718958) and Nd ($\varepsilon_{Nd}(0)$ average −9.1 and range −9.5 to −8.5) isotopic compositions in insoluble dust are similar to those of desert sand from Taklamakan and Gobi, suggesting that the Gobi Desert may be another major aeolian source for Miaoergou Glacier. Our results can be compared with Sr–Nd isotopic ratios from Greenland snow and ice, further demonstrating how the dust from Asian deserts contributes a high proportion of aeolian dust in the Greenland region.

1. Introduction

Mineral dust plays a vital role in climate change and biogeochemical cycles (Jickells et al., 2005). It not only has a direct impact on the climate system through absorbing and scattering solar shortwave radiation, but it can also indirectly influence the precipitation distribution and water cycle by altering cloud microphysical processes (Shao et al., 2011). The IPCC Fifth Assessment Report highlighted that the dust couples global processes of physical, chemical and biogeochemical cycles (IPCC, 2013). The dust storms originating from the Asian continent not only affect traffic and agriculture, but can also interact with the transport of contaminants and pathogens, which could seriously impact on human health (Kellogg and Griffin, 2006). It has been suggested that there could be an interlocking chain comprising changes of atmospheric dust aerosol – soluble iron fluxes – ocean productivity (Han et al., 2011).

Atmospheric wind-borne dust production, mobilization, long-range aeolian transport, and deposition all respond to climatic changes during the glacial–interglacial cycles; vice versa, the dust loads in the atmosphere could also impact on climate change (Lambert et al., 2008). Climate model simulations have indicated that mineral dust deposition on the snow surface can lead to low snow albedo during the melt season. This, in turn, has caused enhanced snow melt and reinforced snow-free peak summer conditions over almost the entire Asian continent (Krinner et al., 2006). Asian dust is transported annually to the central North Pacific, but larger quantities are probably deposited over the western North Pacific and North America, and have even been found in Greenland snow and ice (Biscaye et al., 1997; Husar et al., 2001; McKendry et al., 2001; Osterberg et al., 2008). Even dust originating in the Asian deserts could affect the regional and global climate change (Ginoux et al., 2001; Tegen, 2003; Zhang et al., 2010).

To better understand the earth system, the contribution of each dust source needs to be accurately estimated, which could be very important and beneficial for parameter estimates in climate models. Concentrations of rare earth elements (REEs) and strontium–neodymium (Sr–Nd) isotopic compositions in desert, loess and sediments have been taken as crucial tracers of aeolian dust provenances (Jahn et al., 2001; Sun, 2002; Honda et al., 2004; Grousset and Biscaye, 2005; Yang et al., 2007). In recent years, studies of trace elements, REEs and Sr–Nd isotopic ratios have included the analysis of high-altitude alpine ice cores, which are well suited to revealing the spatial and temporal dust variability in the High Asia region (Kreutz and Sholkovitz, 2000; Kang et al., 2007; Zhang et al., 2009; Wu et al., 2010; Li et al., 2012; Xu et al., 2012; Burn-Nunes et al., 2014).

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http://dx.doi.org/10.1016/j.gloplacha.2015.01.011
0921-8181/

Thus far, it has been too difficult to quantify the specific contributions of each dust/desert source. Although geographic information system (GIS) and air–mass back trajectory methods have been greatly improved, the short time scale of available data is such that these methods are limited in explaining the paleoclimate atmospheric patterns. The dust record in ice cores has been taken as a unique proxy indicator, which could be much better for validating the global dust cycle models under past and present climate conditions (Kohfeld and Harrison, 2001). Ice core analysis is a powerful tool for tracing the dust sources-sinks using geochemical characteristics of dust in the ice core. The Miaoergou Glacier lies in close proximity to arid and semi-arid deserts of the Asian continent, and the aeolian dust is deposited onto the glacier surface by dry and wet deposition and then well preserved in the snow and ice of this and other alpine glaciers. Therefore, ice cores from this region provide a unique medium, for studying the characteristics of well-mixed mid- and upper-tropospheric Asian dust. In this study, we extracted the insoluble dust in a shallow ice core from Miaoergou Glacier, east Tien Shan; then, based on the characteristics of REEs and the ratios of Sr–Nd in the insoluble dust, the dust provenances were identified.

2. Environmental setting

The east Tien Shan (known as the 'the water tower of Central Asia') adjoins the Qinghai–Tibet region, is located in the north of the Pamirs, and is surrounded by vast deserts. To the south lies the Taklamakan Desert, which is the largest desert in central Asia; to the east is the Mongolian Gobi Desert; to the northwest is the Gurbantunggut Desert; and to the west are the Peski Muyunkum and the Peski Sary-Ishikotrau Deserts (Liu et al., 2011). This region is suitable for developing glaciers on account of the unique topographic conditions and climatic characteristics, which play a crucial role in Central Asia's hydrological cycle and Hami oasis. With its East–West orientation, the region covers a large fraction of Central Asia, spanning regions from Uzbekistan to Kyrgyzstan and from southeastern Kazakhstan to Xinjiang (China). Miaoergou Glacier (43°03′19″N, 94°19′21″E, 4512 m asl.) is one of the glaciers in east Tien Shan, and is located in the northern part of the Hami basin to the south of Karlik Mountain (Fig. 1). According to the weather station at Hami, the annual mean air temperature at the 600 hPa level is −11.8 °C, and the average summer temperature is −3 °C. The annual precipitation is around 600 mm, of which most falls in summer and autumn, and the region has a pronounced continental climate (Wang et al., 1986). Westerlies prevail in this region all year round (Sorg et al., 2012). The average elevation of the east Tien Shan is about 4000 m above sea level (masl), and the ridges of the mountains extend into the mid-troposphere. Thus, the Miaoergou ice core can provide an ideal medium for studying long-range transport of Asian dust.

3. Ice core sampling and analysis

3.1. Ice core sampling and decontamination

In 2005, an ice core to the bedrock (58.7 m) was obtained from a dome on the Miaoergou Glacier, and was transported frozen to the

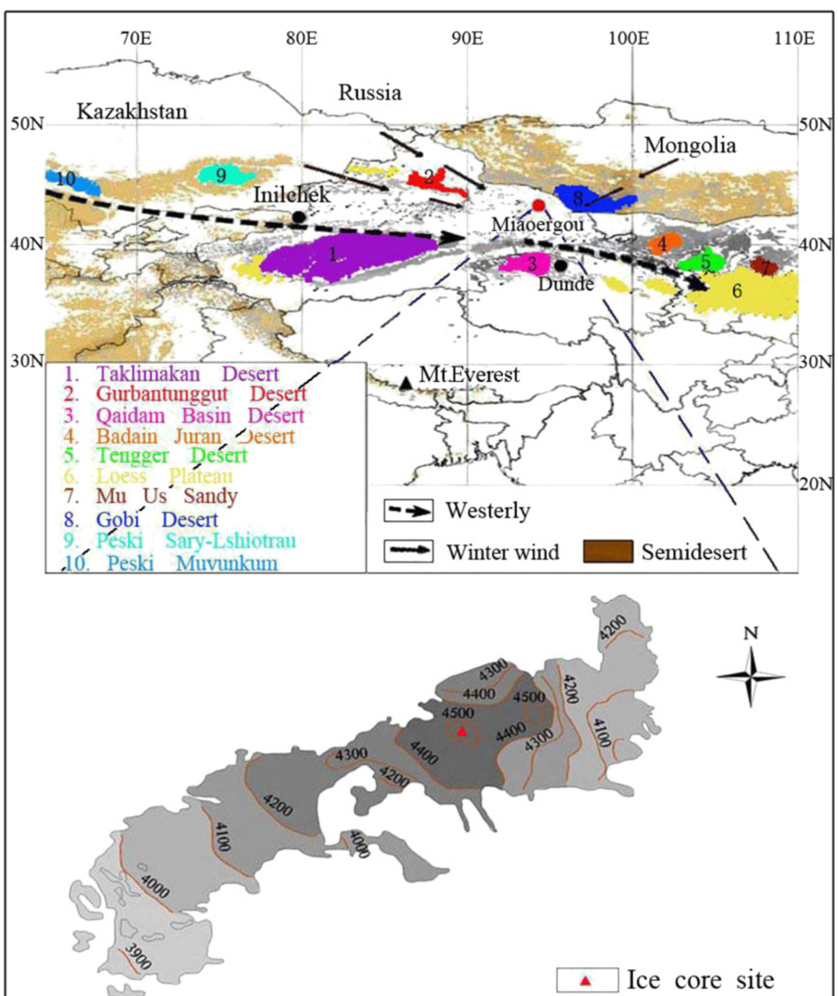

Fig. 1. Location map of the Miaoergou Glacier, Dunde ice cap, Greenland ice cores and deserts distribution in northwestern China.

freezer room (−20 °C) of the State Key Laboratory of Cryospheric Sciences (SKLCS) in Lanzhou, China. The low borehole temperature at the drilling site provides confidence that the environmental information is well preserved in the core (Liu et al., 2011). This study focuses on the top 16 m of the ice core. From top to bottom, subsamples were collected at intervals of about 20–30 cm, yielding a total of 23 discontinuous subsamples. Of these, 17 were analyzed for REEs and 6 were analyzed for Sr–Nd isotopes. Dust flux in Miaoergou a snow-pit is about 92.3 μg · $cm^{-2}a^{-1}$ for particles, which was higher than concentrations at the same latitude in other glaciers (Dong et al., 2008). The decontamination procedure and laboratory equipment followed the successive acid cleaning procedures in SKLCS, which has been described in more detail in previous papers (Liu et al., 2009, 2011). Each subsample was gently melted at room temperature, then immediately filtered through a LCR hydrophilic PTFE membrane filter (0.2 μm pore size and 47 μm diameter, Millipore Corporation) by using pre-cleaned (acid washed) plastic filtration units (Nalgene Filterware 300–4100). Firstly, the filtration units was immersed for one week in the first acid bath (25% Fisher "TraceMetal" grade HNO_3 diluted in Milli-Q ultrapure water), then, was immersed for one week in another acid baths (0.1% Fisher "Optima" grade HNO_3 diluted in Milli-Q water), and finally, washed with Milli-Q water many times before use. Consequently, the insoluble particles with diameter larger than 0.2 μm were collected on the filter. The decontamination procedure and extraction of insoluble particles were carried out under clean room conditions with class 100 to 1000 laminar flow benches.

3.2. Ice core dating and chemical analysis

The ice core was dated by counting annual layers, the seasonality of $\delta^{18}O$, crustal species (Ca^{2+}) and the β activity horizons, yielding an estimated dating uncertainty ±1 year (Liu et al., 2011). The 17 subsamples were each analyzed for the concentrations of REEs in identified years (Table 1). According to the accumulation rate and the indicative high-impurity layers, we are confident that each subsample represents an annual cycle.

After digestion with ultra-pure acid (HNO_3, HF and $HClO_4$, Analytical reagent acids were double-distilled) at 160–180 °C in PTFE screw-top bombs, the concentrations of REEs were measured in insoluble dust by inductively coupled plasma mass spectrometry (ELEMENT XR, Thermo Elemental Corporation). The process was carried out under class 100 laminar flow benches. Firstly, the filter was placed in the PTFE screw-top bombs; next 6 ml (1:1) HNO_3 was added into the bombs, then all solutions were placed in an ultrasonic bath for at least 30 min, ready for next digesting process. Secondly, the solution was digested on a hot plate for 24 h after mixing with 1 ml HF at 180 °C, and the solution was evaporated to near-dryness at 160 °C in the opened bombs. Finally, 5 ml (1:2) HNO_3 was added to the solution, and the samples were heated for a further 4 h. The solutions needed to be made up to a specified volume before analysis (Ferrat et al., 2011). Table 1 shows the calibrated data. Blank values of trace elements in the filters were determined by filtering using ultra pure water (Milli-Q Element, Millipore Corporation). The insoluble dust loading in the 17 subsamples used for calculating the concentration of REEs ranged between 0.15 mg $cm^{-2} \cdot a^{-1}$ and 1.79 mg $cm^{-2} \cdot a^{-1}$, respectively, and while that in the 6 subsamples collected for measuring the ratios of Sr–Nd isotopes was between 1.23 mg $cm^{-2} \cdot a^{-1}$ and 1.81 mg $cm^{-2} \cdot a^{-1}$, respectively. Note that the insoluble dust mass and load does not always have a positive correlation with the concentrations of REEs in the Miaoergou ice core.

The ratios of Sr–Nd isotopes were measured with thermal ionization mass spectrometry (using an IsoProbe-T spectrometer, GV Corporation). All analysis operations were performed at the Analytical Laboratory, Beijing Research Institute of Uranium Geology. Subsamples were firstly digested, following the digestion process described above. Then, the elements Sr and Nd were successively separated, as described in detail by Wu et al (2010). Data were corrected for internal mass bias to $^{86}Sr/^{88}Sr = 0.1194$. The $^{87}Sr/^{86}Sr$ result for the reference material NBS 987 was 0.710229 ± 13 (2σ, n = 10), while its recommended value is 0.710248. Nd isotopes were measured using triple Re filaments in static mode. Data were corrected for internal mass bias to $^{144}Nd/^{146}Nd = 0.7219$. The $^{143}Nd/^{144}Nd$ result for the reference material ShinEtsu was 0.512095 ± 9 (2σ, n = 10), and the recommended value is 0.512110, (Table 2).

4. The characteristics of REEs and Sr–Nd isotopes

4.1. REEs distribution pattern and parameters

The EF_C values of REEs in insoluble dust were calculated using the following equation:

$$EF_c = [X/Ce]_{sample} / [X/Ce]_{crustal} \quad (1)$$

where the more stable element Ce is used as a crustal reference element (Gabrielli et al., 2010). Here Ce represents a crustal reference element, and X represents a given element. If the calculated values of EF_C are close to unity, typically less than 10, then the element likely has a crustal source. Conversely, if the EFc values are larger than unity, typically greater than 10, then anthropogenic sources are more important (Barbante et al., 2004; Liu et al., 2011). The median EF_C values of REEs (including element Y) were less than 2 (range 0.56 to 1.5). This implies that anthropogenic influences were negligible for REEs, and instead the crustal sources were dominant; furthermore it demonstrates that REEs can be stabilized and preserved in snow and ice. REE chondrite-

Table 1
REE abundances (ppm) in insoluble dust from the Miaoergou ice core subsamples.

Yr(AD)	Dust flux (mg · $cm^{-2} \cdot a^{-1}$)	Dust(mg)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
2002	0.26	2.5	33.04	68.86	8.80	30.94	6.99	1.53	6.40	1.01	5.14	1.13	2.93	0.37	2.42	0.41	30.12
1999	0.62	3.9	27.61	58.43	7.48	25.51	5.49	1.24	5.19	0.78	3.72	0.75	2.21	0.27	1.82	0.28	25.90
1998	0.71	4.2	23.14	48.22	5.77	19.10	4.18	0.95	4.15	0.61	2.86	0.63	1.73	0.21	1.40	0.22	21.40
1992	0.23	1.5	29.67	62.55	7.76	26.59	6.23	1.39	6.28	0.94	4.13	0.93	2.79	0.30	2.14	0.34	34.13
1990	0.74	4.6	33.68	59.49	8.09	29.84	6.38	1.38	5.81	0.88	4.31	0.90	2.44	0.30	2.08	0.33	23.31
1987	0.51	3.6	26.24	51.20	5.99	19.96	4.29	0.91	3.22	0.52	2.89	0.62	1.53	0.21	1.25	0.22	18.84
1984	0.55	4.1	26.18	59.28	6.17	19.80	4.16	0.90	3.39	0.55	2.89	0.57	1.45	0.20	1.27	0.21	18.45
1980	2.70	18.5	30.29	57.25	6.75	21.75	4.49	0.87	3.71	0.59	2.94	0.63	1.49	0.20	1.37	0.21	17.18
1977	0.62	4.8	24.62	53.78	5.53	18.18	3.79	0.89	3.18	0.52	2.81	0.58	1.48	0.21	1.28	0.22	18.96
1974	1.79	12.1	26.84	62.83	5.95	19.75	4.00	0.88	3.15	0.51	2.60	0.56	1.37	0.18	1.18	0.20	17.27
1973	1.75	4.9	27.38	62.47	6.91	24.10	5.72	1.16	4.35	0.70	3.82	0.81	2.07	0.29	1.81	0.30	21.93
1971	0.33	1.6	31.00	68.08	8.42	29.27	6.85	1.51	5.78	0.90	4.29	0.93	2.39	0.33	2.11	0.34	36.89
1969	0.32	2.4	22.39	50.41	5.77	21.29	4.69	1.00	4.06	0.61	3.15	0.66	1.72	0.26	1.58	0.23	23.80
1967	1.20	8.8	32.83	76.63	7.47	25.37	5.44	1.10	4.53	0.71	3.48	0.74	1.85	0.26	1.66	0.26	23.73
1963	0.17	0.9	22.09	50.93	6.14	21.68	4.86	1.15	4.40	0.73	3.41	0.73	1.71	0.23	1.68	0.29	24.09
1960	1.38	10.2	32.97	81.84	8.49	26.07	5.59	1.21	4.81	0.76	3.56	0.75	1.92	0.27	1.71	0.28	22.22
1957	0.15	0.71	19.08	44.87	5.91	19.51	4.62	0.99	4.23	0.63	3.08	0.66	1.69	0.22	1.47	0.23	27.68

Table 2
Sr–Nd isotopic composition of insoluble dust from the Miaoergou ice core.

Age	Type	Dust flux ($mg \cdot cm^{-2} \cdot a^{-1}$)	Dust (mg)	$^{87}Sr/^{86}Sr$	2σ	$^{144}Nd/^{143}Nd$	2σ	$\varepsilon_{Nd}(0)$
2000	Insoluble dust	1.72	18.1	0.718958	0.000009	0.512151	0.000007	−9.5
1991	Insoluble dust	1.47	13.7	0.717025	0.000010	0.512201	0.000010	−8.5
1984	Insoluble dust	1.72	16.3	0.717455	0.000014	0.512149	0.000006	−9.5
1977	Insoluble dust	1.66	20.8	0.718065	0.000013	0.512166	0.000007	−9.2
1962	Insoluble dust	1.81	22.9	0.718013	0.000011	0.512199	0.000007	−8.6
1956	Insoluble dust	1.23	11.7	0.718571	0.000012	0.512159	0.000007	−9.3

$\varepsilon_{Nd}(0) = ((^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{CHUR} - 1) \times 10^4, (^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$.

normalized distribution patterns in insoluble dust and upper continental crust (UCC) (Taylor and McLennan, 1985) are shown in Fig. 2. Except for Er, Tm, Yb, and Lu there are differences between the UCC; element Ho showed anomalies in 1987a and 1973a. REE profile patterns are very similar to those of the UCC.

Under special conditions, the post-depositional processes could alter the REE distribution patterns depending on the fractionation characteristics. This process ultimately determines the geological environmental signature of the mineral dust (Zhang et al., 1997). REEs are among the least soluble of the trace elements and are less mobile during weathering (Taylor and McLennan, 1985). REE chondrite-normalized distribution patterns in insoluble dust reveal that LREEs are relatively enriched, and HREEs slightly depleted (Fig. 2). To a certain extent, LREE/HREE ratios could reflect the fractionation degree of REEs. In addition, $(La/Sm)_N$ and $(Gd/Yb)_N$ values were taken as indicating the degree of chemical weathering (Roy and Smykatz-Kloss, 2007). δEu and δCe cannot only indicate the sedimentary environment, but they can also reflect the source rock characteristics (Zhang, 1997). Eu exist divalent (Eu^{2+}) and trivalent (Eu^{3+}), and the properties of Eu^{3+} are usually similar to those of the other REEs. The pattern of the δEu ($= Eu_N / (Sm_N * Gd_N)^{1/2}$) anomaly could be utilized to reflect the characteristics of the source rocks. Specifically, Eu^{2+} can fractionate from the other REEs and lead to an Eu anomaly. δEu > 1 is defined as a positive Eu anomaly, indicating Eu enrichment; δEu < 1 is defined as a negative Eu anomaly, indicating Eu depletion; δEu = 1 is defined as no Eu anomaly. δCe ($= Ce_N / (La_N * Pr_N)^{1/2}$) is similar to δEu, and the difference between δCe and δEu is the critical value (δCe of 1.05). All subsamples of Miaoergou insoluble dust were uniformly characterized by a negative Eu anomaly (δEu average 0.70 and range 0.66 to 0.77). Most of the subsamples had characteristics of being weakly negative; and 4 subsamples of δCe showed a positive Ce anomaly (δCe averaging 1.046 and varying from 0.867 to 1.122). REE ratios in the insoluble dust showed strong similarities between the Nd/Yb, LREE/HREE, Ce/Yb, Eu/Yb, La_N/Sm_N and La/Y.

Principal component analysis (PCA) was used to better synthesize changes in the REEs and quantify the common source relationship between ice cores and potential dust sources of samples in SPSS (http://www.spss.com/spss/). In this study, the first four principal components

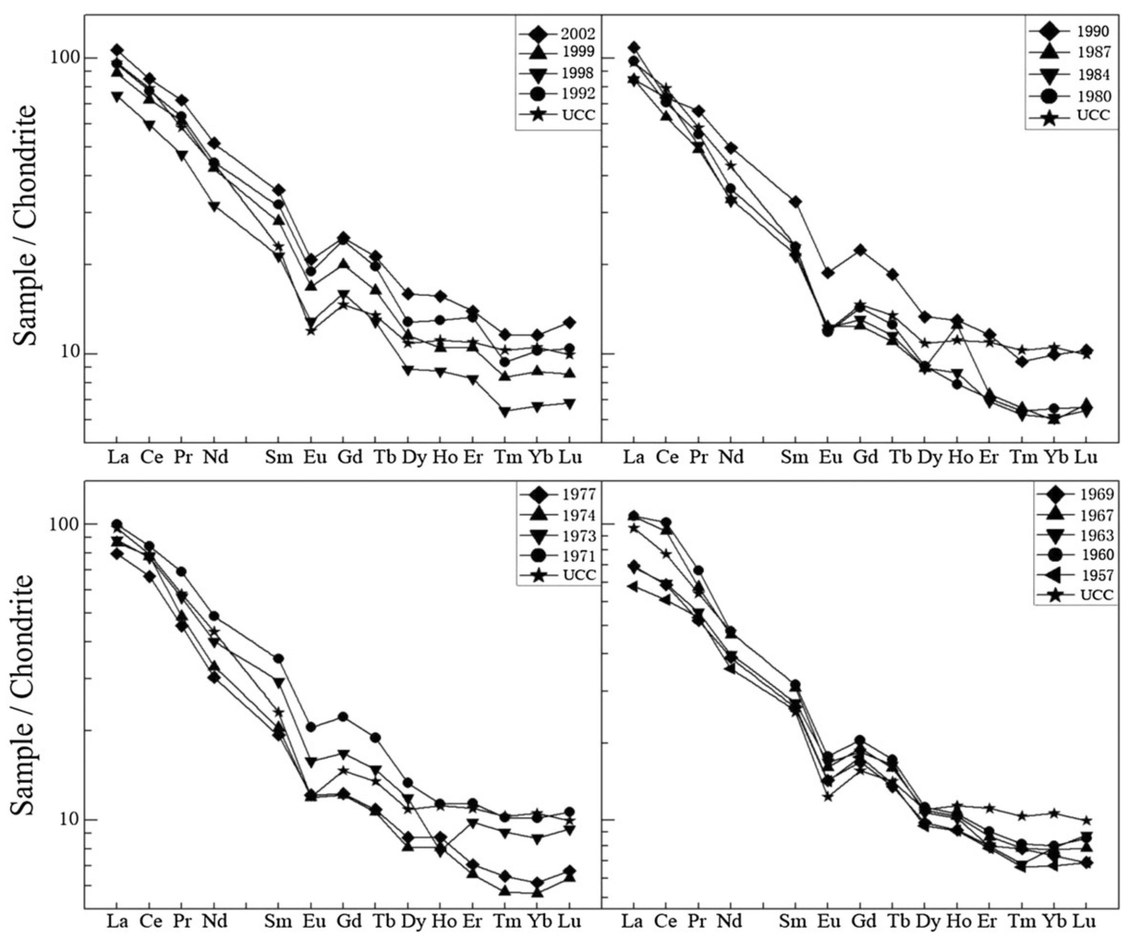

Fig. 2. Chondrite-normalized REEs patterns for the Miaoergou ice core (17 subsamples) and UCC (UCC from Taylor and McLennan, 1985).

(PCs) were extracted and accumulatively reach to a total variance of 94.1%, with the eigenvalue of first three principal components greater than 1. The first and second components accounted for about 41.0%, and 31.7% of the total variance, respectively (Table 3). PC1 with high variance explanation have positive loadings on all REEs except δEu and the loadings of LREE/HREE, Ce/Yb, δCe and Gd_N/Yb_N are significantly high (>0.65), which have strong positive loading on the first principal component. For the PC2, the loadings of δEu, Eu/Yb, ∑REE and La_N/Sm_N are high (>0.58), indicating that there were similarities on the second principal component (Table 4). These results indicated that the first two PCs may contain the common characteristics of those sampling sites. PC scores of each site were also calculated on the first four principal components (Fig. 3). The results demonstrated that there were source relationships in the REEs between Taklamakan Desert and Miaoergou ice core on the LREE/HREE, Ce/Yb, δCe and GdN/YbN reflected by PC1, between Inilchek and Miaoergou ice cores in δEu, Eu/Yb, ∑REE and La_N/Sm_N reflected by PC2.

According to REEs distribution patterns and parameters of the ice core insoluble dust and potential source samples (Figs. 3 and 4), the dust sources of the Miaoergou ice core were divided into two large desert regions. Firstly, in some years (1987 AD, 1984 AD, 1977 AD, 1974 AD, 1971 AD, 1967 AD and 1960 AD, which represent with blue stars), the influence of long-distance dust sources in Central Asia is strong while the influence of local surrounding deserts is relatively weak. In these samples the parameter ratios are higher than those of the other years, indicating enrichment in LREEs and depletion in HREEs. All subsamples had a slightly negative Eu anomaly and a strong positive Ce anomaly. As can be seen from Figs. 3 and 4, we note that REEs parameters in those years closely resemble characteristics of the Inilchek ice core (Kreutz and Sholkovitz, 2000). The physical–chemical reactions repeatedly occur when the dust is subjected to windborne erosion and long-distance transport processes from west to east, which results in the remarkable fractionation. The fractionation in those subsamples is even stronger than in the other samples, which may indicate a multi-sources control of REEs compositions. Furthermore, the Inilchek Glacier is located in the west of the Taklamakan Desert. Only a limited amount of aeolian dust was recorded from this desert, for which a reasonable interpretation is the westerlies, which carry plentiful dust from Central Asia. Therefore, the long-distance dust sources of Central Asia may be taken as the dust sources for the two glaciers in those years. Secondly are the years dominated by local Chinese deserts (2002 AD, 1999 AD, 1998 AD, 1992 AD, 1990 AD, 1980 AD, 1973 AD, 1969 AD, 1963 AD and 1957 AD, which represent with red stars). In those subsamples, the pairs of parameter ratios were less than ratios for the other samples and are strongly consistent with the Chinese desert samples (Yang et al., 2007; Ferrat et al., 2011). The subsamples have a strictly negative Eu anomaly and an obvious negative Ce anomaly. These results indicate that the dust was primarily sourced from the surrounding deserts, and that the dust contribution from long-distance dust sources in Central Asia was relatively weak in those years.

4.2. Sr and Nd isotopic compositions

The $^{143}Nd/^{144}Nd$ ratio in the crust is lower than that in chondrite, so the $\varepsilon_{Nd}(0)$ value is negative. Nd belongs to the rare earth elements, and is immobile during the weathering-deposition process. Acid leaching and separation of the fine-grain size fraction have a weak effect on Sr and no substantial effect on Nd isotopic composition (Meyer et al., 2011). As a consequence, we do not consider those processes in this study, and the corresponding method is identical to that of Wu et al (2010). This enables a comparison with other samples from Asian deserts under the appropriate constraints of the Sr–Nd isotopic composition (Table 5). Furthermore, considering that Nd is relatively independent of pre-treatments, our discussion will mainly focus on the comparison of Nd isotopes (Wu et al., 2010). The fine fraction dust is a good substitute for studying the long range transport of Asian dust (Sun, 2002; Yang et al., 2009). The peak of the number-size distribution of dust in Miaoergou snow-pit samples was <2 μm, and the volume-size distribution obeyed the lognormal function (Dong et al., 2008). Therefore, insoluble dust obtained from the Miaoergou ice core may much better represent the tropospheric Asian dust.

Table 3
Total variance explained in principal component analysis (first four components).

Component	Principal component analysis		
	Eigenvalue	Variance %	Cumulative %
1	3.338	41.720	41.720
2	2.537	31.711	73.430
3	1.015	12.689	86.119
4	.626	7.831	93.950

Table 4
Loadings of each element upon each of four significant principal components.

	Component			
	1	2	3	4
δEu	−.357	.787	.161	.307
LREE/HREE	.935	−.061	.229	.114
Ce/Yb	.989	.099	−.007	.048
Eu/Yb	.467	.842	−.156	.148
∑REE	.181	−.855	−.291	−.063
δCe	.637	.337	.349	−.565
La_N/Sm_N	.487	−.584	.470	.404
Gd_N/Yb_N	.682	.104	−.697	.090

5. Possible source areas for Miaoergou ice core

5.1. Comparison of the ratios of REEs and Sr–Nd isotopic characteristics in insoluble ice core dust with those of surrounding deserts

Fig. 3 and 4 showed that the Taklamakan desert REE parameters are closest to those of the Miaoergou ice core subsamples. We compared REE parameters from southern and northern Taklamakan Desert samples with the Miaoergou subsamples (Yang et al., 2007; Ferrat et al., 2011). Previous studies have shown that the southern Taklamakan desert/Tarim Basin in China frequently experiences strong and very strong dust storms (Qian et al., 2002; Wang et al., 2003); in addition, the dust loads from the southern Taklamakan Desert were clearly higher than those in the north (Wang et al., 2001). Although the results were of little significance, and, the southern Taklamakan Desert samples resembles only weakly to those in this study. These results indicate that the Taklamakan Desert might be an important dust source area for Miaoergou Glacier. There is a pronounced discrepancy in REE parameters between insoluble dust and Qaidam Basin sand (Ferrat et al., 2011). Previous work has demonstrated that northwesterly winds prevail in the Qaidam Basin during the dust storm period (Sun, 2002). A large amount of dust is transported in a northwest direction to downwind regions, and the surrounding mountains of the Qaidam Basin block the dust from the upwind direction, thus the dust from the Qaidam Basin is unlikely to reach Miaoergou Glacier. Thus, it is not the main dust source for Miaoergou Glacier.

REEs data were examined from Badain Jaran and Tengger, whose dust materials display some similarities with those of the insoluble dust (Ferrat et al., 2011). Nevertheless, those deserts are not main dust sources for the Miaoergou Glacier. The reasons are as follows: there are three main cold air mass routes that can cause dusty conditions in Western China. Two of these originate from the west and the northwest, and may cross into the Tien Shan region (Yang et al., 2012). The locations of those deserts are distributed downwind of the Taklamakan Desert and central Asian deserts, thus the dusty weather could provide large volumes of dust from the western deserts which

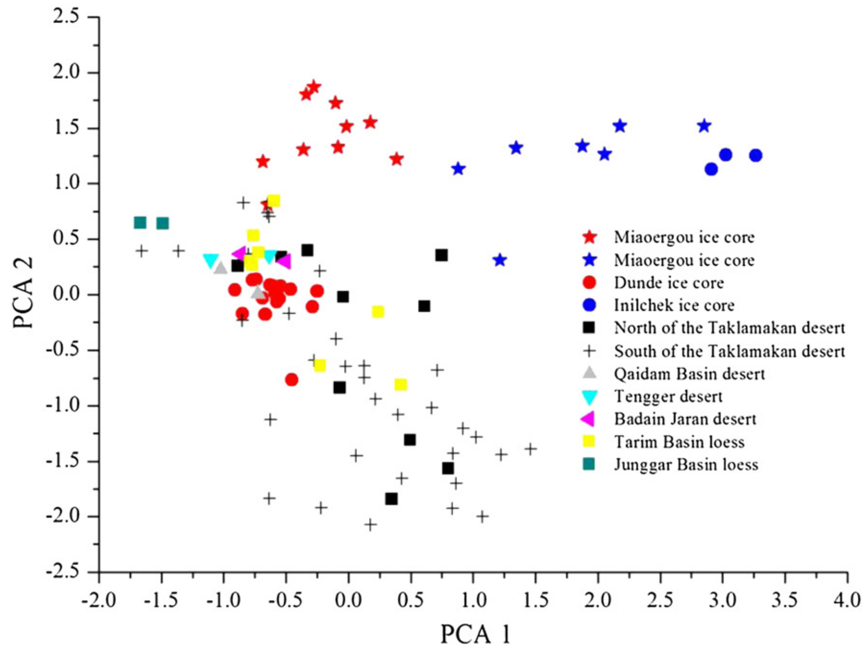

Fig. 3. The PC scores of each site on the four principal components.

may be transported eastward into the Badain Jaran and Tengger Deserts. Regions upwind of those deserts may be taken as a mixture of dust sources for the Badain Jaran and Tengger Deserts.

According to the geographic location of deserts and Sr–Nd isotopic values, the Chinese deserts can be divided into three isotopic regions (Chen et al., 2007): (A) the deserts on the northern boundary of China (including the Gurbantunggut Desert, Hunlun Buir, Onqin Daga and Horqin sandy lands), with the highest $\varepsilon_{Nd}(0) > -7.0$; (B) the deserts on the northern margin of the Tibetan Plateau (including the Taklamakan Desert, Qaidam, Badain Jaran and Tengger Desert), with $\varepsilon_{Nd}(0)$ ranging from -9.5 to -11.7; and (C) the deserts on the Ordos Plateau (the Hobq and Mu Us Deserts), with the lowest $\varepsilon_{Nd}(0) < -11.8$. Based on this study, Sr–Nd isotopic ratios in insoluble dust are consistent with region (B). The Sr–Nd isotopic compositions in insoluble dust show little variation, spanning from 0.717025 to 0.718958 for $^{87}Sr/^{86}Sr$ and -8.5 to -9.5 for $\varepsilon_{Nd}(0)$. Overall, Miaoergou insoluble dust carries markedly higher radiogenic $\varepsilon_{Nd}(0)$ values compared to aeolian desert dust, and it contains typical aeolian deposition

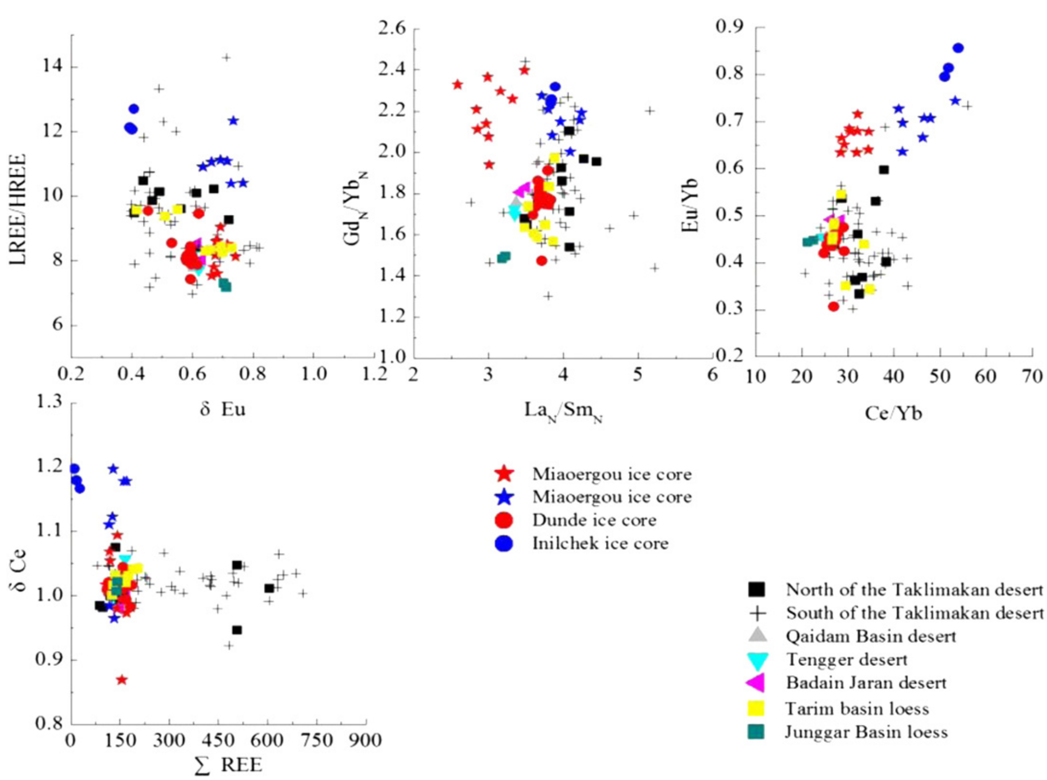

Fig. 4. The REE parameters for the insoluble dust subsamples from Miaoergou ice core and sand from potential source areas: Taklimakan Desert (Yang et al., 2007; Ferrat et al., 2011); Qaidam Basin sand, Badain Jaran and Tengger (Ferrat et al., 2011); and Tarim Basin loess, and Junggar Basin loess (Honda et al., 2004).

Table 5
The pretreatment methods used for the other samples compared in this study.

Samples site (dust type)	Size fraction	Leaching buffering	Reference
Miaoergou ice core (insoluble dust)	Bulk	Ultrapure water	This study
Dunde ice core (insoluble dust)	Bulk	Ultrapure water	Wu et al. (2010)
GISP2 ice core (insoluble dust)	<5 μm	Acid residue	Biscaye et al. (1997)
GRIP ice core (insoluble dust)	<2 μm	Sodium acetate	Svensson et al. (2000)
NGRIP, GRIP, SiteA, Renland, Dye3 (insoluble dust)	Bulk	Ammonium acetate	Bory et al. (2003); Lupker et al. (2010).
Taklimakan Desert (sand)	Bulk	Ultrapure water	Chang et al. (2000); Honda et al. (2004)
Gobi Desert (sand)	<5 μm	Acid residue	Biscaye et al. (1997)
The other deserts in China (sand)	<75 μm	Acid residue	Chen et al. (2007); Rao et al. (2008)
Tarim Basin, Junggar Basin, Qaidam Basin (loess)	Bulk	Ultrapure water	Honda et al. (2004)
North of Pacific ocean (deposition)	Bulk	Ammonium acetate	Pettke et al. (2000)

signatures. Viewed in Fig. 5, the $^{87}Sr/^{86}Sr$ ratios in sands of the Taklamakan Desert vary from 0.712650 to 0.721114, and the $\varepsilon_{Nd}(0)$ values vary from −9.5 to −11.7; the $^{87}Sr/^{86}Sr$ ratios in sands of the Gobi Desert vary from 0.71409 to 0.71449, and the $\varepsilon_{Nd}(0)$ values vary from −5.8 to −8.7 (Biscaye et al., 1997; Honda et al., 2004). It could be deduced that the Miaoergou Glacier's dust is primarily derived from the Taklamakan and Gobi deserts. It is true that the dust from Taklamakan Desert can be transported across the Kumtag Desert, ultimately arriving at Miaoergou Glacier. The glacier is close to the Gobi Desert, from where the air masses from Mogonia can pass into the eastern Tien Shan region; in particular, these air masses could also carry dust from the Mongolian Gobi to this region in spring and winter. It is clear that a mixture of Taklamakan Desert and Gobi materials might contribute the isotopic characteristics of Miaoergou insoluble dust.

Although the Gurbantunggut Desert is close to east Tienshan, the $\varepsilon_{Nd}(0)$ value is remarkably less negative than that of the Miaoergou insoluble dust. The dust loads in Gurbantunggut Desert are smaller than those in the Taklamakan Desert, and the vegetation growth in this desert is much stronger than in the other deserts. Therefore, it is likely that the dust contribution from this desert is negligible. $^{87}Sr/^{86}Sr$ ratios of Qaidam Basin sand samples vary from 0.71661 to 0.73306, and are therefore considerably greater than those of the Miaoergou insoluble dust (Fig. 5). However, the $\varepsilon_{Nd}(0)$ values of the Qaidam Basin (−9.1 to −10.5), Badain Jaran Desert (−10.9 to −7.4) and Tengger Desert (−10.6 to −11.7) sand samples seem to be similar to those of the Miaoergou insoluble dust (Chen et al., 2007), which may merely reflect that this method is insufficient on its own owing to the geochemical similarity, because there are no differences in $\varepsilon_{Nd}(0)$ values of the deserts along the northern margin of the Tibetan Plateau (including the Taklamakan Desert, Qaidam Desert, Badain Jaran Desert and Tengger Desert). As mentioned above, under the modern climate and combined with REE parameters from the ice core and desert sands, the directions of neither the prevailing near-surface wind nor the high-level westerlies support the hypothesis that the aeolian dust of the Qaidam, Badain Jaran and Tengger deserts could be transported westward to Miaoergou Glacier (Wu et al., 2009). The reasonable interpretation is that the dust from the Taklamakan Desert may overwhelm the geochemical information from the Qaidam, Badain Jaran and Tengger deserts.

The $\varepsilon_{Nd}(0)$ differences between Miaoergou insoluble dust and Mu Us sands (ranging from −12.1 to −17.2) and between Miaoergou insoluble dust and Hobq sands (ranging from −11.8 to −14.3) are significantly greater. These regions are located downwind of Miaoergou Glacier; therefore, the Mu Us sand and Hobq Desert can definitely be excluded as aeolian dust sources for Miaoergou Glacier. $\varepsilon_{Nd}(0)$ values in Miaoergou insoluble dust are strongly consistent with loess of the Tarim Basin, but different to that of loess from the Junggar Basin (Honda et al., 2004). These same results were found for the REE parameters (Figs. 3 and 4); thus, the Tarim Basin is also an important loess source area for Miaoergou Glacier.

REE parameters in the Miaoergou ice core are different from those at Dunde (Wu et al., 2009). REE parameters in the Qaidam Basin Desert are closer to those of the Dunde insoluble dust. Because the Dunde ice cap is

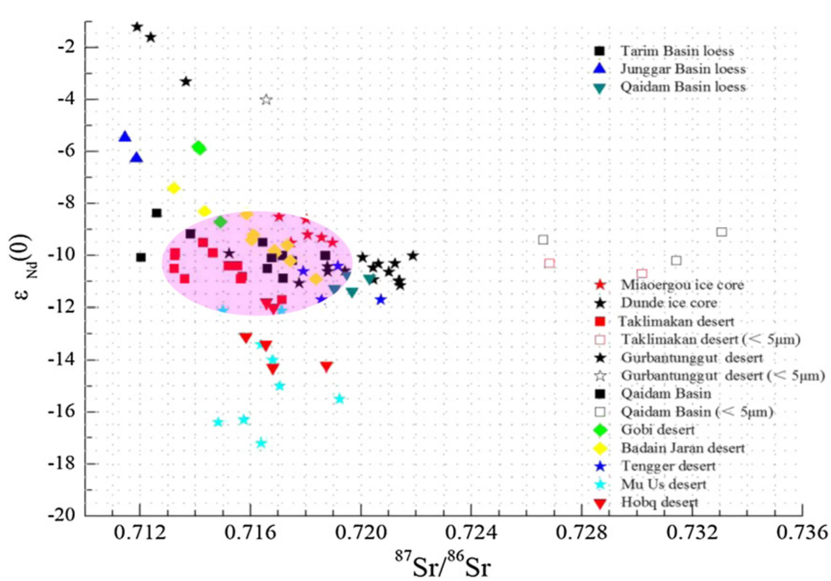

Fig. 5. Sr–Nd isotopic composition of the insoluble dust subsamples from Miaoergou ice core and sand from Chinese desert sands and loess: Gobi Desert (Biscaye et al., 1997); and other deserts (Chang et al., 2000; Honda et al., 2004; Chen et al., 2007); and Tarim Basin loess, Junggar Basin loess and Qaidam Basin loess (Jahn et al., 2001).

located in the southwest of the Qilian Mountain, and lies close to the Qaidam Basin, the potential dust sources are weaker than those accessible to the Miaoergou ice core site. The two ice cores' data emphasize the different dust transport paths under the different atmospheric circulation patterns. Furthermore, the distribution of REE parameters is relatively scattered in subsamples of the Miaoergou ice core. Unless there are multi-sources, there maybe differences in the treatment methods and size-segregated fractions between aeolian dust and insoluble dust in the ice core. However, the atmosphere circulation is very complicated, and this argument needs further attention in future work.

5.2. Comparison with Chinese loess materials

The loess has developed by aeolian accumulation over millions of years. Sources and sinks of loess have been widely studied, and in particular there are still several bifurcations regarding Chinese Loess Plateau sources-sinks (Chen and Li, 2011). Investigations of CLP deposits are crucial for a better understanding of processes influencing the global dust fluxes (Derbyshire et al., 1998). Fig. 5 plots the Sr–Nd isotopes in order to present more clearly the similarities and differences of Miaoergou ice core subsamples and loess material in China. The results show that Sr–Nd isotopes of the Tarim Basin loess have close relationships with those of the Miaoergou ice core (Honda et al., 2004). There is some correlation with the Junggar Basin loess samples (Honda et al., 2004). The prevailing near-surface wind and air masses in the Junggar Basin may influence this region, from where loess is entrained and transported to the Miaoergou Glacier. However, aeolian dust accumulates on the northern piedmont of the Tianshan Mountains, forming loess mantle with an uppermost elevation of up to 2400 m asl, which is much lower than the elevation of the ice core drilling site (4500 m asl). Moreover, the Junggar Basin has far fewer dust storms than the Tarim Basin region (Sun, 2002). The dust derived from the Junggar Desert cannot be easily transported out of the basin. We note that the Tarim Basin/Taklamakan Desert may be considered as the primary loess source for the Miaoergou Glacier. The Sr–Nd isotopes of Dunde insoluble dust indicated the aeolian dust from Tarim Basin could reach the Qilian Mountains (Wu et al., 2010). The similarity between this study and the Taklamakan/Tarim Basin implies the aeolian dust from the latter region can traverse east across the Tienshan mountains.

5.3. The long range transport of central Asian dust

The contribution of Asian dust to the Northern hemisphere is another scientific debate. It has been demonstrated that Asian dust can be transported to Japan, Canada, the French Alps, North Pacific and even Greenland (Biscaye et al., 1997; Grousset et al., 2003; Kanayama et al., 2005; Zdanowicz et al., 2006; Osterberg et al., 2008). In this study, we just compared the isotopic composition of the insoluble dust from Miaoergou subsamples directly with those of the record of North Pacific and Greenland dusts (Fig. 6). In Fig. 1, the location of Miaoergou Glacier is distinct from the Dunde ice cap, but Sr–Nd isotopic ratios from the two ice cores indicate that there are similarities with the Pacific and Greenland regions (Biscaye et al., 1997; Svensson et al., 2000; Bory et al., 2003; Wu et al., 2010). The data from Dunde ice core revealed that the aeolian dust from the Tarim and Qaidam Basins is the most plausible source of the Dunde dust (Wu et al., 2009, 2010). These results provided a good analogue for the long range transport of Asian aeolian dust in Greenland. For elevated interior sites (Site A, GRIP, and NorthGRIP), Sr–Nd isotopic data from those regions correspond well with the Miaoergou and Dunde ice cores, which further demonstrates that the long-range transport of Asian deserts provides mineral dust, in particular to interior and high altitude sites in Greenland (Biscaye et al., 1997; Svensson et al., 2000; Bory et al., 2003; Burton et al., 2007).

The isotopic tracing of the Mu Us Desert, Saharan aerosol, and Dye 3 ice core has not only demonstrated that Asian dust is one potential source for the Greenland dust load, but has also identified the Saharan dust as being an additional dust source to Greenland (Fig. 6). Because the location of Dye 3 ice core is much further south than the other Greenland ice core sites, and hence is closer to easterly transport paths of Saharan dust (Lupker et al., 2010; Aarons et al., 2013). Those results implied that dust from Asian deserts can be transported to higher latitudes (NGRIP) than Saharan dust (Dye 3). This provides new clues regarding Asian dust, because a model has simulated that the Taklamakan Desert dust is deposited largely over the North Pacific (Uno et al., 2009). Furthermore, at ODP Sites 885/886 in the North Pacific (11 Ma), Sr–Nd isotopic ratios (Fig. 6) indicated that Taklamakan Desert and Gobi Desert are the main dust sources for the central North Pacific (Pettke et al., 2000). Consequently, it is important to improve the parameters in future models of Greenland or even the world. Although results are very complicated for the Asian aeolian dust, and the

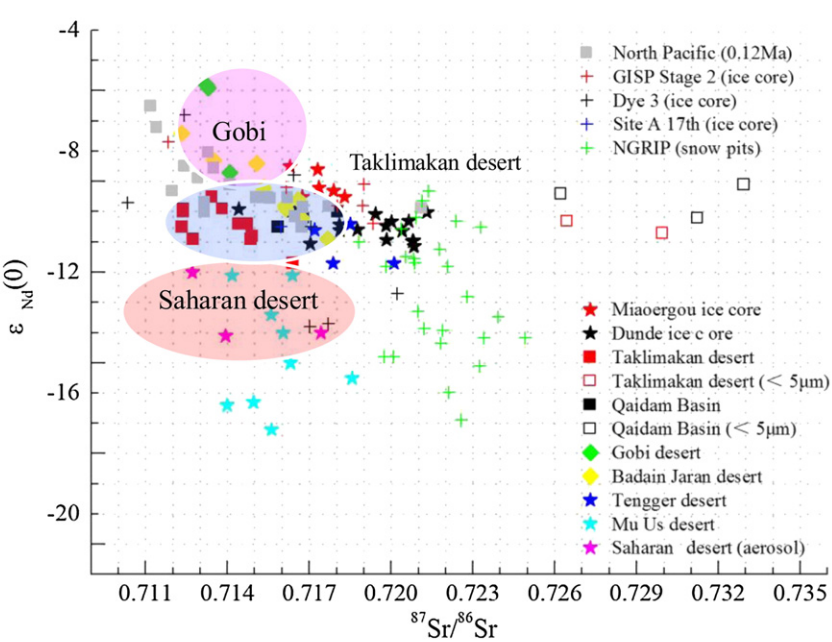

Fig. 6. Sr–Nd isotopic composition of the insoluble dust subsamples from Miaoergou, Dunde and the Greenland ice cores, and sediment from the North Pacific Ocean: Dunde ice core (Wu et al., 2010), Greenland snow and ice (Biscaye et al., 1997; Bory et al., 2002, Bory et al., 2003), North Pacific (Pettke et al., 2000) and Saharan Desert (Aarons et al., 2013).

time-scales are different for each sort of medium, the results discussed here extend the influence area of Asian deserts. Caution is needed in further studies of the effects of Asian deserts at regional or hemisphere scales.

6. Conclusion

Based on our analysis of the characteristics of REEs and Sr–Nd isotopic ratios in a shallow ice core from Miaoergou Glacier, and comparison with the same parameters in dust from Chinese deserts and loess, we draw the following conclusions.

1. The aeolian dust from central Asian deserts, the Taklamakan Desert and Gobi Desert are the primary dust sources for the Miaoergou Glacier.
2. There are similarities in Sr–Nd isotopic ratios in subsamples from the Miaoergou ice core, Badain Jaran and Tengger deserts, but those deserts are not primary dust sources.
3. Sr–Nd isotopic data from alpine and Greenland ice cores imply that the long range transport of Asian dust contributes much dust to the Greenland regions.
4. Limitations of this study are that the conclusions are drawn from a relatively short time-scale and a discontinuous ice core record. Future studies should seek a much older ice core with a continuous time-series. Further, studying REEs in modern snow and ice will strengthen the understanding of their geochemical processes and partitioning between aeolian dust, snow and ice.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 41425003), the National Basic Research Program of China (Grant No.2013CBA01804), and the State Key Laboratory of Cryospheric Sciences (SKLCS-ZZ-2012-01-03).

We would give our great thanks to Zhang C L. Li C J and Dong Z W for their help and also grateful to all field personnel for the scientific expedition to the Miaoergou glacier in 2005.

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