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The environmental implications for dust in high-alpine snow and ice cores in Asian mountains

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ABSTRACT

Dust in ice cores is an excellent proxy for atmospheric dust and can reveal long-term dust history, but the relative contribution from high mountains close to Asian deserts, such as the Tibetan Plateau, remains uncertain. Here we show that dust from high-alpine snow collected from Eastern Tien Shan (Tian Shan), Eastern Pamirs (Muztagata), and Qilian Shan displays a different geochemical composition (e.g. rare earth elements, REEs) to adjacent moraines and neighboring surface soils, but is similar in composition to the upwind remote arid regions. For high-alpine snow dust, the local contribution from moraines and surface soils is minor, with the major source being the Asian deserts. The results have revealed that the snow dust is representative of mid- and upper troposphere dust from Asian deserts, and demonstrates a weak event-based discrepancy but a strong concentration-independent uniformity in composition in the long-term, and confirm the regional environmental implication for the paleo-climatic records from ice cores.

1. Introduction

Atmospheric dust history is pivotal to increasing scientific understanding of its climatic effects over the long-term (e.g. Thompson et al., 1989). The Asian mountain ranges are located adjacent to or even enclosed by the vast Asian arid region, which is one of the major dust sources in the world (Yang et al., 2007a; Wu et al., 2009a). The widely distributed glaciers on these ranges are excellent media to receive and preserve eolian dust from the deserts (Wake et al., 1992, 1994; Wu et al., 2009b). Dust in ice cores recovered from the low- and mid-latitude Asian mountain ranges has important environmental implications. Unlike the glaciers in Greenland and Antarctica that are distant from arid- and semi-arid land, here the neighboring moraines, nearby detrital, alluvial/fluvial deposits, and surface soils can be potential sources of alpine glacier dust in addition to those of the deserts (Hinkley et al., 1997). Therefore, the environmental and climatic implications of the dust found in mountain ice cores might not be as straightforward as those of dust found in polar regions.

The local and background (remote) dusts in Alai-Pamir range have different compositions and concentrations in snow. Although local dust deposition events are common in Central Asia, the deposition of the background dust can be distinguished from the local-source material by its composition (Hinkley et al., 1997). On the glacier surface, especially in the ablation zone, windblown dust particles, often combined with the biogenic materials, can be aggregated to form cryoconite after melting. Cryoconite (glacier surface dust) is common on the Asian alpine glaciers and its source has been discussed (e.g. Takeuchi et al., 2005). Geochemical composition is a powerful and effective tool for atmospheric dust provenance tracing. However, source tracing for dust components of cryoconite by geochemical methods is limited (Li et al., 2011).

Therefore, dust in Asian alpine snow might be a mixture of local and remote sources, as well as natural and anthropogenic source (e.g. Wake et al., 1992; Liu et al., 2011; Dong et al., 2014). This mixture leads to uncertainty regarding the representative dust proxy in snow and ice cores recovered from Asian ranges. The source of dust in ice cores needs to be identified to determine whether there are regional environment implications, and if it represents long-range transported dust. In previous studies, authors have discussed the element composition and provenance of Pamirs ice core dust and aerosol dust, and snow dust from Eastern Tien Shan (Tian Shan) (Wu et al., 2009a, 2010a). For the current study, we took new samples at the two previous sites, and at two new sites from Qilian Shan, to determine the composition of dust in snow or ice cores, and of the nearby moraines and surface soils. The main purpose of this study is to identify snow dust sources from the Tibetan Plateau and Tien Shan ranges, define the climatic implications and to validate use of ice core dust as an indicator of atmospheric dust.

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2. Material and method

In the current paper, three Asian mountain ranges and four sites were chosen for a study of dust in snow and its implications. The Eastern Tien Shan is enclosed by Gurbantunggut to the north, Kazakhstan deserts to the west, Taklimakan to the southwest, and Gobi to the east (Fig. 1). Since March 2006, we have collected surface snow samples weekly or bi-weekly at the Program for Glacier Process Investigation observation site (43°06′N, 86°49′E, 4130 m a.s.l.) in a percolation zone of the eastern branch of Urumqi Glacier No.1 (UG1, Chinese Glacier Inventory No. 5Y730C0029), as described in detail previously (Wu et al., 2010a). Additionally, a total of 25 samples collected from February to December 2008 were used to analyze snow dust composition. The composition of moraine and cryoconite (silt pellet) samples of UG1 were obtained from previous studies (Chang et al., 2000; Li et al., 2011).

The Pamir range is surrounded by Taklimakan to the east, Kara Kum and Kyzyl Kum to the west, Afghanistan and Pakistan to the south. In 2002, we drilled several ice cores at Mt. Muztagata (Muztagh Ata). The lengthways quarter-sections of nine ice tubes (at depths from 31.76 to 40.89 m) from a 93.5 m ice core drilled at 6250 m a.s.l. were cut and grouped into successive subsections at intervals of about 100 cm. Since 2004, we have collected aerosol samples on the terminal moraine of a glacier on a western slope of Mt. Muztagata (Muztagh Ata, 38°70′N, 75°10′E, 4430 m). In this study, new aerosol samples ($n = 7$) collected between 30 June and 13 November, 2011 were used for the element analysis. In the summer of 2010 and 2012, we collected surface soil samples ($n = 15$, 36.88°–38.65°N, 74.92°–75.22°E, altitude ranging from 3051 m to 4576 m a.s.l.) near Mt. Muztagata along the Sino-Pakistan International Highway. The soil samples were mostly collected from the crusted surface soil (mainly fine silts and clays) in dried small depressions.

The Qilian Shan, forming the northern border of Tibetan Plateau, is enclosed by Gobi to the north, Badain Jaran and Tengger to the northeast, Qaidam to the south, and Taklimakan to the west. The Qiyi Glacier (Chinese Glacier Inventory No. 5Y437C18, 39°14′N, 97°46′E) is located in the western part of Qilian Shan. In July 2009, we collected two snow samples at 4800 m, seven cryoconite samples (altitude ranging from 4442 m to 4767 m a.s.l.) on the glacier surface and six moraine samples (altitude ranging from 3944 m to 4868 m a.s.l.) along the valley of Qiyi Glacier. In August 2010, we collected three fresh snow samples (i.e. pristine fallen snow, or snowing when samples were collected) at 4787 m a.s.l., and one aged snow sample at 4856 m a.s.l. at this glacier. The Ningchan River Glacier No. 3 (NCG3, Chinese Glacier Inventory No. 5Y416F003, 37°31′N, 101°49′E) is located at Lenglongling, Eastern Qilian Shan. In July 2009, we collected two fresh snow samples at 4300 m a.s.l. on the NCG3 surface, and three moraine samples (4123 m, 4154 m, and 4186 m a.s.l., respectively) at the glacier terminus. In July 2010, one aged snow sample was collected on the surface on the glacier.

Acid-cleaned wide-mouth Nalgene low density polyethylene (LDPE) bottles were used both as sample scoops and containers. The bottles were kept frozen during transport to the laboratory before filtration. The snow and ice core samples were melted at room temperature and then filtrated with LCR hydrophilic PTFE membrane filters (Millipore Corporation) with the pore size of 0.45 μm (Wu et al., 2010a) in the class 1000 clean room. The aliquots of Qiyi cryoconite samples were sorted by Stokes law to separate the <20 μm fraction, while the Qiyi and NCG3 moraine samples were sieved to separate the <50 μm fraction (Table 1).

The snow dust and aerosol filters, surface soil, moraine and cryoconite samples were digested for inductively coupled plasma mass spectrometry (ICP-MS) (Thermo X-7, Thermo-Elemental Corp.) at the Institute of Tibetan Plateau Research, CAS. The digestion and measurement processes, and detection limit and precision of ICP-MS have been described in detail previously (Wu et al., 2009a). The Sr–Nd isotopic analysis for the UG1 snow dust samples was performed using the same processes described by Wu et al. (2010b). The concentration and grain size of snow dust were analyzed with a Coulter Counter (Beckman MS3, diameter from 1 to 30 μm), and the grain size of cryoconite and moraine with a Microtrac-S3500 laser particle size analyzer (Microtrac Inc.). The analysis of total organic carbon (TOC) and inorganic carbon (IC) content of Qiyi cryoconite was performed using a Shimadzu TOC-VCPH).

3. Results

3.1. Urumqi Glacier No. 1 (UG1), Eastern Tien Shan

In a previous study we discussed the variation of dust concentration and uniformity of dust composition in UG1 snow samples during the period of March 2006 to January 2008 (Wu et al., 2010a). In this study, we carried out further analysis over the period February to

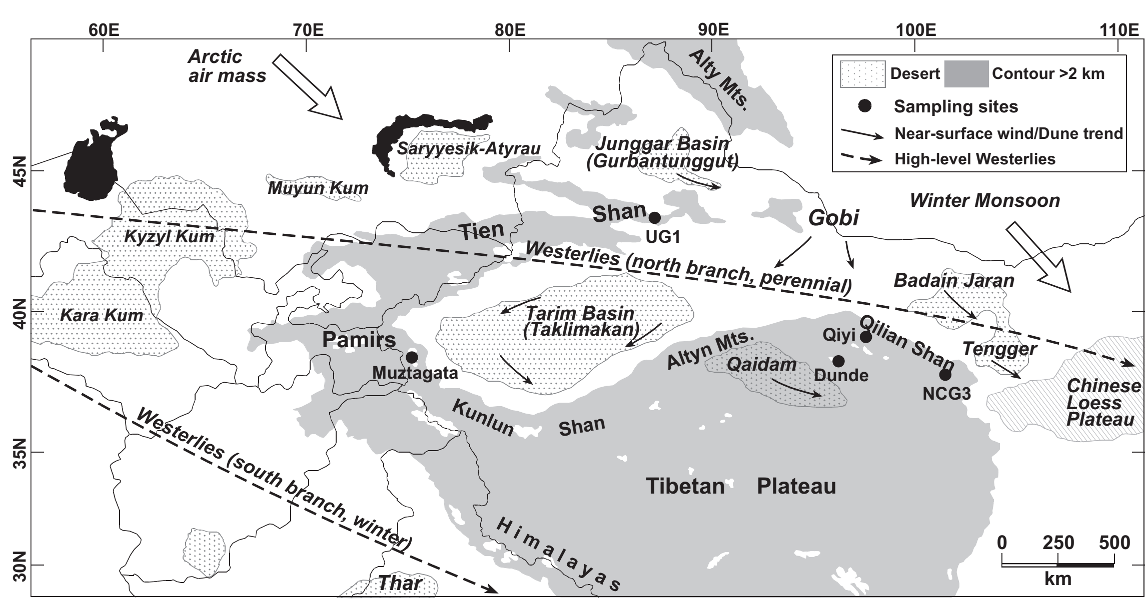

Fig. 1. Sketch map of the location of study sites.

Table 1
Sampling sites and brief descriptions.

Site	Sample type	Sampling date	Note	References
UG1, Tien Shan	Surface snow	2008		Wu et al., 2010a; this study
	Cryoconite		Silt and clay	Li et al. (2011)
	Moraine			Chang et al. (2000)
Muztagata	Ice core	2002		Wu et al., 2009a; this study
	Aerosol	2004–2006; 2011	TSP	Wu et al., 2009a; this study
	Surface soil	2010; 2012	Bulk	This study
Dunde	Ice core	2002		Wu et al. (2009b)
Qiyi	Surface snow	2009; 2010		This study
	Cryoconite	2009	Bulk and <20 μm	This study
	Moraine	2009	<50 μm	This study
NCG3	Surface snow	2009; 2010		This study
	Moraine	2009	<50 μm	This study

December 2008. All of the snow dust, cryoconite and moraine samples have chondrite-normalized distribution patterns (not shown) 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). Therefore, the REE distribution pattern itself seems not effective enough for UG1 dust tracing. The composition of local moraine has a wide range (Chang et al., 2000), but can be distinguished from snow dust and cryoconite by the lower L/H REE, lower δEu, and lower La_N/Sm_N ratios (Fig. 2). One of the moraine samples had a very similar REE composition to snow dust and cryoconite, suggesting the complex composition of moraine material, and its potential contribution to snow dust.

The element compositions of the silt and clay fractions of pellet (cryoconite) collected from the UG1 surface are very similar to that of the upper continental crust, with the exception of a few elements, indicating that the pellet materials are derived mainly from atmospheric dust from remote sources, and that the local provenance makes a minor contribution (Li et al., 2011). The grain size of UG1 cryoconite is about 6.2–6.5 phi (or 11–14 μm), also suggesting eolian origin of mid- to long-range, and that contribution from a local moraine is unlikely. Although the silt and clay fractions of cryoconite seem to have some discrepancies, such as in the Sm/Nd ratio, the cryoconite (pellet) shows very similar composition with snow dust (Fig. 2), showing that they have the same source(s).

The isotopic composition of the snow dust and moraine was further evaluated. The moraine samples have different $^{87}Sr/^{86}Sr$ and $\varepsilon_{Nd}(0)$ ratios to the snow dust, the latter has also been analyzed in another study (Fig. 2). The isotopic ratios of the silicate fraction of snow dust were closer to those of the desert sand in China than those of the soil and bedrock around the glacier, suggesting that the silicate minerals on the glacier were derived from distant deserts (Nagatsuka et al., 2010). A previous study pointed out that dust from the vast arid regions of central Asia is the dominant source for major ions in Tien Shan snow (Wake et al., 1992). Dust in UG1 snow has been studied for provenance tracing by geochemical methods, showing that dust in this glacier comes from the Tarim and Junggar deserts, and from arid regions in the upwind Central Asia, such as Kazakhstan (Wu et al., 2010a). Therefore, the local moraines are neither an important nor major source for UG1 snow dust. The summer and winter UG1 snow samples display no systematic trend in their element parameters, implying that the UG1 dust was uniform in composition throughout the sampling period, and therefore from the stable source(s) (Wu et al., 2010a). This compositional uniformity of UG1 snow dust also indicates that the contribution of local materials is small even during summer, when snow cover disappears and local supply increases.

3.2. Muztagata, Eastern Pamirs

The Muztagata is located in the Eastern Pamirs, which is perennially controlled by the Westerlies. The glacier equilibrium accumulation line is about 5200–5600 m, and the ice core (which was drilled at 6250 m) seldom experienced post-depositional melting. The new ice core samples, with the estimated temporal resolution of more than one year, display a clear similarity in their dust composition (Fig. 3), indicating that they have stable and predominant source(s). Aerosol composition also shows no systematic trend with season, and is independent of aerosol concentration, indicating a rather homogeneous condition for modern atmospheric background dust over the Eastern Pamirs (Wu et al., 2009a). The previous and new aerosol and ice core dust samples lie within a narrow range of composition. The compositional similarity above an elevation of 1800 m (4430 m vs. 6250 m a.s.l.) between the two sites indicates that aerosol and ice core dust are well-mixed atmospheric background dust on a regional scale, and are derived from common sources.

In contrast to ice core and aerosol dust, the moraine and surface soil sample element composition index has a relatively large range, resulting in uncertainty in determining whether local materials are

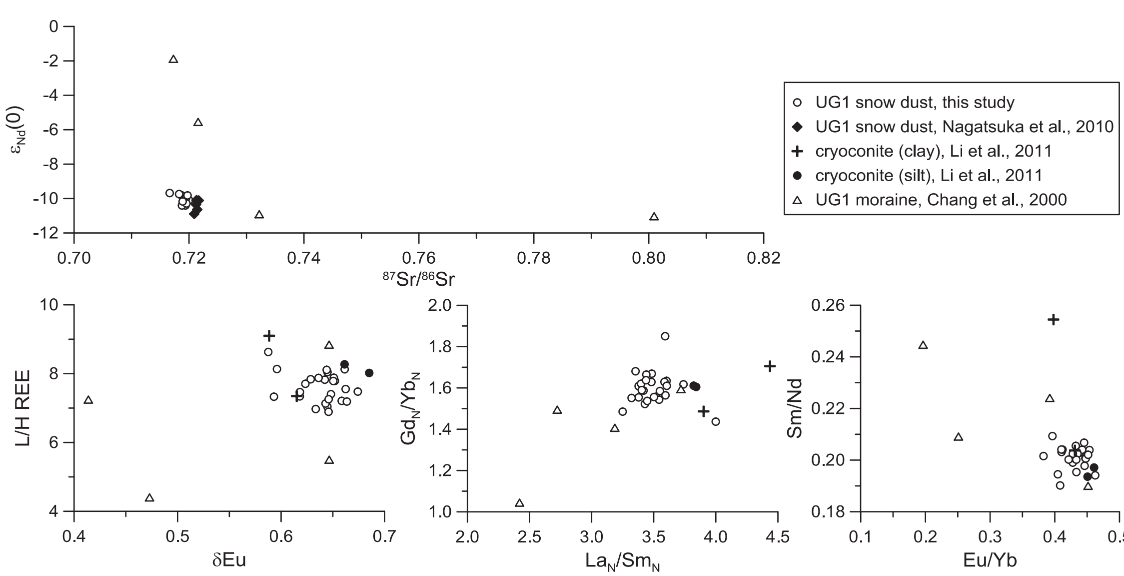

Fig. 2. The geochemical composition of UG1 snow dust, cryoconite (Li et al., 2011) and moraine (Chang et al., 2000).

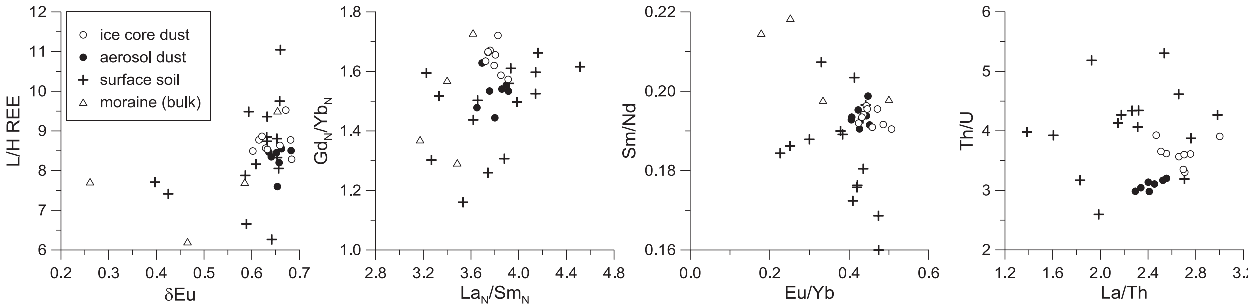

Fig. 3. The composition of new Muztagata aerosol and ice core dust, and their comparison with surface soil (this study) and moraine (Chang et al., 2000).

important contributor to the aerosol and ice core dust. Generally, both aerosol and ice core dust differ from moraine and surface soil. Although samples from the Muztagata moraine have a wide compositional range, they have a strong negative Eu anomaly, lower La_N/Sm_N and higher Sm/Nd ratios compared to aerosol and ice core dust, and can be demarked from the latter. Here we need to point out that the surface soil seems to in part have a common composition with aerosol or ice core dust. This is partly because we collected the crusted, fine silt-dominant, stratified surface soil from dried small depressions, which experience fluvial and/or eolian sorting. This indicates that the aerosol/ice core dust has a different source from the local materials, or the aerosol/ice core dust experienced sorting during transport if partially-derived from local materials. Nevertheless, the local contribution to aerosol and ice core dust is possible, but minor.

3.3. Qiyi Glacier, Western Qilian Shan

Qiyi Glacier (with an area of ~2.7 km^2 in 2005) is located in the western part of Qilian Shan. In this region, the westerlies are the predominant circulation feature, while the Asian monsoon occasionally reaches here in summer (Wang et al., 2010). The elemental composition of 2009 snow samples resembles the 2010 ones (Fig. 4), despite that their La_N/Sm_N and La/Th ratios show a weak discrepancy. The samples in 2010 show a relatively scattered range of composition in L/H REE, La_N/Sm_N and La/Th ratios. The discrepancy between samples in 2009 and 2010 and among the samples in 2010 might be partly due to some snow samples being of an event-based timescale (i.e. fresh snow). Snow dust samples collected while snowing might have short-term implications, and are not identical to long-term conditions, since the mixture of dust particles from different sources will result in a mixed composition. Nevertheless, this discrepancy is relatively weak compared to the difference between snow dust and moraine.

Cryoconite is common on Qiyi Glacier surface, which is suggested to be the wind-blown deposits of desert sand (Takeuchi et al., 2005). Moraine samples show a different physical and geochemical characteristic to the cryoconite and snow dust samples.

As shown in Fig. 4, the Qiyi moraine (<50 μm) sample has a lower L/H REE, stronger negative Eu anomaly and lower La_N/Sm_N ratios, but has higher Sm/Nd and Th/U ratios than the snow dust and cryoconite samples. Therefore, the local moraine is not the major source for snow dust and cryoconite at the Qiyi Glacier. However, there are still some ratios that both snow dust/cryoconite and moraine samples have in common, such as the Gd_N/Yb_N and Th/U ratios, suggesting a possible but minor contribution. The REE distribution patterns (Fig. 5) also show the compositional difference between cryoconite and moraine.

3.4. Ningchan Glacier No. 3 (NCG3), Lenglongling, Eastern Qilian Shan

Lenglongling is located in the eastern part of Qilian Shan. We wanted to determine whether the dust on the glacier surface there is derived from the deserts in western China (Taklimakan and Qaidam), or from the deserts in northern China (Gobi, Badain Jaran, and Tengger), or derives from local materials. All the three NCG3 snow dust samples display clear differences in element composition to the moraine, although both of the two types of material show a scattered range in their element ratios. The moraine has the lower L/H REE, stronger negative Eu anomaly, lower Sm/Nd ratios, but higher Gd_N/Yb_N and Th/U ratios than the dust snow samples (Fig. 6). The REE distributions for snow dust also show a different pattern to that of the moraine (Fig. 5). The compositional differences indicate that the local moraine is not the major source of snow dust.

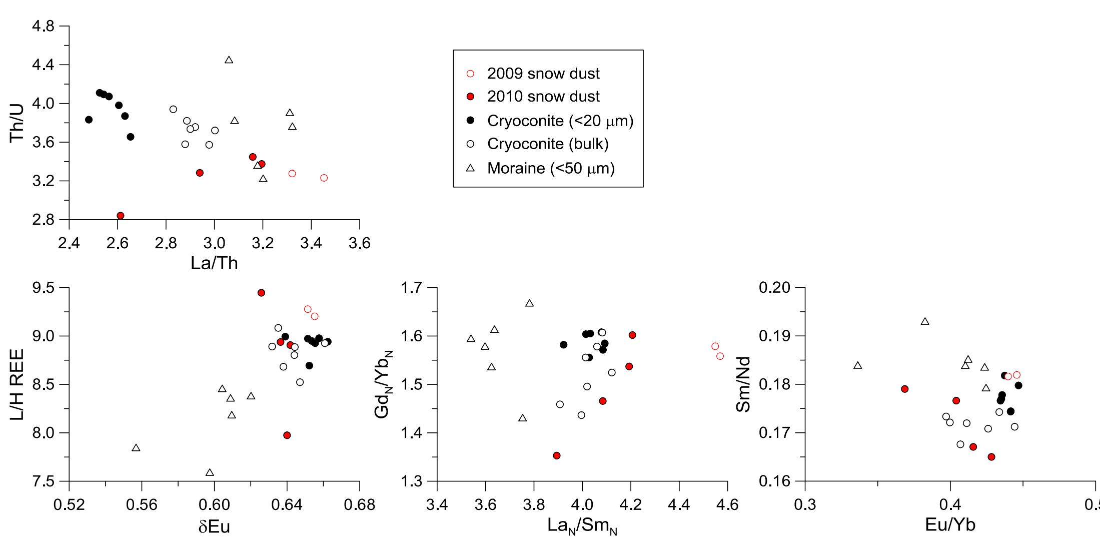

Fig. 4. Composition of snow dust, cryoconite and moraine samples collected at Qiyi Glacier, Western Qilian Shan.

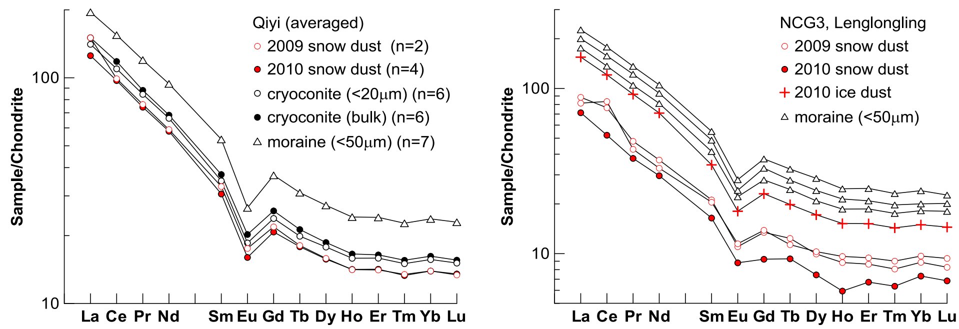

Fig. 5. The REE distribution pattern of averaged Qiyi samples (left) and each NCG3 samples (right), Qilian Shan.

4. Discussion

4.1. The source of high-alpine snow dust at the sites studied

Determining the element composition of dust is highly-effective for source tracing. Th and U are known to have different geochemical behaviors in certain superficial processes. Th is largely insoluble, while the redox-dependent mobility of U is well-documented in weathering environments, leading to preferential leaching of U from alteration profiles and an increase of the Th/U ratio in the residual material. If the adjacent moraine is the major source of snow dust, it is reasonable to expect that the Th/U ratio for snow dust would be higher than that of moraine. However, in both the Qiyi and NCG3 samples, the high Th/U ratios in moraine and the relatively lower ones in snow dust are contrary to this expectation, and indicate that the local contribution is minor, if not unlikely. It is reasonable to assume that they originate from different sources. This is similar to the relatively high Th/U ratios in surface soil, but the lower ones in the aerosol/ice core dust at Muztagata (Fig. 3).

These results indicate that the adjacent moraine and nearby local surface soil are not the major source for high-alpine snow dust. Therefore the upwind remote arid regions are the most likely provenance. The UG1 (Eastern Tien Shan) dust is mainly derived from Tarim Basin (Taklimakan) and Junggar Basin (Wu et al., 2010a), while the major sources of Muztagata dust are the west Asian deserts, such as those in Afghanistan, Tajikistan and even further west (Wu et al., 2009a). The recent sample data from the two sites concurs with previous results and further validates the implications for high-alpine snow dust at Tien Shan and Pamirs.

The snow dust samples from the Qilian Shan, including from the Dunde ice core, Qiyi and NCG3 surface snow, show similarity in element composition, indicating that they have the common major source (Fig. 7). Compared to the composition of adjacent deserts, the Badain Jaran sand materials (Yang et al., 2007b) have lower L/H REE and Gd_N/Yb_N ratios, less negative or even a positive Eu anomaly (0.85–1.48), indicating that the contribution to Qilian Shan snow dust from this desert seems minor, though Badain Jaran Desert was also the potential source for dust in the western Qilian Mountains (Dong et al., 2014). The Tengger is located to the northeast of Qilian Shan, where the prevailing high-level westerlies and north-westerly near-surface winds contradict the possibility of Tengger dust transport to the NCG3. Element composition of the finer fraction (<53 μm, which can serve as the mid- to long-range transport dust particles) of the Taklimakan eolian sediment (Yang et al., 2007a) is similar to that of Dunde, Qiyi and NCG3 dust, suggesting that the Tarim Basin might be the major source area for Qilian Shan snow dust, promoted by the perennial westerlies. Therefore, it is reasonable to conclude that the source of Qilian Shan snow dust comes mainly from Taklimakan. The Sr–Nd isotope analysis suggests that Qaidam is a potential source for Dunde ice core dust (Wu et al., 2010b), although at present element data for Qaidam material is lacking.

Particle grain size can also provide some useful information on the dust source. The dust particle of Muztagata ice core has the mean volume diameter of 1.8–3.4 μm, while the surface soil samples show the mean volume diameter of 17.5–44.9 μm. The median grain size of the Qiyi snow and bulk cryoconite samples respectively averages 1.5 μm (1.4–1.6 μm) and 11.1 μm (9.7–13.6 μm), while the median grain size of the moraine samples averages 36.2 μm. Here we need to point out that due to the different measuring method (laser scattering vs. coulter), the comparison on grain size between moraine/surface soil and snow dust/cryoconite is not straightforward. Even considering this uncertainty, those differences in grain size clearly indicate that the moraine or surface soil itself is not the main contributor to snow dust/cryoconite, unless there is a wind sorting during transport (see discussion in Section 4.2).

4.2. Composition discrepancy between snow dust and cryoconite

Cryoconite is biogenic surface dust on glaciers. The Qiyi cryoconite has the TOC mass fraction of 2.7% (ranging from 1.7% to 4.0%), which is less than the formal result of 8.6% (Takeuchi et al., 2005). This might be due to the different sampling times. However, both results

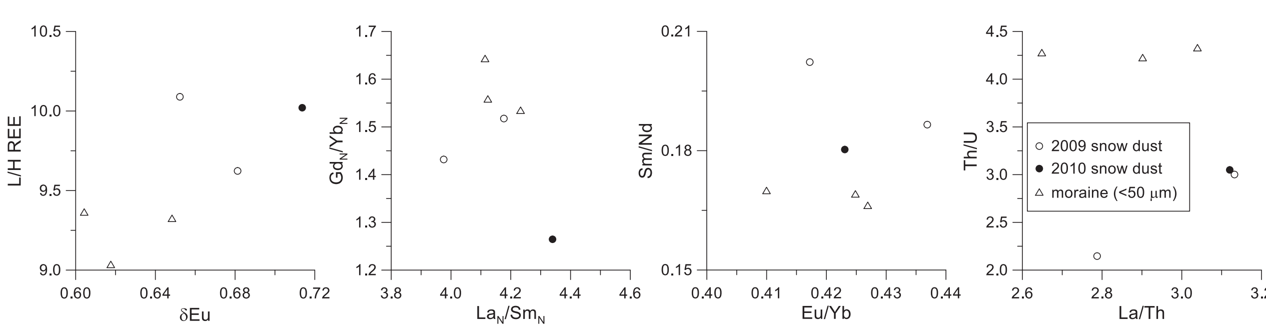

Fig. 6. Composition of snow dust and moraine of NCG3, Lenglongling, Eastern Qilian Shan.

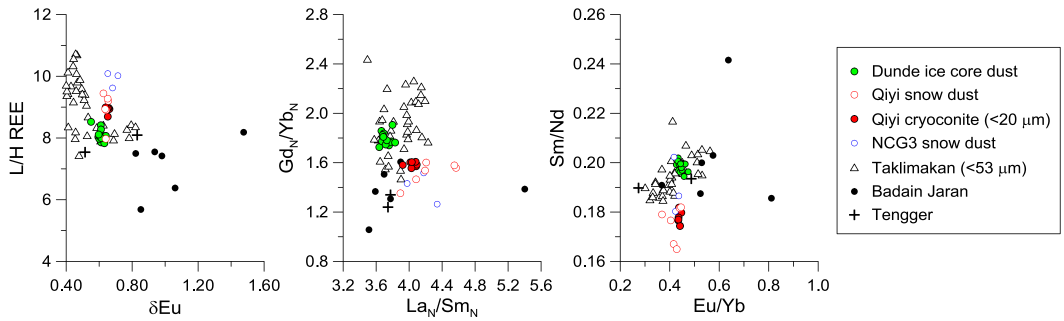

Fig. 7. Element composition for snow dust samples from Qilian Shan (Dunde, Qiyi, and NCG3), Taklimakan, Badain Jaran and Tengger deserts (Yang et al., 2007a,b; Honda et al., 2004).

indicate that mineral dust is the major component of Qiyi cryoconite. The cryoconite samples show a relatively smaller range in element composition than the snow samples, due to the accumulation of dust that will give a much more mixed condition and therefore represent the long-term average composition. Grain size effect on the composition of cryoconite samples seems minor, although the La/Th ratio is slightly higher in the bulk than in the fine fraction (<20 μm). The chondrite-normalized REE distribution for the bulk and fine fractions also indicates the same composition. We also evaluated the impact of altitude on cryoconite composition (Fig. 8) and found that there is no systematic variation of the composition with altitude. The cryoconite at the lowest (4442 m) position is the same in composition to the highest (4767 m) position. These characteristics also indicate that the mineral component of cryoconite is supplied by eolian dust.

When compared to moraine, the composition of snow dust and cryoconite differs. The possible causes of grain size sorting are discussed below.

REE abundance and consequently element ratios are dependent of grain size (Chang et al., 2000). Snow dust particles are finer that those of cryoconite, while cryoconite particles are finer than moraine and surface soil, resulting in some uncertainties in compositional comparison and tracing. The coarse and giant particles contribute significantly to total mass and consequently to bulk composition. Indeed, large particles can be transported several thousands of kilometers away from the source region. Giant particles (>62.5 μm) are found less often at greater distances (>1000 km) (Middleton et al., 2001). Asian dust in Mt. Tateyama (central Japan) snow samples show a median volume diameter 6–21 μm (Osada et al., 2004), while dust particles of up to 60 μm (equivalent sphere diameter) have been transported as far as 2000 km away (Jeong et al., 2013). Therefore, transport of large particles from the remote arid region to the high-alpine glacier surface on the Tibetan Plateau is feasible. The size distribution of dust in Tibetan alpine snow and ice core indicates that coarse particles (diameter >15 μm) are common in the mid- and upper troposphere (Wu et al., 2009c). Although the cryoconite has the greater grain size compared to that of the snow samples, it still mainly comes from the remote arid regions rather than the local moraine.

When dust particles are deposited on the glacier surface, the post-depositional melting might cause a preferential elution of the finer ones but a relative accumulation of the coarser ones. The ablation zone of the Qiyi Glacier during summer almost extends to the col due to recent warming (Wang et al., 2010), favoring the accumulation of dust on the glacier surface to form cryoconite through biogeochemical processes. The elution processes and sorting therefore change the grain size, and consequently the composition of eolian dust.

If this sorting did exist and was responsible for the compositional discrepancy between snow dust (cryoconite) and moraine, the REE abundance of moraine should be less than the cryoconite, since REE abundance increases in the fine fraction of moraine (Chang et al., 2000). However, the snow dust and cryoconite samples display a lower REE abundance than the moraine both in Qiyi and NCG3 (Fig. 5), indicating that this sorting is unlikely. The similarity between

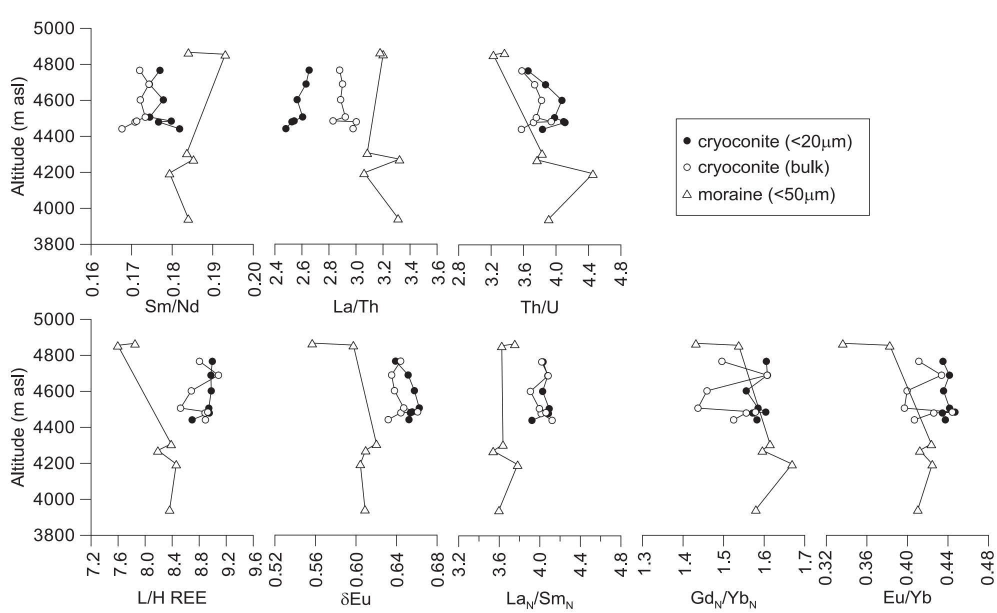

Fig. 8. The Qiyi snow dust, cryoconite and moraine composition against altitude.

Muztagata ice core and aerosol composition, with the elevation between the two sites, also suggests that this sorting is weak, if not impossible (see Section 3.2). Based on the variation of the REE abundance, the sorting seems unlikely, although we cannot evaluate the exact sorting effect on the dust composition.

When compared to snow dust, the composition of cryoconite also differs to some degree (Fig. 4) due to the possible cause of time-dependent deposition. The dust in high-alpine snow might have multiple sources, and its composition can vary due to short-term dust transport, deposition and mixture conditions. If there is a seasonal variation in dust input, it is reasonable that snow dust might have a wide range in composition. The high-resolution of sampling on the event-based time scale might result in dust compositional discrepancy among snow samples, though this discrepancy is weaker than that between the snow dust and moraine. The cryoconite displays a rather centralized range due to its mixed composition. We found that the aerosol and ice core samples with low dust concentration always show a relatively scattered composition, while the high-load samples have a more stable composition, such as the Muztagata aerosol (Wu et al., 2009a). The ice core samples (each may cover one year or multiple years) from Muztagata (Wu et al., 2009a and this study), Dunde (Wu et al., 2009b) and long-term surface snow samples (from March 2006 to December 2008) collected on the UG1 (Wu et al., 2010a and this study) revealed that at each site, the snow dust has an essentially similar composition independent of dust load, and that there is a uniformity in dust composition from a long-term perspective. The snow and ice core dust is either well mixed or derived from a dominant source, although other minor sources are still possible, and this can be detected on the event-based time scale. Therefore, the major snow dust source is the remote arid regions, which is of importance in interpreting the environment and climate implications of dust in ice cores.

4.3. Validation and uncertainties in the study

Other researches have also discussed the local and remote contribution to dust in alpine snow in other regions. Dust isotopic compositions for aerosol samples from the Alps (Jungfraujoch, 3580 m) and for ice core samples from Colle Gnifetti (4455 m) indicate that their major source is the remote Saharan desert (Thevenon et al., 2012). The element composition of snow dust collected at Garabashi Glacier (3856 m), Mt. Elbrus is significantly different from dust generated from local sources (sampled at 2380 m), but similar to the long-range dust transported from the Sahara, showing that the remote arid region is the predominant source (Shahgedanova et al., 2013). At St. Elias Mts., Alaska, snow dust found below 3000 m a.s.l. has local or mixed source(s), while dust found above ~3000 m a.s.l. has the source in the Gobi desert region of northern China and Inner Mongolia (Zdanowicz et al., 2006). Even at some non-glaciated regions, dust in snow or dust aerosol is derived from remote sources as opposed to the local, such as the dust aerosol and dust in rainwater over the summit of Mts. Sefuri (1055 m a.s.l.), southwestern Japan (Miyamoto et al., 2010), and snow dust collected at the San Juan Mountains (Colorado, USA) (Painter et al., 2007). These cases demonstrate that the snow dust is derived from upwind remote source areas, and that the local contribution is minor.

However, as discussed above, the local contribution to snow dust should not be excluded and can become the major source in some cases. On the remote Greenland ice sheet, dust from Renland ice core near the east coast partly comes from local materials (Lupker et al., 2010). Dust in Penny ice core (Baffin Island) has a local source, which can affect the dust concentration via the change of transport distance caused by the expanding and shrinking of ice cap (Zdanowicz et al., 2000). There is a complex wind system in the mountain glacial valley, including "valley wind", "mountain wind", and "glacier wind" that can carry local moraine and other surface soil particles to the glacier surface (Zou et al., 2008). Some occasional events, such as catastrophic landslides, could result in dustfall episodes and high dust concentration in the nearby glaciers, such as in Karakoram (Wake et al., 1994). Ambient moraine around the small glaciers, such as Qiyi and NCG3, might provide material to the glacier surface through local turbulence. The NCG3 has an area of 1.203 km^2 in 2009, with shrinkage of 13.1% since 1972 (Liu et al., 2012), while from 1956 to 2005, the area of Qiyi Glacier has decreased by 6.86% (Wang et al., 2010). The melting will expose more moraine area and consequently might favor its contribution to snow dust on those glaciers. If shrinkage continues under global warming, the local contribution might increase. For dust on glacier surfaces in the ablation zone, especially at the tongue, the local materials (e.g. moraine) might contribute the major fraction.

5. Conclusion

In this study, we analyzed the composition and tracing implication of high-alpine snow dust on glaciers at the four sites of Asia mountain ranges adjacent to the deserts, including UG1 in Eastern Tien Shan, Muztagata in Eastern Pamirs, and the western and eastern parts of Qilian Shan. Our results reveal that the high-alpine snow dust has a clearly distinguishable composition difference from local material (adjacent moraine and surface soil), and is derived mainly from the upwind remote Asian deserts, and that the local contribution is minor. Using the element (especially REEs) ratio as the proxy, we found that the UG1 dust mainly comes from the Taklimakan, Junggar and Central Asia arid regions, the dust in Muztagata ice core and aerosol from the west Asian deserts, while the major source of Qiyi and NCG3 snow dust is Taklimakan.

The snow dust samples with an event-based time scale might have a relatively wide range in composition due to the variation in source and transport. However, there is long-term uniformity in dust composition. The well-mixed cryoconite on the glacier surface resembles the snow dust in composition and is generally similar independent of the altitude. Our result gives robust evidence for validation of dust's climate implication in ice cores recovered from low- and mid-latitude mountains.

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