Environ Geol (2007) 51: 1229–1238
DOI 10.1007/s00254-006-0416-9

ORIGINAL ARTICLE

Mingrui Qiang
Fahu Chen
Jiawu Zhang
Ruiping Zu
Ming Jin
Aifeng Zhou
Shun Xiao

Grain size in sediments from Lake Sugan: a possible linkage to dust storm events at the northern margin of the Qinghai–Tibetan Plateau

Received: 18 October 2005
Accepted: 25 May 2006

M. Qiang (✉) · F. Chen · J. Zhang
M. Jin · A. Zhou · S. Xiao
Key Laboratory of Western China's
Environmental System (Ministry
of Education), CAEP,
Lanzhou University, Lanzhou 730000,
People's Republic of China
E-mail: mrqiang@lzu.edu.cn
Tel.: +86-931-8914529
Fax: +86-931-8912330

R. Zu
Cold and Arid Regions Environmental
and Engineering Research Institute,
Chinese Academy of Sciences, Lanzhou
730000, People's Republic of China

Abstract Samples of surface deposits in the Lake Sugan catchment, as well as surface lake sediments, eolian materials occulted in the lake ice cover, and airborne dust were collected for grain-size analysis. The results show that the coarse fraction of the lake sediments could be transported by ambient winds and to a lesser extent by river flow in the study area. Sediment cores were retrieved from Lake Sugan in December 2000, and ^{210}Pb and ^{137}Cs dating and grain-size analyses were performed on these samples. ^{210}Pb ages and the volume percentage of the fraction of lake sediments >63 μm were used to reconstruct the dust storm history from 1957 to 2000. Observational data for dust storm events collected at a local meteorological station largely agrees with the reconstructed trend for the past 44 years, suggesting that lake sediments can be employed to trace the dust storm history of the northern Qinghai–Tibetan Plateau.

Keywords Lake sediment · Grain size · Dust storm · Lake Sugan

Introduction

Eolian activities are prevalent in the arid environment of northwestern China, most of which is usually regarded as a primary source of dust storms in this region (Zhang 2001). Fang et al. (2004) demonstrated that the Qinghai–Tibetan Plateau is likely to be the main source of atmospheric dust, since the altitude of the plateau is so high [typically more than 3,000 above sea level (a.s.l.)], and dust particles are elevated into the westerly circulation. The dust storm history in such regions is crucial for understanding changes in regional atmospheric circulation and connections between the source region and other regions where windblown dust is deposited, such as the Greenland ice sheet (O'Brien et al. 1995; Bory et al. 2002), the Antarctic ice sheet (Petit et al. 1990), and the north Pacific (Hovan et al. 1989; Rea and Leinen 1988). Atmospheric dust plays a significant role in biogeochemical cycles in the oceans and participates in the regulation of levels of atmospheric CO_2 (Kumar et al. 1995; De Baar et al. 1995). This dust may be more than just an indicator of climate change; it may itself be an agent of climate change (Yung et al. 1996). Therefore, the reconstruction of the dust storm history in arid regions of China will benefit understanding of the relationship between dust emission in source areas and remote records of atmospheric dust, as well as understanding of how the atmospheric dust affects the global climate system.

In the arid and semi-arid zones of China, continuous meteorological records extend back to the 1950s. The record of dust storm events spans less than 50 years, and is too short to elucidate the long-term dust storm history in this area. A review of historical literature has provided some information about dust storm or dust fall events in central and eastern China in the past, and permitted the creation of a 1,700-year dust fall sequence for eastern China (Zhang 1983, 1984). In general, information on dust fall events becomes increasingly scarce in older historical records. Thus, knowledge of the evolution of dust fall based solely on the literature is insufficient to understand the dust storm history over longer time periods, particularly in regions where ancient peoples rarely lived.

The alternative is to resort to geological archives. Loess deposits offer a good archive for atmospheric dust loads (Zhang 2001; An and Xiao 1990), but have often suffered from erosion after deposition and cannot reflect changes in dust storms on decadal to century time scales. In contrast, lake sediments, especially those of closed lakes in arid regions, are considered to be an ideal archive that preserves rich information on past dust storms (Xiao et al. 1997, 1999; Jin et al. 2000; De Deckker et al. 1991; Sun et al. 2000; Dean 1997; Wang et al. 2001; Moreno et al. 2001). The grain size (De Deckker et al. 1991; Jin et al. 2000; Sun et al. 2000), elemental compositions (Dean 1997; Moreno et al. 2001), and magnetic properties (Wang et al. 2001) of lake sediments can reflect the characteristics of the past dust storm events and regional wind regimes. The quantity of coarse particles in lacustrine sediments is an indicator of the wind strength in arid regions, where precipitation and surface runoff are light (De Deckker et al. 1991; Jin et al. 2000). However, there is a lack of knowledge of the modern processes by which lake systems record dust storm events in arid areas.

In the present study, Lake Sugan, a hydrologically closed lake at the northern margin of the Qinghai–Tibetan Plateau, was selected to investigate the region's dust storm history during the past several decades. Observational data on dust storms is available to test the reconstruction of dust storm characteristics from the lake sediments during this interval. Grain-size analysis of different types of sediments in the lake system revealed that the coarse fraction of the lake sediments can potentially be a good indicator of dust storm events.

Study area

Lake Sugan is in a closed basin (the Sugan Basin) in the northern part of the Qaidam Basin on the Qinghai–Tibetan Plateau (Fig. 1) and in the southern part of the Arid Region of China, in which annual mean precipitation is generally less than 250 mm (Fig. 1). Elevation varies between 2,792.5 and 3,000 m a.s.l., and the altitude gradually increases from west to east within the basin. Meteorological data for the study site were obtained from 1957 to 2000 from the Lenghu Meteorological Station. The annual mean precipitation from 1957 to 2000 was 15.8 mm, and the annual mean atmospheric temperature was 2.75°C. Summer rainfall (from June to September) accounts for at least 80% of the annual precipitation. The annual mean potential evaporation is 2,967.2 mm. There have been an average of 55 days with strong wind (≥ 17 m s^{-1} at a height of 10 m above ground) per year during the past 44 years. The number of dust storm days has ranged from 3 to 16 days per year during this period. The study region is dominated by the northwest winds . Vegetation is sparse in the basin, except for a grassland area on the east of Lake Sugan where groundwater seeps out from the subsurface. Most of the basin surface is covered by eolian sand and gravel. A large part of the region is sparsely populated, and the Kazak people herd their livestock there.

Lake Sugan currently has a surface area of about 104 km^2 and a maximum depth of up to 5 m at the southern part of the lake. The mean depth is 2.8 m. The lake water has a pH value of 8.5, an electrical conductivity of 2.2 m S^{-1} (25°C), and a salinity of 31.8 g L^{-1}. As a closed lake with no natural discharge outlet, Lake Sugan is the confluence center for surface water and groundwater in the area and also represents the base level of the water table. The main source of water for the basin comes from two rivers, the Big Harteng River and the Small Harteng River, in the eastern part of the basin (Fig. 1). After reaching the gobi zone of the piedmont plain, the river water entirely infiltrates the 8–15-km wide subsurface layer. Groundwater flows westward. Seeping belts of groundwater in the basin are mainly controlled by the subsurface sedimentary facies. Because clay layer is a water-resisting layer, the groundwater rises to the surface as spring water in the fine earthy plain east of the lake, where it forms rivers that recharge the lake. The rate of the seeping water in this plain is 35×10^4 m^3 day^{-1}, occupying for 37% of the total water of the Big Harteng River and the Small Harteng River (P.F. Guo et al., unpublished data). Also, the groundwater flow with a rate 36×10^4 m^3 day^{-1} directly recharges Lake Sugan (P.F. Guo et al., unpublished data). Therefore, the inflow of the lake is mostly derived from the groundwater, since the precipitation is so little in the basin. This lake has been closed since the late Pleistocene era based on grain-size data from the Mahai Basin to the south of the Sugan Basin (Liu and Zhang 1992). The Qaidam Basin is one of the main sources of dust storms in China (Qiu et al. 2001; Phillips et al. 1993); therefore, Lake Sugan is an ideal site to investigate the dust storm history under a natural background.

Materials and methods

Several different sediments for grain-size analysis were used to establish a possible linkage between the lake sediments and the dust storm history in the area. These sediments included the lake sediments, the sediments in

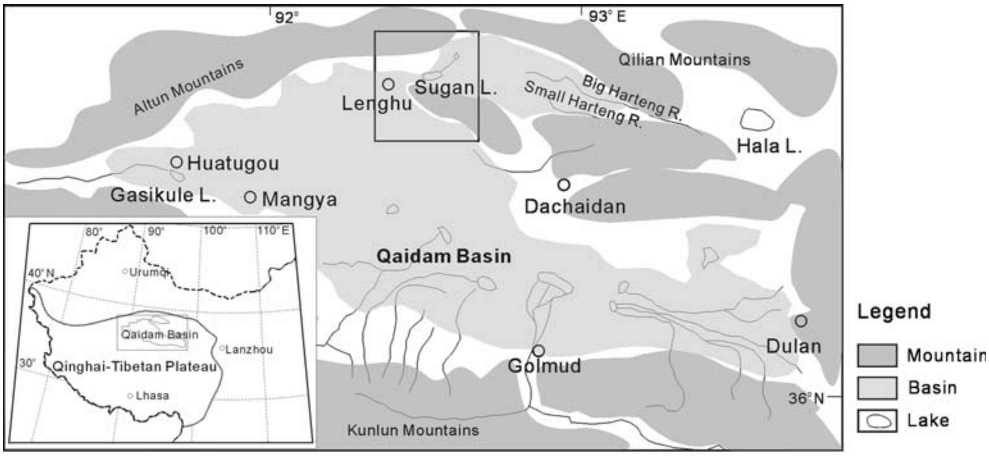

Fig. 1 Location of the study area

the catchment, the eolian materials occulted in the lake ice cover in winter, and the airborne dust collected at the Lenghu Meteorological Station 60 km from Lake Sugan (Fig. 2; Table 1). The samples of the surface lake sediments (L3∼LS, samples labeled L in Table 1) were collected using a GRAB borer on the ice cover in January 2001 (Fig. 2b). Each sample reached a depth of 2–4 cm in the sediments. An ice sample (IS) was also collected because it contained silt and sand particles and thus could offer information about wind conditions during winter. The samples were collected in the catchment at eolian deposits (E1, E3, and E5), at eolian erosion sites (CS2, CS4, and CS6), and in a dry gully (sites CS7 to CS11) south of the lake (Fig. 2a). The CS12 and CS13 samples were collected at the eastern edge of Lake Sugan, close to the mouths of the rivers that feed the lake (Fig. 2a). The dust deposition flux was monitored in the study area at a height of 3.5 m at the Lenghu Meteorological Station , and airborne dust was collected using a columniform aquarium with a diameter of 15 cm and a depth of 30 cm. Airborne dust samples were selected from different seasons for grain-size measurement (Table 1). Two core samples (SG001227-E, SG001227-C) were collected using a Piston corer at Lake Sugan in December 2000. Core SG001227-C is 8.52-m long was drilled very close to the site of core SG001227-01E, which is 0.9-m long. Core SG001227-01E was used for ^{210}Pb and ^{137}Cs dating to determine the modern deposition rate of the lake sediments.

The grain size of the samples were analyzed using a Malvern Mastersizer 2000, which has a measurement range of 0.02–2,000 μm. The samples were pretreated according to the method of Lu and An (1997). The grain-size distribution in core SG001227-C was analyzed at 1-cm intervals. Core SG001227-01E was cut at 1-cm intervals and dried at 110°C. The bulk density of each sample was then calculated. Activities of ^{210}Pb and ^{137}Cs were measured by γ spectrometry. Sediment deposition rates at different levels were obtained according to the "constant rate of supply" (CRS) model (Goldberg 1963).

The numbers of days with dust storms and with strong winds (≥17 m s^{-1}) from 1957 to 2000 (44 years) were obtained from the Lenghu Meteorological Station, respectively. The dust storm and strong wind records were compared with those reconstructed from the lacustrine sediments.

Results and discussion

Variations in grain size and their implications

The mean grain size (*Mz*) values for the lake sediment samples, including one sample (LS) from Small Sugan Lake (about 30 km northeast to Lake Sugan, Fig. 2), ranged from 12.2 to 215.3 μm (Table 1), and averaged 122.3 μm. The mode grain size (most common size) for these samples ranged from 7.2 to 39.6 μm (Table 1), and averaged 11.3 μm. There were three peaks in the curves for grain-size distribution (Fig. 3c, d). The main peak appeared at approximately 10 μm and the other two peaks appeared between 40 and 100 μm and at approximately 1,000 μm, respectively. The fraction between 100 and 1,000 μm was negligible in the lake sediments.

The *Mz* of eolian silt and sand in the IS is 90.4 μm, with a mode of 71.1 μm. The main particle fraction in ice peaked at around 70 μm, with a second peak at a size >1,000 μm (Fig. 3b). The *Mz* values of the samples from the dry gully ranged from 127.6 to 410.9 μm, and averaged 218.1 μm (Table 1). Five of the samples showed a single peak in their size-distribution curves. Sample CS10 showed a broad peak between 10 and 130 μm. The single peak generally appeared between 200 and 1,000 μm, but the sample CS7 had a peak of approximately 90 μm (Fig. 3a). Eolian samples E1, E3, and E5 had similar size-distribution curves (Fig. 3b),

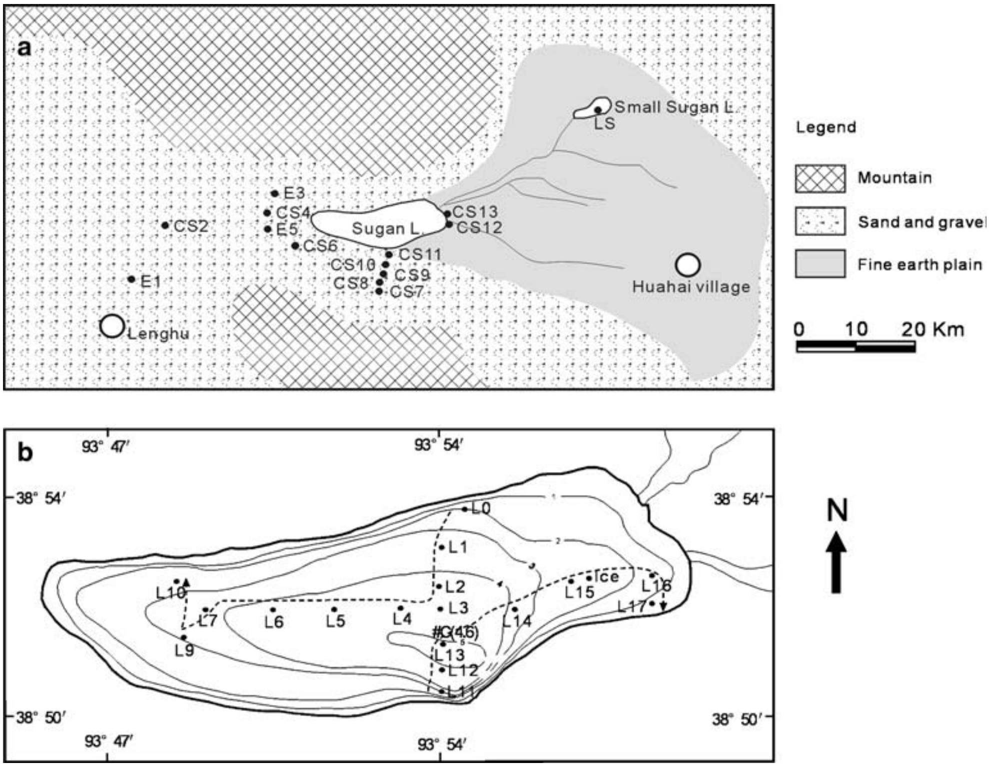

Fig. 2 Distribution of sites where surface samples of **a** the lake catchment and **b** the lake sediments were collected. *Alphanumeric codes* in the figure refer to the samples described in Table 1; *E* and *CS codes* represent samples taken outside the lake; *L codes* represent samples taken within the lake. The symbols *#C* indicate the drilling site where lake sediment cores were collected; *contour lines* represent the water depth (m) in the lake; the *dashed lines with arrows* show the routes we followed while collecting lake sediment samples on the ice cover

and each had a single peak between 100 and 1,000 μm. The *Mz* values of the three samples ranged between 242.2 and 295.6 μm (Table 1). The sites of samples CS12 and CS13 are covered by lake water in the summer, but are exposed to air in winter due to a decrease in the level of the lake. The size-distribution curve for sample CS12 has two peaks, one at around 10 μm and another at >1,000 μm. Sample CS13 has a peak at around 70 μm, similar to that of the IS (Fig. 3b). The CS2, CS4, and CS6 samples mainly contained coarse particles larger than 100 μm. The *Mz* values of these samples ranged from 291.8 to 350.4 μm (Fig. 3b).

Figure 4 shows the grain-size distribution of the two airborne dust samples. The main peak occurs in the range of 100–200 μm, with a weak secondary peak between 10 and 20 μm. The *Mz* value and the mode grain size were 165.6 and 156.4 μm and 154.3 and 151.1 μm, respectively, for samples DF1 and DF2 (Table 1). The magnitude of the 10–20-μm fraction was larger in the DF2 sample, suggesting that the concentration of atmospheric fine-grained dust is higher in spring. The amount of dust during dust storm events is always greater than that under non-storm conditions, and this is based on observations of dust flux at the meteorological station. Only strong winds were able to lift the main grain-size components of the airborne dust (100–200 μm) to the sampling height of 3.5 m. When dust storm events took place in the study area, results suggest that the coarser dust particles must have settled in Lake Sugan.

The differences among the grain-size distributions of the lake surface sediments and the catchment surface deposits indicate that the detrital clastic materials in the lake surface sediments are mainly composed of fine particles, whereas the surface deposits in the catchment are dominated by coarse particles. This suggests that the lake is a location for sedimentation of fine-grained particles produced elsewhere in the basin. The surface of the catchment appears to have undergone considerable erosion, which would account for the lower proportion of fine particles in these samples. This conclusion agrees with previous reports that the surface of the basin suffers from intense eolian erosion (Zhu 1974). The grain-size results from the IS and from the surface lake sediments demonstrate that the 40–100-μm faction might be transported by wind, since these particles represent a negligible fraction of the samples from the surface of the catchment. For example, samples E1, E2, and E3 from eolian deposits lack this component almost entirely. The particles up to about 70 μm in size can be suspended in the air (Wu 1987). On the other hand, the samples from the dry gully (CS8 through CS11) differ dramatically from the L11 and L12 samples collected in the lake near the mouth of the gully (Figs. 2b, 3a, d). There seems to be no input of coarse particles into the lake from the southern basin, even if transient runoff arises due to

Table 1 List of surface samples collected from the Lake Sugan system for grain-size analyses and their corresponding grain-size parameters

Sample no.	Lake depth (m)	Latitude (N), longitude (E)	Mean grain size (μm)	Mode value (μm)	Notes
L0	2.45	38°53.54′, 93°54.26′	110.1	7.3	Surface samples of lacustrine sediment
L1	3.7	38°53.10′, 93°54.00′	153.5	7.3	
L2	4.1	38°52.27′, 93°53.99′	114.7	9.1	
L3	4.5	38°52.00′, 93°54.00′	124.7	8.3	
L4	4	38°52.00′, 93°53.20′	79.2	8.9	
L5	4.5	38°52.00′, 93°51.80′	215.3	15.4	
L6	4	38°52.00′, 93°50.50′	209.5	13.0	
L7	3.3	38°52.00′, 93°49.05′	140.2	8.9	
L9	3.1	38°51.20′, 93°48.40′	109.9	39.6	
L10	3	38°52.39′, 93°48.63′	114.3	10.5	
L11	3.1	38°50.50′, 93°54.00′	59.9	9.8	
L12	3.95	38°50.90′, 93°54.00′	85.3	9.2	
L13	4.5	38°51.40′, 93°54.00′	131.8	9.0	
L14	3.95	38.52.00′, 93°55.30′	12.2	10.4	
L15	3.05	38°52.50′, 93°56.60′	19.7	10.9	
L16	1.4	38°52.50′, 93°58.00′	92.9	7.2	
L17	1.2	38°51.90′, 93°58.00′	111.3	11.5	
LS	0.7	39°03.36′, 94°11.30′	128.3	13.7	
IS		38°52.49′, 93°57.35′	90.4	71.1	Ice sample, including much eolian silt and sand material
E1		38°45.67′, 93°21.26′	253.3	258.6	Eolian sand
E3		38°55.33′, 93°43.87′	295.6	301.1	
E5		38°53.21′, 93°43.42′	242.2	182.3	
CS2		38°49.44′, 93°24.31′	350.4	542.4	Ancient lake shoreline
CS4		38°54.24′, 93°42.99′	305.1	205.6	Sand and gravel land
CS6		38°52.84′, 93°44.96′	291.8	110.9	Bottom of dry lake basin
CS7		38°50.00′, 93°53.78′	127.6	80.4	A dry gully
CS8			193.7	262.4	
CS9			240.0	242.0	
CS10			118.4	201.0	
CS11			410.9	408.2	
CS12		38°51.98′, 93°59.36′	68.7	14.3	Mouth of river
CS13		38°53.94′, 93°58.77′	119.7	77.3	
DF1		38°45′, 93°20′	165.6	156.4	Airborne dust, November 2003–January 2004
DF2			154.3	151.1	Airborne dust, February 2004–April 2004

precipitation in the gully. In fact, there is so little precipitation in the basin that precipitation appears to be incapable of producing enough runoff to carry coarser particles into the lake.

The gully sediments contain few particles > 1,000 μm (Fig. 3a), but the lacustrine sediments contain a small quantity in this size class (generally less than 2%; Fig. 3c, d). There were almost no particles in the > 1,000 μm fraction in the E1, E3, and E5 eolian samples, because the particles in these samples had been well sorted by the wind (Fig. 3b). Although the CS12 and CS13 samples collected at the eastern margin of the lake, where small rivers run into the lake, contain grains > 1,000 μm, this small fraction may not be transported primarily by the rivers that derive from the spring on the silt plain east of the lake. In addition, the rivers cannot transport particles > 1,000 μm to the western part of the lake (e.g., sites L6 and L7), which lies about 20 km from the eastern margin, since no rivers have entered the lake from the western basin during modern times. The lake floor is so flat that turbid current deposits may not arise there. The IS also contains particles > 1,000 μm (Fig. 3b), which seems to exclude the possibility of riverine input. These coarse particles are most likely to be carried by strong winds. Ice cover on the lake lasts from the middle of October until March. During this period, strong winds carry coarse particles onto the ice cover by creeping, especially for particles > 1,000 μm. Because the thermal capacity of these particles is less than that of ice, they heat up and melt the ice beneath them. As a result, the particles become trapped in the ice on sunny days, and then are frozen into the ice at night. When the ice cover melts in spring, the coarse particles drop into the lake and are deposited on its bottom as sediments. This process offers a reasonable explanation as to why coarse grains (> 1,000 μm) appear in the surface sediments of the whole lake.

The sampling sites in Lake Sugan form two profiles: one that runs from west to east, and another that runs from south to north (Fig. 2b). *Mz*, mode grain size, and

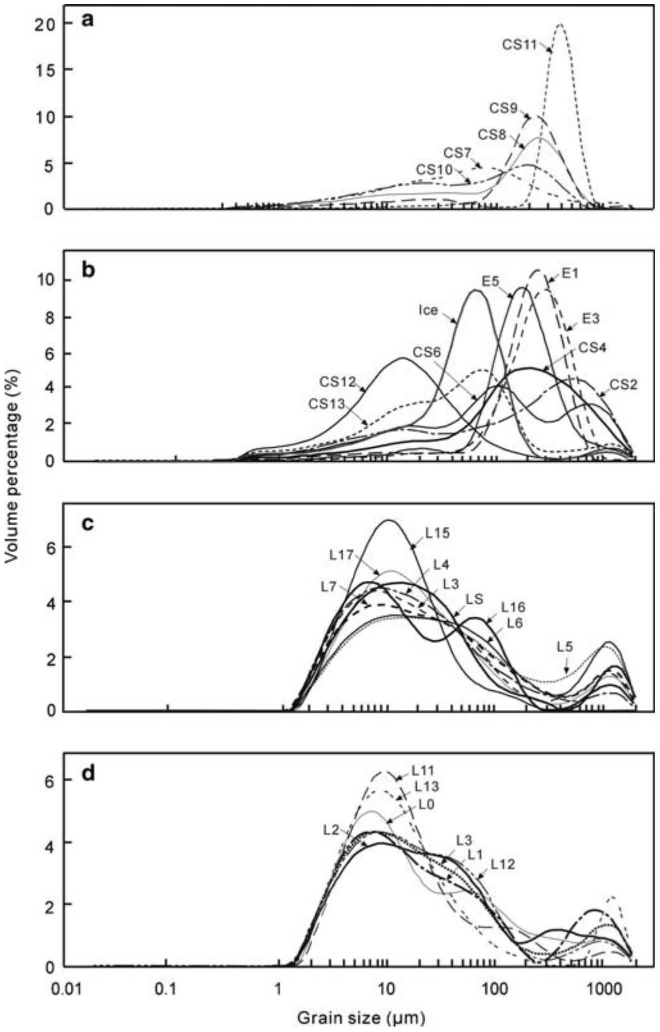

Fig. 3 Frequency distribution curves of grain size for the surface samples collected from **a** a dry gully, **b** the catchment surface and ice, and **c**, **d** the Lake Sugan sediments

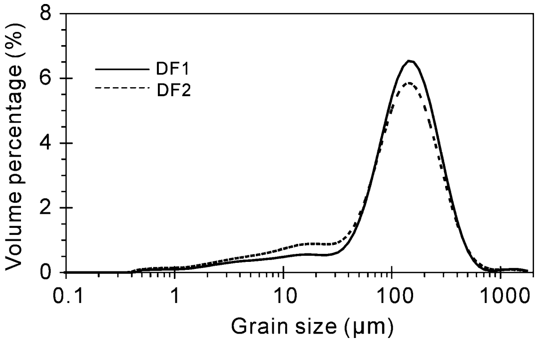

Fig. 4 Grain-size distribution of airborne dust samples collected in from November 2003 to January 2004 (*DF1*) and from February to April 2004 (*DF2*)

the volume percentage of particles > 63 µm in the surface samples moving from the lake's shore to its center along these two profiles were investigated (Fig. 5). In general, if detrital clastic materials are transported mainly by rivers into a closed lake, the particles in the lake sediments should become increasingly fine, moving from the river mouth toward the center of the lake as a result of hydrodynamic sorting (Sun and Li 1986). This does not appear to be the only process at work in Lake Sugan, and particularly not in the western part of the lake. The L7 and L6 sites are closest to the western shore and farthest from the rivers (Fig. 2b), but exhibit higher *Mz* and a higher proportion in the fraction > 63 µm. This suggests that the coarser particles are blown into the lake during dust storms and periods with strong northwest winds. The obvious decrease in *Mz* and the fraction > 63 µm moving from west to east (Fig. 5a–c) is consistent with aerodynamic sorting under the prevalent northwest wind in the study area, and supports the hypothesis about transport of coarse fractions by the wind. The relative higher value of *Mz* and of the > 63 µm fraction in sample L16 may nonetheless result from its location near the eastern shore, where it could be supplied to a limited extent with coarse particles by the rivers that enter the lake at this location (Fig. 2b), or where currents produced by these rivers could transport finer sediments deeper into the lake. The decrease in the fraction > 63 µm moving from L16 to L14 supports the hypothesis that some form of hydrodynamic sorting may occur, assuming that the flow of water from the rivers is not sufficiently strong to transport coarse particles as far as the center of the lake. It may be strong enough to transport finer particles.

Moving from south to north, the fraction > 63 µm increases, indicating that the closer a site is to the northwestern end of the lake, the more abundant the coarse particles are (Fig. 5f). This also supports the hypothesis that aerodynamic sorting dominates in the northwestern end of the lake as a result of the prevailing northwest wind. The mode grain size decreases from south to north and from west to east, respectively (Fig. 5b, e). The modes of the L7 and L6 samples are approximate to the secondary component peak of the airborne dust (Fig. 4), suggesting the possibility of fine-grained particles of the lake sediments inputs by wind. A possible scenario is that cyclones on the several meters scale prevail in the basin in different seasons and may carry fine-grained particles (7–10 µm) into the lake. In fact, the 7–10 µm fraction is the main grain-size component in the lake sediments. However, input of this fraction by rivers at the eastern end of the lake cannot be entirely excluded because these fine-grained particles could be suspended in river water and deposited in the relatively stagnant lake water. Nevertheless, the coarse component of the lake sediments appears to be mainly transported by the wind. Lake Sugan is fed by rivers that derive from groundwater seeping out of the grassland to the east of the lake. They flow slowly and cannot carry large amounts of coarse particles into the lake.

In general, the fraction from 50 to 500 µm could be transported by saltation, and the fraction from 50 to 100 µm can be transported not only by saltation, but also by suspension under strong winds (Holy 1980). In the Sugan Basin, particles 50–100 µm in size might be mainly transported by suspension rather than saltation, because the lake water holds back the saltation of particles in summer. This hypothesis is supported by the fact that the 100–500-µm fraction is negligible in the lake sediments (Fig. 3c, d). The grain-size distribution in the airborne dust suggests that grains > 50 µm could be suspended only if the wind is so strong that a dust storm occurs. In fact, the > 60 µm fraction in lake sediments has been employed to indicate intense eolian activity in the Gulf of Carpentaria in northwestern Australia (De Deckker et al. 1991). Whether the < 50 µm fraction in the lake sediments was transported by rivers or by wind remains uncertain. The high proportion of the 10–20-µm fraction in the lake sediments may indicate an atmospheric dust loading in this arid environment, because this component of the grains is also present in the airborne dust as a smaller, secondary peak (Fig. 4). This hypothesis needs further verification.

As a result of these findings, the coarse particles in the lake sediments can be transported by strong northwest winds under dust storm conditions in the study area. The volume percentage of the > 63 µm fraction in the lake sediments was selected as an indicator of the dust storm events.

^{210}Pb and ^{137}Cs chronology

The specific activities of excess ^{210}Pb and ^{137}Cs in the core sample are shown in Fig. 6a, b. Sediment flux was calculated based on the CRS model described previously (Fig. 6c). The mean sedimentation rate in modern times (since about 1845) is 0.31 cm year^{-1} for Lake Sugan. An age of 155 years BP corresponds to the age of the sample at a depth of 26.5 cm, if the age of the top layer of the core is assumed to be 0. The results for ^{137}Cs show a strong peak in 1963, earlier than the age in that layer estimated based on ^{210}Pb, which is similar to the result for Lake Nanhongshan, near the study area in the West Kunlun Mountains (Zhu et al. 2002). This result may be related to the migration of ^{137}Cs nuclides within the vertical profile (Xiang 1995). However, the ^{137}Cs peak of 1986 is in agreement with the ^{210}Pb dating. Based on these results, the ^{210}Pb ages were used to establish the chronology. The ages of the upper part of core SG001227-01E can then be calculated. The ages match those of the corresponding sections of core SG001227-C, since the two cores were drilled close together.

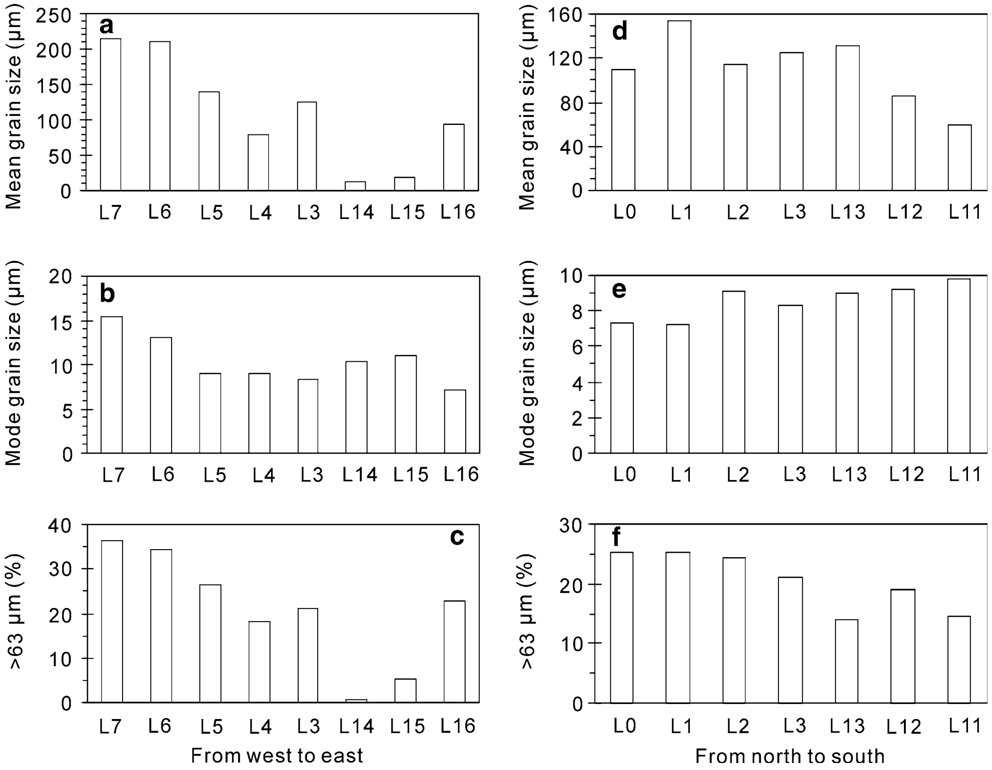

Fig. 5 Variations in mean grain size, mode of grain size, and the > 63 µm fraction in the Lake Sugan surface sediments from west to east (**a**–**c**) and from north to south (**d**–**f**). The sampling sites are presented in Fig. 2b

Comparison of the lake record with observational data on dust storms

According to the ^{210}Pb chronology for core SG001227-C and the coarse fraction data in the lake sediments, the volume percentage of the fraction > 63 μm was selected as an indicator of dust storm events and the dust storm sequence was reconstructed over the past 44 years. Figure 7a shows that the frequency or intensity of dust storm events revealed in the lake record have been increasing over the past 44 years. This is in agreement with the observational data from the Lenghu Meteorological Station (Fig. 7b, c). Although the resolution of the lake record was lower than that of the observational record, the lake record still demonstrates a higher frequency or intensity of dust storms during the late 1980s and the 1990s. The frequency of dust storms in the 1950s averaged about 5 days per year in North China, but increased to 23 days per year during the 1990s (Hu et al. 1999), supporting the dust storm history reconstructed from the lake sediments.

The study area is one of the hyperarid regions of China, where there is no agricultural activity due to the very low amount of rainfall and insufficient vegetation for local people. Most of the area is covered by gobi, by sand and gravel deserts, and by playas. The negligible human activity could not have changed the structure of the basin surface sufficiently to produce more dust emissions. The increase in the frequency or intensity of dust storm events over the past 44 years contradicts previous suggestions that intensified human activity was important in the increase in dust storm events during the past several decades in other regions of China (Hu et al. 1999). Results here suggest that the increase in dust storm events in the study area may have resulted from climate change, such as the changes in atmospheric circulation related to the global warming that appear to have begun during the last half of the 20th century.

Conclusions

Through investigations of the grain-size distribution in samples collected at different sites in the Sugan Basin, the volume percentage of the fraction > 63 μm was chosen in lake sediments as an indicator of dust storm events at the northern margin of the Qinghai–Tibetan Plateau. The increasing frequency or magnitude of the reconstructed sequence of dust storm events is similar to the observational sequence recorded over the past 44 years at the Lenghu Meteorological Station. The strong winds in the study area provide effective dynamic conditions for generating dust storms. The wide distribution of fine-grained material (e.g., silts) in the region also encourages the development of dust storms. Climate change may

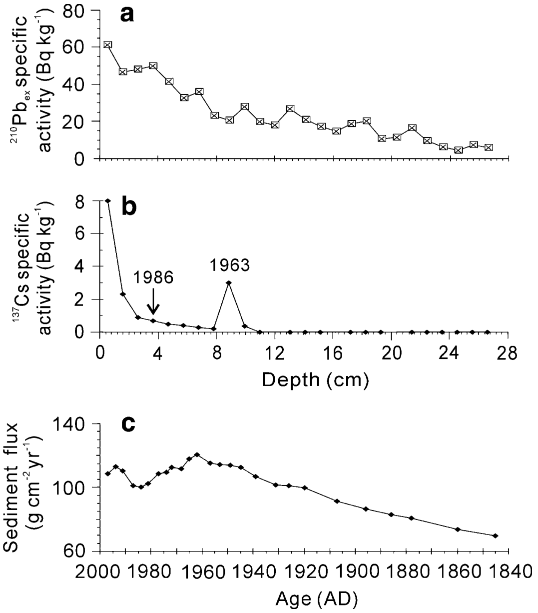

Fig. 6 Results of ^{210}Pb and ^{137}Cs analyses: the specific activities of **a** excess ^{210}Pb and **b** ^{137}Cs, and **c** the sediment flux (g cm^{-2} year^{-1}) in the uppermost part of the SG001227-01E core (over the past 155 years) calculated based on the CRS model

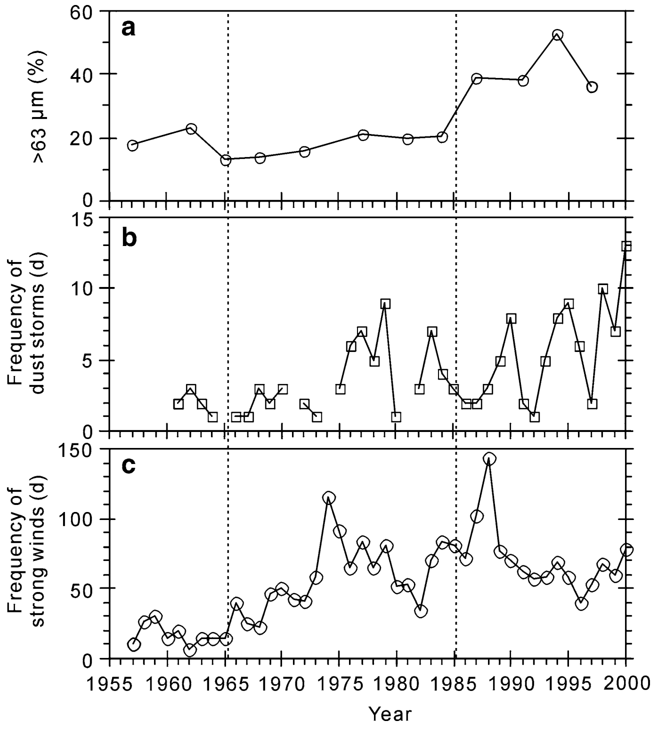

Fig. 7 Comparison of the volume percentage of the fraction > 63 μm in the lake sediments (**a**) with the annual number of days with dust storms (**b**) and numbers of days with strong winds (≥17 m s^{-1}) (**c**) observed at the Lenghu Meteorological Station over the past 44 years

have had an important impact on the observed variations in dust storm frequency and intensity.

The work suggests that further study of dust storm histories based on the analysis of lake sediments should prove productive, especially for periods during which observational data are unavailable. Further work still needs to be carried out to improve the usefulness of this technique. Measurement of elemental compositions of various rare earth elements in samples from lake sediments, surface deposits in the catchment, and airborne dust is planed to trace more precisely the source of the lake sediments. In addition, magnetic parameters of these materials will be measured, such as the magnetic susceptibility and the saturation isothermal remnant magnetism. The results will help identify whether magnetic minerals could have been transported into the lake by winds, and if so, the usefulness of these parameters in reconstructing the dust storm history. Furthermore, the eolian dust deposited under non-dust storm conditions will be collected to improve understanding of the environmental implications of the fine fraction (10–20 μm) of the lake sediments in this study.

Acknowledgments The authors thank Dr. Chengjun Zhang, Mr. Jinbao Li, Fei Meng, Zhiguo Rao, and Lianjiang He from Lanzhou University for their assistance in the fieldwork, and Ms. Kailan Zhang and Mr. Ling Wang for laboratory assistance. The ^{210}Pb and ^{137}Cs dates were measured at the Nanjing Institute of Limnology and Geography Research, Chinese Academy of Sciences. A special thanks is also due to Mr. Weilan Xia for his instructions on how to process the ^{210}Pb and ^{137}Cs data. This research was supported by the National Science Foundation of China (grants 40301051 and 40421101) and the China Postdoctoral Science Foundation (grant 2003034109).

References

An ZS, Xiao JL (1990) A case study on influx of aeolian dust on Loess Plateau in China (in Chinese). Chin Sci Bull 35:220–223

Bory AJ-M, Biscaye PE, Svensson A, Grousset FE (2002) Seasonal variability in the origin of recent atmospheric mineral dust at NorthGRIP, Greenland. Earth Planet Sci Lett 196:123–134

Dean WE (1997) Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: evidence from varved lake sediments. Geology 25(4):331–334

De Baar HJW, De Jong JTM, Bakker DCE, Löscher BM, Veth C, Bathmann U, Smetacek V (1995) Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. Nature 373:412–415

De Deckker P, Correge T, Head J (1991) Late Pleistocene record of cyclic eolian activity from tropical Australia suggesting the Younger Dryas is not an unusual climatic event. Geology 19:602–605

Fang XM, Han YX, Ma JH, Song LC, Yang SL, Zhang XY (2004) Characteristics of dust weather and loess deposition in the Qinghai–Tibetan Plateau: a case study on the process of dust events on March 4, 2003 (in Chinese). Chin Sci Bull 49(11):1084–1090

Goldberg ED (1963) Geochronology with 210Pb. In: Radioactive dating. IAEA, Vienna, pp. 121–131

Holy M (1980) Erosion intensity and predictions. World Desert Res 2:12–62

Hovan SA, Rea DK, Pisias NG, Shackleton NJ (1989) A direct link between the China loess and marine δ18O records: aeolian flux to the north Pacific. Nature 340:296–298

Hu JM, Cui HT, Tang ZR (1999) The temporal and spatial characteristics of dust storm in China and the impacts on developmental trend from human activities (in Chinese). J Nat Disasters 8(4):49–56

Jin ZD, Wang SM, Shen J, Zhang EL, Wang J, Chen Y, Chen ST (2000) The about 400 years dust storm events: evidence from grain size of sediments of Daihai Lake in China (in Chinese). J Lake Sci 12(3):193–197

Kumar N, Anderson RF, Mortlock RA, Froelich PN, Kubik P, Dittrich-Hannen S, Suter M (1995) Increased biological productivity and export production in the glacial Southern Ocean. Nature 378:675–680

Liu SQ, Zhang FS (1992) Sedimentation environment and salinization in the Mahai basin in the Qaidam Basin of China (in Chinese). Geology Press, Beijing, pp. 12–14

Lu HY, An ZS (1997) An experimental study on the impacts on measurement of the grain size of loess sediment from pretreatment (in Chinese). Chin Sci Bull 42(23):96–101

Moreno A, Targarona J, Henderriks J, Canals M, Freudenthal T, Meggers H (2001) Orbital forcing of dust supply to the North Canary Basin over the last 250 kyr. Quaternary Sci Rev 20:1327–1339

O'Brien SR, Mayewski LD, Meeker DA, Meese DA, Twickler MS, Whitlow SI (1995) Complexity of Holocene climate as reconstructed from a Greenland ice core. Science 270:1962–1964

Petit JR, Mounier L, Jouzel J, Korotkevich YS, Kotlyakov VL, Lorius C (1990) Palaeoclimatological and chronological implications of the Vostok core dust record. Nature 343:56–58

Phillips FM, Zreda MG, Ku TL, Luo SD, Huang Q, Elmore D, Kubik PW, Sharma P (1993) ^{230}Th/^{234}U and ^{36}Cl dating of evaporite deposits from western Qaidam Basin, China: implications for glacial-period dust export from Central Asia. Geol Soc Am Bull 105:1606–1616

Qiu XF, Zeng Y, Miao QL (2001) Temporal and spatial distribution, sources and movement paths of the sand storms in China (in Chinese). Acta Geogr Sin 56(13):316–322

Rea DK, Leinen M (1988) Asian aridity and the zonal westerlies: late Pleistocene and Holocene records of eolian deposition in the northwest Pacific Ocean. Palaeogeogr Palaeoclimatol Palaeoecol 66:1–8

Sun YC, Li HS (1986) Clastic rock sedimentary facies and sedimentary environment (in Chinese). Geological Press of China, Beijing, pp. 65–81

Sun QL, Zhou J, Xiao JL (2000) Grain size characteristics of lake sediments and its palaeoenvironmental implications in Daihai Lake of China (in Chinese). Mar Geol Quaternary Geol 21(1):93–95

Wang HY, Liu HY, Cui HT, Abrahamsen N (2001) Terminal Pleistocene/Holocene palaeoenvironmental changes revealed by mineral-magnetism measurements of lake sediments for Dali Nor area, Southeastern Inner Mongolia Plateau, China. Palaeogegr Palaeoclimatol Palaeoecol 170:115–132

Wu Z (1987) Aeolian geomorphology (in Chinese). Science Press, Beijing, pp. 39–44

Xiang L (1995) Limitations in application of 137Cs chronology to lacustrine sediments: a case study on Lake Crawford (in Chinese). J Lake Sci 7(4):307–313

Xiao JL, Inouchi Y, Kumai H, Yoshikawa S, Kondo Y, Liu TS, An ZS (1997) Eolian quartz flux to Lake Biwa, Central Japan, over the past 145,000 years. Quaternary Res 48:48–57

Xiao JL, An ZS, Liu DS, Inouchi Y, Kumai H, Yoshikawa S, Kondo Y (1999) East Asian monsoon variation during the last 130,000 years: evidence from the Loess Plateau of central China and Lake Biwa of Japan. Quaternary Sci Rev 18:147–157

Yung LY, Lee T, Wang CH, Shieh YT (1996) Dust: a diagnostic of the hydrologic cycle during the last glacial maximum. Science 271:962–963

Zhang DE (1983) Analysis of dust rain in the historic times of China. Chin Sci Bull 28:361–366

Zhang DE (1984) Synoptic-climatic studies of dust fall in China since historic times. Sci Sin B 27(8):825–836

Zhang XY (2001) The source distribution, release, transportation and sedimentation of Asia dust and loess deposition (in Chinese). Quaternary Sci 21(1):29–40

Zhu ZD (1974) Conspectus of deserts in China. Science Press, Beijing, pp. 7–9

Zhu LP, Chen L, Li BY, Li YF, Xia WL, Li JG (2002) Environmental changes reflected by the lake sediments of the South Hongshan Lake in Northwest Tibet. Sci China D 45(5):430–439