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Testing the model for linking grain-size component to lake level status of modern clastic lakes

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A B S T R A C T

A model was proposed recently for linking grain-size component to lake level status based on investigations of Daihai Lake in Inner Mongolia. To test this model, grain-size components of the surface sediments of Dali Lake, 500 km northeast of Daihai Lake, were partitioned and their relationships with the lake level status were examined in this study. The data show that modern clastic sediments of Dali Lake contain five distinct grain-size components representing specific depositional processes and sedimentary environments within the lake in common with Daihai Lake. These components are specified as long-term suspension clay, offshore-suspension fine silt, offshore-suspension medium-to-coarse silt, nearshore-suspension fine sand and nearshore-saltation medium sand. In Dali Lake, by contrast, the offshore-suspension components are lacking in more samples from the nearshore zone; the nearshore-suspension and saltation components occur in more samples from the offshore and transitional zone, respectively; and two adjacent components are well separated. These differences would result from higher-energy hydraulics of Dali Lake generated by stronger and more frequent winds occurring in the lake region. Under this hydraulic condition, clastic materials entering the lake and the resultant components would be reworked more seriously during transportation within the lake, leading to further basin-ward transportations of the major components and better separations of two adjacent components. Percentage of the nearshore components is negatively related to water depth, suggesting the grain-size component–lake level status model for the lake. This model was applied to a sediment core from the lake, showing that high percentages of the nearshore components in the core coincide with low precipitations reconstructed on the pollen profile of the same core. The coincidence of two independent proxies demonstrates the wide applicability of the grain-size component–lake level status model to lake's paleohydrological reconstruction.

1. Introduction

It has long been recognized that the grain-size distribution of clastic deposits in lakes may provide an important source of information on changes in the hydrology of lakes associated with regional climatic variations (Friedman and Sanders, 1978; Lerman, 1978; Håkanson and Jansson, 1983; Talbot and Allen, 1996). For specific lakes, however, the conventional grain-size parameters (e.g., modal, mean and median size, skewness, and kurtosis) obtained for the sediment cores do not act as well as expected in reconstructing the history of past changes in the hydrology and climate of lake regions. The reason for this lies in the inherent complexity of polymodal grain-size distributions of lake sediments. In brief, different individual distributions of lake sediments may not only differ in the number of modes but also in the attribute of the major mode. Such inherent complexity implies that different modes within an individual polymodal grain-size distribution of lake sediments might be formed in different sedimentary environments by specific depositional processes (Xiao et al., 2013).

It was suggested that the grain-size distribution of clastic deposits with a single mode (i.e., a single component) should assume a unimodal, symmetric distribution on a logarithmic scale, and that a polymodal grain-size distribution can be considered to be a combination of two or more unimodal distributions that represent two or more components (Inman, 1949; Folk and Ward, 1957; Tanner, 1964; Visher, 1969; Ashley, 1978). In addition, the grain-size distribution of unimodal deposits follows the normal distribution on a logarithmic scale (Krumbein, 1938). With respect to polymodal

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deposits comprising two or more unimodal components, each of the constituent components can be described with sufficient accuracy by the lognormal distribution function (Ashley, 1978; Påsse, 1997; Qin et al., 2005). Based on these observations, Xiao et al. (2013) recently applied the lognormal distribution function to quantitatively fitting and partitioning the grain-size components within individual distributions of the surface sediments of Daihai Lake, a modern clastic lake in Inner Mongolia, identified five distinct grain-size components from the modern clastic sediments, and further proposed a numerical model for linking the nearshore components in the lake sediments to the status of lake levels. The potential value of this model was demonstrated by the coincidences between high percentages of the nearshore components in a sediment core of the lake and low regional precipitations reconstructed on the pollen profile of the same core.

In order to examine the validity of both the numerical model and the five grain-size components proposed by Xiao et al. (2013) for lakes in different areas, we investigate the grain-size components in the surface sediments of Dali Lake in this study. Dali Lake, a modern clastic lake in Inner Mongolia, is located about 500 km northeast of Daihai Lake. It differs from Daihai Lake both in the geology, geomorphology and topographic relief of lake basins and in the regional wind regime despite the similarities in lake morphology and regional precipitation. Studies on the grain-size components of modern clastic sediments of Dali Lake would therefore improve our understanding of the genesis of grain-size components of clastic deposits in lakes and verify the wide applicability of the grain-size component–lake level status model to the paleohydrological reconstruction of different lakes.

2. Study lake

Dali Lake (43°13′–43°23′ N, 116°29′–116°45′ E), a hydrologically closed lake, lies 70 km west of Hexigten Banner, Inner Mongolia (Fig. 1) and sits in an inland fault-depression basin that was formed in the Pliocene to Pleistocene (Li, 1993). It has an area of 238 km^2, a maximum water depth of 11 m, and an elevation of 1226 m above sea level. The lake is located at the northern margin of the E–W trending Hulandaga Desert Land. Hills of basaltic rocks surround the lake on the north and west, and lacustrine plains are present along the eastern shore of the lake. Two permanent rivers from the northeast and two intermittent streams from the southwest enter the lake, but no rivers drain the lake (Fig. 1).

Dali Lake is situated at the transition from semi-humid to semi-arid areas of the middle temperate zone. The climate of the lake region is under the control of the East Asian monsoon (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). In the lake region, mean annual temperature is 3.2 °C with a July average of 20.4 °C and a January average of −16.6 °C. Mean annual precipitation is 383 mm, and ~70% of the annual precipitation falls in June to August. Mean annual evaporation reaches 1632 mm, which is ca. 4 times the annual precipitation. The lake is covered with ice from November to April.

3. Material and methods

3.1. Sediment sampling

The surface sediments of Dali Lake were sampled along the Transects a, b and c, yielding 11 samples for Transect a, 13 samples

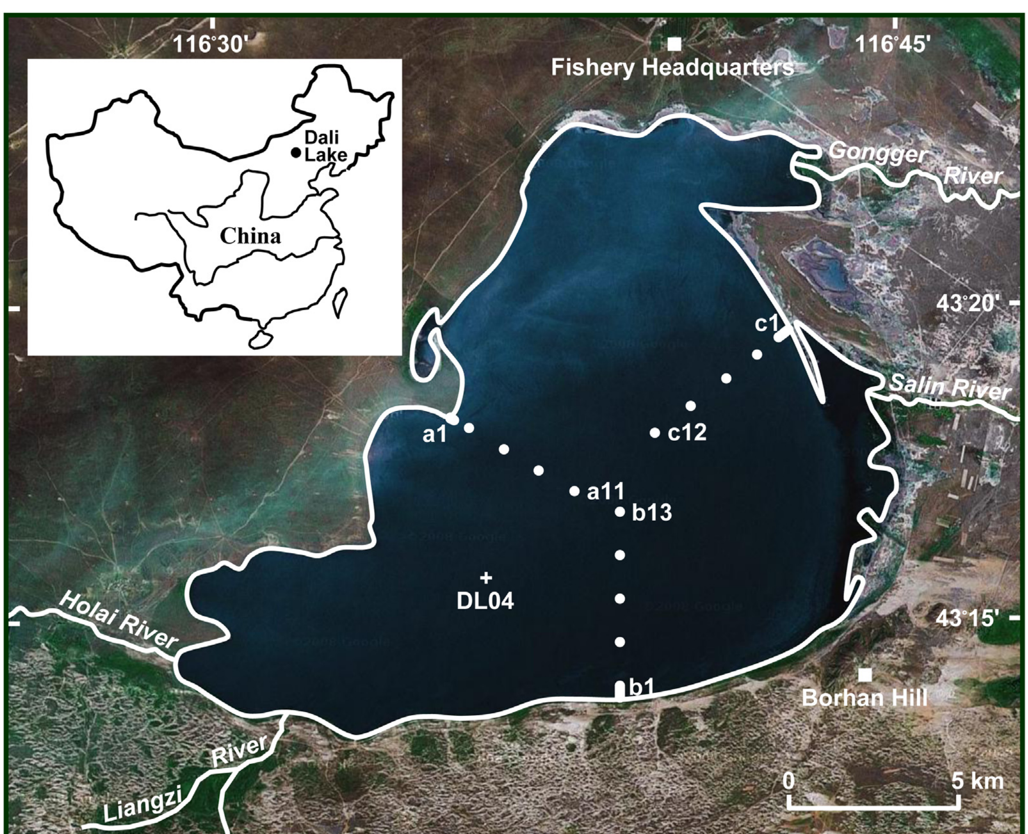

Fig. 1. Map of Dali Lake (from http://maps.google.com) showing locations of the surface-sediment sampling sites along the Transects a, b and c. The coring site of the DL04 sediment core (cross) discussed in the text is shown. The inset gives a sketch map of China showing the location of Dali Lake.

for Transect b and 12 samples for Transect c (Figs. 1 and 2; Table 1). Transects start at a1 (43°18.460′ N, 116°34.747′ E), b1 (43°13.999′ N, 116°39.394′ E) and c1 (43°19.758′ N, 116°42.864′ E) on the lakeshore, respectively, and end at a11 (43°17.060′ N, 116°38.068′ E), b13 (43°16.796′ N, 116°39.014′ E) and c12 (43°18.004′ N, 116°39.849′ E) in the lake center. At each site, a sediment core was extracted in either a 40- or 60-cm long polyethylene tube using a gravity corer. The water–sediment interface and mm-scale thick whitish-gray deposits on the sediment top are clearly discernible in the core tube. The top 1 cm of each core section was cut for a sample of the surface sediments after siphoning the water out of the core tube with a plastic pipe. The water depth and offshore distance of each sampling site were measured at the time of extraction (Figs. 1 and 2; Table 1).

Where n is the number of modes, $x = \ln(d)$, d is the grain size in μm. a_i is the mean value of the ith mode's logarithmized grain size in μm, i.e., $a_i = \ln(d_i)$, and $a_i > 0$. c_i is the percentage of the ith mode, $c_i \geq 0$, and the sum of n c_i equals 100%. σ_i is the standard deviation of the ith mode.

The fitting residual is calculated as follows,

$$dF = \frac{1}{m}\sum_{j=1}^{m}\left(F(x_j) - G(x_j)\right)^2$$

Where m is the number of grain-size intervals. $G(x_j)$ is the measured percentage of the jth grain-size interval. $F(x_j)$ is the fitted percentage of the jth grain-size interval. A lower value of dF indicates a better fitting result.

Table 1
Water depth and offshore distance of 36 surface-sediment sampling sites along the Transects a, b and c in Dali Lake (measurements taken in June 2010).

Sample number	Water depth (m)	Offshore distance (km)	Sample number	Water depth (m)	Offshore distance (km)	Sample number	Water depth (m)	Offshore distance (km)
a1	0.6	0.03	b1	0.5	0.01	c1	0.5	0.03
a2	1.2	0.11	b2	1.0	0.08	c2	1.1	0.11
a3	2.1	0.13	b3	2.1	0.09	c3	2.0	0.18
a4	3.2	0.14	b4	3.0	0.10	c4	2.9	0.26
a5	4.1	0.16	b5	4.0	0.11	c5	4.0	0.30
a6	5.0	0.18	b6	5.0	0.12	c6	5.0	0.32
a7	6.0	0.24	b7	6.1	0.13	c7	5.9	0.35
a8	7.0	0.84	b8	7.0	0.14	c8	7.0	0.39
a9	8.0	2.33	b9	8.1	0.20	c9	8.0	1.17
a10	8.2	3.43	b10	8.5	1.46	c10	8.1	2.52
a11	9.2	4.96	b11	8.6	2.71	c11	8.5	3.91
			b12	8.6	4.07	c12	8.5	5.26
			b13	9.0	5.22			

3.2. Grain-size analysis

Grain-size distribution of all the samples was determined with a Malvern Mastersizer 2000 laser grain-size analyzer. About 200 mg of sediment from each air-dried, disaggregated sample was pretreated with 10–20 ml of 30% H_2O_2 to remove organic matter and then with 10 ml of 10% HCl with the sample solution boiled to remove carbonates. About 2000 ml of deionized water was added, and the sample solution was kept for 24 h to rinse acidic ions. The sample residue was dispersed with 10 ml of 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min before grain-size analysis.

The Mastersizer 2000 has a measurement range of 0.02–2000 μm in grain diameter and a grain-size resolution of 0.166 ϕ in interval ($\phi = -\log_2(D)$, where D is the grain diameter in mm), thus yielding 100 grain-size fractions. The Mastersizer provides the percentage by volume of each grain-size fraction in a sample. The relative error is less than 1% on the 50th percentile and 2% on the outlying percentiles.

3.3. Partitioning of grain-size components

The lognormal distribution function described by Qin et al. (2005) was applied in this study to identify, fit and partition the grain-size components of the surface sediments of Dali Lake. The formula of the lognormal distribution function is expressed as follows,

$$F(x) = \sum_{i=1}^{n}\left[\frac{c_i}{\sigma_i\sqrt{2\pi}}\int_{-\infty}^{\infty}\exp\left(-\frac{(x-a_i)^2}{2\sigma_i^2}\right)dx\right]$$

Fitting experiments begin by assuming the number of modes, n, of the measured polymodal distribution. n is determined by identifying the number of peaks on the measured distribution curve and the skewness of each peak. Each mode of a measured polymodal distribution is described by three parameters (a, c, σ), and a combination of the three parameters of n modes describes the measured polymodal distribution. A program using Visual Basic for applications on a PC Office platform was utilized to perform fitting calculations. For details of the procedure, see Xiao et al. (2013).

Fitting experiments on a sample are accomplished when the residual reaches its minimum, and the combination of the three parameters of n modes with the minimum fitting residual is chosen to represent the measured polymodal distribution. Numerical partitioning of the unimodal components of a measured polymodal distribution can be achieved simultaneously through the fitting because the parameters and distribution functions of each component are determined in the course of fitting. The curves of all the components of a sample and the modal size and percentage of each component are automatically output by the program. The modal size of the ith mode is calculated as follows,

$$\overline{d}_i = \exp(a_i)$$

The modal size of each component is equivalent in value to the mean and median sizes because all the components assume a normal distribution on a logarithmic scale of grain size in μm.

It is necessary to point out that two modes need to be designated for one skewed peak when assuming the number of modes (n) of the measured polymodal distribution. Nevertheless to separate out two strongly overlapped components requires technical skills through trial-and-error fittings after careful observations. In this case, fortunately, the fitting residual increases significantly if the minor component of a skewed mode is ignored.

4. Results

4.1. Identification of the grain-size components

The fitting and partitioning performed with the lognormal distribution function suggest that each polymodal grain-size distribution of the surface-sediment samples taken from Dali Lake consists of a minimum of three to a maximum of five unimodal distributions. These unimodal distributions can be identified as five distinct modes according to the range of modal sizes of each unimodal distribution and the relationship between two adjacent unimodal distributions although the polymodal distributions of different samples may differ both in the number of modes and in the attribute of the major mode. The five modes that represent five grain-size components, respectively, are designated C1 through C5 from fine to coarse modes (Fig. 3).

Three surface-sediment samples of Dali Lake were selected from Transect a to illustrate identifying, fitting and partitioning of grain-size components within an individual polymodal distribution with the lognormal distribution function (Fig. 3). The three samples represent the modern sediments deposited in three different environments of the nearshore zone (sample a3; major mode: C4), transitional zone (sample a7; major mode: C4) and the offshore zone (sample a11; major mode: C2) of the lake (Figs. 1 and 2). The fitting and partitioning result and the minimum residual of each sample are shown (Fig. 3).

It is worthwhile to note that two modes need to be designated for two strongly overlapped components (for instance, C4 and C5 in sample a3, C3 and C2 in sample a7, and C2 and C3 in sample a11; Fig. 3) in order to minimize the fitting residual of the sample. Only when the minor component (C5 in sample a3, C2 in sample a7, and C3 in sample a11; Fig. 3) is considered, can the fitting residual of the sample reach its minimum. This demonstrates the accuracy of the lognormal distribution function in fitting and partitioning the grain-size components of polymodal clastic deposits.

4.2. Characteristics of the grain-size components

The fitting and partitioning of all the 36 samples indicate that the grain-size components C1, C2, C3, C4, and C5 identified from the modern clastic sediments of Dali Lake have their own identifiable characteristics (Figs. 4 and 5; Table 2). The modal sizes of Components C1, C2, C3, C4 and C5 vary within ranges of 0.7–1.6, 1.9–8.8, 10.5–53.0, 68.2–157.7 and 203.0–514.7 μm, respectively. As shown in Fig. 4 and Table 2, the modal sizes of two adjacent components are separated completely from each other. The percentages of Components C1, C2, C3, C4 and C5 in the relevant samples vary within ranges of 0.3–10.3%, 1.0–77.5%, 1.0–68.5%, 5.5–100% and 0.8–100%, respectively. C2, C3, C4, and C5 all display two dominant ranges of the percentages with C2 and C3 showing the lower-percentage range in the majority of the samples and C4 and C5 showing the lower- and higher-percentage ranges in the nearly equivalent number of the relevant samples (Fig. 5). The fitting residual is less than 5.3% with an average of 3.1% for 11 samples from Transect a, less than 8.2% with an average of 4.6% for 13 samples from Transect b, and less than 8.2% with an average of 4.9% for 12 samples from Transect c.

Table 2
Characteristics of the five grain-size components recognized on the polymodal distributions of 36 surface-sediment samples of Dali Lake.

Component	Number of samples	Modal size (μm)		Percentage (%)		Component description
		Min.	Max.	Min.	Max.	
C1	28	0.7	1.6	0.3	10.3	Long-term suspension
C2	32	1.9	8.8	1.0	77.5	Offshore suspension
C3	29	10.5	53.0	1.0	68.5	Offshore suspension
C4	25	68.2	157.7	5.5	100.0	Nearshore suspension
C5	17	203.0	514.7	0.8	100.0	Nearshore saltation

4.3. Distribution of the grain-size components

The statistics of the grain-size components C1, C2, C3, C4 and C5 among all the 36 surface-sediment samples of Dali Lake show that C1, C2 and C3 exist in 28, 32 and 29 samples, respectively, while C4 and C5 occur in 25 and 17 samples, respectively (Table 2).

Among all the sampling sites, the water depth varies from 0.5 to 9.2 m, and the offshore distance ranges from 0.01 to 5.26 km (Figs. 1 and 2; Table 1). The spatial distribution of the 36 samples across the lakebed indicates the overall features about the within-lake distribution of C1, C2, C3, C4, and C5. These are as follows:

(1) C1 exists in the samples that are distributed within the whole lake. Both the modal size and the percentage of C1 remain largely unchanged across the lakebed.
(2) C2 is absent in the samples that are mainly distributed in the nearshore zone of <1.0-m water depth and <0.08-km offshore distance. In the samples in which C2 occurs, it displays much higher percentages in those from the offshore zone than in those from the nearshore and transitional zone, but does not show any trend of changes in the modal size.
(3) C3 is absent in the samples that are mainly distributed in the nearshore zone of <2.9-m water depth and <0.26-km offshore distance. In the samples in which C3 occurs, it not only displays much higher percentages in those from the offshore zone than in those from the nearshore and transitional zone, but also shows a general trend of increases in the modal size from the nearshore zone towards the lake center.
(4) C4 occurs in 25 samples that are distributed within the whole lake. From the nearshore to the offshore zone, C4 decreases in the percentage and slightly in the modal size.
(5) C5 occurs only in 17 samples that are mainly distributed in the nearshore and transitional zone of <7.0-m water depth and <0.84-km offshore distance. From the nearshore to the transitional zone, C5 displays significant decreases in the percentage, but does not show any trend of changes in the modal size.

5. Discussion

5.1. Interpretation of the grain-size components

Dali Lake is located at the transition from semi-humid to semi-arid areas of the middle temperate zone. Meteorological observations suggest that the climate of the lake region is under the control of the East Asian monsoon (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). During the summers, the summer monsoon from the low-latitude Pacific Ocean produces rainstorms and most of the annual precipitation for the region; whereas during the

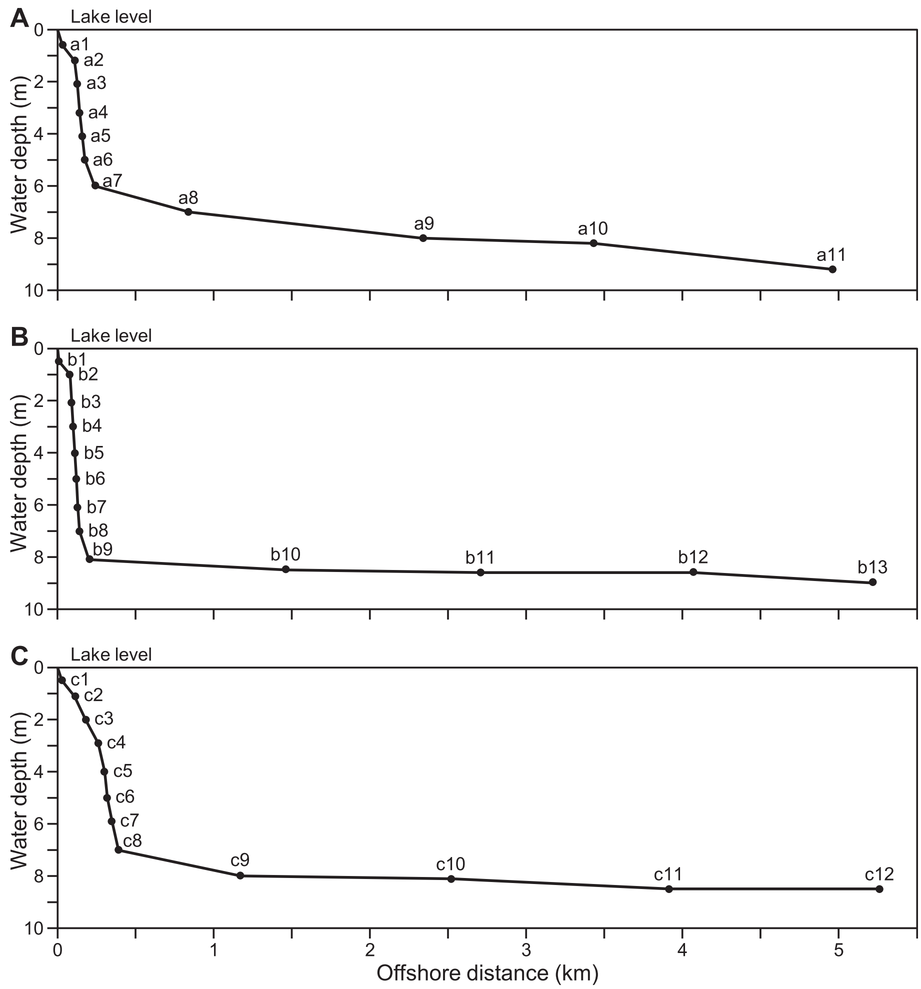

Fig. 2. Profile of the lake floor along the Transects a, b and c showing the sampling sites. (A) Transect a, (B) Transect b, (C) Transect c. The vertical axis indicates water depth, and the horizontal axis indicates offshore distance to the closer lakeshore.

winters, the winter monsoon from the high-latitude Siberian High brings strong winds and dust storms to the region. In view of the geographic location and the basin structure, we infer that clastic deposits in Dali Lake would be derived mainly from fluvial materials transported by the rivers during the summer and autumn season and from eolian dust blown by the winds during the winter and spring season. In addition, shoreline materials eroded by the storm-driven waves could also contribute to the accumulation of clastic deposits in the lake.

Previous studies suggested that the three types of clastic deposits assume different combinations of specific grain-size components due to the difference in their transporting mechanisms (Visher, 1969; Middleton, 1976; Ashley, 1978; Pye, 1987). Fluvial deposits consist of a major saltation medium-sand component (modal size: 200–400 μm) and a minor suspension fine–silt component (modal size: 10–15 μm) (Bennett and Best, 1995; Kranck et al., 1996; Påsse, 1997). Typical loess deposits are composed of a major short-suspension medium-to-coarse-silt component (modal size: 16–32 μm) and a minor long-suspension clay-to-fine-silt component (modal size: 2–6 μm); whereas desert sands are composed of a major saltation fine-to-medium-sand component (modal size: 100–200 μm) and a minor suspension clay-to-fine-silt component (modal size: 2–6 μm) (Pye, 1987; Tsoar and Pye, 1987; Sun et al., 2002). Lake shoreline materials are dominated by unconsolidated sands with a low proportion of silty clay (Sly, 1989a,b). Clastic materials entering the lake through the three kinds of transporting mechanisms all would have been reworked and sorted within the lake by the hydraulic dynamics of lake waters before being deposited on the lake floor (Lerman, 1978; Håkanson and Jansson, 1983; Talbot and Allen, 1996; Xiao et al., 2013). Such that these three types of clastic materials might have been mixed and all the original grain-size components might have been transformed during transportation within the lake (Xiao et al., 2013). It was due to the reworking and sorting by the hydraulic dynamics of lake waters that the bimodality of the three types of clastic deposits was altered, and the polymodality was finally generated for lake sediments. In other words, the strong polymodality of lake sediments would be originated from the attribute of the hydraulic mechanism of a lake that is closely associated with the orientation, shape and size of the lake.

A large lake can be separated into high-energy and low-energy regimes in terms of the fundamental relationship between the interactions of clastic particles and lake waters within the lake (Lerman, 1978; Sly, 1989a, 1989b). In general, the shallow water of the nearshore zone possesses higher hydraulic energy than the deep water of the offshore zone, and the clastic deposits in the lake become coarser with higher hydraulic energy. Based on the spatial distribution of each grain-size component across the lakebed, we interpret Components C1, C2, C3, C4 and C5 in the modern clastic sediments of Dali Lake as representing specific sedimentary

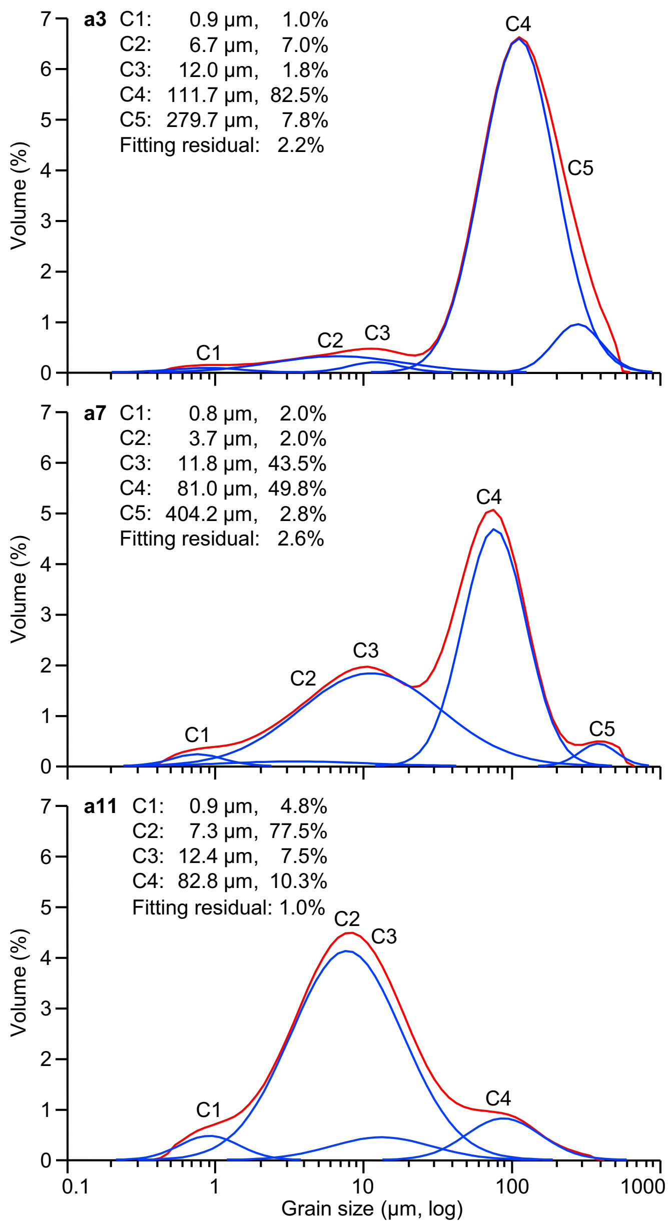

Fig. 3. Frequency distribution curves (red lines) of three representative surface-sediment samples a3, a7 and a11 from the nearshore, transitional and offshore zone of Dali Lake, respectively, illustrating fitting and partitioning of grain-size components (blue lines) within an individual polymodal distribution using the lognormal distribution function. Altogether, five grain-size components can be recognized on the polymodal distributions, and are designated C1 through C5 from fine to coarse modes. The components of each sample are labeled on each curve. Sample number, the modal size and percentage of each component and the fitting residual of each sample are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environments related to different depositional processes within the lake (Figs. 6 and 7; Table 2). C1 (modal size: 0.7–1.6 μm) that exists in the samples distributed within the whole lake may belong to a long-term suspension clay component in a fluid medium, the transportation and deposition of which depend on the intensity of turbulence. C2 (modal size: 1.9–8.8 μm) is absent in the samples mainly from the nearshore zone and displays much higher percentages in the samples from the offshore zone than in those from the nearshore and transitional zone, implying that C2 represents an offshore-suspension fine–silt component. C3 (modal size: 10.5–53.0 μm), also absent in the samples mainly from the nearshore zone, does not only display much higher percentages in the samples from the offshore zone than in those from the nearshore and transitional zone but becomes slightly coarser towards the lake center as well, denoting that C3 represents an offshore-suspension medium-to-coarse-silt component. C4 (modal size: 68.2–157.7 μm) occurs in the samples distributed within the whole lake and decreases both in the relative percentage and in the modal size with increasing water depth, suggesting that C4 represents a nearshore-suspension fine-sand component. C5 (modal size: 203.0–514.7 μm) occurs only in the samples from the nearshore and transitional zone and decreases significantly in the relative percentage with increasing water depth, indicating that C5 represents a nearshore-saltation medium-sand component.

5.2. Comparison between the grain-size components in Dali and Daihai Lake sediments

The grain-size components identified from the Dali Lake sediments show similarities to, as well as differences from, those in the Daihai Lake sediments. The similarities consist in two aspects: 1) the maximum number of grain-size components; and 2) the dominant ranges of the modal size and percentage of each specific grain-size component. Altogether, five distinct components could be identified from the modern clastic sediments of both Dali and Daihai Lake although in some samples only three or four components can be recognized. The dominant range of the modal size of each corresponding component approximates to each other in both lake sediments although exact values of the total range of the modal size are more or less dissimilar; whereas two dominant ranges of the percentage can be seen in each specific component, except in the finest component, in both lake sediments.

The differences also lie in two aspects: 1) the scope of spatial distribution of C2, C3, C4 and C5 within the lake; and 2) the degree of overlapping between two adjacent components of C2, C3 and C4. Both C2 and C3 are absent in a larger number of samples from the nearshore zone in Dali Lake than in Daihai Lake. C4 occurs in the samples that are distributed across the whole lakebed in Dali Lake, but is lacking in the samples from the offshore zone in Daihai Lake. C5 occurs in the samples both from the nearshore and from the transitional zone in Dali Lake, but does in the samples mainly from the nearshore zone in Daihai Lake. Two adjacent components among C2, C3 and C4 are separated completely in Dali Lake, but

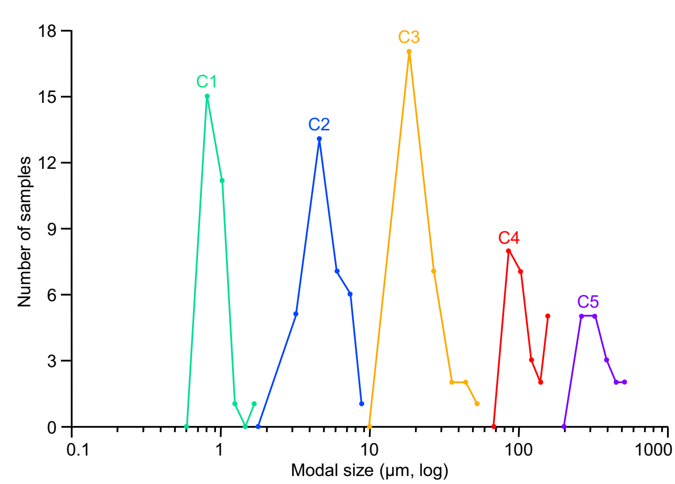

Fig. 4. Frequency of the modal sizes of the five grain-size components, C1 through C5, in 36 surface-sediment samples of Dali Lake.

overlap in Daihai Lake, although C5 is separated from C4 in both lakes.

As discussed above, the polymodality of lake sediments is produced by the reworking and sorting of lake waters. We thus infer that the inter-lake differences both in the scope of within-lake distribution of C2, C3, C4 and C5 and in the degree of overlapping between two adjacent components of C2, C3 and C4 would result from the difference in the hydraulic dynamics of the lake. In view of similarities in the shape and size of Dali and Daihai Lake (Table 3), the difference in hydraulic dynamics can be attributed to the difference in the regional wind regime because the hydraulic energy of lake waters is generated mainly by the winds (Lerman, 1978; Håkanson and Jansson, 1983; Talbot and Allen, 1996). Meteorological observations indicate that the annual mean wind speed and the fresh-gale days per year in the Dali Lake region are distinct from those in the Daihai Lake region, although wind prevails in both lake regions during the winter and spring season with fresh gales occurring mainly in the spring (Table 3). The annual mean wind speed is 3.0 m/s in the Dali Lake region, higher than 2.5 m/s in the Daihai Lake region; whereas during the windy season, a fresh gale blows for ca. 35 days in the Dali Lake region, much more than the 10 days in the Daihai Lake region. These data suggest that the winds are generally stronger and more frequent in the Dali Lake region, giving rise to relatively higher hydraulic energy of lake waters in Dali Lake. Under the condition of higher-energy hydraulics, clastic materials entering Dali Lake and thus the resultant grain-size components could have been reworked to a greater extent during transportation within the lake. As a result, on one hand, more of Components C2 (offshore-suspension fine silt) and C3 (offshore-suspension medium-to-coarse silt) would be transported towards the lake center, leading to absence of C2 and C3 in a larger number of samples from the nearshore zone. C4 (nearshore-suspension fine sand) would be transported from the nearshore and transitional zone further to the offshore zone, leading to occurrences of C4 within the whole lake. C5 (nearshore-saltation medium sand) would be transported from the nearshore zone further to the transitional zone, leading to occurrences of C5 in both the nearshore and the transitional zone. On the other hand, in the course of the hydraulic reworking, the coarse/fine tail of each specific component would be transformed to a part of the adjacent coarser/finer component, resulting in complete separations of two adjacent components among C2, C3 and C4.

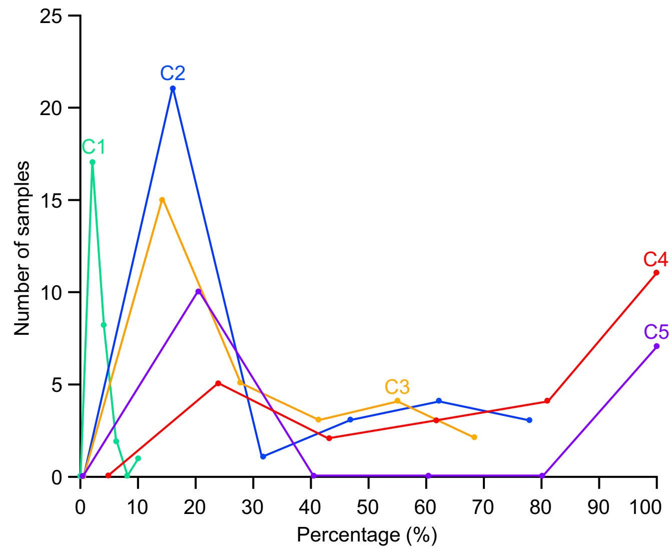

Fig. 5. Frequency of the percentages of the five grain-size components, C1 through C5, in 36 surface-sediment samples of Dali Lake.

5.3. Grain-size component–lake level status model

The grain-size components of the surface sediments of Dali Lake exhibit a spatial distribution across the lakebed that characterizes the modern hydraulic dynamics of the lake. As the hydraulic dynamics of a specific lake are closely related to the water depth and size of the lake (Lerman, 1978; Håkanson and Jansson, 1983; Talbot and Allen, 1996), the observed data from the modern clastic sediments of Dali Lake provide the possibility of establishing a numerical model for linking the grain-size components to the status of lake levels.

Table 4 shows the relationships between the modal size (in ϕ units) as well as percentage of Components C2, C3, C4 and C5 and the water depth. The modal sizes of all the components appear to have nothing to do with water depth; whereas the percentages of the components are related to water depth in varying degrees (Table 4). The percentages of C2 (offshore-suspension fine–silt

Table 3
Comparison between the physiographic features of Dali Lake (Li, 1993) and Daihai Lake (Wu et al., 1993).

Physiography	Dali Lake	Daihai Lake
Location	43°13′–43°23′ N, 116°29′–116°45′ E	40°29′–40°37′ N, 112°33′–112°46′ E
Elevation	1226 m a.s.l.	1221 m a.s.l.
Morphology	Shape: subrounded Area: 238 km^2 Maximum water depth: 11 m	Shape: subrounded Area: 134 km^2 Maximum water depth: 16 m
Geomorphology	Located at the northern margin of the E–W trending Hulandaga Desert Land with hills on the north and west and lacustrine plains along the eastern lakeshore	Bordered by the Manhan Mountains (peak: 2305 m a.s.l.) on the north and Matou Mountains (peak: 2035 m a.s.l.) on the south with hills and low mountains on the east and lacustrine plains along the western lakeshore
Hydrology	Hydrologically closed lake with two permanent rivers and two intermittent streams entering the lake	Hydrologically closed lake with two permanent rivers and three intermittent streams entering the lake
Climate	Located at the transition from semi-humid to semi-arid areas of the middle temperate zone Mean annual temperature: 3.2 °C Mean annual precipitation: 383 mm Mean annual evaporation: 1632 mm Dominant wind direction: northwest Annual mean wind speed: 3.0 m/s Fresh-gale days per year: 35 d Ice-covered months: November to April	Located at the transition from semi-humid to semi-arid areas of the middle temperate zone Mean annual temperature: 5.1 °C Mean annual precipitation: 423 mm Mean annual evaporation: 1162 mm Dominant wind direction: northwest Annual mean wind speed: 2.5 m/s Fresh-gale days per year: 10 d Ice-covered months: November to March

component) C3 (offshore-suspension medium-to-coarse-silt component) show positive relations with water depth (coefficient determination: 0.55 and 0.31, respectively); whereas the percentages of C4 (nearshore-suspension fine-sand component) and C5 (nearshore-saltation medium-sand component) display negative relations with water depth (coefficient determination: 0.70 and 0.31, respectively). Judging from the coefficient determination together with the within-lake distribution of each component, the negative correlation between the C4 percentage and the water depth is most significant. As C4 and C5 are interpreted as the nearshore component, both components can thus be viewed as a whole as representing the nearshore environment. As shown in Table 4 and Fig. 6, the percentage of C4 plus C5 is negatively related to water depth with a coefficient determination of 0.71, higher than that between the C4 percentage alone and the water depth. These data indicate that the Components C4 and C5, interpreted as an indication of the nearshore environments, constitute more of the grain-size distribution in the samples collected from the shallower waters, and might therefore provide a model for reconstructing past water depths from sediment core data.

Table 4
Relationship between the modal size as well as percentage of the grain-size components in 36 surface-sediment samples of Dali Lake and the water depth. In the linear regression equations, *x* represents modal size or percentage of the grain-size components, and *y* represents water depth of the sampling sites.

Grain-size component	Number of samples	Regression equation	Coefficient of determination	Standard error (m)
C2 modal size	32	$y = -0.96x + 13.28$	0.04	2.6
C3 modal size	29	$y = -2.07x + 18.01$	0.25	2.4
C4 modal size	25	$y = 2.76x - 3.83$	0.13	2.7
C5 modal size	17	$y = -0.88x + 6.28$	0.01	2.7
C2 percentage	32	$y = 0.08x + 4.06$	0.55	1.8
C3 percentage	29	$y = 0.08x + 4.42$	0.31	2.3
C4 percentage	25	$y = -0.07x + 9.77$	0.70	1.6
C5 percentage	17	$y = -0.03x + 6.16$	0.31	2.3
C4+C5 percentage	34	$y = -0.07x + 9.55$	0.71	1.5

5.4. Test of the grain-size component–lake level status model

The close relationship between the percentage of the nearshore components (C4 plus C5) in the modern clastic sediments of Dali Lake and the water depth offers a model for reconstructing the history of changes in the lake level during the geological past. Fig. 7 illustrates the percentage of the nearshore components (C4+C5, %) in the DL04 sediment core recovered in the central part of Dali Lake spanning the last 12,000 cal yr (Xiao et al., 2009). The nearshore components display increases in the percentage during the intervals of ca. 11,800–11,500, 10,050–9250, 5900–5350, 4850–4150, 3250–2850, 2150–1600, 1150–900 and 700–250 cal. BP, denoting drops in the lake level during these episodes.

The history of changes in precipitation in the Dali Lake region during the Holocene was quantitatively reconstructed (Fig. 7) based on the pollen profile of the same sediment core (Wen et al., in preparation) and the pollen–climate transfer function for temperate eastern Asia (Wen et al., 2013). As shown in Fig. 7, the mean annual precipitation (MAP, mm) in the lake region decreased obviously during the above periods, suggesting a good correlation between high percentages of the nearshore components in the lake sediments and low precipitations in the lake region.

Modern observations and historical documents show that Dali Lake contracted and the lake level dropped during the low-rainfall years (Li, 1993). The present data indicate that the nearshore

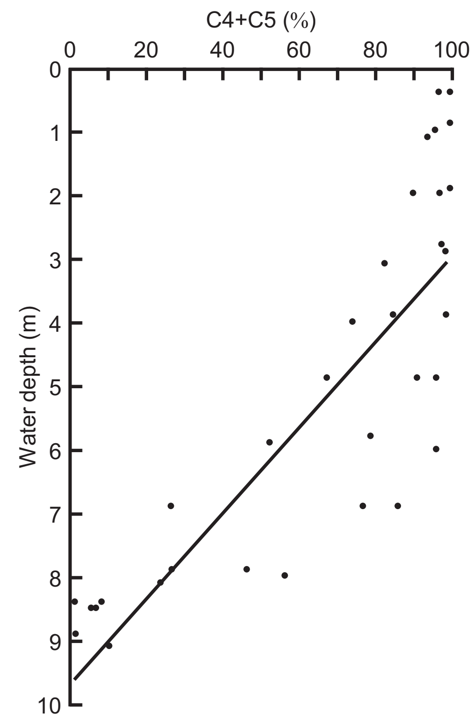

Fig. 6. Percentage of the nearshore grain-size components (C4 + C5, %) in 36 surface-sediment samples of Dali Lake plotted against water depth. The linear regression line is shown. For the regression equation, coefficient determination and standard error, see Table 4.

components increased in the lake sediments when the annual precipitation decreased in the lake region. Such a good coincidence of two independent proxies from the sediment core of Dali Lake demonstrates the wide applicability of both the lognormal distribution function method to partitioning polymodal lake sediments and the grain-size component–lake level status model to deciphering paleohydrological processes of lakes.

6. Conclusions

Application of lognormal distribution function to fitting and partitioning individual, polymodal grain-size distributions suggests that the modern clastic sediments of Dali Lake contain five distinct grain-size components representing specific depositional processes and sedimentary environments within the lake, as those of Daihai Lake do. These components are, from fine to coarse modes, long-term suspension clay, offshore-suspension fine silt, offshore-suspension medium-to-coarse silt, nearshore-suspension fine sand and nearshore-saltation medium sand. In Dali Lake, by contrast, clastic materials entering the lake and the resultant components would be reworked more seriously during transportation within the lake due to higher-energy hydraulics of the lake generated by stronger and more frequent winds occurring in the lake region, thus resulting in further basinward transportation of the major components and better separations of two adjacent components.

The grain-size component–lake level status model generated from Dali Lake was applied to a sediment core from the lake where high percentages of the nearshore components in the core coincide with low precipitation reconstructed from the pollen profile of the same core. This relationship between two independent proxies not only demonstrates the validity of lognormal distribution function

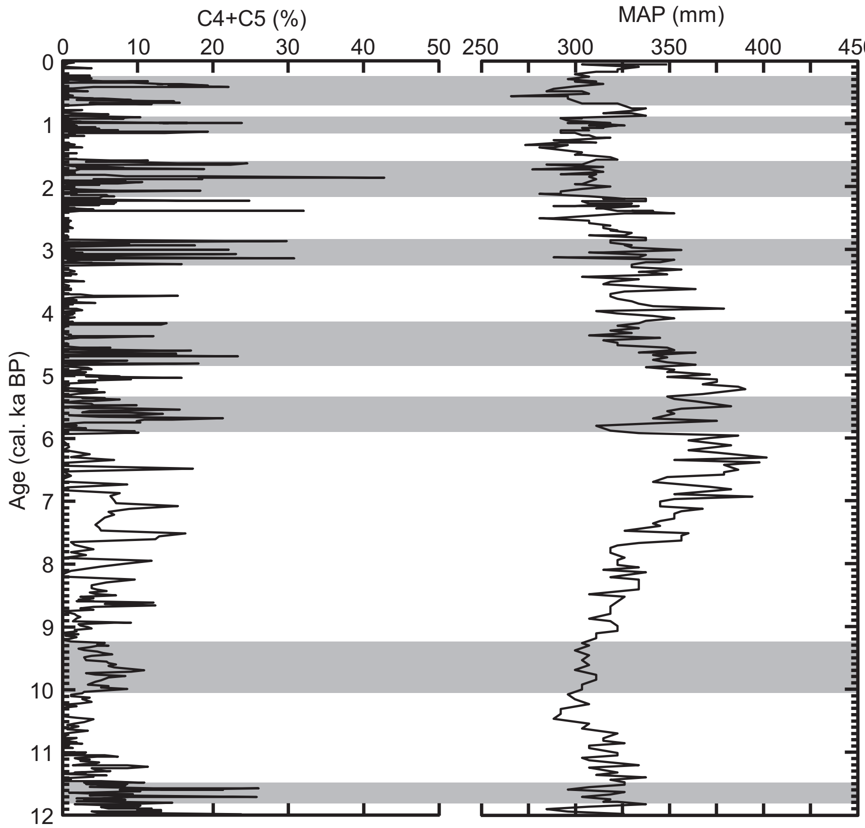

Fig. 7. Percentage of the nearshore grain-size components (C4+C5, %) in the DL04 sediment core recovered in the central part of Dali Lake compared with the mean annual precipitation (MAP, mm) in the lake region reconstructed on the pollen profile of the same core. The chronology was derived from calibrated ages of the reservoir-effect-free radiocarbon dates with the reservoir correction factor being 472 y (Wen et al. in preparation). Shaded bars mark the intervals of lowered lake levels and declined regional precipitations during the last 12,000 cal yr.

in partitioning polymodal sediments but also reveals the wide applicability of the grain-size component–lake level status model to paleohydrological reconstruction.

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References

Ashley, G.M., 1978. Interpretation of polymodal sediments. Journal of Geology 86, 411–421.
Bennett, S.J., Best, J.L., 1995. Mean flow and turbulence structure over fixed, two-dimensional dunes: implications for sediment transport and bedform stability. Sedimentology 42, 491–513.
Chinese Academy of Sciences (Compilatory Commission of Physical Geography of China), 1984. Physical Geography of China: Climate. Science Press, pp. 1–30 (in Chinese).
Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. Journal of Sedimentary Petrology 27, 3–26.
Friedman, G.M., Sanders, J.E., 1978. Principles of Sedimentology. John Wiley, 792 pp.
Håkanson, L., Jansson, M., 1983. Principles of Lake Sedimentology. Springer, 316 pp.
Inman, D.L., 1949. Sorting of sediments in the light of fluid mechanics. Journal of Sedimentary Petrology 19, 51–70.
Kranck, K., Smith, P.C., Milligan, T.G., 1996. Grain-size characteristics of fine-grained unflocculated sediments II: 'multi-round' distributions. Sedimentology 43, 597–606.
Krumbein, W.C., 1938. Size frequency distribution of sediments and the normal phi curve. Journal of Sedimentary Petrology 8, 84–90.
Lerman, A., 1978. Lakes: Chemistry, Geology, Physics. Springer, 363 pp.
Li, Z.G., 1993. Annals of Hexigten Banner. People's Press of Inner Mongolia, 1144 pp (in Chinese).
Middleton, G.V., 1976. Hydraulic interpretation of sand size distributions. Journal of Geology 84, 405–426.
Påsse, T., 1997. Grain size distribution expressed as *tanh*-functions. Sedimentology 44, 1011–1014.
Pye, K., 1987. Aeolian Dust and Dust Deposits. Academic Press, pp. 29–62.
Qin, X.G., Cai, B.G., Liu, T.S., 2005. Loess record of the aerodynamic environment in the east Asia monsoon area since 60,000 years before present. Journal of Geophysical Research 110, B01204. http://dx.doi.org/10.1029/2004JB003131.
Sly, P.G., 1989a. Sediment dispersion: part 1, fine sediments and significance of the silt/clay ratio. Hydrobiologia 176 (177), 99–110.
Sly, P.G., 1989b. Sediment dispersion: part 2, characterisation by size of sand fraction and per cent mud. Hydrobiologia 176 (177), 111–124.
Sun, D.H., Bloemendal, J., Rea, D.K., Vandenberghe, J., Jiang, F.C., An, Z.S., Su, R.X., 2002. Grain-size distribution function of polymodal sediments in hydraulic and aeolian environments, and numerical partitioning of the sedimentary components. Sedimentary Geology 152, 263–277.
Talbot, M.R., Allen, P.A., 1996. Lakes. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Publishing, pp. 83–124.
Tanner, W.F., 1964. Modification of sediment size distributions. Journal of Sedimentary Petrology 34, 156–164.
Tsoar, H., Pye, K., 1987. Dust transport and the question of desert loess formation. Sedimentology 34, 139–153.
Visher, G.S., 1969. Grain size distributions and depositional processes. Journal of Sedimentary Petrology 39, 1074–1106.
Wen, R.L., Xiao, J.L., Ma, Y.Z., Feng, Z.D., Li, Y.C., Xu, Q.H., 2013. Pollen–climate transfer functions intended for temperate eastern Asia. Quaternary International 311, 3–11.
Wen, R.L., Xiao, J.L., Zhai, D.Y., Fan, J.W., Xu, Q.H., Itoh, S., 2014. Holocene Precipitation and Temperature Variations in the Mid-latitude Monsoonal Margin Deduced from Pollen Data from Dali Lake in Northeastern Inner Mongolia, China (in preparation).

Wu, J.Z., Zhang, G.H., Zhang, R., Liu, Z.L., 1993. Annals of Liangcheng County. People's Press of Inner Mongolia, 1057 pp (in Chinese).
Xiao, J.L., Chang, Z.G., Si, B., Qin, X.G., Itoh, S., Lomtatidze, Z., 2009. Partitioning of the grain-size components of Dali Lake core sediments: evidence for lake-level changes during the Holocene. Journal of Paleolimnology 42, 249–260.
Xiao, J.L., Fan, J.W., Zhou, L., Zhai, D.Y., Wen, R.L., Qin, X.G., 2013. A model for linking grain-size component to lake level status of a modern clastic lake. Journal of Asian Earth Sciences 69, 149–158.
Zhang, J.C., Lin, Z.G., 1985. Climate of China. Shanghai Scientific and Technical Publishers, 603 pp (in Chinese).