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A model for linking grain-size component to lake level status of a modern clastic lake

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ABSTRACT

Grain-size distributions of fluvial, eolian and marine sediments were explicated decades ago. For lake sediments, however, there is still great uncertainty in explaining the genesis of grain-size components due to the inherent complexity of their polymodal distributions. In this study, the grain-size components of the surface sediments of Daihai Lake, Inner Mongolia, were partitioned using a lognormal distribution function and the relationship between the identity of each component and the specific sedimentary environment was investigated. The data indicate that the modern clastic sediments of Daihai Lake contain five distinct unimodal grain-size distributions representing five grain-size components. Each of the components retains its identity including modal size, manner of transportation and environment of deposition although the relative percentage varies with the hydraulic condition throughout the lake. These components are specified from fine to coarse modes as long-term suspension clay, offshore-suspension fine silt and medium-to-coarse silt, and nearshore-suspension fine sand and saltation medium sand. The percentage of the components interpreted as an indication of nearshore environments displays a negative correlation with water depth across the modern lakebed, suggesting a model for linking the nearshore components in sediment cores to the lake level status in the geological past. The model was applied to a sediment core from the lake where high percentages of the nearshore components in the core sediments were correlated with low regional precipitations reconstructed on the pollen profile of the same core. The coincidences between two independent proxies do not only demonstrate the validity of lognormal distribution function in partitioning polymodal sediments but also reveals the potential of the grain-size component–lake level status model for lake's paleohydrological reconstruction.

1. Introduction

Grain-size distributions of clastic sediments provide direct information on changes in the source of material, transporting mechanism and sedimentary environment (Friedman and Sanders, 1978). In order to interpret the genesis of each grain-size component within an individual polymodal distribution and to relate the constituent grain-size components to specific depositional processes and sedimentary environments, sedimentologists have made substantial efforts to define different types of grain-size distributions and partition the constituent components of polymodal sediments with the aid of mathematical methods. Fluvial deposits were interpreted to comprise two grain-size components, i.e., a saltation medium-sand component with modal sizes of 200–400 μm and a suspension fine-silt component with modal sizes of 10–15 μm (Middleton, 1976; Ashley, 1978; Bennett and Best, 1995; Kranck et al., 1996; Påsse, 1997). Typical loess deposits consist of a short-suspension medium-to-coarse-silt component with dominant modal sizes of 16–32 μm and a long-suspension clay-to-fine-silt component with dominant modal sizes of 2–6 μm (Tsoar and Pye, 1987; Pye, 1987; Sun et al., 2002; Qin et al., 2005); whereas desert sands are mainly composed of a saltation fine-to-medium-sand component with modal sizes of 100–200 μm and a suspension clay-to-fine-silt component with modal sizes of 2–6 μm (Gillette et al., 1974; Tsoar and Pye, 1987; Pye, 1987; Sun et al., 2002). Deep-sea sediments are dominated by a single eolian component with a modal size of ~2 μm (Rea, 1994; Rea and Hovan, 1995; Boven and Rea, 1998); whereas hemipelagic deposits consist of two eolian components with modal sizes of ~13 μm and ~7 μm, respectively, and a hemipelagic component with a modal size of ~4 μm (Prins et al., 2000; Stuut et al., 2002; Weltje and Prins, 2003).

The grain-size distribution of lake sediments has long been used as a proxy indicator of a lake's hydrological condition that is closely related to the process of changes in the regional climate and environment (Håkanson and Jansson, 1983). Until now, however, there is still great uncertainty in explaining the origin and implication of

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grain-size components of lake sediments because the grain-size distribution of lake sediments is strongly polymodal and its polymodality may be affected by various factors such as the source of clastic materials, shape and size of the lake and the hydraulic dynamics of lake waters. In this study, we applied the lognormal distribution function to quantitatively fitting and partitioning the grain-size components within individual grain-size distributions of 35 surface-sediment samples taken along three transects in Daihai Lake in central Inner Mongolia, China. The aim of this study is to interpret the genesis of polymodal grain-size distributions of lake sediments and relate the constituent grain-size components within individual polymodal distributions to specific depositional processes and sedimentary environments in the lake. We attempt to establish a numerical model for the grain-size components of lake sediments and the lake level status that would be useful to reconstruct the history of past fluctuations in lake level based on data from lake sediment cores.

2. Daihai Lake basin

Daihai Lake (40°29′ to 40°37′N, 112°33′ to 112°46′E) is an inland, closed-basin lake that lies 10 km east of Liangcheng County in central Inner Mongolia, China (Fig. 1). It has an area of 134 km^2, a maximum water depth of 16 m and an elevation of 1221 m a.s.l. (measurements in July 1986; Wang et al., 1990). The lake basin is bordered by the Manhan Mountains (highest peak: 2305 m a.s.l.) on the north and Matou Mountains (highest peak: 2035 m a.s.l.) on the south. Hills and low mountains are distributed on the east and lacustrine plains are present along the western shore. The lake has a catchment of 2289 km^2. Two rivers, the Muhua and Gongba River from the east and west and three intermittent streams from the south enter the lake, but no rivers drain the lake (Fig. 1).

Daihai Lake is located at the transition from semi-humid to semi-arid areas in the middle temperate zone (Fig. 1). The climate of the lake's region is under the influence of the East Asian monsoon (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). During the summers, the warm, moist southeasterly air-masses interact with cold air from the northwest and produce rainstorms and most of the annual precipitation. During the winters, the cold, dry northwesterly airflows prevail and bring strong winds and dust storms to the region. In the lake region, mean annual temperature is 5.1 °C with a July average of 20.5 °C and a January average of −13.0 °C. Mean annual precipitation is 423 mm, and ca. 80% of the annual precipitation falls in June–September. Mean annual evaporation reaches 1162 mm, which is three times the annual precipitation. The lake is covered with ca. 60 cm of ice from November to March.

3. Samples and methods

3.1. Sediment sampling

The surface sediments of Daihai Lake were sampled in May 2010 along the Transects a, b and c, yielding 13 samples for Transect a, 10 samples for Transect b and 12 samples for Transect c (Figs. 1 and 2; Table 1). The transects start at a1 (40°35.864′N, 112°39.299′E), b1 (40°33.126′N, 112°42.686′E) and c1 (40°36.672′N, 112°41.839′E) on the lakeshore, respectively, and end at a13 (40°34.888′N, 112°40.729′E), b10 (40°33.976′N, 112°42.032′E) and c12 (40°34.998′N, 112°41.989′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).

Modern riverbed sands were sampled nearby the mouths of the Muhua and Gongba Rivers (Fig. 1) in August 2009. And modern eolian dust that was trapped on the ice of Daihai Lake was collected in the central part of the lake in March 2004.

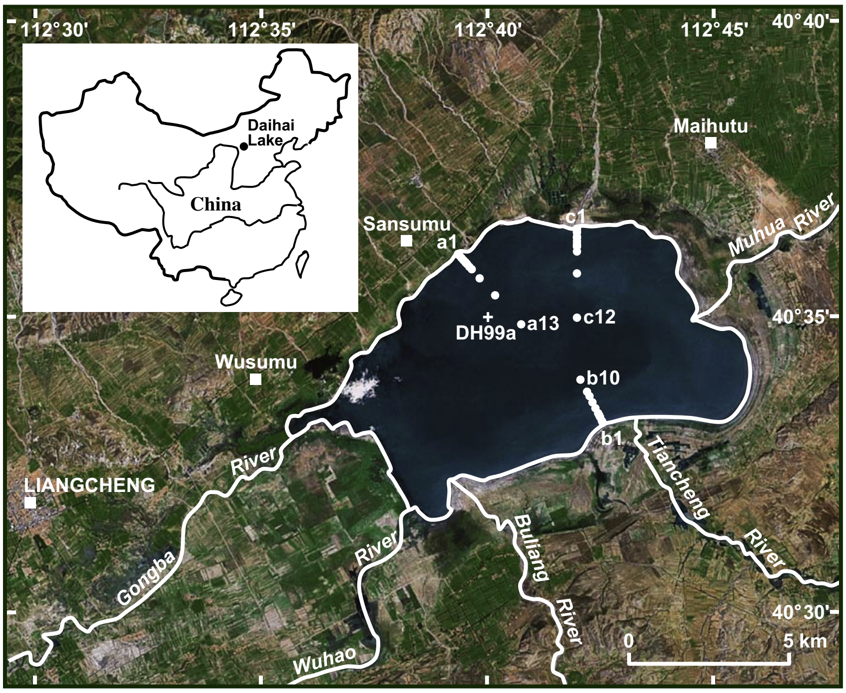

Fig. 1. Map of Daihai Lake (from http://maps.google.com) showing locations of the surface-sediment sampling sites along the Transects a, b and c. The coring location of the DH99a sediment core (cross) discussed in the text is shown. The inset gives a sketch map of China showing the location of Daihai Lake.

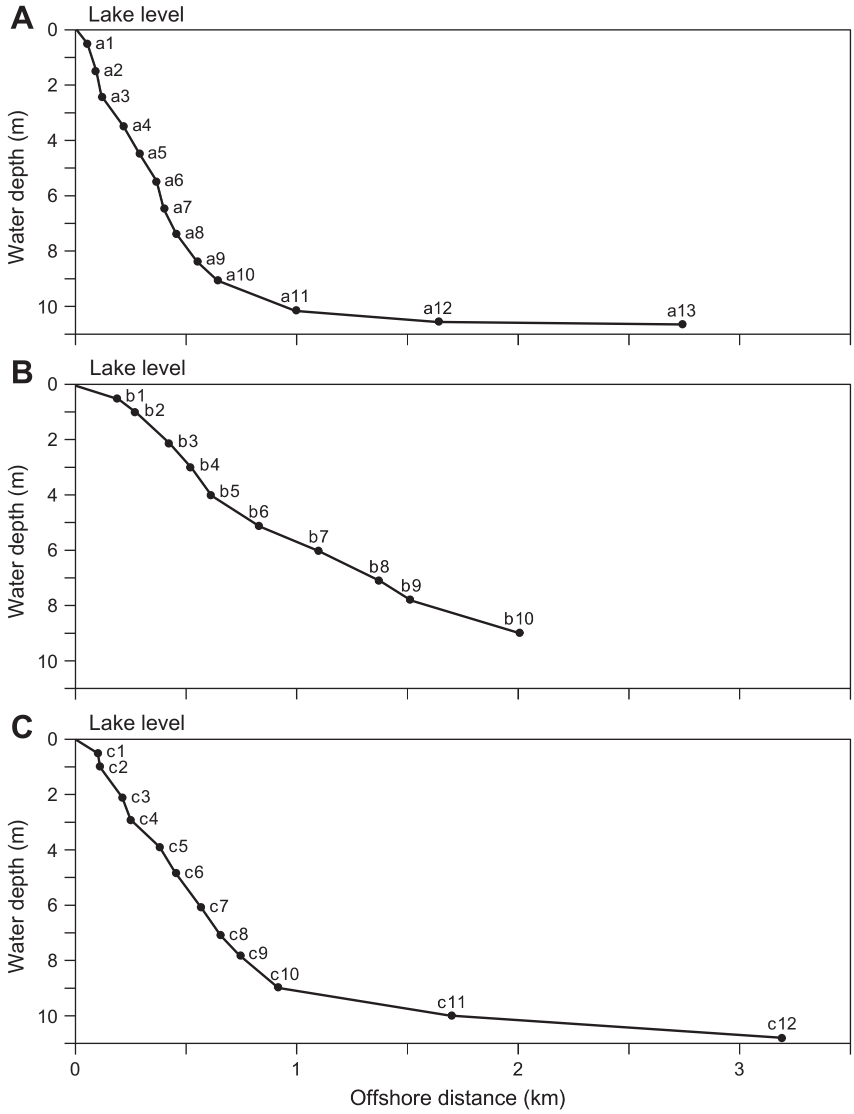

Fig. 2. Profile of the lake floor along the transects showing the sampling sites. (A) Transect a, (B) Transect b, (C) Transect c. The vertical axis indicates water depth, and the horizontal axis indicates offshore distance to the closer lakeshore.

Table 1
Water depth and offshore distance of 35 surface-sediment sampling sites along the Transects a, b and c in Daihai Lake (measurements in May 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	0.5	0.05	b1	0.5	0.20	d	0.5	0.10
a2	1.5	0.09	b2	1.0	0.28	c2	1.0	0.11
a3	2.4	0.11	b3	2.1	0.43	c3	2.1	0.21
a4	3.5	0.22	b4	3.0	0.53	c4	2.9	0.25
a5	4.5	0.29	b5	4.0	0.62	c5	3.9	0.38
a6	5.5	0.37	b6	5.1	0.84	c6	4.8	0.45
a7	6.5	0.40	b7	6.0	1.11	c7	6.1	0.57
a8	7.4	0.45	b8	7.1	1.39	c8	7.1	0.66
a9	8.4	0.55	b9	7.8	1.53	c9	7.8	0.74
a10	9.1	0.64	b10	9.0	2.03	c10	9.0	0.92
a11	10.2	1.00				c11	10.0	1.70
a12	10.6	1.64				c12	10.8	3.21
a13	10.7	2.75						

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 works on the principle of the Mie theory that predicts the way light is scattered by spherical particles and deals with the way light passes through, or is absorbed by, the particle. Based on the Mie theory, assuming that measured particles are perfect spheres, the Mastersizer uses the volume of a particle to measure its size and calculate the diameter of an imaginary sphere that is equivalent in volume by the technique of "equivalent spheres". The Mastersizer 2000 has a measurement range of 0.02–2000 μm in diameter and a grain-size resolution of 0.166 ϕ in interval ($\phi = -\log_2(D)$, where D is grain diameter in mm), thus yielding 100 grain-size fractions. The Mastersizer provides the percentages 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. Fitting and partitioning of grain-size components

The grain-size distribution of clastic deposits with a single component should exhibit a unimodal, symmetric distribution on a logarithmic scale (Inman, 1949; Folk and Ward, 1957; Tanner, 1964; Visher, 1969; Ashley, 1978). When the shape of a grain-size distribution is asymmetric or skewed, the total distribution can be considered to be a combination of several unimodal distributions (Inman, 1949; Folk and Ward, 1957; Tanner, 1964; Visher, 1969; Ashley, 1978). In other words, a polymodal grain-size distribution can be thought to be composed of two or more unimodal distributions that represent two or more grain-size components (modes).

The grain-size distribution of unimodal clastic deposits follows the lognormal distribution (Krumbein, 1938). With respect to polymodal sediments that consist of several unimodal components, each of the components can be described with sufficient accuracy by the lognormal distribution function (Ashley, 1978; Påsse, 1997; Qin et al., 2005). In this study, we applied the lognormal distribution function method described by Qin et al. (2005) to identify, fit and partition the grain-size components of the surface sediments of Daihai Lake. The formula of the lognormal distribution function is expressed as follows,

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

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

The fitting residual is calculated as follows,

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

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

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. Here it is necessary to designate two modes for one skewed peak. Each mode of a measured polymodal distribution is described by three parameters (c, a, σ), and a combination of the three parameters of n modes describes the measured polymodal distribution. By using Visual Basic for applications on a PC Office platform, a program was written to perform fitting calculations. The procedure is as follows.

(1) Place the measured grain-size data of all the samples into a worksheet of MS Excel. (2) Start the program, select the target sample, and the initial values of the estimated parameters (c, a, σ) of each mode in the sample are given automatically by the random number generator within the program and the fitting calculations are performed using the above estimated parameters (n, c, a, σ) and the measured grain-size data to yield the initial fitting residual. (3) The program starts iterative-loop calculations of the four parameters (n, c, a, σ) and designates a group of new parameters in each calculation to obtain the minimum fitting residual value. Here, $0 < c_i < 100$, $a_{i-1} < a_i < a_{i+1}$, $0 < \sigma_i < \sigma$ (σ is the standard deviation of the measured grain-size data of the sample). The increment of each parameter (Δc, Δa, $\Delta\sigma$) in each calculation is designated a low value to ensure a good enough fitting ($\Delta c = 0.01$, $\Delta a = (a_i - a_{i-1})/100$, $\Delta\sigma = \sigma/100$). At the end of each calculation, the program automatically outputs a fitting residual, compares it with the previous lowest residual and chooses the lower one as the minimum fitting residual of the sample. When the iterative-loop calculation is finished, the combination of the three parameters of n modes with the minimum fitting residual is chosen to represent the measured polymodal distribution.

Fitting experiments on a sample are accomplished when the residual reaches its minimum. Numerical partitioning of the unimodal components of a measured polymodal distribution can be achieved simultaneously through lognormal distribution function 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 output automatically by the program while the fitting of the sample is accomplished. 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. The modal size of the ith mode is calculated as follows,

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

As shown in Fig. 3, three samples of the surface sediments of Daihai Lake were selected from Transect a to illustrate fitting and partitioning of grain-size components within an individual polymodal distribution using the lognormal distribution function. The three samples represent the modern sediments deposited in three different environments of the nearshore zone (a1), transitional zone (a9) and the offshore zone (a12) of the lake (Figs. 1 and 2). The fitting and partitioning result and the minimum fitting residual of each sample are shown (Fig. 3).

4. Results

The fitting and partitioning of the lognormal distribution function suggest that each polymodal grain-size distribution of samples from the surface sediments of Daihai Lake is composed of three to five unimodal distributions. These unimodal distributions can be identified as five distinct modes that represent five grain-size components, respectively, according to the dominant range of modal sizes of each unimodal distribution. The five components are designated C1 through C5 from fine to coarse modes in this study (Fig. 3).

As shown in Fig. 3, it is easy to determine relatively separated modes. To separate out two strongly overlapped components (for instance, C2 and C3 in samples a9 and a12), however, requires technical skills through trial-and-error fittings after careful observations. In this case, fortunately, the fitting residual increases significantly if the minor component (C2 in sample a9 and C3 in

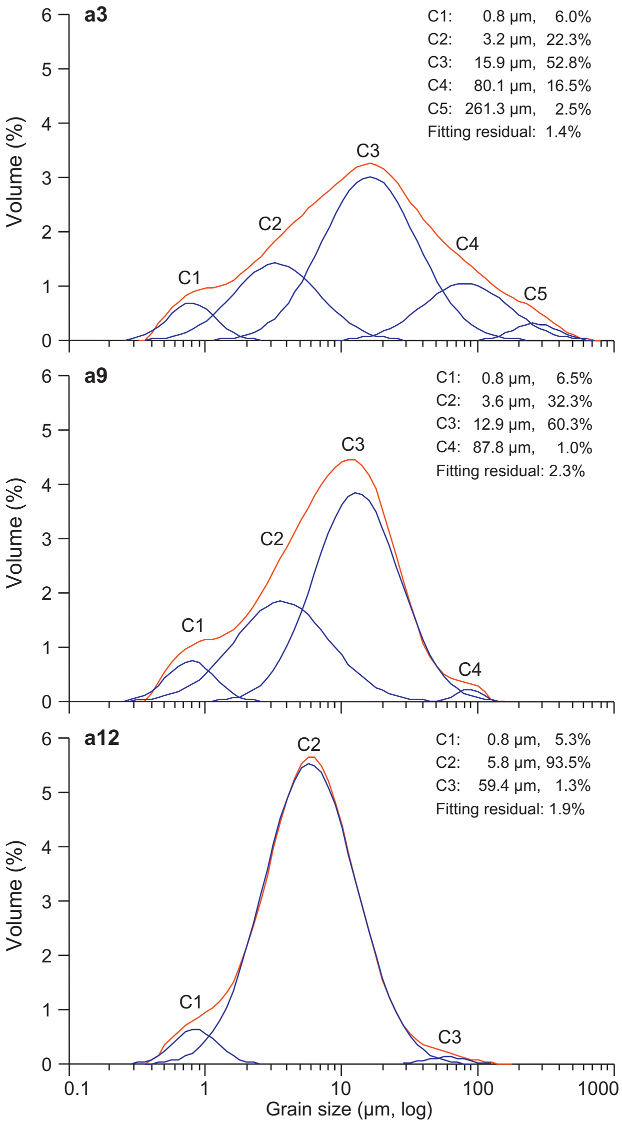

Fig. 3. Frequency distribution curves (black lines) of three representative samples from the surface sediments of Daihai Lake illustrating fitting and partitioning of grain-size components (blue lines) within an individual polymodal distribution using the lognormal distribution function. Altogether, 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 color in this figure legend, the reader is referred to the web version of this article.)

sample a12) is ignored. Such experiments demonstrate the validity and accuracy of the lognormal distribution function in fitting and partitioning the grain-size components of polymodal sediments.

The fitting and partitioning result indicates that the Components C1, C2, C3, C4 and C5 identified from 35 individual grain-size distributions of the surface-sediment samples from Daihai Lake have identifiable characteristics (Figs. 4 and 5; Table 2). The statistics of all the 35 samples show that the Components C1 and C2 exist in all samples, while the C3 is absent from 3 samples, and the C4 and C5 occur in 29 and 9 samples, respectively. The modal sizes of the Components C1, C2, C3, C4 and C5 vary within ranges of 0.7–2.1, 2.1–10.7, 8.0–59.4, 47.7–119.6 and 185.2–433.2 μm, respectively. The percentages of the C1, C2, C3, C4 and C5 in the relevant samples vary within ranges of 0.5–10.8%, 5.0–93.5%, 1.3–81.8%, 0.5–82.5% and 0.8–77.5%, respectively; whereas the C2, C3, C4

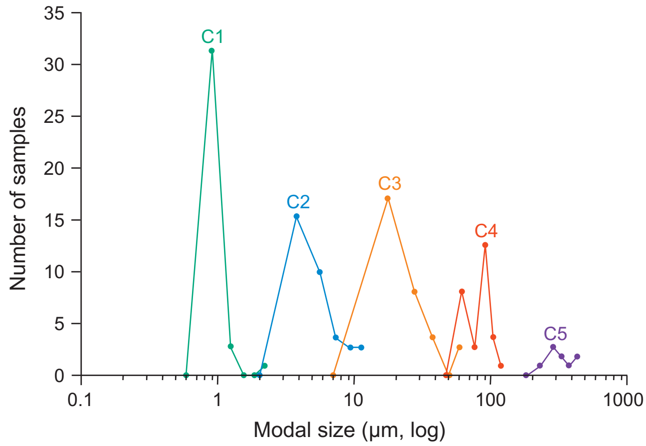

Fig. 4. Frequency of the modal sizes of the five grain-size components, C1 through C5, in 35 samples from the surface sediments of Daihai Lake.

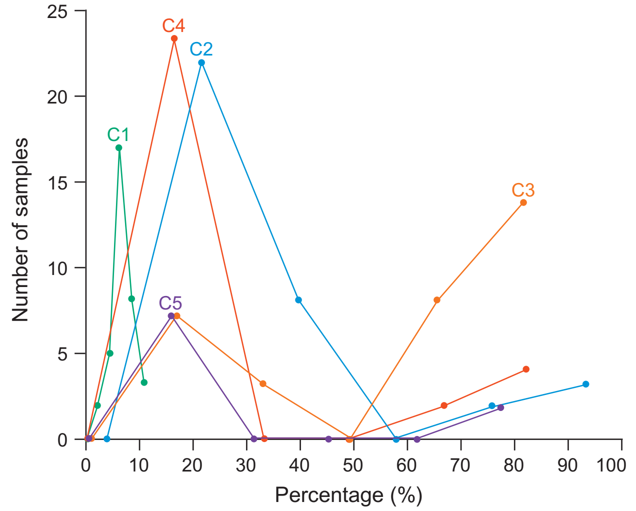

Fig. 5. Frequency of the percentages of the five grain-size components, C1 through C5, in 35 samples from the surface sediments of Daihai Lake.

Table 2
Characteristics of the five grain-size components recognized on the polymodal distributions of 35 samples from the surface sediments of Daihai Lake.

Component	Number of samples	Modal size (μm)		Percentage (%)		Component description
		Min.	Max.	Min.	Max.	
C1	35	0.7	2.1	0.5	10.8	Long-term suspension
C2	35	2.1	10.7	5.0	93.5	Offshore suspension
C3	32	8.0	59.4	1.3	81.8	Offshore suspension
C4	29	47.7	119.6	0.5	82.5	Nearshore suspension
C5	9	185.2	433.2	0.8	77.5	Nearshore saltation

and C5 all display two dominant ranges of the percentages. The fitting residual is less than 3.6% with an average of 2.1% for 13 samples from Transect a, less than 5.6% with an average of 3.4% for 10 samples from Transect b and less than 5.2% with an average of 2.9% for 12 samples from Transect c.

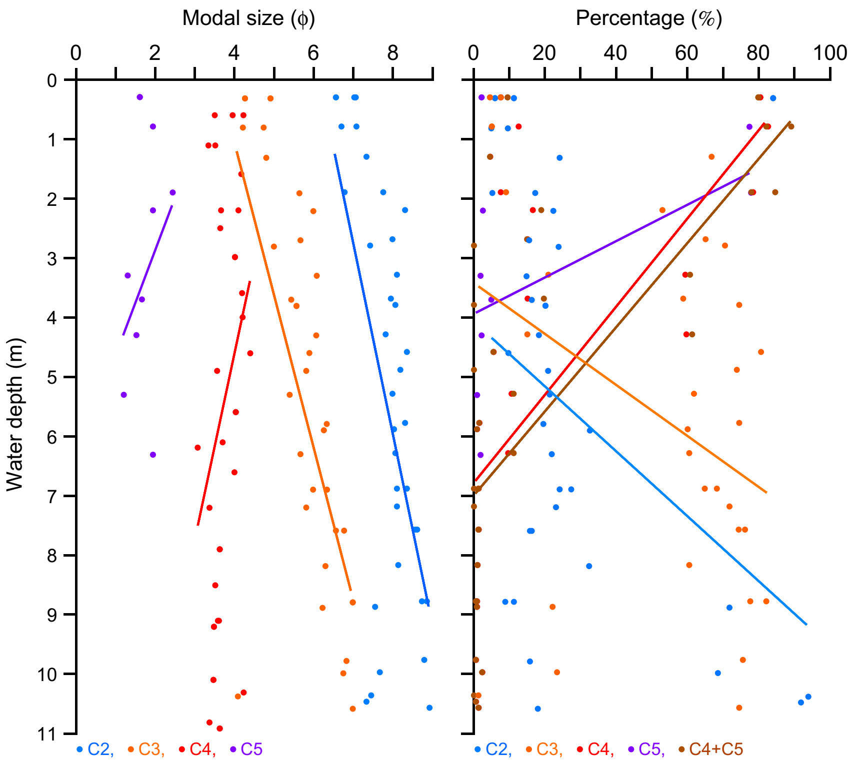

Fig. 6. Modal size and percentage of the grain-size components in 35 samples from the surface sediments of Daihai Lake plotted against water depth. Linear regression lines are shown. For the regression equation, correlation coefficient and standard error, see Table 3.

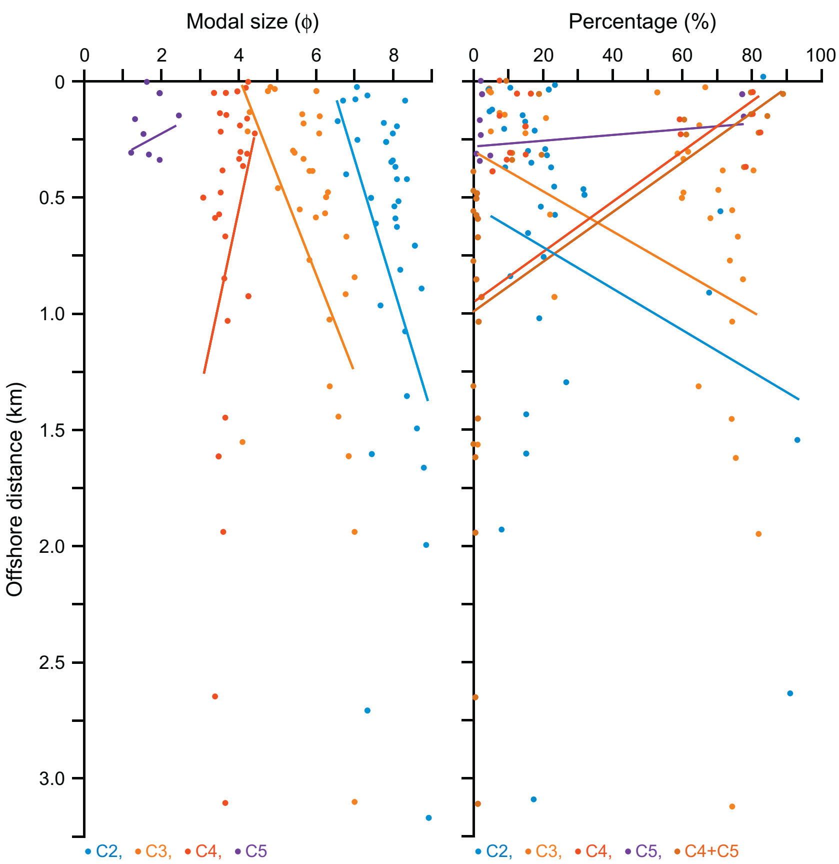

Fig. 7. Modal size and percentage of the grain-size components in 35 samples from the surface sediments of Daihai Lake plotted against offshore distance. Linear regression lines are shown. For the regression equation, correlation coefficient and standard error, see Table 3.

Table 3
Relationship between the modal size as well as percentage of the grain-size components in 35 samples from the surface sediments of Daihai Lake and the water depth as well as offshore distance. In the linear regression equations, x represents modal size or percentage of the grain-size components, and y represents water depth in meters or offshore distance in kilometers of the sampling sites. For data of the grain-size components, see Figs. 6 and 7.

Grain-size component	Regression equation[a]	Correlation coefficient	Standard error (m)	Regression equation[b]	Correlation coefficient	Standard error (km)
C2 modal size	$y = 3.25x - 20.08$	0.37	2.6	$y = 0.55x - 3.58$	0.21	0.70
C3 modal size	$y = 2.58x - 9.39$	0.44	2.2	$y = 0.43x - 1.77$	0.27	0.60
C4 modal size	$y = -3.12x + 17.03$	0.09	3.0	$y = -0.79x + 3.69$	0.11	0.70
C5 modal size	$y = -1.78x + 6.39$	0.11	0.9	$y = -0.09x + 0.39$	0.06	0.06
C2 percentage	$y = 0.06x + 4.02$	0.16	3.0	$y = 0.01x + 0.52$	0.08	0.70
C3 percentage	$y = 0.04x + 3.40$	0.15	2.8	$y = 0.01x + 0.29$	0.13	0.60
C4 percentage	$y = -0.07x + 6.78$	0.38	2.1	$y = -0.01x + 0.95$	0.16	0.70
C5 percentage	$y = -0.04x + 4.73$	0.25	0.8	$y = -0.001x + 0.26$	0.11	0.06
C4 + C5 percentage	$y = -0.07x + 7.21$	0.52	2.1	$y = -0.01x + 1.04$	0.23	0.60

[a] Relationship between the modal size and percentage of grain-size components and the water depth.
[b] Relationship between the modal size and percentage of grain-size components and the offshore distance.

Among all the 35 sampling sites, the water depth varies from 0.5 up to 10.8 m, and the offshore distance ranges from 0.05 to 3.21 km (Figs. 1 and 2; Table 1). The within-lake distribution of the samples in the lake indicates that (1) samples lacking the C3 are mainly distributed in the nearshore zone of <2.1-m water depth and <0.43-km offshore distance; (2) samples lacking the C4 are mainly distributed in the offshore zone of >5.1-m water depth and >0.45-km offshore distance; (3) the C5 occurs mainly in the samples that are distributed in the nearshore zone of <4.5-m water depth and <0.38-km offshore distance; and (4) when the C3 component is absent, the C4 component clearly is present.

Moreover, Figs. 6 and 7 and Table 3 illustrate the relationships between the Components C2, C3, C4 and C5 in the samples from the surface sediments of Daihai Lake and the water depth as well as the offshore distance. As shown in Fig. 6 and Table 3, the modal sizes (in ϕ units) of the C2 and C3 components show positive relations with water depth (correlation coefficient: 0.37 and 0.44, respectively); whereas the percentages of the C4 and C5 components display negative relations with water depth (correlation coefficient: 0.38 and 0.25, respectively). With respect to offshore distance (Fig. 7; Table 3), the modal sizes (in ϕ units) of the C2 and C3 components are positively related to offshore distance (correlation coefficient: 0.21 and 0.27, respectively).

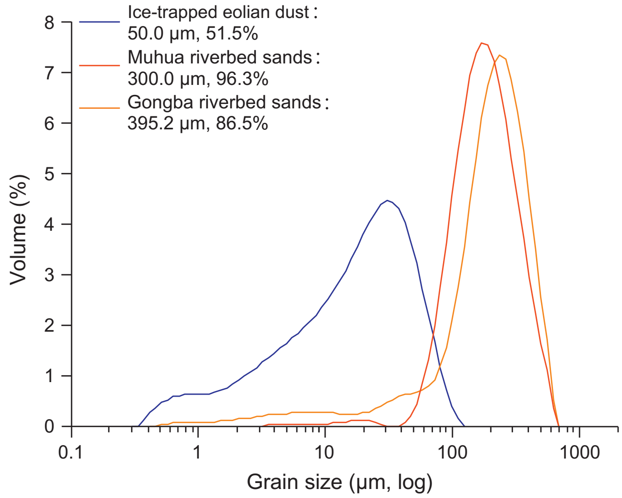

Fig. 8. Frequency distribution curves of modern eolian dust trapped on the ice in the central part of Daihai Lake and modern riverbed sands deposited at the mouths of the Muhua and Gongba Rivers. The modal size and percentage of the dominant component of each sample are shown.

5. Discussion

5.1. Interpretation of the grain-size components

Daihai Lake is located at the transition from semi-humid to semi-arid areas in the middle temperate zone. There are two major rivers entering the lake (Fig. 1). In terms of the geographic location and the basin structure, clastic deposits in Daihai Lake would be mainly derived from fluvial materials transported by the rivers during the summer season and eolian dust trapped on the ice of the lake during the winter and spring season when the northwesterly winds bring dust storms to the lake region. In addition, shoreline materials eroded by storm-driven waves could also contribute to the accumulation of the lake sediments. Clastic materials derived from the three sources will experience reworking and sorting by the hydraulic dynamics of lake waters before being deposited on the lake floor (Håkanson and Jansson, 1983; Talbot and Allen, 1996).

Previous studies suggested that the three types of clastic sediments assume different combinations of specific grain-size components due to distinct transport mechanisms. In order to understand the constituent components of source materials of the Daihai Lake sediments, modern eolian dust trapped on the ice in the central part of the lake and modern riverbed sands deposited nearby the mouths of the Muhua and Gongba Rivers were analyzed for grain-size distribution (Fig. 8).

As shown in Fig. 8, both the ice-trapped eolian dust materials and riverbed sands are composed of multiple components and dominated by their respective coarse component. The dominant component of the ice-trapped eolian dust displays a modal size of 50 μm that is coarser than the modal size (16–32 μm) of the dominant suspension component of typical loess deposits. Modern dust-storm events in the lake region occur mainly in spring when the northwesterly winds are strong and the lake is frozen (Chinese Academy of Sciences, 1984; Wang and Wang, 1993). The finer particles constituting the suspension component of the eolian materials could be blown downwind because of strong winds, and the saltation component comprising coarser particles would be trapped on the lake ice due to diurnal freezing and thawing of the ice surface. Consequently the dominant component of the ice-trapped eolian materials has a larger modal size than that of typical loess deposits. The dominant components of Muhua and Gongba riverbed sands show modal sizes of 300 and 395 μm that well correspond with the modal size (200–400 μm) of the dominant saltation component of typical fluvial deposits.

The nature and distribution of clastic deposits in lakes are controlled by the hydraulic condition of the lake waters (Sly, 1978; Håkanson and Jansson, 1983). Fundamentally, there exists a relationship between the interactions of clastic particles and lake waters within a lake, so that lakes can be separated into high-energy and low-energy regimes (Sly, 1989a,b). 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 lakes become coarser with higher hydraulic energy. Based on the spatial distribution of each grain-size component within the lake, we interpret the Components C1, C2, C3, C4 and C5 of the surface sediments of Daihai Lake as representing different sedimentary modes related to different depositional processes (Table 2). Component C1 (modal size: 0.7–2.1 μm) existing in all samples may belong to a long-term suspension component in a fluid medium, the transportation and deposition of which depend on the intensity of turbulence. Component C2 (modal size: 2.1–10.7 μm) also existing in all samples becomes finer towards the lake center (Figs. 6 and 7; Table 3), implying that the C2 represents an offshore suspension component. Component C3 (modal size: 8.0–59.4 μm) does not only become finer towards the lake center but is lacking in the samples from the nearshore zone as well (Figs. 6 and 7; Table 3), denoting that the C2 also represents an offshore suspension component. Component C4 (modal size: 47.7–119.6 μm) is lacking in the samples from the offshore zone and decreases in the relative percentage in a sample with increasing water depth in the nearshore and transitional zones (Figs. 6 and 7; Table 3), suggesting that the C4 represents a nearshore suspension component. Component C5 (modal size: 185.2–433.2 μm) occurs mainly in the samples from the nearshore zone (Figs. 6 and 7; Table 3), indicating that the C5 represents a nearshore saltation component.

As shown in Fig. 4 and Table 2, the modal sizes of two adjacent components among the C2 (offshore-suspension fine silt), C3 (offshore-suspension medium-to-coarse silt) and C4 (nearshore-suspension fine sand) overlap. This implies an inherent relationship between the two components. We infer that both fluvial and eolian materials entering a lake had been reworked within the lake by the hydraulic dynamics of lake waters before being deposited on the lake floor, so that the attribution of some clastic particles might be transformed from one component to the adjacent component during the hydraulic reworking. In general, the coarse tail of a finer component would be reworked to a part of the adjacent coarser component under the higher-energy hydraulics (closer to the lakeshore); whereas the fine tail of a coarser component would be reworked to a part of the adjacent finer component under the lower-energy hydraulics (closer to the lake center).

5.2. Grain-size component–lake level status model

The grain-size components of the surface sediments of Daihai Lake exhibit a spatial distribution within the lake that characterizes the modern hydraulic condition of the lake. In view of the close relationship between the hydraulic condition of a lake and the water depth and size of the lake (Håkanson and Jansson, 1983; Sly, 1989a,b), these observations provide the possibility of establishing a model for linking sedimentary components to lake level status.

As shown in Fig. 6 and Table 3, the percentages of the C4 (nearshore suspension component) and the C5 (nearshore saltation component) are negatively related to water depth. Both components can be viewed as a whole as the nearshore components, and thus the relationship between the percentage of the C4 plus C5 and water depth as well as offshore distance was analyzed (Figs. 6 and 7; Table 3). The negative correlation between the C4 + C5 percentage and the water depth is most significant (correlation coefficient: 0.52). These data indicate that the C4 and C5 components interpreted as an indication of the nearshore environments do constitute more of the grain-size distribution in the samples

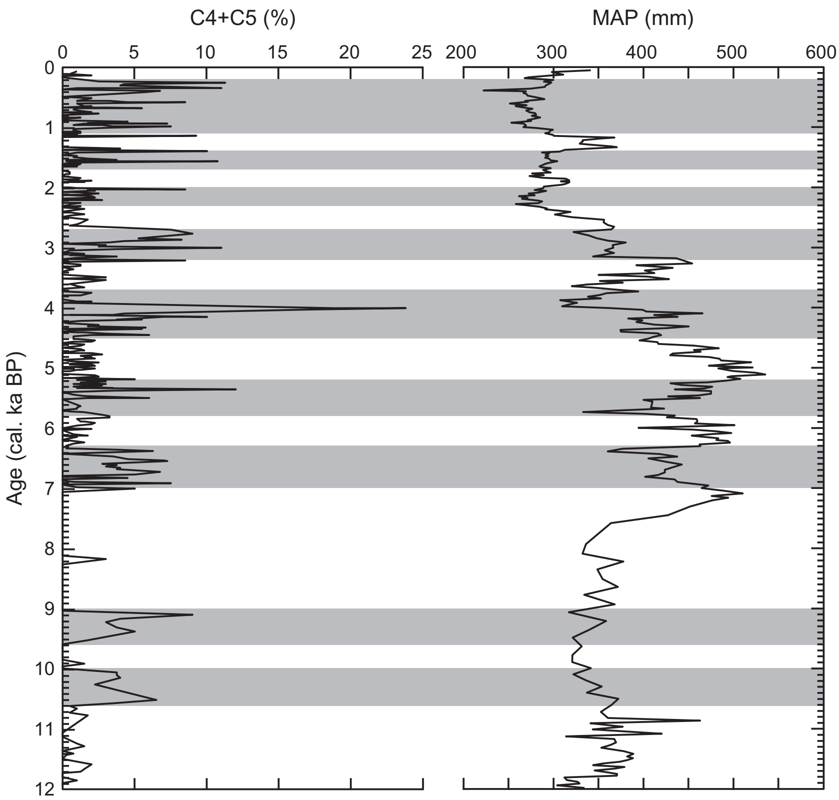

Fig. 9. Percentage of the nearshore grain-size components (C4 + C5, %) of the DH99a sediment core recovered in the central part of Daihai Lake spanning the last 12,000 cal. yr, compared with the mean annual precipitation (MAP, mm) reconstructed on the pollen profile of the same core. The chronology was derived from calibrated ages of reservoir-effect-corrected radiocarbon dates with a correction factor of 366 yr. Shaded bars mark the intervals of lowered lake levels and declined regional precipitations during the Holocene.

collected from the shallower waters and might therefore provide a model for reconstructing past changes in water depth according to the data from sediment cores.

5.3. Application of the grain-size component–lake level status model

The close relationship between the percentage of the nearshore components (Components C4 plus C5) in the surface sediments of Daihai Lake and the water depth offers a model for reconstructing the history of changes in the lake level during the geological past. Fig. 9 illustrates changes in the percentage of the nearshore components of the DH99a sediment core recovered in the central part of Daihai Lake spanning the last 12,000 cal. yr. The hard-water reservoir effect on radiocarbon dating of the bulk organic matter of Daihai Lake sediments was considered to be 366 yr (Xiao et al., 2004). The chronology presented for the DH99a core in this study was derived from calibrated ages of reservoir-effect-corrected radiocarbon dates. As shown in Fig. 9, the nearshore components display increases in the percentage during the intervals of ca. 10,600–10,000, 9600–9000, 7000–6300, 5800–5200, 4500–3700, 3200–2700, 2300–2000, 1700–1400, and 1100–200 cal. yr BP, indicating drops in the lake level during these episodes.

Based on the pollen profile of the same sediment core (Xiao et al., 2004) and the pollen–climate transfer function for temperate eastern Asia (Wen et al., submitted for publication), the Holocene history of changes in precipitation in the Daihai Lake region was quantitatively reconstructed (Fig. 9). The regional precipitation exhibits obvious decreases during the above periods, suggesting a good correlation between the high percentages of the nearshore components in the lake sediments and the low precipitations in the lake region (Fig. 9).

Modern observations and historical documents indicate that Daihai Lake shrank and the lake level fell during the low-rainfall years (Wang and Wang, 1993). Our data indicate that the nearshore components increased in the lake sediments when the mean annual precipitation decreased in the lake region. Such a good coincidence of two independent proxies does not only demonstrate the validity of lognormal distribution function in fitting and partitioning polymodal lake sediments but also reveals the potential of the grain-size component–lake level status model for the research of the paleohydrological history 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 Daihai Lake contain five distinct unimodal grain-size distributions representing five grain-size components. Each of the components retains its identity, including modal size, manner of transportation and environment of deposition, although the relative percentage varies with the hydraulic conditions throughout the lake. These components are specified from fine to coarse modes as long-term suspension clay, offshore-suspension fine silt, offshore-suspension medium-to-coarse silt, nearshore-suspension fine sand and nearshore-saltation medium sand.

Grain-size components interpreted as an indication of nearshore hydrodynamic environments contribute proportionately more to the modern lakebed samples collected from the shallow waters. Such a good relationship provides a grain-size component–lake level status model for lake's paleohydrological reconstruction. The potential value of this model was demonstrated by the coincidences between high percentages of the nearshore components of the core sediments of Daihai Lake and low regional precipitations reconstructed on the pollen profile of the same sediment core.

The success of application of the lognormal distribution function method to partitioning the grain-size components of polymodal lake sediments proves to be a valuable approach to understanding the processes of transportation and deposition of clastic materials within lakes and relating the grain-size components to specific sedimentary environments of lakes.

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