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The link between grain-size components and depositional processes in a modern clastic lake

JULE XIAO, ZHIGANG CHANG, JIAWEI FAN, LANG ZHOU, DAYOU ZHAI, RUILIN WEN and XIAOGUANG QIN

Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China (E-mail: jlxiao@mail.iggcas.ac.cn)

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ABSTRACT

It is widely recognized that lake sediment grain-size distributions tend to be polymodal and consist of two or more grain-size components. However, for specific cases, the genesis of each component usually is poorly understood. In this study, the grain-size components of the surface sediments of Hulun Lake, Inner Mongolia, were partitioned using the log-normal distribution function method and the relationship between the identity of each grain-size component and the hydraulic condition of the lake was investigated in order to relate the constituent components to specific depositional processes in the lake. The data indicate that the modern clastic sediments of Hulun Lake contain six distinct unimodal grain-size distributions representing six 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 and medium to coarse silt, and nearshore-suspension fine sand, saltation medium sand and traction coarse sand. The percentage contribution of several grain-size components interpreted as being indicative of nearshore environments is shown to be correlated negatively with water depth across the modern lake bed; this suggests that the proportion of these components in core data might be useful as a proxy for water depth. This possibility was tested using a sediment core from Hulun Lake where high percentages of the nearshore grain-size components were found to be correlated with low regional precipitation reconstructed from the pollen profile of the same core. The coincidence of two independent proxies does not only demonstrate the validity of log-normal distribution function in partitioning polymodal sediments but reveals the potential of lake sediment grain-size components for the research of lake-level fluctuations during the geological past.

Keywords Grain-size component, Hulun Lake, lake-level status, offshore distance, polymodal sediment, water depth.

INTRODUCTION

The grain-size distribution of lake sediments has long been used to reconstruct the history of changes in the hydrology of lakes associated with regional climatic and environmental conditions (Håkanson & Jansson, 1983). The grain-size parameters, however, can be regarded only as approximate proxies because lake sediments are characterized by polymodal grain-size distributions, and different components within an individual distribution might be formed by different depositional processes (Visher, 1969; Middleton, 1976; Ashley, 1978). A reliable interpretation of the grain-size data obtained from lake sediments requires an adequate understanding of the physical process that may have governed the formation of the grain-size components of polymodal deposits in lakes.

With the aid of high-resolution grain-size data generated by laser grain-size analysers, mathematical methods have been applied to define grain-size distributions and partition the constituent components of fluvial (Kranck *et al.*, 1996; Påsse, 1997), aeolian (Sun *et al.*, 2002; Qin *et al.*, 2005) and marine (Prins *et al.*, 2000; Weltje & Prins, 2003) sediments. Until now, however, little attention has been paid to the partitioning of grain-size components of lacustrine sediments despite the fact that clastic materials deposited in lakes potentially provide an important source of information about changes in regional hydrology and global atmospheric circulation. In this study, the log-normal distribution function method was used to numerically partition the grain-size components within individual grain-size distributions of 40 surface–sediment samples taken along two sections in Hulun Lake in north eastern Inner Mongolia, China. The purpose of this study is to interpret the genesis of polymodal grain-size distributions of lake sediments and relate the constituent grain-size components to specific sedimentary environments.

HULUN LAKE BASIN

Hulun Lake (48°30·667′ to 49°20·667′ N, 117°0·167′ to 117°41·667′ E), the fifth largest lake in China, lies in an inland graben basin in Inner Mongolia (Fig. 1). It has an area of 2339 km^2 and a maximum water depth of 8 m when the elevation of the lake level is 545·3 m above sea-level (a.s.l.; measurements taken in August 1964; Xu *et al.*, 1989). Low mountains and hills of Mesozoic volcanic rocks border the lake on the north west and form a fault-scarp shoreline. Broad lacustrine and alluvial plains scattered with aeolian dunes are present along the southern and eastern shore. The lake has a catchment of 37 214 km^2 within the borders of China. Two major rivers, the Herlun and Urshen Rivers, enter the lake from the south-west and south-east (Fig. 1). The Herlun River rises in the southern part of the Hentiy Mountains in Mongolia and has a total channel length of 1260 km. The Urshen River drains from Beir Lake that has an area of 608 km^2 and a maximum water depth of >50 m, and flows northward through depressions, swamps and dunes into Hulun Lake; it has a total channel length of more than 200 km. Hydrological observations suggest that both rivers remain at a slow and steady flow even during the high-rainfall years and no obvious river floods have occurred since the beginning of observations in 1957 (Xu *et al.*, 1989). The Dalanolom River, an intermittent river, drains the lake when the elevation of the lake level exceeds 543·4 m a.s.l., and enters the lake when the lake level is lower and the high discharge of the Hailar River occasionally supplies water to it during spring floods in May and June (Xu *et al.*, 1989; Fig. 1).

Hulun Lake is located in a semi-arid area of the middle temperate zone. The climate of the Hulun Lake region is under the influence of the East Asian monsoon (Chinese Academy of Sciences, 1984; Zhang & Lin, 1985). During the summers, the warm, moist southerly air masses interact with cold air from the north west and produce most of the annual precipitation. During the winters, the cold, dry north westerly airflows prevail and bring strong winds and dust storms to the region. In the lake region, mean annual temperature is 0·3°C with a July average of 20·3°C and a January average of −21·2°C. Annual precipitation is 247 to 319 mm, and more than 80% of the annual precipitation falls during June to September. Annual evaporation reaches 1400 to 1900 mm, which is five to six times the annual precipitation. The lake is covered with *ca* 1 m of ice from November to April.

SAMPLES AND METHODS

Sediment sampling

The surface sediments of Hulun Lake were sampled in August 2009 along the Transects A and B, yielding 21 samples for Transect A and 19 samples for Transect B (Figs 1 and 2; Table 1). The transects start at A1 (49°9·901′ N, 117°25·364′ E) and B1 (48°59·939′ N, 11714·023′ E) on the north western shore of the lake and end at A21 (49°1·478′ N, 117°41·889′ E) and B19 (48°50·983′ N, 117°31·003′ E) on the south eastern shore. At each site, a sediment core was retrieved in either a 40 cm or 60 cm long polyethylene tube using a gravity corer. The water–sediment interface and millimetre-scale thick whitish-grey 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

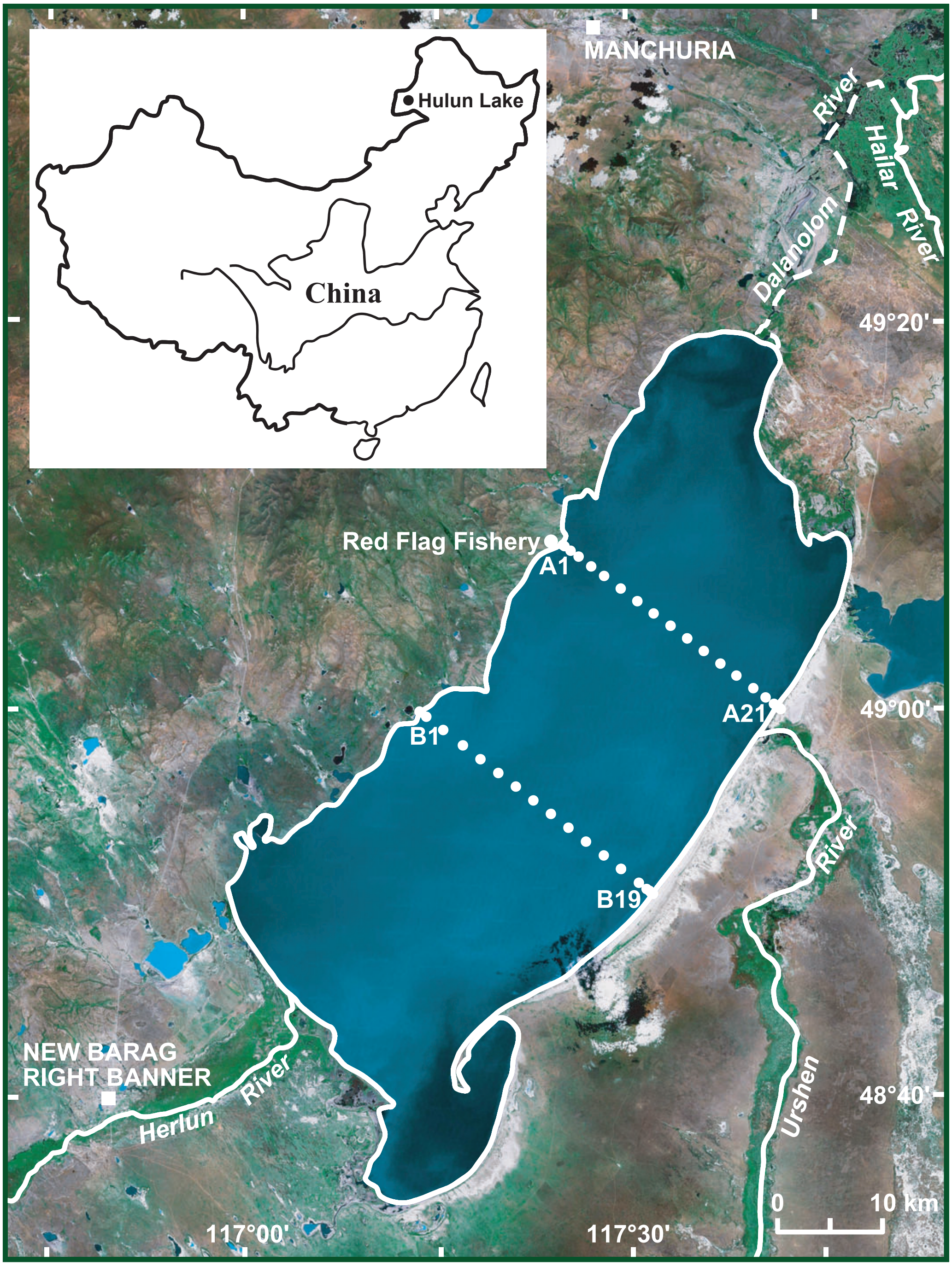

Fig. 1. Map of Hulun Lake (from http://maps.google.com) showing locations of the surface–sediment sampling sites along the Transects 'A' and 'B'. The inset gives a sketch map of China showing the location of Hulun Lake.

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 aeolian dust that was trapped on the ice of Hulun Lake was collected in the central part of the lake (49°6·214′ N, 117°30·012′ E) in March 2009. In addition, modern riverbed sands were sampled close to the mouths of the Herlun and Urshen Rivers (Fig. 1) in August 2009.

Grain-size analysis

Grain-size distribution of all the samples was determined with a Malvern Mastersizer 2000

Table 1. Water depth and offshore distance of 40 surface–sediment sampling sites along the Transects 'A' and 'B' in Hulun Lake (measurements taken in September 2009).

Sample number	Water depth (m)	Offshore distance (km)	Sample number	Water depth (m)	Offshore distance (km)
A1	0·70	0·02	B1	1·00	0·06
A2	1·00	0·05	B2	1·45	0·23
A3	1·60	1·26	B3	1·95	0·82
A4	2·10	1·00	B4	2·35	2·80
A5	2·45	1·88	B5	2·75	5·00
A6	2·85	3·45	B6	2·85	7·00
A7	2·95	5·00	B7	2·85	9·00
A8	3·00	7·00	B8	2·85	11·00
A9	3·10	9·00	B9	2·85	13·00
A10	3·15	11·00	B10	2·85	12·10
A11	3·05	13·00	B11	2·85	10·10
A12	3·00	11·30	B12	2·85	8·10
A13	2·90	9·30	B13	2·80	6·10
A14	2·90	7·30	B14	2·55	4·10
A15	2·85	5·30	B15	2·25	2·10
A16	2·55	3·30	B16	1·75	1·20
A17	2·15	1·80	B17	1·25	0·90
A18	1·60	0·80	B18	0·80	0·70
A19	1·10	0·30	B19	0·40	0·50
A20	0·65	0·10			
A21	0·40	0·02			

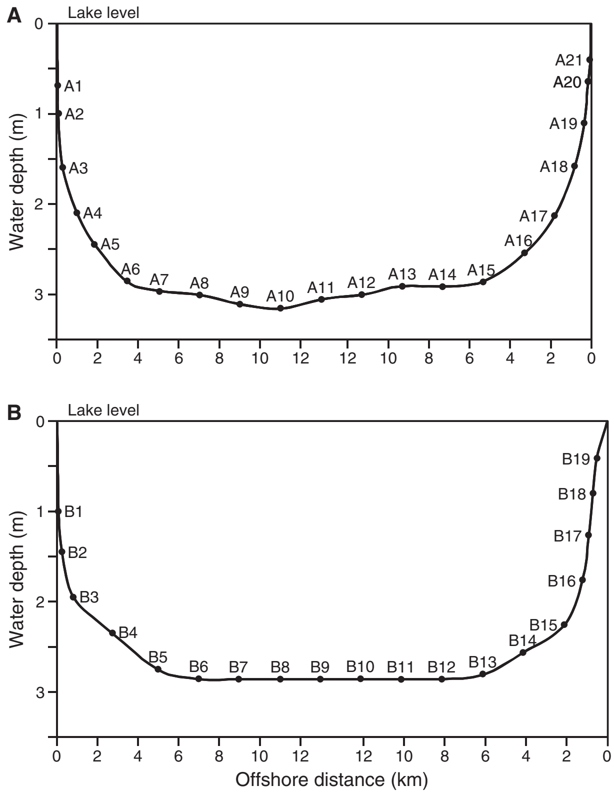

Fig. 2. Profile of the lake floor along the transects showing the sampling sites: (A) Transect A; (B) Transect B. The vertical axis indicates water depth and the horizontal axis indicates offshore distance to the closer (north western or south eastern) lakeshore.

laser grain-size analyser (Malvern Instruments Limited, Malvern, UK). About 200 mg of sediment from each air-dried, disaggregated sample was pre-treated with 10 to 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 to the technique of 'equivalent spheres'. The Mastersizer 2000 has a measurement range of 0·02 to 2000 μm in diameter and a grain-size resolution of $0{\cdot}166\phi$ in interval, thus yielding 100 grain-size fractions [$\phi = -\log_2(D)$, where D is the grain diameter in millimetres]. The Mastersizer provides the percentage by volume of each grain-size fraction in a sample. The relative error is <1% on the 50th percentile and 2% on the outlying percentiles.

Fitting and partitioning of grain-size components

The grain-size distribution of clastic deposits with a single component should exhibit a unimodal, symmetrical distribution on a logarithmic scale (Inman, 1949; Folk & Ward, 1957; Tanner, 1964; Visher, 1969; Ashley, 1978). When the shape of a grain-size distribution is asymmetrical or skewed, the total distribution can be considered to be a combination of several unimodal distributions (Inman, 1949; Folk & 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 log-normal 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 log-normal distribution function (Ashley, 1978; Påsse, 1997; Qin *et al.*, 2005). In this study, the log-normal distribution function method described by Qin *et al.* (2005) was applied to identify, fit and partition the grain-size components of the surface sediments of Hulun Lake. The formula of the log-normal distribution function is expressed as follows:

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

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, $c_i \geq 0$, and the sum of nc_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:

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

where m is the number of grain-size intervals, $F(x_j)$ is the fitted percentage of the jth grain-size interval and $G(x_j)$ 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 and 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.

(i) Place the measured grain-size data of all the samples into a worksheet of MS Excel. (ii) Start the program, select the target sample, and the initial values of the estimated parameters (c, a and σ) of each mode in the sample are given automatically by the random number generator within the program. The fitting calculations are performed using the above estimated parameters (n, c, a and σ) and the measured grain-size data to yield the initial fitting residual. (iii) The program starts iterative-loop calculations of the four parameters (n, c, a and 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 and $\Delta\sigma$) in each calculation is designated a low value to ensure a good enough fitting ($\Delta c = 0{\cdot}01$, $\Delta a = (a_i - a_{i-1})/100$ and $\Delta\sigma = \sigma/100$). 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 log-normal 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 micrometres. The modal size of the ith mode is calculated as follows:

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

To illustrate identifying, fitting and partitioning of grain-size components within a polymodal distribution using the log-normal distribution function, six surface–sediment samples of Hulun Lake were selected from the Transects A and B (Fig. 3). These samples represent the modern sediments deposited in three different environments of the nearshore zone (A2 and B1), offshore zone (A10 and B9) and the transitional zone (A16 and B15) of the lake (Figs 1 and 2). The fitting and partitioning result and the minimum residual of each sample are shown (Fig. 3).

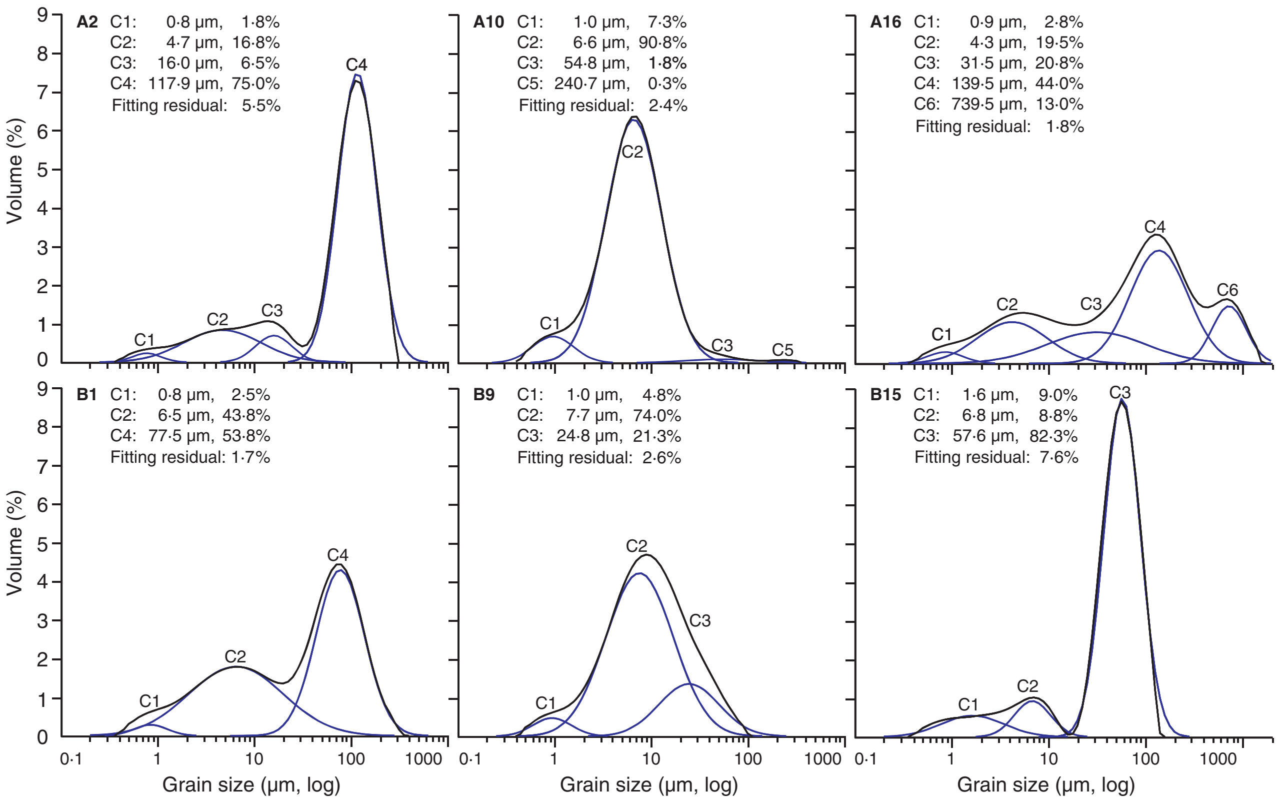

Fig. 3. Frequency distribution curves (black lines) of six representative samples from the surface sediments of Hulun Lake illustrating identifying, fitting and partitioning of grain-size components (blue lines) within a polymodal distribution using the log-normal distribution function. Altogether, six grain-size components can be recognized on the polymodal distributions, and are designated C1 to C6 from fine to coarse modes. The components of each sample are labelled on each curve. The sample number, the modal size and percentage of each component and the fitting residual of each sample are shown.

RESULTS

Fittings of the log-normal distribution function suggest that each polymodal grain-size distribution of samples from the surface sediments of Hulun Lake consists of three to five unimodal distributions. These unimodal distributions can be identified as six distinct modes representing six grain-size components, respectively, according to the dominant range of modal sizes of each unimodal distribution. The six components are designated C1 to C6 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 sample B9 or C3 and C4 in sample A16), however, requires technical skills through trial-and-error fittings after careful observation. Fortunately, in this case, the fitting residual increases significantly if the minor component (C3 in samples B9 and A16) is ignored. Such experiments demonstrate the validity and accuracy of the log-normal distribution function in fitting and partitioning the grain-size components of polymodal sediments.

Grain-size data suggest that the components C1, C2 and C3 to C6 identified from 40 individual grain-size distributions of the surface–sediment samples from Hulun Lake have identifiable characteristics (Figs 4 and 5; Table 2). The modal sizes of C1, C2 and C3 to C5 vary primarily within ranges of 0·8 to 2·3 µm, 3·0 to 9·0 µm, 8·8 to 62·2 µm, 65·7 µm to 160·7 µm and 176·2 to 650·3 µm, respectively. The coarsest component that appears in sample A16 displays a modal size of 739·5 µm (Fig. 3). This component was designated an independent component, C6, because it has a modal size that is much larger than the dominant modal size of C5 (Fig. 3).

The percentages of each grain-size component in a sample were output by the program. The statistics of all 40 of the surface–sediment samples from Hulun Lake (Fig. 5; Table 2) show that

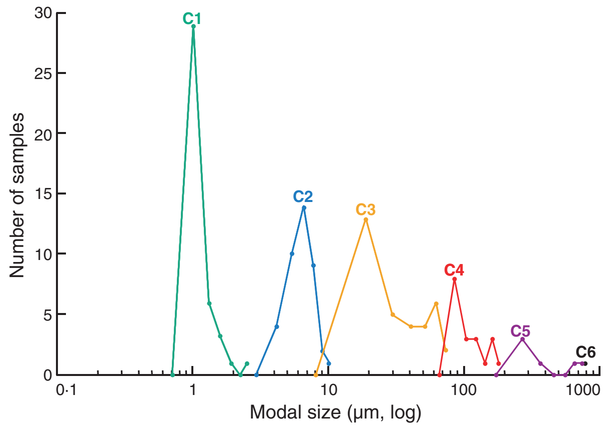

Fig. 4. Frequency of the modal sizes of the six grain-size components, C1 to C6, in 40 samples from the surface sediments of Hulun Lake.

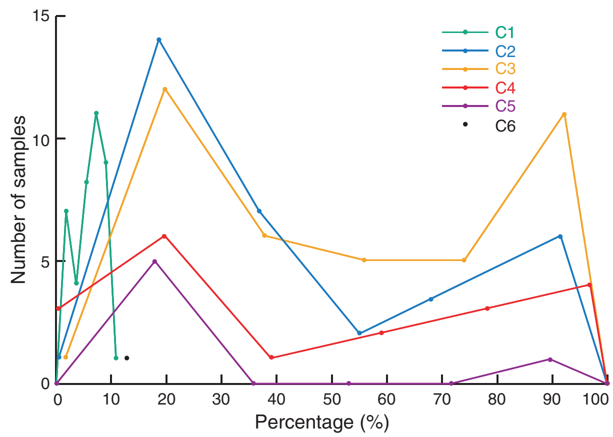

Fig. 5. Frequency of the percentages of the six grain-size components, C1 to C6, in 40 samples from the surface sediments of Hulun Lake.

component C1 constitutes <10% in each sample. In contrast, the components C2, C3, C4 and C5 make up *ca* 90% of some samples and *ca* 20% of the others. The C6 component accounts for 13% in sample A16.

Among all sampling sites, the water depth ranges from 0·40 to 3·15 m and the offshore distance varies from 0·02 km up to 13 km (Figs 1 and 2; Table 1). The distribution of different components in the samples (Figs 6 and 7; Table 2) indicates that: (i) components C1 and C2 exist in all samples; (ii) component C3 is missing from six samples in which the C4 component clearly is present; (iii) component C4 occurs only in 19 samples that are distributed in the zone of <3·050 m water depth and <5 km offshore distance and, when the C4 component is present, the C3 component is either absent or assumes a modal size of *ca* <32 μm; and (iv) the C5 and C6 components occur only in six samples and one sample, respectively.

DISCUSSION

Interpretation of the grain-size components

Hulun Lake is located in a semi-arid area of 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 sediments of Hulun Lake are derived mainly from fluvial materials transported by the rivers during the summer season and aeolian dust trapped on the ice of the lake during the dry and windy spring season. 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 & Jansson, 1983; Talbot & Allen, 1996).

Previous studies suggested that the three types of clastic sediments assume different combinations of specific grain-size components due to

Table 2. Characteristics of the six grain-size components recognized on the polymodal distributions of 40 samples from the surface sediments of Hulun Lake.

Component	Number of samples	Modal size (μm) Min.	Modal size (μm) Max.	Percentage Min.	Percentage Max.	Component description
C1	40	0·8	2·3	0·3	9·3	Long-term suspension
C2	40	3·0	9·0	1·8	92·3	Offshore suspension
C3	34	8·8	62·2	0·5	91·5	Offshore suspension
C4	19	65·7	160·7	0·3	96·8	Nearshore suspension
C5	6	176·2	650·3	0·3	89·5	Nearshore saltation
C6	1	739·5			13·0	Nearshore traction

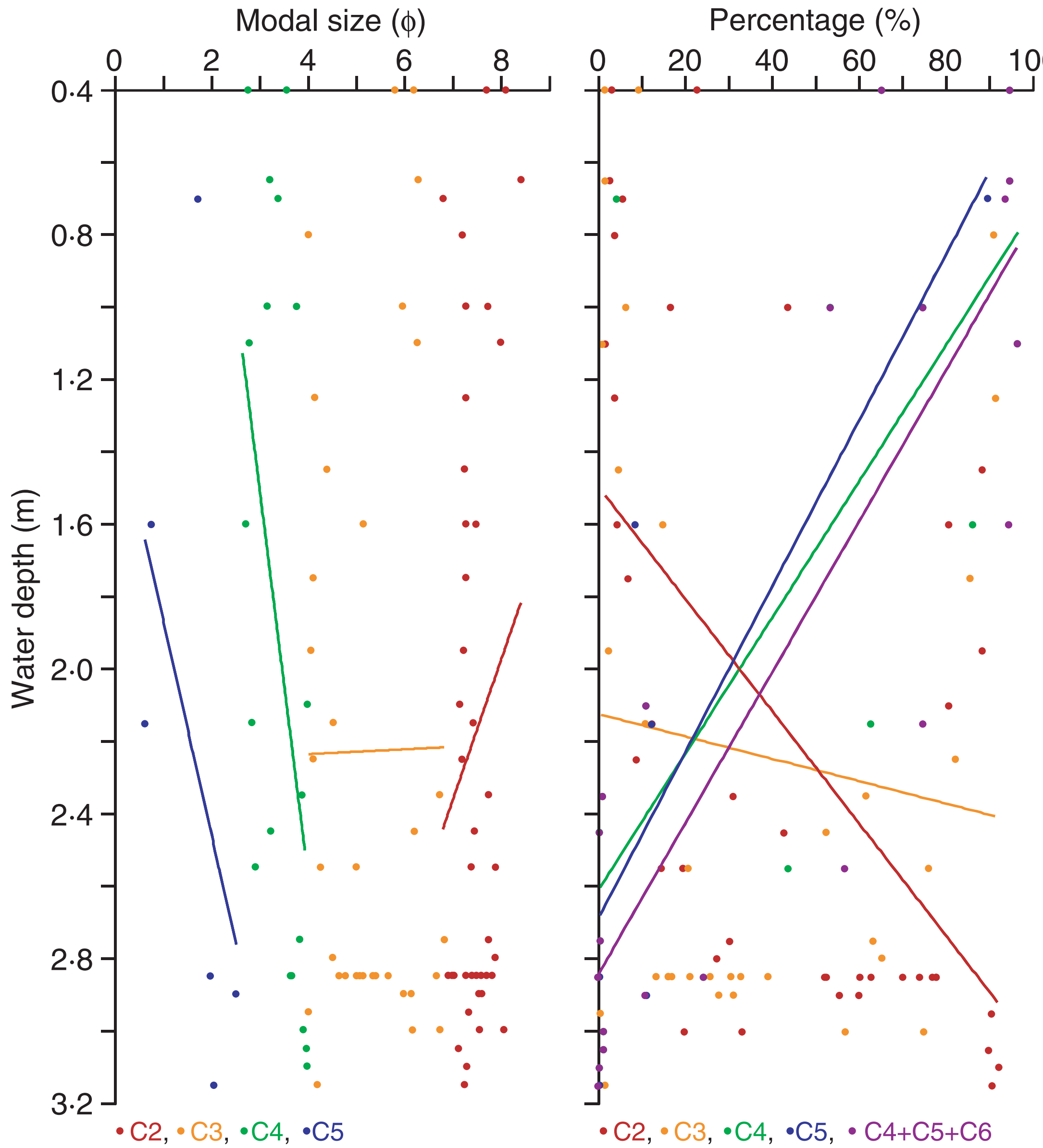

Fig. 6. Modal size and percentage of the grain-size components in 40 samples from the surface sediments of Hulun Lake plotted against water depth. Linear regression lines are shown. For the regression equation, correlation coefficient and standard error, see Table 3.

distinct transport mechanisms. Fluvial deposits are composed mainly of a saltation medium-sand component [modal size (Ms): 200 to 400 μm] and a suspension fine-silt component (Ms: 10 to 15 μm) (Middleton, 1976; Ashley, 1978; Bennett & Best, 1995). Typical loess deposits consist of a short-suspension medium-to-coarse silt component (Ms: 16 to 32 μm) and a long-suspension clay-to-fine silt component (Ms: 2 to 6 μm) (Pye, 1987; Tsoar & Pye, 1987; Sun *et al.*, 2002; Qin *et al.*, 2005), whereas desert sands consist of a saltation fine-to-medium sand component (Ms: 100 to 200 μm) and a suspension clay-to-fine silt component (Ms: 2 to 6 μm) (Gillette *et al.*, 1974; Pye, 1987; Tsoar & Pye, 1987). Lake shoreline materials are dominated by unconsolidated sands with a low proportion of silty clay (Sly, 1978; Håkanson & Jansson, 1983). In order to understand the constituent components of source materials of the Hulun Lake sediments, modern aeolian dust trapped on the ice in the central part of the lake and modern riverbed sands deposited nearby the mouths of the Herlun and Urshen Rivers were analysed for grain-size distribution.

As shown in Fig. 8, both the ice-trapped aeolian dust materials and riverbed sands are composed of multiple components and dominated by the coarsest component. The dominant component of the ice-trapped aeolian dust displays a modal size of 306 μm that is much coarser than the modal size (100 to 200 μm) of the dominant saltation component of typical dune sands. Modern dust-storm events in the lake region occur mainly in spring when the north westerly winds are strong and the lake is frozen (Xu *et al.*, 1989). The suspension and saltation components of the aeolian materials could be blown downwind because of strong winds, and the coarse traction component 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 aeolian sediment has a larger modal size than that of typical dune sands. The dominant component of Herlun and Urshen riverbed sands shows modal sizes of 147 μm and 122 μm that are finer than the modal size (200 to 400 μm) of the dominant saltation component of typical fluvial deposits. Both the Herlun and Urshen Rivers flow through sand dunes and run dry during the dry years (Xu *et al.*, 1989). The sands from the sand dunes, source materials of the fluvial deposits, appear not to have been reworked and sorted sufficiently by the rivers during the process of transportation, so that the dominant component of the riverbed sands displays a modal size that is finer than that of typical fluvial deposits and corresponds with that of typical dune sands.

The nature and distribution of clastic deposits are controlled by the dynamic condition of the transporting media (Inman, 1949; Folk & Ward, 1957; Tanner, 1964; Visher, 1969; Ashley, 1978). Fundamentally, a relationship exists between clastic and hydraulic interactions 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 deposits in lakes become coarser with higher hydraulic energy. Taking the spatial distribution of each grain-size component within the lake, together with these observations, it is inferred here that the components C1, C2 and C3 to C6 of the surface sediments of Hulun Lake represent different sedimentary modes related to different depositional processes (Table 2). Component C1 (Ms: 0·8 to 2·3 μm) which exists in all samples may belong to a long-term suspension component in a fluid medium, the transportation and deposition of which depends on the intensity of turbulence. The C2 (Ms: 3 to 9 μm) and C3 (Ms: 8·8 to 62·2 μm) components represent two offshore suspension components. The C4 (Ms: 65·7 to 160·7 μm), C5 (Ms: 176·2 to 650·3 μm) and C6 (Ms: 739·5 μm) components that occur mainly in the nearshore samples are interpreted as nearshore suspension, saltation and traction components, respectively.

As shown in Fig. 4, the modal sizes of two adjacent components among C2 (offshore-suspension fine silt), C3 (offshore-suspension medium-to-coarse silt), C4 (nearshore-suspension fine sand), C5 (nearshore-saltation medium sand) and C6 (nearshore-traction coarse sand) overlap; this implies an inherent relationship between the two components. The authors infer that clastic materials had been reworked by the hydraulic

Table 3. Relationship between the modal size and percentage of the grain-size components in 40 samples from the surface sediments of Hulun Lake and the water depth, as well as the offshore distance.

Grain-size component	Regression equation*	Correlation coefficient	Standard error (m)	Regression equation†	Correlation coefficient	Standard error (km)
C2 modal size	$y = -0{\cdot}39x + 5{\cdot}07$	0·02	0·9	$y = -3{\cdot}0x + 27{\cdot}02$	0·06	4·2
C3 modal size	$y = -0{\cdot}007x + 2{\cdot}26$	0		$y = 0{\cdot}08x + 4{\cdot}34$	0	
C4 modal size	$y = 1{\cdot}07x - 1{\cdot}68$	0·25	0·8	$y = 4{\cdot}97x - 13{\cdot}55$	0·34	3·2
C5 modal size	$y = 0{\cdot}59x + 1{\cdot}27$	0·23	0·8	$y = 4{\cdot}49x - 2{\cdot}02$	0·48	3·5
C2 percentage	$y = 0{\cdot}02x + 1{\cdot}49$	0·33	0·7	$y = 0{\cdot}07x + 1{\cdot}35$	0·30	3·6
C3 percentage	$y = 0{\cdot}003x + 2{\cdot}12$	0·01	0·8	$y = -0{\cdot}005x + 4{\cdot}94$	0	
C4 percentage	$y = -0{\cdot}02x + 2{\cdot}61$	0·55	0·7	$y = -0{\cdot}06x + 5{\cdot}48$	0·36	3·2
C5 percentage	$y = -0{\cdot}02x + 2{\cdot}69$	0·70	0·5	$y = -0{\cdot}09x + 6{\cdot}92$	0·37	3·9
C4 + C5 + C6 percentage	$y = -0{\cdot}02x + 2{\cdot}85$	0·73	0·5	$y = -0{\cdot}08x + 7{\cdot}01$	0·52	3·0

In the linear regression equation, x represents modal size or percentage of the grain-size components and y represents water depth in metres or offshore distance in kilometres. For data of the grain-size components, see Figs 6 and 7.
*Relationship between the modal size and percentage of grain-size components and the water depth.
†Relationship between the modal size and percentage of grain-size components and the offshore distance.

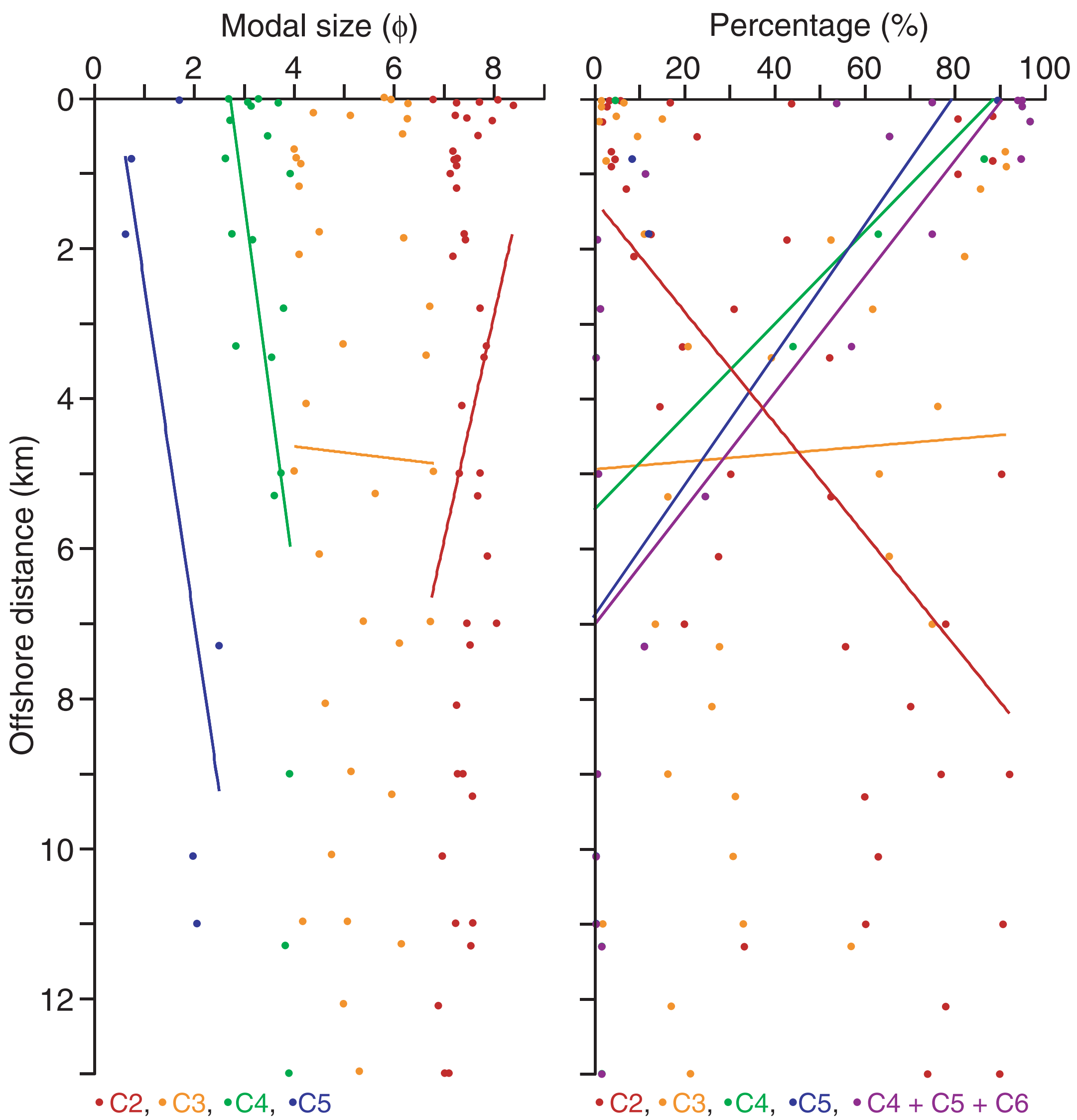

Fig. 7. Modal size and percentage of the grain-size components in 40 samples from the surface sediments of Hulun Lake plotted against offshore distance. Linear regression lines are shown. For the regression equation, correlation coefficient and standard error, see Table 3.

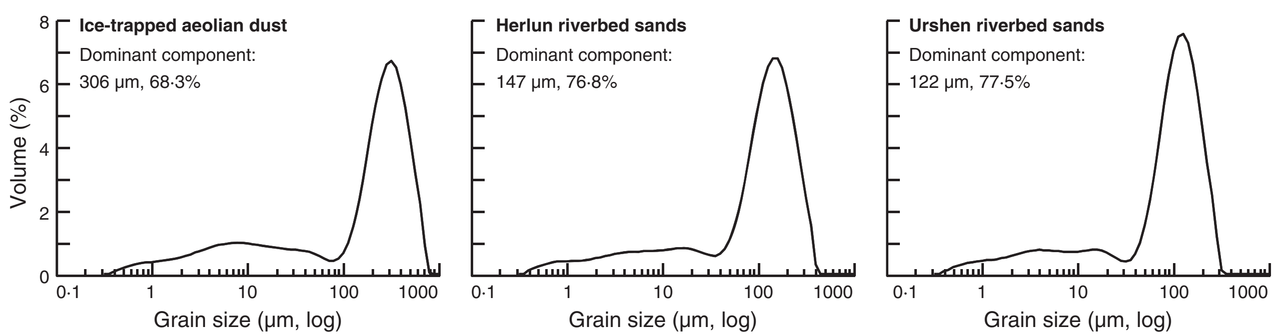

Fig. 8. Frequency distribution curves of modern aeolian dust trapped on the ice in the central part of Hulun Lake and modern riverbed sands deposited at the mouths of the Herlun and Urshen River. The modal size and percentage of the dominant component of each sample are shown.

dynamics of lake waters during transportation within the lake, resulting in the transformation of the attribution of some particles from one component to the adjacent component. In general, the coarse tails of finer components would be reworked to a part of the adjacent coarser component under the condition of higher hydraulic energies (closer to the lakeshore); whereas the fine tails of coarser components would be reworked to a part of the adjacent finer component under the condition of lower hydraulic energies (closer to the lake centre).

Relationships between the major components and the lake levels

The major grain-size components of the surface sediments of Hulun Lake exhibit a spatial distribution within the lake that characterizes the modern hydraulic condition of the lake. The hydraulic condition of a specific lake is closely related to the water depth and size of the lake (Håkanson & Jansson, 1983; Sly, 1989a,b). In general, the hydraulic energy of lake waters intensifies in the nearshore zone. In order to understand implications of the grain-size components for lake levels, the relationships between the modal size and percentage of the major components and the water depth (Fig. 6; Table 3), as well as offshore distance (Fig. 7; Table 3), were analysed.

As shown in Fig. 6 and Table 3, the modal sizes of the major components appear to have nothing to do with water depth; nevertheless, the percentages of the major components (except component C3) in the samples are obviously related to water depth. The C2 (offshore-suspension fine silt) percentages show a positive relation with water depth (correlation coefficient: 0·33), whereas the percentages of C4 (nearshore-suspension fine sand), C5 (nearshore-saltation medium sand) and C4 + C5 + C6 display negative relations with water depth (correlation coefficients: 0·55, 0·70 and 0·73, respectively). With respect to offshore distance (Fig. 7; Table 3), both the modal sizes of C4 and C5 show negative relations with offshore distance (correlation coefficients: 0·34 and 0·48, respectively). The C2 percentages are positively related to offshore distance (correlation coefficient: 0·30), whereas the percentages of C4, C5 and C4 + C5 + C6 are negatively related to offshore distance (correlation coefficients: 0·36, 0·37 and 0·52, respectively). Judging from the correlation coefficient and the number of the samples, the negative correlation between the C4 + C5 + C6 percentage and the water depth is most significant (Fig. 6; Table 3). These data indicate that those components interpreted as indicative of nearshore environments do, indeed, constitute more of the grain-size distribution in samples collected from shallower water and might, therefore, provide a useful means of reconstructing water depths from, for example, sediment core data.

Application of the nearshore component–water depth model

The close relationship between the percentage of the nearshore components in the surface sediments of Hulun Lake and the water depth provides a new method for reconstructing the history of changes in the lake level during the geological past. Figure 9 illustrates the percentage of the nearshore components of the HL06 sediment core recovered in the central part of Hulun Lake spanning the last 11 000 cal yr (Xiao *et al.*, 2009). The nearshore components display increases in the percentage during the intervals of *ca* 9200 to 8500 cal yr BP, 8100 to 7700 cal yr BP, 6600 to 6000 cal yr BP, 4500 to 3600 cal yr BP, 3000

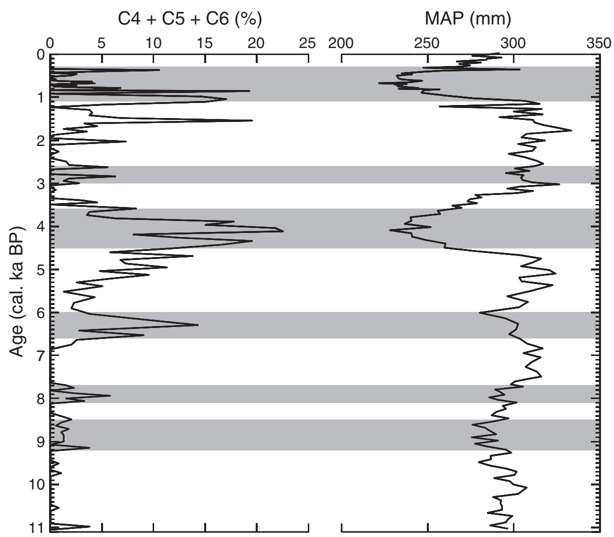

Fig. 9. Percentage of the nearshore grain-size components (C4 + C5 + C6) of the HL06 sediment core recovered in the central part of Hulun Lake spanning the last 11 000 cal yr (Xiao *et al.*, 2009), compared with the mean annual precipitation (MAP, mm) reconstructed on the pollen profile of the same core (Wen *et al.*, 2011). The chronology was derived from calibrated ages of reservoir-effect-free radiocarbon dates (Xiao *et al.*, 2009). Shaded bars mark the intervals of lowered lake levels and weakened regional precipitations during the Holocene.

to 2600 cal yr BP and 1100 to 300 cal yr BP, denoting drops in the lake level during these periods. Quantitative reconstruction of the regional precipitation based on the pollen profile of the same sediment core (Wen *et al.*, 2011) indicates that the mean annual precipitation in the lake region decreased during the above episodes. The high percentages of the nearshore components in the lake sediments can be correlated well both in phase and in amplitude with the low precipitations in the lake region (Fig. 9).

Historical documents and modern observations indicate that Hulun Lake shrank and the lake level fell during the low-rainfall years (Xu *et al.*, 1989). The present data suggest that the nearshore components increased in the lake sediments when the mean annual precipitation decreased in the lake region. Such a good coincidence of variations between two independent proxies does not only demonstrate the validity of the log-normal distribution function method in fitting and partitioning polymodal lake sediments but also reveals the potential of the major grain-size components for the research of the palaeoenvironmental history of lakes.

CONCLUSIONS

Application of the log-normal distribution function method to fitting and partitioning individual, polymodal grain-size distributions suggests that the modern clastic sediments of Hulun Lake contain six distinct unimodal grain-size distributions, representing six 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 and medium-to-coarse silt, and nearshore-suspension fine sand, saltation medium sand and traction coarse sand. Grain-size components interpreted as being indicative of nearshore hydrodynamic environments contribute proportionately more to modern lakebed samples collected from shallow water. The potential value of such relations for palaeoenvironmental reconstruction was demonstrated by applying the log-normal partitioning method to a sediment core from Hulun Lake. High percentages of the nearshore components were found to be correlated with low regional precipitation reconstructed from the pollen profile of the same core. The success of the log-normal distribution function method applied 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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