Grain Size Characteristics of Sediments from Lake Balkhash, Kazakhstan and Their Response to Regional Environmental Change (Postprint)

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Abstract

Grain size parameters in lake sediments record rich information on watershed environmental changes and can provide a reliable approach for reconstructing paleoenvironmental change sequences in regions without instrumental data. Through analysis of environmental proxy indicators such as grain size and magnetic susceptibility in core sediments from Lake Balkhash, combined with radioactive 137Cs dating and instrumental records of watershed climate and lake water level, the characteristics of grain size variations in Lake Balkhash sediments and their environmental implications were investigated. The results indicate that the average content of clay-sized (<4 m) fraction in Lake Balkhash sediments is 20.32%, fine silt (4~16 m) 40.13%, medium silt (16~32 m) 22.86%, coarse silt (32~64 m) 10.55%, and sand (>64 m) 6.13%. Using the grain-size standard deviation method, environmentally sensitive fine-grained components (F1, 6.61~10.00 m) and coarse-grained components (F2, 45.71~69.18 m) were extracted from the sediments. The study demonstrates that against a background of continuously intensifying human activities, variations in the content of grain-size-sensitive components cannot sensitively reflect changes in lake water level, inflow runoff, or even regional climate, but instead exhibit a relatively significant correlation with changes in human activity intensity as reflected by magnetic susceptibility in the sediments (r=0.870, P<0.01). This may be attributed to the transport into the lake of fine-grained clastic materials rich in magnetic substances resulting from enhanced human activities in the watershed; as magnetic susceptibility in lake sediments increases, fine-grained materials in the sediments also increase. These research results can provide an important reference for paleoenvironmental reconstruction studies on long timescales, while also holding scientific significance for revealing the impacts of watershed human activities on lake environments.

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Full Text

Grain-size characteristics of lacustrine sediments in Balkhash Lake, Kazakhstan and its response to regional environmental changes

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Abstract

Lake sediment grain-size parameters contain rich information about watershed environmental changes and can provide a reliable approach for reconstructing paleoenvironmental sequences in areas lacking instrumental data. Through analysis of environmental proxies including grain size and magnetic susceptibility in core sediments from Lake Balkhash, combined with radioactive ^{137}Cs dating and instrumental records of watershed climate and lake water level, this study investigated the grain-size variation characteristics of Lake Balkhash sediments and their environmental implications. The results show that the average contents of clay (<4 m), fine silt (4-16 m), medium silt (16-32 m), coarse silt (32-64 m), and sand (>64 m) components in the lake sediments are 20.32%, 40.13%, 22.86%, 10.55%, and 6.13%, respectively. Using the grain-size standard deviation method, the environmentally sensitive fine-grained component (6.61-10.00 m) and coarse-grained component (45.71-69.18 m) were extracted from the sediments. The study reveals that against the background of intensifying human activities, changes in the content of grain-size sensitive components cannot sensitively reflect variations in lake water level, inflow runoff, or even regional climate. Instead, they show a significant correlation with changes in human activity intensity as reflected by sediment magnetic susceptibility ($r = 0.870$, $P < 0.01$). This is likely related to the transport of fine-grained detrital materials rich in magnetic substances into the lake due to enhanced human activities in the watershed. As magnetic susceptibility of lake sediments increases, fine-grained materials in the sediments also increase. These findings provide an important reference for long-term paleoenvironmental reconstruction research and have scientific significance for revealing the impact of watershed human

activities on lake environments.

Keywords: Kazakhstan; Balkhash Lake; lacustrine sediments; grain size; environmental change

1 Introduction

Over the past century, surface processes in the arid regions of Central Asia have been significantly affected by human activities, particularly lake changes and their ecological environmental effects, which have produced profound impacts on sustainable social development. Lake sediments serve as the primary carrier of watershed surface material transport, recording information about watershed climate and environmental changes, and providing a reliable approach for reconstructing paleoenvironmental sequences in areas lacking instrumental data. Previous studies have reconstructed past millennial-scale water level changes in Lake Balkhash using diatom fossil assemblages, showing that the lake experienced fluctuations from 342.0 m to 396.0 m over the past millennium. Additionally, multiple proxy data have been used to reconstruct temperature and precipitation in the Balkhash Lake basin over the past thousand years, revealing that temperature trends are opposite to precipitation, reflecting the "warm-dry" and "cold-wet" climate patterns characteristic of Central Asian arid regions. The results indicate that lake water level changes over the past millennium are basically consistent with watershed precipitation trends, suggesting that precipitation may dominate lake level fluctuations. Research has also shown that heavy metal enrichment in sediments after 1960 reflects continuous enhancement of human activities in the watershed, with instrumental records indicating significantly intensified human activities since the 1950s.

Lake Balkhash, located in Kazakhstan, is the largest lake in Central Asia and the terminus of the Ili River. Its ecological environment changes have attracted widespread international attention. The lake has a length of 614.0 km, average width of 48.5 km, maximum width of 70.0 km, water area of 18,200 km^2, average depth of 5.8 m, and maximum depth of 26.5 m. The Sarymsek Peninsula divides the lake into eastern and western parts. The eastern lake receives water from the Aksu, Karatal, Lepsy, and Ayaguz rivers, while the western lake is fed by the Ili River. The Ili River delta at the lake' s western end covers an area of 8000 km^2, with numerous lakes, marshes, and saline lands distributed within it. The watershed area is 413,000 km^2, with annual precipitation ranging from 140 mm to 1000 mm. Natural landscapes include forests, grasslands, semi-desert steppes, and lakes and reservoirs, with agricultural land accounting for 10.55% of the total watershed area. Watershed water resources are primarily used for irrigation, rice cultivation, industry, residential water supply, and fisheries, with agricultural irrigation accounting for over 70% of total water consumption.

Grain-size parameters in lake sediments have long been an effective indicator for paleoclimate and paleoenvironment research. Under ideal conditions, from lake shore to center, water depth gradually increases and hydrodynamic conditions gradually weaken, creating a ring-shaped distribution of grain size that increases from lake center to shore in the sequence of clay, silt, sand, and gravel. Under arid climate conditions, lake water level decreases, the lake surface contracts, the sampling point becomes closer to the shore, and grain size becomes coarser. Under humid climate conditions, lake water level rises, the lake surface expands, the sampling point becomes farther from the shore, and grain size becomes finer. Natural sediment grain-size distribution can indicate sediment sources, transport media, transport methods, and energy levels of transport media, and can also identify transport environments and reveal natural environmental changes in watersheds. At annual to decadal scales, when lake water level is relatively stable, rainfall becomes the main controlling factor for grain-size changes. In humid years with greater rainfall, runoff transport power is strong and carries coarser materials into the lake; conversely, in dry years with less rainfall, finer materials are transported into the lake. Due to their sensitivity to regional environmental changes, grain-size parameters are widely used in paleoenvironmental research to reconstruct watershed humidity, lake water level changes, and flood frequency and intensity.

This study focuses on grain-size parameters of lake sediments from Lake Balkhash in Kazakhstan, combined with ^{137}Cs dating, sediment magnetic susceptibility indicators, and instrumental climate and hydrological data from the Balkhash Lake region. The study examines the variation characteristics of grain size in lake core sediments and their response to regional environmental changes, aiming to provide scientific reference for long-term paleoenvironmental reconstruction research.

2 Materials and Methods

A 49 cm sediment core (BK01) was collected from the western part of Lake Balkhash (45°41 05 N, 73°45 05 E) using a UWITEC gravity corer. The sampling site has a water depth of 26.5 m, approximately 34 km from the eastern shore and 36 km from the western shore. In the field, samples were taken at 1 cm intervals, sealed in plastic bags. The specific activity of ^{137}Cs was measured using a high-purity germanium well-type detector (Ortec HPGe GWL) produced by the American GORTEC company. For grain-size analysis: (1) approximately 0.3 g of sample was placed in a 100 mL beaker with 20 mL of distilled water and 10 mL of hydrogen peroxide, shaken and heated to remove organic matter; (2) after complete decomposition of hydrogen peroxide, 10 mL of 10% hydrochloric acid was added and heated to fully react, removing carbonates and organic cement; (3) after the reaction, the supernatant was decanted, 100 mL of distilled water was added, the sample was allowed to settle, then 10 mL of 0.05 $mol \cdot L^{-1}$ sodium hexametaphosphate $[(NaPO_3)_6]$ solution was added, shaken and placed in an ultrasonic disperser for 15 minutes. The processed samples were measured using a Malvern Mastersizer 2000 laser particle size analyzer with a measurement range of 0.02–2000 m and repeat measurement error less than 3%. For magnetic susceptibility measurement, samples were taken at 1 cm intervals and measured using a Bartington MS2 magnetic susceptibility meter for low-frequency magnetic susceptibility, with the average taken after three measurements. Radioisotope dating and grain-size analysis were completed at the Analysis and Testing Center of the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, while magnetic susceptibility testing was completed at the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (Xinjiang Regional Center of Resources and Environment Science, Chinese Academy of Sciences).

3 Results

3.1 Chronology and Grain-size Distribution of Core Sediments

The Chernobyl nuclear reactor accident in 1986 resulted in a peak year for ^{137}Cs. Based on the variation of ^{137}Cs intensity with depth in the Lake Balkhash sediment core (Fig. 2), a ^{137}Cs peak appears at 17 cm. The average sedimentation rate from 17 cm to the surface is 0.50 cm·a^{-1}, from 9-17 cm is 0.41 cm·a^{-1}, and from 18-22 cm is 0.26 cm·a^{-1}. The average sedimentation rate of the entire 49 cm core is 0.35 cm·a^{-1}, which is consistent with the average sedimentation rate of approximately 0.35 cm·a^{-1} at a reference core (BAL-07) located about 68 km north of the sampling site. According to the distribution pattern of ^{137}Cs in lake sediment profiles in the Northern Hemisphere, the main accumulation peak corresponds to the global ^{137}Cs fallout peak in 1963. Below 34 cm, the clay content (<4 m) is relatively high and stable, with small amplitude variations. The clay content is highest (reaching 24.70%) at 10–30 cm.

The average contents of clay (<4 m), fine silt (4-16 m), medium silt (16-32 m), coarse silt (32-64 m), and sand (>64 m) in the core sediments are 20.32%, 40.13%, 22.86%, 10.55%, and 6.13%, respectively. Fine silt content is highest and shows a reverse trend with median grain size. Sand content shows the same trend as median grain size. Coarse silt content is high and stable below 39 cm, while above 25 cm it is low and shows greater variation. Sand content (>64 m) decreases sharply between 25–39 cm and remains low and relatively stable above 25 cm.

3.2 Environmentally Sensitive Components of Lake Sediment Grain Size

The frequency distribution curves of the core sediments show multi-modal characteristics (Fig. 3), indicating that the sediments may originate from the same source but with different depositional dynamic processes, or may result from the interaction of different sources and different depositional dynamic conditions. The standard deviation method was used to extract environmentally sensitive components to reveal the response of sediment grain size to depositional environmental changes. The standard deviation curve mainly reflects the variation differences in content among different grain sizes in different layers of the same core. High standard deviation values reflect large content differences in certain grain sizes, indicating grain sizes that are sensitive to depositional environmental changes.

The grain-size standard deviation curve for the Lake Balkhash core sediments is shown in Fig. 3. Grain sizes corresponding to high standard deviations are more sensitive to environmental changes. The curve shows a main peak at 7.59 m, a secondary peak at 52.48 m, and a minimum peak at 363.08 m. Based on this, the lake sediments can be divided into three sensitive components: fine-grained sensitive component (6.61-10.00 m), coarse-grained sensitive component (45.71-69.18 m), and component (>275.42 m). Since the content of component (>275.42 m) is less than 0.10%, its environmental significance is not discussed.

The content of component (<17.38 m) is negatively correlated with component (>17.38 m), showing a mutually exclusive trend in vertical variation. The variation trend of component (6.61-10.00 m) content is consistent with that of component (<17.38 m), with a correlation coefficient r of 0.870 ($P < 0.01$). Therefore, discussing only the variation trend and causes of sensitive component F1 (6.61-10.00 m) can capture the overall grain-size variation of Lake Balkhash sediments.

From 1963 to 1986, the content of the fine-grained sensitive component remained relatively high. From 1986 to 2000, it remained low and stable, then decreased slightly but remained basically stable. After 2000, the content of the sensitive component decreased rapidly, especially after 2010.

4 Discussion

Grain-size parameters in lake sediments respond to regional environmental changes in complex ways. Studies on Chenghai and Erhai lakes in humid/sub-humid regions show that at centennial to millennial scales, coarse sediments indicate lake contraction and shallow water during arid climate periods, while fine sediments indicate lake expansion and deep water during humid periods. At interannual to decadal scales, coarse sediments indicate humid years with greater rainfall, while fine sediments indicate dry years with less rainfall. Research on Lake Hongzehu indicates that at long timescales, grain size is mainly determined by lake water level, with smaller grain sizes indicating high water levels during humid periods and larger grain sizes indicating low water levels during arid periods. Studies on Lake Xingkai show that at millennial scales, increased coarse silt and sand correspond to low lake levels with reduced precipitation, increased fine silt corresponds to high lake levels with increased precipitation, while increased clay corresponds to quiet water deposition environments during dry climates. In arid regions, Lake Wulungu shows smaller grain sizes and lower lake levels during dry climate periods, and coarser sediments with higher lake levels during humid periods with more precipitation. Research on Hongjiannao Lake in northern Shaanxi indicates that during lake formation in low-lying wetlands, small inflow runoff resulted in weak hydrodynamic conditions and fine-grained sediments; after lake formation, increased rainfall and rising lake levels led to increased fine-grained materials. In the Bosten Lake region, sediment grain-size changes are opposite to lake water level changes at annual to centennial scales.

Overall, lake sediment grain-size changes reflect inflow runoff and lake water level variations. However, comparison of the content of grain-size sensitive components, low-frequency magnetic susceptibility, watershed temperature and precipitation, Palmer Drought Severity Index (PDSI), lake water level, and runoff at the Usharalma hydrological station at the top of the Ili River delta shows that the variation of grain-size sensitive components in Lake Balkhash sediments has poor correlation with lake water level changes (Fig. 5). Before 1960, lake water level changes had some influence on sediment grain size. After 1960, the correlation between sediment grain-size sensitive components and lake water level is very poor. For example, after 1995, although lake water level showed a rapid rising trend, the variation amplitude of the fine-grained sensitive component content was very small compared to lake water level changes, and the two showed a negative correlation during this period.

The low-frequency magnetic susceptibility of the core sediments remained stable and low before 1960, increased rapidly after 1960, and increased slowly after 1986 before decreasing slightly. This indicates that human activities began to develop around 1960 and intensified sharply after 1986. The geochemical characteristics of the core also show differences. Since 1960, potentially toxic elements in lake sediments have been significantly affected by human activities. The correlation coefficient between grain-size component content changes and low-frequency magnetic susceptibility is 0.870 ($P < 0.01$), indicating a significant correlation. Watershed surface soils contain abundant magnetic materials. Human activities destroy vegetation and surface soils, causing soil erosion and transporting large amounts of surface materials into the lake, which increases magnetic materials in lake sediments. Therefore, sediment magnetic susceptibility can reflect the intensity of human activities. Before the dissolution of the Soviet Union, magnetic susceptibility reached its highest level around 1986. After the dissolution, population decreased sharply, irrigation facilities were severely damaged, land was privatized, and large areas of land were abandoned, leading to a certain degree of decline in magnetic susceptibility, which also showed a downward trend during this period (Fig. 5). In recent decades, precipitation in the western Tianshan Mountains has increased, and precipitation in the Balkhash Lake basin has shown a significant increase. Increased precipitation may also lead to enhanced surface erosion, potentially causing increased coarse-grained components and decreased fine-grained components in sediments.

In summary, environmental changes such as lake water level and watershed precipitation have affected grain-size parameters in Lake Balkhash sediments during different periods. However, overall, changes in the content of environmentally sensitive components indirectly indicate the history of soil erosion and human activities in the watershed. This is related to the transport of fine-grained detrital materials rich in magnetic substances into the lake due to enhanced human activities, which increases both magnetic susceptibility and fine-grained materials in lake sediments.

5 Conclusions

Based on the study of lake sediments from Lake Balkhash in Kazakhstan, combined with ^{137}Cs dating, sediment magnetic susceptibility, and environmental change data including watershed climate, runoff, and lake water level, the variation characteristics of grain size in the core sediments and their response to regional environmental changes were investigated. The main conclusions are as follows:

(1) The core sediments from Lake Balkhash are dominated by clay and fine to medium silt components, accounting for 20.32%, 40.13%, and 22.86% of the total, respectively. Coarse silt content is 10.55% and sand content is 6.13%. The grain-size standard deviation method extracted two environmentally sensitive components: fine-grained sensitive component F1 (6.61–10.00 m) and coarse-grained sensitive component F2 (45.71–69.18 m).

(2) Analysis based on the variation characteristics of environmentally sensitive components shows that although environmental changes such as lake water level and watershed precipitation affected Lake Balkhash sediment grain size during different periods, overall, the content changes of environmentally sensitive components indirectly reflect the history of soil erosion and human activities in the watershed. The correlation coefficient between the content of sensitive component F1 and low-frequency magnetic susceptibility is 0.870 ($P < 0.01$), showing a significant correlation.

(3) The increase in magnetic susceptibility of lake sediments is related to the transport of fine-grained detrital materials rich in magnetic substances into the lake due to enhanced human activities in the watershed. As magnetic susceptibility increases, fine-grained materials in lake sediments also increase.

Due to the large area and complex hydrological conditions of Lake Balkhash, the core study conducted in this paper can only reflect the grain-size variation characteristics of the local area at the sampling point, which has certain limitations for overall research on sedimentary environmental changes in Lake Balkhash.

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Note: Figure translations are in progress. See original paper for figures.