Multi-Proxy Records of Environmental Change from Lake Sediments in High-Altitude Arid Regions: A Case Study of Aksayqin Lake (Postprint)

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Abstract

Lake sediments in the northwestern Tibetan Plateau preserve rich records of regional climatic and environmental changes, which is of significant importance for revealing variations in the Tibetan Plateau' s westerly-monsoon circulation system and their interaction processes. By analyzing environmental proxy indicators including grain size, total inorganic carbon (TIC), total organic carbon (TOC), total nitrogen (TN), C/N ratio, and magnetic susceptibility of a sediment core from Aksayqin Lake, a typical lake in the high-altitude arid region of the northwestern Tibetan Plateau, this study investigates lacustrine environmental changes within different sediment depth ranges, including hydrodynamic transportation conditions, lake level changes, and temperature variations in the lake area. Results indicate that the organic matter content in Aksayqin Lake sediments is low, with silt being the dominant component, followed by clay, and sand having the lowest content. The environmental changes recorded by multiple proxies can be divided into the following four stages: Stage I (531~480 cm) was characterized by a relatively warm climate, weak catchment evaporation, low lake aquatic productivity, representing a deep-water environment with weak hydrodynamic transportation conditions. Stage II (480~380 cm) was characterized by a cold and dry climate, strong catchment evaporation, relatively high lake aquatic productivity, representing a shallow-water environment with strong hydrodynamic transportation conditions. Stage III (380~160 cm) was characterized by gradual climate warming, increased inflow water volume, lake expansion, and gradually weakening hydrodynamic transportation conditions. Stage IV (160~0 cm) was characterized by a cold and dry climate, enhanced catchment evaporation, low lake aquatic productivity, representing a deep-water environment with weak hydrodynamic transportation conditions. The research results can provide basic scientific data and theoretical support for the reconstruction

of past climate changes in the northwestern Tibetan Plateau and studies on the relationship between westerly and monsoon variations.

Full Text

Environmental Changes Recorded by Multiple Proxies in Lake Sediments from High-Altitude Arid Regions: A Case Study of Lake Aksayqin

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Abstract: Lake sediments in the northwestern Tibetan Plateau preserve rich information about regional climatic and environmental changes, offering crucial insights into the evolution of westerly and monsoon circulation systems and their interactions. This study analyzes multiple environmental proxies—including grain size, total inorganic carbon (TIC), total organic carbon (TOC), total nitrogen (TN), carbon-to-nitrogen ratio (C/N), and magnetic susceptibility—from a sediment core retrieved from Lake Aksayqin, a typical high-altitude lake in the arid region of the northwestern Tibetan Plateau. The analysis explores variations in lake hydrodynamic transport conditions, lake level fluctuations, and temperature changes in the lake basin across different sediment depths. The results indicate that organic matter content in Lake Aksayqin sediments is low, with sediments dominated by silt, followed by clay, and minimal sand content. The multi-proxy records reveal four distinct stages of environmental change: (1) a relatively warm climate with weak evaporation, low aquatic productivity, and a deep-water environment with weak hydrodynamic transport conditions; (2) a cold and dry climate with strong evaporation, relatively high aquatic productivity, and a shallow-water environment with strong hydrodynamic transport conditions; (3) a gradually warming climate with increasing inflow, lake expansion, and weakening hydrodynamic transport; and (4) a cold and dry climate with enhanced evaporation, low aquatic productivity, and a deep-water environment with weak hydrodynamic transport. These findings provide fundamental scientific data and theoretical support for reconstructing past climate change and investigating westerly-monsoon interactions in the northwestern Tibetan Plateau.

Keywords: multiple proxies; Lake Aksayqin; environmental changes; lake sed-

iment; Tibetan Plateau

1. Study Area

Lake Aksayqin (35°08 -35°17 N, 79°44 -79°55 E) is a closed high-altitude lake located in the Aksayqin Basin in the northwestern Tibetan Plateau (Fig. 1). The lake surface elevation is approximately 4,848 m, with a total area of about 165.8 km^2, maximum length of 19.3 km, and maximum width of 12.5 km. Field measurements in 2015 recorded a maximum water depth exceeding 16.4 m. The lake water salinity is 84.5‰, classifying it as a magnesium sulfate-type inland lake. The region has an average annual temperature of approximately -8 °C and annual precipitation of 25–50 mm, characteristic of a high-altitude arid climate. Prevailing winds are southwesterly and northwesterly, with average wind speeds of 4 $m \cdot s^{-1}$ and over 100 windy days per year. The high elevation and arid climate result in sparse vegetation, dominated primarily by alpine desert flora. The lake basin has a catchment area of 8,150.0 km^2, containing 136 glaciers covering 709.1 km^2 with an ice volume of 136.3 km^3. Glacier meltwater extensively recharges the lake through surface runoff, with a recharge coefficient of 49.3.

2. Methods

2.1 Core Retrieval, Subsampling, and Magnetic Susceptibility Analysis

In July 2015, a 5.31 m continuous sediment core (AKLC15-1) was retrieved from the central open-water area of Lake Aksayqin (35°13 09 N, 79°50 31 E) at a water depth of 16.40 m using a UWITEC piston coring system. The sediment surface appeared dark black. The core was transported and stored under low-temperature conditions. To reflect continuous environmental changes, one half of the AKLC15-1 core was subsampled at 1 cm intervals, yielding 531 samples that were freeze-dried and preserved for subsequent analysis. The other half was sent to the Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Chinese Academy of Sciences, for high-resolution magnetic susceptibility scanning using an Itrax core scanner (Cox Analytical Systems) equipped with a Bartington MS2E sensor at 0.2 cm intervals.

2.2 Grain Size Analysis

Grain size analysis was performed using a Malvern Mastersizer 3000 laser diffraction particle size analyzer (UK), with a measurement range of 0.01–3500 m, ensuring complete grain size distribution curves. The analytical procedure was as follows: 0.2–0.3 g of sample was weighed into a 100 mL beaker, and 10 mL of H_2O_2 was added and heated on a hot plate at 70–80 °C to remove organic matter. After complete reaction, 10 mL of HCl was added while maintaining

70–80 °C to remove inorganic carbon and calcareous cement. The beaker was then filled with deionized water and left to stand overnight. The following day, the supernatant was removed to the 20 mL mark, 10 mL of 0.1 mol·L^{-1} $NaPO_3$ dispersant solution was added, the mixture was shaken and ultrasonicated for 10 minutes before measurement.

Common methods for calculating grain size parameters include graphical and moment methods. In this study, mean grain size (Mz) and median grain size (Md) were obtained directly from the volume-weighted mean diameter D[4,3] and D[5,0] from the instrument software. Standard deviation (σI), skewness (SkI), and kurtosis (KG) were calculated using the graphical method.

2.3 TIC, TOC, TN, and C/N Analysis

TIC and TOC content were analyzed using a Shimadzu TOC-VCPH total organic carbon analyzer. The procedure was as follows: the instrument temperature was set to 200 °C, approximately 150 mg of dry sample was weighed into a quartz boat, which was placed in the sample chamber. After air evacuation, phosphoric acid was added and the quartz boat was moved to the reaction position for measurement. TN content was analyzed using a German Elementar vario MAX cube analyzer, with approximately 500 mg of dry sample weighed into a crucible and placed in the instrument for measurement. After obtaining TN content, TOC content was calculated by difference.

3. Results

3.1 Sediment Grain Size Characteristics

Following conventional grain size classification standards, the AKLC15-1 sediments were divided into clay (<4 m), silt (4–64 m), and sand (>64 m). The results show that Lake Aksayqin sediments have high silt content ranging from 52.38% to 85.88% (average 70.48%), clay content ranging from 11.30% to 34.53% (average 27.64%), and minimal sand content ranging from 0.35% to 19.33% (average 1.88%). Using the modified Folk classification method, the sediments are primarily classified as clayey silt and silt, with minor amounts of clay and sandy silt (Fig. 2).

The mean grain size (Mz) of AKLC15-1 ranges from 7.56 to 37.98 m (average 11.37 m), while the median grain size (Md) ranges from 5.29 to 11.27 m (average 6.50 m). Both parameters show a "fine-coarse-fine" trend throughout the core. Standard deviation (σI) ranges from 1.00 to 2.11 (average 1.58), indicating poor sorting. Skewness (SkI) ranges from -0.34 to 0.07 (average -0.17), nearly symmetrical, suggesting fine sediment particles. Kurtosis (KG) ranges from 1.00 to 1.63 (average 1.24), indicating medium to very narrow peaks.

Examining the vertical variations in sediment composition and grain size parameters (Fig. 3), the bottom interval (531–480 cm) shows relatively stable composition and parameters. In contrast, the 480–380 cm interval exhibits dramatic fluctuations in all sediment components and grain size parameters, indicating significant environmental instability. Above 380 cm, sand content remains consistently low and stable, with variations occurring only between clay and silt. In the 380–160 cm interval, clay content gradually increases while silt decreases; Mz decreases due to increased fine clay particles, though Md remains relatively stable. In the 160-0 cm interval, silt increases while clay decreases; Mz increases due to increased coarser silt particles, while Md remains stable. Notably, σI values increase in the 160-0 cm interval, while KG shows no significant change.

3.2 Other Environmental Proxies

In the AKLC15-1 core, TOC content ranges from 0.24% to 0.59% (average 0.45%), TN from 0.04% to 0.07% (average 0.05%), and C/N ratios from 0.98 to 12.41 (average 5.05%). TOC content peaks in the 460–380 cm interval, while TN peaks in the 460–450 cm interval. TOC shows a fluctuating upward trend with decreasing depth, gradually declining to minimum values after 450 cm. TIC content ranges from 2.99% to 7.70% (average 4.45%), peaking in the 460–450 cm interval. Magnetic susceptibility ranges from 0.54 to 9.21 SI (average 5.42 SI), generally showing a "decrease then increase" trend with decreasing depth, with minimum values in the 450–380 cm interval.

4. Discussion

4.1 Environmental Significance of Multi-Proxy Variations

Lake Aksayqin is a large lake, and its grain size variations can theoretically reflect changes in lake hydrology such as water level and recharge. Based on the variation characteristics of Mz and Md, the AKLC15-1 core can be divided into four depth intervals representing different depositional environments: 531–480 cm (deep-water zone), 480–380 cm (shallow-water zone), 380–160 cm (deep-water zone), and 160–0 cm (deep-water zone).

The lake basin is extremely arid with minimal precipitation; the lake is primarily fed by glacier meltwater from the Aksayqin River. Therefore, lake level fluctuations are closely related to meltwater discharge. Increased recharge enhances hydrodynamic forces, transporting more terrigenous clastic material into the lake and increasing magnetic minerals, thus raising magnetic susceptibility. In glacier-fed lakes, grain size characteristics can indirectly reflect regional temperature changes through meltwater discharge: warm periods increase meltwater, raising lake levels and requiring longer transport distances for littoral sediments to reach the coring site, resulting in weaker hydrodynamic conditions, finer grain sizes, and better sorting. Conversely, cold periods reduce meltwater, causing lake contraction, lower water levels, shorter transport distances, stronger hydrodynamic conditions, coarser grain sizes, and poorer sorting. Generally, fine grains indicate warm, deep-water conditions, while coarse grains indicate cold, shallow-water conditions.

TOC content reflects total organic matter variations, indicating lake nutrient levels and aquatic productivity. The low TOC content (average 0.45%) suggests low nutrient levels and aquatic productivity. The C/N ratio indicates organic matter sources; values of 0.98-12.41 (mostly <10) suggest predominantly endogenous aquatic sources with minimal terrestrial influence. Therefore, TOC primarily reflects aquatic productivity.

TIC content reflects carbonate variations, which in closed basins are sensitive to recharge and evaporation intensity, making them effective climate indicators. In the extremely arid northwestern Tibetan Plateau, increased carbonate content indicates enhanced evaporation and declining lake levels. Thus, TIC can indicate evaporation levels and lake level changes.

Notable anomalies occur at 460-450 cm, 430-420 cm, and 410-400 cm, where multiple proxies show significant fluctuations, suggesting extreme cold events that rapidly reduced meltwater supply, enhanced lake dynamics, shallowing, and increased evaporation.

4.2 Characteristics of Environmental Changes at Different Stages

Stage 1 (531-480 cm): Sediments are dominated by clay and silt with minimal sand (clayey silt lithology). Mz and Md are at their lowest levels, with minimal parameter variation, indicating a deep-water environment with weak hydrodynamics. Low TOC and TN reflect low aquatic productivity, likely due to deep water inhibiting biological growth. Declining but high magnetic susceptibility suggests continuous glacier meltwater supply and terrigenous magnetic material input. Low TIC indicates weak evaporation and sustained meltwater recharge. This stage represents a relatively warm climate with continuous glacier meltwater maintaining a deep, stable lake with weak hydrodynamics and low productivity.

Stage 2 (480-380 cm): All proxies except Md show rapid, significant fluctuations, indicating complex and unstable depositional environments. Sand content is highest, clay lowest, suggesting strong hydrodynamics unfavorable for fine particle deposition. Increased TOC and TN indicate enhanced aquatic productivity in shallow waters. High TIC reflects strong evaporation and low lake levels. High magnetic susceptibility indicates increased terrigenous input. This stage represents a cold, dry climate with reduced meltwater, low lake levels, and strong hydrodynamic conditions. The fluctuations suggest multiple extreme cold events.

Stage 3 (380-160 cm): Sediment grain size fines significantly, with clay increasing then stabilizing and silt decreasing then stabilizing; sand remains near zero. These characteristics indicate stable lake levels with dynamic equilibrium between evaporation and recharge. Fluctuating but decreasing TOC and TN suggest gradually declining aquatic productivity, possibly due to rising water levels from increasing meltwater. Increasing magnetic susceptibility indicates enhanced terrigenous input from intensified erosion. This stage represents a climate transitioning from cold to warm, with increasing meltwater, rising lake levels, and weakening hydrodynamic conditions.

Stage 4 (160-0 cm): Sediments are clayey silt with minor component fluctuations but clear variability, indicating multiple weak hydrodynamic events. TOC and TN show weak fluctuations, reflecting low aquatic productivity. TIC increases significantly, reaching the highest values and indicating strong evaporation. The lowest C/N ratios confirm predominantly endogenous organic matter. High but fluctuating magnetic susceptibility suggests continuous terrigenous input from stable glacier meltwater erosion. This stage represents a cold, dry climate with reduced meltwater, enhanced evaporation, declining lake levels, and weak hydrodynamic conditions.

5. Conclusions

Lake Aksayqin is a typical lake in the northwestern Tibetan Plateau. Its sedimentary record enhances understanding of regional climate history and reveals processes and mechanisms of westerly-monsoon interactions. Multi-proxy analysis of Lake Aksayqin sediments reconstructs past hydrodynamic and environmental changes:

1) The Lake Aksayqin area experiences strong evaporation, with lake water primarily supplied by glacier meltwater. Sediment organic matter content is low and mainly derived from endogenous aquatic organisms. Sediments are dominated by silt (70.48%), followed by clay (27.64%), with minimal sand (1.88%).

2) Integrated multi-proxy analysis reveals four environmental stages: Stage 1 (531-480 cm) had a relatively warm climate with weak evaporation, sustained glacier meltwater recharge, low aquatic productivity, and a deep-water environment with weak hydrodynamics. Stage 2 (480-380 cm) was cold and dry with strong evaporation, reduced meltwater, low lake levels, high aquatic productivity, and a shallow-water environment with strong hydrodynamics, including multiple extreme cold events. Stage 3 (380-160 cm) experienced gradual warming with increasing inflow, lake expansion, and weakening hydrodynamic conditions. Stage 4 (160-0 cm) was cold and dry with enhanced evaporation, low aquatic productivity, and a deep-water environment with weak hydrodynamics.

Lake Aksayqin sediments are highly sensitive to climate and environmental changes. Future work will establish a reliable chronology and combine pollen and biomarker analyses to semi-quantitatively or quantitatively reconstruct past precipitation and temperature changes, providing important theoretical references for understanding climate and water resource changes in the northwestern Tibetan Plateau under global warming.

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