Long-term influences of climate and environment on grain size distribution in a large shallow lake from southwestern China

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Abstract

Grain size is widely utilized in environmental reconstruction across various sedimentary settings; however, its precise interpretation remains challenging. In shallow lakes located in humid regions, grain size interpretation is particularly complicated by complex climatic and environmental fluctuations. Here, we present grain size and end-member modeling analysis (EMMA) of a 4.56-meter sediment core from Yilong Lake in southwestern China to clarify how grain size composition responds to different climatic and environmental forcings. Four end-members (EMs) were extracted from the grain size distributions. EM1 is dominated by clay and fine silt, whereas EM2 displays a bimodal distribution concentrated in the fine silt and sand fractions. Both EM1 and EM2 likely formed under shallow lake conditions, representing low-energy deposition and episodic flood deposition, respectively. EM3 consists of well-sorted silt, while EM4 comprises relatively coarse particles. EM3 and EM4 reflect high hydrodynamic conditions under humid climates, corresponding to deep lake deposition during high-water periods and high-energy inputs from strong hydrodynamic disturbances, respectively.

The different EMs show varied variability patterns, indicating complex responses to multiple factors including precipitation, water level, and vegetation cover since the Last Glacial Maximum (LGM). Notably, under the background of intensified human activities during the late Holocene, the grain size distribution reverted to characteristics similar to the LGM, with increased proportions of EM1 and EM3. Our findings demonstrate that climate, vegetation, lake status, and human activities have collectively influenced sedimentary processes in Yilong Lake over the past 27,000 years. Therefore, precise interpretation of grain size distributions in shallow lakes of humid regions requires reliable prior knowledge and careful consideration of climate and environmental evolution trajectories.

Full Text

Preamble

Long-term influences of climate and environment on grain size distribution in a large shallow lake from southwestern China

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Abstract

Grain size is widely used for environmental reconstruction in various depositional settings, yet its precise interpretation remains challenging. In shallow lakes within humid regions, interpretation of grain size is particularly hindered by complex variations in climate and environment. Here, we conducted grain size analysis and End Member Modeling Analysis (EMMA) on a 4.56 m sediment core from Yilong Lake, southwestern China, to clarify the response of grain size composition to different climatic and environmental factors. Four end members (EMs) were fitted from grain-size distributions. EM1 comprises mainly clay and fine silt, and EM2 shows a bimodal structure concentrated in fine-silt and sand fractions. Both EM1 and EM2 likely formed under shallow-lake conditions, indicating low-energy deposition and episodic flood deposits, respectively. EM3 is composed of well-sorted silt, and EM4 comprises relatively coarse particles. EM3 and EM4 reflect high-hydrodynamic regimes in humid climates, corresponding to deep-lake deposition under abundant precipitation and to high-energy inputs generated by strong hydrodynamic disturbances. Different EMs exhibit diverse variabilities, showing complex responses to multiple factors of precipitation, water level, and vegetation coverage since the Last Glacial Maximum (LGM). Notably, grain-size distributions reverted to LGM-like features, with increased proportions of EM1 and EM3, under intensified human activities during the Late Holocene. Our findings show that climate, vegetation, lake state, and human activities jointly impacted depositional processes in Yilong Lake over the past 27 ka. Thus, in humid-region shallow lakes, precise interpretation of grain size distributions requires robust a priori knowledge and careful consideration of climate and environmental trajectories.

Keywords: grain size; End Member Modeling Analysis; past 27 ka; Southwestern China; Yilong Lake

1. Introduction

As one of the most fundamental and widely applied physical attributes in sedimentology (Blott and Pye, 2001; Folk and Ward, 1957), grain size represents a fundamental proxy for tracing sediment provenance, transport pathways, and dynamic regimes (Mishra, 2023; Sun et al., 2002; Zhou et al., 2019). Across diverse depositional environments, grain size distribution has been widely employed to reconstruct climate change, hydrological variability, and anthropogenic disturbances (Dearing et al., 2006; Liu et al., 2016; Macumber et al., 2018; Mills et al., 2017; Paterson and Heslop, 2015; Xiao et al., 2015). However, grain size composition is jointly impacted by multiple factors, including lithology of source area, intensities of erosion and weathering, hydrodynamic energy, transport mediums, and sedimentary rates. These factors interact across various spatial and temporal scales, imparting high complexity to grain size signals. Thus, it is always challenging to exactly interpret grain size composition during environmental reconstructions.

A comprehensive understanding of the response mechanisms of grain size compositions to specific factors across different depositional settings is essential for their accurate interpretation and application. In arid regions, aeolian input often dominates sediment grain size composition, with specific grain size fractions indicating the intensity of regional aeolian processes and being closely linked to climatic events (Ma et al., 2016). However, variations in aeolian grain size are not only governed by wind strength but also significantly affected by topography and sediment availability, displaying spatial heterogeneity and multi-source mixtures (Nottebaum et al., 2014). In contrast, grain size compositions in humid regions predominantly reflect fluvial transport and hydrodynamic processes. Consequently, coarser grain size composition has been linked to intensified hydraulic processes under increasing precipitation (Ning et al., 2017; Zhang et al., 2021). However, shallow lakes in humid regions are primarily characterized by seasonal recharge and drainage, frequent hydrodynamic fluctuations, varied lake water levels, and anthropogenic disturbances (Mills et al., 2017; Wu et al., 2024; Zhang et al., 2024). Their temporal fluctuations reflect the phase-specific influences of external environmental factors, leading to sedimentary records dominated by varied particles, overlapping modal distributions, and mixed-source inputs (Beuscher et al., 2017; van Hateren et al., 2020). In addition, fluctuations of surface area and water depth can alter sediment transport dynamics, thereby modifying the environmental significance of grain size parameters. Thus, the climatic and environmental implications of grain size indices in shallow lakes carry a certain degree of uncertainty, demanding that a critical step toward their scientific interpretation and effective application lies in contextualizing grain size data within well-constrained depositional frameworks.

End Member Modeling Analysis (EMMA) has demonstrated unique advantages in decoding process-related information embedded in grain size signals and in disclosing hydrodynamic changes, sediment provenances, and depositional events (Dietze and Dietze, 2019; Dietze et al., 2022; Patterson et al., 2022). Specifically, EMMA enables the statistical deconvolution of mixed grain size distributions, allowing the identification of statistically robust and representative grain size components (Eltijani et al., 2022). These components can be directly linked to dominant sedimentary transport or depositional mechanisms, thus providing deeper insights into the driving forces behind sediment accumulation (Dietze et al., 2022; van Hateren et al., 2018). Dozens of efforts with EMMA have been reported in arid regions of aeolian deposition (Kumar et al., 2022; Ma et al., 2020a, 2016), in lacustrine systems (Larsen et al., 2020; Li et al., 2016; Van Wyk De Vries et al., 2022), and in coastal and marine sediments (De Mahiques et al., 2021; Feng et al., 2025; Jiang et al., 2024; Zhang et al., 2020). In contrast, the application of EMMA to shallow lakes in humid environments remains under-investigated, particularly regarding the compositional structure and dynamic behavior of grain size end members in response to multiple interacting environmental drivers.

Within humid regions, southwestern China is characterized by obvious precipitation seasonality and distinct wet/dry seasons, leading to high variability of water levels and hydrodynamics in lacustrine environments. Yilong Lake is a large shallow lake in southwestern China, characterized by strong hydrodynamic fluctuations and high variability of lake water area (Wang and Dou, 1998). Previous efforts have manifested complex interrelationships among climate, hydrological balance, vegetation, and soil moisture over the last 27,000 years (Li et al., 2024; Liao et al., 2024, 2021). However, the long-term impact of climate, vegetation, and human disturbances on depositional processes remains less understood in this typical shallow lake. The questions of whether distinct grain size end members can be preserved throughout different climate backgrounds and what role climate, vegetation, and hydrological balance play in impacting the depositional process need further investigation. Herein, we compiled ensemble data from climate simulation, pollen, geochemistry, and grain size composition to (1) identify the sedimentary dynamic significance and environmental implications of representative grain size end members and (2) explore the mechanisms governing grain size variability under the combined influences of climate, vegetation, and hydrodynamics. Our ultimate goal is to elucidate the response of grain size compositions to environmental changes in shallow lacustrine systems within humid regions and to provide a reference for interpreting specific end members against complex environments.

2.1 Regional settings

Yilong Lake (23.63°–23.70° N, 102.50°–102.65° E; 1414 m a.s.l.) is a shallow tectonic lake situated in central Yunnan Province, southwestern China (Fig. 1a). It ranks among the largest plateau lakes in the region, with a surface area of approximately 38 km^2. The catchment area spans approximately 303.6 km^2, and the lake reaches a maximum depth of 6.2 m, with an average depth of 2.8 m (Wang and Dou, 1998). The lake receives water input from seasonal tributaries, direct precipitation, and subsurface inflows. The Chenghe River, located in the northwest, is the only perennial inflow. Historically, the lake discharged through an outlet at the southeastern margin, which ceased to function after 1978 CE due to declining lake levels associated with both climatic fluctuations and intensified human water consumption (Wang and Dou, 1998).

The lake is influenced by the Asian Summer Monsoon (ASM), with mean annual temperature (MAT) ranging from 17.2°C to 18.1°C and mean annual precipitation (MAP) between 886 and 994 mm (China Meteorological Data Service Center, https://data.cma.cn/en). The wet season from May to October receives over 80% of MAP, and the dry season from November to April is characterized by frequent droughts (Fig. 1b). The natural vegetation mainly comprises evergreen broadleaved forest. However, substantial anthropogenic modification has transformed much of the lakeshore into agricultural and disturbed landscapes, with shrublands and cultivated fields dominating the immediate vicinity. Coniferous forest (primarily pine forest) is present at higher elevations (Fig. 1d).

Figure 1 [Figure 1: see original paper]. The location of Yilong Lake in southwestern China (a), with climate (b), topographical setting (c) and vegetation (d) around the lake.

2.2 Sampling and grain size analysis

In May 2017, a 4.56 m-long sediment core (YLH) was collected from Yilong Lake (23°40.574 N, 102°34.731 E) using a UWITEC system. The core comprises mainly lacustrine mud, with shell-rich clay in the upper 43 cm, silty clay from 43–180 cm, water-saturated silty mud between 180–230 cm, and dense clay-silt below 230 cm. The core was subsampled at 1-cm intervals ($n = 456$) and freeze-dried for subsequent analyses. The age-depth model employed in this study was previously established by Li et al. (2024) based on 15 AMS ^{14}C dates obtained from bulk sediments.

Grain size samples were pretreated with 30% H_2O_2 and 5% HCl to remove organic matter and carbonates, then rinsed with deionized water and dispersed in a 10% $(NaPO_3)_6$ solution. Grain size distributions were determined using a Malvern 3000E laser diffraction particle size analyzer (Malvern Panalytical Ltd.), covering a range of 0.02–2000 µm with 100 size bins. Sediment composition of clay (0–4 m), silt (4–63 m), and sand (> 63 m) was estimated. Grain size parameters of median grain size (D_{50}), sorting coefficient, and skewness were calculated as well.

EMMA was performed using the EMMAgeo package (version 0.9.8; Dietze and Dietze, 2019) to decompose the grain size dataset from Yilong Lake into distinct end members. Prior to modeling, grain size data were log-transformed and centered to reduce skewness and maintain compositional integrity. The optimal number of end members (EMs) was determined based on the proportion of explained variance and overall model stability, ensuring a balance between interpretability and statistical robustness.

2.3 Numeric analysis

Geochemical and mineralogical proxy data, including total organic carbon (TOC), total nitrogen (TN), and elemental concentrations from X-ray fluorescence (XRF), were previously analyzed and published by Liao et al. (2021) and are directly utilized in this study for statistical analysis. Principle Component Analysis (PCA) was applied to the XRF data, with XRF-PC1 capturing a geochemical gradient from authigenic carbonate enrichment to detrital input (Li et al., 2018). Pollen analysis was performed at 4-cm intervals on core YLH (Li et al., 2024). Here, we selected the ratio of arboreal to non-arboreal pollen (AP/NAP) as an indicator of regional forests' dominance over open grassland landscapes. However, the surface of the upper 43 cm was omitted from numeric analyses due to anthropogenic disturbance (Huang et al., 2023). The long-term trajectories of precipitation seasonality (P_{season}) and mean annual precipitation (P_{annual}) around Yilong Lake were extracted from the TraCE-21ka transient climate simulation (Liu et al., 2009). Age-based interpolation was applied to the environmental variables using the na.approx() function from the zoo package (Zeileis and Grothendieck, 2005). The multicollinearity among explanatory variables was assessed by calculating Variance Inflation Factors (VIF) using the car package (Fox and Weisberg, 2019). Based on the VIF results, a subset of environmental predictors including Fe/Mn, C/N, XRF-PC1, AP/NAP, P_{season}, and P_{annual} was retained. All variables were standardized before analysis to ensure comparability and improve inference robustness.

Environmental constraints on grain size EMs were examined using Mantel tests, Redundancy Analysis (RDA), and Structural Equation Modeling (SEM). Mantel tests were conducted to evaluate the strength of association between the Euclidean distance matrices of grain size EMs and environmental variables. Pearson correlation coefficients were calculated, and statistical significance was assessed using 999 permutations (Legendre and Fortin, 2010). RDA was applied to assess linear relationships between grain size EM scores and the selected environmental variables using the rda() function in the vegan package (Oksanen et al., 2025). SEM analysis was applied to evaluate the total, direct, and indirect effects of climate (P_{season}, P_{annual}) and environmental variables (Fe/Mn, C/N, XRF-PC1, and AP/NAP) on the grain size EMs using the piecewiseSEM package (Lefcheck, 2016). A network structure (climate-environment, climate-EMs, environment-EMs) was initially constructed and then continuously adjusted by adding and deleting paths to improve model fit, thereby achieving effective model validation and theoretical consistency. Fisher' s C tests were conducted to assess the global goodness-of-fit of the models ($p > 0.05$ indicated reliable models). All analyses were conducted within R software (version 4.5, R Core Team 2025).

3.1 Grain size composition of YLH

The grain size of the YLH core ranges from 0.2 to 592 µm and is overwhelmingly dominated by silt, with an average content of 70.19%, followed by clay (25.00%) and sand (4.81%) (Fig. 2a [Figure 2: see original paper]). Grain size frequency curves exhibit unimodal distributions concentrated in the 4–37 µm range, while some samples show secondary peaks in the 60–70 µm intervals (Fig. 2b). The median grain size (D_{50}) ranges from 3.17 to 24.5 µm, with a mean of 9.45 µm. Sorting coefficients vary between 1.3 and 4.1, with an average value of 2.76. Skewness ranges from -2.13 to 2.12 (Fig. 2c).

Figure 2. (a) Shepard ternary diagram of the YLH core grain size, (b) grain size frequency curves of selected samples, and (c) grain size parameters of YLH (D_{50}, Sorting, and Skewness).

During the Last Glacial Maximum (LGM, 27–18 cal ka BP), the sediments of YLH comprised primarily clay (~31%) and silt (~65%), with sand content (4%) reaching its minimum. The average median grain size was 7.1 µm, with a mean sorting coefficient of 2.9 and a mean skewness value of -0.08. In the Last Deglacial period (LDP, 18–11.7 cal ka BP), both silt and sand proportions increased slightly, while clay content decreased to ~25%. The average median grain size increased to 9.5 µm, and the mean skewness value decreased to -0.12, suggesting a trend toward coarser sediments and more complex grain size composition relative to the preceding phase.

During the early to middle Holocene (11.7–5 cal ka BP), silt content further increased to 82%, and the average median grain size reached approximately 13.2 µm. The deterioration in sorting implied greater heterogeneity in grain size compositions and enhanced input of coarser materials. In the middle and late Holocene (5–0 cal ka BP), clay content increased to ~30%, and the average median grain size decreased to 8.5 µm, indicating a shift back to finer-grained sediments. The relative increase in sand content suggests a renewed change in sedimentary dynamics during this interval.

3.2 End-member composition of the grain size

A four end-member solution (EM1–EM4) was selected as the optimal configuration based on a comprehensive evaluation of model fit, angle deviation, and end-member inter-correlation (Fig. 3 [Figure 3: see original paper]). EM1 to EM4 accounted for 74% of variance across different grain size distributions and 86% of variance across different depths (Fig. 3a, 3b), capturing the dominant physical processes while avoiding overfitting. EM1, EM3, and EM4 exhibit typical unimodal patterns, whereas EM2 displays a bimodal distribution with distinct high and low peaks (Fig. 3c). Specifically, EM1 is characterized by grain sizes ranging from 0.34 to 114 µm, with a modal size around ~3.3 µm. EM2 exhibits pronounced bimodality, with a primary peak at 5.0 µm and a secondary peak at 57 µm, spanning a size range of 0.38–543 µm. EM3 mainly falls within

1.4–57 µm and peaks at ~15.6 µm. EM4 has a modal size of 24.0 µm, ranging from 0.45 to 160 µm.

Figure 3. Default graphical output of the R function EMMA(). (a, b) Measures of model performance (i.e., class- and sample-wise R^2), (c) end-member loadings and (d) end-member scores. The legend presents the main mode positions (µm) and explained variance of each end member (%).

The temporal variation in end-member contributions reflects the dynamics of distinct sedimentary processes (Fig. 3d). EM1 ranges from 0 to 100%, with an average contribution of 34.6%, peaking at approximately 13.7 cal ka BP. EM1 remains consistently dominant throughout the sequence, particularly during the LGM, followed by marked fluctuations during the LDP and a renewed increase in the late Holocene. EM2 contributes between 0 and 72%, with a mean of 8.6%, and peaks around 16.6 cal ka BP. It exhibits relatively low but rapidly fluctuating values during both the LDP and the late Holocene. EM3 shows a persistent presence across the record, averaging 35.6%, with distinct peaks at ~6.5, 13.8, 22.9, and 24.3 cal ka BP. It exhibits a pronounced increase during the Holocene climatic optimum. EM4 is primarily associated with the Holocene, with an average contribution of 21.2%. Compared with EM3, this upward trend begins earlier, as its abundance starts to rise in the early Holocene and reaches a maximum around 9 cal ka BP.

3.3 Statistical relationships between end-members and environmental proxies

Figure 4 [Figure 4: see original paper] presents the Mantel test and RDA results, highlighting the relationships between end-member compositions and environmental variables. Mantel tests illustrate that EM1 correlates with P_{season} ($r = 0.35$, $P < 0.01$) and, to a lesser extent, with P_{annual}, AP/NAP, C/N, and Fe/Mn. EM2 is related to P_{annual} ($r = 0.16$, $P < 0.01$), with weaker correlations with P_{season} and Fe/Mn. EM3 has weaker but significant associations with P_{annual} and Fe/Mn ($r = 0.09$). EM4 shows the strongest climate-vegetation links (P_{season} $r = 0.28$, P_{annual} $r = 0.16$, AP/NAP $r = 0.28$; all $P < 0.01$). RDA aligns with these patterns from the Mantel test. RDA1 loads strongly on P_{season}, P_{annual}, and AP/NAP, whereas RDA2 is structured mainly by C/N and Fe/Mn. In the ordination, EM1 plots at the negative end of RDA1; EM3 is near the origin with lower RDA2 scores; EM4 lies in the positive quadrant of both axes; and EM2 is close to the centroid.

Figure 4. Mantel test and RDA results illustrating the correlations between grain size EMs and environmental variables.

The SEM models showed satisfactory global fit (Fisher' s $C = 5.699$, $df = 2$, $P = 0.058$; AIC: 2287.4-2397.5), supporting the plausibility of the hypothesized pathways (Fig. 5 [Figure 5: see original paper]). For EM1 ($R^2 = 0.41$), P_{season} had a strong negative direct effect ($\beta = -0.686$, $p < 0.001$); Fe/Mn had a positive effect on EM1 ($\beta = 0.302$, $p = 0.002$) and was positively related to P_{season} ($\beta = 0.549$, $p < 0.001$). Other paths (XRF-PC1, AP/NAP, C/N) were not significant. EM2 ($R^2 = 0.21$) was negatively associated with P_{annual} ($\beta = -0.457$, $p < 0.001$) and positively affected by Fe/Mn ($\beta = 0.222$, $p = 0.043$); other variables (XRF-PC1, AP/NAP, C/N) showed no significant relationships.

For EM3 ($R^2 = 0.20$), positive effects were detected for XRF-PC1 ($\beta = 0.268$, $p = 0.011$) and P_{annual} ($\beta = 0.286$, $p = 0.002$), while C/N ($\beta = -0.426$, $p < 0.001$), P_{season} ($\beta = -0.313$, $p = 0.007$), and AP/NAP ($\beta = -0.18$, $p = 0.021$) were negative.

For EM4 ($R^2 = 0.57$), P_{season} was strongly positive ($\beta = 0.824$, $p < 0.001$), with negative effects from Fe/Mn ($\beta = -0.473$, $p < 0.001$) and XRF-PC1 ($\beta = -0.290$, $p < 0.001$); AP/NAP showed a modest positive effect ($\beta = 0.130$, $p = 0.026$).

Figure 5. Structural equation models (SEMs) and standardized effects of environmental variables on sediment grain size end-member compositions. (a–d) SEMs illustrating the direct and indirect effects of climate and environmental variables on EMs, respectively. (e–h) Standardized total, direct, and indirect effects of key environmental predictors on EMs, respectively. Solid blue and yellow arrows indicate significant positive and negative paths, respectively. Dashed arrows represent non-significant relationships. R^2 values indicate the proportion of variance explained for endogenous variables, with *$p < 0.05$,* ***$p < 0.01$, and*** $p < 0.001$, respectively.

4.1 The implications of grain size EMs

EM1 in the YLH core primarily comprises fine-grained particles of clay and fine silt, which can remain suspended in the water column for extended periods and settle slowly, contributing to their widespread presence in lacustrine sediments (Liu et al., 2016; Ning et al., 2017). This grain size composition likely indicates low-energy depositional conditions, such as still-water sedimentation in central lake basins or low water levels under a background of low precipitation. Fine particles (~4 µm) in Lake Lugu have been attributed to long-range aeolian transport (Zhang et al., 2021b), but fine-grained components (~0.3 µm) in Ximeng Longtan Lake were governed by catchment hydrodynamics and linked to monsoonal precipitation (Ning et al., 2017).

In this study, EM1 shows significant correlations with multiple climatic and environmental variables (Fig. 4), suggesting it was deposited along with high terrestrial sediment input (high C/N) but under stable (and likely low) precipitation (Liu et al., 2009; Zhang et al., 2023). SEM results indicate that the formation of EM1 is primarily regulated by precipitation seasonality (Fig. 5a). Increased precipitation seasonality tends to enhance lake hydrodynamics and intensify water column disturbances, thereby inhibiting the settling of fine particles (Ming et al., 2021). This suggests that evenly distributed precipitation and hydrologically stable conditions are more favorable for the accumulation of EM1. In addition, the deposition of EM1 was positively correlated with the Fe/Mn ratio (Fig. 5a & 6), reflecting decreased lake levels in Yilong Lake (Liao et al., 2021). Further analysis reveals that precipitation seasonality also influences EM1 indirectly through its significant positive effect on Fe/Mn. In contrast, path coefficients from vegetation (AP/NAP), terrestrial input (XRF-PC1), and organic matter composition (C/N) to EM1 are not statistically significant, indicating that EM1 is primarily governed by direct climatic and hydrological controls rather than indirect catchment-related processes. Similar mechanisms have been documented in other lakes, such as Lake Beihaizi (Peng et al., 2023) and Yangying Co on the southeastern Tibetan Plateau (Xu et al., 2025), both of which highlight the critical role of precipitation variability in modulating lake hydrodynamics and redox conditions that favor fine-grained sediment deposition. Given the subtropical monsoonal climate of the study area, characterized by high humidity and limited aeolian activity, EM1 should be indicative of low-energy depositional environments under shallow lake conditions.

EM2 exhibits a bimodal structure (peaking at ~5 and ~57 μm), concentrated in the fine-silt fraction and the sand fraction. The EM2, with poor sorting and discontinuous occurrences at different depths (Fig. 6 [Figure 6: see original paper]), differs markedly from EM1. These features resemble flood deposits (Wang et al., 2021). RDA and SEM analyses show that this EM has a significant negative correlation with annual precipitation and a positive correlation with Fe/Mn (Fig. 4 & 5b). Thus, EM2 tended to occur during drought periods. This fits well with the observation that high EM2 components have been recorded during periods of climate transition, i.e., from LGM to LDP and from LDP to early Holocene (Fig. 6). Meanwhile, EM2 is negatively correlated with AP/NAP and positively correlated with C/N (Fig. 4). Flood depositions are more likely to occur when the watershed has an open landscape (Giguet-Covex et al., 2012; Schillereff et al., 2014) and will directly lead to an increase in terrestrial detrital materials in the sediments (Giguet-Covex et al., 2012; Schillereff et al., 2014; Wang et al., 2021). Therefore, EM2 should represent flood deposition corresponding to episodic sedimentation processes caused by increased rainfall during drought periods and under open vegetation backgrounds.

EM3 comprises well-sorted particles that typically formed under moderate-energy conditions, with potential sources including catchment runoff and episodic high-energy hydrodynamic events in the Yilong Lake sediments. Compared to the clay fraction, silt reflects more variable and climate-sensitive sediment transport processes (Wang et al., 2021; Zhang et al., 2021a). In southwestern China, lake sediments are generally characterized by high proportions of silt component (Li et al., 2017; Zhang et al., 2021), which is typically associated with intensified catchment erosion and elevated runoff during increased regional precipitation (Ma et al., 2020b; Meng et al., 2023; Wang et al., 2021). A coarsening of lake sediments has therefore often been interpreted as indicative of increased precipitation and a shift toward more humid climatic conditions (Chen et al., 2004; Wu et al., 2015). In large shallow lakes such as Yilong Lake, however, the relationship between sediment grain size and hydrological conditions is more complex. Results from the SEM indicate that EM3 variability is regulated by a combination of climate and environmental factors (Fig. 5c). Precipitation shows a positive effect, but precipitation seasonality exerts a negative effect, indicating that EM3 responds to both total precipitation and hydrological stability—i.e., abundant and evenly distributed rainfall favors EM3 deposition.

Meanwhile, XRF-PC1 exerts a significant positive effect on EM3, while C/N shows a significant negative relationship with EM3. Yilong Lake is a carbonate-rich lake where authigenic carbonate precipitation tends to intensify under arid or warm climate conditions (Liao et al., 2021; Boyall et al., 2024; Fubelli and Dramis, 2023). The C/N ratio (< 10) typically indicates a predominant aquatic source of organic matter primarily facilitated by warm conditions as well (Gąsiorowski and Sienkiewicz, 2013; Wu et al., 2023). Thus, intensified monsoon precipitation coinciding with warm conditions led to increased deposition of the EM3 component. In southwestern China, there is a strong positive correlation between the intensity of the summer monsoon and temperatures (Zhao et al., 2021; Zhang et al., 2023), both of which facilitate dense vegetation coverage that enhances soil structural stability and reduces direct detrital transport (Hugo Durán Zuazo and Rocío Rodríguez Pleguezuelo, 2008; Yang et al., 2024). This in turn led to a negative path coefficient between AP/NAP and EM3.

We therefore suggest that EM3 should be the most dynamic component of grain size composition in Lake Yilong, deposited during deep lake conditions and regulated jointly by climate and environment.

EM4 (~24 µm) is composed of relatively coarse particles and is commonly identified in lake sediments across southwestern China (Li et al., 2017; Wu et al., 2015). EM4 displays a wide frequency spectrum with multiple superimposed modes and often corresponds to good sorting coefficients (Fig. 3 & 6). Although EM4 and EM3 fall within medium-grain size ranges, they exhibit clear differences in grain size distribution patterns and temporal variations. This difference indicates that EM4 should represent a high-energy input process formed under strong hydrodynamic or complex disturbance conditions (Paraschos et al., 2025; C. Zhang et al., 2023). SEM results indicate that EM4 is impacted by multiple factors, with precipitation seasonality identified as the dominant variable (Fig. 5d). Strong precipitation seasonality significantly affects the enrichment of EM4 by regulating catchment erosion intensity, runoff timing, and the dynamic transformation of the depositional environment (Li et al., 2017; Ning et al., 2017). This aligns with the observation that medium-coarse-grained end members (20–30 µm) are often closely related to slope erosion and terrestrial detrital input under high precipitation variability (J. Li et al., 2022; Xu et al., 2022). In addition, XRF-PC1 and Fe/Mn show significant negative correlations with EM4, reflecting a close linkage between EM4 and terrestrial clastic input.

Notably, AP/NAP exhibits a significant positive correlation with EM4. Although vegetation coverage is typically considered to suppress erosion and reduce coarse particle input, well-developed vegetation in humid alpine regions could enhance the supply and transport of intermediate-sized particles (~24 µm) from slope surfaces (Bunel et al., 2025; S. Li et al., 2022). This aligns with the positive correlation between EM4 and high AP/NAP ratios (Fig. 4). Therefore, EM4 is primarily influenced by precipitation variability and should represent the outcomes of intensified soil erosion in the watershed under strong hydrodynamic disturbances.

Figure 6. The variations of grain size end-members and environmental variables. (a) Mean annual temperature (MAT); Pollen-based (b) MAT and (c) MAP from Tengchongqinghai lake (X. Zhang et al., 2023); (d) East Asian δ^{18}O record (Cheng et al., 2017); (e) EM2 loading; (f) Fe/Mn; (g) EM1 loading; (h) Precipitation seasonality (P_{season}); (i) AP/NAP; (j) EM3 loading; (k) Annual precipitation (P_{annual}); (l) XRF-PC1; (m) C/N; (n) EM3 loading. Climate variables (a), (d), and (g) are derived from the TraCE-21ka transient climate simulation (Liu et al., 2009).

4.2 Stage-specific variability of grain size EMs

Four EMs of grain size distribution extracted from the sediment of Yilong Lake allow the distinction of varied components derived from different depositional processes (Patterson et al., 2022; van Hateren et al., 2018). EM1 and EM2 likely deposited during shallow lake conditions, with EM1 indicative of low-energy depositional environments and EM2 representing occasionally occurring flood deposition. EM3 and EM4 deposited under high hydrodynamic conditions within a humid climate, with the coarser-grained EM4 associated with short-term high-energy events. Different EMs exhibit diverse variabilities, showing complex responses to multiple factors such as precipitation, water level, and vegetation coverage since the LGM (Fig. 5 & 6).

During the LGM and early LDP, regional climate was cold and dry (Cheng et al., 2017; Wu et al., 2015), resulting in reduced lake levels (Sun et al., 2020; Wu et al., 2015) and increased landscape openness (Wang et al., 2024; Yu et al., 2000). Under these conditions, the grain size composition of Lake Yilong was dominated by EM1 and EM3 (Fig. 6). The lowered lake level provided a relatively stable, low-energy depositional environment that favored the settling of fine particles (EM1). Meanwhile, a certain amount of terrigenous detrital input (Fig. 6l, 6m), accounting for EM3, deposited during summer seasons with intensified monsoonal precipitation. In addition, greater landscape openness enhanced hillslope erosion (Giguet-Covex et al., 2012; Schillereff et al., 2014; Fig. 6i), and millennial-scale climate oscillations and teleconnections occasionally produced episodic increases in precipitation, recorded as short-lived high-energy event layers (EM2). By contrast, overall limited hydrodynamic conditions constrained the effective deposition of coarser material.

During the late LDP, southwestern China underwent a progressive shift toward warmer and wetter conditions (Cheng et al., 2017; Sun et al., 2020; Zhang et al., 2023), leading to dramatic fluctuations of grain size EMs in Yilong Lake.

EM1 decreased since 15 cal ka BP but with short-term increases (Fig. 6g). EM2 fluctuated and peaked during 14–12 cal ka BP, while EM4 increased during 16–14 cal ka BP (Fig. 6). These fluctuations of EMs correspond well to monsoon variability characterized by intensified ASM since 15 cal ka BP but weakening ASM during the Younger Dryas (Cheng et al., 2017; Zhang et al., 2023). The increased monsoonal precipitation likely led to elevated lake levels and intensified hydrodynamic conditions in Yilong Lake, enhancing water-column stability (Li et al., 2008; Magee and Wu, 2017) and facilitating the deposition of EM3. The intensified ASM also contributed to terrigenous inputs (decline in XRF-PC1) and to the deposition of EM4. Meanwhile, the weakened ASM but enhanced precipitation seasonality during the Younger Dryas (Fig. 6d, 6h) should have reduced depositional stability (Kalanke et al., 2020; Schillereff et al., 2014), resulting in pronounced variability in EM1 and EM2 (Fig. 6e, 6g).

During the early to middle Holocene, regional vegetation cover expanded (Li et al., 2024) under abundant precipitation and elevated temperatures (Cheng et al., 2017; Zhang et al., 2023). The elevated lake levels and dense vegetation stabilized the water column (Li et al., 2008; Magee and Wu, 2017), while increased annual precipitation and precipitation seasonality benefited terrestrial detrital input (Giguet-Covex et al., 2012; Schillereff et al., 2014), all of which collectively strengthened EM3 and EM4 (Fig. 6). Occasional increases in EM2 might indicate infrequent extreme precipitation events that can trigger turbidity deposition. Meanwhile, high lake levels might have reduced hydrodynamic disturbances and created a tranquil depositional setting, allowing the deposition of fine-grained EM1 (Fig. 6). During the Late Holocene, both temperature and precipitation were generally decreasing, with a trend toward cooler and drier conditions (Cai et al., 2012; Cheng et al., 2017; Zhang et al., 2023). Meanwhile, human activities gradually intensified in the Yilong basin during the late Holocene (Li et al., 2024), such as deforestation, irrigation, and watershed management, all of which might impact grain size distributions and also the interpretation of EMs. Against this background, the depositional system was dominated by low-energy, stable sedimentation, with EM1 maintaining a high proportion, followed by EM3. EM2 also exhibited large fluctuations, whereas EM4 decreased and even disappeared (Fig. 6). This situation resembles that during the LGM, with lower lake levels benefiting the accumulation of EM1. Intensified human activity altered vegetation composition (Cao, 2025; Pan et al., 2025; Xiao et al., 2018), and EM2 showed pronounced temporal variability likely due to intermittent impacts of localized storm-runoff/flood events (Fig. 6).

4.3 Complexity of grain size distributions in shallow lakes

Lake and catchment states are dynamically changing, influenced by climate change and, in turn, modulating how depositional processes and sediment components record and express climate signals (Van Wyk De Vries et al., 2022). Taking Yilong Lake as an example, the grain size distribution manifests different EM assemblages under different climatic backgrounds (Fig. 7 [Figure 7: see original paper]). Under cold-dry conditions during the LGM and early LDP (27–15 ka), when precipitation was low (Cheng et al., 2017; Wu et al., 2015), lake level was depressed (Sun et al., 2020; Wu et al., 2015), and catchment vegetation was sparse (Wang et al., 2024; Yu et al., 2000), the grain size composition exhibited high variability—typically featuring a unimodal EM1 under low rainfall and a bimodal EM2 under episodes of high precipitation (Fig. 7a). Under warm-humid conditions (15–5 ka), lake level rose and forest cover increased in the catchment (Li et al., 2024). The grain size composition became more stable, with clay fraction decreased but silt deposition increased, in which fine-silt unimodal EM3 under high-precipitation/low-variability and coarse silt unimodal EM4 under high-precipitation/high-variability dominated the grain size distribution (Fig. 7b). Along with intensified human activities, lake level and vegetation composition were altered (Cao, 2025; Pan et al., 2025; Xiao et al., 2018), and the grain size distributions partially reverted to LGM-like features, with increased proportions of EM1 and EM2 (Fig. 7c).

Despite grain size being a valuable proxy for studying fluctuations of lake levels, hydrodynamic conditions within the catchment, and past climate conditions, its interpretation requires additional circumspection. Our findings manifest that climate, vegetation, and limnological parameters strongly impact depositional processes and also grain size interpretations. When applying grain size distribution in climate reconstructions, relying on a single metric such as D_{50} would introduce inevitable but generally overlooked biases. For instance, in Lake Dianchi, median grain size varies with annual rainfall on interannual to multi-year scales, yet sedimentation rate is strongly influenced by land reclamation, damming, and urbanization, revealing clear scale dependence and anthropogenic bias in single-grain size indicators (Wang et al., 2011). Likewise, the long-term record from Lake Qinghai shows that different grain size parameters have different sensitivities to hydrodynamic processes, with skewness and grain size ratios robustly tracking riverine input and monsoon strength, whereas single statistics (e.g., mean or median grain size) respond more variably to climate (Liu et al., 2016). Therefore, climate and environmental reconstructions based on grain size data require comprehensive a priori knowledge and additional attention to the non-linearity and multi-phase nature of grain size–environment relationships.

Our results also highlight the influence of lake state on the interpretation of grain size distributions from shallow lakes. Lake depth controls both the delivery of sediment to the basin and its dispersal toward the depocenter. Deep-water conditions favor the settling of fine particles in the lake center, whereas coarse material is more readily transferred from the littoral zone toward the lake center under shallow conditions (Li et al., 2017; Zhang et al., 2019). However, this process may be impacted by hydrodynamic conditions in open lakes under different climate backgrounds. Taking Yilong Lake as an example, the combination of EM1 and EM3 occurred during low precipitation and shallow lake status during the LGM, while the combination of EM3 and EM4 appeared during high precipitation and deep lake status during the Holocene (Fig. 6). Thus, the complexity of hydrodynamics can strongly affect grain size distributions (Wang et al., 2021;

Zhang et al., 2019). Besides, regional setting and sources of water supply also modulate catchment processes and lacustrine grain size distributions in humid regions—e.g., sedimentation largely regulated by precipitation intensity and watershed vegetation cover in southwestern China (Ning et al., 2017; Wang et al., 2021), while sedimentation governed primarily by glacial activities on the southeastern Tibetan Plateau (Larsen et al., 2020; Li et al., 2016; Van Wyk De Vries et al., 2022). Therefore, future lacustrine EM-based environmental and climate reconstructions should explicitly account for hydrodynamic and geographical backgrounds.

Sedimentary grain size distribution is primarily regulated by climate (Green and Coco, 2014; Schillereff et al., 2014), based on which grain size can resemble long-term trends of climate parameters. However, human activities have increasingly decoupled this relationship during the Late Holocene, especially over the past two millennia. For example, deforestation intensifies soil loss (Pan et al., 2025; Zhang et al., 2022), reservoirs intercept sediment (Syvitski et al., 2005; Vörösmarty et al., 2003), and shoreline embankments and navigation enhance resuspension (Dethier et al., 2017; Scarpa et al., 2019). This is also the case in Yilong Lake sediment, where grain size distributions over the past two millennia resembled those during the LGM, but these two periods have totally different climate conditions. We therefore suggest that strong anthropogenic disturbance has led to obvious deviations of grain size distribution from those under natural climate conditions in Yilong Lake. Methodologically, a multi-proxy framework and segmented analyses should be used to detect human impacts and avoid misattributing anthropogenic signals to climate.

Fig. 7. Schematic diagram of grain size composition changes under different periods and climatic backgrounds: (a) 27–15 cal ka BP; (b) 15–5 cal ka BP; (c) Late Holocene.

5. Conclusion

The grain size composition of Yilong Lake sediments was divided into four EMs through EMMA. EM1 reflects low-energy shallow-lake sedimentation, mainly during the LGM-early deglaciation and the Late Holocene. EM2, with a bimodal distribution, represents flood deposits during drought periods with open vegetation, peaking at 14–12 cal ka BP. EM3 is the most dynamic component, deposited under deep-lake conditions and enhanced in the early-mid Holocene. EM4, composed of coarse particles, is governed by precipitation variability, peaking at 16–14 cal ka BP and in the early-mid Holocene. These EMs reveal distinct components linked to different depositional processes. They display diverse variabilities and show complex responses to multiple factors and climatic backgrounds, including precipitation, lake level, and vegetation coverage, since the LGM. Meanwhile, in the Late Holocene, intensified human activities exerted additional influences on hydrological and catchment processes, potentially altering and biasing the natural signal. Therefore, climate and environmental reconstructions in shallow lakes from humid regions, based on grain size data, require strong prior constraints and explicit attention to the nonlinear, multi-phase nature of grain size-environment relationships. A multi-proxy and phased analytical framework is also needed to detect human impacts and prevent the misattribution of anthropogenic signals to climate.

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