



Variable Late Holocene ^{14}C Reservoir Ages in Lake Bosten, Northwestern China

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Radiocarbon (^{14}C) dating has been widely used in paleoclimate reconstruction. However, the reliability of the ^{14}C age in lake sediments is sensitive to the ^{14}C reservoir effect, especially for a lake in arid regions. In this study, we evaluated the ^{14}C reservoir ages under different hydroclimatic conditions over the past ~2300 years in Lake Bosten, northwestern China, by comparing with different dating results and with multi-proxy indices of a vertical-down sediment core collected in this lake. The ^{14}C reservoir ages during ~1800 to 650 BP (a dry interval) are estimated to be approximately 1170 years older than those during ~650–100 BP and those during 2200–1800 BP (wet intervals). We proposed that variation in ^{14}C exchange rate between the dissolved CO_2 in lake water and CO_2 in the atmosphere, as well as the changing proportion of organic matter in the lake and the catchment, could have contributed to the variable ^{14}C reservoir ages in Lake Bosten. The result of this study suggests that the ^{14}C reservoir effect may be larger in dry periods than in wet periods in the arid/semi-arid area, which should be considered when establishing age models of lake sediment cores from these regions.

Keywords: ^{14}C reservoir age, hydroclimate change, late Holocene, Lake Bosten, arid central Asia

INTRODUCTION

Radiocarbon (^{14}C) dating has been widely used to establish geochronology less than ~50,000 years (Hughen et al., 2004; Reimer et al., 2009), using a variety of dating materials, including fossils of terrestrial and aquatic plants, bulk organic matter, etc. (Snyder et al., 1994; Bennike, 2000). The basis of ^{14}C dating is that the ^{14}C concentration of the living dating material, which exchanges ^{14}C with atmosphere CO_2 directly, is equal to the contemporaneous atmospheric ^{14}C concentration (e.g., Deevey et al., 1954). For example, a terrestrial plant absorbs atmospheric CO_2 during photosynthesis, and its ^{14}C concentration is generally regarded to be identical to the atmospheric ^{14}C concentration. Therefore, land plant debris has been widely used as an ideal ^{14}C dating material in paleolimnology.

However, in many cases, due to the paucity of sufficient terrestrial plant debris in lake sediments, bulk organic matter and aquatic shells are frequently used in radiocarbon dating, and the ^{14}C ages of these materials are generally more or less contaminated by the ^{14}C reservoir effect. This is due to the disequilibrium of ^{14}C concentration between aquatic CO_2 and atmospheric CO_2 , and due

to the partial utilization of the dissolved inorganic carbon (DIC) in lake waters to synthesize both organic and inorganic materials. In addition, the input of “old” materials from the catchment to the lake will also lead to “older” ¹⁴C ages of bulk organic matter than their real ages.

Previous studies have reported markedly different ¹⁴C reservoir ages among different lakes. For example, the ¹⁴C reservoir ages in Lake Wulungu (Liu et al., 2008a), Lake Qinghai (Shen et al., 2005), Chaka Salt Lake (Liu et al., 2008b), Lake Zigê Tangco (Herzschuh et al., 2006), Lake Kusai (Liu et al., 2009), and Lake Harnur (Lan et al., 2018) in northwestern China are estimated to be 760, 1073, 1700, 2010, 3400, and 3560 years, respectively, suggesting that the ¹⁴C reservoir effects in different lakes can vary from hundreds to thousands of years (Table 1). The reservoir ages in the same lake estimated by different studies are also sometimes different. For example, Chen et al. (2006) and Huang et al. (2009) estimated a 1140-year ¹⁴C reservoir age in Lake Bosten. Zhang et al. (2004) proposed an old carbon age of 650 years in the same lake, whereas Wünnemann et al. (2006) contended that the reservoir effect in Lake Bosten is minor and neglectable.

Mischke et al. (2013) showed that the ¹⁴C reservoir ages change spatially even in different sites of a same lake on the Tibetan Plateau. These spatially variable reservoir ages may be related to different degrees of ¹⁴C exchange between atmospheric CO₂ and aquatic CO₂, and may be partly attributed to the different “old” carbon released from erosion of carbon-contained bedrocks. Chongyi et al. (2018) also found that the ¹⁴C ages of total organic carbon in surface sediments in Lake Qinghai vary spatially and attributed these ages to different degrees of ¹⁴C exchange between aquatic and atmospheric CO₂. Hou et al. (2012) studied the ¹⁴C reservoir effect of different lakes in Tibetan Plateau, and they suggested that the ¹⁴C reservoir ages are related to geological settings of the catchment, residence time of lake water, peat/wetland development within the lake catchment, etc.

In addition, ¹⁴C reservoir ages of different periods in a same lake may be variable as well. For example, Zhou et al. (2014) got different ¹⁴C reservoir ages (135, 1143, and 2523 years, respectively) at different depths of a sediment core in Lake Qinghai. The old carbon ages in Lake Xingyun were estimated to vary between 960 and 2200 years over the past 8000 years (Zhou et al., 2015), and these variable old carbon reservoir ages were likely related to the variable input of “old materials” from the catchment under different hydrological conditions. Since changes of ¹⁴C reservoir ages in the same lake may largely affect the accuracy of the ¹⁴C age model of vertical-down sediment cores, it is necessary to assess the ¹⁴C reservoir ages in the same lake in different periods.

Lakes in the arid/semi-arid regions of China, most of which are closed and/or semi-closed lakes, are often high in salinity and alkalinity, and the ¹⁴C reservoir ages of these lakes are variable. Lake Bosten is a widely noted site to study paleoclimatic changes, in Xinjiang, northwestern China, arid central Asia (Mischke and Wünnemann, 2006; Wünnemann et al., 2006). However, previous studies have not fully considered the possibly variable ¹⁴C reservoir ages, and therefore parts of the previously published age models may need to be improved/corrected. In

this study, we assessed the old carbon effects by comparison between the ¹⁴C ages of bulk organic matter and the ¹³⁷Cs and ²¹⁰Pb ages of sediment in Lake Bosten and by comparison between multi-proxy indices extracted from this lake and those from other works.

BACKGROUND AND METHODS

Lake Bosten is a fault lake located at the southern foot of central Tianshan Mountains (41°56′–42°14′N, 86°40′–87°26′E; modern lake level: 1048 m asl). The catchment area is ~55,600 km², and the modern lake area is ~1000 km², with a maximum water depth of ~17 m (Xiao et al., 2010). Lake Bosten is supplied by 13 rivers, among which the Kaidu River is the largest one. River water of the Kaidu River mainly comes from alpine glacier and permanent snowmelt water, as well as seasonal snowmelt water and summer precipitation (Wünnemann et al., 2006).

Annual mean temperature around Lake Bosten is ~8.3°C, and the average temperature in January and July are -9.2°C and 23.6°C, respectively (Huang et al., 2009). Annual precipitation is ~70 mm, mostly falling in the warm season (Figure 1). Annual evaporation is ~2000 mm (Huang et al., 2009). Precipitation in the lower reaches of the lake basin is relatively high; for example, it reaches ~400 mm/a in the eastern part of Tianshan Mountain (Hu, 2004). Water vapor in the study area comes from the Atlantic, Mediterranean, and Caspian Sea water supply (Aizen et al., 2006; Chen et al., 2008; Xu et al., 2019b; Yan et al., 2019). Salinity of modern lake water is unevenly distributed, with a spatially increasing trend from west to east (Jiu et al., 1990). The lowest salinity of the lake is in the Kaidu River estuary (0.20–0.28%; Mischke and Wünnemann, 2006), and the maximum value is in the eastern part of the lake (>2.5%; Jiu et al., 1990). The pH value of lake water is 8.3–9.0 (Mischke and Wünnemann, 2006).

A 153-cm-long sediment core (BL13-1-4; 41°59′10.29″N, 87°09′43.70″E; water depth: 12 m) was collected from the central lake (Figure 1), in August 2013, using a gravity corer (UWITEC). The uppermost 24 cm is typical gray lacustrine sediment; 25–40 cm is gray sandy sediment; 41–137 cm is gray lacustrine sediment; 138–144 cm is sandy gray-white sediment; and 145–153 cm is gray lacustrine sediment. The core was sectioned at every 1-cm interval *in situ* and was stored under low temperature conditions (-20°C) until freeze-dried.

Radioactivities of ²¹⁰Pb and ¹³⁷Cs were determined using a gamma detector [Ortec Germanium (HPGe) well detector; GWL-15-250; Figure 2]. No macroscopic plant debris for radiocarbon dating was observed in the core, and 12 samples were dated using bulk organic carbon at Institute of Surface-Earth System Science (ISESS), Tianjin University, and Beta Analytic (Figure 3 and Table 2). Sedimentary carbonate contents (carb%) were determined by titration with HClO₄ (0.1 mol/L) and NaOH (0.1 mol/L), with uncertainty less than 0.5%. Sedimentary grain size was determined on a Malvern Mastersizer 2000 laser grain-size analyzer, with uncertainty less than 3%. Total organic carbon content (TOC), total nitrogen content (TN), and the organic carbon and nitrogen isotopes were determined (δ¹³C and

TABLE 1 | Comparison of ¹⁴C reservoir ages from different lakes of western China.

Site name	Location	¹⁴ C reservoir age (years)	References
Lake Wulungu	46.98°N, 87.58°E	760	Liu et al., 2008a
Chaka Salt Lake	36.67°N, 99.10°E	1700	Liu et al., 2008b
Lake Zigê Tangco	32.01°N, 90.91°E	2010	Herzschuh et al., 2006
Lake Kusai	35.67°N, 93.33°E	3400	Liu et al., 2009
Lake Hamur	43.11°N, 83.97°E	3560	Lan et al., 2018
Lake Qinghai	36.87°N, 100.17°E	1039	Shen et al., 2005
		658; 737	Henderson et al., 2010
		135; 1143; 2523	Zhou et al., 2014
Lake Bosten	41.99°N, 86.98°E	1140	Chen et al., 2006; Huang et al., 2009
		650	Zhang et al., 2004
		Minor and neglectable	Wünnemann et al., 2006

$\delta^{15}\text{N}$) on an elementary analyzer–mass spectrometer (Flash2000-MAT253), with uncertainty less than 0.1% (Figure 4).

RESULTS

¹³⁷Cs and ²¹⁰Pb Dating

¹³⁷Cs is an artificial nuclide with a half-life of 30.17 years. After 1945, especially in the 1950s, nuclear tests were widely carried out in the world, which led to the rapid increase of atmospheric ¹³⁷Cs concentration. A rapid increase in ¹³⁷Cs activity from natural background (zero) was detected in a large number of undisturbed or weakly disturbed lake sediment cores, and this point was assigned as a time marker of 1952 AD, which is particularly evident in lakes in northwest China (e.g., Yu et al., 2017; Lan et al., 2018; Yan et al., 2019). The atmospheric ¹³⁷Cs fallout peak in the northern hemisphere occurred at 1963 AD (Robbins and Edgington, 1975), and this peak is widely used as a time marker of 1964 AD in lake sediments. Although the 1986 Chernobyl nuclear leak out may generate a ¹³⁷Cs peak in lake sediment, this peak can be hardly detected in northwestern China (Xu et al., 2010; Yu et al., 2017; Yan et al., 2019).

The ¹³⁷Cs curve of the core BL13-1-4 shows no clear peak, suggesting considerable disturbance of the sediments in modern times. Although this disturbance may lead to broadening of the peak, it does not affect the central position of the peak (Xu et al., 2010). The central position of the ¹³⁷Cs peak of core BL13-1-4 occurred at ~15 cm, and it can be recognized as the 1964 AD time marker. Sedimentation rate based on this 1964-year time marker is ~0.29 cm/year. ¹³⁷Cs activity increases rapidly from zero (the background) at 22 cm, indicating the beginning of atmospheric ¹³⁷Cs fallout, corresponding to the 1952 AD time marker (Yu et al., 2017; Yan et al., 2019). Sedimentation rate based on this time marker (1952-year) is ~0.83 cm/year. Such big difference in modern sedimentation rates suggests strong anthropogenic impacts during the recent/modern epoch, such as changes in land use in the catchment and/or roads/factories construction around the lake.

²¹⁰Pb is a daughter of uranium series, with a half-life of 22.23 years. It has been widely used to determine the age of lake sediments of the past 150 years

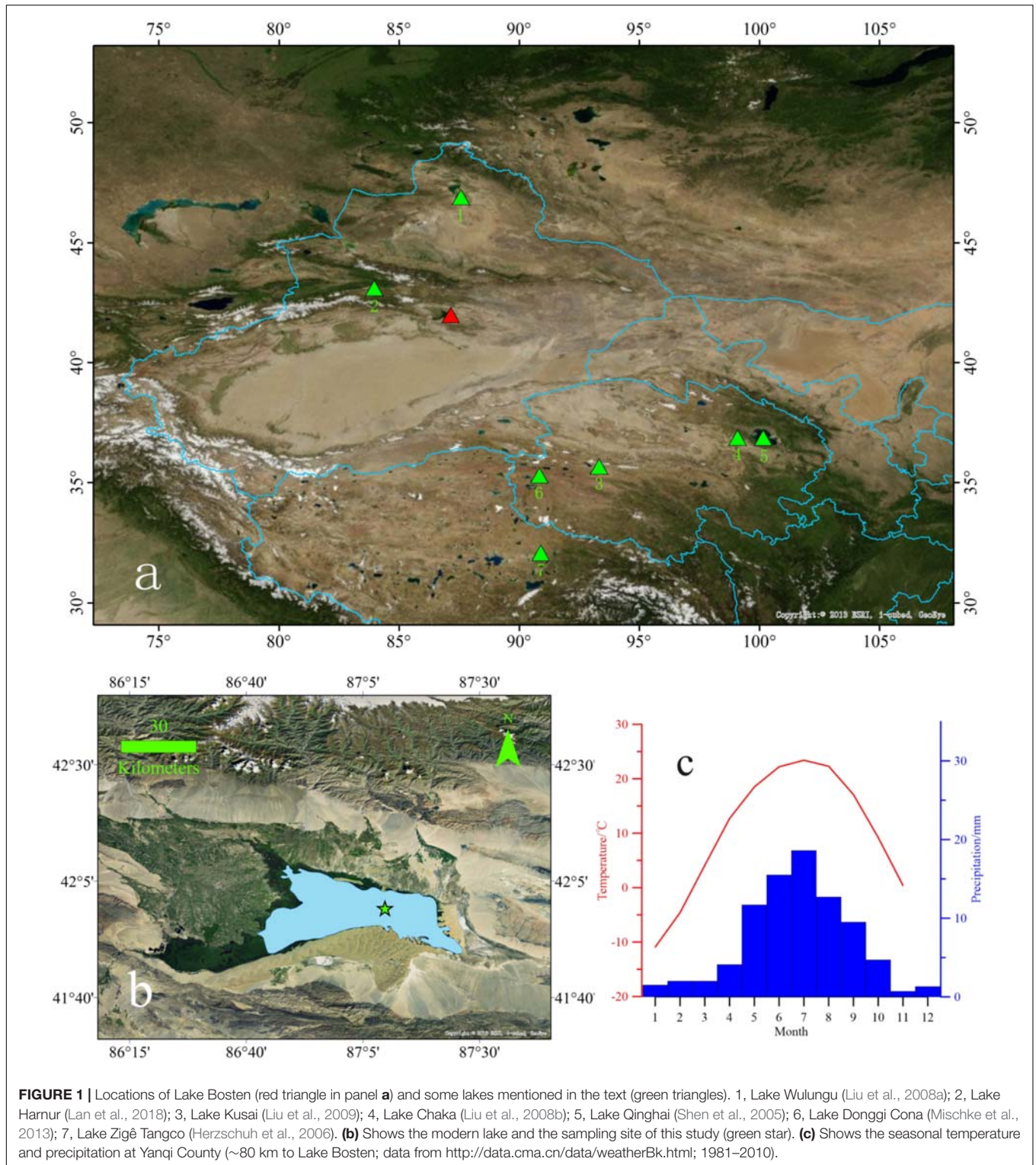
(e.g., Robbins and Edgington, 1975). The commonly used ²¹⁰Pb dating methods include constant initial concentration mode (CIC) and constant rate of supply mode (CRS; Robbins and Edgington, 1975). The ²¹⁰Pb ages of core BL13-1-4 derived from CRS model are similar to the ¹³⁷Cs ages for the uppermost 10 cm, but deviate more and more as depth increases (Figure 2). The ²¹⁰Pb ages derived from the CIC model are quite different with those derived from CRS model and those derived from the ¹³⁷Cs time marker (Figure 2), and such big differences are most likely due to instable sedimentation rates. Because of such variable sedimentation rates, the ²¹⁰Pb dating method can hardly generate reliable ages for the upper section of core BL13-1-4. Therefore, we do not use the ²¹⁰Pb ages, but only use the ¹³⁷Cs ages to assess the old carbon reservoir effect in this study (see below).

¹⁴C Dating

The ¹⁴C ages show linear trends in three intervals (20–50 cm, 60–120 cm, 120–153 cm; Figure 3). ¹³⁷Cs age at 20 cm is –8 a BP, while the corresponding ¹⁴C age is 1025 a BP. We therefore got an old carbon reservoir age of 1033 years for the upper 20–50 cm. Since the ¹⁴C ages of 120–153 cm are linearly correlated to those of 20–50 cm ($r^2 = 0.99$; Figure 3), we assume similar old carbon reservoir ages for both intervals. The ¹⁴C ages of 60–120 cm are bigger than those of the upper and lower intervals. After a correction of 2200 years, the corrected ¹⁴C ages of 60–120 cm fall on the regression line of ¹⁴C ages of the upper and bottom sections (Figure 3). The final age model of core BL13-1-4 is a combination of the ¹³⁷Cs ages of the upper section (0–22 cm) and the corrected ¹⁴C ages of the lower section (23–153 cm). We acknowledge that the chronology of core BL13-1-4 may not be accurate enough regarding high-resolution records; however, it does not influence the topic involved in this study (see below).

Proxy Indices and the Climatic Significance

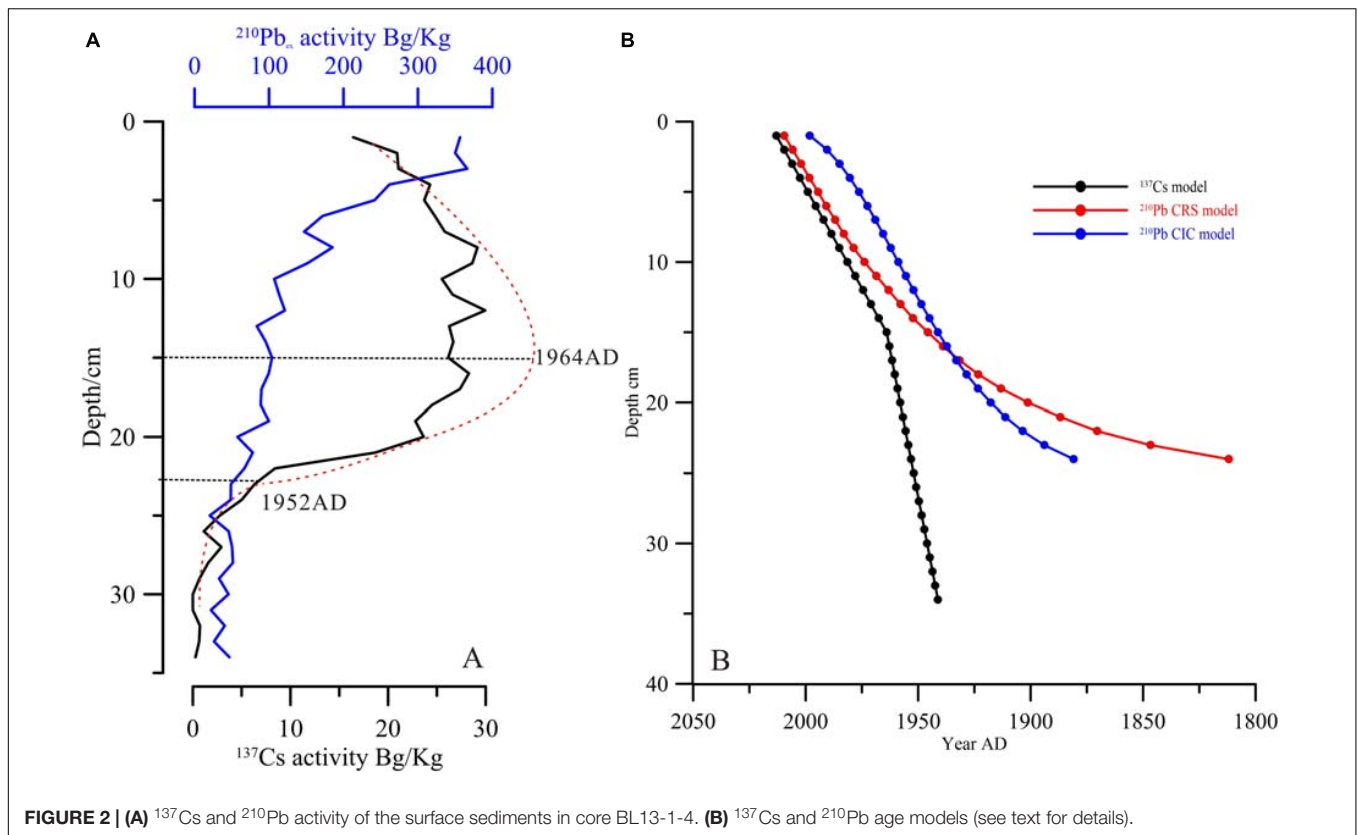
The carbonate content of core BL13-1-4 varies between 31.36% and 54.85%, with an average of 47.61% (Figure 4). Autogenic carbonate is generally precipitated faster and more in waters with higher ion concentration, and thus its content in lake sediment can be used to reflect the budget of water input and evaporation of a lake (Chen et al., 2006). In general, lower carb% in lake



sediment reflects wetter hydroclimatic condition, while higher carb% reflects dryer condition (Chen et al., 2006).

The grain size of core BL13-1-4 varies between 9.21 and 30.87 μm , with an average of 14.38 μm . Sedimentary grain size has different climatic significance under different conditions and

on different time scales. On long-term time scales, the grain size can reflect lake level variations (Liu et al., 2008a), while on short time scales, sediment grain size can record changes in surface runoff intensity, and then changes in precipitation (Xu et al., 2015). As Lake Bosten is an open lake, the decrease in

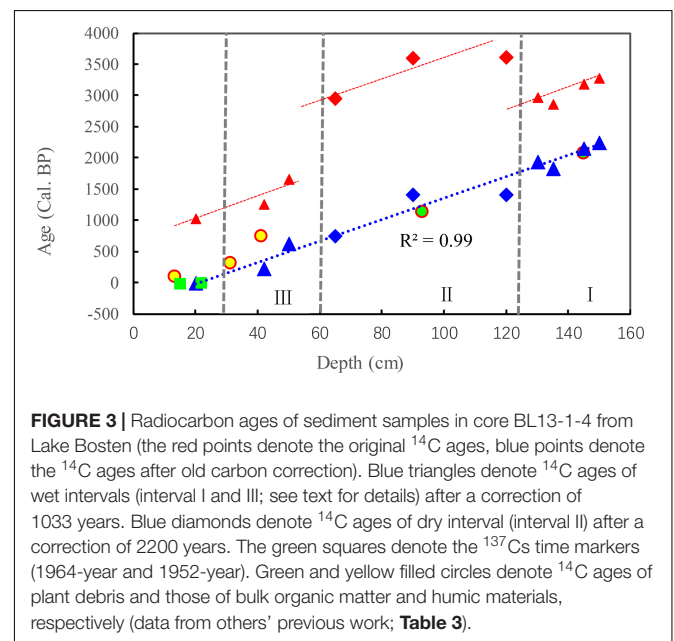


sedimentary grain size in the late Holocene most likely indicates decrease in surface runoff intensity and precipitation; on the contrary, the increase in grain size indicates increase in regional runoff intensity and precipitation.

The $\delta^{15}\text{N}$ of core BL13-1-4 ranges from 2.49‰ to 7.91‰, with an average of 5.88‰. $\delta^{15}\text{N}$ of organic matter in lake sediments is closely related to primary productivity in lakes (Talbot and Johannessen, 1992; Xu et al., 2014, 2016b). During photosynthesis, the fractionation of nitrogen isotope is mainly controlled by nitrogen isotope value of dissolved inorganic nitrogen (DIN) in lake water. Phytoplankton in water tends to absorb ^{14}N in photosynthesis, which leads to gradual enrichment of $\delta^{15}\text{N}$ in lake water DIN pool (Talbot and Johannessen, 1992; Xu et al., 2014, 2016b). Increasing primary productivity in lake would therefore result in higher $\delta^{15}\text{N}$ values in organic matter, and vice versa.

Total organic carbon content of core BL13-1-4 varies between 1.39 and 7.40%, with an average of 3.46%. Sedimentary TOC is a sum of endogenous and exogenous organic carbon, and can reflect the biomass both in lake and in catchment (Meyers, 2003). The primary productivity in the lake is closely related to temperature variations and nutrients supply, while the amount of organic matter transported from the catchment to the lake is also closely related to the biomass and surface runoff intensity in the catchment (Cohen, 2003).

The atomic C/N ratio in core BL13-1-4 varies between 8.36 and 13.47, with an average value of 9.79. Because aquatic phytoplankton and algae contain higher protein content, their



C/N ratio is relatively low and generally falls within the range of 4–10. In contrast, terrestrial plants contain more lignin and cellulose, so their C/N values are higher (generally higher than 20). As a result, C/N ratio can reflect the relative contribution of different sources of organic matter in lake sediments; decrease in

TABLE 2 | ¹⁴C ages of sediment samples of core BL13-1-4 in Lake Bosten.

Sample no.	Lab. no.	Depth (cm)	¹³⁷ Cs age	¹⁴ C age	Cal. ¹⁴ C age (BP; median prob.)*	Old carbon reservoir	Corrected ages (BP)
BL13-1-4-15	LPR-1402-09	15	1964	/	/	/	-14
BL13-1-4-22	LPR-1402-16	22	1952	/	/	/	-2
BL13-1-4-20	TJU/C97	20	/	1126 ± 30	1025	1033	-8
BL13-1-4-42	TJU/C98	42	/	1320 ± 30	1264	1033	231
BL13-1-4-50	Beta 491266	50	/	1750 ± 30	1658	1033	625
BL13-1-4-65	TJU/C99	65	/	2844 ± 30	2951	2200	751
BL13-1-4-90	TJU/C100	90	/	3363 ± 30	3607	2200	1407
BL13-1-4-120	TJU/C101	120	/	3373 ± 30	3616	2200	1416
BL13-1-4-130	Beta 491269	130	/	2860 ± 30	2976	1033	1943
BL13-1-4-135	Beta 491270	135	/	2770 ± 30	2864	1033	1831
BL13-1-4-145	Beta 491271	145	/	3000 ± 30	3186	1033	2153
BL13-1-4-150	Beta 491272	150	/	3060 ± 30	3278	1033	2245

*Calibrated by CALIB 7.0.2 (Stuiver et al., 1998).

TABLE 3 | ¹⁴C ages of sediments in Lake Bosten from some previous works.

Sample number	Depth (cm)	Dating materials	¹⁴ C age	Calib. age*	Corrected ages	References
BST04H	31	TOC	1470 ± 40	1358	325**	Huang et al., 2009
XBWu46	13	OM _{mean}	102 ± 24	111	111	Wünnemann et al., 2006
XBWu25	41	OM _{bulk}	840 ± 40	751	751	Wünnemann et al., 2006
XBWu46	93	Plant	1207 ± 23	1129	1129	Wünnemann et al., 2006
BSTC-01	145	Plant	2099 ± 24	2072	2072	Zhang et al., 2004

*Re-calibrated using CALIB 7.0.2. **This age was dated by bulk organic matter and was corrected by 1033 years.

sedimentary C/N ratio suggests high fraction of organic matter produced in lake, and vice versa (Meyers, 2003).

Late Holocene Climatic Changes at Lake Bosten

The sedimentary proxy indices in core BL13-1-4 in Lake Bosten indicate significant climate change during the late Holocene, and it can be broadly divided into four intervals:

Interval I (126–153 cm), corresponding to 1800–2200 BP: the average sedimentary grain size was relatively big, indicating strong runoff intensities; the carb% was relatively low, both of which suggest higher precipitation during this period. C/N ratio increases, indicating increase in terrestrial organic matter input, which also indicates enhanced runoff transport in the catchment. The coarse sand during 138–144 cm (about 2100–2000 BP) indicates that precipitation may be higher during this period. The sediment $\delta^{15}\text{N}$ is relatively low, indicating relatively weak lake productivity during this period.

Interval II (60–125 cm), the carb% was at a higher level in the corresponding period of 650–1800 BP, indicating that the lake water salinity was higher and chemical deposition rate was faster, suggesting that the water influx to the lake was less than the evaporation. The average sedimentary grain size decreased obviously compared with that of the previous period, indicating that the runoff intensity was weakened and the surface runoff transport capacity was decreased, suggesting that the precipitation may decrease in that period. The C/N

ratio was relatively small, suggesting relatively low contribution of terrestrial organic matter in this period. The high $\delta^{15}\text{N}$ value in this period indicates that the relative contribution of lake productivity is increasing. All these suggest that the biomass in the catchment was relatively low during this period due to less precipitation.

Interval III (28–59 cm), corresponding to 650–100 BP: the carb% firstly decreased and then increased, and the averaged value was relatively low. Sedimentary grain size shows a first increasing and then slightly decreasing trend, and the averaged grain size of this section was coarser than that of the previous section (60–125 cm; corresponding to 650–1800 BP). A sandy layer (25–40 cm) was found in this section. The TOC, TN, and the C/N ratios are higher, suggesting higher biomass in the catchment and larger contribution of terrestrial organic matter to the bulk sedimentary organic matter. The averaged $\delta^{15}\text{N}$ is lower, suggesting low primary productivity of the lake. All these suggest that the catchment was wetter in general, but experienced obvious dry and wet transitions during 650–100 BP.

The surface (1–27 cm) sedimentation rates are strongly influenced by human activities, which can be seen from two aspects. (1) From the ²¹⁰Pb-¹³⁷Cs chronology of surface sediments, it can be seen that the deposition rate has changed dramatically in the modern times as mentioned above. (2) The correlation between different proxy indices in this interval is weak, implying strong human activities during the modern epoch (strong human activity disturbs the relationship between proxy indices and climatic changes under natural background).

DISCUSSION

Old Carbon Reservoir

The basis of the ^{14}C dating is that the initial ^{14}C concentration of the living sample is equal to the atmospheric ^{14}C concentration of the same period (Deevey et al., 1954). However, factors influencing the old carbon reservoir ages are diverse, including (1) recharge of surface/underground water that contains “old carbon” (Deevey et al., 1954; Hendy and Hall, 2006). When the surface/underground water flows through the limestone area, it erodes the limestone or soils in the catchment, and brings “old carbon” into the lake (Olsson, 2009). (2) The ^{14}C exchange between lake water and atmospheric CO_2 . Due to the slow convection rate of some lakes and the lake water stratification, the ^{14}C concentration of lake water is lower than that of atmospheric CO_2 of the same period, and the calculated ^{14}C ages of materials produced in lake are older than the corresponding real ages. For example, some aquatic plants in the lake use CO_2 in atmosphere and DIC in water for photosynthesis, which will result in parts of the “old carbon” used in photosynthesis (Olsson, 2009). (3) the pH value, salinity, and nutrient concentration of lake water may affect the primary productivity of lake, the ^{14}C exchange rate (between aquatic and atmospheric CO_2), and the old carbon reservoir age (Fontes et al., 1996; Shen et al., 2005). (4) The organic matter in lake sediments may be a mixture of terrestrial plants and aquatic plants (phytoplankton/algae), and the relative fraction of these two sources will change with the lake levels and primary productivity over time, which may also affect the age of old carbon reservoir.

Old Carbon Correction

Methods used to correct old carbon reservoir ages generally include three categories: linear regression, stratigraphic correlation, and geochemical modeling.

Linear Regression

Linear regression method has been widely used to estimate the old carbon reservoir age (e.g., Fontes et al., 1996; Sheng et al., 2015; Zhang et al., 2016). Ages of the surface sediments are generally considered to be the time when they were sampled, then the intercept between the linear regression line and age coordinate (at the water-sediment interface) is regarded as the carbon reservoir age. For example, Shen et al. (2005) used linear regression method to estimate the carbon reservoir age in Lake Qinghai, and Fontes et al. (1996) and Hou et al. (2017) used linear regression method to estimate the carbon reservoir ages in Lake Bangongco. By comparing the ^{14}C ages of the bulk organic matter with those of plant residue and inorganic carbonates in sediment core of Lake Zigê Tangco, and by linear regression, Wu et al. (2010) got the carbon reservoir age of 2010 years for this lake. However, the climate, hydrology, and deposition rate should be relatively stable when using linear regression method to evaluate the old carbon effect. If the environment changes largely in different periods, it is better to use piecewise linear regression. For example, by separating linear regression of different layers, Zhou et al. (2014) got old carbon reservoir ages of 135 years,

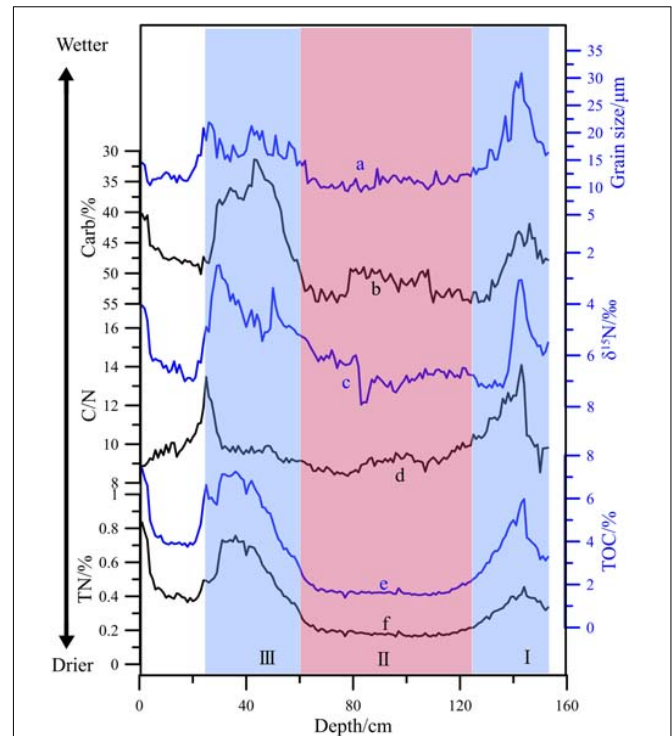


FIGURE 4 | Proxy indices in core BL13-1-4 in Lake Bosten. **(a)** Grain size. **(b)** Carbonate content (Carb%). **(c)** Organic matter $\delta^{15}\text{N}$. **(d)** organic matter C/N ratio. **(e,f)** Total organic carbon content and nitrogen content.

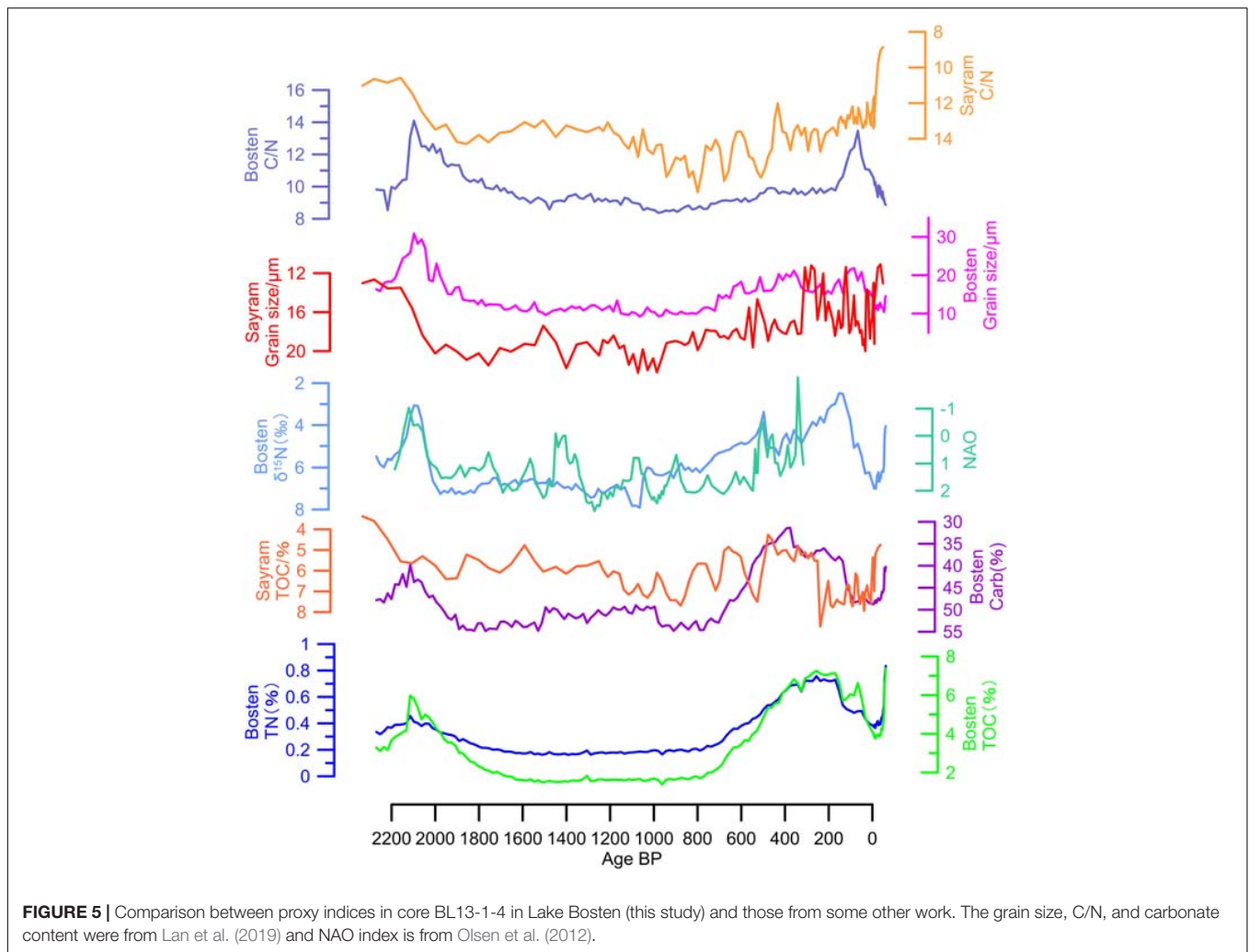
1143 years, and 2523 years for different sections of a core collected in Lake Qinghai.

Stratigraphic Correlation

Lake sediments of the last hundred years can be determined by ^{210}Pb and ^{137}Cs dating methods; by comparison with the ^{14}C ages of the surface sediment and ^{210}Pb and ^{137}Cs ages of the same depth, the old carbon reservoir ages can be estimated. By comparison between the ^{14}C ages of terrestrial plant residues (no old carbon effect), those of the bulk sedimentary organic matter, aquatic plants, and snail shells in the lake sediments of the same layers, the ^{14}C reservoir effect can also be estimated. The old carbon reservoir ages can also be evaluated by comparing the ^{14}C ages of the same layer with the luminescent ages and varve-counting ages (e.g., Hall and Henderson, 2001; Long et al., 2011). For example, by comparing ^{14}C ages of different samples collected from the same layers in sediment core in Xingyun Lake, Zhou et al. (2015) estimated that the carbon reservoir ages of this lake changed from 1150 to 2200 years in the past 8500 years. By comparing the ^{14}C age of organic matter and inorganic carbonate in the surface layer, and ^{14}C age of dissolved organic matter in lake water in Lake Qinghai, Henderson et al. (2010) got an old carbon reservoir age of 658 years.

Modeling of the Old Carbon Reservoir Age

If different ^{14}C sources of a lake can be identified and quantified, then old carbon reservoir age can be estimated by geochemical



modeling. For example, Yu et al. (2007) used geochemical modeling to study the old carbon reservoir ages in Lake Qinghai, and they got an old carbon reservoir age of ~ 1500 years in this lake. Watanabe et al. (2013) calculated the relative contribution of organic matter produced in lake and those in lakeshore wetland at Lake Pumoyum Co, and estimated the old carbon reservoir age. However, as lakes may have experienced considerable environmental changes in the past, the uncertainty of the parameters limits the application of modeling to evaluate the carbon reservoir ages of the past times. It is therefore generally limited to determine the old carbon effect of modern lakes.

Changing Old Carbon Reservoir Effect in Lake Bosten

The different linear correlations of the ^{14}C ages (as shown in Figure 3) and the variation patterns of the proxy indices (Figure 4) imply that the carbon reservoir effect of Lake Bosten was relatively smaller in the humid interval I (59–28 cm, 650–100 BP) and interval III (153–126 cm, 2200–1800 BP), but was significantly bigger (about 1170 years) during the dry interval II (125–60 cm, 1800–650 BP). To verify the changing carbon

reservoir effect and the reliability of the age model for core BL13-1-4 in Lake Bosten, we compared the age model of this study with those published by some previous work. The results show that parts of previous ^{14}C ages (e.g., Zhang et al., 2004; Wünnemann et al., 2006) have a good correlation with the age model obtained in this study (Figure 3). In particular, the ^{14}C ages based on plant residues of some previous work fall on the regression line of this paper, suggesting that our age model (based on separated correction of different old carbon ages in different periods) is rational.

Comparison of Proxy Indices

To further verify the age model in this paper, we compared the proxy indices developed in this study with those of some previous work. As shown in Figure 5, the time series of proxy index based on the abovementioned age model in this study show good synchronicity to those of some other previous work. For example, the grain size, $\delta^{15}\text{N}$, TOC, and carb% of the core BL13-1-4 show that there is a transition from wet to dry in Lake Bosten area around 2100 BP, while some other records, like the grain size and C/N ratio of Lake Sayram (Lan et al., 2019), North Atlantic NAO

index (Olsen et al., 2012), etc., show similar transitions from wet to dry contemporaneously (Figure 5). Another example is that during the period of about 650–500 BP, the grain size, $\delta^{15}\text{N}$, TOC, and carb% of Lake Bosten recorded a transition from dry to wet, which is similar to the climatic transitions inferred from grain size and C/N ratio in Lake Sayram (Lan et al., 2019), the NAO index (Olsen et al., 2012), and the Alpine flood records (Wirth et al., 2013). It is interesting to note that such an obvious hydroclimatic transition from dry to wet seems to have an even wider extension, e.g., in the extended Indian summer monsoon areas (Xu et al., 2016a, 2019a). However, the nature of this hydroclimatic transition needs further study and is outside the scope of this work.

However, some differences do exist between the climate changes reconstructed by different studies, and these may be due to (1) certain errors or methodological differences in different chronologies, (2) differences in the resolution of different indicators, and (3) different responses of proxy indices to climate events or atmospheric circulation in different regions. Neglecting these differences, the results of this study are in good agreement with those obtained by previous studies. Therefore, it is rational to evaluate and correct the different old carbon effects in different periods of Lake Bosten.

Possible Causes of the Changing Old Carbon Reservoir Ages in Lake Bosten

The old carbon effect in core BL13-1-4 of Lake Bosten is significantly higher in interval II than those in other intervals, which may be related to the variable proportion of organic matter produced in lake compared to those of the bulk sediment (due to the different climatic conditions). TOC values are relatively low during 1800–650 BP (60–125 cm), suggesting less organic matter transported from the catchment to the lake during this period. The higher lake water salinity would lead to faster chemical deposition rate, and the high sedimentary carb% (as high as 55%) strongly supports the above inference.

The dry hydroclimatic condition during this interval may lead to relatively low lake levels, consistent with the switch from lacustrine sediment to peaty mud during the interval of ~1000–500 BP in a core collected near the western shoreline in this lake (Mischke and Wünnemann, 2006). The decrease of lake water level and increase of water salinity may have slowed down the ¹⁴C exchange between dissolved CO₂ and atmospheric CO₂, resulting in increase of old carbon age of the DIC pool. At the same time, the decrease of lake level during this period favored nutrient transport to the sampling site, resulting in increasing primary productivity surround the sampling site. The higher $\delta^{15}\text{N}$ values during this period also suggest that the primary productivity around the sampling site was strong. Due to the decrease of organic matter input from the catchment to lake, the relative contribution of organic matter produced in lakes should increase during this period, which can be strongly supported by the significant decreases in sedimentary C/N ratios during this period.

According to the above analysis, the contribution of endogenous organic matter increased during the relatively dry

period at Lake Bosten. Due to partial utilization of DIC to synthesize organic matter, and due to the larger reservoir ages in dry period, the bulk organic matter ¹⁴C age of lake sediments is older. In contrast, the relative lower contribution of endogenous organic matter in wet periods (100–650 BP and 1800–2200 BP) resulted in a smaller old carbon effect in lake sediment.

CONCLUSION

We focused on influence of different hydroclimatic conditions of the old carbon reservoir effect in Lake Bosten. By comparison between ¹³⁷Cs/²¹⁰Pb dating results and radiocarbon ages of the surface sediments and by comparison between multi-proxy indices developed in this study and proxy indices from some previous work, we found that the old carbon effect existed and varied over the past ~2300 years at Lake Bosten. The old carbon reservoir ages of dry periods are likely to be bigger than those of wet periods. We contend that the changing old carbon reservoir ages could be ascribed to different degrees of ¹⁴C exchange between lake water CO₂ and atmospheric CO₂ under different hydroclimatic conditions and to the variable proportion between organic matter produced in the lake and those in the catchment.

As the old carbon effect varies on different temporal and spatial scales for some specific lakes, it would lead to large uncertainty by simply correcting the old carbon effect using one unique old carbon reservoir age. It is necessary to correct parts of the previous ¹⁴C ages (especially those over the arid zone) by a proper method. The method of this study, i.e., by comparing the ¹⁴C ages with other robust dating results and by comprehensive comparison of multi-proxy indices, may serve as a reference method to get reliable age models in paleolimnology.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

HX designed the research. HX, KZ, JL, DY, ES, KY, JZ, and YS performed the research. KZ, HX, JL, PF, and SX analyzed the data. KZ and HX wrote the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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