

Anthropogenic Effect on Deposition Dynamics of Lake Sediments Based on ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ Techniques in Jiuzhaigou National Nature Reserve, China

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Abstract: Radionuclide dating techniques characterized by ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ have recently been applied in the study of lake sediments around the world. In this study, a chronological series of sediment cores was established based on ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ analyses along with the evaluation of sediment properties, such as particle size distribution, total organic carbon (TOC), carbonate content, and acid-insoluble residue, to study sediment accumulation rates, sediment sources, and responses to human activities in the Jiuzhaigou National Nature Reserve in southwestern China. In terms of the particle size distribution of sediments, silt content was the highest, and clay and sand contents were relatively low. The sediments displayed high TOC contents because of the significant amounts of vegetation grown in the lakes. The carbonate content was also high due to the overall geological background of carbonates in Jiuzhaigou. Carbonate content tended to decline from top to bottom in the sediment cores, whereas the acid-insoluble residue tended to increase. These results suggested that the depth variation of the environmental parameters of the sediments in two lakes in Jiuzhaigou would correspond to each other. The results indicated that the sediment rate of Jiuzhaigou was generally high with strong siltation, indicating that serious soil loss was induced by intensive human activities in the basin over the past decades. The increases in the mass accumulation rate, contents of acid-insoluble residue, and mean particle size during the periods of 1840–1900s, late 1930s–early 1950s, 1966–1978, and 2003–2006 revealed the occurrence of severe soil and water loss as a result of extensive agricultural expansion, large-scale deforestation, and road construction in Jiuzhaigou. The deposition rate and the properties of lacustrine sediments could reflect the significant impact of human activities on lake sedimentation during Jiuzhaigou's history.

Keywords: lake sediment; ^{137}Cs ; $^{210}\text{Pb}_{\text{ex}}$; deposition rate; particle size distribution; acid-insoluble residue; Jiuzhaigou National Nature Reserve

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1 Introduction

Lake sedimentation and a sharp reduction in lake area occur along with rapid economic development and intensified human activities, particularly excessive human disturbance. This sedimentation and reduced lake area aggravate the problems of paludification and eutrophication in lakes and inhibit certain lake functions, thus leading to increased difficulties in lake harnessing (Yan *et al.*, 2001; Ketterer *et al.*, 2013). Lakes gradually evolve into marsh and may even disappear under natural conditions over a long period. Distinct changes would occur during the paludification and disappearance processes because of continuous interruption triggered by

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human activities. Numerous studies have been conducted with different emphases, such as sustainable uses of lake resources (Zalewski, 2000; Cruickshank and Grover, 2012; Pavri *et al.*, 2013), water or sediment pollution in lakes by heavy metals and persistent organic pollutants (Smol, 2008; Jernström *et al.*, 2010; Schmid *et al.*, 2010; Bai *et al.*, 2011), lake eutrophication induced by the mass input of nutrients (e.g., nitrogen and phosphorus) (Paerl *et al.*, 2011; Yuan *et al.*, 2011; Schindler, 2012; Søndergaard *et al.*, 2013), and lake siltation and marsh development with respect to natural and/or anthropogenic activities (Xue *et al.*, 2008; Brauneck *et al.*, 2012; Kirwan and Murray, 2012; Noe *et al.*, 2013).

A lake is regarded as the deposition body of endogenous matter and soil erosion from the lake basin; therefore, its aging and decay could be directly or indirectly caused by siltation (Gui *et al.*, 2012; Shrestha, 2013). The dynamic process is influenced by the past variation of the natural environment, such as temperature, precipitation, gusty rainfall, and catastrophe incidents, as well as by human activities. The process of erosion in the basin is affected by not only human activities but also by artificially emitted matter that is overlaid during the transfer process of eroded matter and thus recorded in sediments, which is a type of geological architect (Yan *et al.*, 2013). Soil erosion, environmental conditions, and human activities during corresponding periods can be deduced through chronological research of corresponding depths of samples in sediments and sediment indices of different depths. Thus, the influence of natural and artificial factors on lakes and basins could be analyzed. Global and regional changes in the environment have been sensitively recorded in lacustrine sediments due to its high continuity and deposition rates (Fan *et al.*, 2010; Drevnick *et al.*, 2012; Moreno *et al.*, 2012). By providing scientists with precise environmental information with a one- to 10-year temporal resolution, sediments have the irreplaceable ability to resume the evolutionary series to provide information about the climate and environment on a short-term scale compared with other natural historic records (Jones and Roberts, 2008; Mourier *et al.*, 2010; Zocattelli *et al.*, 2012).

The radionuclide tracing technique characterized by ^{137}Cs has been extensively employed in the study of erosion and deposition world-wide for more than 50

years (Menzel, 1960; Lowrance *et al.*, 1988; Zhang *et al.*, 1997; 2004; Saç *et al.*, 2008; Parsons and Foster, 2011; Benmansour *et al.*, 2013). The fallout from ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ descends on the water surface or on the ground along with rainfall and is immediately absorbed by clay minerals and organic matter in soils or water bodies. The fallout that descended on the water surface gradually settles to the bottom of the lake with the suspended particles. The fallout that descended to the ground is strongly absorbed by the surface soil, without being eluviated and assimilated by plants, and is transported mainly with the soil and sediment particles (Zapata, 2003; Walling, 2004). ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ are the tracing isotopes commonly used in sediment dating of lakes. The former isotope is typically used by the accumulation peak in 1963, whereas the latter is used to calculate the age of sediments at different depths based on regression rates of $^{210}\text{Pb}_{\text{ex}}$ along with depth (Robbins and Edgington, 1975). The relative quantity of sediment yields from different sources in a basin can be analyzed and calculated by contrasting these two isotope contents between source soils and sediments because ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ contents typically vary with different sources of soil (Zhang *et al.*, 1997). The depth changes of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ contents in sediment cores are related to not only atmospheric settlement but also the quantity of sediments poured into the lake (Walling, 2005; Wen *et al.*, 2008).

The Jiuzhaigou National Nature Reserve is a World Natural Heritage Site and Man and Biosphere Reserve. At present, swamping has emerged in certain lakes of this nature reserve. Siltation has occurred at the perimeter of the lakes and protruded to the center with a rapid movement reflected by current monitoring stakes. Sediments are most likely to be derived from soil erosion and the outburst of geological disasters (debris flows or landslides) in upper reaches of the basin (Tang, 1986). Lake siltation and elevation of the lake bottom promote the growth of emerged plants and enable submerged plants to easily acquire sunlight needed for their growth. With the increase in tourist activities, external matter is imported continuously, thus further enhancing the swamping process and raising unfavorable effects on the scenic quality of the reserve. Protection and sustainable use of the landscape resources has been adversely and directly influenced. Therefore, a discussion on sediment rates of typical lakes in Jiuzhaigou is im-

portant to probe sediment sources, to discern and analyze the influence of human activities and natural factors, and to provide a scientific basis and fundamental data for lake deposition and eco-environment conservation in Jiuzhaigou.

The objectives of this study are: 1) to estimate the deposition rates of lake sediments in different lakes based on ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ techniques; 2) to elucidate the sources of sediments and their dynamics; and 3) to explore the influence of anthropogenic activities, such as forest logging, land use change, and tourists, on lake siltation.

2 Materials and Methods

2.1 Study area

The Jiuzhaigou National Nature Reserve is located in the middle and southern parts of Jiuzhaigou County, Tibetan and Qiang Autonomous Prefecture of Aba, in the northwestern part of the Sichuan Province ($32^{\circ}53' - 33^{\circ}20' \text{N}$, $103^{\circ}46' - 104^{\circ}05' \text{E}$), which belongs to the northern pediment of the Peak Gaerna at the southern section of the Minshan Mountain, at the eastern edge of

the Qinghai-Tibet Plateau. As a tributary valley at the sources of the Jialing River of Changjiang (Yangtze) River system, the nature reserve is located in the western part of the Baishui River basin, with a core area of 720 km^2 . The geomorphology of the Jiuzhaigou National Nature Reserve is characterized by high mountains with deep valleys in the Minshan Mountain, with elevations from 1996 m at the mouth of the valley to 4764 m at Peak Gaerna at the end of the valley. The mean annual precipitation is 555.6 mm, which occurs primarily between May and October, accounting for 75% of the mean annual precipitation and typically emerging in the form of rainstorms. Forestland and grassland are principal types of land use, with primary plant communities of the temperate and frigid zones, but with few subtropical plants. A small quantity of cropland remains in the nature reserve, but cultivation has been abandoned since 2003. Two sampling sites in this study are located in the Arrow Bamboo Lake and the Rhino Lake of Jiuzhaigou, with water depths of 48 cm and 65 cm, respectively, and elevations of 2626 m ($33^{\circ}08'08'' \text{N}$, $103^{\circ}52'19'' \text{E}$) and 2299 m ($33^{\circ}10'53'' \text{N}$, $103^{\circ}53'37'' \text{E}$), respectively (Fig. 1).

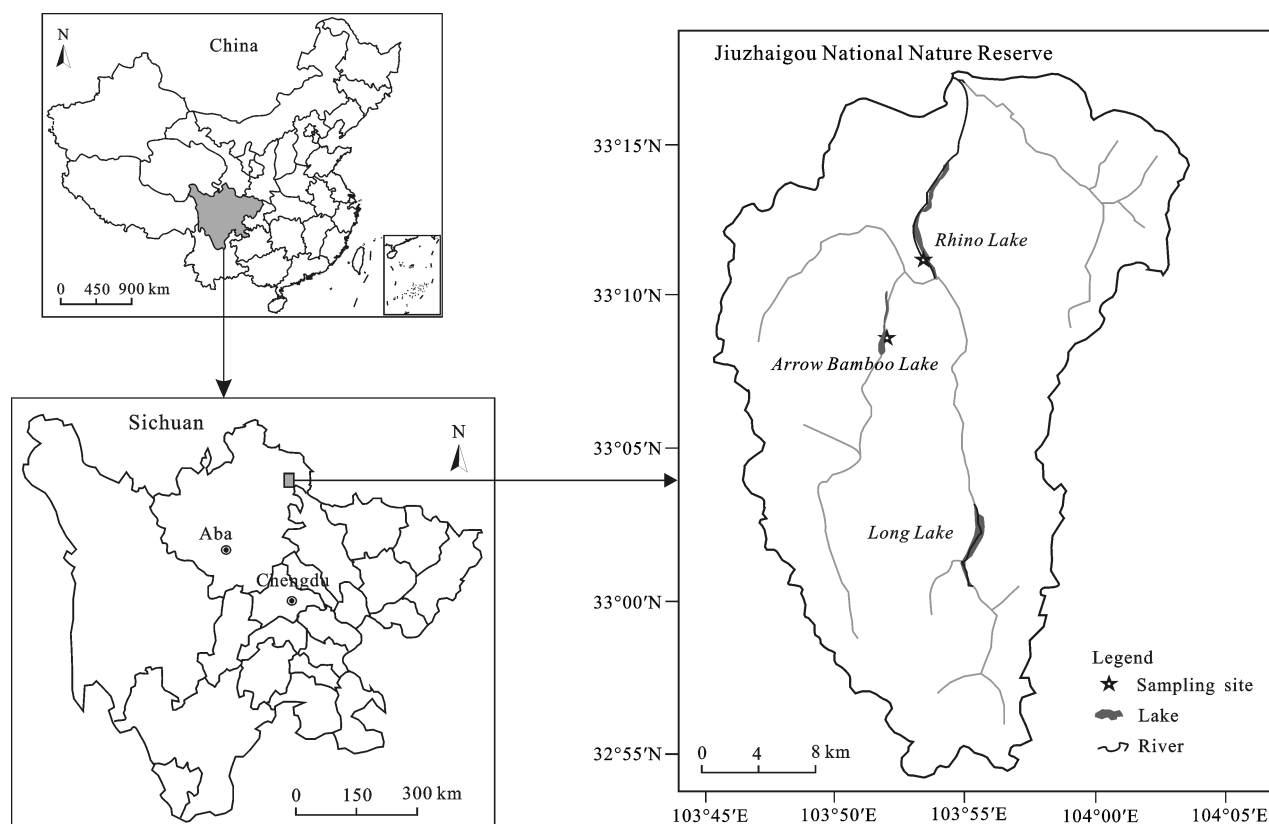


Fig. 1 Location of study area

2.2 Data and processing

2.2.1 Sample collection

The lake sediment core samples were collected by using a piston-style column sediment collector XDB0204 made of transparent organic glass. Two 46-cm-long cores in the Arrow Bamboo Lake (ABL) and two 70-cm-long cores in the Rhino Lake (RL) were obtained in November 2008.

2.2.2 Sample analysis

Sediment samples from the cores were photographed, recorded, coded, and sealed after collection in the field and then transported to the laboratory. Sediment samples were divided at intervals of 1 cm, and relevant information was recorded. The divided subsamples were placed into self-valved bags, sealed, and weighed. After air-drying, grinding, and sieving through a 2-mm sieve, gravel and plant roots were rejected, and the samples were weighed for analyses.

Contents of ^{137}Cs , ^{210}Pb , and ^{226}Ra in the sediment samples were measured using a hyperpure lithium-drifted germanium detector (GWL-120-15) coupled to a Nuclear Data 6700 multichannel gamma-ray spectrophotometer (ORTEC, Oak Ridge, Tennessee, USA) with a counting time of 50 000 s, providing a relative error less than 5%. The divided samples with a mass of 350 g were packed into plastic beakers, and ^{137}Cs , ^{210}Pb , and ^{226}Ra were detected at 662, 4615, and 35 119 keV, respectively. The $^{210}\text{Pb}_{\text{ex}}$ content was calculated by the difference between the ^{210}Pb and ^{226}Ra contents.

Sediment properties were determined by routine analysis methods (Institute of Soil Science, Chinese Academy of Sciences, 1978). The analyzed properties and their methods included: TOC via wet oxidation with $\text{K}_2\text{Cr}_2\text{O}_7$ hydration of the hot potassium dichromate colorimetric method; bulk density by using the oven-dried weight and sample volume; particle size distribution using a laser particle size instrument (Master Size 2000; MALVERN Company, UK); carbonate contents by using the gasometric method; sediment depth via a manual measurement; acid-insoluble residue as measured by completely transferring residues after the reaction onto filter paper, followed by repeated washing with a small quantity of water each time until no Cl^- was detected.

2.2.3 Data calculation

The years of sediment deposition were deduced by the ^{137}Cs data. The year of the top layer in the sediments corresponded to the year of sample collection, the low-

ermost layer of ^{137}Cs attainment corresponded to the year 1952, and the maximum accumulation peak in the sediment profile of ^{137}Cs corresponded to the year 1963 (Robbins and Edgington, 1975). The sediment rate was calculated according to the following equation:

$$S = h / t \quad (1)$$

where S is the sediment rate (cm/yr); h is the deposition depth of the sediments (cm), and t is time (yr).

The Constant Activity (CA) Model or the Constant Initial Concentration (CIC) Model was adopted to calculate deposition rates of $^{210}\text{Pb}_{\text{ex}}$. When the initial specific activity of $^{210}\text{Pb}_{\text{ex}}$ on the sediment-water interface is a constant C_0 (Bq/kg), the specific activity of $^{210}\text{Pb}_{\text{ex}}$ in sediments C (Bq/kg) at a given quality depth Z' (g/cm^2) decays exponentially with the quality depth Z' (Krishnaswamy *et al.*, 1971), according to the following equation:

$$C = C_0 \exp[-aZ'] \quad (2)$$

$$a = \lambda / S \quad (3)$$

where Z' is the quality depth representing accumulation values above a given sediment depth modified by the degree of porosity. λ is the radioactive decay constant of ^{210}Pb ($\lambda \approx 0.031/\text{yr}$).

The age of sediments at a given layer is expressed as:

$$t = \lambda^{-1} \ln(C_0 / C) = Z' / S \quad (4)$$

The sediment primarily originates from eroded yields of the surface layer in the CIC Model, therefore the matter sources are clearly affected by $^{210}\text{Pb}_{\text{ex}}$, i.e., the sediment increases with the increasing $^{210}\text{Pb}_{\text{ex}}$.

Regression analysis was used to obtain correlations between ^{137}Cs , $^{210}\text{Pb}_{\text{ex}}$, TOC, particle size fraction, carbonate contents, and acid-insoluble residue by using SPSS 17.0 software.

3 Results and Analyses

3.1 Distribution of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ in sediment cores

Figure 2 presents the distribution of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ in the sediment profile in the Rhino Lake and the Arrow Bamboo Lake. ^{137}Cs exhibited upward and downward transfer trends in the Rhino Lake (Fig. 2a). Although there was a significant correlation between ^{137}Cs content and sediment depth in the profile (Table 1) and the ini-

tial time mark was apparent, the accumulation peak in the profile was indistinct, so the time mark of 1963 could not be determined. The sediment rate of ^{137}Cs in the Rhino Lake was estimated to be 0.56 cm/yr based on the initial time mark, and the mass accumulation rate was calculated in combination with the bulk density of the sediments at each depth (Fig. 3). The $^{210}\text{Pb}_{\text{ex}}$ contents decreased exponentially with sediment depth in Rhino Lake, and there was a significant correlation between the two variables. The age of each sediment layer could be estimated based on the CIC regression model, providing an average sediment rate of 0.57 cm/yr. This result indicated that the average sediment rate derived from ^{137}Cs in the profile was consistent with that from $^{210}\text{Pb}_{\text{ex}}$. However, there was an apparent discrepancy between the age derived from ^{137}Cs and the time mark of $^{210}\text{Pb}_{\text{ex}}$, which might show that ^{137}Cs was transferred by the decomposition of organics, because there was higher TOC content in the Rhino Lake.

The ^{137}Cs initial time marks of 1952 and 1963 in the Arrow Bamboo Lake were evident (Fig. 2b), and there was a significant correlation between ^{137}Cs and sediment depth in the profile (Table 2), indicating a specific age of sediments. $^{210}\text{Pb}_{\text{ex}}$ exhibited a vertical fluctuation in the profile with an irregular change in depth in the Arrow Bamboo Lake, and correlations between $^{210}\text{Pb}_{\text{ex}}$ content and sediment depth in the profile were not significant. This result indicated that the $^{210}\text{Pb}_{\text{ex}}$ vertical distribution with depth in the Arrow Bamboo Lake does not fit well with the exponential decay model, most likely because sediments in this lake had been greatly disturbed. Although the $^{210}\text{Pb}_{\text{ex}}$ dating result was not ideal, ^{137}Cs dating was available and could be used to check time marks of $^{210}\text{Pb}_{\text{ex}}$ dating at 1864. Average sediment rates were estimated at 0.48 cm/yr after 1952 and 0.30 cm/yr after 1963 by using ^{137}Cs data. In equations (1) to (4), the average sediment rate was 0.32 cm/yr after 1864 by using $^{210}\text{Pb}_{\text{ex}}$ data. As a result, sediment rates can be interpreted accurately by using the combination of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ dating.

3.2 Vertical distribution of lacustrine sediment properties

3.2.1 Particle size distribution

The vertical distribution of particles in diameter in the sediment cores from the Rhino Lake and the Arrow Bamboo Lake is presented in Fig. 4. In these profiles, silt displayed the highest content, followed by sand and

then clay. Contents of sand and clay in the Rhino Lake were slightly lower than those in the Arrow Bamboo

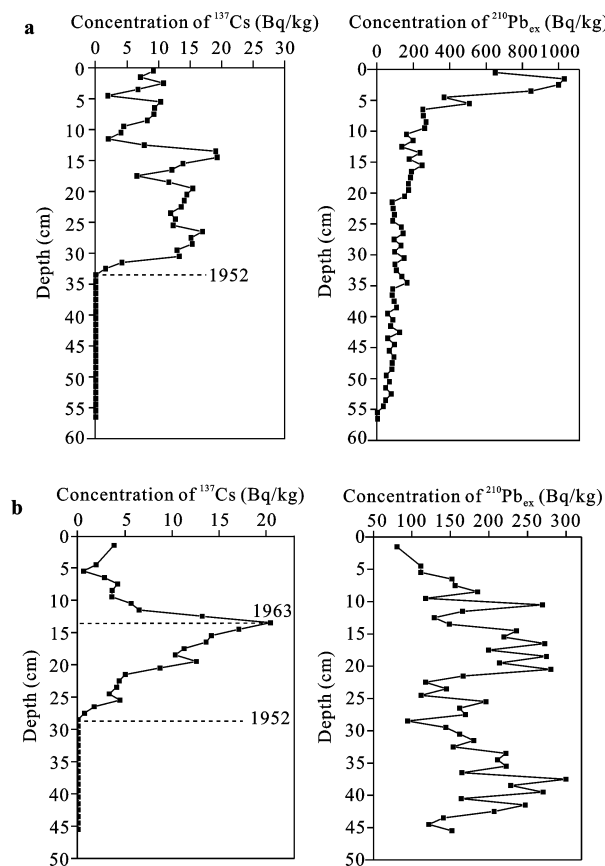


Fig. 2 Distribution of $^{210}\text{Pb}_{\text{ex}}$ and ^{137}Cs in sediment cores. a. Rhino Lake; b. Arrow Bamboo Lake

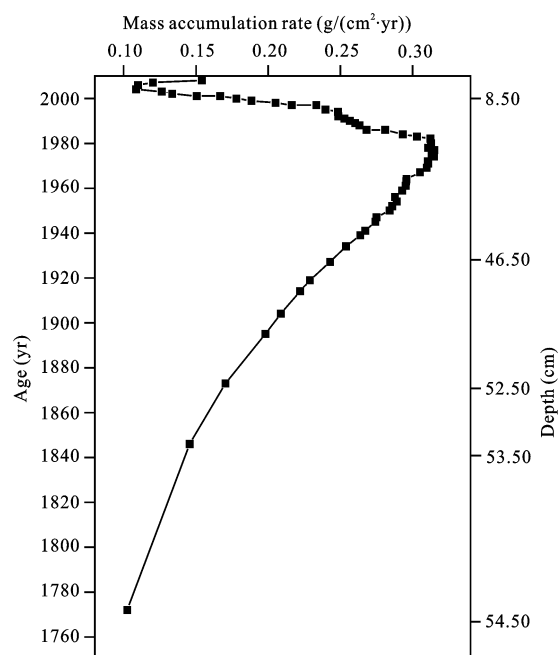


Fig. 3 Mass accumulation rates of sediment in Rhino Lake

Table 1 Correlation coefficients among selected constituents of sediments in Rhino Lake

Item	Depth	^{137}Cs	$^{210}\text{Pb}_{\text{ex}}$	Clay	Silt	Sand	TOC	Carbonate	Sample number
^{137}Cs	–0.623**								57
$^{210}\text{Pb}_{\text{ex}}$	–0.688**	0.246							57
Clay	0.370**	–0.447**	–0.324*						50
Silt	0.560**	–0.318*	–0.381**	0.272					50
Sand	–0.591**	0.377**	0.415**	–0.432**	–0.985**				50
TOC	–0.569**	0.185	0.664**	–0.097	–0.065	0.078			57
Carbonate	–0.696**	0.158	0.604**	–0.232	–0.224	0.251	0.662**		57
Acid insoluble residue	0.639**	–0.129	–0.540**	0.149	0.180	–0.195	–0.664**	–0.933**	57

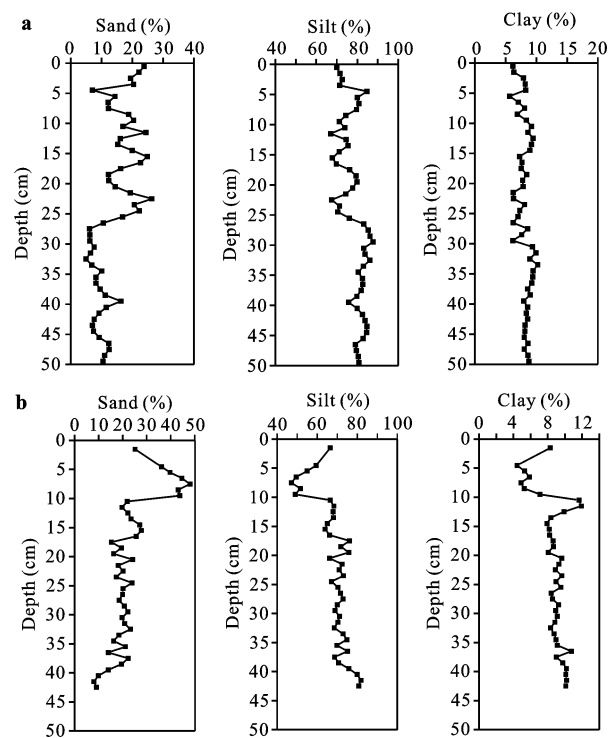
Notes: *: $p < 0.05$; **: $p < 0.01$ **Table 2** Correlation coefficients among selected constituents of sediments in Arrow Bamboo Lake

Item	Depth	^{137}Cs	$^{210}\text{Pb}_{\text{ex}}$	Clay	Silt	Sand	TOC	Carbonate	Sample number
^{137}Cs	–0.544**								43
$^{210}\text{Pb}_{\text{ex}}$	0.217	0.203							43
Clay	0.555**	–0.054	0.322*						40
Silt	0.737**	–0.114	0.292	0.742**					40
Sand	–0.733**	0.108	–0.308	–0.815**	–0.993**				40
TOC	0.603**	–0.021	0.493**	0.562**	0.732**	–0.730**			43
Carbonate	–0.684**	0.085	–0.434**	–0.390*	–0.482**	0.484**	–0.788**		43
Acid insoluble residue	0.775**	–0.160	0.482**	0.526**	0.643**	–0.647**	0.869**	–0.900	43

Notes: *: $p < 0.05$; **: $p < 0.01$

Lake, but silt content was slightly higher in the Rhino Lake than in the Arrow Bamboo Lake.

Table 1 displays significant correlations between the contents of sand ($> 63 \mu\text{m}$), silt ($2\text{--}63 \mu\text{m}$), and clay ($< 2 \mu\text{m}$) and ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ in the sediment core of the Rhino Lake. The contents of sand, silt, and clay were 4.97%–26.30%, 66.99%–87.68%, and 5.64%–10.21%, respectively, with mean values of 13.74%, 78.18%, and 8.08%, respectively. Sand contents, which frequently fluctuated in the profile, reached a maximum value at the depth of 21–24 cm, with an average of 22.12%. The sand fraction fluctuated strongly at a depth of 25–47 cm, displaying a sediment pattern of 'low-high-low' in the vertical direction, with an average of 8.89%. Silt contents also fluctuated frequently in the profile, with a significant and negative correlation with the sand fraction. Silt contents were lower, with an average of 70.92% at a depth of 21–24 cm where sand contents were higher but silt contents were even higher at a depth of 25–47 cm with an average of 82.66%, displaying a sediment pattern of 'high-low-high'. Clay, the finest particle in the sediment that is the easiest to be transferred in the lake, was less influenced by the changes in the lake water

**Fig. 4** Particle size distribution of sediment cores. a. Rhino Lake; b. Arrow Bamboo Lake

energy during the sediment distribution process. As a result, clay contents generally remained stable in all of the sediment profiles.

Significant correlations were found between the clay and $^{210}\text{Pb}_{\text{ex}}$ contents in Arrow Bamboo Lake (Table 2), in addition to correlations found among clay, silt, and sand. Overall, clay contents tended to increase from top to bottom in the profile (Fig. 4b). Silt contents exhibited a similar tendency to clay contents below the depth of 11 cm. Sand contents displayed a significant fluctuation in the profile, obtaining a high value at depth of 7–10 cm, with an average of 44.90%. However, sand contents declined at a depth of 11–44 cm (13.99%–27.84%) without a significant fluctuation (Fig. 4b).

3.2.2 TOC distribution

Figure 5 presents the vertical distribution of TOC in the sediment cores in the Rhino Lake and the Arrow Bamboo Lake. The TOC contents in the Rhino Lake were 1.56%–3.14%, with a relatively high average of 2.25%, implying high organic matter contents in this lake (Fig. 5a). The high TOC content is attributed to the vigorous growth of cattail (*Typha latifolia*) around the sampling points, which produce plentiful roots and plant residuals in the sediment. There were significant correlations between TOC, sediment depth, and $^{210}\text{Pb}_{\text{ex}}$ contents in the sediment core from Rhino Lake (Table 1). The highest TOC content was observed in the surface layer (0–3 cm), with an average of 2.95%, and a relatively constant value at a depth of 4–46 cm with an average of 2.30%, though there were relatively low TOC content at 14 cm and 25 cm. However, a fluctuation in the TOC content occurred at a depth of 47–57 cm, with an average of 2.00%. Thus, TOC contents in the Rhino Lake tended to decline from top to bottom in the profile, with a slight fluctuation, and the lowest values appeared at depths of 25 cm and 48 cm.

TOC contents in the profile were lower in the Arrow Bamboo Lake compared with those in the Rhino Lake, with values of 1.14%–2.37% and an average of 1.90% (Fig. 5b). An increasing tendency of TOC from top to bottom in the profile was observed, except in the surface layer, and there were significantly positive correlations among TOC and sediment depth, $^{210}\text{Pb}_{\text{ex}}$ contents, clay, and silt in the profile; however, there were significantly negative correlations between TOC and sand (Table 2). TOC content was higher in the surface layer (0–4 cm) at 1.75% in the profile, but the lowest content was found at a depth of 5–11 cm, with an average of 1.28%. A grad-

ual increasing tendency with a fluctuation (at 15 cm) occurred at a depth of 12–23 cm with an average of 2.03%, whereas a decreasing tendency was present at a depth of 24–30 cm with an average of 1.73%. The TOC contents remained high and constant at a depth of 31–43 cm with an average of 2.28%, but decreased to a low level at a depth of 44–46 cm, with an average of 1.68%.

3.2.3 Carbonates and acid-insoluble residue distribution

Figure 6 presents the contents of carbonates and acid-insoluble residue in the two lakes. The contents of carbonate and acid-insoluble residue were on average 61.25% and 36.74%, respectively, in the Arrow Bamboo

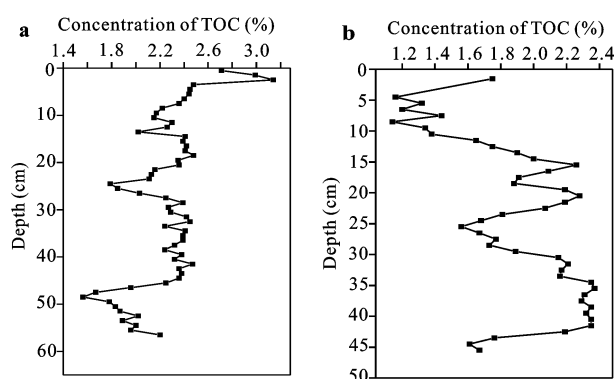


Fig. 5 TOC distribution of sediment cores. a. Rhino Lake; b. Arrow Bamboo Lake

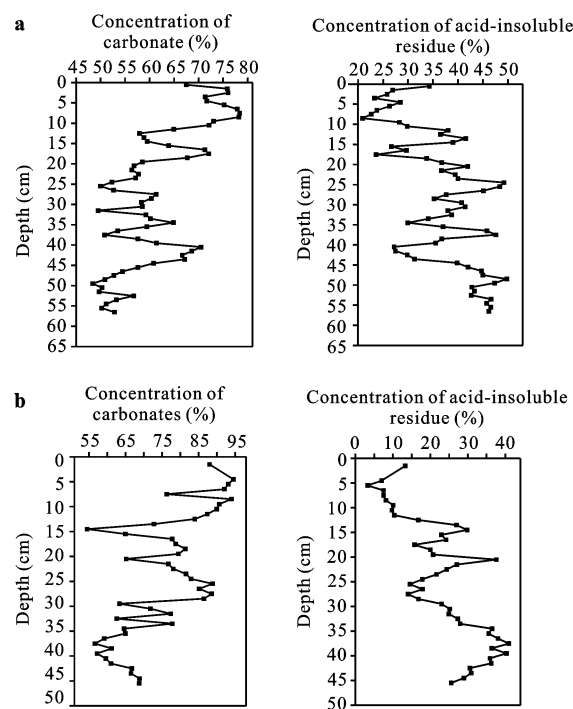


Fig. 6 Contents of carbonates and acid-insoluble residue of sediment in profile. a. Rhino Lake; b. Arrow Bamboo Lake

Lake and 75.37% and 23.03%, respectively, in the Rhino Lake. The content of carbonates in the Arrow Bamboo Lake was higher than the Rhino Lake, but the content of acid-insoluble residue was slightly lower than the Rhino Lake.

The carbonate contents tended to decrease from top to bottom in the profile in the Rhino Lake with a fluctuation. The lower values were observed at depths of 12–15 cm, 21–27 cm, 30–35 cm, 37–39 cm, and 47–51 cm, and there was a significantly negative correlation between carbonate content and sediment depth (Table 1). In addition, carbonate contents were significantly correlated with $^{210}\text{Pb}_{\text{ex}}$ and TOC contents. Unlike changes in carbonate contents in the profile, the acid-insoluble residue content tended to increase from top to bottom with a fluctuation in the sediment profile, and there was a significantly positive correlation between acid-insoluble residue contents and sediment depth. Peak values of acid-insoluble residue appeared at the depths where the lowest values of carbonate contents were present. Additionally, significantly negative correlations were observed between acid-insoluble residue contents and contents of $^{210}\text{Pb}_{\text{ex}}$, TOC, and carbonates.

Similarly, a decreasing tendency of carbonate contents from top to bottom in the profile was observed in the Arrow Bamboo Lake. The lower values were observed at depths of 14–16 cm, 20–25 cm, 30–31 cm, and 37–42 cm, and there was a significantly negative correlation between carbonate content and sediment depth (Table 2). The carbonate contents were significantly correlated with contents of $^{210}\text{Pb}_{\text{ex}}$, TOC, sand, silt, and clay. Unlike changes in carbonates in the profile, contents of acid-insoluble residue tended to increase from top to bottom in the sediment profile, and there was significantly positive correlation between acid-insoluble residue contents and sediment depth. Peak values of acid-insoluble residue appeared at the depths where the lowest values of carbonate contents were present. Significant correlations were also observed between acid-insoluble residue contents and contents of $^{210}\text{Pb}_{\text{ex}}$, clay, silt, sand, TOC and carbonates.

4 Discussion

The depth variation in the depositional environment parameters for the two lakes in the Jiuzhaigou National Nature Reserve tended to correspond to each other. Although there were different responses to the variation in

the lacustrine environment during different periods because of differences among specific geographic positions of sediment core samples, we observed that some common features among the samples had recorded past changes in the Jiuzhaigou National Nature Reserve. In the case of high contents of pore water and organic matter in the sediment of the Rhino Lake, ^{137}Cs may transfer upward along with pore water movement and organic matter decomposition, leading to apparent discrepancies between the sediment year estimated by the $^{210}\text{Pb}_{\text{ex}}$ CIC Model and the time mark determined by ^{137}Cs for this lake. The $^{210}\text{Pb}_{\text{ex}}$ contact by depth on the entire profile did not coincide with the exponential decay law in the Arrow Bamboo Lake. An up-and-down fluctuation was exhibited at the bottom layer, and the fitting coefficient was small, which is only for reference.

The TOC contents in the sediments of both lakes were high because newly deposited plant residue had not been fully decomposed. However, this value in the Rhino Lake was higher than that in the Arrow Bamboo Lake overall. The TOC contents from top to bottom in the sediment profile tended to increase in the Arrow Bamboo Lake but decrease in the Rhino Lake, with a slight fluctuation. Intervals of the temporal series of TOC changes were not identical due to uneven rates of the lake sediment and errors in age dating.

Carbonate contents in the sediments are controlled by authigenic carbonate precipitation in the study area in addition to the input of clastic carbonates introduced by landslide and debris flow (Tang, 1986). Carbonate contents are associated with temperature, pH value, solution, and CO_2 emissions. The mineral composition of carbonates controlled by lake climate and hydro-chemical conditions may be represented by calcite, dolomite, and aragonite. The acid-soluble residue consists primarily of travertine, salts, and dissolvable organic matter in the sediment, and the residues are mainly exogenous debris composed primarily of soil clay minerals. A small amount of exogenous debris includes exogenous mudstone and shale from debris flow, landslide, and collapse and impurities in carbonates. As a result, changes in the contents of acid-insoluble residue in the profile would reflect information about soil and water loss in the drainage.

Pastoral farming has prevailed in the Jiuzhaigou National Nature Reserve since the Western Han Dynasty (over 2000 years ago); however, livestock production was dominant, whereas cropping was secondary with a

limited amount of cultivated land area (Guo, 1993). During the mid-late Qing Dynasty (1800s–1850s), two crops (corn and potato) were introduced to the north-western region of Sichuan Province and became the staple crops, replacing highland barley, wheat, and buckwheat (Guo, 1993). With the introduction of new crops, deforestation occurred to enlarge the cropland in this mountain area while up-down steep slope cropping was treated, and the soil loss likely increased significantly. The mass accumulation rate rose from $0.15 \text{ g}/(\text{cm}^2\cdot\text{yr})$ to $0.20 \text{ g}/(\text{cm}^2\cdot\text{yr})$ from 1840 to 1900s (Fig. 3), whereas the contents of the sand fraction and acid-insoluble residue increased during the same period (Fig. 4a and Fig. 6a).

Poppy (*Papaver somniferum*) was introduced to Sichuan Province in the 1900s, and opium production peaked in Aba in the period between the late 1930s and the early 1950s due to the prohibition of poppy plantations in other regions of Sichuan (Guo, 1993; Liu, 2002; Nima and Tian, 2011). Because of the increase in cropland area in the Jiuzhaigou National Nature Reserve driven by the vast opium production and large economic benefit, the mass accumulation rate continuously increased from $0.23 \text{ g}/(\text{cm}^2\cdot\text{yr})$ to $0.27 \text{ g}/(\text{cm}^2\cdot\text{yr})$ (Fig. 3). After poppy plantations were prohibited in the early 1950s, the sediment rate remained essentially unchanged until 1966, as revealed by the record from the sediment core in the Rhino Lake (Fig. 3).

Roads in the forest areas have been built since 1966 in the study area, and primary forests were logged to form the entrance to Jiuzhaigou by the Department of Forest Industry of Sichuan, with a national investment of 6.0×10^6 yuan (RMB). Primary forest logging shifted from reasonable felling at the early stage of the 'Culture Revolution' (1966–1976) to the small patch clearing and then to clear cutting of large areas. Logs measuring $500\,000 \text{ m}^3$ in primary forests were obtained during the 12 years from 1966 to 1978, resulting in severe deterioration of forest resources. Figure 4 illustrates that depth changes of sediment particle size distribution in the two lakes primarily corresponded to the environmental changes. The results also revealed that there was high $^{210}\text{Pb}_{\text{ex}}$ activity and high contents of acid-insoluble residue in each lake during this period, suggesting that intensive erosion occurred with large amounts of sediments into lakes during this phase. The peak mass accumulation rate of over $0.30 \text{ g}/(\text{cm}^2\cdot\text{yr})$ lasted for more than 10 years, which distinctively indicates the exten-

sive soil loss and rapid sedimentation in the lakes of the Jiuzhaigou National Nature Reserve (Fig. 3).

The Administrative Bureau of the Jiuzhaigou National Nature Reserve was established in the early 1980s, and the forest coverage gradually improved with the artificial and natural rebuilding of the ecological system in Jiuzhaigou. Moreover, the cropland has been shifted to forest or grassland since 1998. In the past 20 years, the mass accumulation rate has been dramatically decreased to $0.10 \text{ g}/(\text{cm}^2\cdot\text{yr})$ (Fig. 3), which approximates the level before 1840; this reduced rate is attributed to the recovery of the natural landscape, although the number of visitors to Jiuzhaigou has been significantly rising. However, an abrupt spike in the mass accumulation rate has occurred since 2003 as a result of the road widening in 2003 to improve the transportation and serve the increasing number of visitors to Jiuzhaigou.

Overall, human activities, such as large-scale forest logging, land use change, and road construction, may change the sediment environment or directly disturb the sediment input into the lake during a short period of time, thus altering the vertical distribution of sediments. Therefore, the sediment rate and properties can reflect the important human activities during the historical period of Jiuzhaigou.

5 Conclusions

The objective of this study was to elucidate the influence of human activities on the increased swamping that has occurred in certain lakes in the Jiuzhaigou National Nature Reserve. This study focused on lake sediment sample collections, comparative analysis of isotope tracing elements $^{210}\text{Pb}_{\text{ex}}$ and ^{137}Cs , and sediment properties, including particle size distribution, TOC, carbonate contents, and acid-insoluble residue, in the sediment cores of the Jiuzhaigou National Nature Reserve. Sediment sources and changes in deposition rates were explored combined with historical data about human activities from literatures in this region. The sediment accurately reflects the effects of environmental changes and human activities in the Jiuzhaigou National Nature Reserve for the last 200 years.

The age at different depths in the Rhino Lake and Arrow Bamboo Lake of the Jiuzhaigou drainage basin was obtained by analyzing $^{210}\text{Pb}_{\text{ex}}$ and ^{137}Cs in the sediment cores. The vertical distribution of $^{210}\text{Pb}_{\text{ex}}$ in the Arrow Bamboo Lake did not display a regular pattern

and had a clear disturbance, whereas the accumulation peak of ^{137}Cs was distinct and can thus be used as an age reference. An exponential decay model can be used to describe the $^{210}\text{Pb}_{\text{ex}}$ vertical distribution in the sediment core collected from the Rhino Lake. Age-dating results by ^{137}Cs were reliable despite certain errors, with clear initial values of the ^{137}Cs vertical distribution but with indistinct accumulation peaks. High TOC contents in the sediment of both lakes resulted from strong vegetation growth. High contents of carbonates in the sediment were closely related to the geological background of carbonates in Jiuzhaigou. Carbonate contents tended to decline from top to bottom in the profile with a fluctuation, whereas contents of acid-insoluble residue tended to increase with sediment depth in both two lakes. The sediment contained the silt fraction showed the highest content and displayed low contents of clay and sand fractions with an overall texture of sandy silt. The two lakes exhibited a similar pattern of vertical sediment distribution in sediment rates and properties, indicating that both are controlled by the same environmental factors.

Deposition rates of the sediment in the lakes were relatively large overall, reflecting the historical environment of severe siltation in the two lakes, serious soil and water loss in the drainage, and intensive human activities. The rise in the mass accumulation rate, acid-insoluble residues, and mean particle size during the periods spanning 1840–1900s, the late 1930s–early 1950s, 1966–1978, and 2003–2006 recorded a few events of severe soil and water loss due to agricultural expansion, large-scale forest logging, and road construction.

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