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Variability of the ^{14}C reservoir effects in Lake Tangra Yumco, Central Tibet (China), determined from recent sedimentation rates and dating of plant fossils

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ABSTRACT

Sediments from lakes provide one of the most important archives for past environmental changes on the Tibetan Plateau. The recent sedimentation rate of modern lakes is widely used as an independent method to calibrate ^{14}C-derived chronologies because ^{14}C values are often affected by a reservoir effect. Terrestrial plant residues in lake sediments are believed to be the ideal material for ^{14}C dating because they normally provide the true ages of the sediments. In this study, we present the spatial and temporal variations in modern sedimentation rates over the past ~150 years and evaluate the reservoir effects of ^{14}C ages determined from bulk sediments and plant residues from Lake Tangra Yumco on the central Tibetan Plateau. The results show that ages determined from plant residues are systematically younger than those of the bulk sediments. However, the reservoir effects associated with the bulk sediments are much more constant than those of the plant residues, highlighting the complicated composition of these macro-remains and the fact that they might not be the best dating materials in Tangra Yumco, especially in southern part. A similar reservoir effect of ~2200 years is observed in the southern and northern parts of Tangra Yumco, based on the dating of modern surface sediments and aquatic plants. This study demonstrates the complexity of the reservoir effect in a closed lake on the Tibetan Plateau, and careful consideration must be paid to the use of different approaches to date different materials in order to establish a reliable chronology.

1. Introduction

Lakes are one of the most important archives for studying past environmental changes, especially in areas where other archives, such as glaciers (ice cores) or trees, are scarce. The Tibetan Plateau (TP), also called “The Third Pole”, is characterized by (semi)-arid climatic conditions with high evaporation rates. However, a large number of closed lakes are widely distributed on the TP. For paleoenvironmental studies using lake sediments, chronology is the most basic and crucial issue. Concerning the temporal coverage of most Tibetan lake sediment records, radio-isotopic analysis (^{210}Pb, ^{137}Cs) for the very young (<150 years) and AMS ^{14}C dating for the past max. 50 ka cal BP are the most valuable and commonly used methods to determine the ages of the deposits. Recently, optical dating has been used more frequently on lake sediments, especially for lake level terraces.

Carbon reservoir effects (R) are common in lacustrine environments all over the world and have also been reported on the TP (e.g., Wu et al., 2010;Hou et al., 2012; Mischke et al., 2013). Different approaches have been used to determine the R and overcome this hurdle in establishing reliable and robust chronologies in

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individual lakes. However, a uniform and effective method has not yet been established. For Lake Nam Co, Zhu et al. (2008) calculated an R between 2476 and 1230 a using modern sediment accumulation rates determined via ^{210}Pb and ^{137}Cs analyses. In Lake Qinghai, Hou et al. (2010) measured ^{14}C ages of lignin phenols and determined an R between 700 and 1600 a in a sediment core. OSL dating was used to evaluate the R in Qingtu Lake in arid northern China and yielded a generally very small reservoir effect (Long et al., 2011). Watanabe et al. (2010) used plant residues separated from lake sediment as dating material and retrieved an R of ~2300 a in Pumoyum Co. Recently, radiocarbon-based chronologies for the late Holocene (max. 4000 cal BP) have been produced using paleomagnetic secular variation data from lake sediments (Kasper et al., 2012; Ahlborn et al., 2015a; Haberzettl et al., 2015).

OSL and cosmogenic nuclide (^{10}Be and ^{26}Al) dating of lake level terraces have been conducted in the basin of Lake Tangra Yumco, and the results indicate high lake levels occurred during different stages in this area (e.g., Kong et al., 2011; Long et al., 2012; Rades et al., 2013, 2015). An investigations of a remnant lake on a former lake level terrace of Tangra Yumco, ~160 m above the present level, revealed environmental and hydrological changes during the Holocene (Miehe et al., 2014). That study addressed a potential carbon reservoir effect by rejecting carbonate lake marl samples from their chronology, instead using bulk organic samples from peat sections in the core. Long et al. (2015) tested post-IR IRSL (pIRIR) signals from polymineral grains from Tangra Yumco to validate a possible hard water effect in ^{14}C ages from bulk organic matter and showed a 2 ka age difference between the two approaches. This difference agreed with radiocarbon ages obtained from an aquatic plant and the sediment–water-interfaces of two sediment cores from the northern part of Tangra Yumco, which were used for reservoir corrections of sediment records covering the past 3 ka. Magnetostratigraphic analyses confirmed this approach for the northern basin (Haberzettl et al., 2015). However, a reliable ^{14}C chronology sequence from lake sediments and a continuous paleoenvironmental record from Tangra Yumco covering more than the past 3 ka are still lacking.

For lacustrine records, multiple dating approaches have been shown to be best suited for establishing robust chronologies (e.g., Hall and Henderson, 2001; Shanahan et al., 2013; Haberzettl et al., 2015; Long et al., 2015). In this paper, we present new results from Tangra Yumco concerning (1) modern sedimentation rates based on ^{210}Pb measurements and (2) AMS ^{14}C chronologies of two sediment cores retrieved from the northern and southern parts of this lake. Furthermore, (3) we determine the Rs by comparing ^{14}C ages of plant residues and bulk sediments from surface sediments and sediment cores, and (4) we evaluate the variability in the ^{14}C ages determined from plant residues in different sediment cores.

2. Materials and methods

2.1. Regional setting

Tangra Yumco is located on the northern flank of the central section of the Gangdise mountain range (central Transhimalaya), within a north–south trending graben that consists of three subbasins (Xu et al., 2006; Cao et al., 2009). Quaternary deposits, which are widely distributed on the lake shore, are mostly of alluvial and lacustrine origin. Magmatic rocks, e.g., 'Rapakivi' granite, are exposed on both sides of the lake as well but cover only small areas (Chen et al., 2006).

Lake Tangra Yumco is located at an altitude of 4550 m a.s.l. at 86°23′–86°49′ E and 30°45′–31°22′ N and has a maximum N–S extent of 72 km and a maximum W–E extent of 19 km. The lake itself is shaped as an "eight"; it is divided into two parts by a bottle-neck-like structure only 3 km in width (Fig. 1). The southern part has a maximum water depth of 110 m and is characterized by rather gentle slopes (Fig. 1). The northern part is deeper, with a maximum depth of 230 m, making Tangra Yumco the deepest lake on the TP (Wang et al., 2010). The connection between these two parts possesses water depths of up to 130 m with steep slopes typical of a graben structure (Akita et al., 2015). The total lake area of Tangra Yumco has been relatively stable since 1972, with a minimum of 831.2 km^2 in 1989 (Landsat 5 TM, Jan. 24, 1989) and a maximum of 846.5 km^2 in 2013 (Landsat 8 OLI, Nov. 18, 2013). However, there has been a continuous increase in lake area since 1989. Based on the bathymetric data, the water volume of Tangra Yumco is estimated to be 708.9×10^8 m^3; thus, the present mean depth of this lake is 83.7 m.

The lake's water is characterized as brackish and alkaline, with a conductivity of 12,200 μS cm^{-1} and a pH of 10.2 in June, 2012. In late summer (September 2009), during the thermal stratification period, a thermocline appeared between 24 and 40 m water depth. During this phase, the water body had a minimum temperature of 1.6 °C in the hypolimnion (Wang et al., 2010).

The recent water balance of Tangra Yumco is mainly driven by precipitation and surface runoff delivered to the lake by more than 10 intermittent tributaries that are only active during the summer. Two large perennial rivers in the northwest and southeast of the southern part also provide water to Tangra Yumco (Fig. 1). The remaining inflows are small, short, and intermittent streams.

2.2. Sampling

Four sediment cores were retrieved from the northern and southern parts of Tangra Yumco (Fig. 1). Two cores, DCG09-1 (length: 60 cm; water depth: 80 m) and TAN10-5 (length: 140 cm, water depth: 180 m) were recovered from the northern part, using a modified ETH-gravity corer (Kelts et al., 1986). From the southern lake part, the cores DCG10-2 (length: 77 cm, water depth: 80 m) and DCLC10-1 (length: 260 cm, water depth: 80 m) were retrieved close to each other using a gravity and a piston corer, respectively (Fig. 1). Surface sediments were collected using a Van Veen grab sampler in different areas of the lake. The upper portions (<2 cm section) of all samples were used in further analyses. All the samples were collected during two field campaigns in September of 2009 and 2010. Gravity cores DCG09-1 and DCG10-2 were sliced at 0.5 cm intervals for the upper 20 cm during the field work for ^{210}Pb and ^{137}Cs measurements. The other cores were closed tightly with flower foam and tapes for safe transportation to the laboratory in Lhasa; there, they were sliced at 1 cm intervals.

2.3. Laboratory analysis

The ^{210}Pb and ^{137}Cs activities of the uppermost core sediments were measured by a well-type high-purity germanium gamma spectrometer (ORTEC GWL-120-15) at an interval of 0.5 cm. Samples were placed into a cylindrical centrifugal tube and sealed with Parafilm® for at least three weeks to allow radioactive equilibration prior to the measurement (Appleby, 2001). Each sample was measured for 22.2 h (i.e., 80,000 s) and excess ^{210}Pb activity ($^{210}Pb_{ex}$, unsupported ^{210}Pb) was calculated from total ^{210}Pb minus the ^{226}Ra activity.

The samples selected for AMS ^{14}C dating (2-cm-thick samples) were wet-sieved through 63 and 125 μm meshes. The fraction >125 μm was treated with 1.2 mol l^{-1} HCl and NaOH to remove carbonates and humic acid matter (AAA treatment). The remaining material was regarded as the plant residue concentration (PRC) of the sediments. The fraction <63 μm was treated with 1.2 mol l^{-1} HCl to remove carbonates. The remaining carbon content was then regarded as the total organic carbon (TOC) fraction of the sediment. The treated samples were combusted and purified to obtain CO_2 and

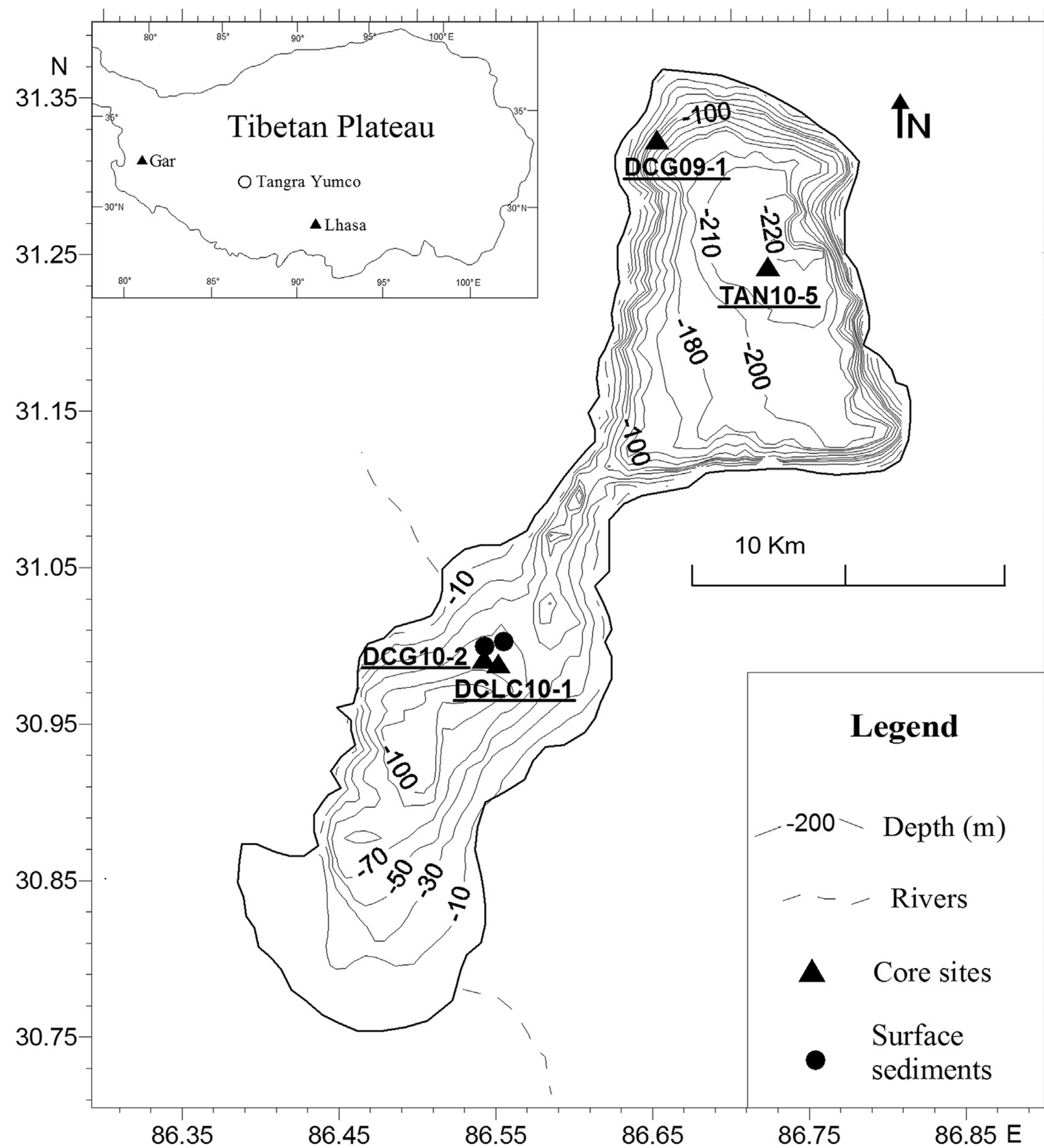

Fig. 1. Bathymetric map showing the sampling sites in Tangra Yumco; the inset map shows the location of Tangra Yumco on the Tibetan Plateau.

finally graphite targets for ^{14}C analyses. Measurements were performed with a Tandetron Accelerator Mass Spectrometry system (AMS, Model-4130, HVEE) at the Center for Chronological Research, Nagoya University. Simultaneously, the $\delta^{13}C$ values ($^{13}C/^{12}C$, ‰, VPDB) of the material were measured using an isotope ratio mass spectrometer (IRMS, MAT-252, Thermo Finnigan). Ten samples were analyzed from the core DCLC10-1 (six TOC and four PRC samples) and four samples from the core TAN10-5 (two TOC and two PRC).

Using a similar sample preparation (acid washes for bulk sediments and acid/alkali/acid treatment for plant materials), the AMS ^{14}C ages and $\delta^{13}C$ values (measured in an IRMS system) were determined for two sediment surface samples (DCS10-3, DCS10-4) from the southern part of the lake, close to the position of the core DCLC10-1 (Fig. 1), at Beta Analytic (Miami, FL, USA).

2.4. *Age determination*

For age–depth modeling using the ^{210}Pb measurements, both the CRS (constant rate of ^{210}Pb supply) and the CIC (constant initial ^{210}Pb concentration) models were applied (Appleby and Oldfield, 1978; Appleby, 2001). Each 0.5-cm slice of sample was air dried and weighted. Using the area of the pipe and the CRS model-based age of each layer, the dry mass accumulation rate (expressed as mg cm^{-2} a^{-1}) was determined. For the AMS ^{14}C ages from the two cores and the surface sediments, the conventional ^{14}C ages was calibrated using the OxCal software (v4.2.4), utilizing the IntCal13 dataset (Reimer et al., 2013) and the atmospheric radiocarbon dataset (Hua et al., 2013).

3. Results

3.1. *Modern sedimentation rates*

The activities of $^{210}Pb_{ex}$ in cores DCG09-1 and DCG10-2 exhibited similar attenuation curves. According to the CRS model, the average sedimentation rates are 0.25 and 0.50 mm a^{-1}, respectively (Figs. 2 and 3A). As a comparison, the average sedimentation rates based on the CIC model are 0.18 and 0.49 mm a^{-1}, respectively.

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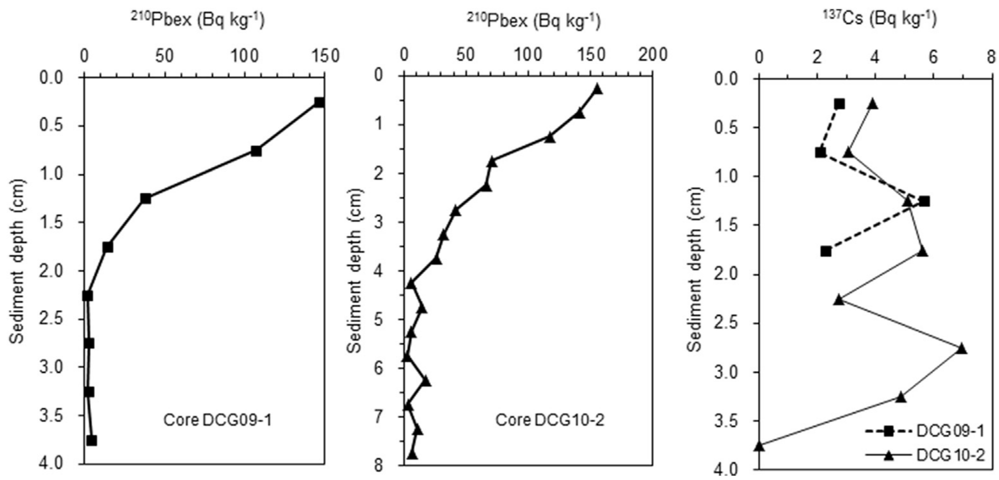

Fig. 2. Variations in ^{210}Pbex and ^{137}Cs activities of gravity cores DCG09-1 and DCG10-2 from Tangra Yumco.

According to the CRS model a distinct change in sedimentation rate occurred in 1916 AD in the sediment core DCG10-2. The average sedimentation rate was 0.26 mm a^{-1} before 1916 AD and 0.64 mm a^{-1} after (Fig. 3A). However, a decrease in the average sedimentation rate from 0.50 to 0.18 mm a^{-1} is observed after 1899 AD in the sediment core DCG09-1 (Fig. 3A). The dry mass accumulation rates average 14.13 and 30.65 mg cm^{-2} a^{-1} in cores DCG09-1 and DCG10-2, respectively. The highest dry mass accumulation rate, 154.24 mg cm^{-2} a^{-1}, is observed in core DCG10-2 at 1916 AD, and concordant variations in dry mass accumulation rates in both cores occurred during 1869 AD to 1899 AD (Fig. 3B).

Table 1
Conventional ^{14}C and calibrated ages of two sediment cores from Tangra Yumco.

Sample name	Core depth (cm)	Materials	Conventional ^{14}C age (BP ± 1σ)	Calibrated age (2σ) (cal BP)	Calibrated median age (cal BP)	δ^{13}C (‰)	Lab code (NUTA2-)
DCLC10-1-2,3	1–3	TOC	4123 ± 28	4820–4520	4660	−28.5	16637
DCLC10-1-49,50	48–50	TOC	4200 ± 31	4850–4620	4730	−28.9	16638
DCLC10-1-99,100	98–100	TOC	4569 ± 28	5450–5060	5290	−27.9	16639
DCLC10-1-149,150	148–150	TOC	6353 ± 38	7420–7170	7290	−26.9	16640
DCLC10-1-199,200	198–200	TOC	5513 ± 29	6400–6270	6310	−25.5	16644
DCLC10-1-260	259–260	TOC	6912 ± 30	7830–7670	7740	−24.4	16645
DCLC10-1-2,3	1–3	PRC	1845 ± 30	1870–1710	1780	−32.1	16627
DCLC10-1-10,11	9–11	PRC	1470 ± 25	1400–1300	1350	−20.8	16628
DCLC10-1-74,75	73–75	PRC	3632 ± 27	4080–3860	3940	−22.0	16629
DCLC10-1-199,200	198–200	PRC	3539 ± 28	3900–3720	3830	−29.2	16630
TAN10-5-35,36	19–21	TOC	3873 ± 34	4420–4150	4310	−26.4	16646
TAN10-5-126,127	110–112	TOC	6272 ± 37	7280–7020	7210	−36.3	16647
TAN10-5-35,36	19–21	PRC	1074 ± 25	1060–930	970	−23.6	16631
TAN10-5-126,127	110–112	PRC	3347 ± 26	3690–3480	3590	−17.1	16632

TOC: total organic carbon of bulk sediments.
PRC: plant residue concentrations.

3.2. *Calibrated ^{14}C ages for sediment cores DCLC10-1 and TAN10-5*

The calibrated ^{14}C ages determined on TOC from the sediment cores DCLC10-1 and TAN10-5 are generally in stratigraphic order. Core DCLC10-1 has one age reversal at a depth of 149 cm (Table 1, Fig. 4A). In contrast, plant residues from the same core show a rather scattered pattern with two reversals at 10 cm and 74 cm sediment depth. In sediment core TAN10-5, the calibrated ages determined on sediment TOC and PRC at two depths show a similar offset of 3335 and 3620 years (Fig. 4B). In both sediment cores, the ages from identical layers but of different material (TOC vs. PRC) show an offset between 2475 and 3620 years (median ages of calibrated data), with older ages associated with the TOC (Table 1, Fig. 4).

3.3. *Calibrated ^{14}C ages of surface sediments*

As shown in Table 2, two surface samples from the southern part of Tangra Yumco yield similar median ages, DCS10-3: 2570 cal BP and DCS10-4: ~2210 cal BP, with similar δ^{13}C values. The plant residue sample DCS10-4 contains 106.0 ± 0.3 pMC and is thus younger than 0 BP (1950 AD). If calibrated, this sample has an age of −57 cal BP (2007 AD), which is very close to the year of sampling in 2010 AD (Table 2). In addition, two surface sediment samples and one aquatic plant collected from the northern part were dated to comparable ages of 2240, 2130, and 2040 cal BP (median ages).

3.4. *δ^{13}C values of plant residues and sediment TOC*

The δ^{13}C values of the sediment TOC from core DCLC10-1 range between −28.9‰ and −24.4‰, whereas those of the PRC range from −32.1‰ to −20.8‰. In sediment core TAN10-5, the δ^{13}C range

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Table 2
Conventional ^{14}C and calibrated ages of surface sediments from Tangra Yumco (pMC means percent modern carbon).

Sample name	Sediment depth (cm)	Materials	Conventional ^{14}C age (BP ± 1σ)	Calibrated age (cal BP)	Calibrated median age (cal BP)	$\delta^{13}C$ (‰)	Lab code (Beta-)
DCS10-3	0–2	TOC	2460 ± 30	2710–2370	2560	−22.9	375375
DCS10-4	0–2	TOC	2170 ± 30	2310–2060	2210	−21.3	375377
DCS10-4	0–2	PRC	106.0 ± 0.3 (pMC)	−6 or −59	−57	−27.3	375378
TAN10-1[a]	surface	TOC	2200 ± 30	2320–2140	2230	−25.2	291393
TAN10-4[a]	surface	TOC	2140 ± 30	2310–2000	2130	−22.3	295002
Modern water plant[a]\		\	2070 ± 40	2150–1930	2040	−13.6	289070

[a] Data from Haberzettl et al., 2015.

is between −36.3‰ and −26.4‰ for sediment TOC and between −23.6‰ and −17.1‰ for PRC (Table 1, Fig. 5). The $\delta^{13}C$ values of the sediment TOC from sediment core DCLC10-1 exhibit a slight decreasing trend from bottom to top, but the variability in plant residues is higher.

4. Discussion

4.1. Sedimentation rate and its spatio-temporal variability

Large Tibetan lakes at high elevations are generally characterized by a low recent sedimentation rate, e.g., <1 mm a^{-1}, due to low aquatic productivity and little terrestrial sediment supply from the catchments (Wang et al., 2011). The low recent sedimentation rates of Tangra Yumco between 0.18 mm a^{-1} and 0.64 mm a^{-1} during the past 150 years, as indicated by the ^{210}Pb CRS model (Fig. 3A), are comparable with that from deeper areas of typical large lakes on the TP, such as Lake Qinghai (0.18 mm a^{-1}, Zhang et al., 2009), Nam Co (0.43–0.98 mm a^{-1}, Wang et al., 2011; Kasper et al., 2012), Mapam Yumco (0.31 mm a^{-1}, Wang et al., 2013), and Taro Co (0.49–0.58 mm a^{-1}, Ma et al., 2014; Haberzettl et al., 2015).

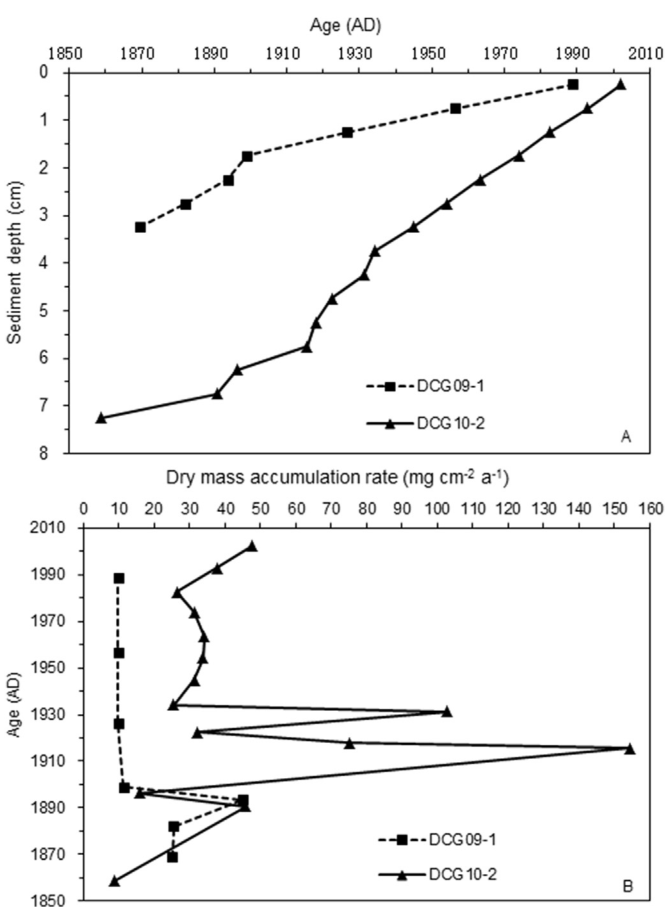

Fig. 3. Age–depth models (A) and dry mass accumulation rates (B) calculated by the CRS model of gravity cores DCG09-1 and DCG10-2 from Tangra Yumco.

The dry mass accumulation rates reveal similar spatial discrepancies between the two cores and display more small-scale temporal variability (Fig. 3B). Increases in accumulation rates are observed in both cores from the 1870s, reaching a high value of ~45 mg cm^{-2} a^{-1} in 1890 AD, and then decreasing dramatically. Subsequently, significant fluctuations in the accumulation rate in core DCG10-2 are recorded, whereas the accumulation rate in core DCG09-1 is more or less constant up to the present. The different patterns of temporal variability in the accumulation rates in the two cores probably indicate that different factors influence the two sites.

Sedimentation rates in sediment cores are generally controlled by many factors, such as water depth, subaqueous basin morphology, sediment focusing, river inflow, etc. (Wang et al., 2009, 2011). Sediment core DCG10-2 from the southern part of Tangra Yumco shows a much higher sedimentation rate than DCG09-1 (twice as high on average) and other cores from the deepest area in the northern part (Haberzettl et al., 2015). This difference likely results from the influences of terrestrial supply associated with the rivers that primarily discharge into the southern part of Tangra Yumco (Fig. 1). Core DCG10-2 is located in the central area of southern part of Tangra Yumco; thus, it receives more sediment from the two major tributaries. In this case, the southern part of the lake appears to act as a proximal sediment trap for the distal northern part.

The results also show a generally constant sedimentation rate from the 1930s at both sites, despite the distinct difference in actual rates. However, the changing sedimentation rate after ~1900 AD differed between the two sites (Fig. 3A, B). In the center area of the southern basin where core DCG10-2 was collected, the significant increase in the sedimentation rate likely reflects a hydrological change that resulted in a stronger terrestrial input to the lake. This change is interpreted as a wet interval with increased precipitation and subsequent runoff that delivered additional sediment to the coring location during that period. This might correspond to a 9.2-m higher-than-present lake level at Mapam Yumco in 1907 (Wang et al., 2013). In contrast, core DCG09-1 features an almost constant and low sedimentation rate, with a slight decreasing trend after 1900 AD, indicating a rather stable depositional environment likely resulting from an inadequate terrestrial supply from the catchment. The much higher and more variable sedimentation rate in core DCG10-2 suggests a more sensitive response to the hydrological changes within the catchment compared to core DCG09-1.

4.2. Low intensities of ^{137}Cs activity

Low intensities of ^{137}Cs activity were detected in both cores DCG09-1 and DCG10-2, with peaks of <7 Bq kg^{-1} (Fig. 2). ^{137}Cs is an artificial radioactive isotope that is transported by air, washed out by precipitation, and finally deposited in lake sediments. The low

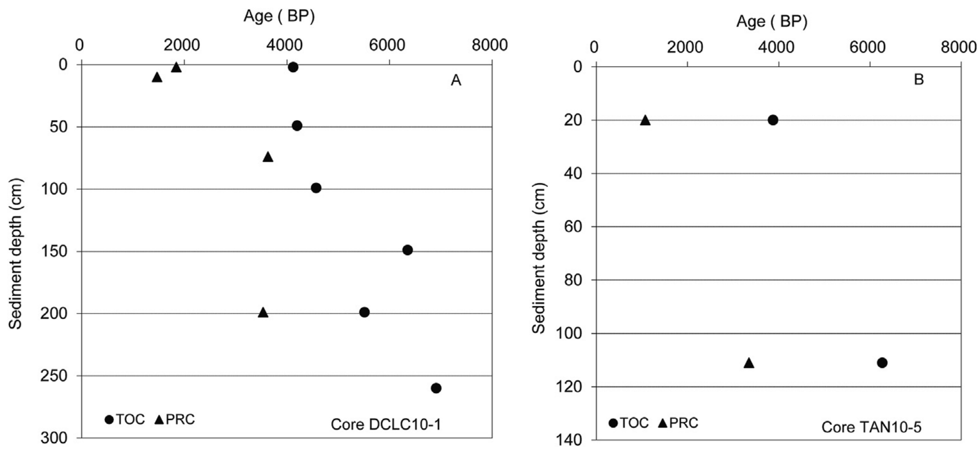

Fig. 4. Age–depth plots of two sediment cores from Tangra Yumco. The ages based on TOC (bulk total organic carbon) and PRC (plant residues concentration) show an offset in both cores.

activities of ^{137}Cs observed in Tangra Yumco sediments might indicate that this area was not strongly influenced by ^{137}Cs-supplying air mass, such as the Indian Ocean Summer Monsoon or the Westerlies, during the past 60 years. Today, this location is in the terminal area of both atmospheric circulation systems (transitional zone between monsoon and Westerlies, Yao et al., 2013). An extremely weak ^{137}Cs activity was also detected in the eastern area of Lake Taro Co, which is also located in the central area of the TP and was therefore not used to establish the chronology (Ma et al., 2014; Haberzettl et al., 2015). However, a short core retrieved from the western part of Taro Co has a slightly higher intensity of ^{137}Cs, with peaks that were effectively used to verify a ^{210}Pb-based chronology (Zhang et al., 2012). In Mapam Yumco, La'ang Co and Peiku Co, which are located on the northern slope of the Himalayas, similarly low ^{137}Cs intensities (max. 12 Bq kg^{-1}) were observed (Wang et al., 2013; Yang and Turner, 2013). Additionally, Yang and Turner (2013) argue that a downward diffusion of Cs occurs in many sediment archives on the TP, further complicating the use of this method. In contrast, ^{137}Cs intensities in sediments from Lake Qinghai and Nam Co were much higher than at Tangra Yumco, allowing the use of this dating method (Zhang et al., 2009; Wang et al., 2011, 2015; Yang and Turner, 2013).

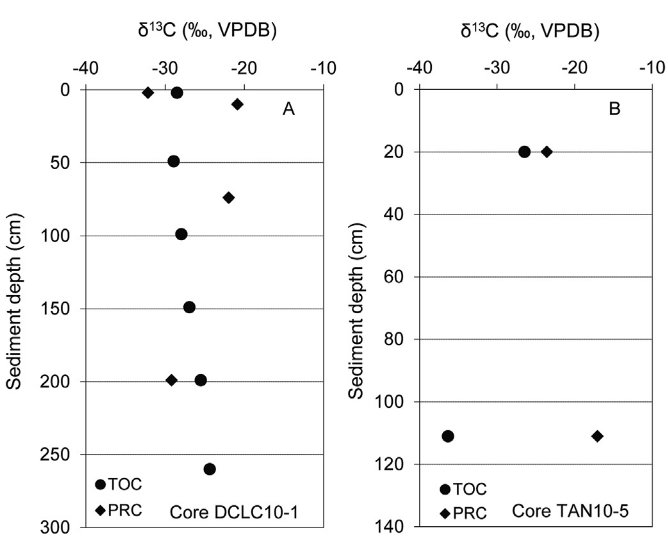

Fig. 5. δ^{13}C values determined on TOC (bulk total organic carbon) and PRC (plant residues concentration) dating samples from two sediment cores from Tangra Yumco.

4.3. δ^{13}C results

On the TP, the δ^{13}C values from plants and organic carbon of bulk sediment have been used to distinguish between terrestrial and aquatic species (e.g., Watanabe et al., 2010; Ma et al., 2014). Based on a large number of samples from different vegetation types distributed over a wide area on the TP, the δ^{13}C values of living terrestrial plants are in a range between −27.73‰ and −25.39‰ (Wang et al., 2004; Zhou et al., 2013). At Tangra Yumco, the δ^{13}C values of the plant residues (−32.1‰ to −17.1‰, Table 1) from the two sediment cores are typical for C_3 plants (−35‰ to −20‰, O'Leary, 1981), indicating that these plant residues in the sediments are likely composed primarily of terrestrial plants with minor proportions of aquatic plants. If this is the case, the AMS ^{14}C data obtained from the plant residues should be less affected by an R and would hence be assumed to provide more reliable age determinations. However, the δ^{13}C values of plant residues in core DCLC10-1, compared with that of bulk sediments, vary significantly, from −32.1‰ to −20.8‰, likely indicating changes in the composition of the plant residues (Table 1, Fig. 5A). The plant residues with higher δ^{13}C values might be related to larger contributions from aquatic plants because they have much heavier δ^{13}C values (Mayr et al., 2005, 2009; Watanabe et al., 2010).

4.4. Reservoir effect based on the different ages from the cores and surface sediments

The ^{14}C ages determined on PRC and bulk TOC show distinct differences in both sediment cores as well as in the surface sediments. The differences between the ages determined on the PRC and the bulk TOC from the same sediment depths are assumed to be caused a larger proportion of old carbon incorporated into the bulk TOC, which makes these samples appear much older. However, the age discrepancies vary markedly due to variability of the PRC in the sediment cores, indicating a variable uptake of old carbon.

4.4.1. Southern part

In the southern part of the lake, two 0–2 cm surface sediment samples show similar bulk TOC ages of 2560 cal BP (DCS10-3) and 2210 cal BP (DCS10-4), whereas the age of DCS10-4 based on plant residues was determined to be −57 cal BP (2007 AD, Table 2). The "real age" of the mixed uppermost 2 cm of surface sediment might be expected to be ~1995 AD based on core DCG10-2 calculation and the recent sedimentation rate of 0.64 mm a^{-1}, resulting in a "real age" of the DCS10-4 sample that is 45 years younger than AD 1950. Thus, the age from bulk TOC of DCS10-4 is 2255 years older than the estimated actual age. This discrepancy can be attributed to the presence of a carbon reservoir effect.

In sediment core DCLC10-1, the ages from different materials display different patterns. At two depths where both TOC and PRC ages were obtained, the age discrepancies were 2278 ^{14}C years at the 1–3 cm depth and 1974 ^{14}C years at the 199 cm depth (Fig. 4A; Table 1). The much older ages obtained from TOC indicate more old carbon was incorporated into the bulk sediments than in the PRC materials. However, the PRC ages are still much older than the reasonable ages, especially at the upper surface layer (1–3 cm, 1780 cal BP, Table 1). This might be ascribed to reworking of fine organic matter in the sediments. The inverse order of the two ages in the upper part further supports the assumption of reworking. However, despite one outlier ^{14}C age at 149 cm depth, the ages obtained from the bulk TOC exhibit a more reasonable stratigraphic order. It remains very hard to explain the old age of 4123 BP at the surface. Reworking of the old materials is one possibility, likely resulting from strong terrestrial input from the river. With respect to the fact that a similar old age is observed in another nearby core, DCLC11-1 (^{14}C age of 3360 BP at 2 cm core depth, unpublished data), which was retrieved by the same piston coring system, it is likely that a certain portion of the upmost layer may be missing, either due to the coring technology or erosional processes in the lake.

The TOC age pattern in core DCLC10-1 appears to exhibit a rather constant reservoir effect over time, as has also been applied in other cores in Tangra Yumco (Haberzettl et al., 2015). Here, a reservoir effect of 2255 years, determined from the surface sediment very near the location of core DCLC10-1, is used to correct the reservoir effect for the entire core. After correcting for the reservoir effect and calibrating the ^{14}C ages, the TOC ages of the uppermost sediment and at 199 cm depth are similar with those of the uncorrected PRC (i.e., 1810 cal a BP vs. 1780 cal a BP at surface and 3485 cal a BP vs. 3830 cal a BP at 199 cm depth, Fig. 6A). It is indicated that the uncorrected PRC ages are out of stratigraphic order and apparently too old for the chronology. Therefore, the corrected TOC ages are used to establish the chronology. As a result, the core DCLC10-1 covers a time span of 5400 cal a BP (Fig. 6A).

4.4.2. Northern part

The northern part of Tangra Yumco is characterized by deeper water, steep subaqueous slopes, and a smaller catchment area compared with the southern part. Recent studies have shown the R in this area to be 2000 a, as deduced from both luminescence dating and ^{14}C dating of surface sediments (Haberzettl et al., 2015; Long et al., 2015). This value is very similar to the R determined in the southern part. In sediment core TAN10-5, both bulk TOC and PRC ages were obtained at two depths and displayed similar offsets of 2800 a at 20 cm and 2925 a at 111 cm sediment depth (Fig. 4B, Table 1). Using linear extrapolations based on the PRC and TOC ages result in surface ages of 575 BP and 3350 BP, respectively (Fig. 4B). The R of the PRC-based ages, 575 a, might be attributed to old carbon contained in the PRC materials. The higher δ^{13}C values of the PRC probably indicate the inclusion of some aquatic plants because they have much heavier δ^{13}C values. Compared to the older ages of the surface sediments in core DCLC10-1, the estimated ages of the surface material in core TAN10-5 appear to be more reasonable. Because too little ^{14}C data are available, it is very difficult to evaluate the reservoir effect of core TAN10-5. However, based on the fact that the bulk surface sediment samples of parallel cores of TAN10-5 and modern water plants yielded similar ages in northern part of Tangra Yumco, it is likely that a reservoir effect of 2140 a is reasonable in core TAN10-5 (Table 2, Haberzettl et al., 2015).

After reservoir effect correction and calibration, the calibrated TOC ages are still much older than the PRC ages, implying the PRC ages are more reliable in core TAN10-5 and thus the chronology can be established based on the uncorrected PRC ages (Fig. 6B). The unreasonably old TOC ages are likely due to influences from subaqueous mass movements (e.g., turbidity currents), as has been investigated by Akita et al. (2015). Compared with a parallel core (Haberzettl et al., 2015), the two PRC ages of core TAN10-5 almost fit the chronology of core TAN10-4.

4.5. Variability in PRC ages in Tangra Yumco

In both cores, much younger ages were obtained from PRC than from TOC at the same core depth, implying the PRC ages provide a more reliable chronology in terms of the old carbon effect, especially for a given core section. However, a closer look at all the PRC ages in a single core reveals prominent discrepancies between the cores from the northern and southern parts of Tangra Yumco. In the northern part, PRC ages from core TAN10-5 provide a rather reliable chronology despite the limited availability of data. In southern part, the PRC ages failed to provide reasonable ages, which were either too old or out of stratigraphic order (Fig. 6A). This discrepancy indicates that more old or "dead" carbon is present in the processed PRC samples from the southern basin. This is likely attributable to different conditions in the subaqueous landforms and terrestrial

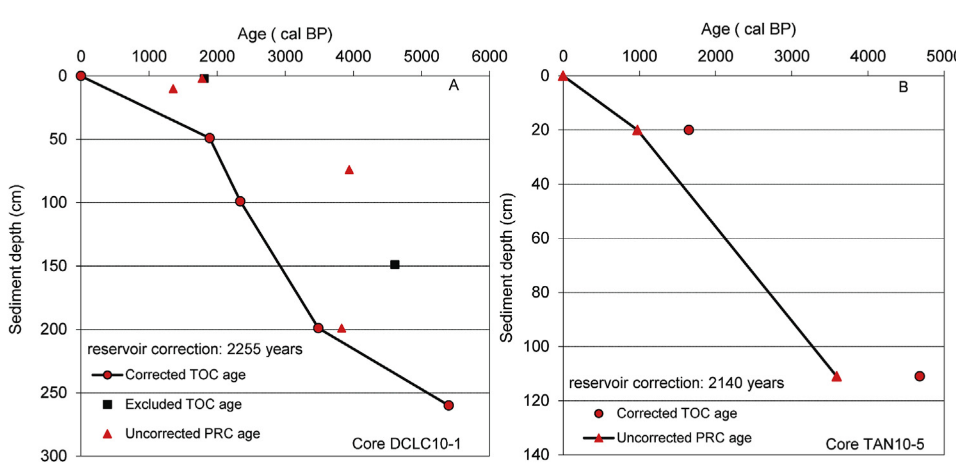

Fig. 6. Reservoir effect-corrected TOC (bulk total organic carbon) ages versus PRC (plant residues concentration) ages from two sediment cores from Tangra Yumco.

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supply in the two basins. In the southern basin, the relatively gentle slope, shallower water depth and more extensive shallow areas foster the growth of aquatic plants grow and allow more aquatic plants to be transported and deposited in the central area of the basin, possibly causing the larger reservoir effect.

Dead carbon transported by tributaries from the catchment into the lake is assumed to be an important source of the reservoir effect, generating so-called inherited ages (e.g., Fontes et al., 1996; Hendy and Hall, 2006). In addition, a residence age, which is caused by long-term stratification and a lack of through-flow, could also contribute to the reservoir effect (Hendy and Hall, 2006). As a large deep closed lake, Tangra Yumco must have a long water residence time, resulting in inadequate CO_2 exchange between the lake water and the atmosphere. However, these factors primarily influence inorganic carbon material or aquatic living plants. In our results, the R values from the PRC base ages from the northern part were generally smaller than those from the southern part. This difference can be attributed to the higher proportion of aquatic plant residues in the sediments from the southern part. In a peat sediment record within Tangra Yumco, ^{14}C ages from pollen were also reported to be seriously affected by the reservoir effect, consequently providing ages that were too old (Miehe et al., 2014). Constant reservoir effects were revealed from Tso Moriri, NW Himalaya, with values of 3800 vs. 3319 a and 365 vs. 741 a for bulk TOC sediment vs. aquatic plants, respectively (Leipe et al., 2014; Mishra et al., 2015).

The reservoir effect in lake sediments may be affected by many factors, such as catchment bedrock distributions, climate change and associated chemical weathering and erosion, terrestrial vegetation, soil development, crustal CO_2 from springs or faults, lake stratification and the history of lake exposure after ice covering (e.g., Fontes et al., 1996; Hendy and Hall, 2006; Watanabe et al., 2010; Hou et al., 2012; Mischke et al., 2013). These factors likely vary in the southern and northern parts of Tangra Yumco, resulting in different R values in the lake water. The organic matter in the sediments of Tangra Yumco is primarily of autochthonous origin and was produced by phytoplankton with a ratio of TOC to total nitrogen of <10. The old carbon included in the bulk TOC therefore comes from the aquatic plants, which assimilate carbon from lake water. The PRC samples likely contain a certain proportion of aquatic plants, which introduces old carbon and results in varying degrees of the reservoir effect. Although plant residues extracted from the bulk sediment have the potential to provide more reliable ^{14}C ages by reducing the influence of the reservoir effect, careful attention must be paid to the composition of the macro-remains. To elucidate the sources of organic matter in the sediments and the modern terrestrial/aquatic plant distribution in the catchment, fractionation studies on the δ^{13}C values of organic matter are believed to be useful approaches to evaluate the reservoir effect in a lake (e.g., Mayr et al., 2005, 2009; Watanabe et al., 2010).

5. Conclusions

Based on our ^{210}Pb measurements and AMS ^{14}C dating results from four sediment cores in the southern and northern parts of Tangra Yumco as well as on the ^{14}C ages of surface sediments, the reservoir effects associated with bulk sediment- and fossil plant residue-based ^{14}C ages are assessed. The results show that the modern sedimentation rates of Tangra Yumco are 0.18–0.64 mm a^{-1}, based on two short cores. These rates correspond to average dry mass accumulation rates of 14.13 and 30.65 mg cm^{-2} a^{-1}, revealing distinct spatial and temporal variability within the lake. The ^{14}C ages derived from plant residues are systematically younger than those from bulk sediment organic carbon, demonstrating that the plant residue-based approach can provide a more reliable chronology. However, old carbon can still be present in the plant residues extracted from the lake sediment in Tangra Yumco, likely reflecting the influence of aquatic plants. Our results show that the reservoir effects in the plant residues in Tangra Yumco are complicated through time, highlighting the fact that careful attention must be paid when using the macro-remains for dating. As a comparison, the reservoir effects of bulk sediment-based ^{14}C ages are relatively constant throughout a core. In general, similar reservoir effects of approximately 2200 years in the southern and northern basin of Tangra Yumco are observed. Our study demonstrates that a combination of modern sedimentation rate measurements and ^{14}C dating of both the bulk sediment and plant residues provides a valuable approach for obtaining a reliable chronology in a lake with reservoir effects.

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