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PRIMARY RESEARCH PAPER

Radiometric dating for recent lake sediments on the Tibetan Plateau

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Abstract We present radiometric data from nine lakes across the Tibetan Plateau, and compare their reliability in relation to recent research. Unsupported ^{210}Pb profiles show, except for one particular lake, non-exponential decline of ^{210}Pb activity with sediment depth. Stratigraphic dates based on global atmospheric nuclear weapons maximum fallout of ^{137}Cs (1963) support the use of the constant rate of ^{210}Pb supply (CRS) model in four of the dated cores. The discrepancy in the others is likely due to recent increased input of catchment-derived ^{210}Pb. ^{210}Pb dates in this study suggest that post depositional diffusion of ^{137}Cs activity has been significant. The practice of assigning early 1950s dates (start of global atmospheric thermonuclear testing) to lake sediment sequences on the Tibetan Plateau should be used with caution. ^{137}Cs profiles from Tibetan lake sediment cores and their geographical distribution suggest that ^{137}Cs derived from the 1986 Chernobyl accident or atmospheric testing in China was not sufficient to form a significant peak effective for dating.

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Introduction

The Tibetan Plateau has been the subject of much palaeoenvironmental research, because of its geographical position and recognised role in Asian climatic and hydrological systems. Due to its size, relative isolation, and paucity of documentary/environmental monitoring data, lake sediment archives have been widely used to reconstruct past environmental conditions and processes across the Tibetan Plateau. Reliable lake sediment chronologies are absolutely critical in constructing records of recent environmental change and upscaling from individual lakes to regional patterns.

Naturally occurring ^{210}Pb has been used to reliably date ice cores and recent sediment sequences spanning the past 100–150 years since the early 1960s (Goldberg, 1963; Krishnaswami et al., 1971). It has developed into a widely used technique with different models used for calculating ^{210}Pb dates (Appleby, 2001, 2008), whch has been applied to a range of depositional settings. Man-made radionuclides have been released into the environment by atmospheric nuclear weapons testing and accidents (e.g., Chernobyl in 1986). Global dispersal and fallout of artificial radionuclides commenced with atmospheric thermonuclear bomb testing in the early 1950s. The incorporation of artificial radionuclides such as ^{137}Cs and ^{241}Am into lake sediment sequences parallel the atmospheric fallout history of the isotopes in the northern and southern hemisphere (Pennington et al., 1973; Appleby et al., 1991) starting around 1951–1952, with a significant increase from 1954 (Cambrary et al., 1989; UNSCEAR, 2000). Intensive atmospheric testing continued through the late 1950s, reaching a peak in 1963, prior to the 1963 Limited Test Ban Treaty (LTBT) (Appleby, 2001). Atmospheric fallout of artificial radionuclides declined steadily from the 1963 to 1964 maxima (Cambrary et al., 1989). ^{210}Pb dating of lake sediments has been successfully corroborated by independently determined stratigraphic records of artificial radionuclides (principally ^{137}Cs and ^{241}Am) during the last three decades (cf. Appleby, 2008).

Many sediment cores taken from the Tibetan Plateau in the last decade have used ^{210}Pb and ^{137}Cs radiometric chronologies for reconstructing recent environmental change. The onset of ^{137}Cs activity in Tibetan cores has been widely used to date the 1950s (e.g., Shen et al., 2001; Zhang et al., 2002; Zhu et al., 2002, 2003; Li et al., 2004; Wu et al., 2001, 2002, 2003, 2006, 2007a, b; Wang et al., 2008, 2009, 2011; Liu et al., 2009; Zhang, 2009; Jin et al., 2010; Kasper et al., 2012). However, due to potential mobility of ^{137}Cs in lake sediments (Crusius & Anderson, 1995; Appleby, 2001), especially in saline lakes that contain high concentrations of monovalent cations (Foster et al., 2006), the onset of ^{137}Cs activity can lose its function for dating the early 1950s.

Peaks in ^{137}Cs activity also appear to have been incorrectly ascribed in some sediment cores on the Plateau. For example, Jin et al. (2010) suggest that well-resolved ^{137}Cs peaks measured in sediment cores from Lake Qinghai are derived from the 1986 Chernobyl accident, even though the 1963 peaks are indistinct, and the transport of Chernobyl radionuclides to the Plateau is known to have been limited (Wheeler, 1988; Wu et al., 2010).

In addition, although atmospheric nuclear bomb tests were conducted in north western China from the mid 1960s to 1980, the radionuclide fallout signal to lakes distant from the Lop Nor test area (Fig. 1) is indistinct (Wu et al., 2010), and therefore, may not be able to form peaks that can be used confidently for dating.

This paper presents both reliable lake sediment chronologies and accumulation rates from cores taken to reconstruct atmospheric pollution across the region (Yang et al., 2010). We also discuss recent published data to clarify the use of ^{137}Cs records for dating Tibetan lake sediments and highlight factors that can affect sediment radiometric results and data interpretation.

Methods

Study sites

The lakes in the northern area of the Qinghai-Tibetan Plateau are situated at altitudes ca. 3000 m a.s.l. and the sites in the central and southern areas above 4500 m a.s.l. (Table 1). Figure 1 shows the location of the lakes collected by the authors in 2006–2007. The Plateau is predominantly a steppe landscape with mean annual precipitation <500 mm for most areas (Zhang et al., 2003). The lakes and their catchments reflect the geomorphological and hydrological range of environments found across the Tibetan Plateau (Table 1). Livestock production on the Plateau has significantly increased since 1980 (Du et al., 2004; Cui & Graf, 2009), resulting in grassland degradation and soil disturbance in many lake catchments.

Sampling and measurements

Sediment cores were taken from deep areas of six lakes from the northern and central Tibetan Plateau in August 2006 and three lakes from the southern Plateau in August 2007 (Fig. 1). Cores from Nam Co and Peku Co were taken from sub-basins owing to logistics of sampling from the maximum depth of the lakes.

Cores were retrieved by a Renberg gravity corer (8.5 cm inner diameter polycarbonate tube). The cores were sliced using a stainless steel blade in the field at 0.25 cm intervals from the surface to 5 cm, and then at 0.5 cm intervals from 5 cm to the base. Soil samples were collected from a 20 cm depth exposed profile from a flat area in the catchment where soil movement by water and wind was assumed to be limited. Samples were taken from the surface to 5 cm at 0.5 cm intervals and at 1 cm intervals to 20 cm.

Core and soil samples were refrigerated (4°C) until being processed at UCL. 2 cm^3 subsamples were measured for wet density and dry weight (105°C for 24 h) to calculate sediment dry density for ^{210}Pb and ^{137}Cs inventory calculations. After freeze-drying,

Fig. 1 Location of the lakes cored for this study and (*inset*) location of the Tibetan Plateau with respect to China. Lop Nor is the location where China's atmospheric nuclear bomb testing took place

Table 1 Site, lake, and core depth information on the sampled Tibetan Plateau lakes in this paper

Site	Location		Altitude (m)	Catchment area (km^2)	Lake area (km^2)	Lake water salinities (g L^{-1})	Coring water depth (m)
	N	E					
Qinghai Hu	36°42′	100°15′	3,191	29,661	4,340	16.6	25.3
Keluke Hu	37°17′	96°52′	2,813	12,360	56.7	0.7	8.3
Gaihai	37°08′	97°33′	2,845	1,925	32	138.8	10.5
Cuo Na	32°02′	91°30′	4,617	3,199	182.4	0.2	12.4
Cuo E	31°25′	91°29′	4,531	1,020	61	4.5	8.4
Nam Co	30°46′	90°55′	4,630	8,486	1,961	1.1	21.6
Cuolong Co	29°07′	85°23′	4,564			57.9	1.2
Peku Co	28°48′	85°31′	4,595	1,980	284.4	2.6	16.5
Kemen Co	28°41′	85°56′	4,652	60	2.3	3.6	4.2

subsamples were homogenized for radiometric dating and other analyses (Yang et al., 2010).

Samples (0.5–2 g dry weight depending on sample density) from the lake sediment cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs, and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detectors. ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV gamma rays emitted by its daughter isotope ^{214}Pb. All samples were counted in airtight containers following 3 weeks storage to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662 and 59.5 keV. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity (e.g., LDE, LEB). Corrections were made for the effect of self-absorption of low energy gamma rays within the sample. Unsupported ^{210}Pb activity was calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity. This is based on the assumption that the intermediate daughter product, ^{222}Rn, is in equilibrium with ^{214}Pb (i.e., ^{226}Ra) after the sample has been sealed for 3 weeks. The chronologies for the cores were calculated by using the ^{210}Pb and ^{137}Cs data following the procedures described in Appleby (2001).

Although the cores were sliced at a high resolution, only selected depth intervals were used for gamma counting. Gamma counting is time consuming, expensive and from experience, contiguous counting of core samples does not significantly improve the dating. We counted samples from a spread of samples downcore first, to get an approximate timescale, before focusing on sample depths based on their assumed ages.

Soil core samples from the lake catchments were gamma counted and ^{210}Pb inventories calculated, to estimate atmospheric ^{210}Pb deposition in the region (Appleby et al., 2003; Yang et al., 2010).

Results

Cores from eight of the nine lakes sampled have ^{210}Pb profiles showing an irregular decline of unsupported ^{210}Pb activity with depth (Figs. 2, 3, 4), suggesting changed rates of sediment accumulation in the last ca. 150 years. The maximum value of ^{210}Pb activity in unsupported ^{210}Pb activity profiles (Figs. 2, 3, 4) is below the surface except in the core taken from Lake Qinghai, implying that the ^{210}Pb concentration has been diluted in the surface sediments due to increased sediment accumulation. Most of the ^{137}Cs profiles from the eight cores exhibit well-resolved ^{137}Cs peaks (Figs. 2, 3, 4), while the Peku Co core has measurable ^{137}Cs only in the top 3.5 cm. The erroneous and unusable ^{210}Pb and ^{137}Cs profiles from Cuolong Co reflect the character of the shallow hyposaline lake. In the well-dated eight cores, the equilibrium depths of total ^{210}Pb with supported ^{210}Pb (corresponding to an age of ca. 150 years) are deeper than 18 cm (except the cores from Qinghai and Peku Co) (Table 2). Most of the cores show that they can provide decadal or sub-decadal temporal resolution for palaeolimnological analyses.

Northern Tibetan lakes

In the three cores taken from the northern lakes (Fig. 2), unsupported ^{210}Pb activities decline irregularly with depth. In the Qinghai core the decline, however, is reasonably exponential with depth between 4 and 7 cm, indicating relatively uniform sedimentation rates in this section. The significant non-monotonic trough-like features in the Gaihai core profile may record episodes of rapid sediment accumulation. All of the northern cores have well resolved ^{137}Cs peaks showing that sedimentation has occurred without significant physical and biological post-depositional mixing. Use of the constant initial ^{210}Pb concentration (CIC) model was precluded by irregular variations in the ^{210}Pb profiles (Appleby, 2001). The simple ^{210}Pb CRS model assigns the depth of 1963 at 3.2, 12.5, and 7.5 cm while well-resolved ^{137}Cs peaks are from sample depths of 3–3.25, 12–12.5, and 7.25–7.5 cm in the Qinghai, Keluke, and Gaihai cores, respectively. The good agreement between both measurements suggests that the supply rates of ^{210}Pb were relatively constant and the CRS model is applicable to dating the cores.

Central Tibetan lakes

Significant flattening of ^{210}Pb profiles occur in the upper sections of the cores collected from the central area (Fig. 3). ^{137}Cs activity core profiles have well defined peaks that appear at the base of the relatively constant ^{210}Pb activity in the cores, which suggests a long-term burial plus turbational mixing process (Berner, 1980). The defined peak of ^{137}Cs activity in the individual profiles, especially the rapid decline in ^{137}Cs in the sediments above the peak, suggests that sediment mixing in these cores is limited. The significantly lower surficial ^{210}Pb activities at these sites suggest increased sedimentation rates in recent years. ^{137}Cs peaks in the Central Tibet cores are derived from the 1963 atmospheric testing fallout maximum. This is confirmed by detectable ^{241}Am in the depth intervals adjacent to the ^{137}Cs maximum samples in the Cuo Na and Nam Co cores. The simple CRS model places the 1963 depths at 13.3 and 14.5 cm in the Cuo E and Nam Co cores, which are slightly above the ^{137}Cs peaks in the cores (15.5–16 cm and 16.5–17 cm, respectively). The 1963 depth (15.5 cm) in the Cuo Na core calculated by the simple CRS model is significantly above the 1963 depth (21.5–22 cm) suggested by the ^{137}Cs record. The discrepancies between the 1963 depths of the simple CRS model and the peak of the ^{137}Cs record in each core suggest episodic change in both rates of

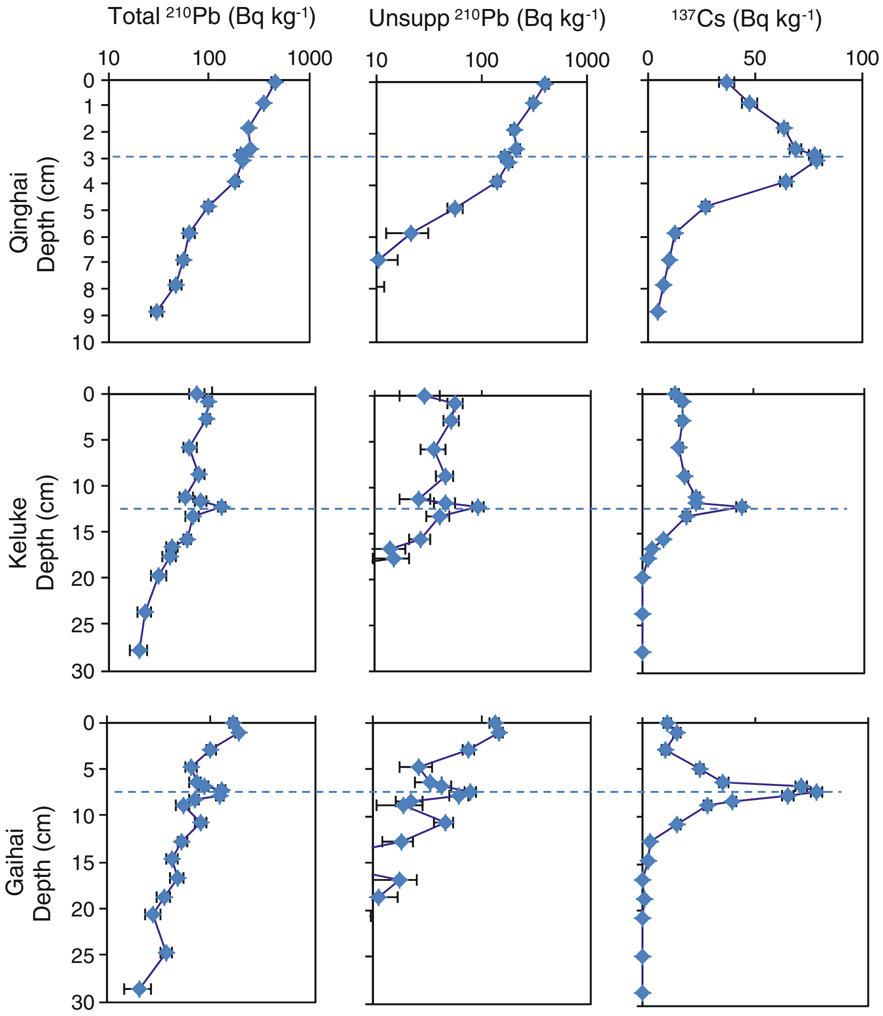

Fig. 2 Fallout radionuclides in the sediment cores taken from the northern area of the Tibetan Plateau; showing total, unsupported ^{210}Pb and ^{137}Cs concentrations versus depth. The *dashed line* indicates 1963 according to the simple CRS model, showing agreement between the CRS model date and the ^{137}Cs date

sedimentation and ^{210}Pb supply. The shallower 1963 age/depths determined by the simple CRS model, than those suggested by the ^{137}Cs record alone, indicates that the unsupported ^{210}Pb flux to the sediments in these lakes has increased in recent years. This enhanced input of soil and unsupported ^{210}Pb associated with it to lakes is in accordance with measurements of increased precipitation, runoff (Kasper et al., 2012) and lake levels (Krause et al., 2010; Zhang et al., 2011) in Tibetan catchments, e.g., recent patterns between glacial meltwater and lake levels of Nam Co (Wu & Zhu, 2008).

Because of the discrepancy between 1963 depths derived from the simple CRS model and related ^{137}Cs peaks for individual cores, the ^{210}Pb chronologies for the cores need to be corrected by referring to the ^{137}Cs records (Appleby, 2001). For ^{137}Cs, a small lag of 1 year or so could occur between the maximum atmospheric fallout and peaks in sediment temporal records mainly due to delay in catchment input (Robbins et al., 2000). Catchment soils for these Tibetan lakes are generally very sandy, that have less capacity than organic or clay soils in delaying catchment to lake ^{137}Cs input. Furthermore, good agreement between the ^{137}Cs peaks with 1963 dated by the ^{210}Pb CRS model in the northern area lake sediments, would suggest that the lag in sediment ^{137}Cs peak formation is negligible. Therefore, we use the ^{137}Cs peak as 1963 to correct the CRS model in the central Plateau lake sediments. Chronologies for these central area cores were calculated by applying the CRS model step-wise to each time-bound section, by fitting the 1963 ^{210}Pb date to the ^{137}Cs peak depth (Fig. 5). There are still errors in these chronology

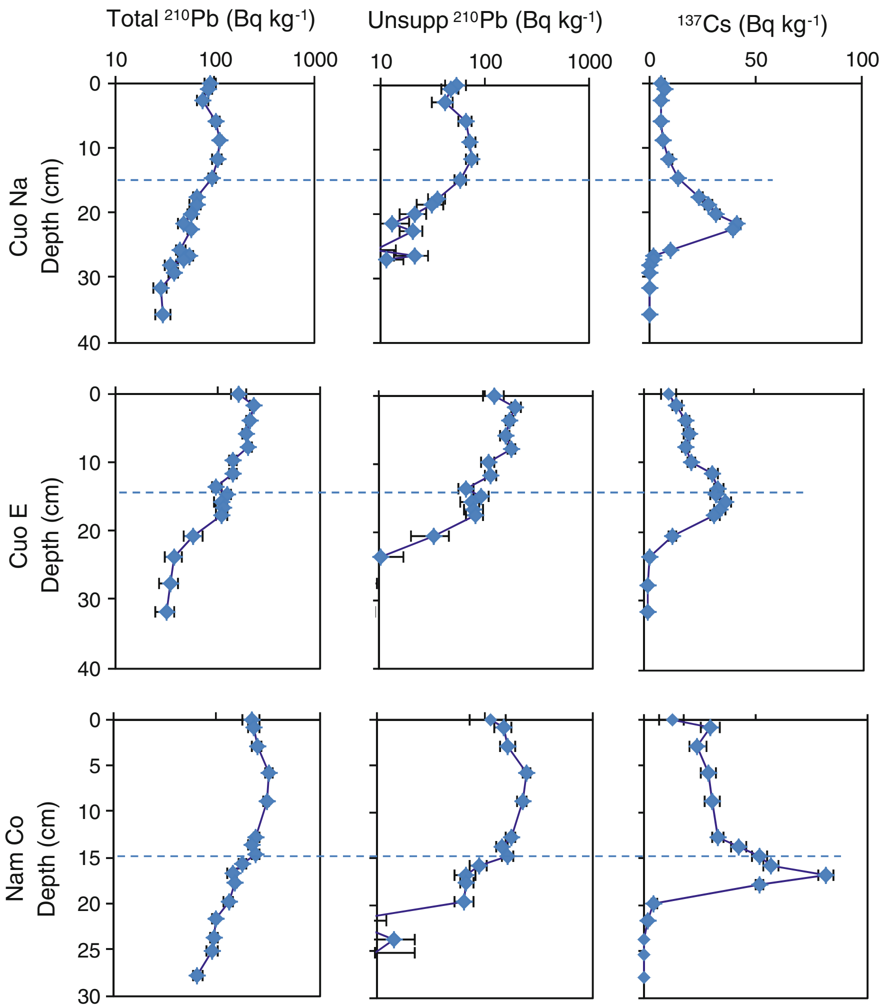

Fig. 3 Fallout radionuclides in the sediment cores taken from the central area of the Tibetan Plateau; showing total, unsupported ^{210}Pb and ^{137}Cs concentrations versus depth. The *dashed line* indicates 1963 according to the simple CRS model, showing discrepancy between uncorrected CRS model date and the ^{137}Cs date

calculations; the change in ^{210}Pb flux almost certainly did not occur in 1963 and was more likely a gradual, as opposed to step-wise, change. Nonetheless, these section-corrected chronologies should be more accurate than the simple CRS model ones.

Sediment accumulation rates are generally below 0.2 g cm^{-2} year^{-1} at the core sites even with an increase in recent years (Fig. 5). The Cuo Na core is unusual, however, with two enhanced sediment accumulation periods in the last 50 years. The first occurred in the 1960s, due most likely to urban expansion of the small town Amdo in the catchment, road construction and soil erosion. The second period, which reached the highest level of 0.8 g cm^{-2} year^{-1} around 2004, corresponds with the construction phase of the Qinghai-Tibet railway through the catchment. These periods also increased the input of unsupported ^{210}Pb stored in the catchment topsoil into the lake. With reference to the ^{137}Cs date, the unsupported ^{210}Pb fluxes calculated by the CRS model in the Cuo Na core have increased from a mean of ca. 290 Bq m^{-2} year^{-1} (pre-1960s) to a mean of ca. 360 Bq m^{-2} year^{-1} in recent years. Following the highest ca. 2004 level, sediment accumulation rates have decreased (Fig. 5).

Southern area

In the Peku Co core, the equilibrium depth of total ^{210}Pb with supported ^{210}Pb occurs at a depth of ca. 3 cm. Based on the unsupported ^{210}Pb inventory for the core, the mean unsupported ^{210}Pb flux for the core location can be estimated to be 17 ± 2 Bq m^{-2} year^{-1} (Table 2). The ^{210}Pb flux in the Peku Co lake core is

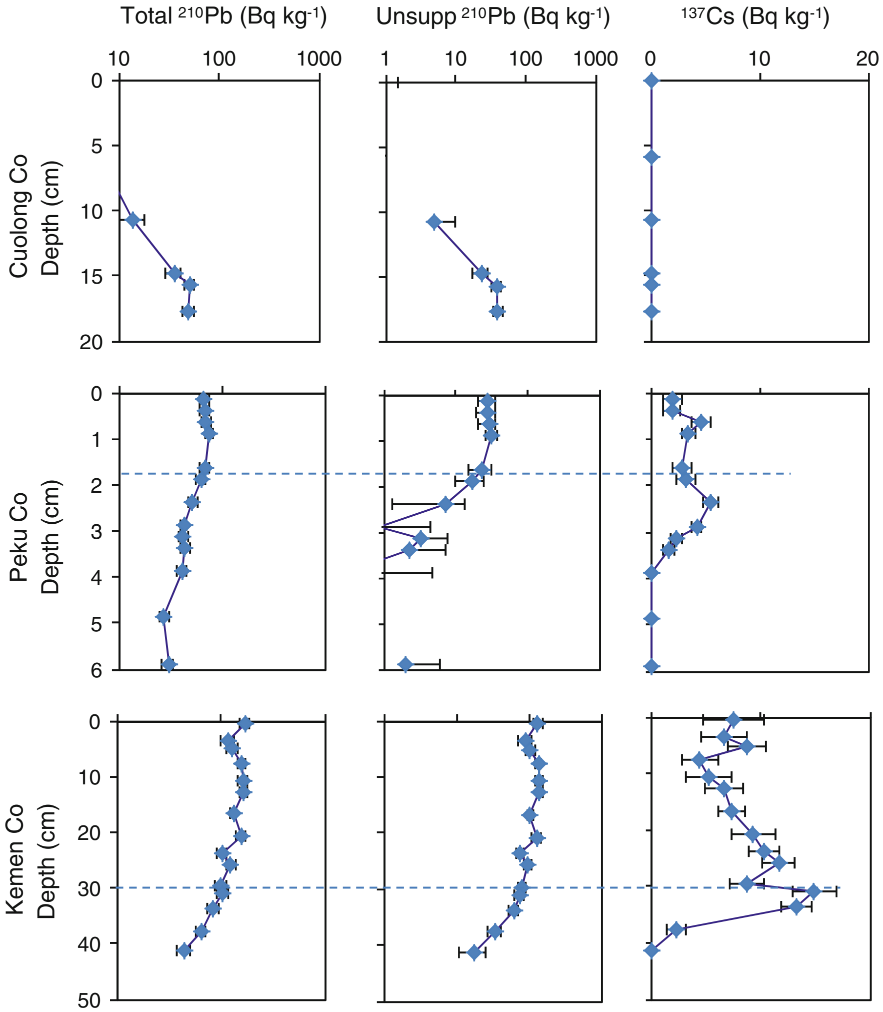

Fig. 4 Fallout radionuclides in the sediment cores taken from the southern area of the Tibetan Plateau, showing total, unsupported ^{210}Pb and ^{137}Cs concentrations versus depth. The *dashed line* indicates 1963 according to the simple CRS model, showing near agreement between the CRS model date and the ^{137}Cs date

Table 2 ^{210}Pb and ^{137}Cs inventories and ^{210}Pb fluxes in sediment cores taken from lakes in the Tibetan Plateau

Site	^{210}Pb inventory (Bq m^{-2})	^{210}Pb flux (Bq m^{-2} year^{-1})	^{137}Cs inventory (Bq m^{-2})	Equilibrium depth (cm)	^{210}Pb/^{137}Cs
Qinghai Hu	4,852	151 ± 5.4	1,560	8	3.11
Keluke Hu	2,599	80 ± 6.2	1,176	18.5	2.21
Gaihai	4,458	138 ± 9.8	2,037	25	2.19
Cuo Na	9,353	291 ± 16.4	3,366	28.5	2.78
Cuo E	10,963	382 ± 15.4	2,498	28	4.39
Nam Co	3,688	131 ± 8	925	26	3.99
Peku Co	548	17 ± 2	114	3	4.81
Kemen Co	5,666	185 ± 8.5	474	>42	11.95

significantly lower than the soil section profile measured in the catchment (Table 3). The unsupported ^{210}Pb flux in the Peku Co lake core, which is about 17% of that in the catchment soil profile, suggests that fine-grained sediments have been reworked and transported away from the core site. The ^{137}Cs inventory in the

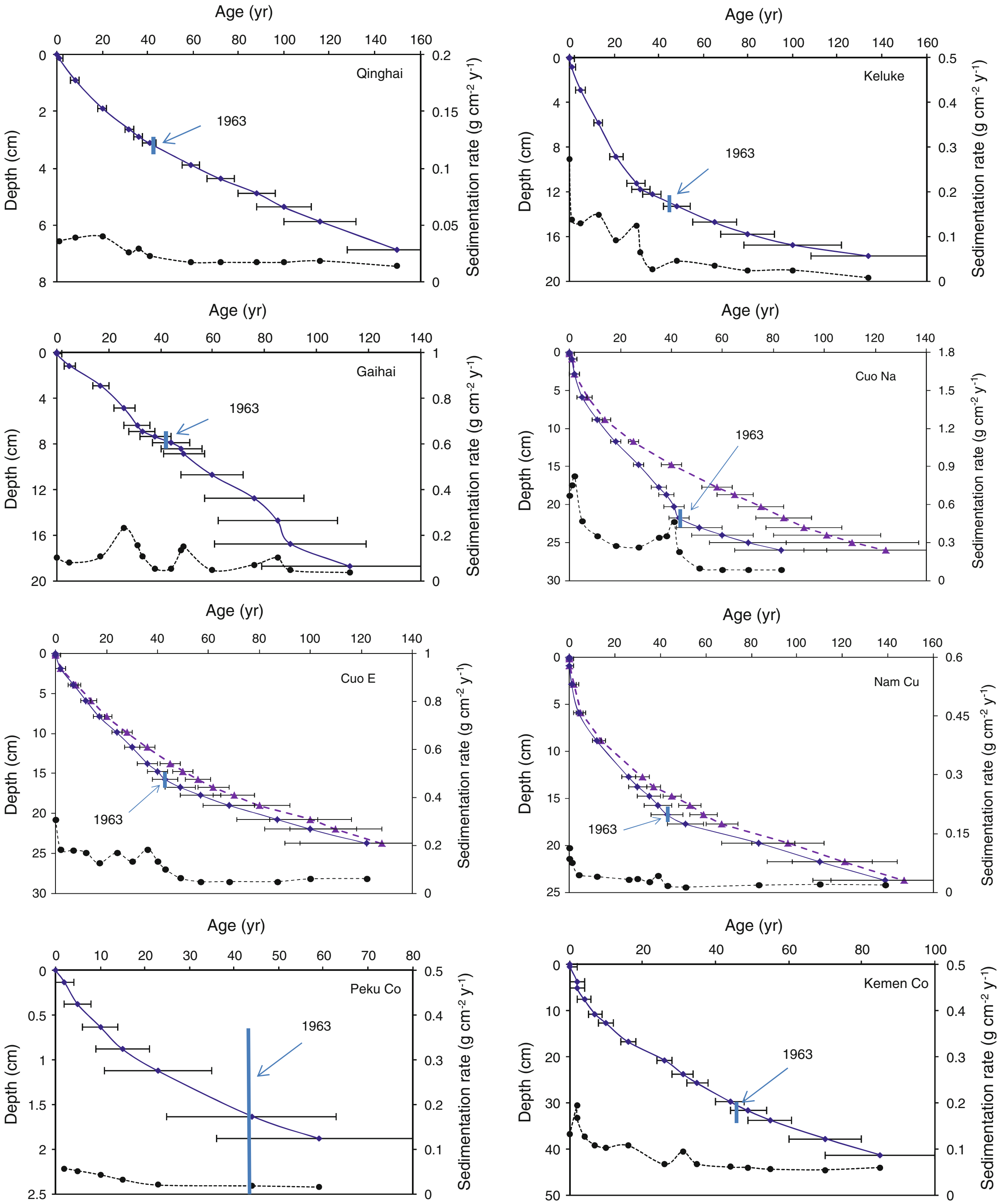

Fig. 5 Sediment chronologies versus depth for eight dated cores taken from the Tibetan Plateau. The *solid line* shows the CRS age (for the Cuo Na, Cuo E, and Nam Co cores the ages were corrected, and the *dashed line* with triangles is uncorrected CRS model age). The *dashed line* with *filled circles* indicates sedimentation rate

Peku Co core is the lowest of the dated cores (Table 2) with the low ^{137}Cs activity also due to fine-grained sediments being preferentially transported away.

The ^{137}Cs inventory in the Kemen Co core is also low. The lake is situated in glacial outwash deposits adjacent to a glacial melt water river, separated by sandy soils with gravels and boulders. Due to high solubility, ^{137}Cs is likely to be lost from the lake water to the river through ground water exchange, though there may be other factors creating the low ^{137}Cs inventory.

The ^{210}Pb profiles in the Peku Co and Kemen Co cores show flattening features in the upper sections that could indicate sediment mixing. However, variations in organic content measured by LOI in the ^{210}Pb flattened sections of the cores suggest that this is limited.

Detectable ^{137}Cs occurs only in the top 3.5 cm of the Peku Co core with relatively high values between 0.5 and 3 cm. The ^{137}Cs profile is poor for dating, indicating that the 1963 depth is in the 0.5–3 cm section. In the Kemen Co core the ^{137}Cs peak is at 31.5–32 cm while the CRS ^{210}Pb model places the 1963 depth at 29.5–30 cm. This suggests that sediment mixing has been limited in Kemen Co. The irregular ^{210}Pb profiles in the Peku Co and Kemen Co cores suggest variable rates of sedimentation. Sediment accumulation rates for the Peku Co core are extremely low, from 0.015 g cm^{-2} year^{-1} in the 1940s gradually increasing to ca. 0.057 g cm^{-2} year^{-1} in the 2000s (Fig. 5). In the Kemen Co core, sediment accumulation rates were relatively uniform at ca. 0.044 g cm^{-2} year^{-1} (pre-1950s) but have fluctuated and increased to 0.13 g cm^{-2} year^{-1} to the date of sampling (2007) (Fig. 5).

^{210}Pb and ^{137}Cs in hypersaline lake sediments: the Cuolong Co sediment core

Saline lakes are capable of producing accurate and relatively undisturbed ^{210}Pb sediment chronologies (e.g., Legesse et al., 2002). In this study, 3 of the lakes are saline (>5 g L^{-1} of total dissolved salts, see Table 1), and fallout records of ^{210}Pb and ^{137}Cs in the Qinghai Hu and Gaihai cores were satisfactory for dating. However, the skewed distribution of ^{210}Pb in the Cuolong Co core provides an example of the ineffectiveness of radiometric dating sediments from shallow, hypersaline lakes. In this core, ^{210}Pb only appears below 10 cm, and activities increase with depth to 18 cm at the base of the core (Fig. 4). The upper part of the core consists of ~20% Na and S, respectively, and SO_4^{2-} is the major anion in the lake water, which suggests that most surface sediments are Na_2SO_4. Solubility of Na_2SO_4 varies with temperature. It increases by an order of magnitude between 0 and 32.4°C, where it reaches a maximum of 49.7 g Na_2SO_4 per 100 g water (Linke & Seidell, 1965). Air temperatures can range in a year by 30°C (Yang et al., 2011) on the Tibetan Plateau. Due to shallow water depths and temperature variations in an enclosed basin, considerable amounts of Na_2SO_4 and other salts are annually dissolved and precipitated. ^{210}Pb solubility is much less affected by temperature, so while Na_2SO_4 and other salts are dissolved, associated ^{210}Pb is left on the sediment surface. Reprecipitation of salt then forms a new layer on top of the old surface, and through this process ^{210}Pb is concentrated and migrated downward. In this core, other elements also show this redistribution, e.g., higher concentrations of Al, Si, Ca, K, Pb, Hg, and organic matter occur in the lower part of the core (below 10 cm). The profiles of Pb and Hg of the Cuolong Co core (Fig. 6) clearly show that the top 10–15 cm of sediments have been affected by Na_2SO_4 dissolution and precipitation.

Discussion

The dating results suggest a general increase in lake sediment accumulation in recent years across the Plateau. This precludes the use of the CIC model as increased sediment accumulation would have diluted

Table 3 ^{210}Pb and ^{137}Cs inventories and ^{210}Pb fluxes in soil cores taken from different regions in the Tibetan Plateau

Site name	Soil core	^{210}Pb inventory Bq m^{-2}	^{210}Pb flux Bq m^{-2} year^{-1}	^{137}Cs inventory Bq m^{-2}	^{210}Pb/^{137}Cs
Qinghai Hu	TPNA	3,563	111 ± 7	2,019	1.76
Cuo E	TPCB	1,950	60.7 ± 5.5	428	4.56
Peku Co	TPSB	3,182	99.1 ± 7.3	177	17.98

initial unsupported ^{210}Pb activities, especially since the 1960s (Fig. 5), when ^{210}Pb profiles show an irregular decline with depth. CRS modelled dates agree well with the ^{137}Cs records in at least half of the dated cores, although there is a discrepancy in the dates derived from the central area cores. Our data also indicate that ^{210}Pb deposition flux on the Plateau has been relatively stable in the last 100 years, with increased ^{210}Pb flux to lake sediments attributed to catchment in-wash.

^{210}Pb, ^{137}Cs inventories and ^{137}Cs sources in the sediment cores

^{210}Pb inventories in our lake sediment cores vary by a factor of 20, and the ^{137}Cs inventories by a factor of 29.5, suggesting different levels of sediment focussing—sediments being re-suspended and moved toward or away from the core location. The inventory ratios of ^{210}Pb/^{137}Cs in our Tibetan cores are at a similar level (2.19–4.81) except the core from Kemen Co (11.95) (Table 2). The similarity of ^{210}Pb/^{137}Cs ratios may reflect the ratio in atmospheric deposition, as relatively closed lake systems with high evaporation rates avoid losses of ^{210}Pb and ^{137}Cs in different proportions in lake water through outflow due to their different solubility. The ^{210}Pb/^{137}Cs inventory ratio in Kemen Co is significantly higher than other sites, likely due to a greater loss of ^{137}Cs from lake to river.

^{210}Pb inventories do naturally differ between lakes, even within the same lake, due to differences in depth and sedimentation patterns. Geologically generated atmospheric ^{222}Rn and ^{210}Pb concentrations in rainfall, however, should regionally be at a similar level. The similarity of ^{210}Pb/^{137}Cs inventory ratios in the lakes studied implies that the distribution of atmospheric ^{137}Cs across the Tibetan Plateau has been relatively even like ^{210}Pb.

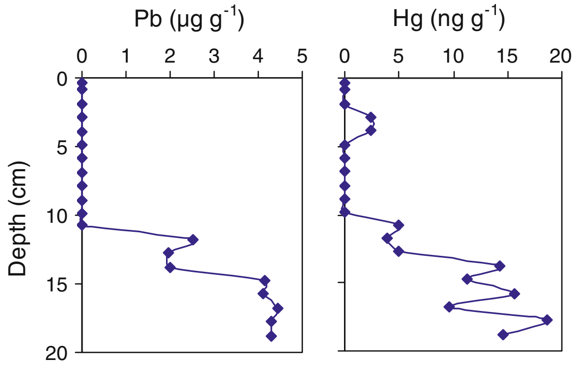

Fig. 6 The Pb and Hg concentration profiles in the Cuolong Co core, showing these trace metals have been re-distributed and migrated downward beneath the cyclic precipitation/dissolution depth

The fallout maximum of ^{137}Cs in 1963 derived from atmospheric testing of nuclear weapons is globally ubiquitous (Appleby, 2001). The agreement of ^{210}Pb chronologies with the well-resolved ^{137}Cs peak for 1963 in our dated Tibetan cores indicates that historical and global atmospheric nuclear weapon testing is the major source of ^{137}Cs in the Tibetan sediments. In the ^{137}Cs profiles there are no clear peaks corresponding to an age/depth ca. 1986. Atmospheric dispersal of radioactive Chernobyl fallout occurred over a short timescale (up to 40 days). North West Europe was the principal destination of radioactive material from Chernobyl, with the western Soviet Union and other European countries receiving 97% of the total ^{137}Cs emission derived from the accident (Anspaugh et al., 1988, OECD, 2003). Although, the atmospheric plume of material was detected globally (in Japan and North America) the amounts were low compared to Western Europe. China overall was little affected (Wheeler, 1988; Wu et al., 2010). Even within the UK, where Chernobyl fallout was significant, many lake cores do not show the 1986 ^{137}Cs peak (e.g., Bennion et al., 2001; Yang, 2010) due to the irregular, precipitation-dependent nature of atmospheric fallout and catchment/lake processes following the event. Chernobyl fallout is unlikely therefore to have formed a ^{137}Cs peak that can be confidently used to date sediments in Tibetan Plateau lakes.

The apparent increase of ^{210}Pb/^{137}Cs inventory ratios from north to south over the Tibetan Plateau may be due to differences of tropospheric air influence (Yang et al., 2010) or China's nuclear bomb testing programme. China's atmospheric and underground nuclear bomb tests were conducted at Lop Nor between 1964 and ceased (in the atmosphere) in the mid 1980s (Wu et al., 2010). The relatively even distribution of ^{137}Cs in the atmosphere across the Tibetan Plateau suggests that China's nuclear bomb testing has not been a major contributor of ^{137}Cs to the region. Wu et al. (2010) demonstrate that less than 40% of ^{137}Cs in lake sediments 500 km away from Lop Nor is derived from China's nuclear tests.

Therefore, the main source of ^{137}Cs in Tibetan lake sediments is the "global" contribution derived from the fallout of atmospheric nuclear weapons testing that peaked in 1963.

^{137}Cs dating issues for lake sediments on the Tibetan Plateau

The ^{137}Cs profiles in this study reveal that diffusion of ^{137}Cs in the sediment column can be significant. The advent of ^{137}Cs activity in the Keluke and Gaihai cores occurs, according to the ^{210}Pb chronology, at the end of the 19th century (17 and 19 cm, respectively). In the Qinghai core, total ^{210}Pb activity reaches equilibrium with supported ^{226}Ra at ca. 8 cm, but the first appearance of ^{137}Cs extends beyond this. ^{137}Cs is more soluble than ^{210}Pb in lake sediments, particularly in saline lake sediments. ^{137}Cs can be displaced by monovalent cations with low hydration energy and an ionic radius similar to Cs^+ such as Na^+, K^+, and NH^+. This results in ^{137}Cs re-mobilisation and/or loss of ^{137}Cs to the water column (Foster et al., 2006; Comans et al., 1989). Depth-dependent diffusion rates can be calculated using the sediment thickness from the depth dated to 1954 to the depth the ^{137}Cs record starts, divided by the time diffusion has occurred. In our cores these show a similar level at around 0.1 cm year^{-1}, except the Peku Co core at 0.031 cm year^{-1} (Table 4). This may be that the cored sediments have similar physical and geochemical properties conducive to post depositional ^{137}Cs diffusion. ^{137}Cs profiles will also have been affected by ^{137}Cs deposition in the catchment and its subsequent transport to the lake and sediment surface.

Although the onset of the ^{137}Cs record in sediment cores has been used widely for dating "1954" with the beginning of atmospheric nuclear weapon testing (e.g., Pennington et al., 1973; Rember et al., 1993), unrecognised ^{137}Cs diffusion in Tibetan lake sediments can cause considerable error. For example, in our Qinghai core, this age/depth error could be more than a century. Recent published lake studies in the Tibetan region that use the onset of ^{137}Cs records to provide a date of ca. 1952–1954 (e.g., Jin et al., 2010; Kasper et al., 2012; Li et al., 2004; Liu et al., 2009; Shen et al., 2001; Wang et al., 2008, 2009, 2011; Wu et al., 2001, 2002, 2003, 2006, 2007a, b; Zhang et al., 2002, 2009; Zhu et al., 2002, 2003) might include such an error. Some of them have solely used the ^{137}Cs record (e.g., Wu et al., 2002; Zhang et al., 2009), others have used both ^{137}Cs and ^{210}Pb records for dating, but with marked discrepancies between them (e.g., Wu et al., 2004; Wang et al., 2009), and some confirm the 1954 ^{137}Cs date with ^{210}Pb, but use an incorrectly estimated equilibrium depth of total ^{210}Pb with supported ^{210}Pb (e.g., Wu et al., 2007; Kasper et al., 2012; Wang et al., 2011). Sediment accumulation rates in Tibetan cores are overall not high, so use of the onset of ^{137}Cs for dating can easily cause significant age/depth errors. For example, after using the onset of ^{137}Cs activity to date 1952 in sediments, Shen et al. (2001) and Zhang et al. (2002) calculated that sedimentation rates from 1952 to 1963 were ~5 times higher than before and after the period.

Although diffusion may affect the vertical distribution of ^{137}Cs in Tibetan lake sediments, it is still reasonable to use the ^{137}Cs activity peak for dating. ^{137}Cs diffuses both up and down, but not as suggested by Zhu et al. (2002) and Qiang et al. (2007) that the ^{137}Cs peak position was "moved down".

By attributing the onset of the ^{137}Cs record to 1952, Wang et al. (2008) conclude that there is a considerable difference in the depth of 1963 between the ^{137}Cs

Table 4 Onset (^{137}Cs activity > 2 Bq kg^{-1}) depths of the ^{137}Cs records for the Tibetan cores, the related ^{137}Cs activities and ages of the sediments in the depths, and depth-dependent diffusion rates

Site	Depth (cm)	^{137}Cs activity (Bq kg^{-1})	Time (AD)	^{137}Cs diffusion rate (cm year^{-1})
Qinghai Hu	6.88	9.9 ± 0.8	1,850	0.098
Keluke Hu	17.75	2.9 ± 0.7	1,870	0.082
Gaihai	14.75	2.6 ± 0.6	1,916	0.116
Cuo Na	27.75	2.3 ± 0.6	1,903	0.101
Cuo E	23.75	3.3 ± 0.8	1,888	0.130
Nam Co	19.75	5.0 ± 1.4	1,924	0.078
Peku Co	3.13	2.4 ± 0.5	1,850	0.031
Kemen Co	37.75	2.3 ± 0.8	1,928	0.095

record and the ^{210}Pb CRS age/depth model. By using the onset of the ^{137}Cs record to date 1952, Jin et al. (2010) suggest that the ^{137}Cs peak was derived from the 1986 Chernobyl accident. As discussed above, ^{137}Cs fallout from the Chernobyl accident is unlikely to have generated a distinguishable peak on the Tibetan Plateau. Some recent studies have also ascribed an indistinct post-1963 ^{137}Cs peak to 1986 in lake sediments from the Tibetan Plateau (e.g., Wu et al., 2001; Wang & Li, 2002; Zhu et al., 2002; Qiang et al., 2007; Zhang et al., 2009). Indistinct peaks can be formed in sediment ^{137}Cs records due to a number of reasons, for example sediment focusing, catchment erosion, changes in sediment composition and radiometric counting errors.

Conclusions

Our data show that many lakes on the Tibetan Plateau have the potential of providing reliable decadal and sub-decadal temporal resolution for recent palaeolimnological research. We have recognised a general division in sediment accumulation rates, fairly low and stable rates (0.01–0.05 g cm^{-2} year^{-1}) before the 1950s (except for slight increase in the northern Keluke and Gaihai cores) and a variable increase in post 1950s sediment accumulation (with identifiable peaks in the 1970–1980s). The Cuo Na core chronology and sedimentation rates allude to direct human impact in the lake catchment significantly increasing sediment accumulation.

Vertical ^{137}Cs diffusion in sediment cores represents a risk in incorrectly ascribing the onset of ^{137}Cs activity to 1954. Peaks of ^{137}Cs activity in cores derived from the global fallout maximum from atmospheric testing are, however, well resolved in the sediments and good for dating 1963. ^{137}Cs records in the ^{210}Pb dated cores demonstrate that the 1986 Chernobyl fallout is unlikely to form a significant peak that can be confidently used for dating.

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