Journal of Hydrology (2006) **329**, 568–576

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/jhydrol

Sediment sources and the flood record from Wanghu lake, in the middle reaches of the Yangtze River

Chaolu Yi [a,b,*], **Huifang Liu** [c], **Neil L. Rose** [d], **Hong Yang** [d,e], **Leyi Ni** [e], **Ping Xie** [e]

[a] *Institute of the Tibetan Plateau Research, Chinese Academy of Sciences, Shuangqing Road 18, Beijing, 100085, China*
[b] *Key Laboratory of Cryosphere and Environment, Chinese Academy of Sciences, Lanzhou 730000, China*
[c] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China*
[d] *Environmental Change Research Centre, University College London, 26 Bedford Way, London, WC1H 0AP, UK*
[e] *Donghu Experimental Station of Lake Ecosystems, State Key Laboratory for Freshwater Ecology and Biotechnology of China, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China*

Received 25 January 2005; received in revised form 24 January 2006; accepted 9 March 2006

KEYWORDS
Laminated sediments;
Yangtze river;
Sediment geochemistry;
Flood sources

Summary A sediment core was collected from the centre of Wanghu Lake, in the Middle Reaches of the Yangtze River. The recent part of the core was dated using a combination of ^{210}Pb and spheroidal carbonaceous particle (SCP) techniques. Extrapolating this chronology dated the laminated section of the core, between 723 and 881 mm, to the first half of the 18th century and this section was selected for detailed study. The thicknesses of the laminae were measured using reflecting and polarizing microscopes whilst geochemistry was determined by an electron probe. The thickness of the dark layers was found to be positively correlated with titanium concentrations, and negatively correlated with aluminium and potassium concentrations. The thickness of the light layers was found to be negatively correlated with the concentrations of titanium. It is concluded that the dark layers were deposited from the Fushui River, a tributary of the Yangtze River, under periods of normal flow whilst the light layers were mainly deposited from the Yangtze River itself during flood periods. Documentary evidence for floods occurring in the lake catchment corresponded with thick laminations of high titanium concentration. Further, two of the three thickest, light laminations with low titanium concentrations were found to be synchronous with recorded flood dates of the main Yangtze River in its Middle Reaches, but one was synchronous with a local drought. These data suggest that the lake sediment provides an archive of the relative water levels of the Yangtze and Wanghu including floods of both the main Yangtze River and the local hydrological regime.

---

[*] Corresponding author. Tel.: +86 10 62429382; fax: +86 10 62849886.
E-mail address: clyi@itpcas.ac.cn (C. Yi).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2006.03.008

Introduction

Evidence interpreted from sediment records has been widely used in hydrological studies. Sediment yield has been related to precipitation histories (Lamoureux, 2000; Royall, 2000) and peak flows (Evans et al., 2000) whilst sedimentary facies have been used to reconstruct ancient variations in discharge (Alexander et al., 1999) and inorganic sediment layers to determine hydrological events through the Holocene (Brown et al., 2000; Nesje et al., 2001). Lacustrine sedimentary sequences have been used to infer the magnitude and frequency of flood events through the Late Pleistocene to the Holocene in Australia (Kos, 2001) and in the Holocene in the USA (Pederson, 2000), northwestern Russia (Gey et al., 2001) and in China (Zhu et al., 1997; Yang et al., 2000; Yin et al., 2001). On a more recent time-scale Mulder et al. (2001) used turbidites from the Mediterranean basin to identify flood frequency and magnitude over the 20th century whilst Goff et al. (1998) used sediment cores and sediment traps in Wellington embayment, New Zealand, to relate accumulation rates to flood events. The record of flooding has also been identified from the accumulation rate of overbank deposits from the Waipaoa River, New Zealand (Gomez et al., 1998) and from the grain size, microfabric and sedimentation rate of sediment cores taken from Taihu Lake on the Yangtze delta in east China (Yi et al., 2004).

Although laminations in varved sediments have been used extensively in order to study seasonal and annual environmental changes (e.g., Hardy et al., 1995; Gajewski et al., 1997), laminated sediments are also present, to some extent, in lakes located alongside large river systems where sediment supply mainly comes from river discharge. However, the information that can be extracted from the laminations of these lakes and in particular, how these relate to sediment sources has, so far, received little attention. The aim of this paper is to study the historical sources of bedload and flood events by interpreting the thickness, geochemistry and mineral composition of the laminated section of a sediment core taken from Wanghu Lake in the Middle Reaches of the Yangtze River.

Regional setting

Wanghu Lake (29°52′N; 115°21′E) is located in Yangxin County, Hubei province, on the south bank of the Middle Reaches of the Yangtze River (Fig. 1). Before reclamation in the 1960s and 1970s, the lake had a surface area of 80.9 km^2, but this has now been reduced to 42.3 km^2. The lake has a mean depth of 3.7 m, a maximum recorded depth of 5.2 m and lies at an altitude of 17 m.a.s.l. The catchment has an area of 5310 km^2 and while this is used mainly for agriculture, it includes mining for coal, iron, aluminum, copper and manganese. About 30 years ago, the 196 km long Fushui River, originating in the Mufu Mountains in southeastern Hubei province, drained into the lake and the lake water in turn drained to the Yangtze River at Fuchi. However, since July 1967, the Fuchi Flood Gate has separated the free connection of the lake with the Yangtze whilst a 27.7 km embankment was built along the southeast of the lake between 1975 and 1978. As a consequence, the Fushui River now discharges into the Yangtze on the eastern bank of the lake (Fig. 1) and river water from the Upper and Middle Reaches of the Yangtze River now passes Wanghu.

Research methods

Collection and treatment of the samples

Two parallel sediment cores were taken from the centre of Wanghu in November 1997 using a static-pressure corer fitted with polyvinyl chloride (PVC) tubes with an internal diameter of 48 mm. The two cores were taken simultaneously by taping the two tubes together. The upper 70 cm of one core was extruded vertically at 1 cm intervals and used for ^{210}Pb dating purposes. The other core, 94.3 cm long, was cut longitudinally using an electro-osmotic guillotine (Sturm and Matter, 1972) in order that the lithostratigraphic properties could be identified and described, and the core then prepared for thin-sectioning. Sub-samples with a length of 15–25 mm (determined by the thickness of the laminae) were cut using an electro-osmotic blade with a thickness of about 0.1 mm. These sections were then immersed in acetone several times to remove the water

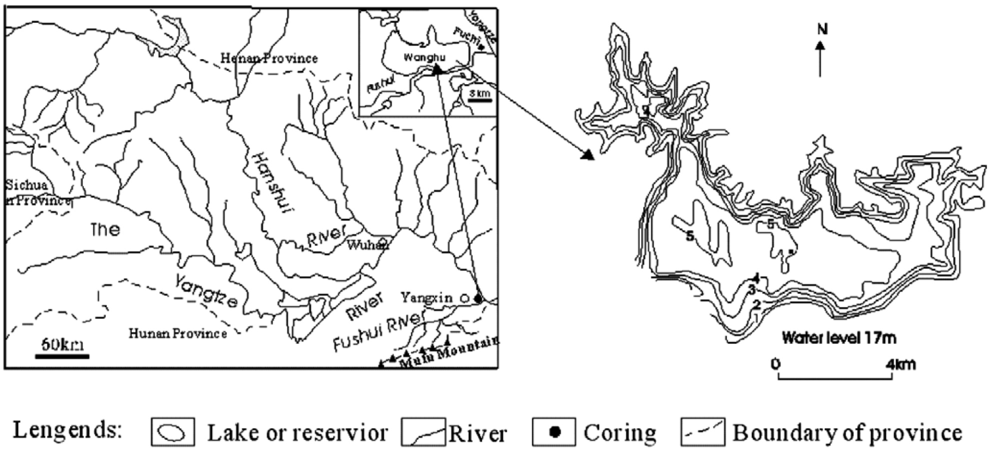

Figure 1 Location map of Wanghu and coring location.

before being impregnated with an unsaturated polyester in a pressure-reduced container (Gajewski et al., 1997). Once the polymer had hardened, the samples were then ground into slices 0.4 mm thick, polished and sprayed with carbon.

Measurement of lamina thickness

Sediment lithostratigraphy was first visually assessed using a reflecting optical microscope prior to carbon spraying. Laminae were observed between 43 and 90 cm depth. However, after the removal of the water from the sediment, in preparation for thin-sectioning, not all these laminae remained visible to the naked eye although laminae in the section 723—881 mm could still be observed under the microscope (Fig. 2). This section was therefore chosen for detailed study. The thickness of each lamina was measured using a polarizing microscope at 40—80 times magnification to a resolution of 0.00625—0.0125 mm. Each lamina was measured at three or more points in order to determine the mean thickness. The original total length of wet sediment was 158 mm, but the sum of the laminae mean thicknesses totalled only 151.62 mm. This is a reduction of 4.2% and the mean laminae thicknesses were corrected accordingly.

Elemental analyses

The elements Si, Al, Fe, Ti, Mn, Mg, Ca, Na, K, Cu and Zn were measured quantitatively using an electron probe (JEOL JXCA-733) with a 40 μm diameter beam using the Chinese National Standard method (GB/T 15617-1995) for quantitative electron probe microanalysis of silicate rocks. The theoretical background to this method is described in Heinrich (1981). Analyses were made at two or three points on each lamina in order to calculate a mean concentration. Laminae with a thickness of more than 1 mm were analysed at four points whilst those thinner than 40 μm were not analysed. The X-ray intensity of each element was determined from a standard sample using a voltage of 15 kV; a current of 20 mA; 5 s for background measurement and 20 s for measurement of peak values. The X-ray intensity of the same element in the samples could then be measured using the same conditions.

The chemical composition of six samples from the sediment core were also determined by X-ray fluorescence (XRF) analysis (Chinese National standard GB/T 14506.28-1993 'Determination of major and minor elements in silicate rocks: X-ray fluorescence spectrometric method') in order to compare with the electron probe results. This analysis was undertaken using a Siemens SRS-303 automatic sequential wavelength dispersive X-ray fluorescence spectrometer with a rhodium end-window X-ray tube operating at a voltage of 50 kV and a current of 50 mA. These analyses had a precision of better than 3% for the major and minor elements. Two additional surface sediment samples were collected, one each from the edge, and from in the channel, of the Fushui River about 2 km up-stream from Wanghu and their chemical compositions were also analyzed by XRF. These samples were used to determine geochemical composition of the river sediments in order to make a comparison with those from the lake core laminae.

In order to determine which minerals in the sediment core contained titanium, the geochemical composition of several individual mineral grains, with a grain size of 10—20 μm, were also analysed using the electron probe as described.

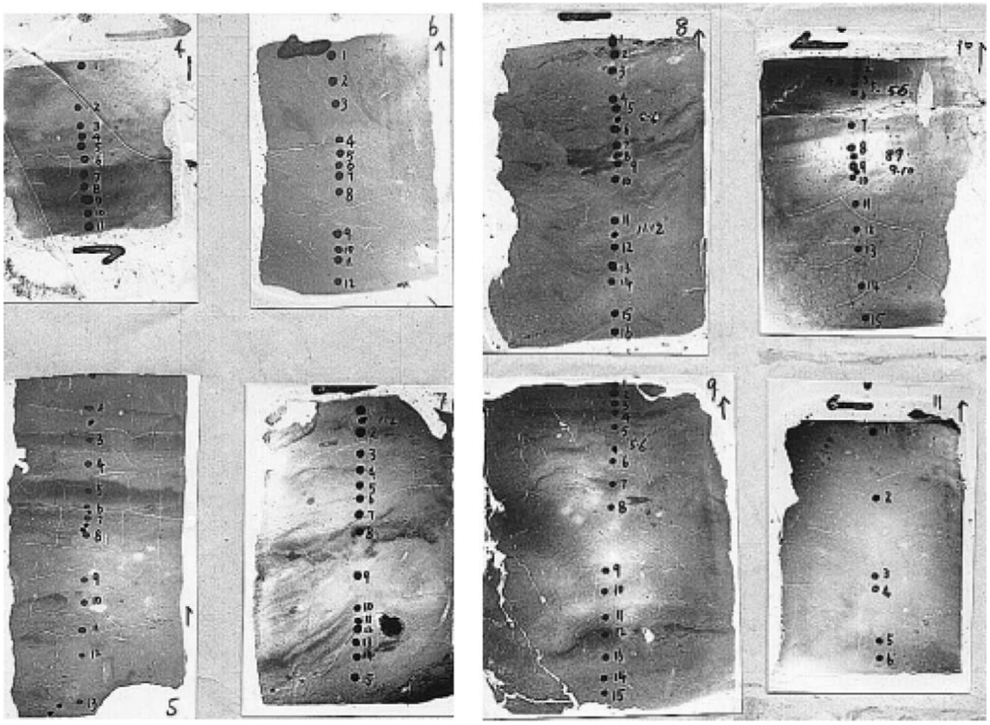

Figure 2 Reflecting microscope photographs showing laminated sections 723—881 mm.

Sediment dating

Dried sediments (2.4—3.0 g) were stored in sealed containers for three weeks to allow radioactive equilibration and then dated radiometrically by analysing for ^{210}Pb and ^{226}Ra by direct gamma assay at the National Key Laboratory for Estuary and Coastal Sediment Dynamics and Morphodynamics, East China Normal University using GWL-120210-S well-type, coaxial, low background, intrinsic germanium detectors fitted with NaI(Tl) escape suppression shields (Appleby et al., 1986). There are two principal methods for determining the initial ^{210}Pb activity of a sediment layer necessary for the calculation of its ^{210}Pb date. These are the CRS (constant rate of unsupported ^{210}Pb supply) model (Appleby and Oldfield, 1978) and the CIC (constant initial ^{210}Pb concentration) model. The CRS model is more flexible than the CIC model, and will give the same results as the CIC model if the initial concentration is constant over time. The atmospheric input of ^{210}Pb is assumed to be constant from year to year and the ^{210}Pb in these inorganic sediments is considered to be immobile. There are no reasons to believe that the flux of ^{210}Pb would have changed significantly over time during the past decades. Such changes would require a change in the amount of precipitation or in the general air mass transport in the region. Such drastic regional changes have not been reported (Eriksson et al., 2004). In addition, if the sedimentation rate increases because of eutrophication, the ^{210}Pb is diluted, and the CIC model cannot be used (Fitzpatrick et al., 2003). Consequently, sedimentation rates were calculated using of the constant rate of supply of allochthonous ^{210}Pb (Appleby and Oldfield, 1978; Eriksson et al., 2004).

The radiometric chronology of the recent sediment was supplemented by use of the spheroidal carbonaceous particle (SCP) technique. SCPs are only produced from the high temperature combustion of fossil-fuels and hence the concentration profile in the sediment record provides an unambiguous marker of contamination from these sources (Rose, 2001). SCP concentration profiles have been found to be highly repeatable and robust across a region and hence characteristic features of the profiles can be used to date sediment cores (Rose et al., 1995). In Wanghu, SCP analysis was undertaken on 16 samples between the surface and 15 cm depth using the method described in Rose (1994). The cumulative SCP concentration profile was compared with regional coal combustion statistics and the good temporal agreement allowed dates to be ascribed to sediment levels for the core (Boyle et al., 1999).

Since the two sediment tubes were taped together upon coring and the two cores were taken at the same place at the same time, we have assumed them parallel and dates have been ascribed to the undated core accordingly. Lithological comparisons between the two cores supported this assumption.

Results

Lithostratigraphy

Dark grey and brownish-yellow sediments were found at depths of 0—2 and 2—5 cm, respectively, both with coarse organic fragments. Below this depth to the core bottom, the sediment is composed of greyish-brown clay. Laminae were observed between 43 and 90 cm. They are roughly horizontal, but sloping, and are composed of alternating light (brownish-yellow) and dark (black or dark grey) layers. Of the modern fluvial sediment, that collected in the Fushui River about 2 km from Wanghu Lake was greyish-green to dark grey whilst that collected from the Yangtze River near the lake was greyish-yellow to pale yellow.

Sediment chronology

The activities of total and unsupported ^{210}Pb are shown in Fig. 3. Both total and unsupported ^{210}Pb decline irregularly with depth, show an apparent net decline below 10 cm and exhibit maximum activity at 6 cm. Unsupported concentrations of ^{210}Pb decline abruptly below 10 cm and equilibrium with the supporting ^{226}Ra is reached at 44 cm. The

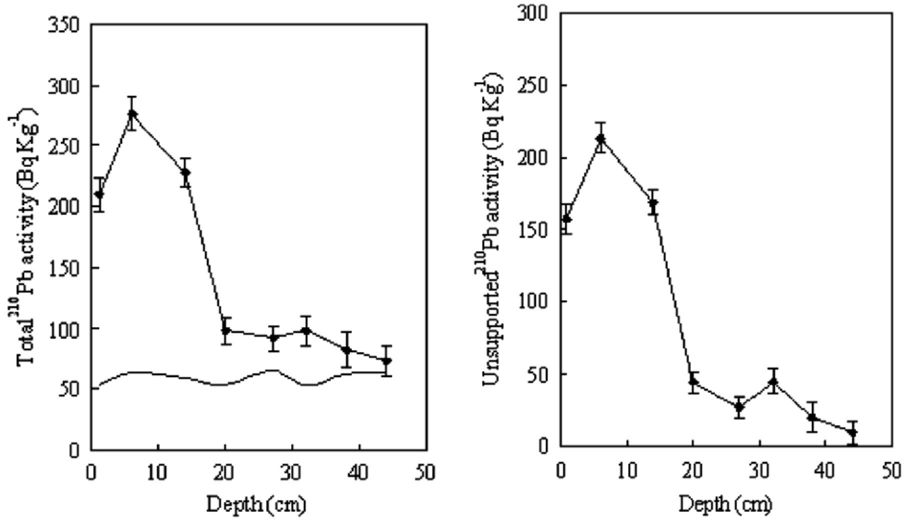

Figure 3 Fallout radionuclide concentrations in the core, showing (a) total and supported ^{210}Pb and (b) unsupported ^{210}Pb.

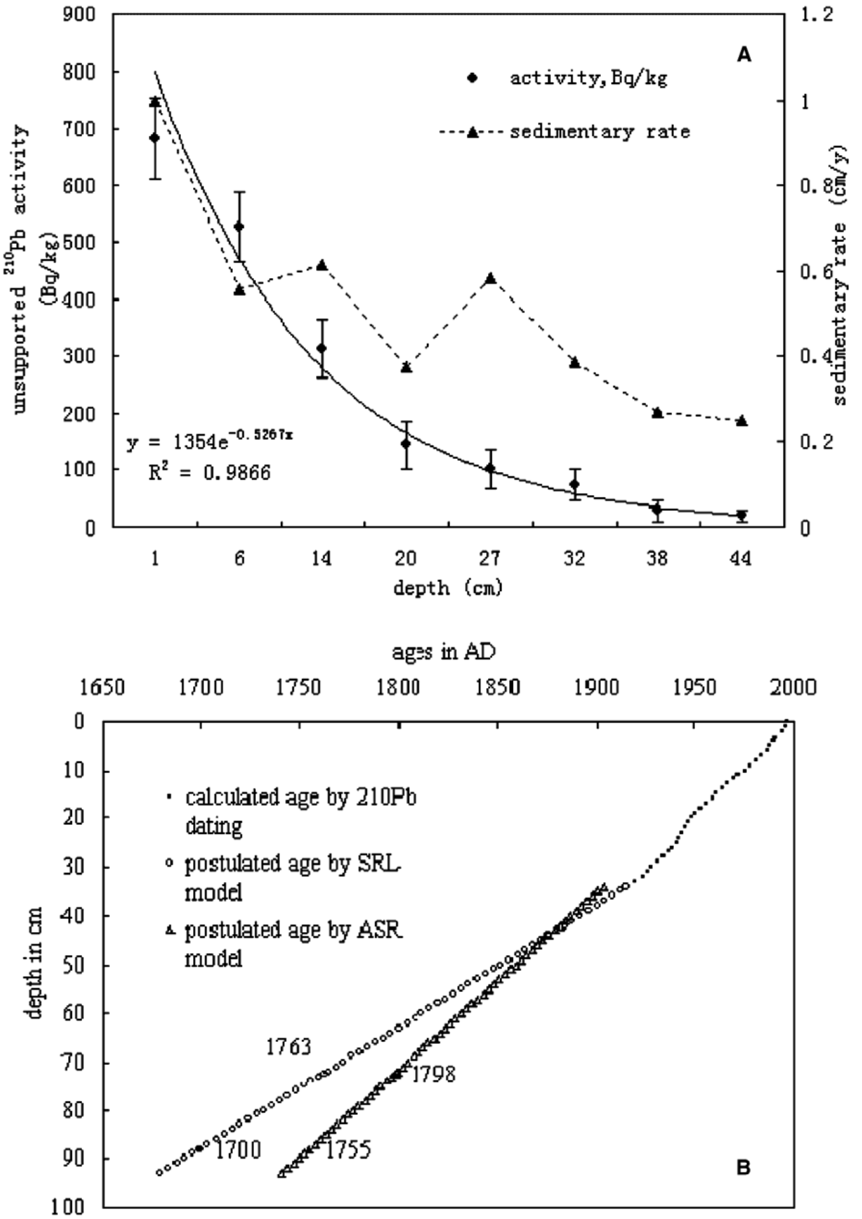

Figure 4 ^{210}Pb sediment ages showing the constructed chronology. (A) Fallout radionuclide concentrations in Wanghu core showing accumulated unsupported ^{210}Pb and sedimentary rate. Short bars are errors. (B) Radiometric chronology showing CRS model ^{210}Pb dates. Estimated ages of laminated sediment are shown as solid symbols within the open symbol data series. Open symbol ages are extrapolated. The solid dotted line is the age vs. depth from radiometric dating. ASR is 'average sedimentary rate' and SRL is 'sedimentation rate in lower sediment'. Sediment ages in open circles were extrapolated from these rates, respectively.

accumulated unsupported ^{210}Pb activities decline exponentially ($y = 867.04e^{-0.0846x}$; $r = 0.99$, significant at the 99% level). Using these ^{210}Pb data, the CRS model provides a chronology for the uppermost 44 cm of the sediment core (solid dots in Fig. 4A) with an average sedimentation rate of 0.364 cm yr^{-1}. However, below 35 cm the sedimentation rate is calculated to be lower, at 0.25 cm yr^{-1}. The SCP data suggest a rate of 0.31 cm yr^{-1} over the upper 12 cm. These two independent means of dating the sediment core therefore show good agreement, and based on these rates, extrapolation of the chronology suggests that the laminated section of the core (723—881 mm depth), began 297—242 years before present (YBP), or 1700—1755 AD and ended 199—234 YBP, or 1763—1798 AD (Fig. 4B).

Laminae thickness and geochemistry

One hundred and three alternate dark and light layers, or 51.5 'coupled laminae', were counted in the 72.3—88.1 cm core section. The average thickness of these coupled layers was 3.07 mm with a standard deviation of 0.561. The 51 light layers had a mean thickness of 2.06 mm but ranged between 1 and 8 mm resulting in a high standard deviation of 0.771. The thickness of the 52 dark

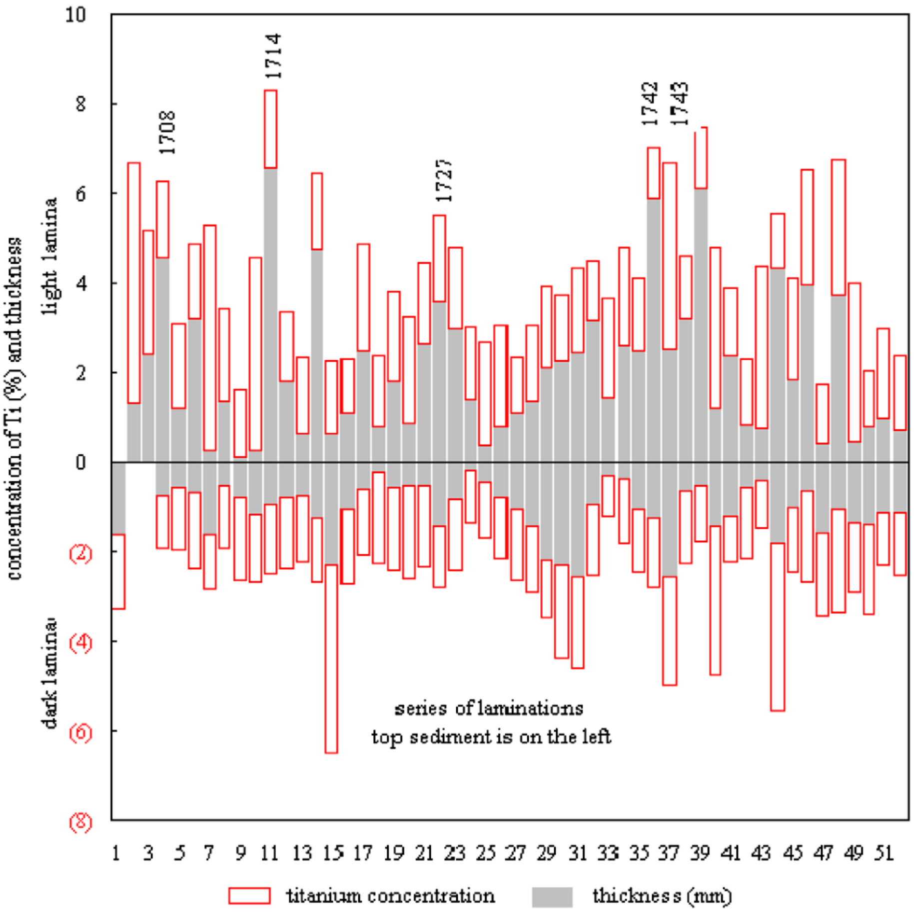

Figure 5 Vertical changes of the thickness and TiO_2 concentration in the laminated section of the sediment profile with best estimates of dates for selected levels.

layers varied by less than 3 mm so the mean thickness of 1.01 mm had a lower standard deviation of 0.606. These changes in thickness are shown in Fig. 5. The total thickness of the light layers is 105.2 mm, whilst that of the dark layers is only 52.9 mm.

Laminae thickness is not significantly correlated with any geochemical constituent if the dark and light layers are considered together as a 'coupled layer'. However, the thickness of the dark and light layers are related with some geochemical elements if they are considered separately. Mean TiO_2 concentrations are 1.7% and 2.2% by weight for the dark and light layers, respectively. Of the modern fluvial sediments, the Ti concentration is 4.57% in the sediment from the Fushui River, and is therefore considerably higher than the average concentration in either dark or light laminae. However, the concentration of Ti is positively correlated with the thickness of the dark layers ($r = 0.467$; $n = 50$; $p < 0.01$) and negatively with the thickness of the light layers ($r = -0.274$; $n = 51$; $p < 0.05$). Significant correlations of $p < 0.01$ were also found for Al_2O_3 ($r = -0.343$; $n = 51$; mean value = 20.5%) and $p < 0.15$ for K_2O ($r = -0.229$; $n = 51$; mean value = 2.7%) in the dark layers.

The sum of the geochemical components analysed by the electronic probe equates to 69.7% of the light layers and 71.3% of the dark layers. As the water has been removed, the 'missing' percentages comprise organic matter (OM) and voids filled with the unsaturated polyester. The average content of OM and voids in light layers is thus 30.3% and 28.7% in the dark layers. These are not significantly different.

Discussion

Hydrological information from sediments

Source of sediment load

The average concentration of Ti in both dark and light laminae is higher than that of suspended sediment from the Middle and Lower Reaches of the Yangtze River (0.93—1.32%) (Zhang et al., 1995). These data suggest that the Wanghu sediment was at least partly derived from the Fushui River, which flows through an area of metamorphic geology containing a high proportion of the titaniferous minerals rutile and ilmenite (Data source: Geological Survey of Hubei Province; 1:200,000 map) found to exist in the laminae.

Generally, higher discharge causes a greater concentration of heavy minerals as found in the dark layers. It will also elevate the total amount of bedload deposited into the lake resulting in thicker laminae. The thickness of the dark layers in Wanghu is positively correlated with Ti concentration, but negatively with the concentrations of K and Al and this suggests that the dark layers were mainly deposited from the Fushui River. Furthermore, the dark layers are similar in appearance to that of the sediment from the Fushui River, but this colouration cannot be accounted for by a higher organic content in the dark layers as the mean organic and void contents of light and dark layers are similar at 30.3% and 28.7%, respectively.

However, there is a negative correlation between the thickness of the light layers and the concentrations of Ti, and in particular, Ti concentration in the six thickest light layers is quite low (Fig. 5) indicating a depletion in heavy minerals. This can be explained if more of the sediment comprising these light layers is derived from the low Ti Yangtze River sediments rather than the higher Ti Fushui River. Deposition of large quantities of lighter coloured sediment from the Yangtze was possible, during flood periods, when the river drained back into Wanghu and it is suggested that this process was the source of these light layers with some minor input from the Fushui. This is supported by the fact that the light layers are brownish yellow, similar to that of the sediment from the Yangtze River. In summary, during the flooding season, 90—95% of the sediment load was derived from the Yangtse River and its tributaries as the river waters flowed back into Wanghu and formed the light layers in the sediment record. However, outside the flooding season, the main source of sediment was from the Fushui River bringing dark and Ti-rich minerals with it. During these periods, river flow was reversed and Wanghu drained into the Yangtze River.

Based on the Annals of Yangxin County, embankments and sluice gates were built to dredge the waterways in the lower reaches of the Fushui River, and along the Yangtze River near Yangxin, in the middle of the 19th century. Further, during the 1970s, the embankments of the Fushui catchment underwent large-scale renovation and several reservoirs were built in the upper reaches of the river. The watercourse of the Fushui River was changed to drain into the Yangtze River directly without direct connection to Wanghu. This new drainage system also lowered the lake water level and reduced flooding. As a consequence, the lake became shallower and wave action became stronger disturbing the bottom sediments. The combination of the loss of the main source of the dark sedimentary material and the greater physical perturbation of the record resulted in the loss of laminae formation.

The changes of relative water level

Based on several decades of record in the Annals of Water Conservancy of Hubei Province and our direct observation, the Yangtze water is known to flow backward into Wanghu in summer except during drought periods when the water levels in the Yangtze River are also low. There are three possible combinations of river level and lake level which allow for the deposition of a large amount suspended sediment into the lake.

(i) Both the Yangtze River and Wanghu levels are high, and the Yangtze river and its tributary the Fushui River are both in flood and Wanghu is full of water.
(ii) The Yangtze River level is high or moderate and Wanghu water level is low as may occur when there is a drought in the Fushui River catchment. In this instance, water from the Yangtze River may drain back into the lake.
(iii) The Yangtze River level is moderate and Wanghu water level is high, when the Fushui River is in flood.

The titanium concentrations in the light layers should therefore be low for case (ii), high for case (iii) and intermediate for case (i). Furthermore, the thickness of the laminae is closely related to the relative water levels of the river and the lake and the period of flooding. Lamina thickness can therefore be used to estimate the extent of flooding.

The thicknesses of the coupled laminae vary greatly, between <1 and 7.5 mm, suggesting that sediment accumulation was not consistent. Five coupled laminae are 6 mm thick or more suggesting these are flood-derived sediments. These are laminae 11, 14, 36, 39 and 44 (Fig. 5). Variation in the thickness of the light layers also implies changes in flood severity. Three light laminae (11, 36 and 39) are considerably thicker than the others, with thicknesses of 6.54, 5.86 and 6.09 mm and Ti concentrations of 1.76%, 1.14% and 1.38%, respectively. These Ti concentrations are lower than the average, suggesting that the sediment load deposited during these flood events was derived from the Yangtze River.

Hydrological information from documentary evidence

Based on the average accumulation rate of the recent sediments, the laminated section of the core is estimated to begin between 1700 and 1800 AD. In the Annals of Yangxin County and the Annals of Water Conservancy for Hubei Province, floods and droughts have been recorded since 1171 AD and divided into four classes: major flood, minor flood, major drought and minor drought. Here, ''major'' and ''minor'' mean that flood or drought occurred in more than 20 counties and 10—20 counties in Hubei Province, respectively. Based on these four grades, Qiao (1963) analyzed the floods and droughts from 1700 to 1949 and showed that the severity of flooding was related to the hydrological regime of the Middle Reaches of the Yangtze River. Flood frequency was observed to be relatively constant from 1600 to 1830 (2 per decade), but there were more floods between 1831 and 1849 (3.3 per decade). Between 1700 and 1800, there were 15 floods in 1705,1706,1708,1709, 1714, 1716, 1724, 1727, 1742, 1764, 1767, 1769, 1782, 1788 and 1822 in Hubei Province, including five major ones in 1727, 1742, 1767, 1769 and 1788. There were three floods simultaneously in both the Yangtse and Fushui Rivers in 1708, 1714 and 1727 and a flood in the Fushui River alone in 1743. There were four droughts in the Yangtze catchment in 1768, 1778, 1785 and 1802, including two major droughts in 1778 and 1802 and two simultaneous droughts, in 1778 and 1785, in Fushui River. There were two droughts in the Fushui River catchment alone in 1744 and 1786.

Possible correlation of hydrological information between sediments and documentary records

Based on the average sediment accumulation rate of 3.64 mm a^{-1} for the whole core and 2.5 mm a^{-1} for the lower part, the laminated section was estimated to have been deposited between 1700–1755 and 1764–1799 AD (Fig. 3B). The average annual sediment accumulation rate (2.5 mm a^{-1}) is thus smaller than the average thickness of the laminations (3.1 mm) implying that each lamination was formed over a period of longer than one year, which would seem illogical. The SCP profile suggests an average sediment accumulation rate of 3.1 mm a^{-1}. If this is correct it would imply on average, one lamina was formed every year and therefore extrapolation would date the laminated section to between c.1713 and c.1764 AD.

Between 1700 and 1800, the historical record of floods and droughts showed only one separate flood event for the Fushui River in Yangxin County and this occurred in 1743. However, this flood did not affect the whole Province suggesting that the Yangtze water level was not high. This would mean that the Yangtze would not drain back into the lake and that the sediment load in Wanghu would have come mainly from the Fushui River. Therefore, the dark lamination for 1743 should be thicker, with a Ti concentration much higher than the mean value of 1.7–2.2%. If a Ti concentration of 2.5% is chosen as a threshold, then the 1743 lamination might be any one of laminae 2, 15, 37, 40, 43, 46 or 48. Since it was a flood event, the sediment deposit should also be greater than the average thickness of the coupled laminae (3.1 mm), and only laminations 37, 46 and 48 also fit this criterion with thicknesses of 5.07, 4.58 and 4.74 mm, respectively. Furthermore, it is known that in the previous year there was a major province-wide flood, and no flooding in the Fushui River, and this should have resulted in a thick, light layer with only moderate Ti concentration. Only laminae 36 and 37, fulfill all these sequential criteria and the years 1733 and 1734 can therefore be allocated to these layers. In a similar way, a flood recorded for both Yangxin and the whole of Hubei Province in 1708 can be allocated to lamina 4. These recorded events therefore help to secure the dating extrapolated from radiometric and SCP chronologies and imply that the laminated section of the core was deposited between 1705 and 1758 (see dates in Fig. 5).

Three light laminations are considerably thicker than the others, suggesting that three big floods affected Wanghu. These laminae date to 1714, 1742 and 1745. The former two are consistent with documentary records of floods in 1714 and 1742 whilst the latter does not appear in historical records. However, apart from flood events, the Yangtze water level could also be high relative to that of Wanghu due to a decreased lake water level resulting from a local dry climate. 1744 was a drought year in Yangxin County and no drought or flood was recorded in this year for either the Middle or Upper Reaches of the Yangtze (Qiao, 1963; Water Conservancy of Hubei Province, 1987; Cai, 1999; Xin and Wen, 1997; Qiao and Chen, 1999; Yi, 2003). The dark layer in the coupled laminae 39 is one of the thinnest dark laminae and its Ti concentration is low, indicating a small discharge to the lake (Fig. 5). Therefore, an explanation for the thick light layer in 1744 may be that a local drought caused lake level to drop resulting in an inflowing of the Yangtze River despite the lack of flooding at this time.

Conclusions

Laminations in the sediment record of Wanghu were formed by changes to the drainage of the Yangtze River and its tributary, the Fushui River, into the lake. Geochemistry and thickness of the laminations in the sediments deposited in a period from the early to the mid-18th century show that the light layers in the sediment came mainly from the Yangtze River, draining back into the lake during floods, whilst dark layers were formed as a result of a greater influence by the discharge from the Fushui River. The sediment provides an archive of the source of sediment load and the relative water levels of the Yangtze and Wanghu including both floods of the main Yangtze River and the local hydrological regime. Flood records in the sediment were found to be synchronous with events in historical documentary records.

Acknowledgements

The project was supported by the Key Project of the Chinese Academy of Sciences ''Studies on the mechanisms and control of lake eutrophication in the Middle and Lower Reaches of the Yangtze River'' (KZCX1-SW-12); the National Science Foundation of China (Grant No. 49971081); The Royal Society of London (Joint Project Q607/KB); and the 100 Talents project of the CAS, 2005. We are grateful to Professor Qi Lu at State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences for his suggestions and preparing sediment slices, to Mr. Xianxing Wu for field work, and to Dr. Xu Yu for ^{210}Pb dating in the National Key Laboratory for Estuary and Coastal Sediment Dynamics and Morphodynamics, East China Normal University.

References

Alexander, J., Fielding, C.R., Jenkins, G., 1999. Plant-material deposition in the tropical Burdekin River, Australia: implications for ancient fluvial sediments. Palaeogeogr. Palaeoclimat. Palaeoecol. 153, 105–125.

Annals of Water Conservancy of Hubei Province. 1987.

Annals of Yangxin County, 1993. New China Press, Wuhan.

Appleby, P.G., Oldfield, F., 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5, 1–8.

Appleby, P.G., Nolan, P.J., Gifford, M.J., Oldfield, F., Anderson, N.J., Batterbee, R.W., 1986. Lead-210 dating by low background gamma counting. Hydrobiolgia 141, 21–27.

Boyle, J.F., Rose, N.L., Bennion, H., Yang, H., Appleby, P.G., 1999. Environmental impacts in the Jianghan Plain: evidence from lake sediments. Water Air Soil Pollut. 112, 21–40.

Brown, S.L, Bierman, P.R., Lini, A.K., Southon, J., 2000. 10 000 yr record of extreme hydrologic events. Geology 28 (4), 335–338.

Cai, D.Z., 1999. A textural research in to the carved steles of floodwater through the ages in Jianling River basin. J. Sichuan Teachers College (natural Science edition) 20 (2), 160–167.

Eriksson, M., Holm, E., Roos, P., Dahlgaard, H., 2004. Distribution and flux of ^{238}Pu, ^{239}, ^{240}Pu, ^{241}Am, ^{137}Cs and ^{210}Pb to high arctic lakes in the Thule district (Greenland). J. Environ. Radioactiv. 75, 285–299.

Evans, J.K., Gottgens, J.F., Gill, W.M., Mackey, S.D., 2000. Sediment yields controlled by intrabasinal storage and sediment conveyance over the interval 1842-1994: Chagrin River, northeast Ohio, USA. J. Soil Water Conserv. 55, 264—270.

Fitzpatrick, F.A., Garrison, P.J., Fitzgerald, S.A., Elder, J.F., 2003. Nutrient, Trace Element, and Ecological History of Musky Bay, Lac Courte Oreilles, Wisconsin, as Inferred from Sediment Cores. US Geological Survey Water-Resources Investigations Report 02-4225.

Gajewski, K., Hamilton, P.B., McNeely, R., 1997. A high resolution proxy-climate record from an arctic lake with annually-laminated sediments on Devon Island, Nunavut, Canada. J. Paleolimnol. 17, 215—225.

Gey, V., Saarnisto, M., Lunkka, J.P., Demidov, I., 2001. Mikuhno and Valdai palaeoenvironments in the Vologda area, NW Russia. Global Planet. Change 31 (1—4), 347—366.

Goff, J.R., Dunbar, G.B., Barrett, P.J., 1998. Monthly to decadal sediment accumulation rates in a semi-enclosed embayment. J. Coastal Res. 14 (2), 461—471.

Gomez, B., Eden, D.N., Peacock, D.H., Pinkney, E.J., 1998. Floodplain construction by recent, rapid vertical accretion: Waipaoa River, New Zealand. Earth Surf. Proc. Landforms 23 (5), 405—413.

Hardy, D.R., Bradley, R., Zolitschka, B., 1995. The climatic signal in varved sediments from Lake C2, northern Ellesmere Island, Canada. J. Paleolimnol. 16, 227—238.

Heinrich, K.F.J. (Ed.), 1981. Electron Beam X-Ray Microanalysis. Van Nostrand Reinhold, New York, p. 361.

Kos, A.M., 2001. Stratigraphy, sedimentary development and palaeoenvironmental context of a naturally accumulated pitfall cave deposit from southeastern Australia. Austr. J. Earth Sci. 48 (5), 621—632.

Lamoureux, S., 2000. Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves. Water Resour. Res. 36, 309—318.

Mulder, T., Migeon, S., Savoye, B., Jouanneau, J.M., 2001. Twentieth century floods recorded in the deep Mediterranean sediments. Geology 29, 1011—1014.

Nesje, A., Dahl, S., Matthews, J.A., Berrisford, M.S., 2001. A 4500 yr record of river floods obtained from a sediment core in Lake Atnsjöen, eastern Norway. J. Paleolimnol. 25, 329—342.

Pederson, J.L., 2000. Holocene paleolakes of Lake Canyon, Colorado Plateau: paleoclimate and landscape response from sedimentology and allostratigraphy. Geol. Soc. Am. Bull. 112, 147—158.

Qiao, S.X., 1963. The problem of historical floods and droughts in Hubei Province and their relation with the perennial solar activities. Acta Geogr. Sin. 29, 14—23.

Qiao, S.X., Chen, Z.H., 1999. Records of historical floods in Chuangjiang river (upper stream of the Yangtze River) through the carved steles. Hubei Weather (1), 4—7.

Rose, N.L., 1994. A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. J. Paleolimnol. 11, 201—204.

Rose, N.L., 2001. Fly-ash particles. In: Tracking Environmental Change Using Lake Sediments. In: Last, W.M., Smol, J.P. (Eds.), Physical and Chemical Techniques, vol. 2. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 319—349.

Rose, N.L., Harlock, S., Appleby, P.G., Battarbee, R.W., 1995. The dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle concentration profiles. Holocene 5, 328—335.

Royall, D., 2000. Lake-sediment based evaluation of recent sediment yield from a small Appalachian watershed, Thompson Lake, Virginia. Phys. Geogr. 21, 68—88.

Sturm, M., Matter, A., 1972. The electro-osmotic guillotine, a new device for core cutting. J. Sed. Petrol. 42, 987—989.

Xin, Z.L., Wen, Q.X., 1997. Investigation and textural research of historical floods in Xiluodu waterpower station in the Jinshajiang river (upper stream of the Yangtze). Waterpower (11), 14—16.

Yang, D.Y., Yu, G., Xie, Y.B., Zhan, D.J., Li, Z.J., 2000. Sedimentary records of large Holocene floods from the middle reaches of the Yellow River, China. Geomorphology 33, 73—88.

Yi, Z.W., 2003. Fuling Stone Fish (a kind of carved steles) in the Three Gorges – ancient water station of the Yangtze River. Quart. J. Yangtze River Annals (74—75), 1291—1296.

Yi, C.L., Appleby, P.G., Boyle, J.F., Rose, N.L., Dai, X., Xie, P., 2004. The sedimentary record of a significant flooding event in Lake Taihu on the Yangtze delta, China. J. Coastal Res. 43, 89—100 (Special issue).

Yin, C-M., Qiu, W-L., Li, R-Q., 2001. Holocene paleofloods in the north China plain. J. Beijing Normal Univ. (Natural Science) 37, 280—284 (in Chinese with English abstract).

Zhang, C.S, Wang, L.J., Zhang, S., 1995. Metal speciation in sediments and suspended matter in the middle-lower reaches of the Chanjiang River. China Environ. Sci., 342—347.

Zhu, C., Yu, S.Y., Shi, W., 1997. Holocene deposits and paleo-floods on the north bank of the Yangtze River. Geog. Res. 16, 23—30 (in Chinese with English abstract).