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Carbon isotopes and lignin phenols for tracing the floods during the past 70 years in the middle reach of the Changjiang River

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Abstract
The Lake Tian E Zhou (TEZ, an oxbow lake) was formed during the rerouting of the Changjiang River in 1972, with strong influences from the main river channel and flood events. Herein, a sediment core was collected from the Lake TEZ for the measurements of carbon isotopes and biomarkers, including stable carbon isotopes ($\delta^{13}C$), radiocarbon composition ($\Delta^{14}C$), and lignin phenols, as well as lead-210 to reconstruct recent heavy flood events over the past 70 years. At the 24–26 cm interval, the sediment contained the highest OC%, TN%, and lignin phenols content, as well as significantly depleted ^{13}C but enriched ^{14}C, corresponding to the extreme flood event in 1998. In addition, statistics from *t*-test showed that lignin phenols normalized to OC ($\Lambda 8$), the concentration of 3, 5-dihydroxy benzoic acid (3, 5-BD), and the ratio of p-hydroxy benzophenone to total hydroxyl phenols (PHB/HP) were all significantly different between the layers containing flood deposits and the layers deposited under normal non-flood conditions ($p<0.05$). These results indicate that the later three parameters are highly related to flood events and can be used as compelling proxies, along with sediment chronology, for hydrological changes and storm/flood events in the river basin and coastal marine environments.

Key words: flood record, carbon isotopes, lignin phenols, Changjiang River, Lake Tian E Zhou

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1 Introduction

Organic carbon (OC) preserved in sediments is a net sink for CO_2 and is important in controlling the level of atmospheric CO_2 and, as such, is a key component in the global carbon cycle (Falkowski et al., 2000; Hedges et al., 1997). Rivers transported approximately one third of OC buried in the sea, which is of terrigenous origin, rather than via other pathways such as aeolian transit (Dalzell et al., 2005). Thus, rivers play a critical role in the regional carbon cycling. During fluvial discharge, extreme climatic events such as floods have a significant influence on the flux and composition of OC. Floods strongly influence the transport of OC by river systems (Dalzell et al., 2005; Yu et al., 2011; Wu et al., 2007). For example, extraordinary flood in the Changjiang River during July and August in 1998 resulted in a three and half fold increase over normal levels in the fluxes of particulate organic carbon to the East China Sea (Yu et al., 2011; Wu et al., 2007). Due to the importance of floods in the transportation of OC, it is essential to reconstruct historical floods through the analysis of sediment cores from river drainage basins (Bianchi et al., 2013; Dhillon and Inamdar, 2013; Korponai et al., 2016; van Metre and Horowitz, 2013; Wang et al., 2014).

The Changjiang River is one of the world's largest rivers, with a drainage area of 1.8×10^6 km^2 and a water discharge of 960 km^3/a (Chen et al., 2008). During 2003 and 2004, it carried about 2.83×10^9 kg of particulate OC to the East China Sea, of which 76% was transported during the flood season (Lin et al., 2007), which may also result in non-steady state deposition in coastal environments. However, the relationship between flood events and sediment composition and/or depositional history is poorly understood in the Changjiang Basin and coastal environment in the East China Sea. Previous studies have used geochemical and bulk parameters from core sediments to reconstruct flood events in the Changjiang Basin. Wang et al. (2011) analyzed multiple elements in a core from the subaqueous delta of the Changjiang River Estuary, and reconstructed the 600-a flood history of the basin between 1350 and 1950. Zhan et al. (2010) analyzed grain size and bulk OC profiles in a core sampled from a central bar, and concluded that human activities in the previous 50 years had disturbed flood deposit layers. However, few studies have used lignin phenols as tools for flood reconstruction in the Changjiang drainage basin.

The Lake Tian E Zhou (TEZ) is in the middle of the Changjiang River, with a catchment area of 68.7 km^2 and with mean water coverage of 18.97 km^2. It was formed in 1972 when the Chang-

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jiang Channel was rerouted and straightened. Historically, its lower section was always connected to the river. However, the flow was disconnected after the extreme flood event in 1998. After the 1998 flood, the local government built a dam to control the water level of the lake (Fig. 1). Prior to 1998, during floods the river transported massive amounts of sediment and organic carbon (OC) to the oxbow lake. Hence, sediment and OC burial in the lake might preserve signals from flood events.

Fig. 1. Location of the TEZ core (29.78°N, 112.56°E) from the oxbow lake in Hubei Province, China (a) and the sedimentary phase of the core (b).

While some studies have been successful in reconstructing flood events from cores, using parameters such as bulk organic matter (OM) content and grain size composition (Wang et al., 2011; Zhan et al., 2010), few studies have used biomarkers in reconstructing these events (Bianchi et al., 2015). Lignin phenols are useful biomarkers for tracing terrigenous OC from river to ocean (Hedges et al., 1997). A series of proxies based on lignin phenols could provide detailed information on the content, source and degradations state of terrestrial OC. During floods, loading of lignin is usually much higher under normal hydrodynamic conditions, due to strong water scouring, and the lignin is fresher (Dhillon and Inamdar, 2013). While the distinction of lignin phenols between different hydrological conditions is valuable for tracing OM transportation by floods, its application is limited in coastal oceanic environments due to the unstable depositional environment and low sedimentation rate. The characteristics of lignin phenols have the potential to provide accurate flood records in core sediments from stable depositional environments within a river basin, which are not subjected to any bias from long distance transport and resuspension or reworking in the dynamic coastal zone.

In this study, a sediment core was collected from the lake in April 2007 (Fig. 1). Grain size, stable isotopic and radio organic carbon (δ^{13}C and Δ^{14}C), OC%, TN% and lignin phenols at different depths in the core were analyzed along with excess lead-210. The main goal was to investigate the sedimentology and geochemical profiles, in order to determine if these parameters could be used as an approach to trace historic floods in the Changjiang Basin.

2 Materials and methods

2.1 *Sample collection*

The core (a total length of 70 cm) was collected from the lake in Hubei Province, during April 2007 (29.78°N, 112.56°E; Fig. 1). The sampling location was on the shore, 2 m from the water's edge, in an area that is submerged during the wet season. The core was collected using a plastic pipe (diameter 10 cm) and was kept in a cold ice chest during transport to the laboratory, where it was cut into sections (1 cm intervals) which were then dried in an oven at 50°C.

2.2 *Chronology*

Excess ^{210}Pb was measured using an HPGe gamma-ray detector (Canberra Be3830). Dried samples were sealed in plastic boxes (Φ35 mm×35 mm) for three weeks to establish a secular equilibrium between ^{226}Ra and its daughter products, ^{214}Pb and ^{214}Bi. The activity of total ^{210}Pb was directly determined at 46.3 keV (refs). The ^{226}Ra activity was determined at 295.2 keV, and ^{214}Pb at 351.9 keV, and ^{214}Bi at 609.3 keV (46.1%) and 1 120.3 keV (15%). Excess ^{210}Pb activity was estimated by subtracting the ^{226}Ra activity from the total ^{210}Pb activity. Detector efficiencies and sample geometry were calibrated using efficiency curves obtained from LabSOCS (Bronson, 2003).

2.3 *Grain size analysis*

Sediment grain size was determined with a laser particle size analyzer (Coulter-LS100Q, Berkman Coulter Corporation, USA) that was used to divide each sample into 93 size fractions between 0.2 μm and 2×10^3 μm. The chemical pretreatment procedure followed Luo et al. (2012), and mean grain diameter, along with the relative proportions of clay, silt and sand are reported here. The clay, silt and sand particles are defined here as <4, 4–63 and >63 μm, respectively (Trefethen, 1950).

2.4 *Bulk chemical analysis (OC%, TN%, $\delta^{13}C$ and $\Delta^{14}C$)*

The samples were acidified with 1 mol/L HCl to remove inorganic carbon prior to measurements of OC and $\delta^{13}C$. TN was measured directly in samples that had not been treated with acid. OC and TN were measured with an elemental analyzer (CHNOS Vario EL III) and $\delta^{13}C$ values using isotope ratio mass spectrometry (IRMS; Delta Plus XP, Thermo Finnigan). The relative standard deviation (RSD) for OC and TN values was <3%. $\delta^{13}C$ values were calculated:

$$\delta^{13}\mathrm{C} = \left(\frac{R_{\mathrm{sample}}}{R_{\mathrm{standard}}} - 1\right) \times 1\ 000, \tag{1}$$

where R is the molar ratio of ^{13}C and ^{12}C. Vienna Peedee Belemnite (V-PDB) was used as the standard. The precision was less than 0.1‰.

Radiocarbon ($\Delta^{14}C$) analysis was performed at the National Ocean Sciences Accelerator Mass Spectrometry (AMS) facility at Woods Hole Oceanographic Institution. The sediment, after removal of inorganic carbon, was combusted to CO_2, which was converted to graphite via Fe/H_2 catalytic reduction. The graphite was analyzed to obtain the radiocarbon composition from AMS. Radiocarbon values were expressed as $\Delta^{14}C$ in ‰, which was calculated:

$$\delta^{14}\mathrm{C} = \left(\frac{R_{\mathrm{sample}}}{R_{\mathrm{standard}}} - 1\right) \times 1\ 000, \tag{2}$$

where R is the molar ratio of ^{14}C and ^{12}C.

$$\Delta^{14}\mathrm{C} = \delta^{14}\mathrm{C} - 2(\delta^{13}\mathrm{C} + 25) \times \left(1 + \frac{\delta^{14}\mathrm{C}}{1\ 000}\right). \tag{3}$$

The general paradigm is that a more depleted value of $\Delta^{14}C$ means the older the organic carbon.

2.5 *Lignin phenols analysis*

Lignin phenols were analyzed following the alkaline CuO oxidation method (Hedges and Mann, 1979a, b). Dried and ground sediment was placed into a PTFE mini-bomb and digested with CuO and $Fe(NH_4)_2(SO_4)_2$ in 2 mol/L NaOH in the absence of O_2 at 160°C for 3 h. After cooling to room temperature, ethyl vanillin was added as a recovery standard, followed by 37% HCl to adjust the pH to <2. The reaction products were extracted with ethyl acetate (EtOAc), dried and converted to trimethylsilyl derivatives using 99% Bis(trimethylsilyl)trifluoroacetamide (BSTFA)+1% Trimethylchlorosilane (TMCS). Lignin phenols were then analyzed using gas chromatography (GC; Agilent 6890 series) equipped with a DB-1 column (i.d. 30 m×0.25 mm; film thickness 0.25 μm) and a flame ionization detector. The oven temperature was set at 100°C, then increased to 270°C (held 12.5 min) at 4°C/min. Σ8 and Λ8 are reported as the sum of eight phenolic products normalized to 10 g dry weight (dw) sediment and 100 mg OC, respectively. The 3, 5-BD (3, 5-dihydroxybenzoic acid, an additional CuO oxidation product that can be used as an indicator of soil degradation, was determined and normalized to OC (Farella et al., 2001; Hedges and Mann, 1979a, b). The PON/P ratio was used to trace the contribution of vascular plants because p-hydroxy acetophenone (PON) is derived mainly from plants, while the remaining two p-hydroxy phenol phenols (PAL+PAD) are typically derived from proteins and saccharides. The ratios of cinnamyl and syringyl phenols to the vanillyl phenols (C/V and S/V) were used to trace the different sources of lignin phenols. The lignin phenol vegetation index (LPVI) was calculated as follows:

$$\mathrm{LPVI} = \left[\frac{S(S+1)}{V+1} + 1\right] \times \left[\frac{C(C+1)}{V+1} + 1\right], \tag{4}$$

where V, S and C were expressed in % of the Λ8. The data were used in further identifying the source of lignin phenols (Tareq et al., 2004). The acidic to aldehyde group of vanillyl phenols [(Ad/Al)v] was employed as an indicator of lignin degradation.

2.6 *Statistical analysis*

Pearson analysis was used to test the correlation between different parameters. An independent t-test was conducted to compare the mean values of parameters for flood layers and normal layers, and Levene's test was used to examine the homogeneity of variance. All the analyses were performed using SPSS 20.0 for Windows (SPSS IBM, USA).

3 Results

3.1 *Sedimentation rate*

The sedimentation rate for the core was determined using ^{210}Pb geochronology. As shown in Fig. 2, the excess ^{210}Pb declined with depth, the rate of decline varying between the 0–24 cm and 26–70 cm sections of the core. The variation between the two sections would usually be ascribed to hydrodynamic variations and/or human interference. We divided the core into two parts and calculated the sedimentation rate using the constant activity model (CA) in each part. The rate was 2.83 cm/a in the upper 0–24 cm section and 0.74 cm/a in the 26–76 cm section. Based on these rates, the core represents sediment deposit in the lake between 1942 and 2007. The variation in sediment rate between 0–24 cm and 26–76 cm might be caused by the dam building in the lower section. Before the dam building, in the wet season, the Changjiang River carried sediments to the sampling station, and these sediments represented the signals of the hydrologic regime of the river. However, the sediment core of 0–24 cm was deposit massively after the dam building, which recorded the regional environmental change.

3.2 *Core description and grain size*

The core consisted of yellow, yellow grey, and grey sediments (Fig. 1). The 0–40 cm and 55–68 cm sections were mainly yellow and yellow grey, but in the other sections the sediment was predominantly grey. The 24–26 cm section contained some plant tissues, which might indicate that strong hydrodynamic conditions prevailed during that time period. As shown in Fig. 3, the mean grain size varied with depth. Between the 0 and 24 cm, sediment grain size was mostly in the 4.3 to 5.0 μm and that increased to the 5.7–7.4 μm size range in the depth of 40 cm. Sediment grain size continued to increase with depth between 40 and 55 cm, and then steadily decreased until the depth of 68–70 cm, where sediment abruptly changed to sand-sized grains. The proportions of clay, silt and sand also varied sharply with depth along the core

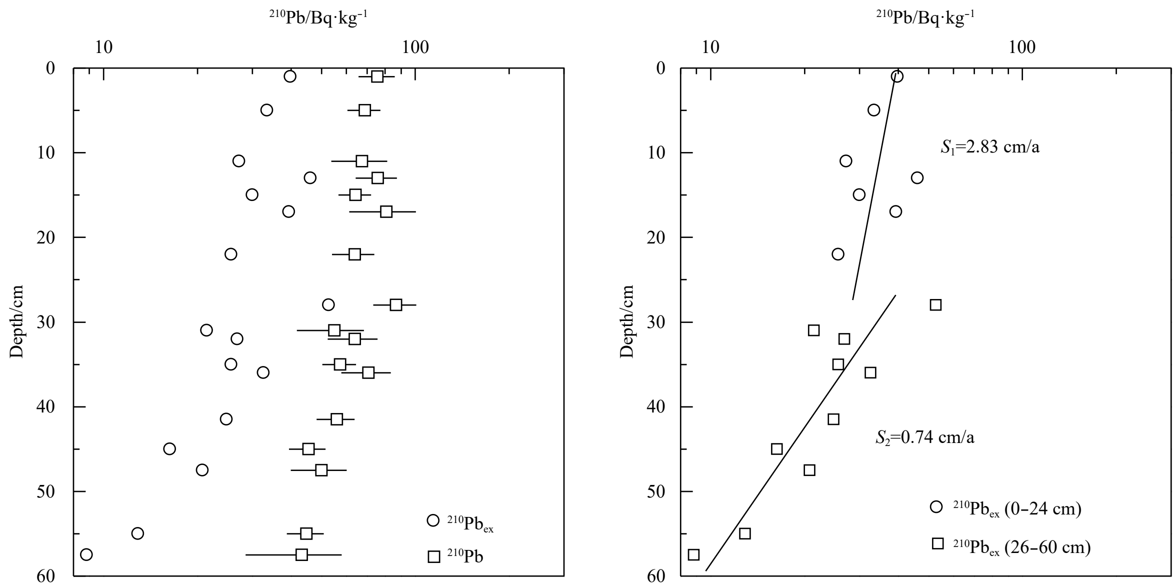

Fig. 2. ^{210}Pb profiles along the TEZ core.

(Fig. 3). The proportions in clay and silt were inversely correlated in all layers, except the 68–70 cm layer, where a negative correlation was observed between them (r^2=0.85, p<0.001). Sand was absent between the 0–26 cm, but was present at a nearly constant percentage in the 26–68 cm section; the maximum proportion of sand was at a depth of 68–70 cm. The absence of sand between 0 and 26 cm indicated that the construction of the dam had changed the hydrological conditions and sediment sources in the lake (Fig. 1).

3.3 *Bulk properties (OC, TN, δ^{13}C and Δ^{14}C)*

The OC% value varied from 0.22% to 3.13% with an average of 0.85% (Fig. 4). The 68–70 cm layer had the lowest value, while the highest was measured at 24–26 cm. The average value of TN% was 0.09%, with a range of 0.02%–0.33%. As with the OC profile, the lowest and highest TN% values were observed at 68–70 cm and 24–26 cm, respectively. The C/N ratio was calculated as the ratio of organic carbon to total nitrogen by mole. In the core, C/N varied from 9.6 to 17.2 (average 11.3). The variations in OC and TN along the core had a similar trend, and there was a positive correlation between them (r^2=0.95, p<0.001, Fig. 5). δ^{13}C ranged from –29.4‰ to –23.0‰, with the lowest value at the 24–26 cm, indicating different OC sources with depth. Three samples were selected (0–1 cm, 24–26 cm and 68–69 cm) for measuring Δ^{14}C and results are shown in Fig. 4. The youngest OC appeared at the 24–26 cm, with a Δ^{14}C value of –7.4‰. The surface layer (0–1 cm) and the bottom layer (68–69 cm) both had more depleted Δ^{14}C values than the middle layer between 24–26 cm (Fig. 4).

3.4 *Lignin phenols*

The lignin phenols (Σ8 and Λ8) varied analogously with OC% and TN% throughout the core (Fig. 6). As expected, the 24–26 cm layer contained the highest concentration of lignin phenols and the 68–70 cm layer the lowest. The 3, 5-BD is produced from plants by bacteria in soil and can be used as an indicator of soil OC input (Dittmar et al., 2001). In the core, the trend of 3, 5-BD was comparable to the trends of OC% and lignin content. The 24–26 cm layer had the highest concentration of 3, 5-BD, indicating a significant amount of soil-derived OC. PON/P was employed to distinguish the signals of OC from fresh plants (Dittmar et al., 2001). There were several extremely high values of PON/P (Fig. 6). The highest values of C/V, S/V and LPVI were observed in the 24–26 cm layer, and the lowest appeared between 68–70 cm; there were no significant changes in the remainder of the core. The variation in (Ad/Al)v with depth showed an opposite compared to those for Σ8 and Λ8. The highest (Ad/Al)v value was observed at the 68–70 cm depth, which also has the lowest lignin content. The lowest (Ad/Al)v value was at 24–26 cm, which has the highest concentration of lignin phenols.

4 Discussion

4.1 *Record of 1998 flood in the core*

All available parameters measured from the TEZ sediment core (Fig. 1) pointed to a typical flood deposit in the 24–26 cm layer, which corresponded to the 1998 flood. The organic geochemistry data also support this inference. During field sampling, a large amount of plant tissue was observed in the 24–26 cm layer and, despite removing the tissue prior to chemical analysis, OC%, TN%, δ^{13}C and lignin phenols were all significantly different in the 24–26 cm layer vs. other layers (Figs 4 and 6). OC and TN values in the 24–26 cm layer were three times higher than the average values for the rest of the core. High values of OC% and TN% in flood layers have also been reported for a core collected from a newly-emerged bar in the lower Changjiang River in 2010 (Zhan et al., 2010). The δ^{13}C value at 24–26 cm layer was as low as –29.4‰, which is significantly more depleted than the values measured for other layers (t-test, p<0.05). Most of the plants around the Changjiang River use the Calvin cycle (C3) to absorb CO_2 and have depleted δ^{13}C values (–26‰ to –32‰, Still et al., 2003; Wu et al., 2007). Although soil carbon is derived from fresh plants, its δ^{13}C value is more positive than that of plants due to biodegradation. In the Changjiang Basin, the δ^{13}C of soil organic carbon varies from –20‰ to –24‰ (Yu et al., 2011). The δ^{13}C value for the 24–26 cm layer is within the range for fresh plants, but lower than the range reported for soils. Thus, the depleted δ^{13}C values in the 24–26 cm layer indicates that fresh plant tissue contributes significantly to the OC in this layer. This is in accord

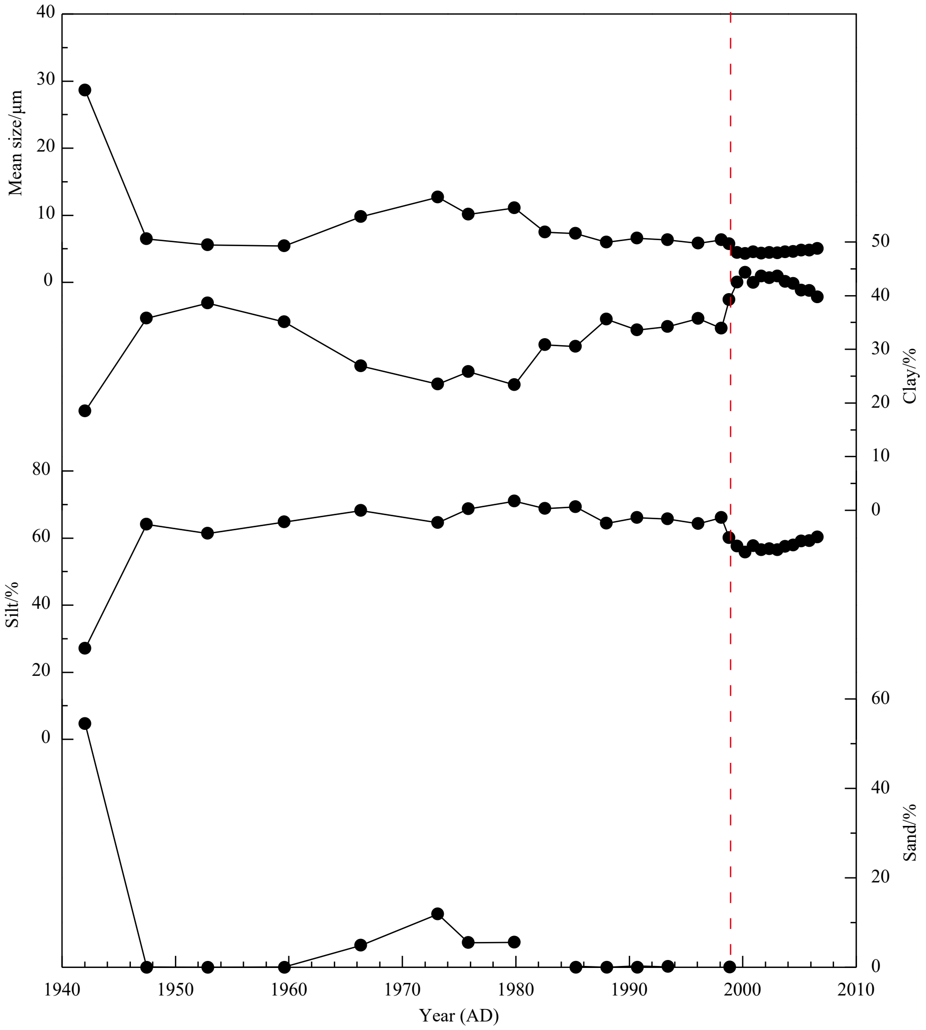

Fig. 3. Grain size distribution in the TEZ core. Red dashed line refers to the time of dam building in the lower estuary of the TEZ oxbow lake.

with observations that flood deposits typically contain OC from fresh plant tissue (Zhan et al., 2010). The $\Delta^{14}C$ value can be used as an indicator of the age of OC. A more depleted $\Delta^{14}C$ means the older the OC. Different source OCs contain different $\Delta^{14}C$, such that the $\Delta^{14}C$ of fresh plant tissues is greater than 0, but the value of fossil OC is less than –1 000 (Hedges et al., 1997). For the three sediment layers of the core, the $\Delta^{14}C$-OC in the 24–26 cm was most enriched (Fig. 4), and the converted OC age of this layer was about 5 a BP. The distinction in bulk properties between 24–26 cm and other layers implies that this layer contains much fresh, supported by higher $\Delta^{14}C$ and lower $\delta^{13}C$ values, and a high content of OC, which might be transported by the extreme heavy flood in 1998. The difference in bulk properties between the 24–26 cm layer and other layers implies that this layer contains a large amount of fresh OC that might have been transported by the extreme flood in 1998.

The content and composition of lignin phenols are also distinct in the 24–26 cm section. As shown in Fig. 6, the $\Sigma 8$ and $\Lambda 8$ are eight times and one time higher in this layer than in other layers, respectively; they are also higher than the values of surrounding soils in the Changjiang Basin (Yu et al., 2011). According to the *t*-test, both $\Sigma 8$ and $\Lambda 8$ in the 24–26 cm layer are significantly different from other layers (both $p<0.05$). C/V and S/V in the 24–26 cm layer are 1.51 and 0.28, respectively, significantly higher than the average values for other layers (*t*-test: both $p<0.05$; Fig. 6). The ranges of C/V and S/V values in the 24–26 cm layer indicate an elevated contribution from non-woody angiosperms. The results suggest that C/V and S/V were strongly influenced by biodegradation processes in soil. Degradation by fungi in soil would decrease the contents of C, S and V group phenols, with the degradation preference C>S>V. This difference in degradation rate results in a decrease in C/V and S/V. In the core, the distinct C/V and S/V values in the 24–26 cm layer also indicate that a relatively large amount of fresh plant tissue is present in this layer. Similar to C/V and S/V, the LPVI value in the 24–26 cm layer is much higher than that in other layers (Fig. 6). The acid to aldehyde ratio of the V group of phenols [(Ad/Al)v] is an index reflecting the degree of degradation of lignin. In the 24–26 cm layer, the (Ad/Al)v value is 0.20, which falls within the range of fresh plant tissue and is significantly lower than the mean value for the other layers (0.47±0.11, Yu et al., 2011). Low (Ad/Al)v value indicates that the flood carried a large quantity of fresh plant tissues to the location of the TEZ core. The 3, 5-BD is another CuO oxidation product that originates from soil OC. The concentration of the 3, 5-BD in the 24–26 cm layer is higher than that in the other layers, indicating that this layer contains abundant soil-derived

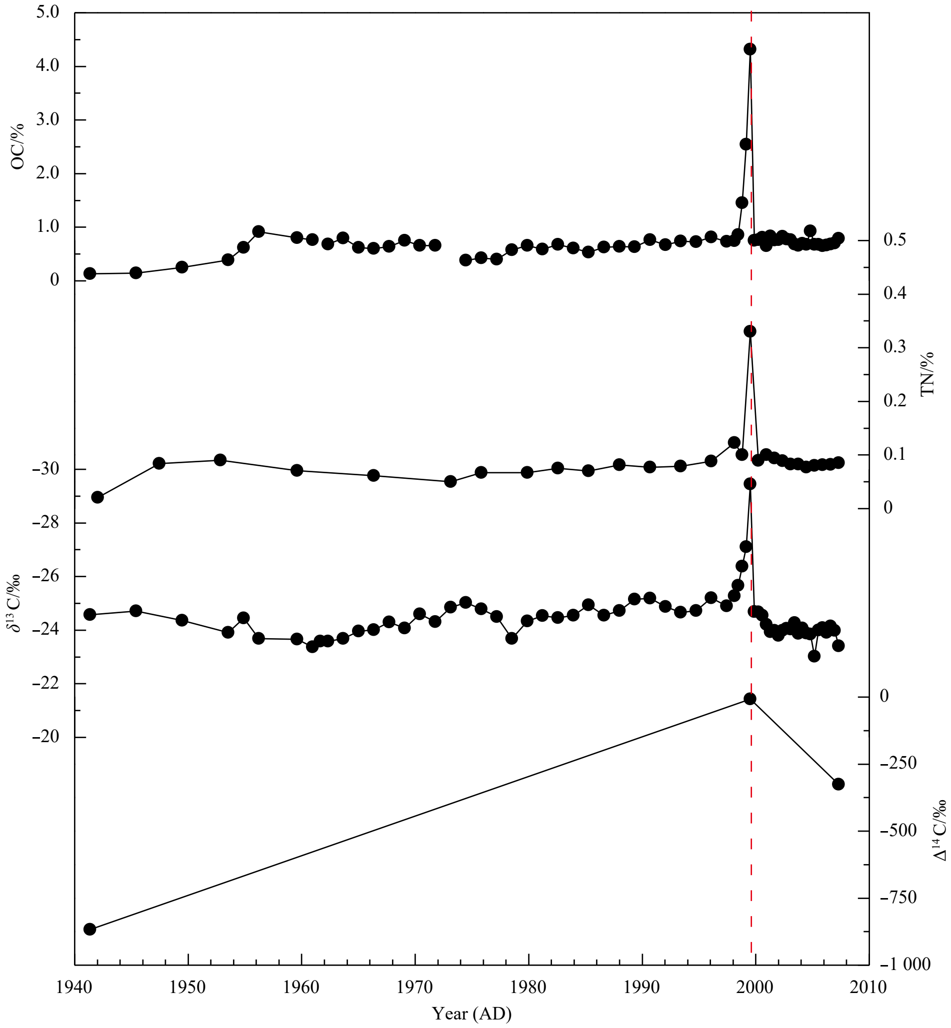

Fig. 4. Bulk properties along the TEZ core. Red dashed line refers to the flood deposit of 1998.

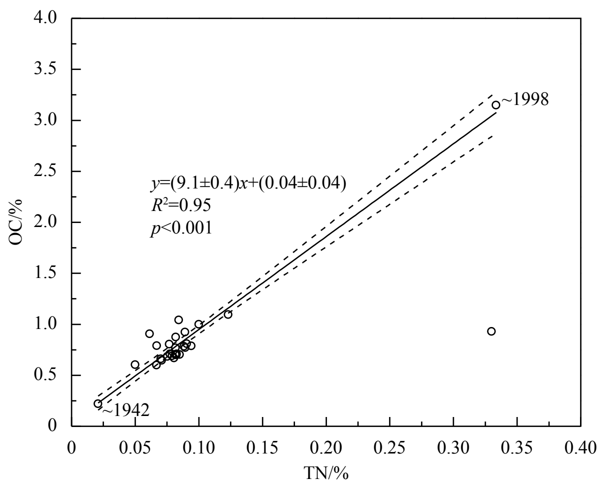

Fig. 5. Correlation between OC and TN. Unbroken and dashed lines refer to linear regression and 95% confidence band.

OC. PON is the ketone group of P phenols, which originate from the degradation of lignin. PAL and PAD are the other two phenols of the P group and are usually derived from protein. The PON/P ratio is defined as the percentage of PON relative to the total P phenols. A high PON/P value implies a high contribution of plant-derived OC (Dittmar et al., 2001). In the 24–26 cm layer, PON/P is higher than that in other layers, and several layers below the 24–26 cm also show high values (Fig. 6). The high value of PON/P in the 24–26 cm layer suggests that the 1998 flood transported a large amount of plant-derived OC to the TEZ oxbow lake. In the 24–26 cm layer, all the organic geochemistry indices are significantly different from those in other layers. This clearly indicates that this layer contained materials mostly from flood deposit. With reference to the sediment chronology and flood record in the Changjiang Basin (Shi et al., 2004), it can be inferred that this layer was deposited during the flood of 1998.

Due to the construction of a dam in the lower estuary of the oxbow lake (Fig. 1), the sediment profiles of TEZ did not prominently show flood events since 1998. The flood events in the Changjiang Basin, according the Shi et al. (2004), are listed in Table 1, while Fig. 6 (red dashed lines) shows the sections of the TEZ core in which the geochemical parameters are significantly different from adjacent layers. Based on sediment chronology derived from ^{210}Pb depth profiles, the layers shown in Fig. 6 are related to the flood events of 1949, 1954, 1969, 1980–1983, 1991 and 1998, respectively. The 2–3 year differences between some individual flood events and historical documents may be the results of analytical errors from the ^{210}Pb dating or unstable hydrological con-

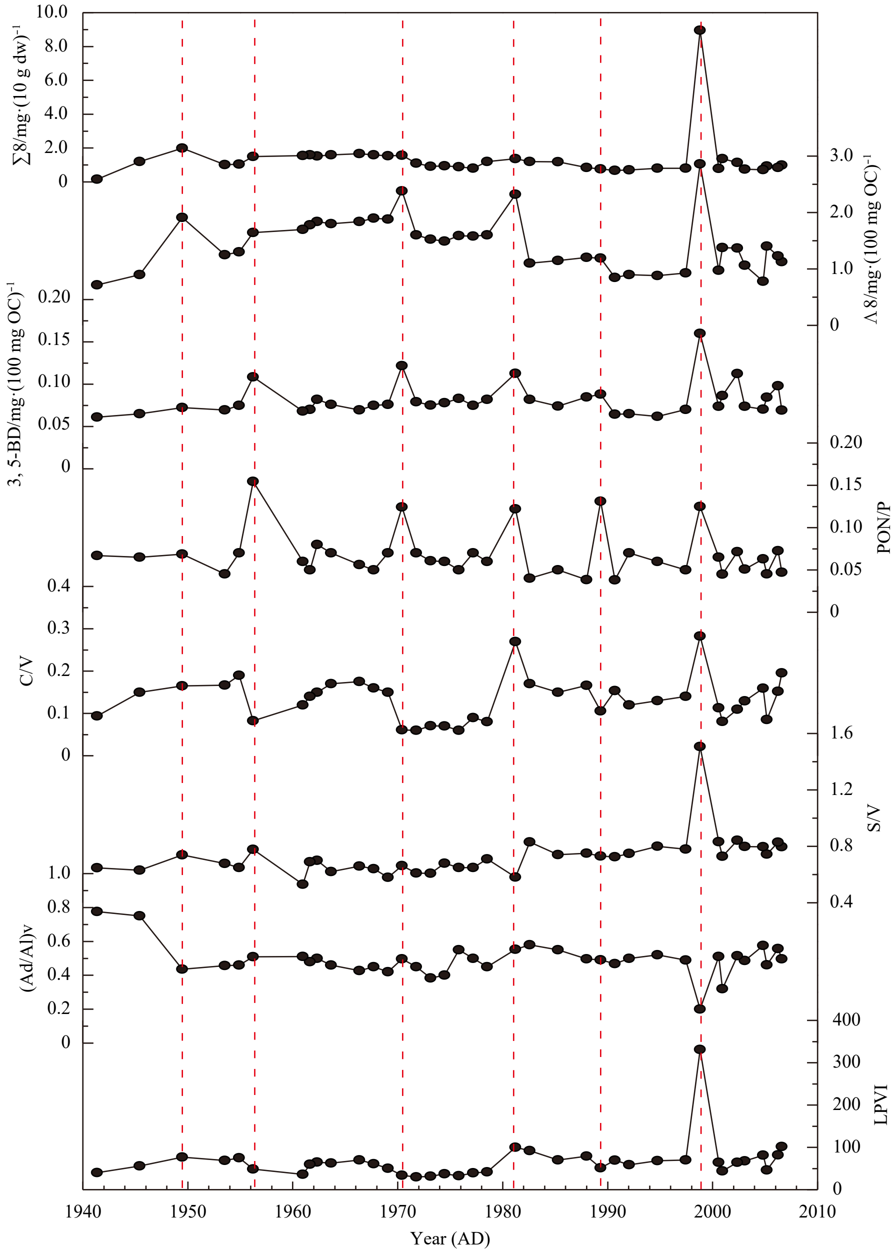

Fig. 6. Lignin-derived phenol profiles along TEZ core. Red dashed lines represent the six flood deposits in the past 70 years, which occur around 1949, 1954, 1969, 1980–1983, 1991, and 1998, respectively.

ditions (Zhan et al., 2010). Except for the 24–26 cm layer, the Λ8, 3, 5-BD and PON/P parameters are the most prominent indictors of flood events. The high values clearly indicate an increase in the contribution of plant and soil OC to these layers. During flood events, the high-water level and rapid water flow would erode surface soil, and transport large quantities of fresh plants and soil OC to the sampling sites. Hence, the Λ8, 3, 5-BD and PON/P values are higher in layers deposited during floods than in non-flood layers. This characteristic of flood deposits has also been observed in the Changjiang River Estuary. We also investigated the lignin profiles of a core (E4) sampled in the subaqueous delta of the estuary and found that annual sediment discharge was the main factor controlling lignin content in the core. In the E4 core, high precipitation indeed corresponded to high lignin content and, as a result, the E4 core provides a record of flood events in the Changjiang Basin. These results support the notion that lignin phenol concentrations and component ratios are a suitable proxy for flood deposits in sediments.

4.2 *Characteristics of flood deposits*

By comparing the 1998 flood deposit with other layers with or without flood events in the core, distinct differences among these layers can be identified. As shown in Fig. 7 and Table 2 based on statistics, the grain composition shows an abrupt change at the 24–26 cm layer (Fig. 3). Above this layer, sand is absent from the core and the proportion of clay is relatively high. This is consistent with the local hydrodynamic variations, whereby the construction of a dam has prevented sand from reaching the sampling location (Jia et al., 2015). The grain size profile shows no difference between flood and non-flood layers, in contrast to those

Table 1. Recognized flood events in Changjiang Basin during 1940–2007 (Shi et al., 2004)

Year	Area	Level	Layer in TEZ core
1998	the whole stream	heavy flood	24–26 cm
1991	middle and low stream	flood	33–34 cm
1980–1983	middle and low stream	flood	39–40 cm
1969	middle and low stream	flood	47–48 cm
1954	the whole stream	heavy flood	57–58 cm
1949	middle and low stream	flood	62–63 cm

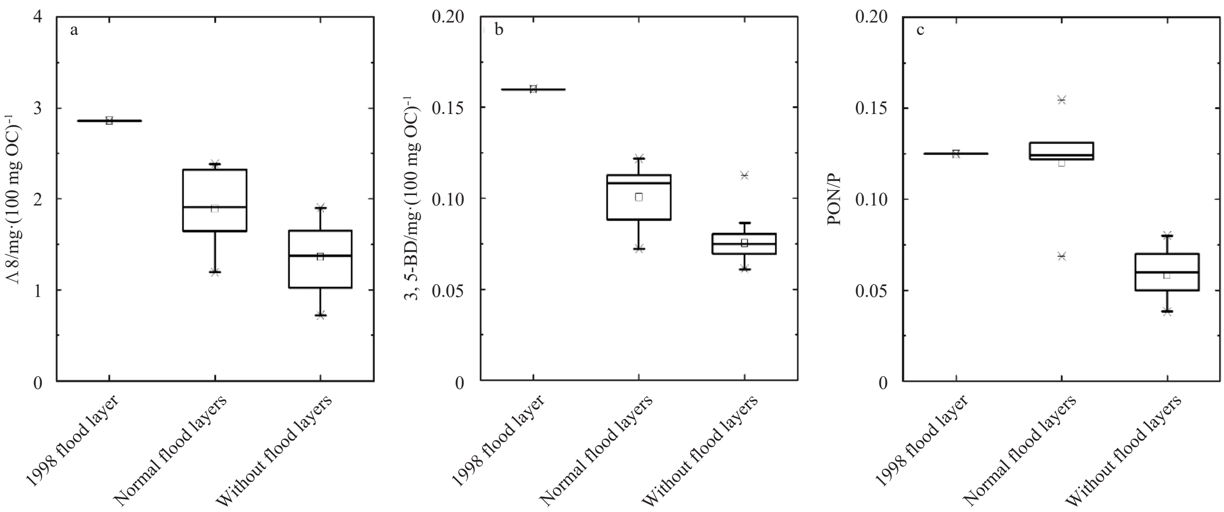

Fig. 7. Λ8 (a), 3, 5-BD (b) and PON/P (c) in different types of deposits in the TEZ core.

Table 2. The *t*-test results between three different type deposits (at 95% confidence interval)

	Flood at 1998 vs. no flood layers	Floods without 1998 vs. no flood layers	Flood at 1998 vs. floods without 1998
Grain size	$p>0.05$	$p>0.05$	$p>0.05$
OC%	$p<0.05$	$p>0.05$	$p>0.05$
TN%	$p<0.05$	$p>0.05$	$p>0.05$
$\delta^{13}C$/‰	$p<0.05$	$p>0.05$	$p<0.05$
$\Sigma 8$/mg·(10 g)$^{-1}$	$p<0.05$	$p>0.05$	$p<0.05$
$\Lambda 8$/mg·(100 mg)$^{-1}$	$p<0.05$	$p<0.05$	$p>0.05$
3, 5-BD/mg·(100 mg)$^{-1}$	$p<0.05$	$p<0.05$	$p>0.05$
S/V	$p<0.05$	$p>0.05$	$p<0.05$
C/V	$p<0.05$	$p>0.05$	$p>0.05$
(Ad/Al)v	$p<0.05$	$p>0.05$	$p<0.05$
PON/P	$p<0.05$	$p<0.05$	$p>0.05$
LPVI	$p<0.05$	$p>0.05$	$p<0.05$

reported by Zhan et al. (2010), who observed a relationship between grain size and flood events. Secondly, the organic parameters observed in the other flood deposit layers are less distinct than in the 24–26 cm layer (Fig. 7, Table 2). Notably, Σ8, C/V, S/V, LPVI and (Ad/Al)v are considerably more pronounced in the 24–26 cm flood layer. However, the flood layers at depths below 26 cm all have comparable values of Σ8, C/V, S/V, LPVI and (Ad/Al)v. This might reflect two factors. First, the dam construction in the lower estuary of the oxbow lake in 1999 cut off the lake's seasonal connection to the main stream of the Changjiang River, thereby altering the hydrodynamic conditions of the lake. Prior to 1998, deposition and erosion were apparently in balance with each other, and each wet season flow to the lake would erode the low-density material from previous flood deposits. This low-density material contains the highest proportion of OC and fresh lignin (Ertel and Hedges, 1985). As a result of the removal of material, the flood deposits prior to 1998 did not contain as high level of OM as observed for the 1998 flood deposit. This mechanism resulted in the similar values of Σ8, C/V, S/V, LPVI and (Ad/Al)v in all of the flood layers observed at depths below 24–26 cm. Second, the degradation of OM over time may have contributed to the lower OM content in the older flood deposits, observed in the core below the 1998 deposit. The area surrounding the core was only covered seasonally with water, in which microorganisms would quickly degrade lignin. Feng and Simpson (2007) reported that the OM in subsoil was quickly and efficiently degraded in a vertical soil profile of Alberta grassland soil. This biodegradation may lead to the low lignin concentration in the flood deposits that formed prior to 1998.

5 Conclusions

From the investigation of depth profiles in the TEZ core, the following main conclusions can be made. First, grain size did not seem to be related to flood events in the core, even though floods would generally be expected to transport a larger quantity of coarse particles to the lake. Second, the extreme flood event of 1998 is clearly preserved by the organic indices, such as elevated concentrations of OC, TN and lignin phenols, in addition to lowest value of $\delta^{13}C$. However, these parameters are less sensitive in identifying other floods events preserved in the core. Further, the PON/P, 3, 5-BD concentration and lignin phenols (normalized to OC), on the other hand, are clear markers of all flood events in the middle of the Changjiang River. Our results reported here have extended the application of lignin phenols as compelling markers to the reconstruction of extreme flood events in the river basin and likely coastal marine environments.

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