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Interpretation of the environmental change of Dongting Lake, middle reach of Yangtze River, China, by ^{210}Pb measurement and satellite image analysis

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Abstract

The present study examined the recent environmental history of the Dongting Lake, located in the middle Yangtze River region, central China. The sediment was recovered by 22 vibrocores in different lake sectors, primarily characterizing subaqueous delta and bay subfacies. High sedimentation rates, revealed by ^{210}Pb measurement in different subfacies of the lake, ranged from 0.77 to 2.33 cm/year. These rates equate to deltaic sedimentation associated with mobile channels resulting from Yangtze flood events. Satellite images confirm that the Dongting Lake does not contain the biggest Yangtze floods. Moreover, comparative bathymetric surveys verify that the Dongting Lake has lost almost two-thirds of its total area in the past century, due primarily to siltation by Yangtze sediment. In the late 19th century, a major flood-induced channel avulsion resulted in the coupling of the 'Four-Tributary' subbasin to the Dongting Lake, causing a massive increase in the sediment supply into the lake since then. Hydrological data demonstrate that about 83% of the lake's annual sediment influx are derived from the Yangtze. In addition, pressures from a growing population and associated human activities, such as reclamation, embanking, aquaculture, slope modification and deforestation, are compounding the loss of the lake surface area and associated storage capacity. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Dongting Lake; Human impact; Sedimentation rate; Yangtze floods

1. Introduction

River–lake systems are important subcomponents controlling the catchment-scale sediment transport processes, alluvial adjustment and flood response to global change (Saucier, 1994; Gupta and Asher, 1998; Kingeman et al., 1998; Webb et al., 1999). Dongting Lake, the largest interior lake of China, is located in the middle Yangtze River region (Fig. 1). This lake drains into the Yangtze and is fed by the four middle Yangtze tributaries (collectively known as the Four Tributaries) flowing into the lake from the northwest. To the south and southwest of the Dongting Lake exist four rivers, which are Xiangjiang, Zishui, Yuanjiang and Lishui (Fig. 1). These do not belong to the Yangtze drainage basin

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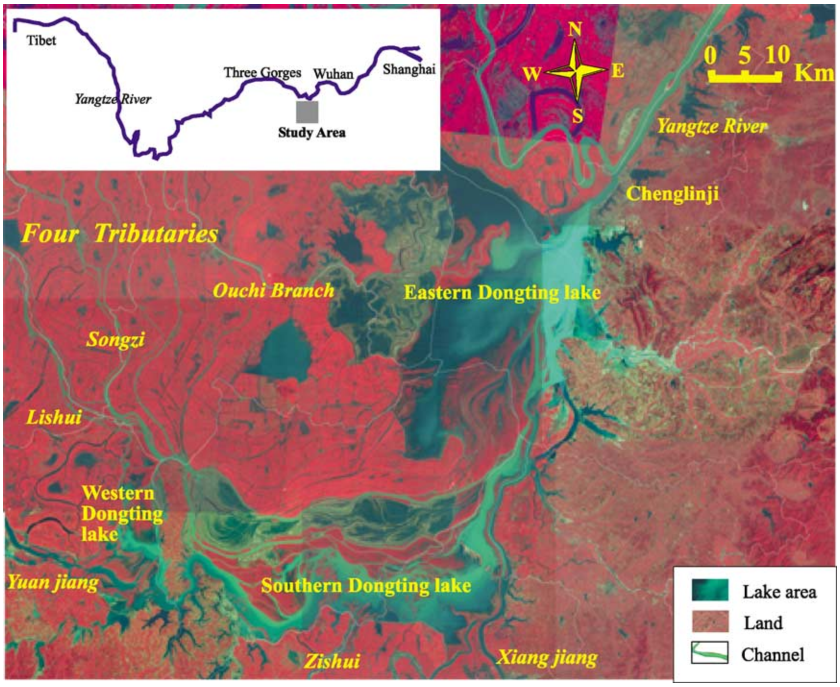


Fig. 1. Satellite image of May 1995 (Landsat TM) showing the Dongting Lake drainage basin in relation to the Yangtze River, Four Tributaries in the west and Four Rivers in the south.

and also flow into the lake with a large amount of sediment and freshwater discharge. These are collectively referred to as the Four Rivers.

The present lake occupies a water area of 1310 km^2 on the average. It can expand to 2691 km^2 during the annual flood season and shrink to 709.9 km^2 in the annual dry season (Huang, 1999). Previous investigation indicates that 41.4% of the annual lake discharge are derived from the Yangtze River, and the rest primarily from the Four Rivers (Lin, 1985). Eighty-three percent (1.21×10^8 m^3) of the total sediment are carried into the lake from the Yangtze, and 17% (0.23×10^8 m^3) from the Four Rivers to the south and southwest (Lin, 1985). Over the past 150 years, the lake area has decreased from ~ 6000 to ~ 2000 km^2 (Bian et al., 1993) due to both natural siltation and human activity, such as littoral land reclamation. Inevitably, these combined processes have altered the system's response to the Yangtze floods. Flood modulation of the Dongting Lake had been changed considerably from 293×10^8 m^3 in 1949 to 174×10^8 m^3 in 1983 (Tao, 1989).

Throughout the Quaternary, tectonic subsidence has promoted the accumulation of hundreds of meters of terrigenous sediments interrupted by several major truncations (Cai and Guan, 1982; Cai et al., 1984; Zhou et al., 1984). During the last glaciation, the Dongting Lake area was deeply incised for > 25 m by palaeochannels (Yang, 1986). By contrast, the present riverbed is only 10–12 m deep. During the Holocene, the palaeovalley gradually aggraded due to fluvial siltation. The eastern outflow at Chenglinji (Fig. 1) is rock-controlled and forms the exit connecting the basin to the Yangtze (Shi and Cai, 1996). A large depression, the Dongting Lake, was formed to the west of Chenglinji, and began to serve as an efficient reservoir for storing and releasing Yangtze backwater flows and also inflows from the other river systems (Zhang et al., 1994).

Over the past decades, the Dongting Lake has experienced intensifying human activity. The lake margins have been reclaimed heavily for agriculture, and deforestation has prevailed in its upper catchment and adjacent area (Mei et al., 1995; Du, 1999).

It is anticipated that the Dongting Lake will continue to shrink, and in the near future, may serve only as a river channel during the nonflood conditions. However, the construction of large hydraulic works, such as the Three Gorges Dam, may help decelerate the lake shrinkage as a large fraction of sediment will be trapped behind the dam (Zhang et al., 1995). The complexity of this background gives added significance to studies of the middle Yangtze region. The present study reconstructs the recent evolution of the system by combined ^{210}Pb sedimentation measurement and remote sensing survey. This analysis was required for local government long-term land management and environmental planning.

2. Methods

Twenty-two vibrocores were taken in 1991 and 1992 in the Dongting Lake, of which 14 (E1–E9, E13, E19, E24, D1 and D3) were from the eastern Dongting; five (M4, M5, M7, W1 and W2) from the southern Dongting; and three (M1, M3 and M6) from the western Dongting (Fig. 2). These vibro-

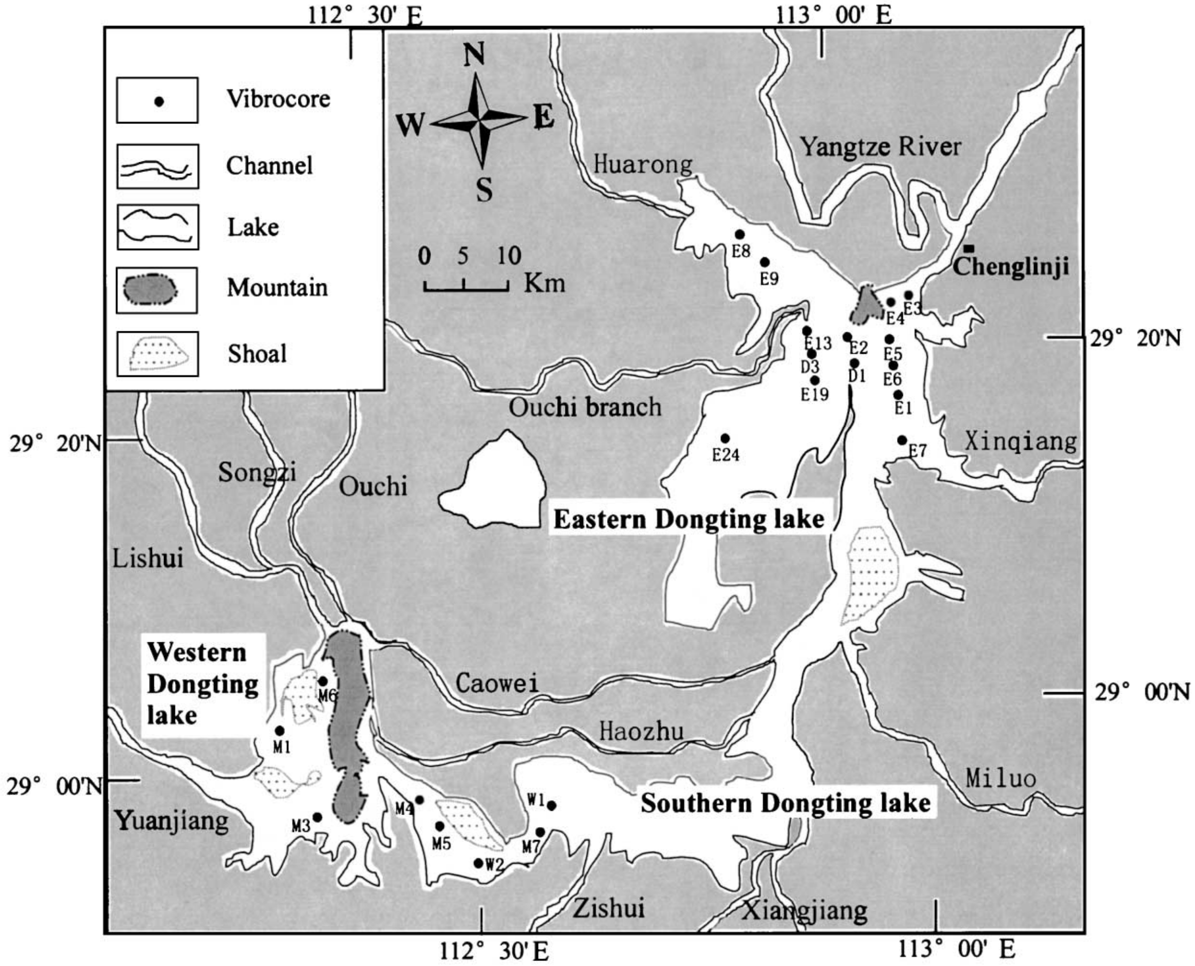


Fig. 2. Vibrocore location in the Dongting Lake.

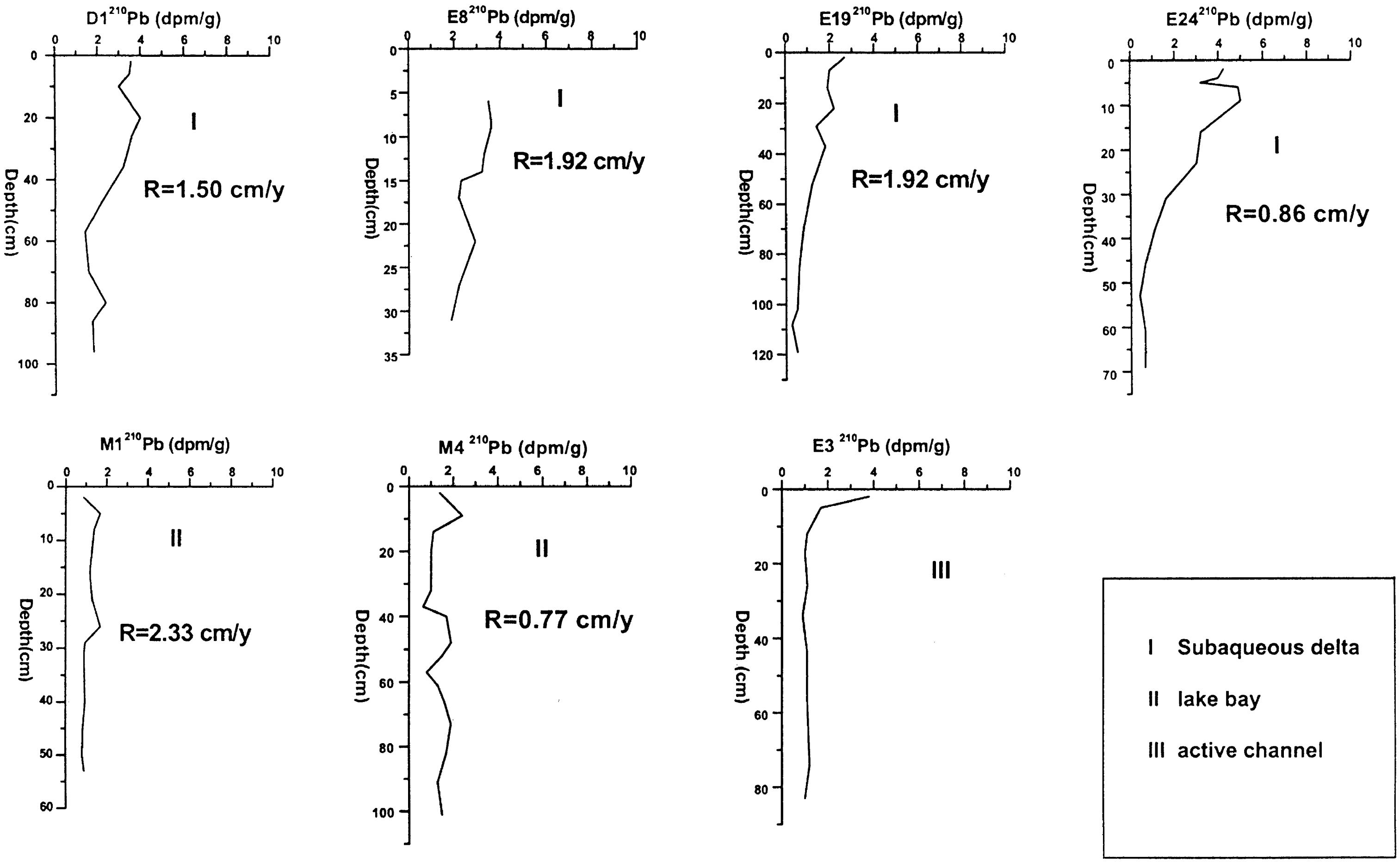


Fig. 3. Result of ^{210}Pb measurement of the seven vibrocores. Vibrocore location refers to Fig. 2.

Table 1
Sedimentation rate of the Dongting Lake (rates listed in descending order) derived from ^{210}Pb measurement of the seven vibrocores

Cores	Core depth (cm)	Average dry weight (g/cm^3)	Average supported (dpm/g)	Average unsupported (dpm/g)	Sedimentation rate (cm/year)
M1	65	1.20	2.05	1.12	2.33
E19	119	0.80	2.93	1.32	1.92
D1	95.8	1.14	4.13	2.68	1.50
E8	31	1.09	4.16	2.83	1.18
E24	69	1.09	3.95	2.37	0.86
M4	101	1.70	2.18	1.42	0.77
E3	85	1.11	1.40	1.40	0

cores, which are 5 cm in diameter and range from 31 to 126 cm in length, were split in the field immediately after recovery. Sedimentary properties, such as colour, texture, structure, root traces and biogenic occurrences, were noted. Cores were then subsectioned into 2-cm intervals and sealed in plastic bags

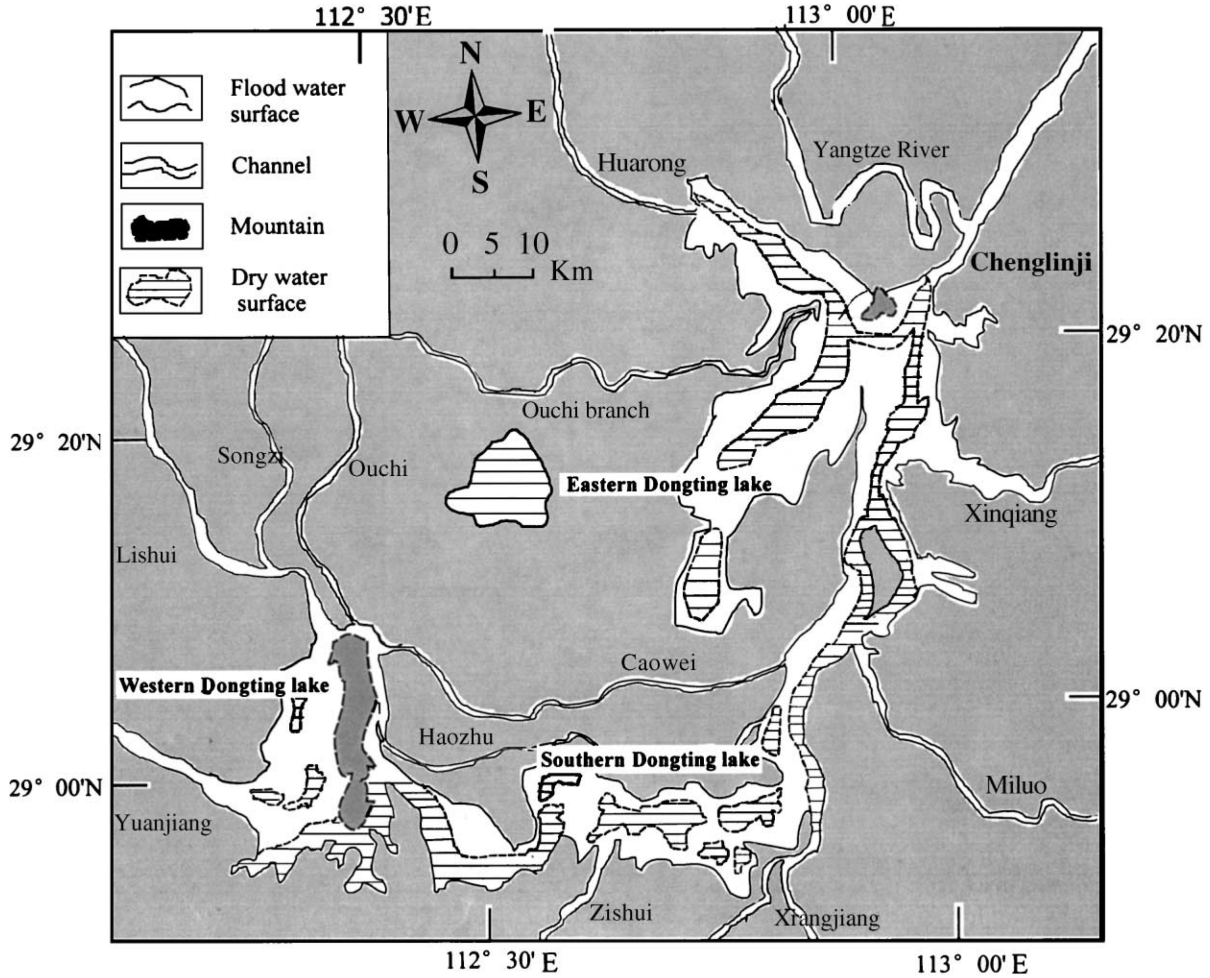
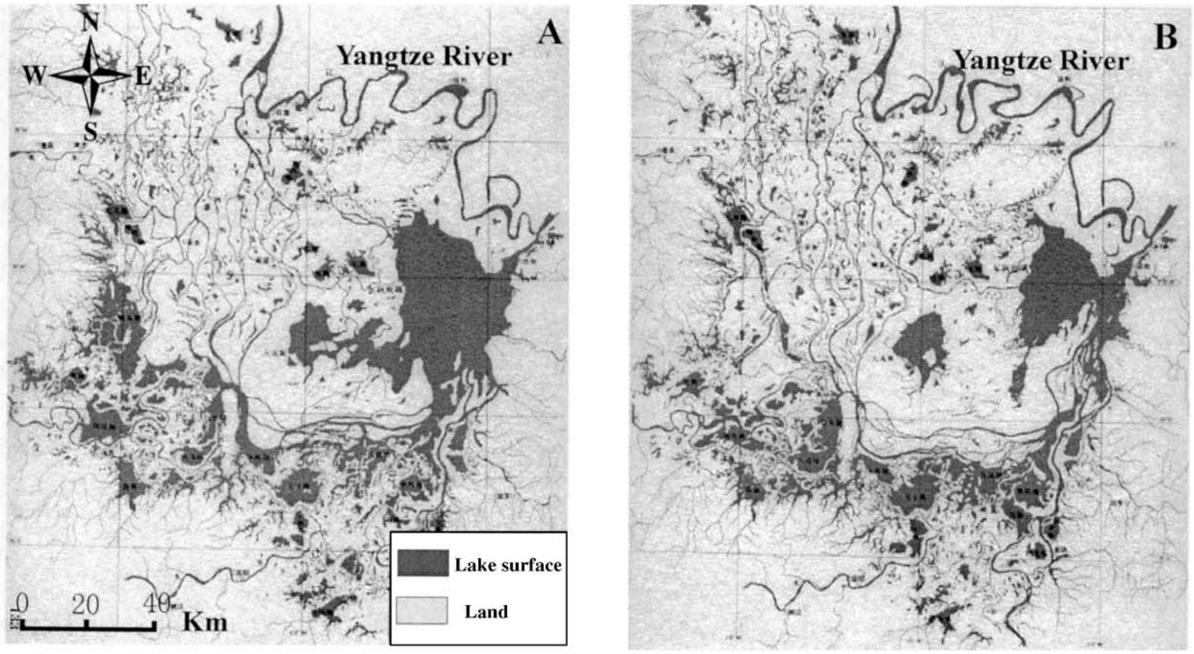
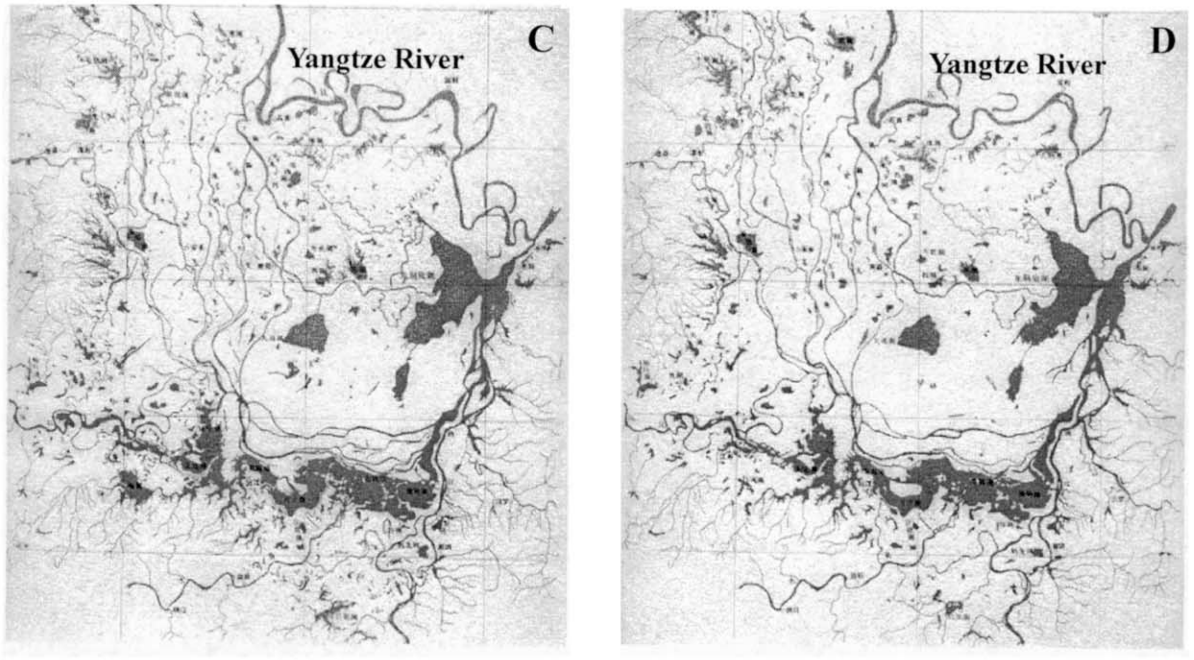


Fig. 4. Environment of the Dongting Lake (Landsat TM, February 1989).



A: Dongting lake surface in 1930's B: Dongting lake surface in 1950's



C: Dongting lake surface in 1970's D: Dongting lake surface in 1980's

Fig. 5. Area changes of the Dongting Lake in the 1930s, 1960s, 1970s and 1980s based on historical bathymetry investigation (Japanese Land Survey Bureau and General Army Consultation, 1941; China Army General Consultation, 1960) and Landsat images (29 April 1976, 20 April 1978 and 25 April 1984).

for return to the laboratory. Samples selected from seven vibrocores (D1, E3, E8, E19, E24, M1 and M4) were prepared for ^{210}Pb and ^{226}Ra measurement by the following procedure:

1. weighing of wet mass;
2. drying in oven at 50 °C;
3. weighing after drying;
4. grinding the samples and sieving through a 2-mm mesh.

The prepared samples were then sent for the measurement of ^{210}Pb and ^{226}Ra at the Guangzhou and Nanjing Geographic Institute, Chinese Academy of Science. The radioactivity content (in dpm/g) of these seven vibrocores was obtained (Fig. 3). Sedimentation rates were also calculated by the application of the constant rate of supply (CRS) model (Appleby and Oldfield, 1978). The results are shown in Table 1.

Information on the surface area of the lake during the dry season was interpreted from Landsat imagery, December 1989 (Fig. 4). For comparative purposes, the situation during the floods of August 1998 are shown in Fig. 5. In addition to the information shown in Fig. 5, data on the bathymetry of the Dongting Lake were available for several periods: the 1930s bathymetry (1:50,000) prepared by the Japanese Land Survey Bureau and General Army Consultation (1941); and the 1960s bathymetry (1:100,000) produced by the China Army General Consultation (1960). Landsat images for 29 April 1976, 29 April 1978, and 25 April 1984 were used to derive a representative lake surface area during the dry season. These surveys are summarized in Table 2.

Table 2
Dongting Lake decadal area changes

Lake time	Eastern Dongting Lake area (km^2)	Southern Dongting Lake area (km^2)	Western Dongting Lake area (km^2)
1930s	1454	626	294
1950s	861	707	517
1970s	587	589	312
1980s	551	561	196

3. Data observation

3.1. Lake sediments

Vibrocores in the eastern Dongting Lake showed two main sediment facies. Vibrocores proximal to the Ouchi river mouth, including D3, E13, E19, E2 and D1 (Fig. 2), were dominated by yellowish-gray to brownish-yellow fine sand and clayey silt. Sand and silt layers (about 5–10 cm thick) are interbedded. Small-scale ripple bedding occurs in the profiles, but erosional contacts were generally absent. Organic matter was relatively low, but plant debris was common. In contrast, those in distal to river mouth zones, including E1, E5 and E6, were dominated by gray to dark gray silt and clay. Sediments were rich in organic matter, usually of massive structure and evidence of burrowing. Sediment contact was gradational.

Cores E3 and E4, positioned at the inner Chenglinji exit, consisted primarily of yellow to gray fine sand in the upper 30 cm, and gray silts and clay, rich in organic matter below. E8 and E9, sited in the northwestern bay of the Dongting Lake, were made up of gray silty clay and clayey silt. Sediments were massive in structure and organic matter appeared throughout.

Sediment revealed by vibrocores M4, M5, M7, W1 and W2 of the southern Dongting Lake consisted mostly of yellowish gray interbedded silty clay and clayey silt, with massive structure and parallel bedding. No erosional contacts were present and organic matter occurred throughout. Sediments from vibrocores M1, M3 and M6 of the western Dongting were similar in nature to those described for the southern Dongting basin.

3.2. ^{210}Pb measurement and sedimentation rate

Three types of ^{210}Pb profiles (I, II, III) were recognized in the radiometrically dated vibrocores. All cores evidenced declining ^{210}Pb activity concentrations with depth (Fig. 3). Type I is represented by four vibrocores (E19, E24, E8 and D1) located in the eastern Dongting Lake, demonstrating a gradual decrease in ^{210}Pb (dpm/g) downcore with small fluctuations in the content. The unsupported ^{210}Pb radioactivity decreases from 3–4 to < 2 dpm/g, with a marked decline at a depth of 40–60 cm (Fig. 3). The calculated sedimentation rates of these four vibrocores are listed in descending order: 1.92 cm/year (E19), 1.50 cm/year (D1), 1.18 cm/year (E8) and 0.86 cm/year (E24) (Table 1).

Type II is represented by two vibrocores (M1 and M4) located in the western and southern Dongting Lakes, respectively. These profiles show a very subtle decrease in ^{210}Pb-value downcore. The unsupported ^{210}Pb content declines from surface values of $\sim 2\text{–}<1.5$ dpm/g at the base of the vibrocore. Sedimentation rates calculated were 2.33 cm/year for M1 and 0.77 cm/year for M4.

Type III is represented by the vibrocore E3 located in the inner Chenglinji exit, recording an unsupported ^{210}Pb value of ~ 4 dmp/g in the top 5 cm of the core section and of ~ 1 dmp/g below this depth. The sampling resolution was too crude to allow a sedimentation rate to be derived.

3.3. Satellite imagery to record the lake area variation

The satellite image of February 1989 indicates that the water surface of the Dongting Lake was generally less than 3–5 km wide and served primarily as a major tributary to the Yangtze (Fig. 4). It was estimated that the surface area of the western Dongting Lake during the dry season was 22.8 km^2; the water surface of southern Dongting Lake was 468.9 km^2; and that of the eastern lake was 241 km^2 (Zhang et al., 1995). In contrast, the surface area of the Dongting Lake during the wet season is typically twice as large as during the dry season (Huang, 1999). Our previous survey also recorded that the lake area had been reduced dramatically in the period from the 1930s to the 1980s (Table 2). In 1980s, the eastern Dongting Lake was only 38% of the 1930s area (Fig. 5). The southern Dongting Lake lost only 4%, but the western Dongting Lake was reduced by a third (Du et al., 1999).

4. Discussion

4.1. ^{210}Pb measurement relative to sediment sources

^{210}Pb measurement has been widely used to determine sedimentary processes, including sedimentation rates in lakes and reservoirs (Oldfield and Appleby, 1984; Sandman and Simola, 1990). Dated cores in the eastern Dongting Lake were obtained chiefly from different subaqueous delta facies associated with sediment inputs from the Ouchi River. Water depth of the subaqueous delta ranges from 2 to 3 m. Vibrocores evidenced higher ^{210}Pb levels concentrated in their upper 40–60 cm. Sedimentation rates declined with distance from the delta mouth to relatively low levels in the distal lake setting, i.e. 1.92 cm/year in E19, 1.50 cm/year in D1, 1.18 cm/year in E8 and 0.86 cm/year in E24 (Fig. 2 and Table 1). Generally, these sedimentation rates correspond to a deposition period of 30–60 years.

We propose that the higher sedimentation rates in the eastern Dongting Lake actually reflect the historical migration of the Ouchi river channel. Prior to the 1950s, this river, like the other three, flowed southward into the southern Dongting Lake. The Ouchi River changed its course to the present one apparently due to a major Yangtze flood event that occurred in 1954 (Zhong, 1987). On the basis of hydrometric data, the annual sediment load (averaged from 1951 to 1988) of the Ouchi River transported into the eastern Dongting Lake was 0.5043×10^8 m^3, i.e. 39.2% of the total annual sediment budget of the Dongting Lake (Hydroelectric Bureau of Hunan Province, 1989).

In the western Dongting Lake, vibrocore M1 recorded the highest sedimentation rate (2.33 cm/year) of the present study (Table 1). This phenomenon can be attributed to extensive erosion in the western and southern drainage basin (Fig. 1). Data from the Songzi River (Hydroelectric Bureau of Hunan Province, 1989) indicate an annual sediment load of 0.2413×10^8 m^3 (18.7% of the total Dongting receives), whereas Yuanjiang annually contributes 0.0899×10^8 m^3 (7%) and Lishui annually contributes 0.0445×10^8 m^3 (3.5%).

The lowest sedimentation rate was recorded in M4 (0.77 cm/year) obtained from the southern Dongting Lake where sediment inputs are relatively minor. On the basis of hydrometric data, the annual sediment load (averaged from 1951 to 1988) of the Zishui River was 0.0195×10^8 m^3, i.e. 1.5% of the total annual sediment budget of the Dongting Lake (Hydroelectric Bureau of Hunan Province, 1989). In addition, higher radioactivity content focusing on the top 5 cm in E3 in the Eastern Dongting Lake may interpret coarser grain size (mostly, silt and fine sand) in the river channel of Chenglinji (Fig. 1), which is not favourable for radiometric adsorption.

4.2. Satellite imagery interpretation of the lake environmental change

A series of satellite images clearly indicates that the Dongting Lake has been greatly reduced in size over the past decades. During the dry season, the lake narrows to a river channel, but expands dramatically during the wet season. Large areas can be inundated in floods. The overflow from the Yangtze flood of August 1998 inundated an area of $>4.4\times10^4$ ha adjacent to the lake (Fig. 6).

4.2.1. Eastern Dongting Lake

Presently, the eastern Dongting basin has a water area of 460 km^2, and receives an annual sediment load of 0.545×10^8 m^3 (Hydroelectric Bureau of Hunan Province, 1989). The Ouchi delta and associated coastline is expanding rapidly eastward and will ultimately obstruct by siltation the subaqueous river channels, which flow into the Yangtze River via the Chenglinji exit (Fig. 1). According to the lake bottom topographic maps (Zhang and Cai, 1987), the aggradation rate of the distal sand levee can be approximated to 3 cm/year. Assuming that this rate of growth continues, much of the eastern Dongting Lake would degrade into several separate diffluent bays, especially during the dry season. Also, intensifying human activities, such as reclamation and

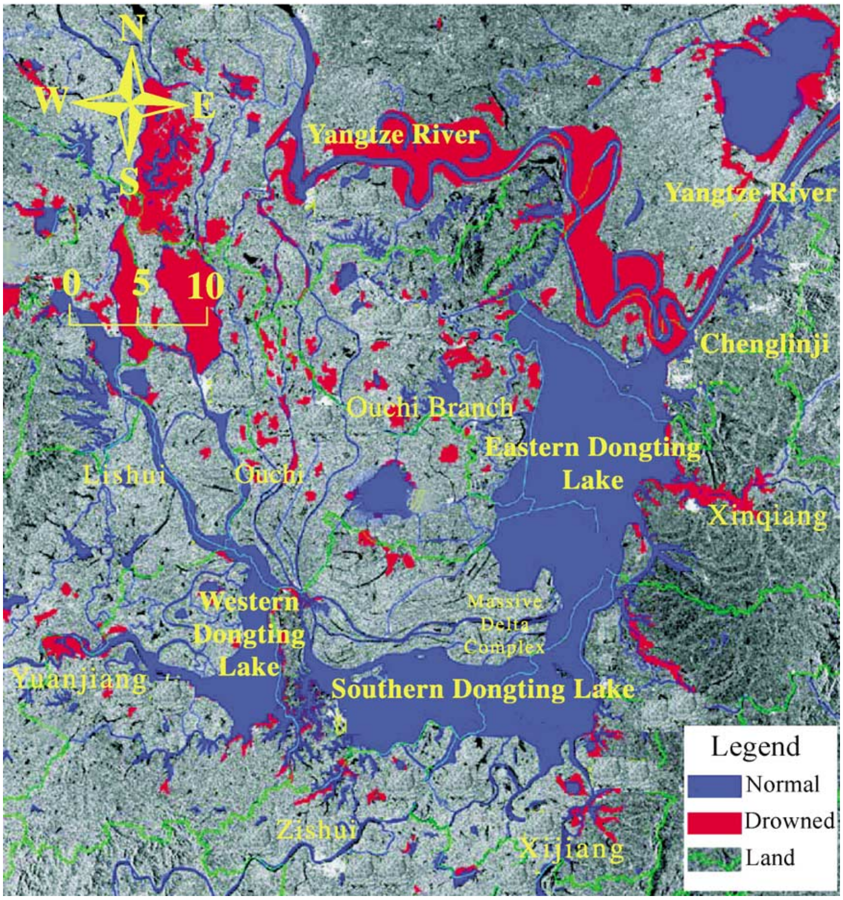


Fig. 6. Satellite image (Radarsat, Canada) showing the August 1998 flood in the Dongting Lake.

farming on slopes, are exacerbating the reduction in the lake area.

4.2.2. Southern Dongting Lake

The present southern Dongting Lake has a water area of 516 km^2 and receives an annual sediment influx of 0.226×10^8 m^3 (Hydroelectric Bureau of Hunan Province, 1989). The lake consists obviously of four sectors as evidenced by the lake bottom topography (Zhang and Cai, 1987). The western sector of the lake now ranges in water depth from 25 to 30 m, the remainder only functions as diffluent basins during the flood season. The fragmentation is exacerbated by human activity, especially reclamation. Subaqueous sandbars extending from the northern bank of the Southern Dongting Lake (Fig. 1) form a large shallow shoaling system.

According to a SPOT image (May 1986), the northern bank of the southern Dongting Lake was only 3.4 km away from the southern bank. Natural levees of the Zishui (Fig. 1) are elevated 29–30 m in the delta zone. Comparing the bathymetric maps from 1952 and 1988 (Zhang, 1991), the natural levees have risen 4–5 m during the last 40 years, i.e. approximately 10 cm/year. The rate of surface area shrinkage for the southern Dongting Lake is about 5.0 km^2/year over the last 30 years (Zhang et al., 1995). Thus, the southern Dongting Lake tends to dry out to several diffluent lakes, separated by mud flats topped with reed patches in the dry season.

4.2.3. Western Dongting Lake

The current western Dongting Lake has a water area of 190 km^2 and receives 0.297×10^8 m^3 of sediment annually, derived primarily from the Four Tributary system (Hydroelectric Bureau of Hunan Province, 1989). This channel system was formed by a large flood-induced avulsion event that occurred in 1860s (modified afterwards by human activity), which coupled the Yangtze and Dongting Lakes (Zhong, 1987). Subsequently, the sediment that routed from the Yangtze began to enter the western lake to form the two large-scale subaqueous deltas, comprising of emergent sandbars, submerged natural levees and swamps. These delta facies are mainly positioned in front of the Lishui and Yuanjiang river mouths (Fig. 1). Due to considerable siltation, sandbars in the river mouth area have been gradually elevated to ~28 m close to the present mean lake water level of 30 m (Du and Cai, 2000).

By comparing the lake bathymetry measured in 1964 and 1988, the average aggradation rate of levees in the Lishui River equates to 6 cm/year (Zhang et al., 1995), implying that the large part of the western Dongting Lake will be elevated to ~30 m and will be subaerially exposed within 30 years. The western lake area decreased by 115.3 km^2 from 1950s to 1970s and by 108.6 km^2 from 1970s to 1980s (Zhang et al., 1995). Landsat data indicate a water area of 208 km^2 in April 1984 and 23 km^2 in February 1989. Again, intense human activity over the last 50 years has exacerbated the morphological change (Zhang et al., 1995).

5. Conclusions

^{210}Pb measurement of the Dongting Lake reveals high sedimentation rates ranging from 0.77 to 2.33 cm/year. Spatial variations correspond to sediment inputs from a large array of tributary river systems.

A series of satellite images reveals that the Dongting Lake presently behaves as a major river channel during the dry season. Even in the wet season, the lake capacity in terms of water storage and surface area is limited largely by sedimentation. This obviously limits the effectiveness of the lake to attenuate Yangtze water level, especially during the big floods.

The Dongting Lake has shrunk by almost two-thirds of its area of a century ago. This can be attributed both to natural siltation from upstream sediment sources and intensifying human impact, such as reclamation and aquaculture. Channelization of the Four Tributaries to the Dongting Lake in 1860s caused by a major flood has accelerated the loss of storage capacity.

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References

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

Bian, H.X., Wang, W.C., Gong, X.L., 1993. The Evolution of Dongting Lake. Hunan Science and Technology Press, Changsha, China (in Chinese).

Cai, S.M., Guan, Z.H., 1982. It is impossible for the ancient Yunmen swamp across the Yangtze River. Oceanologia et Limnologia Sinica 13, 129–141 (in Chinese, with English abstract).

Cai, S.M., Guan, Z.H., Kong, Z.C., Du, N.Q., 1984. Natural environment as reflected in sedimentary facies and sporo-pollen assemblages in the Quaternary Dongting basin. Oceanologia et Limnologia Sinica 15, 527–538 (in Chinese, with English abstract).

China Army General Consultation, 1960. Topography of Yiyang, Yuyang, Xiangyin, Yuanjiang, Hanshou, Huarong, Nanxian, Xingqiang, Zhuxikuo, and Xihu (1:100,000; in Chinese, unpublished).

Du, Y., 1999. A study on the environmental evolution of the Dongting Lake in historical period. PhD thesis, Wuhan University, Wuhan, China (in Chinese, with English abstract).

Du, Y., Cai, S.M., 2000. The development character of the Dongting Lake deltas in neoteric time. Journal of World Science—Technology Research and Development 22, 5–8 (in Chinese, with English abstract).

Du, Y., Cai, S.M., Zhao, Y., 1999. The evolution, development trend and flooding analysis of the Dongting Lake. In: Xu, H.Z., Zhao, Q.G. (Eds.), The Symposium of Flooding Disaster and Scientific and Technological Countermeasure of the Yangtze River. Science Press of China, Beijing, pp. 96–100 (in Chinese).

Gupta, A., Asher, M.G., 1998. Environment and the Developing World. Wiley, Chichester, 360 pp.

Huang, J.L., 1999. The change of wetland and analysis of flood control in Dongting Lake. In: Xu, H.Z., Zhao, Q.G. (Eds.), The Symposium of Flooding Disaster and Scientific and Technological Countermeasure of the Yangtze River. Science Press of China, Beijing, pp. 106–112 (in Chinese).

Hydroelectric Bureau of Hunan Province, 1989. Data Report on Hydrology and Meteorology Hydroelectric Bureau of Hunan Province, Changsa, 184 pp. (in Chinese).

Japanese Land Survey Bureau and General Army Consultation, 1941. Topography of Shizitan, Muopanzhou, Xingjiankuo, Junshan, Gonganxian, Yuanshi, Shenjindu. China Map Publisher, Beijing (1:50,000).

Kingeman, C.P., Beschta, L.R., Komar, D.P., Bradley, B.J., 1998. Gravel–Bed Rivers in the Environment. Water Resources Publications, LLC, Monograph, 832 pp.

Lin, C.K., 1985. The evolution and management of Dongting Lake: Part I. The sedimentation of the Dongting Lake. Geography and Territorial Research 1 (4), 28–37 (in Chinese, with English abstract).

Mei, L., Zhang, G.X., Yan, C.G., 1995. Study on the Original Development of Two Lakes Plain. Jiangxi Education Press, Nanchang, China (in Chinese).

Oldfield, F., Appleby, P., 1984. Empirical testing of ^{210}Pb dating models for lake sediments. In: Haworth, E.Y., Lund, J.W.G. (Eds.), Lake Sediments and Environmental History. Leicester Univ. Press, Leicestershire, pp. 93–124.

Sandman, A.L., Simola, H., 1990. Drainage ditch erosion history as recorded in the varved sediment of a small lake in East Finland. Journal of Paleoclimatology 3 (2), 161–169.

Saucier, T.R., 1994. Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley. The Mississippi River Commission, Vicksburg, MS.

Shi, Q., Cai, S.M., 1996. Study on Ancient Yunmeng Swamps. Hubei Education Press, Wuhan, China (in Chinese).

Tao, J.Y., 1989. The influence of straightening the Jingjiang River and the Dongting Lake. Journal of Central China Normal University, Natural Sciences 23, 263–267 (in Chinese, with English abstract).

Webb, H.R., Schmidt, G.J., Marzolf, R.G., Valdez, A.R., 1999. The Controlled Flood in Grand Canyon. American Geophysical Union, Washington, DC, Monograph, 367 pp.

Yang, D.Y., 1986. The paleoenvironment of the mid-lower regions of the Changjiang in full-glacial period of late Pleistocene. Acta Geographica Sinica 41, 302–310 (in Chinese, with English abstract).

Zhang, X.Y., 1991. The evolution of the Dongting Lake and delta sedimentation. Masters dissertation, Institute of Geodesy and Geophysics, Chinese Academy of Sciences (in Chinese, with English abstract).

Zhang, X.Y., Cai, S.M., 1987. Study on the recent evolution of the Dongting Lake. Unpublished report of Institute of Geodesy and Geophysics, Chinese Academy of Sciences, 20 pp. (in Chinese).

Zhang, X.Y., Cai, S.M., Sun, S.C., 1994. Evolution of the Dongting Lake since Holocene. Journal of Lake Sciences 6, 13–21 (in Chinese, with English abstract).

Zhang, X.Y., Du, Y., Cai, S.M., 1995. An analysis on evolutional tendency of the Dongting Lake. Resources and Environment in the Yangtze Valley 4, 64–69 (in Chinese, with English abstract).

Zhong, Y.P., 1987. The evolution of the Four Tributary connecting between the Yangtze River and the Dongting Lake. Technical Report of Hydroelectric Bureau of Hunan Province, Changsa, 21 pp. (in Chinese).

Zhou, G.Q., Chen, T.S., Zhao, S.Q., 1984. The origin and evolution of the Dongting Basin. Journal of Hunan Geology 3, 54–65 (in Chinese).