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Geochemical records in recent sediments of Lake Erhai: implications for environmental changes in a low latitude–high altitude lake in southwest China

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Abstract

Sediment cores were collected from Lake Erhai, which is located on the Yunnan–Guizhou Plateau, a landform formed by the uplift of the Himalayas. These sediments were deposited up to about 697 ± 15 years ago based on $^{210}Pb_{ex}$ and ^{137}Cs dating. $\delta^{13}C_{inorg}$, $\delta^{18}O_{inorg}$ and $\delta^{13}C_{org}$ values and concentrations of C_{inorg}, C_{org}, N and P within the sediment cores have been measured. C_{org} has an average deposition flux of 12.7 g/m^2, and an accumulation flux of 7.20 g/m^2. The calculated decomposition rate constant is 0.017 a^{-1} with a half life of 40 a. $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ values range from −1.6 to −7.9‰ and −5.7 to −13.6‰, respectively, and show similar trends over the past 700 years, which is interpreted to be controlled mainly by temperature, corresponding to climatic changes of two and half periods of a 'warm–cold–warm' cycle. $\delta^{13}C_{org}$ ranges from −25 to −28‰, indicating that the organic matter originated mainly from land-derived plants, with overprinting from anthropogenic activities over the past 460 years (since 1537 AD). N and P_{org} concentrations show a similar vertical distribution to C_{org}. Atomic ratios of organic carbon and nitrogen (C/N) are 5.8 and 6.8 for the deposition and accumulation stages, respectively, similar to the Redfield ratio in the ocean. The C/P ratio, however, is higher than that in the ocean. The vertical distribution of carbon in the sediment cores indicates that Lake Erhai has the characteristics of both an inland lake (land-derived organic matter) and the ocean (similar C/N ratio). The lower C/N and C/P ratios in the lake Erhai sediments are characteristic for a lake at high altitude and in a subtropical region. This 'low latitude–high altitude effect' is probably related to the uplift of the Himalayas.

Keywords: Recent lake sediments; $\delta^{13}C_{inorg}$; $\delta^{18}O_{inorg}$; $\delta^{13}C_{org}$; C–N–P relationships; Low latitude–high altitude effect; Lake Erhai

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1. Introduction

In order to establish a quantitative model of environmental evolution it is necessary to obtain high-resolution data of elemental cycles and mass equilibrium recorded in the Earth system (Walker, 1983; Berner, 1991, 1994; Berner et al., 1983; Lasaga and Berner, 1998; François and Goddéris, 1998; Tajika and Matsui, 1990, 1993; Meyers et al., 1998). Lake sediments include materials originating from both the terrestrial surface and atmospheric deposition and preserve a continuous, high-resolution record of regional and global environmental information. This can be utilized to reconstruct past environmental evolution on variable time scales of 1000, 100, 10, 1 a, or even seasons. In addition, lake waters and sediments provide a sensitive indicator of regional pollution resulting from industrialization (Wan, 1988; Graney et al., 1995). Extracting environmental information recorded in lake sediments is therefore of major significance in studies of the past environmental changes and the prediction of future trends in environmental evolution.

The uplift of the Himalayas and the formation of the Tibetan Plateau have contributed to global environmental changes over the past 15 Ma (Raymo and Ruddiman, 1992; Berner, 1997; Canfield, 1997; Tajika, 1998). The uplift of

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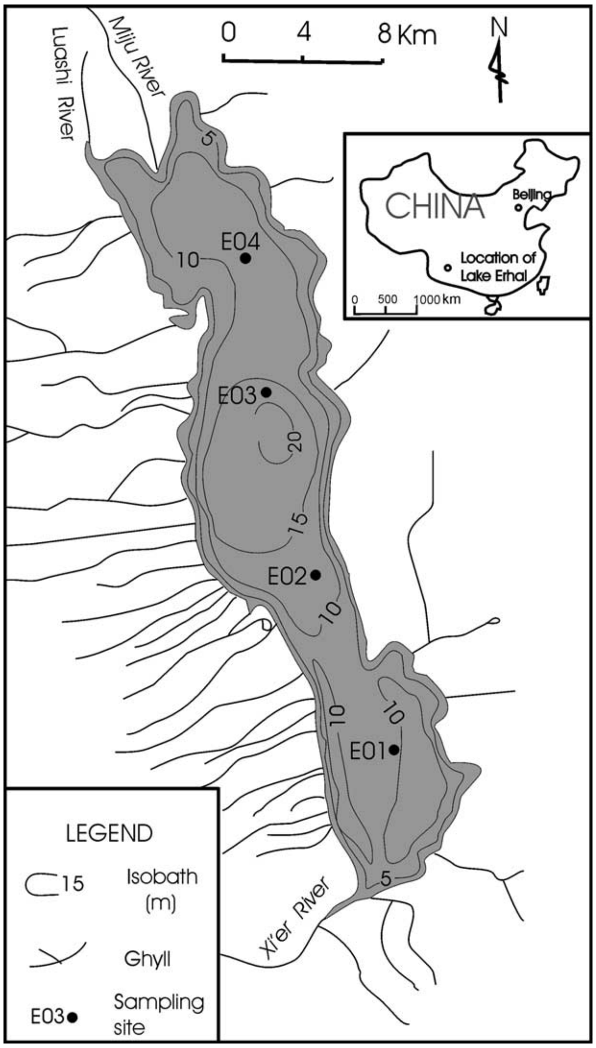

Fig. 1. Schematic map of sampling sites in Lake Erhai, SW China.

the Himalayas has produced a three-tiered landform in southern China, resulting in apparent environmental changes on variable time scales. The Yunnan–Guizhou Plateau is the middle tier on the eastern slope of the Himalayas. It is a complex geomorphological unit characterized by low latitude–high altitude with large altitude gradients. This area is affected by both the southeastern (Pacific Ocean) and southwestern (Indian Ocean) monsoons. Superimposed on the natural climatic changes are more recent anthropogenic influences due to industrialization and changes in agricultural practices. The environmental changes due to uplift of the Himalayas and anthropogenic activities should be recorded in the lake sediments in this region. It is important to differentiate between anthropogenic impacts and those from natural environmental evolution.

In order to understand the effects of the uplift of the Himalayas and the related influence of the Indian and Pacific Monsoons in southern China, Lake Erhai, the largest fault lake in the western Yunnan Plateau, has been selected for a study of the geochemical record in recent sediments. Lake Erhai is located in the northern city of Dali in Yunnan Province (100°5′–17′E, 25°35′–58′N). It is 42 km in length from NNW to SSE, and 8.4 km in maximum width (Fig. 1). The surface of the lake is about 1974 m above mean sea level. The water area is 249.8 km^2 with a watershed some 2656 km^2 in extent. It has an average depth of 10.5 m, a maximum depth of 20.9 m, a volume of 2.88×10^9 m^3, a water residence time of 2.75 years and an annual water discharge of 8.13×10^8 m^3 (Wan et al., 1988; Shen, 1989). Lake Erhai and adjacent areas have a subtropical monsoon climate, which is apparently affected by the Indian monsoon, with an average annual precipitation of 1060 mm, temperature of 15 °C, and potential evaporation of 1970 mm. The catchment area of Lake Erhai is mainly underlain by sedimentary and metamorphic rocks, specifically carbonate and siliciclastic rocks and gneisses. Because of the influence of the carbonate bed rock and the subtropical monsoon, the lake water has the following characteristics (Wan et al., 1988): (i) weakly alkaline (pH 8.0(8.5); (ii) low salinity; (iii) solutes in lake water dominated by Ca^{2+}, Mg^{2+} and HCO_3^-, which represent more than 60% of the total equivalent anions and cations; (iv) with ion concentrations $Ca^{2+} > Mg^{2+} > Na^+ > K^+$, and $HCO_3^- \gg SO_4^{2-} \gg Cl^-$.

This study of recent lake sediments is based firstly on the determination of high resolution, chrono-geochemical records. The environmental information is extracted from sedimentary layers of known age. The age–depth relationship of the selected cores in this study has been estimated using ^{137}Cs and ^{210}Pb dating (Wan, 1999; Wan et al., 1999; Xu et al., 1999). On the basis of the above sedimentation dating, the study aims to analyze the isotopic composition of C and O together with elemental C, N and P in recent Lake Erhai sediments in order to unravel biogeochemical environmental information over the past several hundred years.

Table 1
Descriptions of sediment cores

Core No.	EH911208-3-4	EH911208-3-5	EH940713-3-1	EH940713-3-2	EH940713-1-1
Sampling date	08/12/91	08/12/91	13/07/94	13/07/94	13/07/94
Site No.	E03	E03	E03	E03	E01
Water depth (m)	16	16	15	15	7
Core length (cm)	90	83	12	41	24
Analytical items	$\delta^{13}C_{inorg}$, $\delta^{13}C_{org}$, $\delta^{18}O_{inorg}$	C_{org}, N	C_{inorg}, C_{org}, N	^{210}Pb–^{137}Cs-dating C_{inorg}, C_{org}, N, P	^{210}Pb-dating C, N

Table 2
Carbon and nitrogen speciation in Lake Erhai sediments from core EH940713-3-2 and core EH9407-13-3-1

Depth (cm)	Mass depth (g/cm^2)	Age (AD)	Porosity (%)	C_{total} (wt%)	C_{org} (wt%)	C_{inorg} (wt%)	C_{org}/C_{total} (%)	N_{org} (wt%)	C_{org}/N_{org} (by atom)
EH940713-3-2									
0.3	0.09	1993	96.8	3.17	2.82	0.36	88.7	0.58	5.7
0.8	0.21	1990	96.8	3.09	2.66	0.43	86.0	0.56	5.6
1.3	0.25	1989	95.6	3.45	2.83	0.62	82.1	0.58	5.7
1.8	0.31	1988	95.5	3.15	3.07	0.08	97.4	0.55	6.5
2.8	0.43	1985	95.3	3.18	2.80	0.38	87.9	0.58	5.7
3.8	0.62	1981	94.5	3.10	2.80	0.30	90.4	0.56	5.8
4.8	0.79	1977	91.5	3.21	2.33	0.89	72.4	0.50	5.5
5.8	1.03	1972	92.0	2.74	2.43	0.31	88.8	0.47	6.1
6.8	1.32	1966	89.5	2.98	1.96	1.02	65.7	0.35	6.5
7.8	1.60	1960	89.0	1.99	1.67	0.32	84.0	0.28	7.1
8.8	1.91	1953	87.8	2.10	1.62	0.48	77.2	0.27	7.0
9.8	2.23	1946	85.8	1.88	1.51	0.37	80.1	0.27	6.5
10.8	2.59	1938	83.2	1.94	1.44	0.50	74.1	0.29	5.7
11.8	2.95	1930	85.6	1.85	1.51	0.34	81.5	0.26	6.8
12.8	3.31	1923	84.8	1.92	1.55	0.38	80.4	0.28	6.5
13.8	3.65	1915	85.9	1.80	1.43	0.36	79.8	0.27	6.2
14.8	4.02	1907	84.9	1.77	1.42	0.36	79.9	0.23	7.1
15.8	4.38	1899	86.4	1.78	1.54	0.23	86.9	0.29	6.1
16.8	4.75	1891	85.7	1.76	1.63	0.13	92.6	0.23	8.2
17.8	5.11	1883	86.0	1.70	1.49	0.22	87.4	0.24	7.2
18.8	5.48	1875	85.4	1.67	1.60	0.08	95.5	0.23	8.1
19.8	5.82	1868	87.2	1.68	1.45	0.24	85.9	0.22	7.6
20.8	6.16	1861	86.8	1.78	1.52	0.25	85.7	0.22	8.0
21.8	6.57	1852	86.7	1.65	1.49	0.15	90.7	0.23	7.6
22.8	6.93	1844	84.9	1.61	1.48	0.13	92.2	0.27	6.5
24.8	7.65	1828	85.2	1.62	1.56	0.06	96.1	0.24	7.5
26.8	8.43	1811	85.6	1.63	1.52	0.11	93.3	0.24	7.3
27.8	8.79	1803	85.9	1.64	1.50	0.15	91.2	0.25	6.9
28.8	9.15	1796	84.6	1.60	1.47	0.13	91.8	0.27	6.4
29.8	9.50	1788	85.8	1.66	1.57	0.09	94.8	0.35	5.2
30.8	9.86		86.0	1.62	1.56	0.06	96.2	0.26	7.1
31.8	10.26		85.2	1.67	1.60	0.07	95.9	0.27	7.0
32.8	10.65		85.5	1.67	1.67	0.00	99.8	0.35	5.5
33.8	11.01		85.7	1.66	1.56	0.10	94.1	0.27	6.7
34.8	11.38		84.9	1.68	1.62	0.06	96.6	0.22	8.7
35.8	11.76		85.9	1.71	1.55	0.17	90.3	0.28	6.4
37.8	12.60		84.9	1.77	1.59	0.17	90.2	0.25	7.5
38.8	12.98		83.3	1.75	1.65	0.10	94.4	0.29	6.6
39.8	13.36		84.5	1.87	1.63	0.24	87.1	0.26	7.4
40.8	13.74	1696	85.6	1.68	1.51	0.17	89.8	0.26	6.7
EH940713-3-1									
0.5				2.93	2.65	0.28	90.6	0.48	6.5
1.5				2.52	2.26	0.26	89.8	0.30	8.8
2.0				2.98	2.66	0.32	89.2	0.44	7.0
2.5				2.86	2.52	0.34	88.1	0.36	8.2
3.0				2.83	2.22	0.61	78.4	0.30	8.5
3.5				2.96	2.60	0.36	87.8	0.45	6.8
4.0				2.84	2.52	0.32	88.9	0.23	12.8
4.5				2.80	2.34	0.47	83.4	0.17	16.2
5.0				2.61	2.24	0.37	85.8	0.17	15.1
5.5				2.30	1.83	0.47	79.6	0.13	16.2
6.5				3.60	3.08	0.53	85.3	0.56	6.5
7.5				2.63	2.09	0.55	79.3	0.18	13.6
8.5				2.48	2.01	0.47	81.2	0.27	8.8
9.5				2.43	1.99	0.44	81.7	0.19	12.5
10.5				2.57	2.03	0.53	79.2	0.16	15.1
11.5				2.37	1.88	0.49	79.2	0.20	10.8

Table 3
Phosphorus speciation, N_{org}, and N_{org}/P_{org} ratios in sediments from core EH911208-3-4

Depth (cm)	Mass depth (g/cm^2)	P_{total} (μg/g)	P_{ads} (μg/g)	P_{Fe} (μg/g)	P_{ca} (μg/g)	P_{inorg} (μg/g)	P_{org} (μg/g)	N_{org} (wt%)	N_{org}/P_{org} (by atom)
0.25	0.09	1512.4	166.3	111.3	488.9	358.1	387.9	0.58	32.9
1.75	0.31	1493.7	115.4	166.6	511.3	314.1	386.3	0.55	31.5
5.75	1.03	1461.4	144.5	152.3	528.2	309.3	327.1	0.47	31.6
10.75	2.59	1279.3	113.9	103.8	411.0	392.8	257.8	0.29	25.2
18.75	5.48	1237.6	115.4	114.4	404.1	362.2	241.5	0.23	21.1
40.75	13.74	1079.0	78.2	5.6	365.0	378.6	251.6	0.26	23.1

2. Sampling and analytical methods

2.1. Sampling

Sediments were collected from the deep part of the lake (site 3) and from close to the outflow (site 1) on 8 December 1991 and 13 July 1994 (Fig. 1, Table 1) using the sediment collector described in Yuan et al. (1993). The cored sediments were undisturbed, as indicated by the clear water–sediment interface and the preservation of fine lamination in the sediments. The top 0.5 cm of sediments consists of brownish yellow particles, representing sediments from the suspended layer. This is followed by a 0.5–1.0 cm thick greyish-yellow sub-diffusive layer at the water–sediment interface containing sporadic concretions. Below 1.0 cm the sediments become dark in color and some black flecks appear at a depth of 4 cm. Gas bubbles appear at a depth of 10 cm due to the decomposition of organic matter in the early diagenetic stage. The cores were immediately sectioned at 0.5–1 cm intervals in situ after collection. All wet samples were weighed and freeze-dried. After weighing the dry samples were ground through a 0.15 mm sieve for geochemical analyses. The porosity and mass depth of each layer were calculated in terms of their wet and dry weights. During the sectioning, the consistency of the sediment cores collected at site 3 were compared, for example, core EH911208-3-4 and core EH911208-3-5 both have the same shell-enriched layer at a depth of 78.0 ± 0.3 cm.

2.2. Analytical methods and results

C_{inorg}, C_{org}, N and P abundances in sediments were determined using a PE2400 SERIES II CHNS element analyzer (Tables 2 and 3). Dry samples were placed in 1N HCl with ultrasonic vibration to remove carbonate. After filtration the residuals were dried under a temperature of less than 60 °C for organic composition analysis. Repeat measurements of standard samples have shown that analytical accuracy was 1–14% for C and 10% for N. The phosphorus concentrations were determined using the procedure outlined by Ruttenberg (1992) and Filippelli and Delaney (1996), which divided phosphorus into adsorbed phosphorus (P_{ads}), iron-bound phosphorus (P_{Fe}), bio-carbonate phosphorus (P_{Ca}), inorganic phosphorus (P_{inorg}) and organic phosphorus (P_{org}) fractions. All the extracted P was determined by spectrophotometer.

Samples from core EH911208-3-4 were selected for the measurement of $\delta^{13}C_{inorg}$, $\delta^{13}C_{org}$ and $\delta^{18}O_{inorg}$ isotopic compositions of carbonate and organic matter in sediments (Table 4). In preparation for $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ analyses, sediment samples were roasted at 475 °C for 15 min to remove organic matter. Carbon dioxide (CO_2) was produced by phosphoric acid to determine $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ values on a MAT 251 mass spectrometer. The standard deviation of duplicate analyses was ±0.5‰. For the carbon isotopic composition of organic matter samples from which carbonate had been removed were placed into pre-combusted quartz tubes. CuO was added to the samples, and the tubes were evacuated and sealed. The tubes were heated to 850°C for 1 h to generate CO_2 gas, which was isolated cryogenically on a vacuum line. The organic carbon isotope content of CO_2 was measured on a MAT 252 (or MAT 251) mass spectrometer with a precision better than ± 1‰. All isotope values are expressed by the conventional delta (δ) notation,

$$\delta^{13}C \text{ or } \delta^{18}O = [(R_{sample}/R_{std}) - 1]1000‰$$

where R_{sample} and R_{std} are the $^{13}C/^{12}C$ or $^{18}O/^{16}O$ isotope ratios corresponding to the sample and the conventional PeeDee Belemnite (PDB) carbonate standard, respectively.

Samples from sediment cores EH940713-1-1 and EH940713-3-2 were selected to determine ^{210}Po activity for $^{210}Pb_{ex}$ sedimentary dating using α-spectroscopy (Table 5). Samples from EH940713-3-2 were taken to determine ^{137}Cs activity using a Canberra S-100 Multi-channel (16384) Analyzer (Table 5).

3. Sediment dating

The sediments in Lake Erhai were dated using ^{137}Cs and ^{210}Pb (Wan, 1999; Xu et al., 1999). The sedimentation rates in Lake Erhai were calculated based on these age constraints (Table 5). The sedimentation rates at sites EH940713-1-1 and EH940713-3-2 are similar, ranging from 0.044 to 0.048 g/cm^2 a. At EH940713-3-2, the sedimentation rate determined by ^{137}Cs (0.047 g/cm^2 a) is close to the rate based on $^{210}Pb_{ex}$, confirming the reliability of the dating. In addition, ^{137}Cs dating results show that mean sedimentation

Table 4
$\delta^{13}C_{org}$, $\delta^{13}C_{inorg}$, and $\delta^{18}O_{inorg}$ values and $\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$ ratios in sediment from core EH911208-3-4

Depth (cm)	Mass depth (g/cm^2)	Calculated age (AD)	$\delta^{13}C_{inorg}$ (‰)	$\delta^{18}O_{inorg}$ (‰)	$\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$	$\delta^{13}C_{org}$ (‰)
0.4	0.06	1991				−26.77
1.3	0.24	1987	−5.2	−9.6	0.54	−28.06
2.3	0.46	1982				−27.14
3.3	0.70	1977	−6.0	−9.8	0.61	−27.50
4.3	0.96	1971				−27.36
5.3	1.22	1965	−6.0	−10.9	0.55	−27.32
6.3	1.49	1960				−27.29
7.3	1.77	1954	−3.3	−9.4	0.35	−27.38
8.3	2.05	1947				−27.07
9.3	2.34	1941				−24.94
10.3	2.64	1935	−2.0	−8.4	0.24	−26.67
11.3	2.94	1928	−3.0	−9.2	0.33	−26.07
12.3	3.24	1922	−1.8	−7.9	0.23	−26.39
14.3	3.86	1908	−1.9	−8.4	0.23	−27.31
15.3	4.18	1901	−1.7	−7.4	0.23	−27.74
16.3	4.50	1894	−2.0	−8.4	0.24	−27.33
17.3	4.82	1887	−2.2	−8.6	0.26	−26.19
18.3	5.14	1880				−26.73
19.3	5.47	1873	−2.4	−8.0	0.30	−26.04
20.3	5.80	1866				−27.17
21.3	6.13	1859	−2.7	−9.5	0.28	−27.33
23.3	6.81	1844	−2.6	−9.0	0.29	
24.3	7.15	1837				−26.43
25.3	7.49	1829	−2.8	−10.4	0.27	−25.03
27.3	8.18	1814	−2.3	−9.4	0.24	−25.41
28.3	8.53	1807				−26.65
29.3	8.88	1799				−26.05
30.3	9.23	1791				−26.36
31.3	9.59	1784	−4.0	−10.7	0.37	−25.84
32.3	9.94		−3.9	−13.6	0.29	−26.40
34.3	10.66		−4.8	−11.7	0.41	−26.37
35.3	11.02		−3.9	−13.6	0.29	−26.56
36.3	11.39					−26.34
38.3	12.12					−25.83
39.3	12.48		−4.8	−11.7	0.41	−26.96
41.3	13.22					−27.02
42.3	13.60					−27.17
43.3	13.97	1688	−2.7	−9.7	0.28	−26.11
45.3	14.72					−27.02
46.3	15.10					−27.08
47.3	15.48		−3.9	−10.3	0.38	−27.26
48.3	15.86					−25.81
50.3	16.63					−26.95
51.3	17.01					−25.54
52.3	17.39					−26.51
53.3	17.78					−25.16
54.3	18.17					−25.57
55.3	18.56	1589	−4.9	−9.9	0.49	−25.11
58.3	19.73		−4.9	−10.5	0.47	−26.71
60.3	20.52					−26.68
61.3	20.92					−27.16
62.3	21.31					−27.47
63.3	21.71		−3.0	−7.7	0.39	−27.28
64.3	22.11					−27.31
66.3	22.91					−27.55
67.3	23.31	1485	−1.6	−5.7	0.28	−28.03
68.3	23.71					−27.88
69.3	24.12		−2.4	−7.2	0.33	−27.41
70.3	24.52					−27.33
71.3	24.93		−4.7	−9.1	0.52	−27.52
72.3	25.33					−27.64
73.3	25.74					−27.53
74.3	26.15					−27.54
75.3	26.56					−27.64
76.3	26.97					−27.45
77.3	27.38		−3.1	−9.5	0.33	−27.56
78.3	27.79	1388				−27.58
79.6	28.32		−7.9	−10.6	0.75	−27.48
80.6	28.74					−27.34
82.6	29.57		−5.9	−8.8	0.67	−27.19
83.6	29.98					−27.27
84.6	30.40					−27.70
85.6	30.82		−5.0	−7.8	0.64	−27.83
86.6	31.23					−27.83
87.6	31.65					−27.87
88.6	32.07		−2.6	−6.5	0.40	−27.88
89.6	32.49	1286				−27.85

Table 5
^{137}Cs and ^{210}Pb dating of Lake Erhai sediments and calculated sedimentation rates

Dating method	Core No.	Time marker (calendar year)	Mass depth (g/cm^2)	Sedimentation rate (g/cm^2 a)
^{137}Cs	EH940713-3-2	1964	1.455	0.048 ± 0.003
		1975	0.888	0.047 ± 0.002
		1986	0.370	0.046 ± 0.005
		Average		0.047 ± 0.002
^{210}Pb$_{ex}$	EH940713-3-2	0.433–7.277		0.045
	EH940713-1-1	Full core		0.044

rates in the deep part of the lake (site 3) have been very stable over the past 35 years (Table 5). This suggests a consistent sedimentation rate and a continuous sedimentary record in the deeper part of the lake. The bottom of core EH911208-3-4 at 90 cm represents sediments deposited 697 ± 15 years ago (i.e. 1280–1310 AD), calculated using the mean deposition rate of 0.046 ± 0.001 g/cm^2 a. At EH911208-3-5, the bottom of core at 83 cm, consists of sediments deposited about 646 ± 15 years ago (i.e. 1331–1361 AD). Sediment cores collected at site 3 with an average sedimentation rate of 0.046 ± 0.001 g/cm^2 a are used in the following calculations.

4. Carbon in sediments

There are two carbon processes in lake sediments: the first is solution and precipitation of inorganic carbonate, and the second decomposition of organic matter and transformation of organic carbon. Precipitation of carbonate is regarded as the major sink for inorganic carbon during endogenic and authigenic processes (Jones and Bowser, 1978). Organic carbon in lake sediments comes from terrestrial bio-detritus, biorelicts of plankton and benthos, fatty acids, the hydrocarbons and protein from microorganisms at the lake bottom. Organic matter in sediments takes part in various biochemical and geochemical reactions and is one of the active biogeochemical species. In early diagenesis, decomposition of organic material in sediments could produce HCO_3^-, changing the alkalinity of pore-waters and the concentration of dissolved inorganic carbon (DIC), and, therefore, changing the equilibrium relationships of carbonate in pore-water (Emerson, 1976; Lerman, 1979; Berner, 1980; Tang and Wan, 1992).

Table 6
Carbon speciation in sediments from core EH940713-3-2 and core EH940713-3-1

Core No.	Selected mass depth (g/cm^2)	C_{total} (wt%)	C_{org} (wt%)	C_{inorg} (wt%)	C_{org}/C_{total} (%)
EH940713-3-2	0–41	2.05	1.79	0.27	87.9
	0–11.8	2.70	2.24	0.46	82.6
EH940713-3-1	0–11.5	2.73	2.31	0.42	84.2

Comparing vertical profiles among total, organic and inorganic carbon in cores EH940713-3-2 and EH940713-3-1 (Table 6, Fig. 2), the following features can be observed:

(1) C_{total} and C_{org} in vertical profiles of the cores show a similar trend, with concentrations decreasing gradually within the top 10 cm of the cores, and then tending towards a constant value;
(2) C_{org} in the sediments dominates C_{total}. The average contents of C_{total}, C_{org} and C_{inorg} in core EH940713-3-2 (41 cm length) are 2.05, 1.79 and 0.27%, respectively, and the mean C_{org} content is about 87.9% of the C_{total} (Fig. 2a);
(3) C_{inorg} concentrations in the core are not only lower but show a distinct fluctuation within 10 cm of the top of the core (Fig. 2b); and
(4) The vertical profiles of C_{total}, C_{org} and C_{inorg} are generally comparable for different cores. The different carbon fractions at an equivalent depth were similar in EH940713-3-2 and EH940713-3-1 (Table 6, Fig. 2b and c).

4.1. Organic carbon in sediments

In a similar way to the decomposition of organic matter in oceanic sediments during early diagenesis (Tromp et al., 1995), C_{org} vertical profiles in sediment cores of Lake Erhai show three distinct stages, i.e. 'deposition–decomposition–accumulation' (Fig. 3, Table 7). The 'deposition stage' refers to the first few years of the sedimentary record where particulate organic matter has been deposited from lake waters at the sediment interface. The concentration of C_{org} is maintained at a constant value without apparent decomposition during this period. The 'decomposition stage' is an early diagenetic stage that lasts several decades, during which organic matter is decomposed by bio-oxidation. As a result, the concentration of C_{org} rapidly decreases during this period. The 'accumulation stage' preserves the residual C_{org} that survives the decomposition stage.

The content of organic carbon during the deposition stage reflects the depositional flux of organic matter through the lake waters, which is directly related to the productivity of ecological systems. The concentration in the accumulation stage is a residual of the decomposition of organic

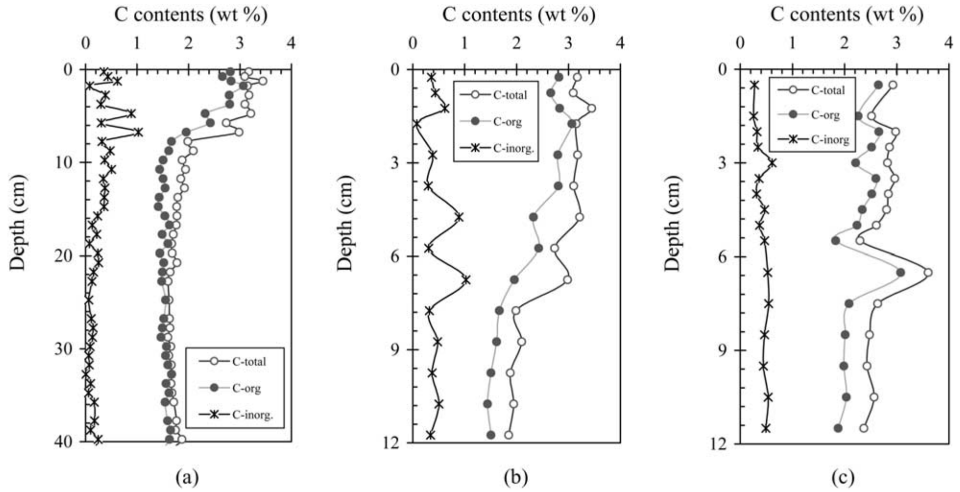

Fig. 2. C_{total}, C_{org} and C_{inorg} in sediments from core EH940713-3-2 (a and b) and EH940713-3-1 (c), Lake Erhai. Note: the C content in the upper 12 cm sediments in (a) is enlarged as (b).

matter after early diagenesis, the fraction that remained relatively stable in the carbon cycle. The carbon accumulation flux (Table 7), therefore, represents relatively stable carbon after decomposition. In any environmental study, the difference between deposition and accumulation fluxes should be clearly distinguished when evaluating changes in pollutant concentrations recorded in aquatic sediments over recent decades (Wang and Cappellen, 1996; Viollier et al., 1995; Kolak et al., 1998; Vallius and Lehto, 1998; Winkels et al., 1998; Gustafsson and Gschwend, 1998). In some studies, differences between the deposition flux and accumulation flux have been ignored. Both were ambiguously regarded as a measure of primary productivity leading to unnecessary confusion.

Fig. 3 shows the vertical distribution of C_{org} in cores EH940713-3-2 and EH911208-34. Although the two cores were collected at the same site in different years and seasons, they have similar vertical profiles, indicating the similarity in the biogeochemical behavior of C_{org} after deposition (Fig. 3a). Based on the variations of C_{org} in the vertical profiles, depositional flux, decomposition rate constant, and accumulation rate have been calculated (Fig. 3b, Table 7). The mean deposition flux for C_{org} in the deep part of the lake was 12.7 g/m^2 a, whereas the accumulation flux was 7.20 g/m^2 a. This means that the accumulation flux of C_{org} after early diagenesis was only 54.5% of the deposition flux. The average decomposition rate constant for C_{org} during early diagenesis was 0.017 a^{-1} and average half life was 40.4 a (Table 7).

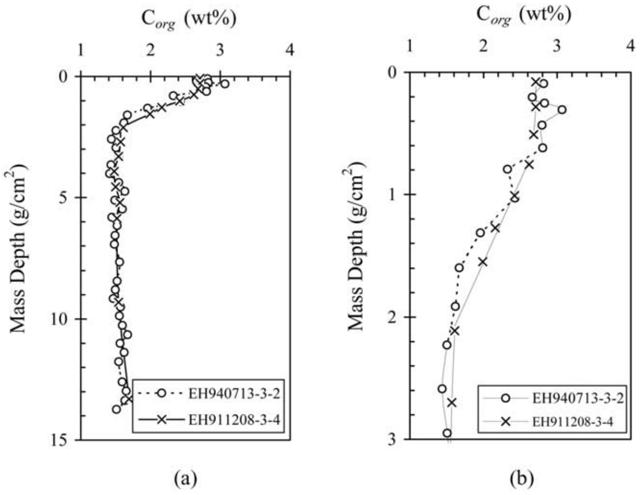

Fig. 3. C_{org} in sediments from cores EH940713-3-2 and EH911208-3-4. The C_{org} of the upper 3 g/cm^2 of sediment in (a) is enlarged as (b).

4.2. Inorganic carbon in sediments

The reservoir of C_{inorg} in sediments is carbonate minerals, mainly calcite. Previous study (Tang and Wan, 1992) has shown that:

(1) Pore-water in the upper part of the sediment core is undersaturated with respect to calcite, because of a higher rate of decomposition of organic matter during early diagenesis. With increasing depth in the sediment cores, the HCO_3^-/Ca^{2+} ratio increases and pore-waters become gradually saturated with carbonates (Tang and Wan, 1992).

(2) The effects of early diagenesis on carbonate sediments are characterized by dissolution of allogenic and endogenic carbonate and precipitation of authigenic carbonate minerals.

Carbonate deposition flux in the lake is associated with the deposition of land-derived carbonate minerals, as well as the direct precipitation of endogenic carbonate from lake waters. Although the Lake Erhai catchment has a well-developed carbonate landscape with a mineralogy composed mainly of low magnesium calcite with a molar content of $MgCO_3$ of about 5%, endogenic carbonate may dominate the deep part of the lake away from the main input

Table 7
Calculated fluxes of C_{org}, N_{org}, P_{org}, P_{total} during depositional, decomposition, and accumulation stages in Lake Erhai sediments

Content	Core No.	Deposition stage		Decomposition stage		Accumulation stage	
		Depth (cm)/time(a)	Deposition flux (g/m^2 a)	Depth (cm)/time(a)	Decomposition rate constant (a^{-1})	Half life (a)	Accumulation flux (g/m^2 a)
C_{org}	EH940713-3-2	4/13.5	13.0	10/35	0.0177	39.1	7.08
	EH911208-3-4	4.5/13.0	12.4	10/33	0.0166	41.7	7.32
	Average	4/13	12.7	10/34	0.0172	40.4	7.20
N_{org}	EH940713-3-2	4/13.5	2.62	10/35	0.0234	29.6	1.21
P_{org}	EH940713-3-2	10/48.5	0.18				0.12
P_{total}	EH940713-3-2	10/48.5	0.69				0.55

source. CO_2 assimilation during photosynthesis by plankton in lake waters is one of the major factors resulting in deposition of endogenic carbonate. Enhancement of plankton photosynthesis consumes CO_2 and leads to the reaction equation:

$$Ca^{2+} + 2HCO_3^- \Leftrightarrow CaCO_3 + H_2O + CO_2$$

moving towards the right, resulting in precipitation of endogenic carbonate. In addition, strong evaporation of lake water can also cause carbonate precipitation.

The C_{inorg} vertical profile in core EH940713-3-2 shows that C_{inorg} contents in sediments start to decrease below a depth of 10 cm and then reaches a constant value, with slight fluctuations, below 15 cm depth (Fig. 2a). This is compar-

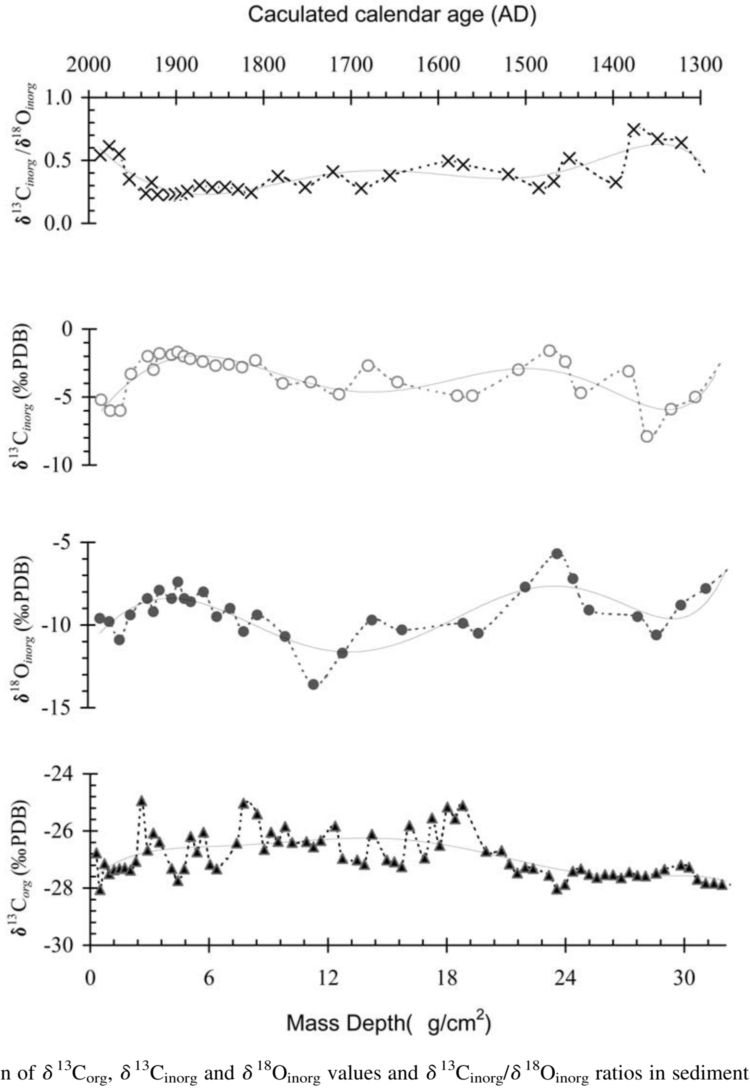

Fig. 4. The temporal variation of $\delta^{13}C_{org}$, $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ values and $\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$ ratios in sediments from core EH911208-3-4.

able with the vertical trend for C_{org} in the sediments. On the basis of tending towards an equilibrium concentration below a depth of 15 cm, the calculated C_{inorg} accumulation flux in core EH940713-3-2 is about 0.62 g/m^2 a, which is only 8.6% of that of C_{org}. The accumulation flux of total, organic and inorganic carbon in the deep part of Lake Erhai, therefore, was 7.4, 6.8 and 0.62 g/m^2 a, respectively.

5. Isotopic composition of carbon and oxygen in sediments

5.1. $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ in lake sediments

$\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ of carbonate in lake sediments can vary seasonally, reflecting seasonal variations in temperature, bioactivity, and productivity (Ostrom et al., 1997). Carbon isotopic composition in endogenic carbonate in lake sediments depends on the $^{13}C/^{12}C$ values of the DIC in the lake waters. DIC isotopic compositions in lake waters are affected by photosynthesis–respiration and atmospheric CO_2, as well as by the hydrological conditions of the lake (McKenzie, 1985; Herczeg, 1988).

Based on the analyses of six water samples collected at different depths of the lake waters at the site of EH911208-3-4, the average $\delta^{13}C_{(DIC)}$ is $-6.1 \pm 0.9‰$. Since the calculated theoretical isotopic fractionation between $\delta^{13}C_{(CaCO_3)}$ and $\delta^{13}C_{(DIC)}$ ranges from 0.09 to 0.97‰ when pH 8.5, $T = 10–25$ °C (Veizer, 1992), the $\delta^{13}C$ in endogenic carbonate should be -6.0 to $-5.1‰$. The average $\delta^{13}C_{inorg}$ values for the top 0–5 cm of sediments is $-5.7‰$, close to the predicted equilibrium carbon isotopic value range of lake waters (Table 4). Therefore, in stratified, eutrophic, and fresh-water lakes, large seasonal photosynthesis events and their corresponding $^{13}C/^{12}C$ in DIC could be also recorded in endogenic carbonate and stored in lake sediments.

Fig. 4 shows the vertical variations of $\delta^{13}C_{org}$, carbonate $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ in sediments from EH911208-3-4. The vertical variation of $\delta^{13}C_{inorg}$ is similar to that of $\delta^{18}O_{inorg}$. The synchronous change of $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ is one of the characteristics for enclosed lakes that are dominated by isotopic composition exchange between water and air and biogeochemical process (Talbot, 1990). Although Lake Erhai is not strictly an enclosed lake, its $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ values also have this characteristic because of its relatively long residence time (~2.75 a) and high evaporation rate. The synchronous change of $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ in sediment cores, thus, not only occurs in enclosed lakes but also in non-restricted lakes with long residence time and high evaporation rate.

The synchronous changes of $\delta^{13}C_{inorg}$ and $\delta^{18}O_{inorg}$ in Lake Erhai carbonates can be used to interpret climatic changes if input of allogenic carbonate remains consistent. When the atmospheric temperature in the lake region increases, evaporation intensifies and ^{18}O is enriched in lake waters. The reason for corresponding synchronous change of $\delta^{13}C_{inorg}$ is less certain. An increase in temperature, however, could enhance organic production in the lake and, therefore, increase values of $\delta^{13}C_{(DIC)}$ in the lake waters. During the past 700 years, $\delta^{18}O_{inorg}$ and $\delta^{13}C_{inorg}$ values vary over two and a half periods of ‘heavy–light–heavy’ (Fig. 4), which are interpreted to be a response to ‘warm–cold–warm’ climatic changes in the Lake Erhai region. In addition, a decrease in the $\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$ ratio (Fig. 4) can be attributed to the increasing of $\delta^{13}C_{inorg}$ values as a result of enhanced biogenic production due to the temperature increase. The decrease in $\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$ ratios in past a few century (Fig. 4) could, therefore, be related to enhanced biogeochemical action; whereas an increase in $\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$ ratios corresponds to diminution of bioactivity in the lake. Fluctuations of $\delta^{18}O_{inorg}$, $\delta^{13}C_{inorg}$ and the $\delta^{13}C_{inorg}/\delta^{18}O_{inorg}$ ratio in the different periods, therefore, reflect changes of climate and biomass productivity during these periods.

5.2. $\delta^{13}C_{org}$ in lake sediments

Organic matter in lake sediments originates from both biorelicts derived from the catchment and aquatic biomass residuals produced within the lake. The former reflects the characteristics of biogeochemical process within the watershed, whilst the latter indicates hydrological conditions and productivity within the lake itself. Different species produce different biochemical components in the lake and its catchment. Changes in the community structure of a species result in variations in the type and quantity of organic matter deposited in the lake. The abundance of organic matter and the elemental and isotopic composition of organic matter are related to bioactivity, climate, hydrological conditions and bedrock lithology within the lake and its catchment. In addition, the initial constituents of organic matter in sediments are subject to modification by microbial activities.

In general, the source of organic matter varies in different lakes (Hedges and Keil, 1995; Wachniew and Rózanski, 1997; Ostrom et al., 1998). Organic matter from the catchment can be a significant source for low productivity lakes. High productivity lakes are dominated by organic matter produced in the water bodies of lakes (Brunskill et al., 1971; Gorham et al., 1974; Wetzel, 1975). $\delta^{13}C_{org}$ values range from -22 to $-32‰$ for C3 plants, -6 to $-19‰$ for C_4 plants, -10 to $-23‰$ for Crassulacean acid metabolism (CAM) plants, and -10 to $-50‰$ for aquatic plants, whilst lake sediments with multiple sources of organic matter can have variable $\delta^{13}C_{org}$ values (Talbot and Johannessen, 1992; Meyers and Eadie, 1993). Isotopic compositions of C_{org} in sediment core EH911208-3-4 are plotted in Fig. 4, which shows:

(1) $\delta^{13}C_{org}$ values of in Lake Erhai range from -25.0 to $-28.0‰$, which are isotopically lighter than other

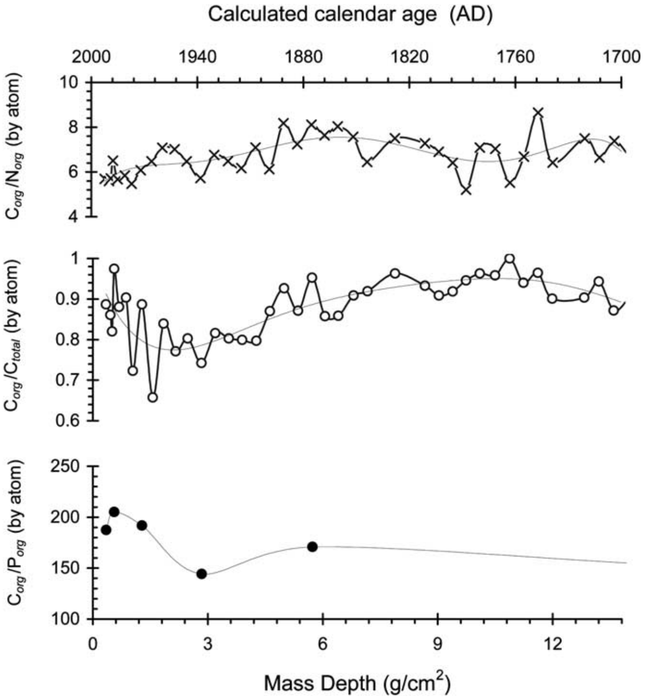

Fig. 5. Atomic ratios of C_{org}/N_{org}, C_{org}/C_{total}, and C_{org}/P_{org} in core EH940713-3-2.

carbon sources, indicating that organic matter in Lake Erhai originates mainly from land-derived higher plants;

(2) Within the upper 62 cm (or upper 25 g/cm^2) of the sediment core (i.e. up to 1537 AD), $\delta^{13}C_{org}$ values fluctuated frequently with small amplitudes, implying that the impacts of anthropogenic activities on plant productivity in the Lake Erhai watershed was initiated at least 460 years ago;

Table 8
Atomic ratios of C_{org}, N_{org} and P_{org} in sediments from core EH940713-3-2

	C_{org}/N_{org}	N_{org}/P_{org}	C_{org}	N_{org}	P_{org}
Deposition stage	5.8	32	186	32	1
			1	0.17	0.0054
Accumulation stage	6.8	22	152	22	1
			1	0.15	0.0066
Redfield ratio	6.6	16	106	16	1
			1	0.15	0.0094

(3) elow the depth of 62 cm (or upper 25 g/cm^2), $\delta^{13}C_{org}$ values stabilized to -27.0 to -28.0‰, which can be used as the background baseline value for $\delta^{13}C_{org}$ in Lake Erhai sediments.

6. Relationships between carbon, nitrogen and phosphorus

C, N and P are fundamental elements for biogeochemical cycles, and their distribution should reflect the basic characteristics of regional ecosystems. Carbon is a bridge that connects organic biomass and the inorganic world. Carbon transformation could result in evolution between inorganic and organic materials, between biomass and non-organic carbon. Study of the geochemical speciation and composites of C and related elemental N and P can provide a valuable way to resolve the input from anthropogenic and natural sources.

6.1. Characteristics of C_{org}/N_{org} in sediments

Atomic ratios among elemental C_{org}, N_{org} and P_{org} have been calculated on the basis of their concentrations in the

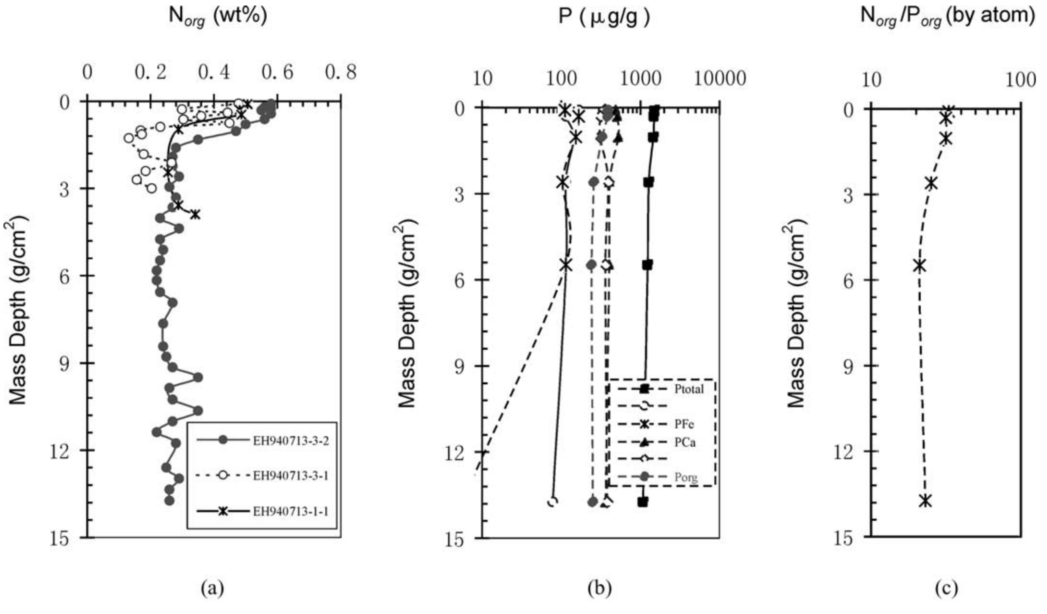

Fig. 6. N_{org} (a), P speciation (b), and N_{org}/P_{org} (c) ratio in sediments from core EH940713-3-2.

organic matter of lake sediment at the deposition and accumulation stages (Figs. 5 and 6) and compared with C_{org}, N_{org} and P_{org} characteristics of marine organic matter. The atomic ratio of $C_{org}/N_{org}/P_{org}$ for the marine algal protoplasm is typically 106:16:1 (Table 8), which is also called the Redfield ratio (Redfield et al., 1963). The pattern of the vertical profile of N_{org} of sediments from core EH940713-3-2 is similar to that of C_{org}, and can be divided into three stages, deposition–decomposition–accumulation, as organic matter progressively breaks down (Fig. 6a). Their chrono-sequences are also the same. However, the decomposition rate constant of organic nitrogen is 1.4 times that of C_{org} at the accumulation stage, and its half life is only 3/4 that of C_{org}. In addition N_{org} has the same decomposition time as C_{org}, so its accumulation rate is about 46.0% of its deposition flux. In comparison the organic carbon accumulation rate is 54.5% of its deposition flux (Table 7). Although the vertical profiles of N_{org} content in other sediment cores are irregular, their trends are similar (Fig. 6a).

The concentrations of both C_{org} and N_{org} in sediment are subject to change due to the decomposition of organic matter that depends on the activity of microorganisms in the sediments (Sarazin et al., 1992). Atomic ratios between C_{org} and N_{org} maintain a consistent relationship in both the deposition (5.8) and accumulation stages (6.8), suggesting that the decomposition of organic matter is not very selective. The ratios of C_{org}/N_{org} in sediments are similar to the Redfield ratio (Table 8). As organic matter in buried sediments is generally better preserved than the suspended organic particulates in the water column (Ishiwatari et al., 1980; Hedges and Keil, 1995), the C_{org}/N_{org} atomic ratio of 6.8 during the accumulation stage can be considered representative for Lake Erhai sediments.

Differences in C/N found in various lakes result from different source materials (Bainers et al., 1994; Meyers, 1994; Meyers and Ishiwatari, 1993; Mayer, 1994; Hedges and Keil, 1995). Generally, C/N is 20 for cellulose plant detritus and C/N = 4–12 for non-cellulose plant detritus. C/N ratios in zooplankton are lower than those in phytoplankton. C/N in the upper sediments of many lakes ranges from 6 to 14. C_{org}/N_{org} in Lake Erhai sediments ranges from 5.8 to 6.6, and $\delta^{13}C_{org}$ was −27.6‰, indicating that the main source of organic matter in Lake Erhai originates from land-derived non-cellulose plants. A change of C_{org}/N_{org} and $\delta^{13}C_{org}$ values might also be related, among other things, to the type of organic matter from the catchment ecosystem.

6.2. Phosphorus in sediments

The burial of phosphorus in sediment is closely related to that of organic matter (McManus et al., 1997). The distribution of phosphorus species in the surfacial sediments in core EH940713-3-2 is $P_{Ca} > P_{org} > P_{inorg} > P_{Fe} > P_{ads}$ (Fig. 6b), and their abundance changes with sediment depth. Trends for P_{Ca}, P_{org} and P_{total} are comparable and similar to the trend for the C_{org} decomposition. P_{inorg} values increases with burial depth as a result of P_{org} transformation during early diagenesis of organic matter. Contents of P_{Fe} and P_{ads} were lower, with only minor fluctuations. Based on the average contents, the deposition fluxes of P_{total} and P_{org} at the water–sediment interface were calculated as 0.69 and 0.18 g/m^2 a, respectively; and for their accumulation flux below a depth of 10 cm as 0.55 and 0.12 g/m^2 a, respectively (Table 7).

The relative abundance of N and P in lakes is a major marker of lake eutrophication. In Lake Erhai sediments, the ratio of N/P reaches 32 in the deposition stage, but it decreases to 22 during the accumulation stage, which is close to the Redfield ratio of 16 (Table 8, Fig. 6c). This suggests that P is low in Lake Erhai and that P concentrations are a limiting factor for eutrophication in Lake Erhai. This is similar to the results from other lakes investigated on the Yunnan–Guizhou Plateau (Bai et al., 1996; Wu et al., 1996).

6.3. Relationships of C/N/P in sediments

The composition of seawater is more stable, and less affected by terrestrial sources, than lake waters. The growth of phytoplankton in seawater, unlike that in lake water, is not restricted by the supply of N and P nutrients. Therefore the composition of depositional particulates in seawater is relatively uniform, and their C/N/P values are consistent, similar to those of living cells. In comparison to seawater, concentrations of C and N in lakes are much higher. Usually, large deep lakes have sufficient nutrients, as well as stable physical–chemical–hydrological conditions, and their ratios of C, N and P are, therefore, close to the Redfield ratio (Hecky et al., 1993). If the ratios of nutrient elements in the lakes were close to the Redfield ratio, the phytoplankton would have adequate nutrition with an optimum growth rate that is close to that of the ocean.

In fresh water lakes, organic particulates can be considered as originating mainly from terrestrial environments if they have high C/N, C/P and N/P ratios compared with the Redfield ratio. In general, C/N, C/P and N/P values of particulates in lakes are higher than those in the ocean. Specifically, the ratios are relatively low in lakes in polar regions but higher in oligotrophic lakes in equatorial and temperate zones, or in lakes that have long water residence times. Comparing the atomic proportions of C_{org}, N_{org} and P_{org} in core EH940713-3-2 in the deposition stage to the accumulation stage (Table 8, Fig. 5), the following conclusions can be drawn:

(1) $C_{org}/N_{org}/P_{org}$ ratios are closer to the Redfield ratio of the marine organic matter at the accumulation stage than that at the deposition stage, especially for the C_{org}/N_{org} ratio which is similar to that of the ocean (0.15);
(2) P_{org}/C_{org} ratio at the deposition stage is 0.0054, but increases to 0.0066 at the accumulation stage owing to

the decomposition of the organic matter. This ratio, however, is still lower than the Redfield ratio of 0.0094.

7. Summary and conclusions

(1) The vertical variations of C_{total}, C_{org} and C_{inorg} throughout the cores are relatively small. C_{total} and C_{org} show similar trends; C_{org} is the dominant form, accounting for 87.9% of the C_{total}. Because pore-waters are undersaturated with respect to calcite, contents of C_{inorg} show slight fluctuations through the core profiles.

(2) The vertical profiles of C_{org} in Lake Erhai sediment have distinct characteristics with three stages of deposition–decomposition–accumulation resulting from the decomposition of organic matter during early diagenesis; Average deposition and accumulation fluxes for C_{org} are 12.7 and 7.2 g/m^2 a, respectively. The accumulation flux is 54.5% of the deposition flux. The accumulation flux for C_{inorg} is 0.62 g/m^2 a, only 8.6% for the C_{org}. During early diagenesis, the decomposition rate constant of the C_{org} is 0.017 a^{-1} and the half life is 40 a.

(3) $\delta^{18}O_{inorg}$ and $\delta^{13}C_{inorg}$ values in the Lake Erhai sediment show similar trends. The positive excursion of $\delta^{18}O_{inorg}$ can be interpreted due to stronger evaporation of lake water due to higher seasonal temperatures, whereas an increase in $\delta^{13}C_{inorg}$ values can be attributed to an increase in organic production related to higher temperatures. $\delta^{18}O_{inorg}$ and $\delta^{13}C_{inorg}$ trends of two and a half periods of heavy–light–heavy isotopic ratios can be interpreted as a result of climatic change of warm–cold–warm during the past 700 years in this area. The ratio of $\delta^{18}O_{inorg}$ and $\delta^{13}C_{inorg}$ tends to increase with time, suggesting a diminution of biogeochemical activity.

(4) The C_{org} isotopic compositions in the sediment are light, ranging from −25 to 28‰ with range of only 3‰, indicating that organic matter originated mainly from terrestrial plants. Records over the upper 62 cm of the sediment core, i.e. 460 years (AD 1537–present) show frequent small fluctuations in $\delta^{13}C_{org}$ suggesting that biological production was stable with a clear anthropogenic impact in the Lake Erhai region. Below a depth of 62 cm, $\delta^{13}C_{org}$ remained constant with an average background value of −27‰.

(5) N_{org} in the sediment shows similar vertical profiles to the C_{org}. The average deposition flux of N_{org} is 2.62 g/m^2 a, with 1.21 g/m^2 a for the accumulation flux which is just 46.0% of the deposition flux; the decomposition rate constant of N_{org} is 1.4 times that of C_{org}, but its half life is only 3/4 of the C_{org}. The concentrations of P species from highest to lowest are P_{Ca}, P_{org}, P_{inorg}, P_{Fe} and P_{ads}. The vertical trends in concentration of P_{org}, P_{total}, and P_{Ca} in the sediment cores are similar, and similar to the C_{org}. Concentrations of P_{inorg} increase with depth due to transformation of the P_{org}. Mean depositional fluxes for P_{total} and P_{org} are 0.69 and 0.18 g/m^2 a, respectively, with accumulation fluxes of 0.55 and 0.12 g/m^2 a.

(6) The mean ratios of C_{org}/N_{org} are 5.8 and 6.8 for the deposition and accumulation stages, respectively. The C_{org}/N_{org} ratio at the accumulation stage is similar to the Redfield ratio in the ocean. The C_{org}/N_{org} ratios and $\delta^{13}C_{org}$ values suggest that organic matter in the sediments originates mainly from land-derived non-cellulose plants. C_{org} and C_{org}/N_{org} tend towards a constant value at depth, suggesting that signatures of the watershed ecosystem can be preserved in the organic carbon in the sediments.

In conclusion, Lake Erhai is an inland lake with C, N and P geochemistry characterized by a ‘low latitude–high altitude effect’, which may be attributed to the uplift of the Himalayas. Future study will focus on a comparison of sediments between different lakes in order to reveal trends in the influence of the Himalayas uplift.

Acknowledgements

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