Recent climate changes recorded by sediment grain sizes and isotopes in Erhai Lake*

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Abstract By careful sampling and accurate analysis of recent sediments, the time series of sediment grain sizes and $\delta^{18}O$, $\delta^{13}C$ of carbonates in recent 700 years are successfully established, based on which the evolutionary history of the regional climate and environment in Erhai Lake is reconstructed. The results show that the climatic succession type in the region of Erhai Lake is warm-dry and cold-humid alternatively, and there exist 200 and 400 years of quasi-periodical changes in temperature and 100, 200 and 400 years of quasi-periodical changes in aridity/humidity regime. The two coldest periods in recent 700 years occurred in the 14th century and the duration of 1550—1800 AD. The latter period may be the imprint left of the Little Ice Age.

Keywords: lake sediments, mean grain size, carbonate, isotope, climate changes, Erhai Lake.

For the past 50 years, the global palaeoclimate has been successfully reconstructed by geologists using a variety of natural records such as ice core, loess and deep-sea sediments[1—6]. However, these studies mostly focused on the southeast monsoon zone and mainly dealt with long time span (more than 1 000 000 years), long time scale (thousand to ten-thousand years) climate changes. Along with the appearance of a series of global environmental problems such as "greenhouse effect", soil desolation and shortage of freshwater, the short time scale climate changes (annual, decadal and century scale) occurred relatively close to the present have become increasingly concerned. For this reason, the main aim of the Past Global Changes/Palaeoclimates of the Northern and Southern Hemispheres (PAGES/PANASH) project will be at acquiring continuous and high-resolution natural records in recent 2 000 years[7,8].

As a main lodging of surface substances, lake sediments continuously and sensitively reflect regional and global environment with annual to decadal resolution. Undoubtedly this information is very useful to accomplish the PAGES/PANASH project. As an important tache for comparing the East Asian Monsoon with the Indian Monsoon, the palaeoclimate study in the southwest monsoon zone has major implications for extending and perfecting the Asian palaeomonsoon study[9]. Until now the investigation on the palaeoclimate in this region has not been extensively conducted. In this study, Erhai Lake, located on Yun-Gui Plateau, is selected to reveal the characteristics of climate change in the southwest monsoon zone, and to reconstruct the evolutionary history of the regional climate and en-

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vironment.

1 Methods

Two sediment cores (EH911208-3-4, 90 cm; EH911208-3-5, 82 cm) were obtained from deep-water location of Erhai Lake in 1991, using a self-designed sediment-water interface sampler[10]. The sediment cores were perfectly preserved, the suspended layer was not disturbed and the interface water was clear. They were cut into 0.5—1.0 cm pieces upon sampling.

$\delta^{18}O$ and $\delta^{13}C$ of sediment carbonates in the core EH911208-3-4 were determined by the phosphoric acid method[11]. The samples were ground to homogeneous powders and baked for 15 min at 475℃ with flowing N_2 to remove organic matter. Then the samples were reacted with 100% phosphoric acid in a vacuum tube for 6 h at 25℃. The extracted CO_2 was purified and the carbon and oxygen isotopic ratios were measured by the MAT-252 gas mass spectrometer. The results are expressed with reference to the Peedee Belemnitela (PDB) standard with an error less than 0.1‰.

Grain sizes of the core EH911208-3-5 were measured by the scanning photo sedimentography (Analysette 20, Germany). The measure range of grain sizes is 0.5—500 μm with an error less than 3%.

2 Results and discussion

2.1 Sediment grain sizes in Erhai Lake

Sediment grain sizes in the core EH911208-3-5 are smaller than 60 μm. The major fraction of sediments is fine silt (2 μm—20 μm) which accounts for 62.6%—84.1%. The coarse silt (20 μm—60 μm) accounts for 4.6%—29% and the clay fraction (< 2 μm) 4.0%—25.1%. Thus, the Erhai sediments can be nominated as clay silt.

Dating result of radionuclides ^{137}Cs and $^{210}Pb_{ex}$[12,13] shows that the average sedimentation rate in Erhai Lake is $0.046\ g \cdot cm^{-2} \cdot a^{-1}$, according to which the age for each sediment sample was obtained by high-resolution calculations. Time series of sediment grain sizes in the core EH911208-3-5 are shown in fig. 1. It can be seen that mean sediment grain size varies from 8.55 μm to 15.52 μm, showing a "W" type (solid line) change trend with time.

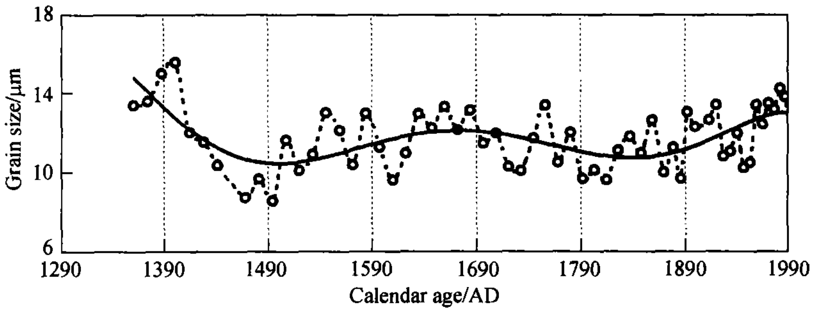

Fig. 1. Variation of mean sediment grain size in the core EH911208-3-5.

The previous studies have pointed out that physical energy of lake water is an important factor determining sediment grain size. Fine sediments and coarse sediments represent respectively lower and higher physical energy of lake water, namely higher water level and lower water level[14,15]. In fact, this rule is applicable only to closed lakes in long time scale studies. Erhai Lake is a semi-enclosed spillover lake. In the past several hundred years, the water level possibly did not fluctuate violently. In order to control the water level of Erhai Lake, a water gate was built at the exit in 1963 by the local government. Before that, the water level was naturally modulated. Hydrological data from the Dali Hydrological Station shows that the water level of Erhai Lake basically stabilized at 1 974 m (table 1), with interannual variations less than 0.40 m, although the rainfall varies greatly from 1952 to 1963. This shows the inherent characteristics of the semi-enclosed spillover lake, and it is related to the relatively small replenishment coefficient of the lake water defined by the ratio between catchment area and water area. Erhai Lake has a water area of 249.8 km^2, a catchment area of 2 470 km^2 and a replenishment coefficient of 10. In contrast, replenlishment coefficients in Dongting Lake and Poyang Lake are 86.6 and 45.3 respectively with interannual variations of water levels 13.18 m and 7.46 m[16], much greater than that of Erhai Lake.

Table 1 Changes of the water level and rainfall in Erhai Lake

Year/AD	Rainfall/mm	Water level/m	Year/AD	Rainfall/mm	Water level/m
1952	—	1 974.16	1958	653.8	1 973.90
1953	—	1 974.27	1959	1 031.6	1 974.04
1954	960.1	1 974.14	1960	802.3	1 973.98
1955	1 121.8	1 974.14	1961	1 115.9	1 974.29
1956	897.1	1 974.03	1962	1 105.6	1 974.26
1957	1 107.0	1 974.15	1963	927.8	1 973.88

—Not determined.

As a semi-enclosed spillover lake, Erhai Lake had a very small fluctuation of the water level over the past several centuries. Accordingly, fluctuation of the water level is not the main factor controlling sediment grain sizes in Erhai Lake, and variation of sediment grain sizes in the core EH911208-3-5 cannot be interpreted in terms of large-amplitude fluctuation of the water level. Instead, rainfall changes in the drainage basin may be the key factor dominating sediment grain sizes. It is obvious that when rainfall is heavy, runoff flow is strong enough to bring coarse terrestrial particles to the lake's deepwater part, where the coarse particles are deposited, resulting in larger grain sizes; contrarily when rainfall is light, runoff flow is too weak to convey coarse particles, so only finer particles can be transported to the lake's deepwater location and deposited, resulting in smaller grain sizes. Therefore, variation of sediment grain sizes, to some degree, reflects rainfall changes, and thus can indicate changes in the aridity/humidity regime: coarser sediments indicate humid period with heavy rainfall and finer sediments reflect dry period with light rainfall.

2.2 Carbon and oxygen isotopes of carbonates in Erhai sediments

The results of isotopic analyses show that $\delta^{18}O$ of carbonates in the core EH911208-3-4 varies between −13.6‰ and −5.7‰; $\delta^{13}C$ of carbonates varies from −7.9‰ to −1.6‰. They display synchronous fluctuation and experienced alternately heavy-light changes in recent 700 years (figure 2).

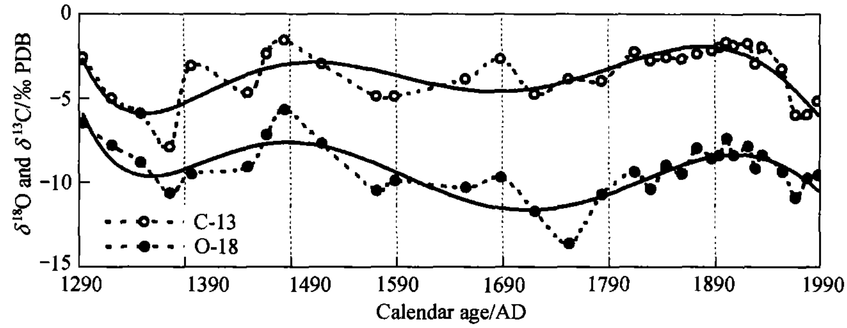

Fig. 2. Variation curves of $\delta^{13}C$ and $\delta^{18}O$ of sediment carbonates in the core EH911208-3-4.

Many studies show that photosynthesis of hydrophyte can lead to considerable fractionation of carbon isotopes. Photosynthesis is an important process for green plants to transform inorganic C into organic C, and its essence is the reducing action of carbon. The dynamic mechanism of the isotopic fractionation is that $^{12}CO_2$ is preferentially dissolved into cytoplasm and transformed into glycerophosphoric acid, thus ^{12}C is selectively enriched in plant, leaving lake water relatively enriched in ^{13}C. Autogenetic carbonates are precipitated in isotopic equilibrium with the lake water[17—19], so they are also enriched in ^{13}C. During warmer period, photosynthesis of hydrophyte boosts up, which leads more CO_2 to be absorbed by plants, leaving lake water more enriched in ^{13}C. At the same time, stronger evaporation during high-temperature period can also result in isotopic fractionation in the CO_2 exchange process between the lake water and the atmosphere[20]. $^{12}CO_2$ is preferentially diffused into the atmosphere, leaving lake water more enriched in ^{13}C and resulting in higher $\delta^{13}C$ of autogenetic carbonates. Therefore, the variation of $\delta^{13}C$ of autogenetic carbonates can reflect palaeotemperature changes. If geological background in the basin and the carbon isotopic composition of terrestrial carbonates are relatively stable, variation of $\delta^{13}C$ of sediment carbonates mainly represents that of autogenetic carbonates and has the same palaeoclimate implication of autogenetic carbonates: high $\delta^{13}C$ indicates higher temperature while low $\delta^{13}C$ indicates lower temperature. Terrestrial carbonates in Erhai Lake mostly come from Dali limestone distributed abroad in the drainage basin. $\delta^{13}C$ and $\delta^{18}O$ of Dali limestone are 0.0‰ and −4.6‰ respectively while those of sediment carbonates are −7.9‰—−1.6‰ and −13.6‰—−5.7‰ respectively, which shows that in deepwater location, autogenetic carbonates account for a considerable proportion of sediment carbonates and variations of $\delta^{13}C$ and $\delta^{18}O$ of sediment carbonates represent mainly that of autogenetic carbonates in Erhai Lake.

$\delta^{18}O$ of autogenetic carbonates depends on both $\delta^{18}O$ of lake water and temperature. Its change mainly reflects the variation of $\delta^{18}O$ of lake water and is secondarily affected by the change of fractionation coefficient due to changing temperature of lake water[21]. Generally, $\delta^{18}O$ of lake water is determined by $\delta^{18}O$ of atmospheric precipitation, temperature and evaporation. In the region with heavy rainfall and small change in temperature, $\delta^{18}O$ of atmospheric precipitation is the decisive factor.

Seasonal changes of oxygen isotopic composition of precipitation at many stations in the world follow the "temperature effect": $\delta^{18}O$ of precipitation is higher in hot summer than in cold winter[22]. However, analytical data from Kunming Observatory[23] (table 2) shows that during hot summer with prevailing summer monsoon (from June to October), $\delta^{18}O$ of the rainwater is low, varying between − 15.87‰ and − 8.2‰, much lower than those in other months varying between − 4.73‰ and + 1.24‰. Obviously, this does not correspond to the "temperature effect". The "temperature effect" seems to be unimportant in this region.

Table 2 The oxygen isotopic composition of the atmospheric precipitation at the Kunming Observatory in 1980

Date	Temperature/℃	Rainfall/mm	$\delta^{18}O$/‰
26 Mar.	11.5	1.4	0.80
16 Apr.	12.0	0.7	1.24
8 May	12.9	7.1	−4.73
22 May	17.7	3.0	0.29
6 Jun.	19.3	5.1	−9.55
12 Jun.	19.8	9.4	−9.42
29 Jun.	20.9	1.7	−15.20
6 Jul.	20.2	9.2	−9.39
24 Jul.	18.1	5.2	−11.73
5 Aug.	18.9	7.9	−11.11
12 Aug.	17.4	2.0	−10.19
18 Aug.	18.1	16.2	−14.87
28 Aug.	20.4	12.3	−15.87
27 Sep.	16.4	5.3	−10.02
8 Oct.	17.3	1.1	−13.49
14 Oct.	15.4	20.9	−8.20
15 Dec.	8.6	2.1	−3.75
21 Dec.	7.3	2.1	−4.44

In the region affected by the Asian monsoon, moisture sources of precipitation in different seasons may be different. The surplus of deuterium of the rainwater (*d*-index), equal to $\delta^{2}H-8\delta^{18}O$, can represent the isotopic characteristics of vapor and bears the important information of evaporation process in the moisture source region[22,24]. Higher *d*-index occurs where the evaporation rate is high and the climate is dry. Lin's investigation on the *d*-index of the rainwater in Tengchong, Yunnan[24] shows that the *d*-index of the rainwater averages 17.7 in winter, revealing the fast non-equilibrium evaporation for inland vapor sources, while it averages 9 in summer, suggesting the slow equilibrium evaporation in the Indian Ocean vapor source. Thus it can be seen that the moisture sources of precipitation in summer and in winter are different in the southeast monsoon zone. The winter moisture comes from inland while the summer moisture comes from the Indian Ocean, which may be the reason resulting in the abnormal seasonal changes of $\delta^{18}O$ of the rainwater in this region. Yao's investigation on $\delta^{18}O$ of snow in Qinghai-Tibet Plateau shows that $\delta^{18}O$ of snow formed by ocean air mass is 14.63‰ lower than that formed by inland air mass[25].

To sum up, during the summer monsoon prevailing period, $\delta^{18}O$ of vapor coming from the Indian Ocean becomes lower and lower because of repetitious fractionations in precipitation processes on the way to the Asian inland. Thus $\delta^{18}O$ of rainwater is low. In contrast, during the winter monsoon prevailing period, $\delta^{18}O$ of rainwater is relatively high due to higher $\delta^{18}O$ of inland vapor. Consequently, the oxygen isotopic composition of the rainwater in this region does not follow the "temperature effect". In addition, the "rainfall effect"[22] can result in similar result. In Yunnan Province, summer precipitation is much more than winter precipitation, so $\delta^{18}O$ of rainwater is higher in winter than in summer. It has been pointed hereinbefore that $\delta^{18}O$ of atmospheric precipitation indirectly affects $\delta^{18}O$ of autogenetic carbonates through controlling $\delta^{18}O$ of lake water. Therefore, lower $\delta^{18}O$ of autogenetic carbonates corresponds to lower $\delta^{18}O$ of rainwater, more summer precipitation and strengthened summer monsoon; higher $\delta^{18}O$ of autogenetic carbonates corresponds to higher $\delta^{18}O$ of rainwater, less summer precipitation and weakened summer monsoon. Erhai Lake is located in the southwest monsoon zone where most precipitation occurs between June and October, accounting for more than 80% of annual total rainfall[16]. Summer precipitation dominates annual total rainfall and determines the aridity/humidity regime. Therefore, $\delta^{18}O$ of autogenetic carbonates in Erhai Lake can be used to reveal the aridity/humidity cycles of the regional climate: lower $\delta^{18}O$ indicates humid period with more rainfall and stronger summer monsoon while higher $\delta^{18}O$ suggests dry period with less rainfall and weaker summer monsoon. It has been pointed hereinbefore that variation of $\delta^{18}O$ of sediment carbonates mainly represents that of autogenetic carbonates in Lake Erhai, thus it has the same palaeoclimate implications of autogenetic carbonates.

2.3 Climate changes of Erhai Lake in recent 700 years

The trend-line of $\delta^{13}C$ in fig. 2 shows that the carbon isotopic composition came through a "heavy→light→heavy" change within 1290—1490 AD, revealing a 200-year "warm→cool→warm" period of the regional climate; another "heavy→light→heavy" change occurred within 1490—1890 AD, reflecting a 400-year "warm→cool→warm" period which consists of two 200-year sub-periods, namely within 1485—1688 AD and 1688—1901 AD.

From 1901 to 1935 AD, $\delta^{13}C$ of sediment carbonates stayed high which shows the continuous increase of temperature. Afterwards, there occurred about 40 years of cooling trend and from the 1980s to the present the temperature has been rising degree by degree.

The two coldest periods in recent 700 years are revealed respectively by the lowest $\delta^{13}C$ during the 14th century and 1550—1800 AD. Zhu's study[26] has shown that the warmer period during the 13th century was short and it was colder in the 14th century than in the 13th century and at present. The cold period within 1550—1800AD may be the imprint left in the southwest zone by the Little Ice Age which generally refers to the cold period in Europe within 1550—1850 AD[27]. The global warming at the beginning of this century continued until the 1940s, which was well recorded in Erhai Lake. This shows that temperature variations in the region of Erhai Lake are closely linked to the global temperature changes. Global climatic factors play an important role in modulating the regional climate of Erhai Lake.

As mentioned above, large mean sediment grain sizes indicate humid period with more rainfall while small mean grain sizes suggest dry period with less rainfall. High $\delta^{18}O$ of sediment carbonates indicates dry period with less rainfall while low $\delta^{18}O$ reflects humid period with more rainfall. Therefore, both sediment grain sizes and carbonate oxygen isotopic composition have palaeoclimate implications for revealing the aridity/humidity changes, large mean sediment grain sizes and low $\delta^{18}O$ of carbonates indicating humid climate, contrarily suggesting dry climate. From figs. 1 and 2, it can be seen that $\delta^{18}O$ of sediment carbonates shows contrary trend as sediment grain sizes. This means that both $\delta^{18}O$ of sediment carbonates and sediment grain sizes can be reliably used as aridity/humidity change indicators, thus the aridity/humidity changes of the recent 700 years in the region of Erhai Lake are reconstructed. The regional climate came through a 200-year "dry→humid→dry" period within 1290—1490 AD. From 1490 to 1890 AD, it experienced a 400-year "dry→humid→dry" period during which there exist 100- and 200-year subperiods. From the beginning of this century, it had been developing towards the humid, but after the 1980s it began to become drier.

In addition, from figs. 1 and 2 it can also be seen that sediment carbonates display covarying $\delta^{13}C$ and $\delta^{18}O$ while sediment grain sizes show inverted fluctuations, suggesting that the basic climate succession type in the region of Erhai Lake is warm-dry and cool-humid alternately. This may reveal the different climate change characteristics in the southwest monsoon zone from that in the southeast monsoon zone where the climate combination type is warm-humid and cool-dry by turns[1]. The particular geographic location, special physiognomy type and strong influence of the rising Qinghai-Tibet plateau in the southwest monsoon zone may have contributed to the difference.

3 Conclusions

Palaeoclimate implications of all kinds of climate change indications should not be applied mechanically in reconstructing palaeoclimate. Only after concretely analyzing the geological setting and the hydrological regime in the given region and lake, can credible conclusions be obtained. Based on fine dissection and discrimination of sediment grain sizes and $\delta^{18}O$, $\delta^{13}C$ of sediment carbonates in Erhai Lake, the following conclusions are drawn: (i) $\delta^{13}C$ of sediment carbonates can indicate palaeotemperature changes while sediment grain sizes and $\delta^{18}O$ of sediment carbonates have the palaeoclimate implications for the aridity/humidity changes. (ii) The basic climate succession type in the region of Erhai Lake is warm-dry and cool-humid alternately. There exist 200- and 400-year quasi-periodical changes in temperature and 100-, 200- and 400-year quasi-periodical changes in aridity/humidity regime. (iii) The 14th century and 1550—1800 AD are the two coldest periods in recent 700 years, the latter of which may be the imprint left in the southwest zone by the Little Ice Age. (iv) On one hand, the regional climate in Erhai Lake shows consistency with the global climate. On the other hand, it takes on specific regional characteristics. Therefore, to strengthen palaeoclimate study in this region is very important and meaningful in theory and practice for extending contents of global changes, realizing climate change characteristics in the southwest monsoon zone and perfecting the Asian palaeomonsoon study.

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