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Environmental characteristics of Mid-Holocene recorded by lacustrine sediments from Lake Daihai, north environment sensitive zone, China

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Abstract Climate proxies, such as total organic carbon and nitrogen (TOC, TN), carbonate content ($CaCO_3$), grain-size and pollen of the sediment core retrieved from enclosed Lake Daihai which lies in the north China environment sensitive zone are analyzed to reconstruct the environment evolution of the area based on high-resolution radiocarbon chronology. The results reveal that the TOC and TN contents of the sediments correlate well with pollen percentage and pollen flux variations during the Holocene, and both reach their peak values simultaneously at 6.7—3.5 ka BP (calendar age, 7.6—3.6 ka BP). Since 6.7 ka BP, both the $CaCO_3$ and organic matter contents of the core have simultaneous variations, and their high values also occur during 6.7—3.5 ka BP. While during 9.0—6.7 ka BP (calendar age, 10—7.6 ka BP) relatively lower level of organic matter content and pollen flux correspond to the higher level of carbonate content. The above relations suggest that during 6.7—3.5 ka BP, the productivity and effective precipitation were greatly improved in the lake drainage area, and this would probably strengthen the hydrodynamic conditions, enhancing organic matter, pollen and carbonate inputs from terrestrial sources. Such processes would account for the enrichment of both organic matter and carbonate in the sediments. While during 9.0—6.7 ka BP, the lower level of organic matter, pollen flux but high carbonate content show depressed productivity and declined vegetation coverage. The higher carbonate content at this stage would have probably resulted from the higher evaporation ratio of the lake water under relatively drier climate conditions. Therefore, it is inferred that during 6.7—3.5 ka BP, the climate was more humid with abundant rainfalls and vegetation was more flourishing in the Lake Daihai area. This can be seen as Holocene Climate Optimum (HCO). As a result, this has evident discrepancies with the traditional notion that the HCO occurs at Early Holocene or early Mid-Holocene.

Keywords: Lake Daihai, Mid-Holocene, lacustrine sediments, environmental characteristics.

One of the goals for paleaoenvironmental research is to predict the tendency of future climate and environmental changes based on the understanding of the past. The key approach is to find similar pictures which happened in the past. By understanding the background and mechanism of the paleaoenvironmental changes, reliable parameters and verifications can be provided for the numerical model to predict the tendency of future climate and environmental changes. The Mid-Holocene as the nearest and warmest stage after the Glaciation, the basal climate factors are similar to what is like today[1−3]. So much attention has been paid to Mid-Holocene by paleaoenvironment researchers as an analogy to future climate and environmental changes.

The climate and environment evolution during Holocene, especially during Mid-Holocene, has been a major topic for Chinese researchers, and some representative points of view have come into being. Based on analysis of records such as pollen assemblages, lake sediments and paleosols, it is inferred that a generally warm and wet Holocene megathermal occurs at intervals of 8.5—3.0 ^{14}C ka BP and a megathermal maximum is at intervals of 7.2—6.0 ^{14}C ka BP[4−6]. Based on the asynchronous variations of solar insolation, the diversities of spatial and temporal precipitation distributions in Holocene are proposed using the incre- ment of summer monsoon precipitation[7−9]. Based on the bi-relationships of temperature and precipitation, dry or humid Mid-Holocene is reconstructed in regions of China with the consideration of precipitation/evaporation ratio and effective moisture[10]. With the improvement of research methods, some researchers begin to propose some different points of view to the traditional notion regarding the Holocene especially the Mid-Holocene in recent years[10−14]. However, as it is said in the recent research, the asynchrony exists and the lack of precise correspondence of climatic records constructed on the basis of proxy data from different parts of China is a result of the different locations and elevations of the sampling sites, the different resolutions of the source material, and the varied climatic conditions within China. Therefore, further work is needed[14].

Lake Daihai, the object for this research, is located in the north environment sensitive zone in north China. Since last century, much attention has been paid to the research of climate and environmental changes[15−26]. But the results from different researchers regarding the Holocene, especially the Early and Mid-Holocene climate and environmental changes have evident discrepancies even debates[24−26]. In this paper, the detailed history of climate and environmental changes in Lake Daihai since Holocene especially Early and Mid-Holocene are reconstructed based on high-precision Accelerator Mass Spectrometry (AMS) radiocarbon chronology and multiple analyses of proxies, and some new understandings are obtained regarding the characteristics of Early and Mid-Holocene in the area.

1 Geographic setting

Lake Daihai (112°33′31″—112°46′40″E, 40°29′27″—40°37′06″N, 1200 m a.s.l.), an enclosed lake, lies in Liangcheng County, center Inner Mongolia, north China. The lake is bordered by the mountains, with an altitude of 1300—2300 m. The ellipse-shaped lake has a maximum extent of 20 km along the northwest-southeast axis and maximum width of 14 km along the northeast-southwest axis. It covers an area of 160 km^2 with a maximum water depth of 16 m, and the drainage area is 2289 km^2

Lake Daihai is geographically located in the semiarid area and semi-humid transition belt, which is also the environment sensitive belt in north China. In winter, the climate in the lake area is controlled by cold continent high-pressure system, such as the Serbian-Mongolian Highs, which bring cold and dry air from the continent high latitudes. While in summer, warm and moisture air originating from the low latitudes ocean can reach the lake area and bring more precipitations (Fig. 1). The mean monthly temperature is −13 to −15℃ in January and 17 to −20.5℃ in July. From June to August, rainfall occupies about 66% of the annual 350—450 mm precipitation. The mean annual evaporation is 1938 mm. Vegetation in the lake drainage is influenced by the topography, from mid-lower mountains in the northwest to the Daihai basin, vegetation ranges from arid forest, shrub grassland to semiarid grassland[27].

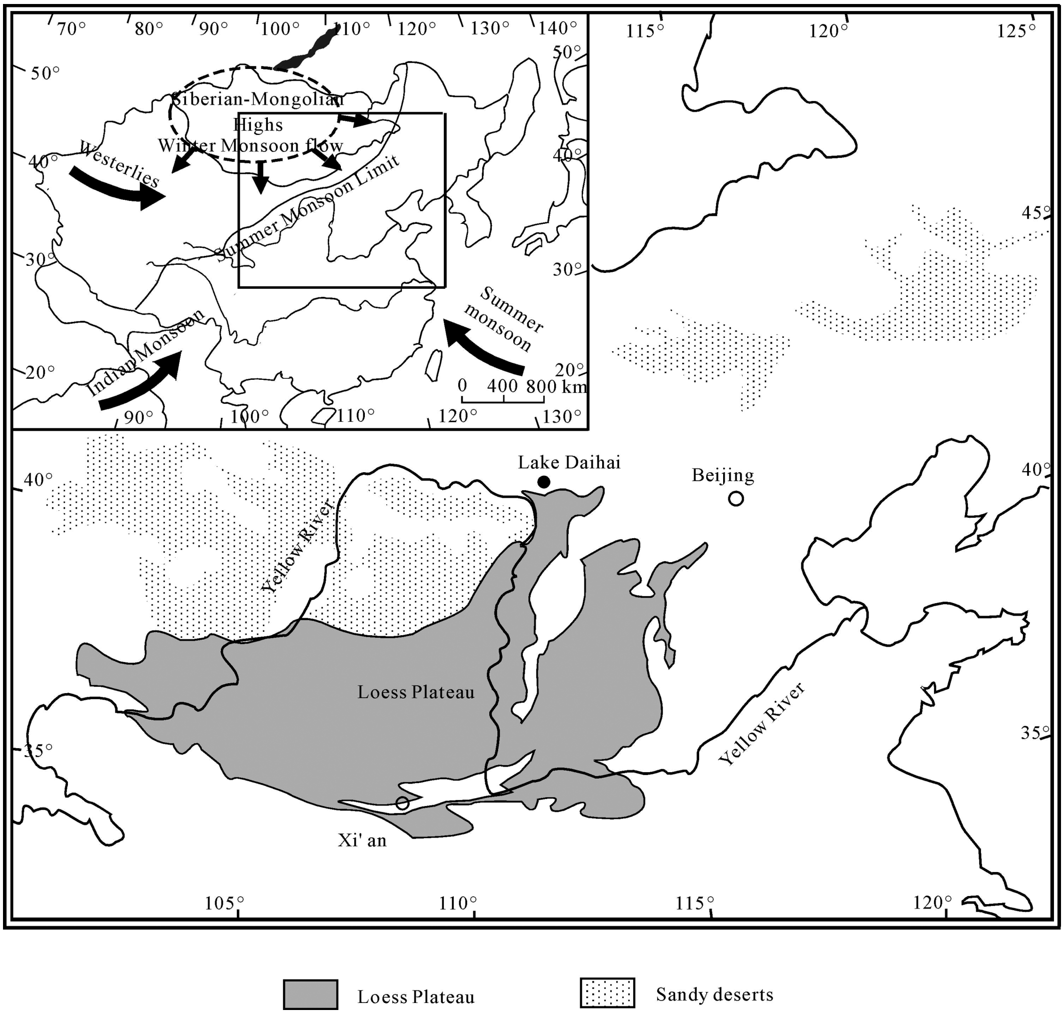

Fig. 1. Geographical location and the climate system of the area studied.

2 Material and method

2.1 Sampling and lithology of the core

Two parallel cores were retrieved using piston devices in the center of the lake with a recover rate over 95% by the Sino-Japanese research team in 1999. The cores were named DH-99A and DH-99B respectively. Lithologically, the two cores correlate well. Therefore, the uppert part of DH-99B is chosen for analysis in this study. According to the lithology and hues variations the lithological descriptions of the upper 12.87-m-long core are as follows: 12.87—12.26 m: grayish fine-medium sand with mud; 12.26—9.80 m: mainly grayish silt clay with laminas, and two subdivision can be identified, oyster-grayish silt clay with concentrated laminas at depth intervals of 12.26—11.70 m, shallow grayish silt clay with laminas at depth intervals of 11.70—9.80 m respectively; 9.80—4.30 m: grayish silt clay; 4.30—0 m: brown, yellow grayish clay with humus1).

The core was sampled in the field at intervals of 2 cm. These samples were sealed in plastic bags, and then transported to the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS) for refrigera-

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1) Sun Q L. Climate and environment evolution since the last 13, 000 years recorded by Lacustrine sediments in Lake Daihai, Dissertation for Master Degree, Institute of Earth Environment, Chinese Academy of Sciences, 2000, 1—78

tion. In the laboratory, the core was analyzed at 2 to 10 cm intervals for multi-proxy tests.

2.2 Climate and environment proxies

The organic matter in the sediments such as the variations of total organic carbon (TOC) and nitrogen (TN) are commonly seen as a direct reflection of the amount of organic inputs, the paleoproductivity and preservation conditions after deposition in the lake area. So they have a close relationship with the climate and environmental changes in the past[28,29]. For enclosed lakes in semiarid area, the precipitation variations almost become a controlling factor to the environmental changes. The increases of precipitation not only improve the vegetation coverage and productivity in the lake drainage but also play a key process in terrestrial material transportation to the lake. The C/N ratio in limnology research is often used as a proxy to evaluate the relative contribution of the land-derived sources and autochthonous sources of organic matter to the total organic matter in the sediments, and further to indicate the source changes under different climate and environmental conditions[28−30]. The carbonate in the lake sediments usually come from the following sources: terrestrial debris and soluble carbonates inputs, carbonates from dust, and the carbonate formed by biochemistry reactions of the aquatic biota. The above sources enrich the carbonates in the sediments by means of hydrological transportation, evaporation and photosynthesis.

A CS-344 elemental analyzer was employed to determine the content of TOC and TN in sediments in the Institute of Geography & limnology, CAS, after the samples were treated with HCl to remove inorganic carbon. The measure precision was ±0.15%. Alkaline titration was used to calculate the carbonate content of the samples in IEECAS after the samples were reacted with superfluous HCl[31].

Pollen percentage and concentration variations in the sediments are major approaches to reconstruct the paleovegetation changes. In this study, pollen was extracted using acid-alkyrli-free method with a sample volume of 2 mL. The Lycopodium tablet was added as exotic marker to each sample in order to calculate pollen concentration[32,33]. In this paper, the traditional proxy of pollen concentration was replaced by pollen percentage and pollen flux as environment proxies. That is, for 2 mL volume of each sample in this paper, it has a time span from tens of years to several hundreds of years, so the lower or higher concentration of pollen does not actually reflect the amount of pollen at given time and given surface of the sediment due to the differences in the deposition ratio. Thus, it is difficult to reflect the actual vegetation status in a given time. In this paper, pollen flux was adopted by calculating the $P_c \times L$ (P_c represents the concentration of a single sample, grains·cm^{-3} in unit; L represent the linear deposition ratio of two adjacent samples, cm·a^{-1} in unit). The pollen flux here is defined as amount of pollen at a given time and given surface of the sediment (grains·cm^{-2}·a^{-1}·10^{2} in unit), this would be more reasonable in reconstructing the vegetation changes in the lake drainage.

Grain-size analysis was carried out with laser particle analyzer made by Malvern Co. Ltd., England in IEECAS. Samples were treated with H_2O_2 and HCl respectively to remove organic matter and carbonate in advance[34]. The samples for radiocarbon ages of different depths of the core were sent to Tokyo University, and determined on the AMS facility of the university.

3 Results

3.1 Chronology

The chronology sequence of the core consists of 12 AMS ^{14}C ages (Table 1). The deposition rate of the core has an evident change around 9.90 m according to the age/depth curve. It increases to an average of 1.83 mm/a at the upper part of the core from an average of 0.24 mm/a at the lower part. As for the upper part, the deposition rate changes almost linearly. Because of the lower deposition rate at intervals of 9.90—10.90 m, in order to improve the reliability of the chronology, depth correlations between DH-99B and DH-99A are adopted on the basis of lithology, structure and hues variations to determine the age of DH-99B using the corresponding age of DH-99A. It was inferred that the 9.89 m of the DH-99A is corresponding to the 10.14 m of DH-99B, so the age 6593±34 a at 9.89 m of DH-99A can be applied to 10.14 m of DH-99B as a reasonable controlling age point (Fig. 2).

Table 1 AMS results for core DH-99B

Laboratory number	Depth (m)	Dating material	δ^{13}C (‰)	AMS ^{14}C age (aBP)	Calibrated age Age (2δ) (cal. aBP)
Tka-12097	2.00	organic matter	δ^{13}C= −24.8	1550±70	1592—1302
Tka-11998	4.00	organic matter	δ^{13}C= −25.5	2310±70	2487—2150
Tka-12156	6.00	organic matter	δ^{13}C= −25.2	3470±120	4085—3465
Tka-12001	8.00	organic matter	δ^{13}C= −25.3	4860±70	5731—5469
Tka-11999	8.00	organic matter	δ^{13}C= −25.1	4830±80	5723—5327
Tka-12098	8.00	organic matter	δ^{13}C= −25.3	4730±70	5601—5310
Tka-12099	9.90	organic matter	δ^{13}C= −25.1	5420±150	6496—5908
Tka-12100	9.90	organic matter	δ^{13}C= −25.1	5370±90	6310—5929
Tka-12207	10.90	organic matter	δ^{13}C= −25.4	8920±100	10239—9634
Tka-12000	11.80	organic matter	δ^{13}C= −25.2	10290±140	12825—11342
Tka-12101	12.54	organic matter	δ^{13}C= −25.0	16210±110	20010—18707
NUTA-2724[a)]	9.89	organic matter	δ^{13}C= −25.1	6593±34	7565—7430

a) DH-99A age (Xiao *et al.* 2004), corresponding to age at 10.14 m of DH-99B.

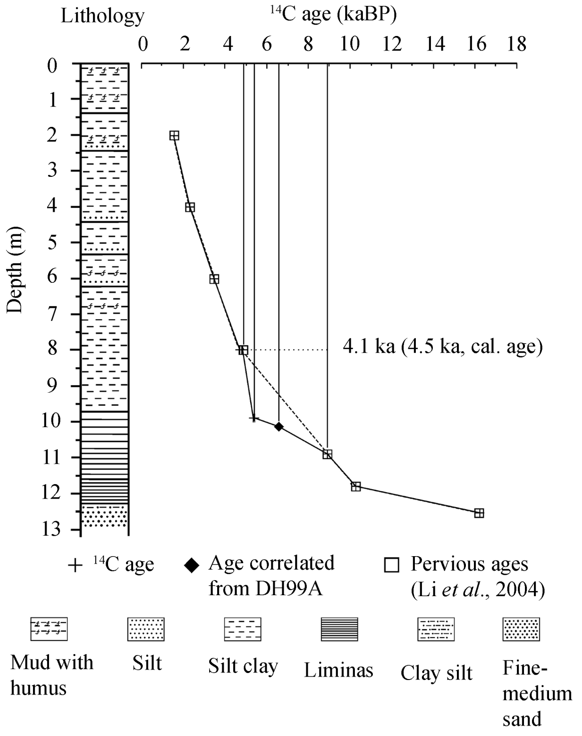

Fig. 2. Lithology and age-depth variations of DH-99B core.

As for the possible "carbon reservoir effects" in lakes in semiarid regions, it is difficult to estimate such effects on the actual ages of the sediments because the "carbon reservoir effects" differ through time. In the paper, the deposition rate of the upper 9.90 m of the core shows nearly linear variations. Suppose the "carbon reservoir effects" keep constant during this period, the age at the surface of the sediment can be extrapolated to 410 a with linear regression. Therefore, the age of 410 a can be approximately considered to result from "carbon reservoir effects" in the lake sediment. This is close to a 360 a effecte from DH-99A using the same method[25,26].

Regarding the abrupt deposition rate change below 9.90 m of the core, gradual transition can be identified both in lithology and hues changes without abrupt deposition discontinuity. DH-98 and DH-99A cores retrieved from other places in the lake center also show continuity of deposition at their similar parts. Pervious study on the aragonite carbonates dating in the laminas below 12 m of this core actually showed a very lower deposition rate[23], so it is possible for the laminas of upper 12 m to have a lower deposition rate. The DZ1 core located on the beach also indicates similar variations of deposition rate with that of DH-99B[17]. Therefore, the occurrence of large-scale discontinuity in Lake Daihai sediments around 9.90 m is almost impossible. This indicates that the deposition environment has suffered great changes around 9.90 m.

3.2 *Organic matter and carbonate content*

The variations of organic matter (TOC, TN) and carbonate content ($CaCO_3$) during the Holocene can be divided into several periods (Fig. 3). Except 9.0—6.7 ka BP period, the TOC, TN and $CaCO_3$ contents have simultaneous variations during other periods of Holocene. The higher values of TOC, TN and $CaCO_3$ occur simultaneously at periods of 6.7—3.5 ka BP, 3.2—2.6 ka BP and 1.7—1.2 ka BP, and this correlates well with the higher C/N ratio values in the sediments. This would indicate the higher productivity during

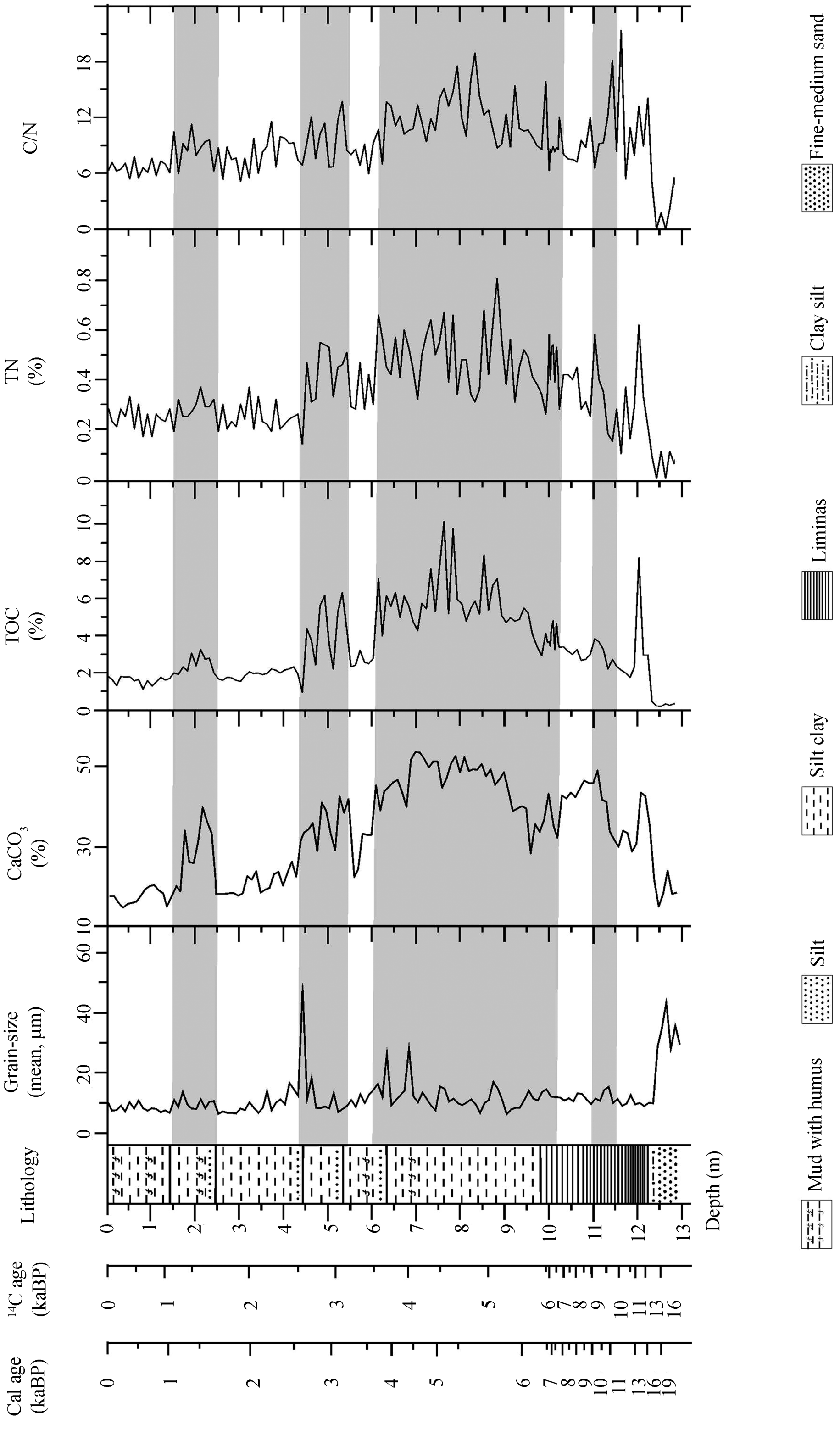

Fig. 3. Organic matter and carbonate content variations of DH-99B core.

these periods in the lake drainage, and the organic matter in the sediments mainly came from the terrestrial sources. As for enclosed lakes in semiarid regions, the terrestrial material is mainly transported by water flow, so the water flow inevitably brings some soluble and insoluble carbonate from terrestrial source around the basin into the lake when organic matter is carried. Compared with lower level CO_2 in the atmosphere and the carbonate carried by dust, the carbonate sources from loess and other unconsolidated sediments around the basin will occupy a large proportion of the total carbonate in the lake sediments even at humid climate conditions. Further the carbonate in the sediment will get enriched by the evaporation. Simultaneously, humid climate conditions have also enhanced the productivity of both aquatic and hydrophytes in the lake drainage. The pH value of the lake water will rise for much CO_2 in the lake water is consumed by photosynthesis, this enables some carbonate to be separated out after saturation and further enriched in the sediments. Such processes would probably account for both enrichment of carbonate and organic matter in the lake sediments. While at 9.0—6.7 ka BP, higher carbonate content occurs with lower organic matter content and lower productivity of the lake drainage, and that lower deposition rate also indicates the deficiency of terrestrial material inputs. Therefore, the higher carbonate content in the sediments would probably result from the separation of soluble carbonate in the water, that is, from the higher evaporation of the lake water.

3.3 *Variations of pollen flux and percentage*

Variations of pollen flux, pollen percentage and TOC of the core are presented in Figs. 4 and 5. As a whole, the herbs and trees pollen flux have shown synchronous variations during the Holocene. The high levels of pollen flux occurs at periods of 10.2—9.0 ka BP, 6.7—3.5 ka BP and 3.2—2.6 ka BP. Other periods such as 9.0—6.7 ka BP and 3.5—3.2 ka BP, the pollen flux shows a relatively low level. The variations of pollen percentage reveal that the predominant vegetation differs with higher or lower periods of pollen flux. During 10.2—9.0 ka BP, coniferous and broadleaved vegetation which is composed mainly of *Pinus* and *Betula* begins to expand in the lake area, indicating the improvement of humidity, as a whole, the grassland vegetation mainly consisting of *Artemisia*, Chenopodiaceae and *Ephedra* still occupies a predominant position. At 9.0—6.7 ka BP, trees pollen mainly consisting of *Pinus*, *Betula*, *Ostryopsis* and *Quercus* begins to take a predominant position indicating gradual expansion of coniferous and broadleaved vegetation. But the vegetation coverage in the lake drainage would be still low from the lower level of pollen flux in this period. At 6.7—3.5 ka BP, coniferous and broadleaved vegetation not only takes the predominant position but shows larger scale expansion. The pollen flux of the sediment also reaches the highest level of the Holocene. All these indicate that the humidity condition is greatly improved, and the vegetation status is the most flourishing period in Holocene. This would be seen as the Holocene climate optimum. At 3.5—3.2 ka BP, the sharp decline in pollen flux may indicate a temporary climate reversal. At 3.2—2.6 ka BP, the pollen flux of the sediment shows a relative lower level. The pollen percentage variations indicate that the herbs and trees pollen take the predominant position alternatively. Generally, these reflect the intensive variability of humid and dry climate in the lake drainage. The pollen flux shows a very low level after 2.6 ka BP. This may indicate the recession of natural vegetation in the lake drainage under the effects of both human activities and increased climate aridity.

4 Discussion

The above results and analyses indicate the Holocene Optimum occurs at the period of 6.7—3.5 ka BP (cal 7.6—3.6 ka BP) in the lake drainage area, all the multiple proxies of the DH-99B core demonstrate flourishing of vegetation and thriving of productivity. This climate and environment optimum is also verified by more and more geomorphology and archeology evidence in the Lake Daihai area. e.g. The terrace evidence shows that lower lake level occurred after 3.5 ka BP and the terraces are covered by loess deposits. While at 4.5 and 6.7 ka BP, large-scale lake incursions occurred indicating relatively high lake levels during these periods[15—17]. The archaeology evidence also

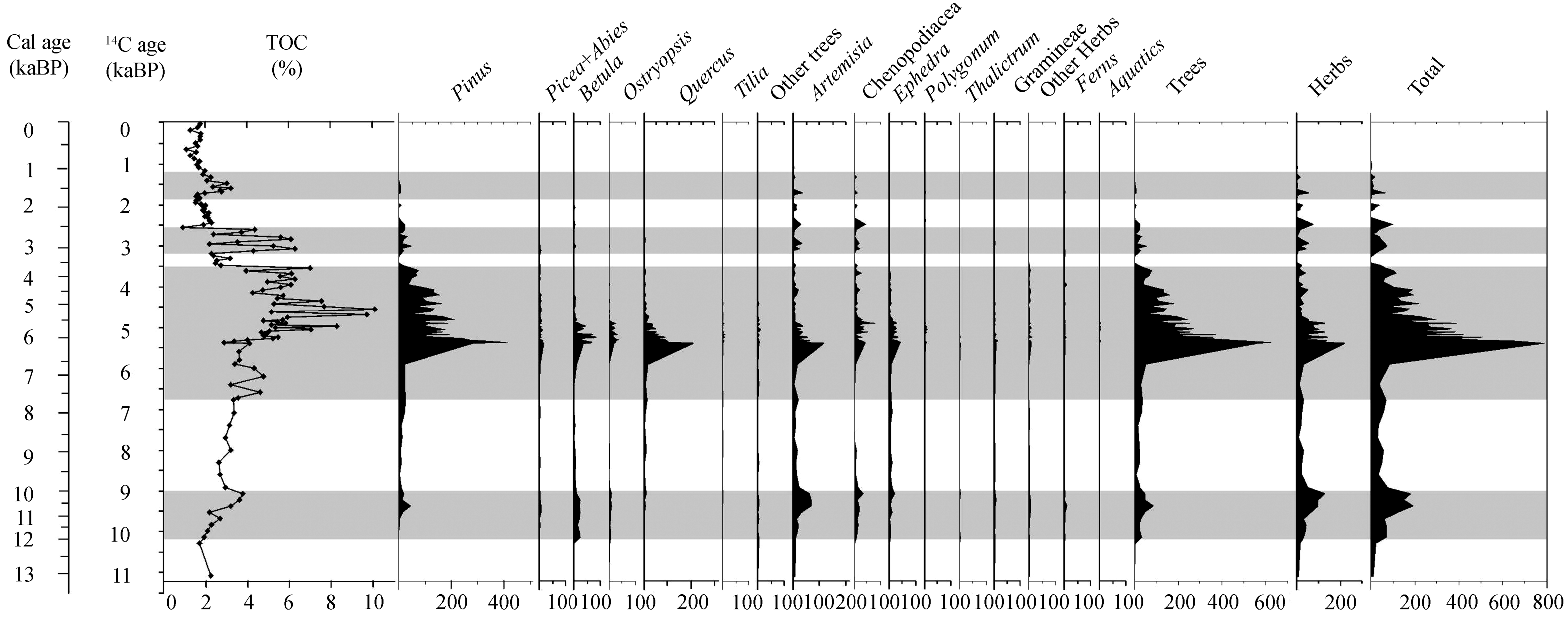

Fig. 4. Variations of pollen flux and organic carbon content of core DH-99B. (Pollen flux unit: grains·cm^{-2}·a^{-1}·10^{2}).

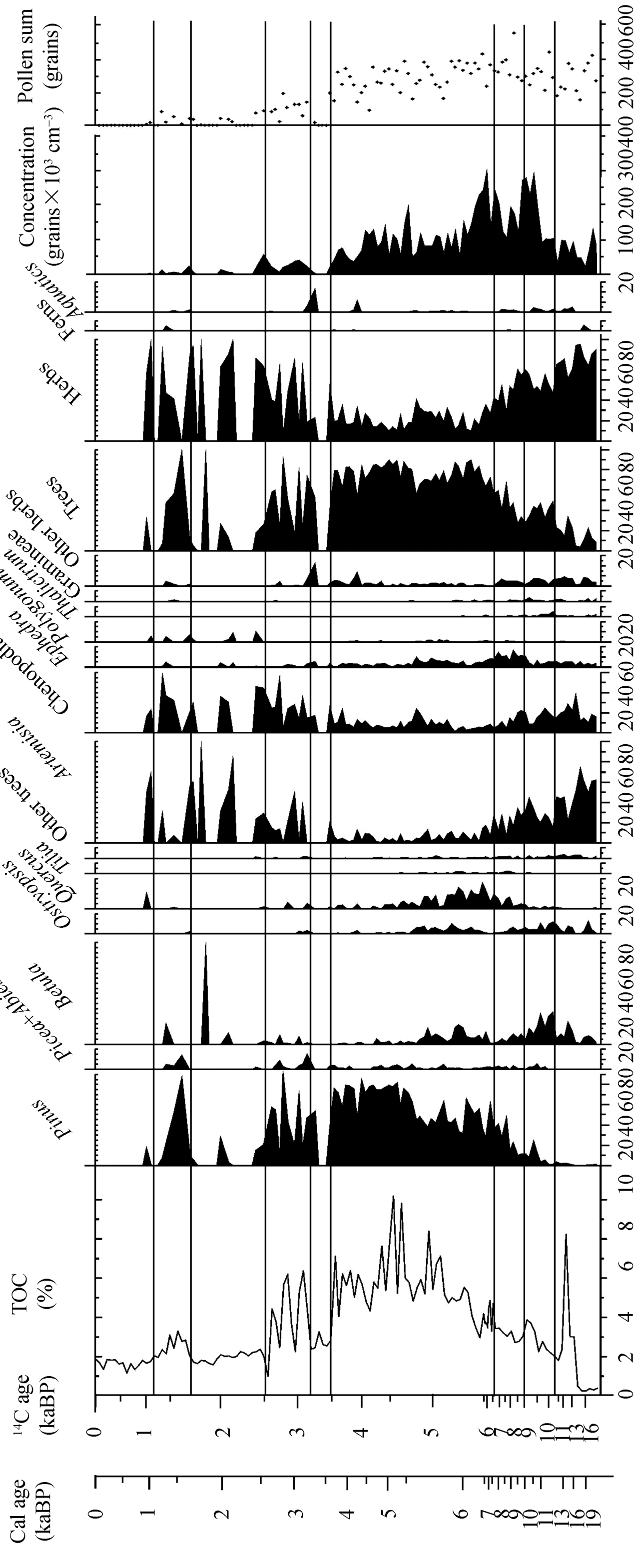

Fig. 5. Variations of pollen percentage and organic carbon content of core DH-99B.

demonstrated that the highest annual temperature in the Lake Daihai area occurred during 6000—5000 a BP and the precipitation reached its peak at 5000—4000 a BP with annual precipitation of ca. 650 mm. The distribution of paleoculture relics in the Lake Daihai area reveals that the distribution of the relics of Longshan Culture (1300—1400 m a.s.l.) is higher than that of Yangshao Culture (1200—1300 m a.s.l.). This denotes that lake level gradually increased after late Yangshao Culture (around 5.0 ka BP), and people build their shelters near the water[35−37]. These geomorphology and archaeology evidence correlates well with the results retrieved from the sediment core.

Many records from the Inner Mongolia Plateau and margins of the present monsoon area also demonstrate that humid climate conditions prevailed after about 6.5 ka BP, *e.g*. research work in Midiwan, southern margin of the Mu Us Desert reveals humid climate conditions when eolian sand deposit was replaced by peat sediment at 6.0—3.5 ka BP[38]. High resolution work in Jingbian near the Mu Us Desert also indicates that the humid optimum period occurred during the interval of 5.5—2.7 cal ka BP, not in early Holocene or early Mid-Holocene traditionally regarded[39]. In Lake Yanhaizi, middle Inner Mongolia, the sediment analysis reveals a generally dry Holocene Megathermal period at 8.0—4.3 ka BP, while the humid environment condition is identified from 4.3 to 3.2 ka BP[10]. Pollen analysis carried out in Lake Daojiao in Daqing Mountain, Inner Mongolia shows that warm-dry and warm-humid conditions prevail at intervals of 7.8—7.1 ka BP and 7.1—4.4 ka BP respectively[40]. The new pollen results from Lake Qinghai show that the total pollen and trees pollen concentration reaches a high level after 6.5 ka BP (cal 7.4 ka BP), and that indicated a relatively humid climate condition[41]. These results roughly coincide with what is revealed by Lake Daihai sediment that climate optimum occurred at 6.7—3.5 ka BP.

The climate and environment optimum during 6.7—3.5 ka BP (cal.7.6—3.6 ka BP) which is characterized by flourishing vegetation and thriving productivity of the lake drainage has some discrepancies with previous results on the same sediment core which reveals a warm and humid condition during 10—7 ka BP[24], although the same pollen data are used1). Such a difference mainly results from two reasons. First, previous time scale has evident deficiency. As seen in Fig. 2. the previous chronological sequence of the core lacks effective dating age control between 8.9 and 4.8 ka BP, a time span of 4.1 ka (cal. 4.5 ka) approximately occupies a half of the Holocene, and the absent age is unfortunately located in the key period of Early and Mid-Holocene. Furthermore, the prominent change in lithology around 9.90 m and its possible deposition environment change during this period are difficult to locate due to the absence of enough dating ages. In this way, the previous pollen results inevitably make a confusion of environment information which should be belonged to Early and Mid-Holocene respectively. In this paper, new AMS ^{14}C dating ages are adopted. Two ages of 5420 a and 5370 a are added to the depth of 9.90 m and a supplement age of 6593 a obtained by depth/age correlation of the parallel core is also added to the depth of 10.14 m. These three controlling ages added catch the key points of the changes in deposition rate of the core during this period. Therefore, the improper distribution of environment information which results from the low deposition ratio and big time gaps between different core depths is avoided to a great extent. The Early Holocene climate and environment changes in previous studies should be after early Mid-Holocene under the new time scale.

Secondly, the pollen flux is adopted to evaluate the vegetation biomass in the lake drainage. This successfully settles the difficulty of environment information evaluation in a given time which results from the differences of deposition rate for each sample. Due to the unwariness of prominent deposition ratio changes around 9.90 m and the resolution differences of each single sample, it would be difficult for the previous pollen concentration data to correctly reflect the actual environment changes. This has evident discrepancies with the environment information reconstructed by the pollen flux data which is based on a given time scale. For example, the high pollen concentration value is identified at 10.0—7.0 ka BP in previous studies, how-

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1) See footnote 1) on page 970.

ever, under the new time scale, pollen flux shows high level during 6.7—3.5 ka BP rather than during 10.0—7.0 ka BP. The introduction of pollen flux as a proxy in this paper, not only sets up a good correlation of pollen flux with other proxies, but makes the new result closer to the environment information retrieved from parallel core DH-99A[25,26]. For instance, the climate optimum indicated by pollen data of the two cores commences respectively at cal. 7.6 ka (^{14}C age 6.7 ka BP) and cal. 7.9 ka. The minor time gap between the two cores just comes from the differences in dating space and time resolution of the samples analyzed. The samples analyzed at intervals of 4 cm for DH-99A and 10 cm for DH-99B. The resolution difference of the two cores below 9.90 m is 300 a for a single sample analyzed.

Regarding the reasons for Mid-Holocene climate changes, some scholars interpret this on the basis of solar insolation forcing. That is, due to the orbital parameter changes of the Earth, the summer solar insolation increases at high latitudes, raises the annual temperature and enhances the seasonal diversity of winter and summer. Simultaneously, the differences of solar insolation distributed in different latitudes enlarge the gradients of thermal circulation between sea and land, which lead to the strength of monsoon circulation, and brings more precipitations in the monsoonal area[42,43]. This mechanism would account for a warm or wet climate and environment status in middle and east China in Early and Mid-Holocene[7−9,44,45]. But more records from the Loess Plateau and west China tend to show a relatively dry Mid-Holocene, e.g. large-scale drought events occurred at cal. 7000—5000 a. It is considered that the major reason for the dry climates in Mid-Holocene is that there is less rainfall from the weakening summer monsoon[11,12,46,47]. The relationships of temperature and humidity in Mid-Holocene are also discussed by researchers. It is indicated that the major reason for the dry Mid-Holocene in Inner Mongolia results from high evaporations under high temperatures which reduce the effective precipitation[10].

Information retrieved from this study indicates that the variations of effective precipitation during Mid-Holocene would account for the major environment changes in the Lake Daihai area. The research regarding the distributions of pollen in the surface sediment in Lake Daihai reveals that pollen in the sediments is mainly (ca. 80%) transported by water flow[48]. Therefore, pollen flux as a proxy to denote the variations of effective precipitation (effective moisture) in lake drainage area is helpful. In the Early Holocene, the expansion of coniferous and broadleaved vegetation at 10.2—9.0 ka BP indicated that the climate began to become humid. The organic matter content in the sediments also indicated the enhanced productivity and increased precipitation in the lake drainage. During 9.0—6.7 ka BP, the prominent characteristic is that the very low deposition rate is corresponding to low pollen flux, organic matter content but high carbonate content in the sediments. These indicate the deficient of material inputs and low vegetation coverage under low productivity of the lake drainage. During this period, the high carbonate content in the sediment would probably indicate less effective precipitation in the lake drainage and high evaporation of the lake water when the terrestrial matter input is deficient. According to previous studies, the main type of carbonate in Lake Daihai sediments is calcite, and dolomite just appears in some enclosed shoals where terrestrial matter supply is deficient. So the appearance of aragonite carbonate in the laminas of the sediment during 9.0—6.7 ka BP at least shows high mineralization of the lake water, that is the high evaporation ratio. Similar result is also obtained by analyzing the relationships of annual precipitation, evaporation with temperature variations from the adjacent weather station in Liangchang County. It is inferred that the rate of increase in evaporation (E) is much higher than that of increase in precipitation (P) when temperature increases[10,17]. This indicates that although in this period precipitation increases with temperature increase as it is in middle or east China, the increment in precipitation is unable to compensate the loss of effective moisture which results from the evaporation increase. The general climate condition in the lake drainage would not be humid. Around 6.0 ka BP, many records demonstrate a decline in monsoon precipitation in monsoonal areas in the Northern Hemisphere when the solar insolation decreased. But in Lake Daihai, during 6.7—3.5 ka BP, it shows a climate and environment optimum characterized by high productivity, flourishing vegetation and sufficient terrestrial matter input. The reason for this is that although the actual precipitation will decrease with declined tendency of temperature, the evaporation will decrease simultaneously which probably compensates the loss from decreased precipitation, thus increasing the effective precipitation and humidity in the lake drainage.

High carbonate content in the sediment under relatively humid conditions in Lake Daihai has its counterpart in Lake Qinghai[49]. The relation of lake water salinity and carbonate content is complicated, for the salinity is not solely determined by carbonate content changes. In this paper, carbonate from terrestrial matter input and photosynthesis by the biomass in the lake have different mechanisms with carbonate originating from evaporation and salinity increase of the lake water. Under dry climate conditions, the terrestrial matter input decreases, and the salinity of lake water would have a prominent correlation with carbonate content.

5 Conclusion

In this paper, some possible speculations on the reasons of environmental changes in Lake Daihai are presented based on the core records and correlations with other environment records in the region. In fact, some characteristics of Lake Daihai, such as relatively higher altitude, enclosed basin, vegetation coverage and hydrological status would make the climate feedback to global changes more complzicated, thus having some characters different to what is recorded in east and west China. In this research, all proxies of lake sediments truly demonstrate a relatively feasible and humid climate and environmental conditions during 6.7—3.5 ka BP in Mid-Holocene rather than in Early and or early Mid-Holocene as traditionally regarded. However, to have a full understanding of the climate and environmental changes especially the fluctuations of humid and dry climates in Lake Daihai, supplement is needed besides the information retrieved from the lake center. How to reconstruct the lake level fluctuations based on high-quality chronology of the terraces around the lake during the Holocene to directly indicate the history of humid and dry climate and environmental changes, thus to have an effective correlation with the information retrieved from the core sediment is important work needed to be carried out in the future.

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