



Lake evolution of the terminal area of Shiyang River drainage in arid China since the last glaciation

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Abstract

Investigations of geomorphology and sedimentology, and analyses of radiocarbon dates, grain size and carbonate of the sediment at the present-dry closed basin in the terminal area of Shiyang River in arid China were conducted to recover the history of palaeolake change since the last glacial. The terminal area was covered by eolian sand before 13,000 ¹⁴C BP. Lacustrine deposits covered the eolian sand after 13,000 ¹⁴C BP, but were succeeded rapidly by eolian or fluvial deposits ca. 11,200–10,000 BP. This fact plus the grain-size distribution and CaCO₃ content showed that climate was extremely dry during the last glacial, but wet–dry oscillations characterized the late glacial. A single coalescent lake, over 45 m deep and 2130 km², formed between 10,000–6400 ¹⁴C BP in the basin. The lake disintegrated into several shallow carbonate lakes or swamps gradually after 6400 ¹⁴C BP. Eolian sand reached into the most part of the basin during the period. The lake evolution in the area generally reflects the East Asian summer monsoon history forced by Northern hemisphere insolation. Short time-scale lake fluctuations also existed in the area since the last glacial. © 2002 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

The present climate and environment in northwest China is extremely dry with severe drought, desertification and sand-dust storms. Relatively wet conditions, however, have existed for a long time and lakes have been quite ubiquitous in the arid region during the Quaternary. These lakes preserved rich information of past climatic and environmental changes, which may play an important role in understanding regional and global climatic change. Numerous lakes in the Tibet Plateau (Chen and Bowler, 1985, 1986; Wang and Fan, 1987; Geng and Zhang, 1988; Huang, 1988; Du et al., 1989; Li et al., 1989b, 1991, 1994; Chen et al., 1990; Huang et al., 1990; Kong et al., 1990; Li, 1990, 1992; Gasse et al., 1991, 1996; Li and Zhang, 1991; Lister et al., 1991; Wang et al., 1991; Gu et al., 1992, 1993; Wang, 1992; Wang and Shi, 1992; Hu and Wang, 1995), lakes in Inner Mongolian Plateau (Song and Yang, 1988; An et al., 1990, 1993; Wang, 1990; Feng and Wang, 1991; Wang and Feng, 1991; Li et al., 1992; Li and Wang, 1993; Wang and Ji, 1995; Jiang and Wei, 1997) and lakes

in the Xinjiang inland basins (Yan et al., 1983; Li et al., 1989a; Wang and Jiao, 1989; Li, 1993, 1996; Wu, 1994; Wu et al., 1994; Yang and Wang, 1994; Rhodes et al., 1996) have been studied to recover the environmental and climatic history in arid west China. However, most research lacked detailed investigation of lake basins. Furthermore, there is still a lack of high quality data relating to the arid desert areas in northwest China. The closed terminal basin of the Shiyang River in arid China on the summer monsoon margin areas (Fig 1A) is one of the ideal sites to study palaeolake evolution and its response to monsoon fluctuations.

According to historical records, some researchers believed that there was a large coalescent lake named Zhuyeze at the terminal area in early Chinese history, and the desiccation of the lake solely resulted from human impact (Feng, 1963; Li, 1998). Pachur et al. (1995) have found that a large lake existed during MIS 3 in the area and extended to the Tenger Desert. Zhang and Wunnemann (1997) gave details of radiocarbon chronology of the lake sediment and terraces. However, the lake evolution and climatic changes during the Holocene are still unclear. Since 1996 our research program has focused on the palaeolake at the terminal and adjoining areas, such as Tenger desert. The

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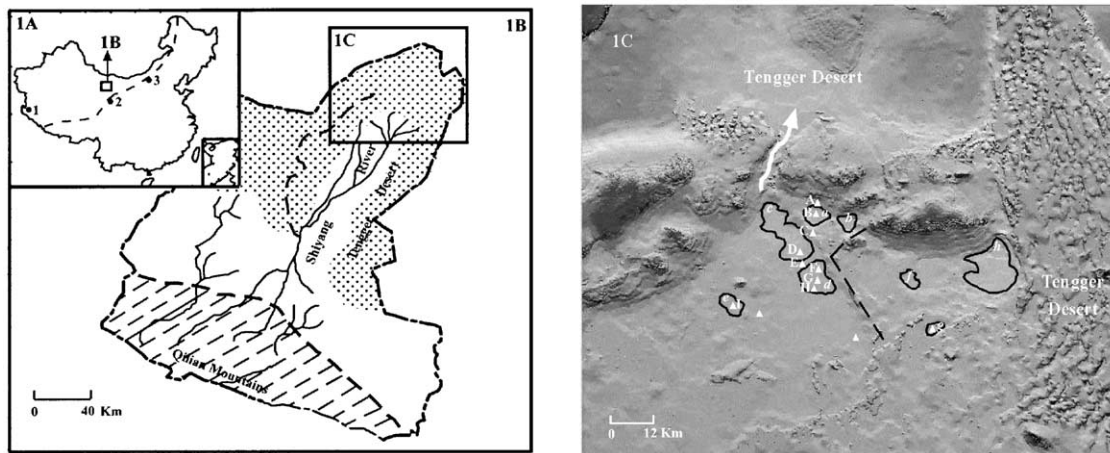


Fig. 1. (A) Location of Shiyang River drainage in arid China. The north boundary of the present Asian summer monsoon is shown by dotted line (revised from Gao et al., 1962). Black filled circles and numbers 1–3 mark the locations of Bangong Co, Qinghai Lake and Lake Daihai. (B) The Shiyang River drainage and location of the terminal lake area inserted. Dashed line is former Shiyang River channel, named Daxihe River in history. Dotted area is covered by dune sand; the shaded area is Qilian Mts. (C) TADEM image map, showing topography of the terminal area. The desiccated lake basins closed by solid lines are a-L. Xixiaochi, b-L. Dongxiaochi, c-L. Yema, d-L. Dongping, e-L. Sanjiaocheng, f-L. Xijian, g-L. Mawangmiao and h-L. Baijian. The triangles and the capital letters mark the investigated sections (see Fig. 2). The lowest pass of the closed basin is marked by the arrow; the division between the eastern and western parts of the terminal lake by the dashed line.

preliminary result of one core was summarized in our paper (Chen et al., 1999a). Here, we present detailed discussions about the temporal and spatial histories of the palaeolake at the terminal area in the Tengger desert, the large desert regions in the margin of the Asian summer monsoon in China, since the Last Glacial, especially during the Holocene.

2. Study area

Shiyang River (Fig. 1B), originating from the Qilian Mountains up to 5000 m above sea level (ASL) is an endorheic drainage system and flows for a distance of 260 km from Qilian Mountains in the south to Tengger Desert in the north. The river drains a vast catchment with an average runoff of $14.7 \times 10^8 \text{ m}^3/\text{yr}$ according to 20 yr of statistics, 95% of which is from the upper reach, i.e., Qilian Mountains, and only 5% is supplied by runoff and precipitation in the middle and lower reaches of the drainage (Chen and Qu, 1992). Minqin Basin, a Tertiary sedimentary basin filled with up to 300 m Quaternary lacustrine sediment and surrounded by moving dunes of Tengger Desert is located in the lower reach of the Shiyang River drainage. Rocky hills, Precambrian and Palaeozoic metamorphic and crystalline rocks covered with Cenozoic lacustrine sediment, demarcate the northern boundary of the Minqin Basin. The southern boundary is marked by the foothills of the Qilian Mountains. The terminal area of Shiyang River consists of several basins in the northeast part of Minqin Basin, such as Lake Yema, Lake Dongping, Lake Xixiaochi, Lake Dongxiaochi, Lake Baijian, Lake

Xijian, and Lake Mawangmiao (Fig. 1C). Because of the diversion of the river water for agriculture and industry, no regular water except during flooding has reached the terminal area since the beginning of this century and the lakes have been totally dry since the 1950s. At the present there is hardly any freshwater lake at the terminal area, and only small seasonal alkaline lakes exist in the several lowest basins, such as Lake Baijian and Lake Xixiaochi. Many parts of the area are covered with moving dunes and salt marshes.

As the Shiyang River drainage is at the western margin of the Asian summer monsoon limit (Fig. 1A), the summer monsoon influences the area from July to September and brings rainfall to the area. In the winter, cold and dry continental air masses frequently influence the area and are responsible for the dryness and low temperature. The mean annual temperature and precipitation in the terminal area are 7.8°C and 115 mm, respectively, while potential evaporation is over 2600 mm. The vegetation, consisting of grass and shrubs is mainly concentrated in places, where the groundwater level is near the surface. Nearly no vegetation cover is present in the Tengger desert area around the terminal area. Lakes and vegetation in this area sensitively respond to the summer monsoon variations.

3. Methods

3.1. Topography of terminal area

Topographic features are analyzed by local surveys at the terminal area and Terminal Area Digital Elevation

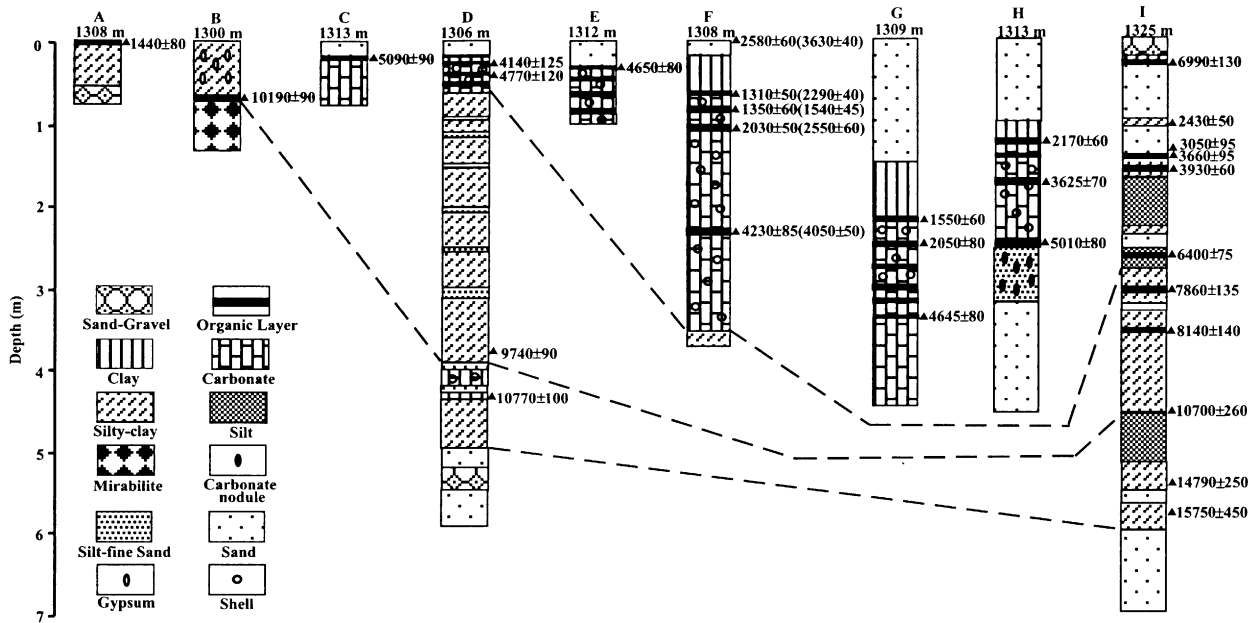


Fig. 2. The stratigraphy of lacustrine sections (sites shown in Fig. 1C) at the terminal area. Uncorrected radiocarbon dates (year) of organic matter are indicated beside the lithological sections. Another five carbonate dates are indicated in brackets beside section F. The dashed lines show the stratigraphic boundaries. Sections are (A) Beishan, (B) Xixiaochi, (C) Shaliang, (D) Yema, (E) Feishuiling, (F) Dongping, (G) Zhiyun, (H) Huokan, (I) Sanjiaocheng.

Mode (TADEM, Fig. 1C). The latter was created with relief contours based on 1:100,000 topographic maps, using ARC/INFO and PCI software. Topographic features were used to study the temporal and spatial distributions of palaeolakes in the area. The topographic boundaries of the terminal area were distinctly shown in TADEM (Fig. 1C). Rocky hills over 1400 m ASL are situated at the north and west margins of the terminal area. Moving dunes of the Tengger desert higher than 1330 m ASL and wider than 100 km are at its eastern margins. Several rocky hills over 1350 m ASL are located at the south of the terminal area. The altitude of the present dry lake floor is from about 1280 m to 1325 m. In the former terminal lake area, the Huangmaojing hill up to 1353 m ASL and NW–SE sand ridges over 1330 m ASL divided the area into two parts, the east and west parts of the lake. In the east part of the lake area there are several desiccated lake basins such as Lake Baijian (*h* in Fig. 1C), Lake Mawangmiao (*g* in Fig. 1C) and Lake Xijian (*f* in Fig. 1C). In the west part are Lake Yema (*c* in Fig. 1C), Lake Dongping (*e* in Fig. 1C), Lake Xixiaochi (*a* in Fig. 1C) and Lake Dongxiaochi (*b* in Fig. 1C). The first two lakes are also separated from Lake Xixiaochi and Lake Dongxiaochi by a sand ridge (about 1314–1320 m ASL). The topographic features imply that the terminal area was a closed hydrological system with a number of small basin centers. Based on our field survey in combination with the TADEM, a lake environment had previously been widespread in the terminal area of Minqin Basin.

Based on the TADEM and field investigation, there are also several low basins in Tengger Desert at the north of the terminal area (Fig. 1C). Lacustrine sediments are found in such low basins, indicating that lakes have covered part of the Tengger Desert. The altitudes of these basins are below 1300 m ASL and the lowest basin is only 1240 m ASL, which is much lower than the terminal area of the Shiyang River in the Minqin basin. The terminal area is separated from the basins in Tengger desert by its north boundary hills. The lowest pass of the hill named Beishan Pass and covered by moving dune sand, is only 1325 m ASL, which is 40 m higher than the lowest lake floor of the terminal area. One of our investigated sites is Sanjiaocheng at altitude of 1325 m ASL, in which lake sediment is found to be below surface of 2–3 m (Fig. 2J). The site was at the terminal lake margin and is obstructed by Tushanzi hill at its northeast. Although a small local lake could be formed in the area when the terminal lake-level was low, it could be united to the main terminal lake when lake-level was higher than the Beishan Pass. According to the TADEM Map (Fig. 1C) and lacustrine sediment distribution (Fig. 2), it is speculated that a large coalescent lake have most possibly existed at the terminal area, and recharged the catchment area in Tengger Desert through Beishan Pass during the Holocene.

3.2. Field investigations and lithological stratigraphy

The lakeshore terraces and lacustrine sediment in the west part of the terminal area were investigated in detail

(Fig. 1C). Investigation was carried across the terminal area from north to south, including the southern foot of the north boundary rocky hills, Lake Xixiaochi, Lake Yema and Lake Dongping in the center, and Sanjiaocheng at the margin (Fig. 1C). The lithological investigations were carried on using dug holes and cores (Fig. 2).

The southern foot of the rocky hills, over 1320 m ASL and typical Gobi and desert, is strongly denuded by wind. The bedrock of the hills is exposed and covered partly with moving dunes. No lakeshore or lake terrace was found during our field investigation, although fifteen sites at different altitudes from 1300 to 1350 m were dug to different depths from 0.8 to 2.0 m. Pluvial granule and angular gravel covers the hill slope. The only lake sediment, grayish black organic silt-clay, is found at site A at about 1308 m ASL. It is very likely that lacustrine deposits or lakeshore terraces at high altitude in the slope if the lake reached the hill pass were eroded, because of strong winds in the region.

The center and margins of the terminal area are covered with saline-alkali marsh and moving dunes at present. Lacustrine deposits, however, are extensive in the area (Fig. 2). It was investigated by digging trenches or drilling at different depths in the dry lake floor and at the topographic boundaries between lake centers. Lithology shows the possible correlation between different sections. There are three important stratigraphic boundaries in these sections (Fig. 2). The first stratigraphic boundary appeared at a depth of 5.00 m in Yema section (Fig. 2D) and at a depth of 6.00 m in Sanjiaocheng section (Fig. 2I). Below the boundary, eolian sand appeared in both sections, and above the boundary lake sediment formed, indicating the shift from last glacial to late glacial in the area according to the ^{14}C dates. At Yema section, carbonate sediment covered by eolian sand was transitional to silt-clay lacustrine sediment at depth of 3.92 m, implying another important stratigraphic boundary. The boundary was also evident in the other sections (Fig. 2). A mirabilite layer grades to silty-clay lacustrine sediment at Xixiaochi (Fig. 2B), and the silt-sand by silty-clay at depth of 4.6 m at Sanjiaocheng. The boundary implies lake expansion in the terminal area. Carbonate sediment with four high organic layers appears from 0.6–0.2 m deep in the Yema section. The same situation can also be seen in three other sections (Fig. 2F–H). Carbonate layers (Fig. 2C and E) beneath dune sand at the topographic boundaries between Lake Xixiaochi, Lake Yema, and Lake Dongping deposited at same time according to the ^{14}C ages. The occurrence of the carbonate layer implies a decrease and salinization of the lake in the center of the terminal lake, corresponding to the silt deposits from 2.84 m depth in the Sanjiaocheng section. This forms the third important lithological boundary.

3.3. Chronological control

Chronological control of the sections at the terminal area is mainly based on conventional radiocarbon dates of bulk organic carbon and carbonate. Additional AMS ^{14}C dates of bulk organic carbon and charcoal were determined from the Yema and Sanjiaocheng sections. A total of 36 ^{14}C dates provides chronological control. ^{14}C dates from bulk organic carbon are likely more reliable than carbonate dates. The latter may especially be subject to errors due to “hard-water” or “old carbon” effect. Parallel dates of carbonate and bulk organic matter on five layers at Dongping section revealed age deviations from 200 to 1000 yr between bulk organic radiocarbon dates and carbonate dates (Fig. 2F). The carbonate dates also frequently shows reverses with depth at both Dongping sections. However, even the bulk organic ^{14}C dates may deviate from true depositional ages in lake sediment. The surface sample at Dongping section is dated at 2580 ± 60 yr BP, and at Sanjiaocheng section at 6990 ± 130 yr BP (Fig. 2). Because lakes or marsh existed during the 1950s in the two areas, the ages are definitely too old. Also, the ages are older than the other dates below the surface at the two sections. We believe that the reverses of bulk organic dates are caused by the input of older organic carbon due to strong human-intruded soil erosion over the last few hundred years. Thus, these dates are not used in chronological control. Furthermore, we find that radiocarbon dates of bulk organic carbon below the surface was also older than about 500 yr, which is deduced from bulk organic ^{14}C dates and charcoal dates at Sanjiaocheng. At a depth of 1.45 m, the charcoal radiocarbon date is 3110 ± 80 yr BP, while the bulk organic matter dated at 3660 ± 90 yr BP. Charcoal ^{14}C ages should be more accurate and represent the true age of the lake sediment. Therefore, 500 yr are subtracted from all the bulk organic ^{14}C ages from lake deposits in this study.

According to our ^{14}C dates, the lacustrine sediments above the first stratigraphic boundary at the terminal area deposited during the late glacial. The appearance of lakes was widespread at about 14,000–13,000 yr BP during the late glacial in the Tenger desert and adjacent region (Pachur et al., 1995). In this study, we defined 13,000 yr BP tentatively as the boundary age between last glacial and late glacial at the terminal area (Fig. 4). The ^{14}C age for the base of the lacustrine deposits above the second stratigraphic boundary at the terminal area was set at 10,000 yr BP based on the ^{14}C dates at Xixiaochi, Yema and Sanjiaocheng sections. The age is generally concordant with the accepted Pleistocene–Holocene transition age in China (Shi et al., 1994). Using the linear relationship between depth and ^{14}C dates, the mean sedimentation rates of carbonate silt are between 0.4 and 0.6 mm/yr at three sections in Lake

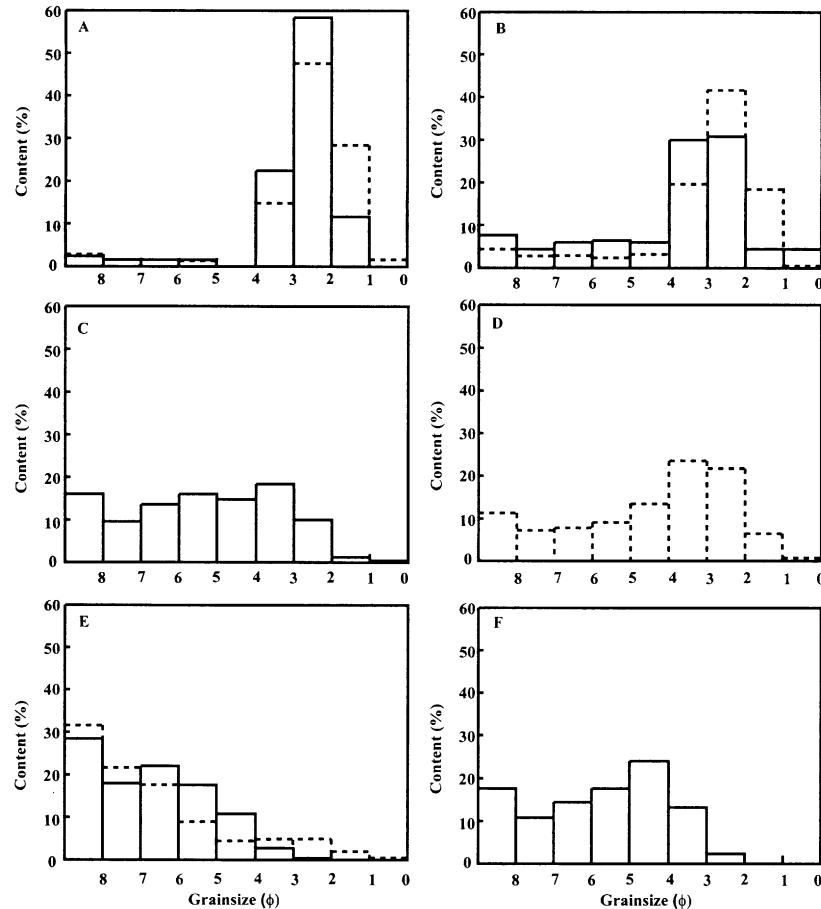


Fig. 3. Grain size distributions of sediments at Yema section (solid line) and Sanjiaocheng section (dotted line). (A) moving dune sand between the two sections, (B) eolian sand layers, (C) carbonate layer, (D) silt and sand layer, (E) silt-clay layers, (F) eolian silt-sand layer in lacustrine sediment (0.6–3.9 m) at Yema section.

Dongping. The bottom age of carbonate silt is 6300 yr BP at Dongping section, using linear extrapolation of the sedimentation rates. The basal age of carbonate silt layer at Zhiyun section is unknown because the base of the layer was not dug through (Fig. 2G). It should be older than 5500 yr based on the measured ^{14}C dates at the section. At the lake marginal section, Sanjiaocheng, the lacustrine silt-clay deposit changed to silt and sand, responding to the transition from lacustrine silt-clay to carbonate silt in the center of the terminal lake. The measured ^{14}C date of the transition at Sanjiaocheng section is 6400 ± 70 yr BP. Therefore, the third stratigraphic boundary can be placed at about 6400 yr BP (Fig. 4). The ages at both Yema and Sanjiaocheng sections will be linearly interpolated and extended.

3.4. Grain size distribution

Grain size of Yema section and Sanjiaocheng section was measured at 2 cm intervals, using a CoulterS1300 and a MasterSize2000 laser grain size analyzer, respectively. Grain sizes of moving dune around the two section areas were also measured using a Master-

Size2000. Carbonate in the samples was removed by repeatedly adding 15% HCl and washing the excessive HCl using a centrifuge. The organic matter in the CaCO_3 -free samples was then removed by adding H_2O_2 and heating for 4 h at 80°C . Finally, 2 ml of Calgon was added to the sample to disperse the particles. The treatment ensures that the measured particle size mainly represents the grain size of the terrestrial portion of the sample. In the flat terminal area, coarse grain size may only be transported by wind through frequently strong dust- and sandstorms in the region. The other possibility is that the coarse grains were brought by streams when lake-level was extremely low. Shi et al. (1998) showed that a large portion of detrital material in the lake is of eolian origin, and the coarser particles of the sand layers in the Lake Yema core originate from sand storms.

The moving dune sand has a high content of sand (over 90.0%) and a low content of silt and clay (below 10.0%), forming a prominent peak of fine sand in the distribution curve (Fig. 3A). The eolian silt and sand layers at both Sanjiaocheng and Yema sections, confirmed by sand SEM photos (Shi et al., 1998), have the same distribution as the dune sand (Fig. 3B). The

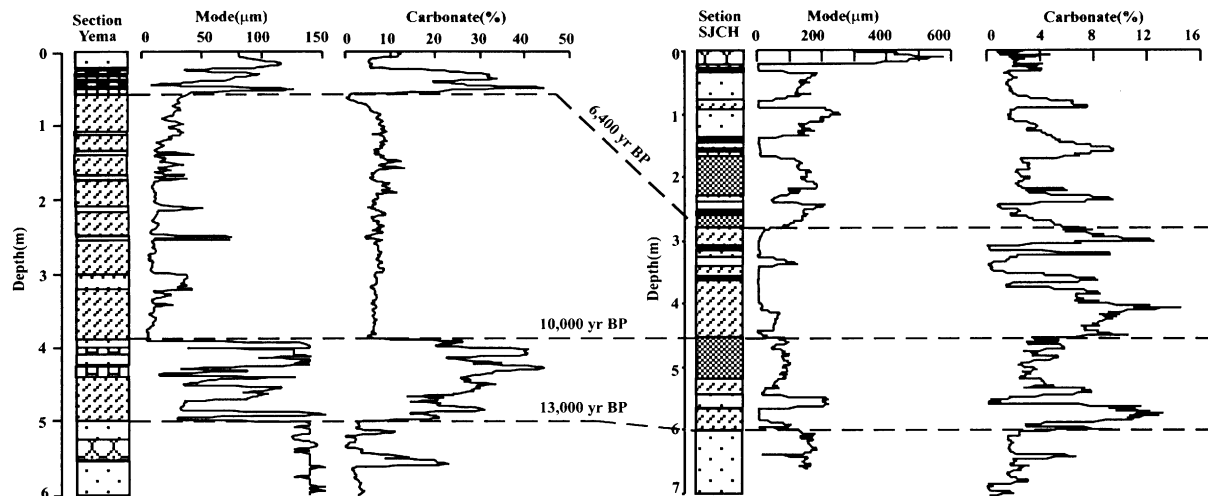


Fig. 4. Variations of mode grain size and carbonate content at Yema and Sanjiaocheng sections versus depth. The stratigraphic boundary ages are shown. Lithological legends are as in Fig. 2.

sand content is about 60–80% and the prominent size is fine sand. It is believed that these eolian sand layers at the two sections were deposited from strong sandstorms around the terminal lake area, resulting from reworking of the desiccated former lake floor. The grain size of lacustrine sediment at the two sections is quite different from eolian layers, i.e., 60–70% fine silt and clay and <10% sand (Fig. 3E), which is a typical grain size distribution of lake sediment. Silt lacustrine sediment at Sanjiaocheng section and carbonate sediment at Yema Lake is characterized by mixed deposits, with fine silt (about 40–60%) and coarse eolian sand up to 60% (Fig. 3C and D). It is easily understood that these kinds of sediments represent shallow lake environments into which eolian detritus was input, because of the dune desert around the area. At Yema section, very thin pure sand layers (1–4 cm) are found within the lacustrine silt-clay (0.6–3.9 m deep). These layers consist of up to 50% sand and coarse silt, and 50% clay and fine silt (Fig. 3F), implying abrupt eolian deposition of sandstorms in the lake environment. Therefore, the deposition environment has changed greatly since the last glacial, even during the Holocene.

3.5. Carbonate content

Carbonate contents of Yema section and Sanjiaocheng section were measured at 2 cm intervals using a Calcimeter (Fig. 4). Mineralogical analyses show that 95% of the carbonate is authigenic, and the detrital contribution is minimal. Therefore, carbonate in the lacustrine sediment at the terminal area is likely to reflect a chemical precipitation controlled by balance between the evaporation of the lake surface and the runoff of the Shiyang river drainage, considering that rainfall can be neglected in the terminal area.

At Yema section, the highest carbonate content, higher than 40%, appears at 0.2–0.6 m and 3.9–5.0 m depth, indicating a closed shallow lake with high condensation and precipitation of carbonate. The lowest carbonate content occurred in the eolian sand and fluvial sediments, coinciding with a desiccated lake or river input to the center of the terminal lake. The carbonate content of the silty-clay lacustrine sediment at 0.6–3.9 m depth at the section, <10% is between the two types of sediments. Diatom analysis shows that there are both planktonic and benthic types of diatoms indicating an alkaline, but fresh water, mesotrophic lake in this part of the sediment. Ostracoda analysis also gives the same results (Rich Battarbee, pers comm). At Sanjiaocheng section, the highest carbonate content, from 8% to 14% is in the lacustrine silty-clay sediment, and low carbonate contents occur in the eolian sand and fluvial sediment. As the Sanjiaocheng section is at the margin of the terminal lake and was drained by the old Shiyang River, it is easy to form a channel lake of the river when lake-level was low. It is impossible to precipitate relatively high amounts of carbonate in the Sanjiaocheng area because of the lack of closed conditions in the channel lake, with plentiful water input and output through the lake.

4. Palaeolake evolution in the terminal area since late Pleistocene

4.1. Last glacial (before ca. 13,000 yr BP): desert environment

In the west part of the terminal lake area, none of lacustrine sediments and lakeshore terraces during last glacial has been found so far. At Yema section, an

eolian sand layer appears below 4.98 m (up to 6.0 m), suggesting that Lake Yema was dry and covered with dunes before 13,000 yr BP. An intervening fluvial gravel layer (5.2–5.5 m) within the eolian layer demonstrates that Shiyang River once reached the center of the terminal lake area sometime before 13,000 yr BP. The area of the lake Yema extended to the pass of the Shiyang River during the period. The thick mirabilite layer in the section Xixiaochi indicates that Lake Xixiaochi became a playa in that period. According to Pachur et al. (1995), no lacustrine sediments have also been found in the eastern part of the terminal lake area during 22,000–13,000 yr BP, and eolian sand deposit covered Lake Baijian, the lowest part of the terminal area, in that period. A thicker dune sand layer was deposited at the bottom of Sanjiaocheng section before 15,750 ^{14}C BP, which at least indicates a wide distribution of dunes at the margin of the terminal lake area. Therefore, it is deduced that the terminal lake was dry, and eolian sand and dunes covered the lake floor during the last glacial. Playas may have existed only in some low centers of the terminal area during the period.

4.2. Late glacial (ca. 13,000–10,000 yr BP): rapid changes of closed terminal lake and separated lakes

Based on the radiocarbon dates and the first stratigraphic boundary age, lacustrine sediment started to deposit in the terminal area about 13,000 yr BP. At Yema section, the carbonate silty-clay sediment with fine grain size deposited between 4.98 and 4.44 m deep, indicating that Lake Yema started to form 13,000–11,200 BP after the dry last glacial. This is correlated well with the history of Lake Baijian in the east part of the terminal area (Pachur et al., 1995; Zhang and Wunnemann, 1997). Carbonate enriched silt and eolian sand at depth of 4.44–3.90 m substituted for the carbonate silty-clay, in which carbonate content reaches 50%. Lake Yema became even shallower and more saline from 11,300 to 10,000 ^{14}C yr BP at the end of the late glacial. Eolian sand with grain size over 140 μm in the carbonate sediment indicates that Lake Yema was possibly dry some time before 10,000 yr BP. Grain size and CaCO_3 proxies show the rapid changes of the lake environment during the late glacial (Fig. 4). At the Sanjiaocheng section, silt and silty-clay lacustrine sediment appears from 6.00 m, implying that a lake environment also formed in the margin of the terminal lake area at the beginning of the late glacial. Eolian sand and fluvial silt covers the lacustrine sediments, forming silty-clay lacustrine sediments and eolian sand interbeds from a depth of 4.62 to 6.00 m (Fig. 4). Both sites, therefore, show frequent oscillations of lake environment (Fig. 4), which should be a reflection of global late glacial climatic events. The events, especially the

Younger Dryas event, were not detected at Lake Baijian at the east part of the terminal area (Pachur et al., 1995) probably because the site is too close to the Tenger desert. Additionally, the different CaCO_3 content at the two sites most probably indicate that the lake in Sanjiaocheng area may be isolated from the main lake such as Lake Yema in the center of the terminal area during the period.

Before the Holocene, mirabilite was deposited in Xixiaochi area (Fig. 2), suggesting Lake Xixiaochi still was a playa during the later glacial, separated from lake Yema by the low hill, 13 m higher than the base of Xixiaochi. Consequently, we deduced that the lakes were separated from each other at the terminal area during the late glacial. Lake Yema in the center of the terminal area was closed, and Lake Sanjiaocheng at the margin of the terminal area may connect with the lake in the center through old Shiyang River.

4.3. Early Holocene (ca. 10,000–6400 yr BP): a coalescent open lake

Extensive early Holocene lacustrine sediments are found at the terminal area (Fig. 2), indicating that the lakes expanded strikingly in the period. At Xixiaochi, the silty-clay lacustrine sediment covers the thick mirabilite formed in last glacial. The ^{14}C date of the high organic layer at the bottom of the silty-clay is $10,190 \pm 90$ yr BP, indicating that the salinity of Lake Xixiaochi decreased since the early Holocene. At Lake Yema, lacustrine silty-clay and clayey-silt at depths of 0.60–3.92 m deposited after 9740 ± 90 yr BP (Fig. 5). The mean mode grain size of the terrestrial detritus is finer than 30 μm , indicating a large and deep lake during the period. The steady carbonate content, below 10%, is far lower than the content during the late glacial period, implying that the lake was fresh, as supported by diatom and ostracoda species in the lacustrine sediment. In the margin of the terminal area, silty-clay lacustrine sediment is present from 4.52 to 2.84 m deep at Sanjiaocheng section, corresponding to ages from 10,000 to 6400 yr BP. The mean mode grain size is fine and carbonate content is nearly same as that at the Yema section. Between Sanjiaocheng, at the margin of the terminal lake area, to Yema at the center, lacustrine sediment is extensively 2–3 m below the surface. Thus, the terminal lake extended to Sanjiaocheng during the early Holocene. Zhang and Wunnemann (1997) showed that Lake Baijian in the eastern part of the terminal lake area also extended during the early Holocene and formed a high lakeshore terrace 8700 yr BP. It is speculated that the terminal lake during the early Holocene was a coalescent single lake.

Although lakes at the terminal area extended strikingly during early Holocene, it is difficult to directly define the altitude of lake-level because lakeshore

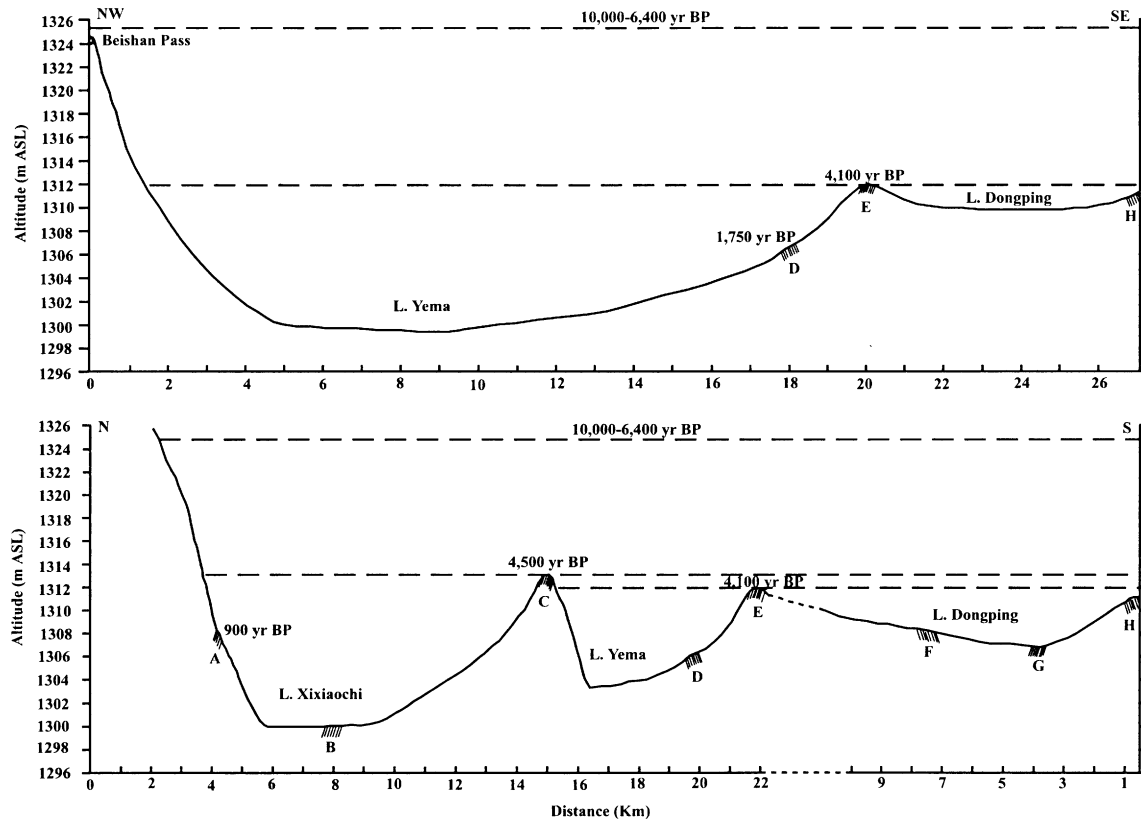


Fig. 5. Lake evolution stages across the terminal area, shown by dashed lines. The upper trends NW–SE across Lake Yema and Lake Dongping, while the lower trends N–S across Lake Xixiaochi, Lake Yema and Lake Dongping. The capital letters show section sites. The eolian and flood deposits at the top of different lacustrine sediments were removed from the figure in order to recover the true altitudes of past lake-levels.

terraces have not been found in the west part of the terminal area. The fresh lake, inferred from lithology, diatom and ostracoda, and carbonate content of the lacustrine sediment, implies that the lake was not closed but open during the early Holocene. According to the TADEM, the only possible water outlet is Beishan Pass at the northwestern rocky hill (Fig. 1C). The simulation using TADEM indicated that the terminal lake became open and fresh only when the level rose up to 1325 m ASL. If so, the lakes at the terminal area united and formed a large coalescent terminal lake with an area of 2130 km² (Fig. 6). The lake received the water from Shiyang River and output its water into the Tenger desert through the Beishan Pass. The altitude of lacustrine sediment during the early Holocene at Sanjiaocheng section is about 1322 m, lower than 1325 m elevation of Beishan Pass. It is highly possible that the coalescent lake extended to Sanjiaocheng area and deposited lacustrine sediments. Thus, the lake-level reached above 1325 m and the deepest lake water was over 45 m during the early Holocene. The western and eastern parts of the terminal area united into a single terminal lake with three islands in the lake (Fig. 6).

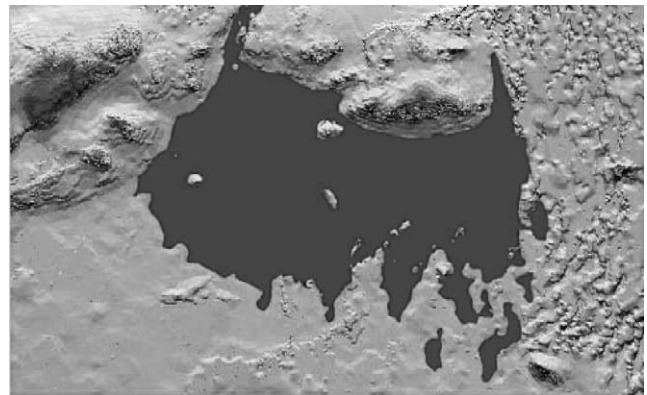


Fig. 6. The simulated distribution of the coalescent lake at the terminal area during the early Holocene (10,000–6,400 yr BP) using TADEM. The altitude of the lake-level is 1325 m.

4.4. Middle and late Holocene (ca. 6400 BP–present): disintegrated and desiccated terminal lake

Carbonate-enriched lacustrine sediment is widely existed in the west part of the terminal area after the early Holocene. The carbonate sediments in Lake Yema,

Lake Dongping (Fig. 2D–H) and the watershed between Lake Yema and lake Xixiaoichi (Fig. 2C) imply that the three lakes were still united before 4500 ^{14}C BP, but became closed (Fig. 5). The lake-level declined below the altitude of the Beishan Pass in the northwestern hill, and lake would not recharge the catchment area in the Tenger Desert. After 4500 ^{14}C yr, Lake Xixiaoichi separated from Lake Yema and Lake Dongping, while the latter two lakes separated before 4100 ^{14}C yr (Fig. 5). The transition from the early to middle Holocene is rather abrupt, as indicated by the proxies in the Yema section (Fig. 4). The mean mode grain size increases over 100 μm and a lot of eolian sands deposited in the lake. The carbonate content exceeds 40%, far higher than that during the early Holocene. There are several grayish black organic layers within the carbonate sediment layer at the sections in Lake Yema and Lake Dongping (Fig. 2D–H, Fig. 4), implying possible lake-level fluctuations after the early Holocene.

After 4100 ^{14}C yr, the separate three lakes experienced different falling processes. Lake Xixiaoichi declined and was sustained by local catchment from the north boundary hills. The lake was even 8 m higher than the present lake floor at 900 ^{14}C yr (Fig. 5). Gradually, Lake Xixiaoichi developed to a salt lake and deposited the gypsum. At present, the lake is a saltpeter pool used for industry. In Lake Yema, carbonate sediment ended at 1750 ^{14}C (Fig. 5), and the lake became a seasonal water pool during historical time. Lake Dongping also developed to a seasonal lake and frequently recharged by flooding from the new channel of Shiyang River during historical time, forming the brown clay deposited at top of the carbonate layers at the three sections of Lake Dongping (Fig. 2F–H). Frequent strong floods of Shiyang River have been documented in the local historical books (Feng, 1963; Li, 1998). The lake even existed in the 1950s.

Along with the disintegration of the coalescent lake and lake-level decrease during the middle and late Holocene, the lake at Sanjiaocheng separated from the terminal main lakes and again became a channel lake of Shiyang River. At Sanjiaocheng, lacustrine silt sediments were deposited at above 2.82 m depth since 6400 ^{14}C BP. The mode grain size, over 150 μm , and low carbonate content indicate a shallow lake in which eolian sands were deposited during the middle Holocene. The lake was totally dry, and dune sand covered the area shortly after 6000 BP, which could correlate with thick dune sand at Huokan section (Fig. 2H). Ash and pottery pieces around Sanjiaocheng show that humans had occupied the former lake area after 3000 ^{14}C BP, although the lake had subsequently covered the area twice.

Corresponding to the lake change in the west part of the terminal area, lakes in the eastern part of the terminal area also decreased during the middle and late

Holocene. Lake Baijian has preserved three lakeshore terraces at ca. 5200, 2500, and 1400 yr BP (Pachur et al., 1995; Zhang and Wunnemann, 1997), suggesting that lake-level also fluctuated during middle and late Holocene. These terraces are correlated to some high-organic layers at the sections in the west part of the terminal area (Fig. 2D–H). Because the lakes were separated, the heights of different lakes could be different simultaneously during middle and late Holocene events. However, the lake changes may be correlative because of the common controlling fact, i.e., climate, if the human influence is neglect.

5. Climatic implications for palaeolake evolution

In arid China, effective precipitation is more significant and sensitive than temperature in the aspect of environmental change. Fluctuations of lake in the arid region are mainly controlled by effective precipitation, which relies on the ratio of precipitation and evaporation and summer monsoon. Because the Shiyang River drainage is located in the western margin of present limit of the Asian summer monsoon, the main rainfall is provided by the summer monsoon in the drainage every year. The change in recharge of the Shiyang River since the early 1960s was evidently driven mainly by summer precipitation, rather than by snow in the winter in the Qilian Mountains (Chen and Qu, 1992). The palaeolake evolution at the terminal area has not only documented the general trend of the dry and wet conditions of the Shiyang River drainage, but also has sensitively responded to shifts of the Asian summer monsoon since the last glacial.

Extremely dry conditions were documented by the desiccated lakes and extensive dune sand at the terminal area before 13,000 yr BP, suggesting that the summer monsoon weakened and did not influence the drainage area. This was recorded by the lowest lake-levels of Bangong Co, Qinghai Lake and Lake Daihai (Fig. 7) located along the present summer monsoon margin (Fig. 1A). The wet condition and the onset of terminal lakes in the Shiyang River drainage system starting at ca. 13,000–11,200 yr BP indicated that summer monsoon intensified, and the drainage was under the summer monsoon regime during the late Last Glacial. The result matches the rises of lake-level in Bangong Co, Qinghai Lake and Lake Daihai (Fig. 7). In the late Pleistocene/Holocene transition, the lakes at the terminal area experienced a rapid desiccation at ca. 11,200–10,000 BP, representing a brief climatic deterioration event in drainage, coinciding with a falling episode in Bangong Co, Qinghai Lake and Lake Daihai (Fig. 7). Strong eolian sand activity along Huolan Mountains at the east of the Tenger desert was reported in the period (Madsen et al., 1998). The dry event in arid

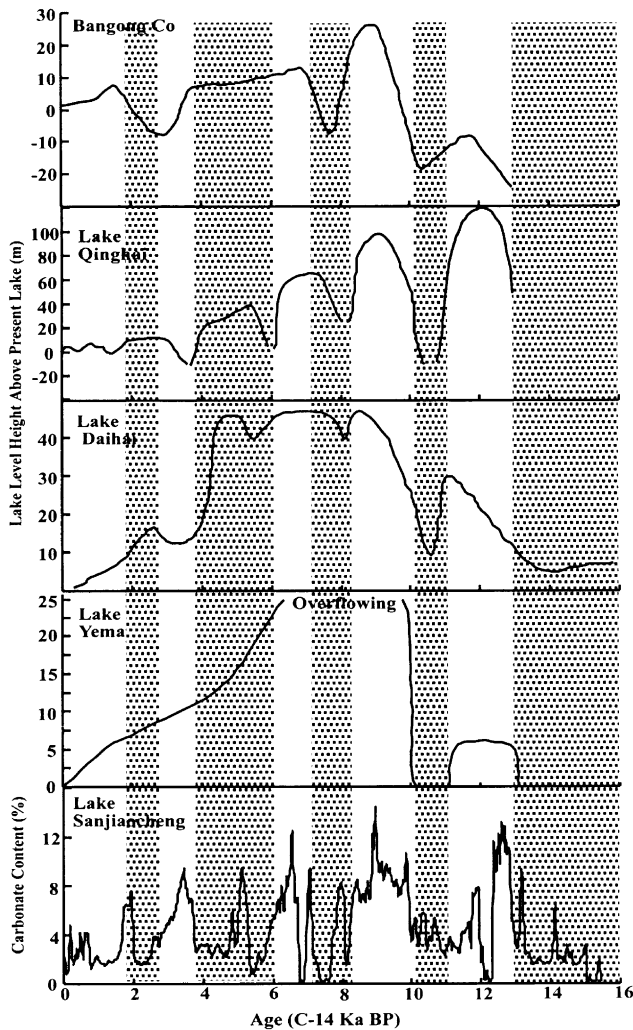


Fig. 7. Lake-level fluctuations in arid China since the last glacial. Bangong Co and Qinghai Lake (after Wang, 1992) in the Tibet Plateau, L. Daihai (after An et al., 1993) in Inner Mongolian Plateau, and Lake Yema in Shiyang River drainage. Carbonate content of Sanjiaocheng section indicates rapid summer monsoon fluctuations since the last glacial. The decrease and desiccation of lakes are marked by dots.

China during the late glacial may represent regional responses to the global Younger Dryas event, indicating that the summer monsoon weakened abruptly in the Younger Dryas period.

A coalescent fresh open lake occurred and reached its maximum extent at the terminal area between 10,000 and 6400 yr BP, indicating a moist climate. During the period the moisture in the catchment and runoff of Shiyang River was considerably higher than at present. Because temperature during early Holocene was also high (Shi et al., 1994), evaporation is expected to have been high. Therefore, a strong summer monsoon connected with high rainfall could be deduced. The moist conditions and stronger summer monsoon regime are also documented by high lake-levels in Bangong Co, Qinghai Lake and Lake Daihai (Fig. 7). In summer, the

present summer monsoon region and its northern and western margins experienced a humid climate in early Holocene. It was believed that the summer monsoon during early Holocene even reached inland China, far from the present summer monsoon limit (Li, 1990).

The dry condition in the drainage is found after 6400 yr BP, indicated by the disintegration and decrease of the terminal lakes. The formation of small closed carbonate lakes and swamps points to drier climate, and indicates that summer monsoon weakened again and the drainage frequently was out of the monsoon regime during the middle and late Holocene. This change is also shown by the rapid declines of Bangong Co, Lake Qinghai and Lake Daihai at about 6000–4000 yr BP (Fig. 7).

However, except for the general trend of lake-level changes since the last glacial, the proxies of the palaeolake environment show millennial climate variations in the Shiyang River drainage since the last glacial (Fig. 4). The rapid millennial changes not only existed in the well-known late glacial but also during the whole Holocene. Some of the events such as the 7700–7200 ^{14}C yr dry event (Fig. 7) are consistent not only with those recorded in arid China (Lister et al., 1991, Van Campo et al., 1993), but also with the rapid cold event recorded in Greenland (Alley et al., 1997) and the dry episode in Africa, Asia, and North America (Gasse and Van Campo, 1994; Stager and Mayewsk, 1997). The periodical climatic fluctuations in the drainage will be further analyzed using more proxies in another paper.

The general summer monsoon change since the last glacial documented by the palaeolake evolution of Shiyang River supports the simulation results of the Asian monsoon by the GCM (Prell and Kutzbach, 1987) and CCM0 (An et al., 1993; Wu et al., 1994) models. Our result also supports the modeling result that the Asian summer monsoon was forced by variations of Northern Hemisphere insolation, i.e., an orbital forcing mechanism (Kutzbach, 1981; Kutzbach and Otto-Blie, 1982; Kutzbach and Street-Perrott, 1985; Kutzbach and Liu, 1997). However, the reason for the rapid millennial variations of summer monsoon documented in the terminal lake of Shiyang River since the late last glacial is still unknown. The low latitude oceans, such as the Pacific Ocean and Indian Ocean may respond to rapid interglacial climatic changes in China (Chen et al., 1999b).

6. Conclusion

The lakes were dried up and covered with dunes or became playas at the terminal area and the Shiyang River drainage experienced extreme arid period during the last glacial. Lakes occupied the terminal area during 13,000–11,200 BP and dried up rapidly during

11,200–10,000 BP. The climate in the drainage experienced wet condition and brief extreme arid event corresponding to Younger Dryas during the late glacial. Rapid millennial climatic variations in the drainage were recorded in the Sanjiaocheng section in the period.

A coalescent open lake with a depth over 45 m and area over 2130 km² formed between 10,000 and 6400 BP in the terminal area. The lake was recharged by the Shiyang River and flowed out into the Tenger Desert through Beishan Pass in the northwestern marginal rocky hills. Therefore, Climate was much moistest and summer monsoon was strongest since the late glacial in the drainage area. Sandstorms, however, happened frequently. Millennial, even decadal climatic changes were also documented in the terminal lakes. The coalescent lake had disintegrated and decreased since 6400 ¹⁴C BP. The main stages of lake decline in the west part of the terminal area happened at 4500 ¹⁴C BP, when Lake Yema and Lake Xixiaochi separated and 4100 BP when Lake Yema and Lake Dongping separated. The closed shallow carbonate lakes and swamps formed gradually during the middle and late Holocene. The trend of climate was toward aridification in the drainage basin. However, fluctuations and limited expansion of the terminal lake in response to wet episodes in the drainage are documented at Sanjiaocheng.

The terminal lake evolutions imply that monsoon climate changed greatly at the present summer monsoon margin since the last glacial period. The result supports the modeling results that the East Asian summer monsoon was forced by Northern Hemisphere insolation. Millennial and even decadal monsoon climatic variations, however, were also documented in the lake evolution. The mechanism of the changes is still unknown.

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