Palaeolake and palaeoenvironment between 42 and 18 kaBP in Tengger Desert, NW China

ZHANG Hucai[1], MA Yuzhen[1], PENG Jinlan[2], LI Jijun[1], CAO Jixiu[1], QI Yuan[1], CHEN Guangjie[1], FANG Hongbing[1], MU Defen[1], H. J. Pachur[3], B. Wünnemann[3] & FENG Zhaodong[1]

1. National Laboratory of Western China's Environmental Systems, MOE, Lanzhou University, Lanzhou 730000, China;
2. Nanjing Institute of Geology and Paleontology, Academia Sinica, Nanjing 210008, China;
3. Geolaboratory, Institute of Geographical Sciences, Free University of Berlin, Malteser, Str. 74-100, 12249 Berlin, Germany

Correspondence should be addressed to Ma Yuzhen (e-mail: yzhma@lzu.edu.cn)

Abstract **Comprehensive field investigations and laboratory analyses show that palaeolakes, including fresh-mesohaline water Megalake Tengger and other semi-connected, isolated water bodies, during late Pleistocene covered an area of more than 20000 km^2, which is more than half of the Tengger Desert in NW China. Stratigraphic correlation and chronological evidence indicate that before ca. 42000 aBP the area was more arid. The palaeolakes started to develop around 40000 uncal. ^{14}C aBP but until 37000 ^{14}C aBP their scope was limited. High water levels established from 35000 ^{14}C aBP lasted until 22000 ^{14}C aBP. Lake levels regressed between 22000 and 20000 ^{14}C aBP but transgressed from 20000 to 18600 ^{14}C aBP. Subsequently, water level declined further and the Megalake Tengger finally desiccated at around 18000 ^{14}C aBP. Megalake Tengger possessed a fresh-mesohaline water property, implying that the regional precipitation increased significantly. During the period of Megalake Tengger, the climate was warmer-humid than present. The annual rainfall was 250 to 350 mm more than that of today and the temperature was 1.5 to 3.0℃ higher.**

Keywords: Tengger Desert, palaeolake, palaeoenvironment, NW China.

The Tengger Desert, located in the semiarid area of northwestern China, with a total area of 36000 km^2, is the fourth largest desert in China[1]. The desert itself is bounded to the south by the Qilian Mountains and by the Yabulai Mountain, which separates the Tengger Desert from the Badanjilin Desert, to the northwest. The Helan Mountain, which stretches in a north-south direction, functions as a barrier for the eastern Asian Monsoon and separates the Tengger Desert from the Mo Us sandy land to the east. To the southeast, the desert stretches to the Loess Plateau. Climatically, the area is situated at the intersection between arid-hyperarid northwestern China, the arid-semiarid southeast and the cold-high mountain-plateau regions in the southwest. Coupled with the meandering of the Westerly-Jet, strong seasonal influences of the East Asian Monsoon reach the area during summer, resulting in rainfall from July to September. Cold and dry air masses originating in the Siberian-Mongolian High Pressure generally prevail in winter. The mean annual temperature and precipitation are 7.8℃ and 115 mm respectively, while the potential evaporation is about 2600 mm[2].

During the last ten years, extensive, systematic and detailed field investigations have been conducted in NW China by both Chinese scientists and scientists from Sino-Germany bilateral cooperation groups. Geomorphological, sedimentological, palaeobiological and chronological studies have led us to conclude that there existed vast areas of lakes during the Late Pleistocene in Tengger Desert and its adjacent areas[3—5]. A pan-palaeolake development phase in the presently extreme, arid and semiarid areas in the Old World Desert Belts (OWDB) during Late Pleistocene might have important global significance.

1 Material and method

The locations and elevations of previously studied sections[3,4, 6,7] were systematically remeasured by survey GPS and cross-checked with topographical map gridding. For this study, we excavated and sampled several new sections and refined the chronology and stratigraphy of the Baijian Hu terraces, which were first reported by Pachur et al.[3]. We also re-excavated two of the previously studied sections, Duantouliang (DTL, at 39°37′21″N, 103°55′13″E) and nearby Tudongcao (TDC, at 39°32′53″N, 103°46′37″E), and re-sampled them in denser intervals for various analyses, especially for dating to establish the chronology.

Conventional ^{14}C dating was conducted in three different laboratories: Lanzhou University and Lanzhou Desert Institute of China, and the Bundesanstalt für Geowissenschaften und Rohstoffe in Hannover of Germany. AMS dating was done in Beta, Miami, USA. The materials used for dating include organic material, charcoal, and carbonate. When there is no alternative, fossil shells were used for ^{14}C dating. To avoid inconsistence, we chose the same species of shells that were not reworked. The recommended procedures were strictly followed in cleaning and preparing the samples. The pre-treated samples were treated again in the laboratory according to the standardized procedures. At the same time, the shells used for dating were analyzed by X-ray diffraction to assure that shells consisted only of aragonite without any recrystallization, which ascertains that carbonate exchange did not occur between the ground waters and the shells.

(ⅰ) Baijian Hu Terraces and fossil assemblages. Complete and well-preserved lake terrace sequences and associated fossil assemblages are probably the best

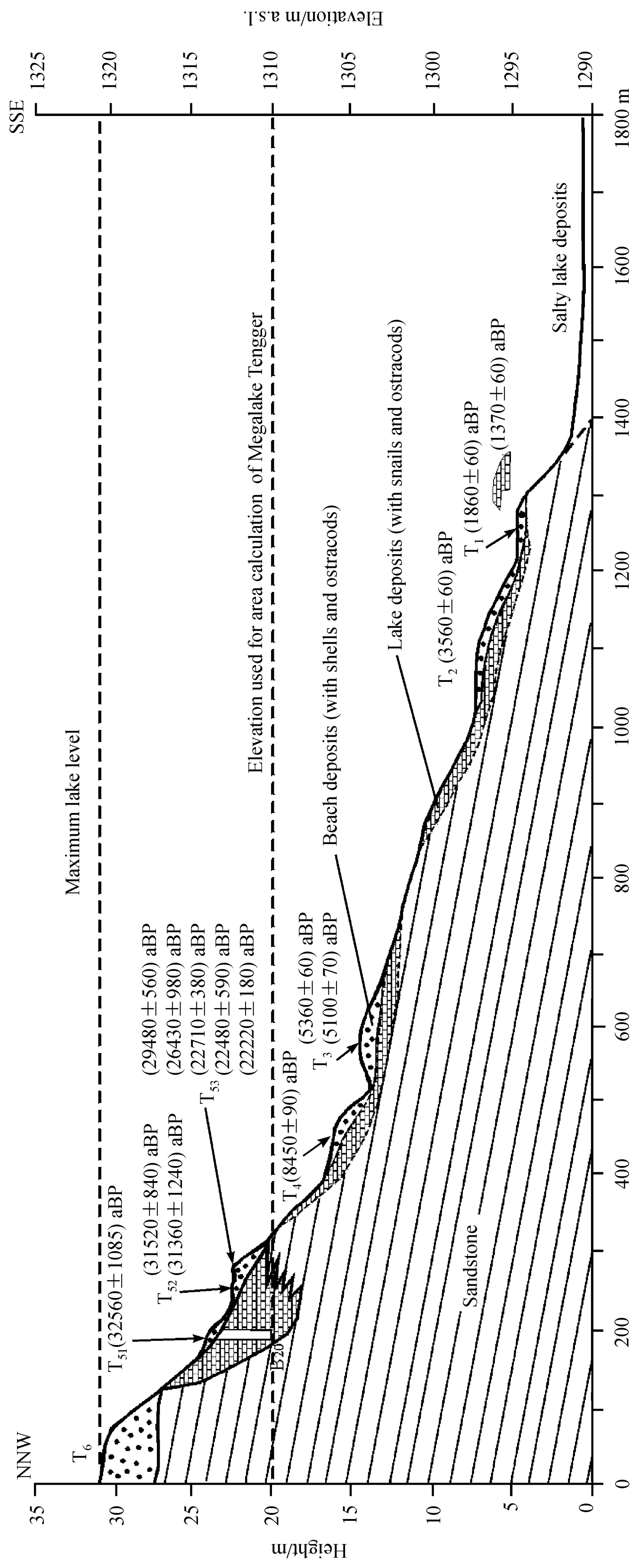

Fig. 1. Cross section of lake terraces at Baijian Hu and their dating (modified after Pachur et al., 1995).

evidence for reconstructing palaeolake level stands. Our investigations identified six terraces (fig. 1) in the northeast Baijian Hu (39°09′N, 104°10′E). The highest terrace T_6 is 30—31 m above the present Baijian Hu playa surface. The second terrace T_5, the Main Terrace, is about 22 m above the playa surface. T_5 can be divided into three parts: a broken terrace T_{5-1} on the outer side and two well-preserved parallel terraces T_{5-2} and T_{5-3} on inner side. The terrace T_{5-1}, was partially eroded by lake water during the formation of T_{5-2}, suggesting that the water level during T_{5-2} might have been higher than during T_{5-1}. On all three terraces, we found abundant fresh-water fossil shells, identified as *Corbicula fluminea* and *Cubicula largillierti* and snails *Gyraulus chinensis*.

Other terraces (T_4, T_3, T_2 and T_1) occur at 15.7 m, 14 m, 7—8 m and 4—4.5 m above the playa surface, respectively. Their sediments are rich in fossil snails, which sometimes occur as a distinct (5 cm thick) layer. The T_6 is not dated for lack of datable matter. The T_{5-1} was dated at (32560 ± 1090) ^{14}C aBP. Two dates for the T_{5-2} are (31520 ± 840) aBP and (31360 ± 1240) aBP. Five dates were obtained on the T_{5-3} range from 30000 to 22000 aBP, (29480 ± 560) aBP, (26430 ± 980) aBP, (22710 ± 380) aBP, (22480 ± 590) aBP and (22220 ± 180) aBP. The T_4 was dated at (8450 ± 90) aBP. The T_3 has two dates: (5360 ± 60) aBP and (5100 ± 70) aBP. T_2 was dated at (3560 ± 60) aBP and the lake deposits associated with T_1 was at (1860 ± 60) aBP and (1370 ± 60) aBP.

(ii) Regional distribution of the palaeolake deposits and their correlation. Lake deposits are widely distributed in the Tengger Desert and adjacent areas. The typical sections that represent the Late Pleistocene Megalake Tengger are shown in fig. 2. The Jilantai Section (number 1 in fig. 5) is 800 cm thick, with the portion from depth 240 cm to depth 687 cm being composed of fine clayey deposits. Sedimentary and geochemical properties indicate that this portion was deposited under stable and deep-water conditions. The top of the clayey deposit was dated at (25230 ± 610) ^{14}C aBP on carbonate nodule. We disregarded the root residual date obtained from the same level (7130 ± 110 ^{14}C aBP) because the root was probably a later penetration of a tree. The clayey silt deposits at depths of 210—185 cm was dated at (15770 ± 210) aBP and a carbonate crust at depths 140—130 cm at 9360 aBP. These two carbonate-enriched layers are widely distributed in the area, indicating widespread shallow water swamp or semi-lacustrine environments. Also noticeable is the red-brownish crust at the depth of 50 cm underlying the top dune sand unit.

To northwest from the Jilantai section, vastly occurred fluvial fan deposits associated with geomorphologically traceable terraces. Identified fossils shells in the fluvial fan deposits (including *Corbicula fluminea* and *Cubicula largillierti* and snails *Gyraulus chinensis*) are very similar to species found in the Baijian Hu terraces, probably implying that these fluvial-fan associated terraces are correlative with the main palaeolake terraces at Baijian Hu. This tentative terrace correlation was also corroborated by vast fluvial fan deposits dated between (30350 ± 470) and (21970 ± 160) aBP[8]. Although the7re

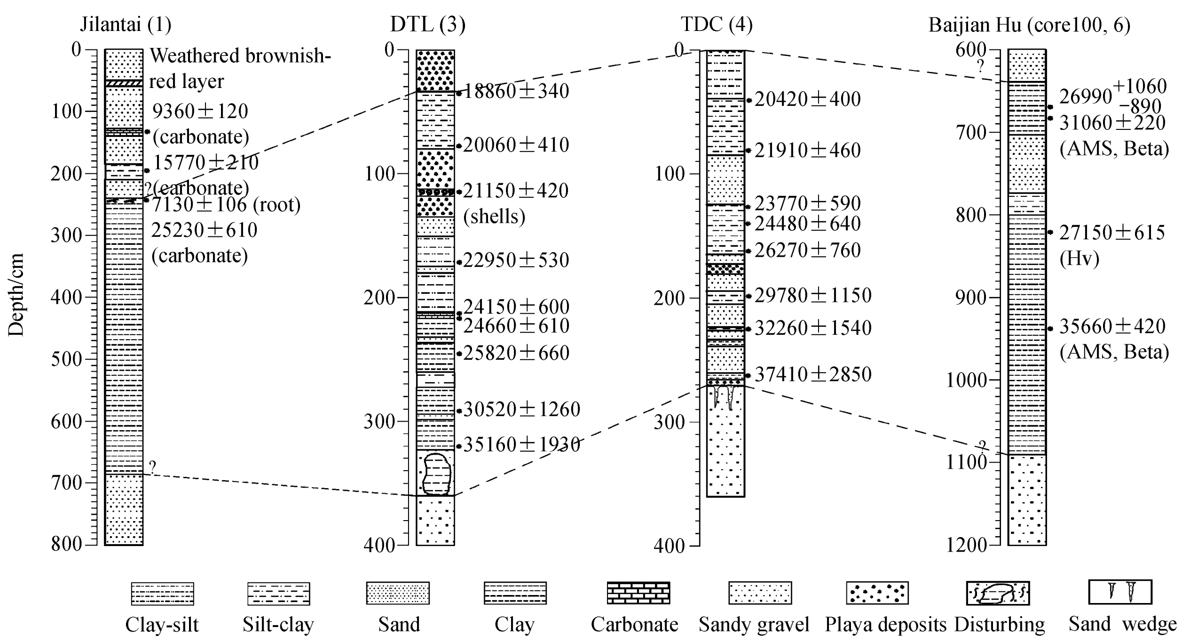

Fig. 2. Stratigraphical columns of the Late Pleistocene palaeolake deposits (the numbers indicate localities of the sections and/or studied sites shows in fig. 5).

is no age control at the bottom of the lacustrine deposit (240—687 cm), the regional stratigraphic correlation suggests that the lacustrine deposit at the Jilantai section be deposited synchronously with those at the TDC and DTL sections. As for the Baijian Hu core (number 6 in fig. 5), the date of (35660 ± 420) aBP at the middle of the lacustrine deposit does undermine our interpretation that the Megalake Tengger was at its maximum from approximately 35000 to 22000 aBP. But since the Baijian Hu core is located at the central part of the Megalake Tengger, the older date at the bottom of the lacustrine deposit (>35660 aBP) may simply mean that the Megalake Tengger started earlier in its center. A regional correlation of these representative sections shows that the Late Pleistocene palaeolake deposits are thinner and coarser in the western part of Tengger Desert (e.g. Duantouliang and Tudongcao) than in the eastern part (e.g. Jilantai).

The oldest date at the low part of DTL section is (35160 ± 1930) aBP, and (35660 ± 420) aBP in Baijian Hu core. Based on the dates on each of the section (see fig. 4), using different sedimentation rates, it can be concluded that the Late Pleistocene palaeolake was initiated around 42000—40000 aBP. This estimation is highly uncertain and needs further refinement.

Drillings in the Yabulai Basin, the western part of Tengger Desert, revealed that the Quaternary deposits are more than 400 m thick and dominated by lacustrine sediments. In the eastern slope of the Yabulai Mountain, flat topped fluvial fans, probably fluvial terraces, developed at the elevations between 1300 and 1350 m a.s.l. (fig. 3(a)). We investigated a 4-m-thick section (fig. 3(b)) exposed by river downward cutting and observed six layers of fine silt-clay at the section, marked as A, B, C, D, E and F. Three samples, YBL1, YBL2 and YBL3, were taken for pollen and microfossil analyses. A charcoal sample in YBL1 and an organic matter sample in YBL2 were dated at (29430 ± 1090) aBP and (25390 ± 690) aBP respectively. The species of ostracod microfossils include *Iiyocypris gibba*, *Heterocypris salina*, *Eucypris* sp., *Candona Candida*, *Candona Compressa*, *Limnocythere inopinata* and *Cyprideis torosa*. These species indicate a fresh-water deltaic-lacustrine environment, suggesting that these six layers of fine silt-clay were deposited in transitional environments between river and palaeolake. This sequence at 1310—1320 m a.s.l. correlates well with the terrace sequence at the Baijian Hu, which elevated at 1310—1321 m a.s.l. and represents the high lake levels of the Megalake Tengger.

(iii) Typical limnological Deposit——Duantouliang (DTL) section. The 400-cm DTL section can be divided into six stratigraphic units, as shown in fig. 4.

Unit 1 (0—34 cm) consists of well-sorted carbonate-cemented beach gravel interbedded with silty clay deposits containing fossil shell fragments.

Unit 2 (34—80 cm) consists of light brown to slightly gray-green clayey fine sand and gravel, cemented by carbonate and enriched in fossil snail fragments. The two dated samples were from depths of 34 — 40 cm (18860 ± 340 ^{14}C aBP) and 75—80 cm (20060 ± 410 ^{14}C aBP).

Unit 3 (80—150 cm) consists of sand and gravel enriched in fossil shell fragments. The unit can be divided into five sub-units. From 80 to 113 cm is a well-sorted, un-cemented beach-gravel layer containing numerous fossil shell fragments; from 113 to 118 cm is a layer of fossil shells (*Corbicula fluminea müller* and *Corbicula largillierti philippi*), dated at (21150 ± 420) ^{14}C aBP; from 118 to 125 cm is a sandy gravel layer cemented by carbonates; from 125 to 135 cm is a well-sorted, un-cemented beach gravel; and from 135 to 150 cm is sand.

Unit 4 (150—322 cm) consists mainly of lacustrine deposits with fragments of fresh-water snails. This unit can be divided into eleven sub-units (designated as a, b, c, …, k). Unit 4a, from 150 to 175 cm:, is clayey-silt in the upper part and silty-clay in the lower part. The lower part contains fossil snails. A sample from 170—175 cm was dated at (22950 ± 530) ^{14}C aBP. Unit 4b, 175—180 cm, is silty sand containing fragments of fossil shells; Unit 4c, from 180 to 211 cm, contains brown-yellowish silty-clay layers interbedded with fine silt layers from 180 to 190 cm, and grayish fine silt layers interbedded with grayish clay layers from 190 to 200 cm. From 200 to 202 cm is a marker layer of brownish, silty clay. From 202 to 211 cm is a grayish silt layer interbedded with a grayish clay layer containing fossil snails. Unit 4d, from 211 to 217 cm, is a bedded clay layer enriched in carbonate and fossil shells and snails. The organic matter in the sample was dated at (24150 ± 600) ^{14}C aBP. Unit 4e, from 217 to 232 cm, contains clay layers interbedded with fine silt layers enriched in fossil snails. A sample at the depths of 220—224 cm was dated at (24660 ± 610) ^{14}C aBP. Unit 4f, from 232 to 236 cm, is a brown-yellowish sand layer. Unit 4g, from 236 to 260 cm, consists of grayish clay layers interbedded with grayish fine silt layers. A sample at 242—246 cm was dated at (25820 ± 660) ^{14}C aBP. Unit 4h, from 260 to 272 cm, is a silt layer. Unit 4i, from 272 to 294 cm, is a grayish clay layer containing fragments of fossil snails. A sample from 290—294 cm was dated at (30520 ± 1260) ^{14}C aBP. Unit 4j, from 294 to 298 cm, is a light brownish fine silt layer with fossil snails. Unit 4k, from 298 to 322 cm, is a bedded clay layer with fossil snails. A sample from 317—322 cm was dated at (35160 ± 1930) ^{14}C aBP.

Unit 5 (322—360 cm) is a disturbed and mixed layer of red-brown silt-sand-gravel deposits capped with a thin yellow-brownish clay layer.

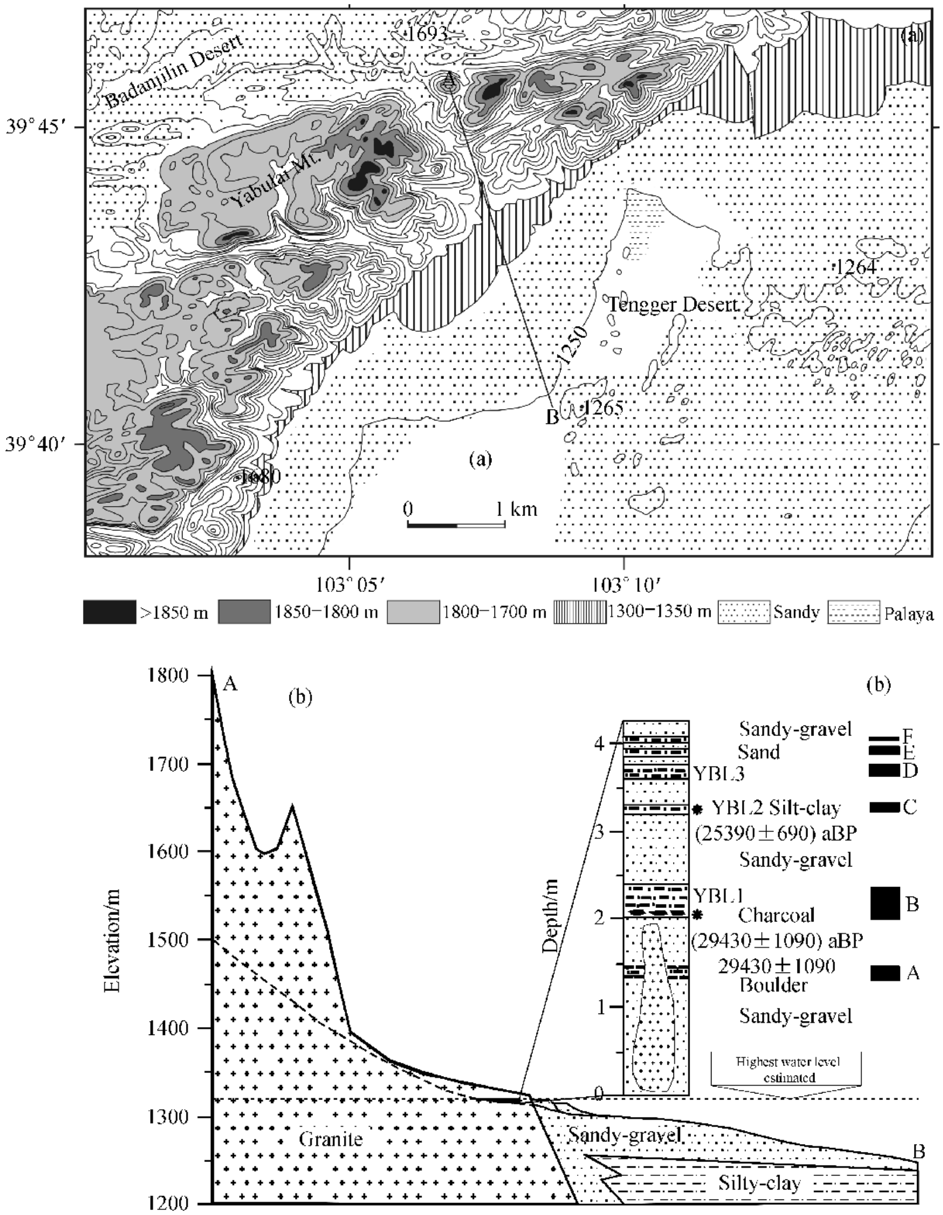

Fig. 3. Geomorphological map of Yabulai Mountain (a) and cross section A—B (b).

Unit 6 (360—400 cm) consists of brown-red silt-sand-gravel deposits. This layer is widely distributed in the area and thus regarded as a regional stratigraphic marker.

On the basis of the regional stratigraphical and chronological correlation[9] and age extrapolation, the bottom of the section appears to have formed between 42000 and 40000 ^{14}C aBP. The nearly linear relationship between dates and depths reinforced our confidence in the ^{14}C dates and reduced the possibility that there was a depositional hiatus in the section.

2 Data and results

All the dates on the samples from limnological deposits and fossils are listed in table 1. They are considered to be reliable because firstly, most of them are the dating results of organic matter and multi-laboratory results are comparable. Secondly, in the same section, e.g. DTL and TDC sections, there is no reverse between the dates and the statistic analysis shows a high age-depth correlation. Dates from the same sampling site are also comparable. For example, samples from $T_{5\text{-}2}$ (taken from the same layer at different times and analyzed by different laboratories) were dated at (31520 ± 840) aBP and (31360 ± 1240) aBP

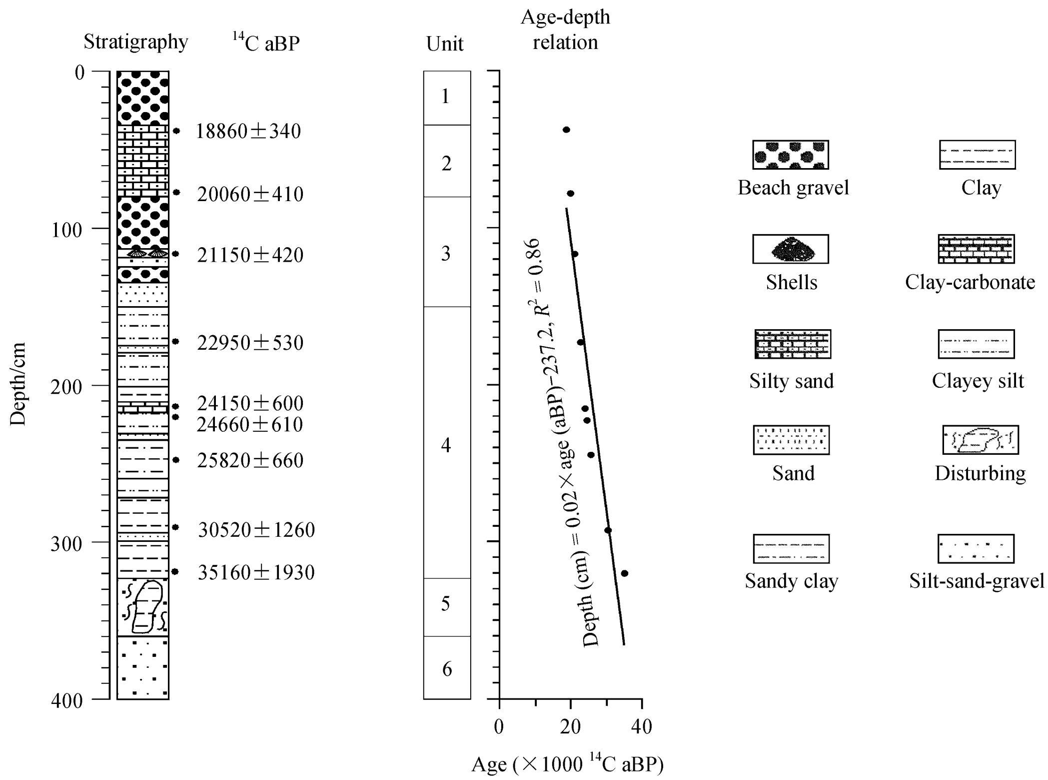

Fig. 4. DTL section and the relation between age-depth.

(table 1). Dates on inorganic carbon are variable and usually older than those on organic matter because of the dead carbon effect. For example, the samples at 92 cm in Baijian Hu section were dated at (6420 ± 70) aBP (Lanzhou University, China) and (6670 ± 100) aBP (Hannover, Germany). Samples from 370 cm in the Hongshui River section (lower) were dated at (13220 ± 100) aBP (inorganic carbon) and (11470 ± 160) aBP (organic matter). Our discussions are based on the dates of organic matter and shells.

(i) Age of the Magelake Tengger and the scope of the palaeolakes. The sequence of Baijian Hu terraces represents the high water level stands of the palaeolake in Tengger Desert. Even without dating on the highest terrace T_6, geomorphological features indicate that it represents the oldest and highest water stand. It was hypothesized that this highest terrace was formed between 38—32 kaBP[3].

^{14}C data show that T_5 was formed between 32560—22220 aBP. This agrees with the ages of the palaeolake deposits and high water levels indicated by TIC index from the DTL section. Almost continuous deposition sequence of DTL section represents the period of lake phase in Tengger Desert. This Magelake Tengger lasted for 13000 years between 35—22 kaBP, even the water level declined abruptly at around 30520, 25290 and 23100 aBP.

Based on the elevation of Baijian Hu terraces and the distribution of lacustrine-fluvial deposits in the Yabulai Mountain area with the reference of the elevation of regional lake deposits, it can be deduced that the high water level of the Megalake Tengger during the Late Pleistocene was between 1310—1321 m a.s.l. The palaeolake area calculated along the 1310 m hypsometeric contour is 16000 km^2[3]. It was later found that there are several separated palaeolakes in the eastern part of the desert. Because this elevation (1310 m) is 2 m lower than the actual main beach T_5 (which is 22 m above the present playa surface, with elevation of 1312 m a.s.l.) and 8—9 m lower than T_6 (which is 30—31 m above the present playa surface, with elevation of 1318—1319 m a.s.l.), the recalculated total area of the palaeolakes between 35000 and 22000 aBP in the Tengger Desert should be at least 20000 km^2 (fig. 5), which takes up more than half of the total area of Tengger Desert. Based on the species of microfossil (Peng et al., 1998) and geochemical data[10], the Megalake Tengger was a fresh to mesohaline lake with a depth ranging from 20 to 60 m. Also documented by terrace sequences and associated deposits are drastic lake level fluctuations during the development of the Megalake Tengger.

(ii) Geochemical index and the lake level fluctua-

Table 1 Radiocarbon dates in Tengger Desert and its adjacent areas

Locality	North latitude	East longitude	Depth/height /cm	C-14 age/aBP	Material/Lab[a].	Source/remarks
Jilantai	site 1 in fig. 5		135	9360 ± 120	carbonate/LDI	Uncalibrated/author
			192	15770 ± 210	carbonate/LDI	
			240	7130 ± 106	organic/LDI	
			240	25230 ± 610	carbonate/LDI	
Yabulai	39°43′51″	103°07′09″	325	25390 ±690	organic/LDI	Uncalibrated/author
			202	29430 ± 1090	charcoal/LDI	
DTL	39°37′21″	103°55′13″	37	18860 ± 340	organic/LDI	uncalibrated/author
			77.5	20060 ± 410	organic/LDI	
			116	21150 ± 420	shell/LDI	
			172.5	22950 ± 530	organic/LDI	
			214.5	24150 ± 600	organic/LDI	
			222	24660 ± 610	organic/LDI	
			244	25820 ± 660	organic/LDI	
			292	30520 ± 1260	organic/LDI	
			319.5	35160 ± 1930	organic/LDI	
TDC	39°32′53″	103°46′37″	42	20420 ± 400	organic/LDI	uncalibrated/author
			82.5	21910 ± 460	organic/LDI	
			127	23770 ± 590	organic/LDI	
			137.5	24480 ± 640	organic/LDI	
			164	26270 ± 760	organic/LDI	
			198.5	29780 ± 1150	organic/LDI	
			226.5	32260 ± 1540	organic/LDI	
			263	37410 ± 2850	organic/LDI	
Baijian Hu Terrace	39°09′	104°10′	T_{51}	32520 ± 840	shell/LZU	uncalibrated/author
			T_{52}	31520 ± 840	shell/LZU	
				31360 ± 1240	shell/LDI	
			T_{53}	29480 ± 560	shell/LZU	
				26430 ± 980	shell/LDI	
				22710 ± 380	shell/LDI	
				22480 ± 590	shell/LZU	
				22220 ± 180	shell/LZU	
			T_4	8450 ± 90	snail/LZU	
			T_3	5360 ± 60	snail/LZU	
				5100 ± 70	snail/LZU	
			T_2	3560 ± 60	snail/LZU	
			T_1	1860 ± 60	carbonate/Hv	
				1370 ± 60	carbonate/LZU	
Baijian Hu Core	39°01′17"	104°01′37"	638	31060 ± 220	AMS/Beta	uncalibrated/authors
			670	26990 ± 1060	carbonate /Hv	
			820	27150 ± 620	carbonate /Hv	
			936.5	35660 ± 420	AMS/Beta	
Baijian Hu Section	39°00′54″	104°00′54″	26	970 ± 60	carbonate/LZU	uncalibrated/authors
			34	1910 ± 60	carbonate/LZU	
			56.5	3320 ± 130	carbonate/Hv	
			92	6420 ± 70	carbonate/LZU	
			92	6670 ± 100	carbonate/Hv	
Alashan-zuoqi	site 11 in fig. 5		112.5	21020 ± 360	organic/LDI	uncalibrated/author
			197.5	19900 ± 330		
			212.5	15850 ± 220		
			312.5	9720 ± 120		
Hongshui River (Upper)	38°10′46″	102°45′53″	7.5	3160 ± 90	organic/LDI	uncalibrated/author
			57.5	3620 ± 120		
			122.5	4410 ± 80		
			127.5	4520 ± 90		
			192.5	5060 ± 120		
			277.5	5840 ± 120		
			325	6550 ± 80		
			400	6920 ± 70		
			475	7290 ± 120		
Hongshui River (Lower)	38°10′44"	102°45′56″	95	9760 ± 130	organic/LDI	uncalibrated/author
			175	10370 ± 130	organic/LDI	
			275	10738 ± 150	organic/LDI	
			345	11470 ± 160	organic/LDI	
				13220 ± 100	carbonate/LDI	
			370	12030 ± 90	organic/LZU	
				11760 ± 590	organic/LDI	
			416	16330 ± 190	organic/LZU	
				16520 ± 160	organic/LDI	
			580	20600 ± 260	organic/LZU	
				20690 ± 860	organic/LZU	

a) LDI = Lanzhou Desert Research Institute, the Chinese Academy of Sciences, China; LZU = Geography Department, Lanzhou University, China; Hv = Bundesanstalt für Geowissenschaften und Rohstoffe in Hannover of Germany; Beta, Miami of USA.

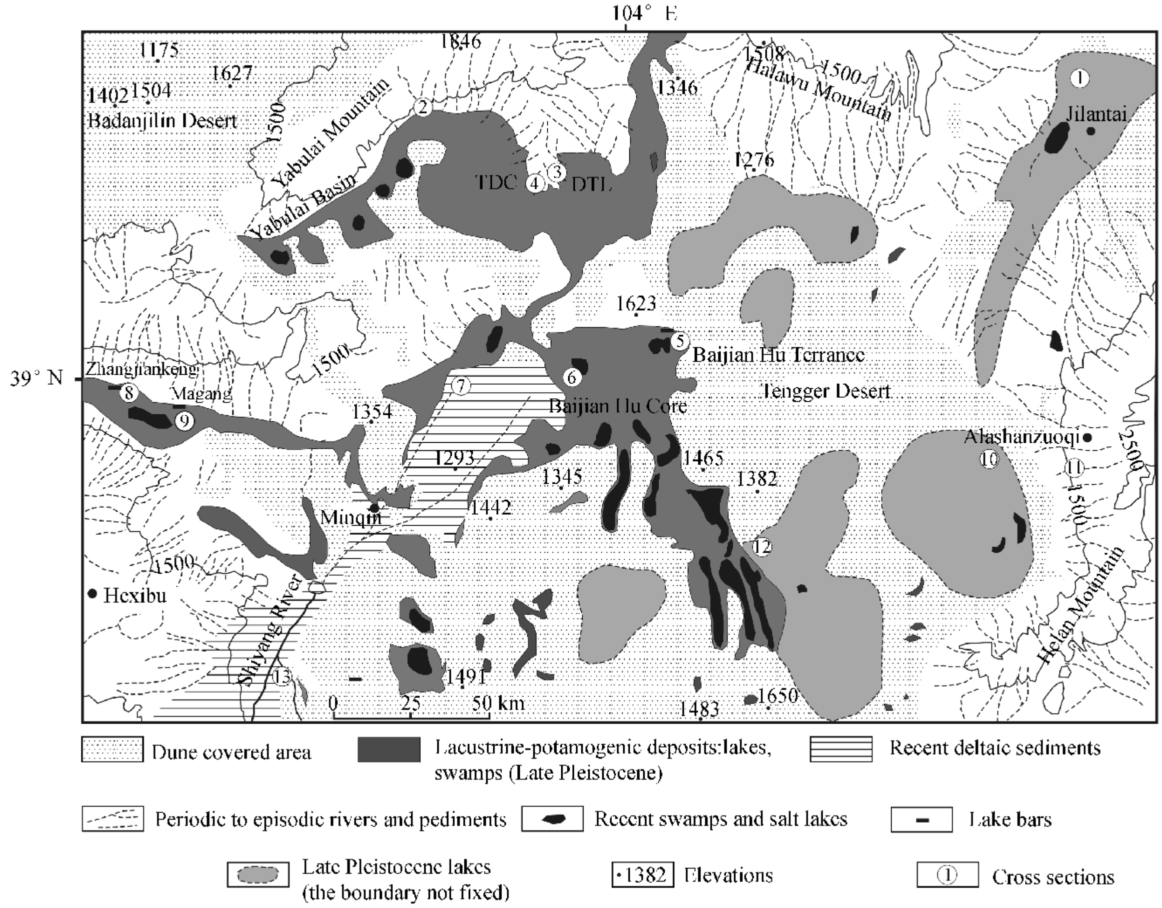

Fig. 5. Reconstructed scope of palaeolake areas in Tengger Desert and adjacent areas based on the distribution patterns of the palaeolake deposits and morphological closure, localities (circled numbers) of the studied sections.

tion. The statistical results (the maximum, minimum and average) of the DTL section indicate that the geochemical composition varies widely, affording an opportunity to distinguish the depositional environments. Elemental geochemical data (fig. 6) show a high correlation among the contents of TIC, Ca and Mg. The total organic carbon (TOC) contents, with the highest value of 0.69%, are generally low. The relationship between total inorganic carbon (TIC) and lithology suggests that the TIC content is a good indicator of the depositional environment. For example, the TIC values are lower than 2% for typical sand layers, around 2% for beach sediments, and higher than 2% for lacustrine deposits. The stratigraphic characteristics of lacustrine deposits and corresponding TIC values indicate that the higher the TIC values, the higher the lake levels. But it should be reminded that this TIC-water depth relation is not a simple linear one.

(iii) Paleaoenvironment during the Magelake Tengger: relationship between the water level fluctuation and the climate. Using different sedimentation rates of DTL and TDC sections, it can be calculated that the earliest palaeolake occurred at round 42—38 kaBP in the Tengger Desert area. The history of climatic change in the Tengger Desert can be reconstructed on the basis of the proxies from the DTL section. In the bottom portion of the section, at the depths of 400—360 cm (ca. 42000—38000 ^{14}C aBP), TIC, TOC, Ca, Mg, S and Na are all low, and the pollen spectra (which will be published separately) is dominated by *Artemisia*, *Chenopodiacea* and *Cupressaceae*, *Juniperus* and *Gramineae*. The climate during this period was dry as indicated by the pollen spectra, but the effective soil moisture might have been relatively high as suggested by the low contents of soluble elements and red-brownish deposits different from the deposits of other parts in the section.

From 360 to 322 cm (38000 to 35390 ^{14}C aBP), the DTL section contains a mixture of the overlying lacustrine deposits and the underlying playa sediments. This layer corresponds to the pollen sub-zone 1_2 and represents a cooling of the climate, leading to an increase in the content of *Picea* and a decrease in the total pollen. In the nearby TDC section, sandy wedges were found in the playa layer, and the overlying deposit was dated at (37410 ± 2850)^{14}C aBP. The sandy wedges indicated a period of

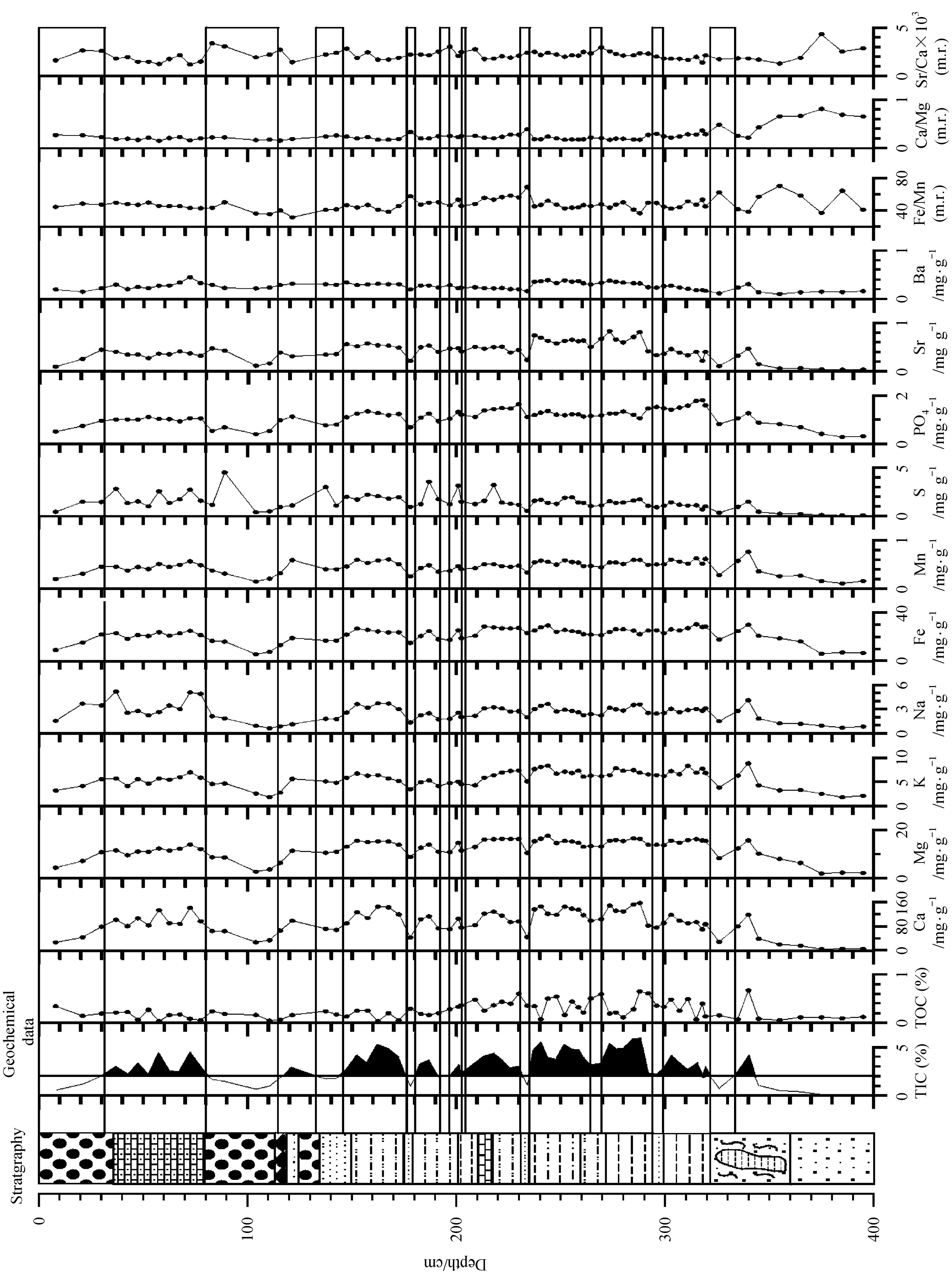

Fig. 6. Elements and environmental geochemical index of DTL section.

cold. Permafrost activity formed the sandy wedges at the TDC site and disturbed the strata at the DTL site, from ca. 38000 to 35390 ^{14}C aBP.

From 322 to 113 cm (35390 to 21070 ^{14}C aBP) is the main phase of the Megalake Tengger. TOC, TIC, Ca, Mg and Sr are all generally high, but there were abrupt decreases at 31490—30330 ^{14}C aBP, 25390—25190 ^{14}C aBP and 23260—23030 ^{14}C aBP. The high-frequency, large-amplitude oscillations of lake levels and pollen assemblages thus indicate climatic instabilities during this period.

From 113 to 80 cm (2070—20140 ^{14}C aBP), the TIC content decreased and the lake level lowered so much that the area where DTL and TDC sections are located became a beach. Herbs (e.g., *Artemisia*, *Chenopidiaceae*, *Grami nea*) and some needle-leaf trees (e.g. *Cupreseaceae*) dominated the pollen spectra. From 80 to 34 cm (20140—18760 ^{14}C aBP), corresponding to the pollen zone 3_2, increases in TIC and related chemical elements suggest that the lake level rose again. From 18760 ^{14}C aBP onward, the lake level declined again, and a new beach environment formed. This was sustained until ca. 18000 aBP, when the palaeolakes disappeared completely from the Tengger Desert.

Stratigraphical property, Pollen, grain size and geochemical data show that the low water level was coincident with the cold climatic episodes[10]. This implies that the warm-humid climate results in the increase of the water level and the cold-dry climate leads to the decline of the water level.

The primary stable oxygen isotope analysis results show that the $\delta^{18}O$ value of the typical limnological deposits of Megalake Tengger in DTL is between –6.9% and –8.0‰. Based on the study results of the Hongshui River section in the same region[10], it can be calculated, with caution and used as a reference, that the average annual temperature during the formation of Megalake Tengger is about 1.4 to 3.0℃ higher than today. On the other hand, the presence of the thermophilous species *Ilyocypris gibba* and the occurrence of fossil valves of the male *Limnocythere inopinata* indicate the water temperature was above 10℃, which is 2.2 to 3.0℃ higher than today. Thirdly, pollen data from Yabulai and DTL sections imply that the forest line was as low as the elevation of the Yabulai Mountain, which is 400—600 m lower than at present. Based on this forest line decline, it can be calculated that the annual temperature during the Magelake Tengger was 2.0—3.0℃ warmer than at present and the annual precipitation was 250—350 mm higher than today.

Based on the above discussions, it can be summarized that the general climate condition during the development of Megalake Tengger is that the annual temperature was 1.5—3.0℃ warmer than today and the annual precipitation was 250—350 mm higher than today.

3 Discussion and conclusions

A Megalake Tengger began to occur around 42000—40000 aBP and fully developed between 35000 and 22000 aBP covering more than 20000 km^2 during the Last Glacial interstadial, isotope stage 3. Both lacustrine and fluvial deposits indicate that the rainfall during this interval increased greatly, with a large precipitation to evaporation (P/E) ratio. The widely distributed palaeolakes and high water levels demonstrated that the climate and palaeohydrology was quite different from today. This occurrence is supported by pollen[6], microfossils[7], grain size and geochemical analyses[11].

High lake level is not only a local phenomenon to the Tengger Desert. Synchronous high water levels of palaeolakes can also be found in northwestern Bandanjilin Desert[5] and north Xinjiang[12]. Our investigation and analyses show that in the southeast of Qinghai Lake, the fresh-water species of fossil snail in beach gravel layer, located at about 140 m higher than the present lake level, was dated at (33980 ± 1100) ^{14}C aBP. The carbonate crust covering the gravel from the same sampling sites was dated at (27210 ± 470) aBP, which was believed to represent the exposure time of the gravel layer from the water. Around Hala Lake, the carbonate crust covering the gravel from the measured highest beach, which is 23 m higher than the lake level at present, was dated at (26190 ± 520) aBP and can be compared with the dating on the carbonate crust from Qinghai Lake. The dating indicates that there existed high water levels between ca. 27000 and 35000 aBP in Qinghai Lake and Hala Lake and coincident with the results by Chen and others (1990)[13]. It can be correlated with other high palaeolake levels occurring during the period on the Tibetan Plateau[14, 15], where ice core studies show that the temperature during the isotope stage 3 was as warm as that of the Last Interglaciation[16,17]. It can also be correlated with the multiple soil-forming events in the northern Mongolian Plateau from approximately 40000 to 22000 aBP[18] and reducing-dominated environment in the western Chinese Loess Plateau from approximately 40000 to 20000 aBP[19]. Even more, the high water levels were found in Konya Lake in Turkey[20], Arabian Desert[21] and Northeastern Sahara[22]. The formation and expansion of palaeolakes and increase of the water levels in the OWDB imply drastic regional to hemispheric re-organizations of the hydrological circulation and the climate and may provide crucial clues for the processes and dynamics of climate change during Late Pleistocene.

This work provides new evidence for regional to hemispheric climate changes but the mechanism why and how this palaeolake were formed are unclear and under debate[9, 23, 24]. In the future, correlation with the palaeolake development history and modeling lake development processes in the arid-semiarid areas in both Northern and Southern hemispheres may provide very important information for global climate changes. It may also contribute a great deal to the understanding of the causes and mechanisms of the Last Glacial Maximum, providing useful information for modeling future climate changes.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 49971015) and the National Key Project for Basic Research on Desertification in Northern China (Grant No. G2000048700).

References

1. Zhu, Z. D., Liu, S., Wu, Z. et al., Deserts in China, Institute of desert research, Academia Sinica (in Chinese), 1986, 1—132.
2. Agricultural Regional Commission, Report of Agricultural Regionalification of Minqin County, Gansu Province (in Chinese), 1985, 157—172.
3. Pachur, H. -J., Wünnemann, B. and Zhang, H. C., Lake evolution in the Tengger Desert, Northwestern China, during the last 40,000 years, Quaternary Research, 1995, 44: 171.
4. Zhang, H. C., Wünnemann, B., Preliminary study on the chronology of lacustrine deposits and determination of high palaeolake levels in Tengger Desert since Late Pleistocene, Journal of Lanzhou University (in Chinese), 1997, 33(2): 87.
5. Wünnemann, B., Pachur, H. -J., Zhang, H. C., Climatic and environmental changes in the deserts of Inner Mongolia, China, since the Late Pleistocene, Quaternary Deserts and Climatic Changes (eds. Alsharhan, A. S., Glennie, K. W., Whittle, G. L. et al.), Balkema: Rotterdaman and Brookfield, 1998, 381—394.
6. Ma, Y., Zhang, H. C., Li, J. J. et al., On the evolution of the palynoflora and climatic environment during Late Pleistocene in Tengger Desert, Acta Botanica Sinica (in Chinese), 1998, 40(9): 871.
7. Peng, J. L., Zhang, H. C., Ma, Y. Z., Late Pleistocene liminic ostracods and their environmental significance in the Tengger Desert, Northwest China, Acta Micropalaeontologica Sinica (in Chinese), 1998, 15(1): 22.
8. Hofmann, J., Geomorphologische Untersuchungen zur jungquartären Klimaentwilung des Helan Shan und seines westlichen Vorlandes, Berliner Geographische Abhandlungen, 1994, 57: 1.
9. Zhang, H. C., Ma, Y. Z., Li, J. J. et al., Late Paleolake evolution and abrupt climate changes during Last Glacial period in NW China, Geophysical Research Letters, 2001: 28(16): 3203.
10. Zhang, H., C., Wünnemann, B., Ma, Y. Z. et al., Lake Level and Climate Change between 40,000 and 18,000 ^{14}C aBP in Tengger Desert, NW China, Quaternary Research, 2002.
11. Zhang, H. C., Ma, Y. Z., Wünnemann, B. et al., A Holocene climatic record from arid Northwestern China, Palaeogeography, Palaeoclimatology, Palaeoecology, 2000, 162: 389.
12. Rhodes, T. E., Gasse, F., Lin, R. et al., A late Pleistocene-Holocene lacustrine record from Lake Manas, Junggar (northern Xinjiang, western China), Palaeogeography, Palaeoclimatology, Palaeoecology, 1996, 120: 105.
13. Chen, K. Z., Bowler, J. M., Kelts, K., Palaeoclimatic evolution within the Qinghai-Xizang (Tibet) Plateau in the last 40000 years, Quaternary Sciences (in Chinese), 1990, 1: 21.
14. Li, B. Y., Zhang, Q. S., Wang, F. B., Lake evolution history in Karakulun-West Kunlun Mountains, Quaternary Sciences (in Chinese), 1991, 1: 64.
15. Li, B. Y., Zhu, L. P., "Greatest Lake Period" and its paleo-environment on the Tibetan Plateau, Journal of Geographical Sciences, 2001, 11(1): 34.
16. Thompson, L. G., Yao, T. D., Davis, M. E. et al., Tropical climate instability: the Last Glacial Cycle from a Qinghai-Tibetan Ice Core, Science, 1997, 276: 1821.
17. Yao, T. D., Thompson, G. L., Shi, Y. F. et al., Climatic change since last interglaciation in Gulia ice core, Science in China, Ser. D (in Chinese), 1997, 27(5): 447.
18. Feng, Z. -D., Gobi dynamics in the northern Mongolian Plateau during the past 20,000 yr: preliminary results, Quaternary International, 2001, 76/77: 77.
19. Feng, Z. D., Chen, F. H., Tang, L. Y. et al., East Asian Monsoon Variations and Gobi Dynamics in stages 3 and 4, Catena, 1998, 33: 29.
20. Roberts, N., Erol, O., De Meester, T. et al., Radiocarbon chronology of the Late Pleistocene Konya Lake, Turkey, Nature, 1979, 281: 662.
21. McClure, H. A., Radiocarbon chronology of late Quaternary lakes in the Arabian Desert, Nature, 1976, 263: 775.
22. Pachur, H. -J., Wünnemann, B., Late Pleistocene Lake Deposits in the Great Sand Sea of Egypt, Palaeogeography, Palaeoclimatology, Palaeoecology, 1999.
23. Liu, T. S, An, Z. S, Chen, M. Y. et al., A premary comparison of palaeoclimate between Northern and Southern Hemispheres during last 0.6 Ma, Science in China, Ser. D (in Chinese), 1996, 26(2): 97.
24. Shi, Y. F., Yu, G., Liu, X. D. et al., Reconstruction of the 30—40 kaBP enhanced India monsoon climate based on geological records from the Tibetan Plateau, Palaeogeography, Palaeoclimatology, Palaeoecology, 2001, 169: 69.

(Received June 12, 2002)