Lake-expanding events in the Tibetan Plateau since 40 kaBP

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Abstract Since 40 kaBP, the current endorheism on the Tibetan Plateau had experienced at least four lake-expanding events, at 40—28 kaBP, 19—15 kaBP, 13—11 kaBP, 9.0—5.0 kaBP, respectively. The 40—28 kaBP and 9.0—5.0 kaBP lake-expanding events, corresponding to the global warming periods, were mainly determined by the abundant summer monsoon rainfall brought by strong Indian monsoon, aroused by enhanced solar radiation at earth orbital precessional cycle. The 40—28 kaBP lake-expanding event, also called the great lake period or the pan-lake period, for several great lake groups had come into being by the interconnection of the presently isolated and closed lake catchments. The total lake area over the Tibetan Plateau was estimated at least up to 150000 km^2, 3.8 times of the present, and the lake supply coefficients were about 3—10. The 9.0—5.0 kaBP lake-expanding, with a total lake area of 68000 km^2, less than the above mentioned reflected the Indian monsoon rainfall less than that of 40—28 kaBP. The expanded lakes at 19—15 kaBP and 13—11 kaBP, distributed in these basins with more or less existing glacial, indicated plenty of glacial meltwater discharged to balance evaporation on expansive lake surface. At the same time, the enhanced precipitation by the westerlies at 19—15 kaBP and by Indian monsoon at 13—11 kaBP plays an important role in maintaining the high lake level. Heinrich events greatly affected the evolution of climate system over the Tibetan Plateau, and thus gave a clear boundary of the high lake level change in the late Quaternary.

Keywords: the Tibetan Plateau, lake-expanding event, monsoon rainfall, glacial meltwater, precessional cycle, Heinrich event.

On the Tibetan Plateau, there are a great number of lakes, including many salt lakes that are mainly distributed in the north-west area. Exhibited by arc-like lakeside sand ridges around the present lakes in many closed basins, first reported by many exploiters[1—3], the Tibetan Plateau probably experienced lake-expanding events or even pan-lake ones in the Quaternary period. The relationship of interglacial and glacial, pluvial and inter-pluvial, and the lake-expanding period is an ever-important climatic stratigraphy object of the Quaternary[1]. But, to these days, no satisfying answer has been given. However, over the last forty years, with more researches of climate changes of Greenland by ice core[4], discovery of Heinrich events[5] in North Atlantic, development of the mechanism of North Atlantic deep-water circulation[6], and reconstruction of Indian monsoon change in the Quaternary[7,8], and the Tibetan Plateau by lake sediments[9—30], it is possible to present an integrated history of high lake levels on the Tibetan Plateau for the past 40 kaBP. Based on a literature survey of 42 lake basins on the Tibetan Plateau and records of palaeoclimate change of Indian Ocean and North Atlantic Ocean, this paper focuses on the high lake level stands on the Tibetan Plateau for several key phases since 40 kaBP and examines their causes by comparison of palaeoclimate records.

1 Methods and data processing

1.1 Lake level and climate change

If the underwater exchanges between adjacent lake basins are ignored as a closed hydrological system, the equation of water balance for a lake basin can be written: $PS + B_w = E_l S_l + E_b S_b$, where P is the precipitation (assumed to be the same for both lake and basin), S is the basin area (excluding the glacial area), B_w is the glacial meltwater, E_l, E_b are the evaporation for the lake and basin, and S_l, S_b are the lake area and lake basin area, respectively.

If B_w is small enough to be ignored, there exists a positive correlation between lake area S_l and effective precipitation ($P–E_b$) which indicates the moist content of climate. That is, when it is wet, the lake expands. As we know, under cold conditions with little rainfall, for low evaporation, it is probably very wet. This condition, unlike with rich precipitation, probably might maintain the lake level stably but cannot result in markedly lake expanding.

When B_w is relatively large, and effective precipitation ($P–E$) is very low, if evaporation for the lake surface is lower than the summation of runoff into the lake and precipitation for the lake surface, there exists a negative correlation between lake area and $P–E$ for basin. That is, although climate is dry, the lake expands for large meltwater, which probably comes into being at glacial melting period.

Generally speaking, in those basins with great glacier in glacial period, lakes probably underwent expanding not only under wet climate but also under dry climate condition.

1.2 Sensitive degree of lake

The mutation of lake area (km^2) with climate changes is expressed as: $\tau = S_l / [(dS_l/dD) \cdot (E_l–H)]$, where D (m) is the depth of lake, H (mm) is the total depth of runoff and precipitation at unit lake surface, the others are the same as above. If dS_l/dD = 25 (near to the landform of Qinghai Lake basin between 3200—3400 m), $E_l–H$ is 100 mm/a (near to the hydrological condition of Qinghai Lake level in the last century)[1)], and lake area is 100 km^2, 1000 km^2, 10000 km^2, respectively, τ is near 40 years, 400 years, 4000 years, respectively. That means, under the above condition, it takes 4000 years for a deep lake, with an area of 10000 km^2, to shrink to dry status, and for

1) Qing Boqiang, Impact of climate changes to inner lake of Asia——past, today, and future, Ph.D Thesis of the Chinese Academy of Sciences, 1993.

lake of 1000 km^2, 100 km^2, it takes 400 years, 40 years to dry, respectively.

1.3 Lake-expanding period/event

The lake-expanding period/event is defined as follows: some lakes in the current inner-flow area of the Tibetan Plateau had undergone high-invariable lake level stand at the same time. This definition is threefold: first, lake-expanding period/event is a birth and death process shown by paleolake sand bars; thus, lake-expanding event comprises lake-expanding stage, lake maintaining stage and lake-shrinking stage (only referring to the initial phase of shrinking, in this paper); third, it is at the same time that lakes show their expanding behavior.

1.4 Data resource and processing

All the references of the palaeolakes climate records cited in this paper were collected from the relevant journals and monographs published over the past forty years. Based on high lakeside sand ridges/terraces and lacustrine sediments analysis, the high palaeolake level (excluding the influences of non-climate factors, such as tectonic movement and river sediments) was reconstructed. Subsequently, we calculated the palaeolake area grounded on careful geomorphologic surveys on 1:100000 topographic maps with the relative height of palaeolake level above the present one (termed palaeolake height in the following).

In the comparison of climate records, we applied the primal age control (including calendar years, ^{14}C and U-Th ages) of the records which is the same for the lakes in the Tibetan Plateau. However, it is based upon the ^{14}C ages that this paper plotted the lake-expanding periods for the past 40 kaBP.

2 Lake expanding events and their relevant records

Statistical results are listed in tables 1—4, where A^1 denotes U-Th dating, A^2 denotes TL dating (A is the age), the others are ^{14}C datings, and the top boundary and the bottom boundary mean the minimum and maximum of dated ages at corresponding lake-expanding period, the definite integers are interposed ages computed by sediment rate. Fig. 1 gives the spatial distribution pattern of palaeolakes in the Tibetan Plateau.

On the basis of synthetical analysis of palaeolake sediment records (including terraces and sand ridges), between 40 and 0 kaBP, four lake-expanding events (or lake water-desalted periods) were recognized and defined as follows.

2.1 9.0—5.0 kaBP lake-expanding event

This period is roughly in accord with the Holocene warm and moist phase[16] in the south of the Tibetan Plateau. At this period, almost all of the lakes with palaeoclimate records show a postive water budget with a relatively high lake level, except individual examples, such as Qarhan lakes, which was in low lake level condition like the present, in the north of the Tibetan Plateau, and with a total area 1.2—2.5 times that of the present. The relative height is drastically different

Table 1 Climate and palaeolake records at 9.0—5.0 lake-expanding event

Lake	Lat./° N	Lon./° E	Time/aBP		Sediment	LA(pa/pr)	RH	Ref.
Bangong Co	33.5	79.5	6750±235	3330±200	LS		>15	[10]
Banddag Co	34.9	81.5	7670±250		LS/pollen	120(1.13)	10	[2]
Lungmu Co	34.6	80.4	7670±140	7290±200	LT	635(6.55)	97—62	[9]
Sumxi Co	34.6	80.2	8200±150	6890±150	LT	86.6(3.52)	32	[9]
Baiku Co	29.0	85.6	8370±285	6150±200	LS/pollen	>340(1.2)	>35	[2]
Zhari Namco	31.0	85.5	7010±150		LS	>1540(1.54)	>53	[2]
Chabyer Caka	30.5	83.5	8725±135	5315±135	LT	480—810 (2.23—3.77)	49—19	[11]
Co Ngoin	31.5	91.5		6300±600	LS	138(2.25)	12	
Zige Tangco	32.1	92.8	8300±800	5800±200	LS/LT	246(1.29)	8	
Maindong co	33.5	78.9		4525±120	LS/pollen	>75(1.22)	>10	[2]
Gorre Co	34.6	92.5	8000	5500	LS/ ostracode			[12]
Wulukekule Lake	35.7	81.7	8000	6505±77	LT/ LS	>18(1.17)	>4	[14]
Aqigekule Lake	37.0	88.3		6705±108	LS	>860(2.49)	>40	[13]
Bailikekule Lake	36.7	89.0		6311±77	LS	>26(5.91)	>25	[13]
Xiaoshazi Lake	36.0	90.7	8356±172	6000	LS	>60(2.4)	>20	[13]
Bunan Lake			8111±192	7996±183	LS		>2	[14]
Kekexili Lake	35.6	91.0	5580±163		LS	>460(1.53)	>22	[14]
Kusai Lake	35.6	93.0	6024±172		LS		>3	[14]
Nara Yumco	28.3	92.0	6380±100	3625±100	LS/pollen	>32.8(1.22)	>5	[2]
Qinghai Lake	37.0	100.5	6860±130	5310±125	LT/ LS	6408(1.48)	100—20	[15]

Notes (for tables 1—4): Lat. = latitude (° N), Lon. = longitude (° E), LA(pa/pr) = lake area (km^2) (palaeolake/present lake), RH = relative height (m) of palaeolake level, Ref. = references, LS = lacustrine sediments, LT = lakeside terraces .

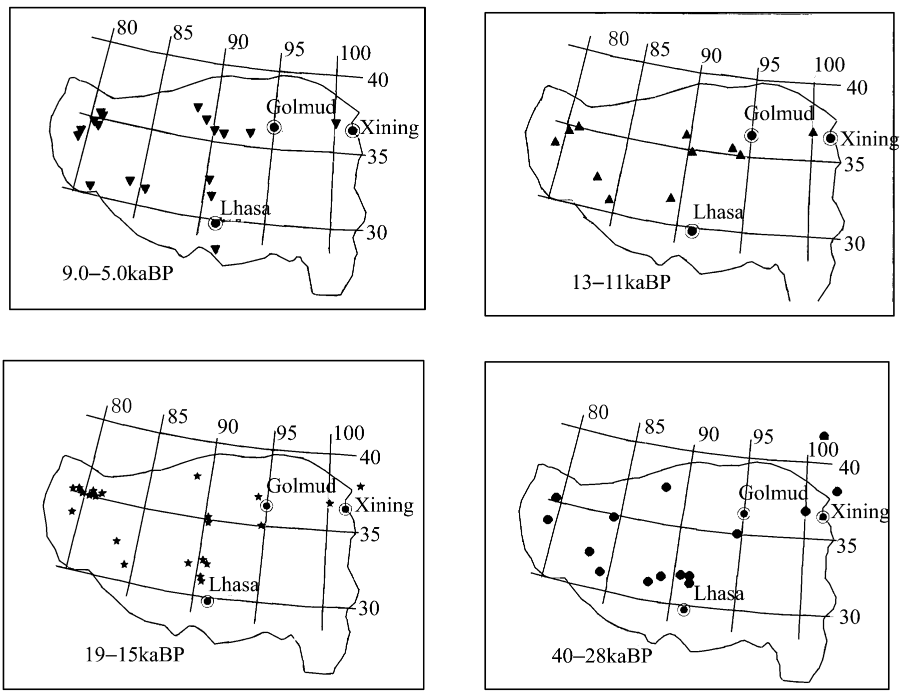

Fig. 1. Spatial distribution of lakes with palaeoclimate records over the Tibetan Plateau.

from one basin to another for the landform of local basin and climate conditions. With the area up to 6.6, 5.9 times that of the present, respectively, Lungmu Co in North Tibet and Bailikekule Lake in Kekexili region experienced the most obvious lake-expanding status during this period of time. Based on an incomplete statistical result, the overall lake area on the Tibetan Plateau is estimated probably up to 68000 km^2 (39000 km^2 at present)1), 1.77 times that of the present，and the lake supply coefficients were near 5—25, which are similar to those in the center part of the Tibetan Plateau1).

In Jiangxi Channel at the south bank of Qinghai Lake in north-east margin of the plateau, the lakeside terraces (termed T3, T2 and T1 in ref. [15],100—73 m, 65—25 m, and 26—7 m high above the present lake, respectively, with ^{14}C dated between 6860±130 aBP and 4830±130 aBP on T2, 1880±90 aBP on T1) is a gently sloping palaeolake beach plain made up of gravels, sand and silt[15]. In Chabyer Caka, a famous salt lake, in the southwest part of the interior of the plateau, multi-stage lakeside terraces were also found around the present lake[11], which provided palaeo-shoreline records. The Holocene terraces are made up of five beach sand ridges 49—19 m higher than the present lake, with ^{14}C dated to (8725±135) aBP on the fifth one, and (5315±135) aBP on the first[11]. The distribution of lakeside terraces of the above two basins suggested that, during 9.0—5.0 kaBP, lake levels were relatively stable at some stages with a whole tendency of shrinking.

Table 2 Climate and palaeolake records at 13—11 kaBP lake-expanding event

Lake	Lat./°N	Lon./ °E	Time/kaBP		Sediment	LA(pa/pr)	RH	Ref.
Qinghai Lake	37.0	100.0	12100±265		LT	8100(1.87)	108	[15]
Gorre Co	34.6	92.5	13035±155		LS/ostracode	>29.5(1.26)	>3	[12]
Chabyer Caka	30.5	83.5	12535±180		LT	1150(5.35)	64	[11]
Baijian Lake	40.5	103	12817±142		LT		23	[17]
Chagcam Caka	32.6	82.4	13400±160		LS/pollen	>29(1.23)	>2	[2]
Jieyue Lake	35.0	90.2	13409±569		LS		>2	[14]
Salt Lake	35.5	93.4	13618±299		LS	>52(1.58)	>3	[14]
Wulanwula Lake	34.8	90.5	12359±253	10997±252	LS/LT	>550(1.01)	>1	[14]
Ashenkule Lake	35.7	81.6		11743±260	LT	16(1.52)	>3.5	[13]
Bailikeku Lake	36.7	89.0		12253±280	LT	18(4.09)	20	[13]
Serling Co	31.8	89.0		10100±2000	LT	5800(3.45)	89	[1]
Lungmu Co	34.6	80.4		11410±290	LT	>200(2.06)	>72	[10]

From the distribution of high lake side terraces and their radiocarbon-dated chronologies, as early as 9.0—8.3 kaBP, most of the lakes mainly in the south, central and east part of the plateau began expanding and probably in a short period of time reached the highest level of the Holocene.

1) Fan Yunqi et al., Lake mark of Qinghai-Xizang Plateau, 1995 unpublished.

Late to 5300—3300 aBP stage, lakes had already drastically been shrinking. And almost all the lakes with records over the Tibetan Plateau experienced highest level of Holocene at 9.0—5.0 kaBP. Of course, the evolution sequences in different basins are probably different to some degree.

Table 3 Climate and palaeolake records at 19—15 kaBP lake-expanding event

Lake	Lat./°N	Lon./ °E	Time/aBP		Sediment	LA(pa/pr)	RH	Ref.
Bieletan Lake	36.9	94.5	20600	16000	LS			[18]
Co Nag	32.0	91.5	21347±1130	20916±1205	LS		>45	[19]
Corre Co	34.6	92.5	19210±455	15237±461	LS	>29.5(1.26)	>3	[12]
Hongshan Lake	35.5	79.0	17015±151	15310±178	LS	>83(5)	>19	[20]
Banggong Co	33.5	79.5		16100±220	LS/ Ostracode			[20]
Chabyer Caka	30.5	83.5	18000	13000	LS		<69	[11]
Pangkog co	31.7	89.5		16800±210	LS			[11]
Chagcam Caka	32.6	82.4	20000±350	15400±160	LS	25.7(1.15)	>1	[2, 11]
Baijian Lake	40.5	103	23370±380	16540±120	LT/LS		23	[17]
Bangdag Co	34.9	81.5	15880±115	15938±126	LT	158(1.48)	40	[10]
Tianshuihai Lake	35.2	79.5	22795±1210	14497±340	LS	>450(45)	40—50	[21]
Wulanwula Lake	34.8	90.5	18530±415	*18217±390*	*LT*/LS	552.7(1.02)	1.5	[14]
Xijinwulan Lake	35.2	90.5	22100±1840 a)		LS	>371(1.07)	>1	[14]
Gozha Co	35.0	81.0	21500±200		LT	261(1.03)	3	[10]
Akesaiqin Lake	35.2	79.8	18520±305	16235±120	LT	312.5(1.88)	5	[10]
Ashenkule Lake	35.7	81.6		15256±100	LS	40(3.81)	~7.5	[13]
Aqigekule Lake	37.0	88.3		16765±149	LT	640(1.82)	5	[13]
Nam Co	30.8	91.0		14500±4600	LT		20.5	[1]
Yang Lake(？)	35.4	84.7	20000±170	16120±195	LS			[22]
Bam Co	31.2	90.5		17200±4400	LT		85	[1]
Zige Tangco	32.1	92.8	19220±387	15500±1200 b)	*LT*/LS	>272(1.42)	>10	
Qarhan Lake	36.5	95.0	16400±450	15700±340	LS			[23,25]

a) See footnote 1) on page 302.
b) See footnote 1) on page 305.

2.2 13—11 kaBP lake-expanding event

The age of this lake-expanding event is mainly centered at 13—11 kaBP, with ^{14}C dated to (13409±569) aBP of the oldest sample of lacustrine sediment from Jieyue Lake[14], and to (10997±252) aBP of the youngest sample from lakeside terrace of Wulanwula Lake[14] both in Kekexili region, in accord with Bolling/Allerod warm stage of the late glacial period[31]. The lakes, especially those with more or less glacier at present, such as Charbyer Caka[11], Qinghai Lake[15], Baijian Lake[17] in the north of the Qilian Mountains, Serling Co[1] in the central part of the Tibetan Plateau, Lungmu Co[10], and Bailikekule Lake in the north of the Tibetan Plateau[13] show the most significant expanding, with area 1.5—5.4 times that of the present.

Table 4 Climate and palaeolake records at 40—28 kaBP lake-expanding event

Lake	Lat. °/N	Lon./ °E	Time/aBP		Sediment	LA(pa/pr)	RH	Ref.
Banggong Co	33.5	79.5	39453±3263	24847±655	LS/pollen	>1031(1.63)	>59	[34]
Tianshui-hai/Akesaiqin Lake	35.2	79.5	41962±1300a)	23947±1300	LS/LT	>1403(7.98)	>60	[21]
Chagcam Caka	32.6	82.4		28495±1.33	LS/ LT/pollen	1831(32.93)	134	[11]
ChabyerCaka/ Taro Co/ Laggor Co	30.5	83.5	29330±420	*23770±600*	LS/ LT/pollen	>4729(5.97)	>180	[11,35]
Gerre Co	34.6	92.5		32510±2109	LS	>31.5(1.34)	>5	[14]
Qarhan Lake	36.5	95.0	*38600±680*	24000±420	LS/ LT/ ostracode	9547(1.65)	20—25	[23—25]
Qinghai Lake	37.0	100	39000a)	26000a)	LS/ LT/pollen	8100(1.87)	108	[23—26]
Serling Co/Bangoin Co	31.7	89.0			LS/ LT/pollen	>10000(5.94)	>100	[11]
Gasong Lake/Suoguo Lake	42.0	100.0	34010^{+1540}_{-1290}	29280±360	LT/ ostracode	33000	30	[17]
Gering Co	31.0	88.3	35000±3000		LS			[22]
Aqigekule Lake	37.0	88.3	36750±1320	22522±670	LS			[22]
Yang Lake(?)	35.4	84.7	46850±2970	34735±820	LS			[22]
Baijian Lake	40.5	103	33500±1085	23130±590	LT/ LS/ ostracode	16200	27	[17]
Zige Tangco	32.1	92.8		23.6±2.3b)	LT	>272(1.42)	>10	
Co Nag	32.0	91.5	35000	25397±964	LS		>47	[19]
Co Ngoin	31.5	91.5		24.9±1.8b)	LS	>220(3.58)	>30	

a) See footnote 1) on page 302.

b) See footnote 1) on page 305.

2.3 19—15 kaBP lake-expanding event

At the last glacial maximum, many lakes in the Tibetan Plateau show a relatively high level status or a lake water-desalting condition. With an upper boundary ^{14}C dated to 15000 aBP or so, and a lower boundary ^{14}C dated to 23000—21000 aBP or so (table 3), it was around 19—15 kaBP that many lakes started expanding. However, most of these lakes are distributed in existing glacial area, which is similar to that of 13—11 kaBP lake-expanding period. We also notice the lake expanding in some basins, such as Hongshan Lake[20], Bangdag Co[10], Akesaiqin Lake[10], Aqikekule Lake[13] and Ashenkule Lake[13] in the north-west of the Tibetan Plateau are the most significant.

Indicated by geochemistry analysis of lacustrine sediments from Dachaidan Lake[18], Qarhan Lake[25], Bangoin Co[11], Chagcam Caka[11], Bieletan Lake[18], the salinity of lakes is lower than that of the earlier and later stage at 19—15 kaBP, which were different from the gradual increasing transition of salinity in Chabyer Caka[11] and Tianshuihai Lake[32] at the same time. Demonstrated by the Erlangjian profile at the south bank of Qinghai Lake, Qinghai Lake is in a low level status, with the characteristics of building a set of sediments of gravels and sand at the south beach[23]. However, evidences from lakeside terraces in Zige Tangco, Bam Co[1], Nam Co[1], Aqigekule Lake[13], Akesaiqin Lake[10], Gozha Co[10], Wulanwula Lake[14], Bangdag Co[10] and Baijian Lake[17], which were characterized by constructing beach sand ridges around palaeolake beach, exhibited the lake levels were relatively stable at the glacial maximum. At the end of this period, with the deterioration of climate conditions, some lakes became dry or near dry[10,32], a new cycle of chemical rock salt sediments started in Qarhan Lake[24,25], Bieletan Lake[24], and Chabyer Caka[11], and Chacam Caka[11] evolved to salt lake (fig. 2).

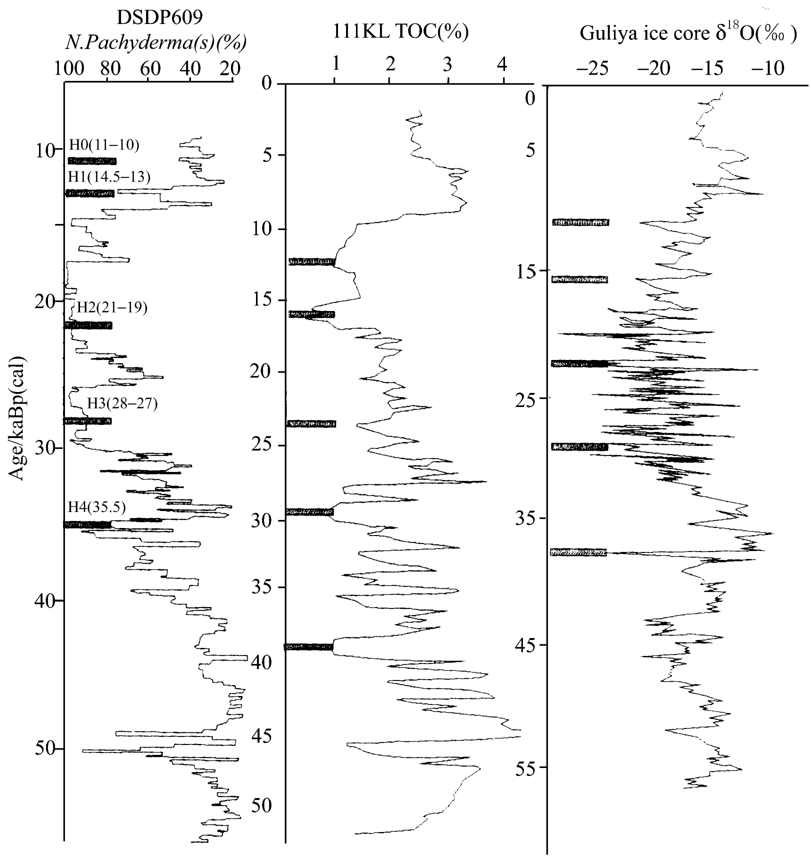

Fig. 2. Correlation of climate records from DSDP609 core (Bond et al. 1993)[36], 111KL core (Schulz et al. 1998)[7], Guliya ice core (Yao 1999)[37], and their Heinrich events.

2.4 40—28 kaBP lake-expanding event

At 40—30 kaBP, with a few spanning for a longer period between 45—43 kaBP[22] and 24—22 kaBP[25,11], numerous lakes had taken the highest lake levels for the past 40 ka in large areas of western China. Some authors called it the pan-lake period[27] or the great lake period[33].

In Chabyer Caka catchment, multi-stage higher lakeside terraces[11] (sand ridges included) found mainly in the east part of the basin provided palaeo-shoreline records before the Holocene. The highest terrace with relative height about 180—200 m, the same high as local overflow plane, indicated the lakes reached a maximum (Taro Co and Laggor Co comprised in) around 40—30 kaBP estimated by Zheng et al.[27]. The 9th, 8th, 7th, 6th terraces are 179 m, 124 m, 89 m, 69 m higher than the present lake level (Chabyer Caka), respectively, with samples from 7th and 6th radiocarbon-dated to (23770±600) kaBP and (22670±380) kaBP, respectively. Investigating topographical feature of the basin, we know at least at some time before (23770±600) kaBP, coincident with the formation of the 7th terrace, Chabyar Caka, Taro Co and Laggor Co have already separated from each other, and the unitive large palaeolake disappeared.

In Qarhan Lake, three samples from the upper, middle and lower parts of a ridge profile at south-east bank, radriocarbon-dating to (38600±680) kaBP, (35100±900) kaBP and (28650±670) kaBP[23], respectively, show the ridge roughly formed between 40—28 kaBP, suggesting the lake level was relatively stable at that time. Records of lacustrine sediments from ZK-88-01 core in the north-eastern margin of Qarhan Lake, at 41.9—21.5 kaBP, called lake water desalting period by Zhang et al.[25], showed the characteristics of lacustrine detritus sediments comprising several interlayers of chemical rock salt, suggesting fresh water occurring at (41.9—21.5) kaBP, having been interrupted by short saline water episodes.

Evidence from Baijian Lake[17], a dry salt lake today, showed that, before (33500±1085) kaBP, the palaeolake had come into being, about 32 m higher than the present lake floor; between (33500±1085) kaBP and (27200±975) kaBP, the lake has been shrinking gradually; and from (27200±975) kaBP to (23130±590) kaBP, the lake experienced sharply shrinking status, with the lowest lake level 23 m above lake floor, which was still a little higher than the palaeolake level in the Last Glacial Maximum (fig. 3).

At 40—28 kaBP period, the lake levels in Tibetan Plateau were generally 30—280 m higher than the present, and for the interconnection of the present separated adjacent basins, several lake groups came into being and a few great lakes each with an area of $n\times10^4$ km^2 occurred over the Tibetan Plateau: in the north of the Qilian Mountains, Gaxun-Sogo Lake[17] and Baijian Lake[17] were near 16200 km^2 and 33000 km^2 respectively; in the south of Qilian Mountains, Qinghai Lake[23] and Qarhan Lake[23] were up to 8100 km^2, 9547 km^2 respectively; also two great lakes made up of Chabyer Caka, Taro Co, Laggor Co and Serling Co, Bange Co were in the southwest of the Tibetan Plateau with an area of 4729 km^2 and 10000 km^2 respectively; and in north Tibet, a united lake of 1043 km^2 comprising Tianshuihai Lake, Kushuihai Lake and Akesaiqin Lake occurred at the south foot of Kunlun Mountains[10, and Chacang Caka and Bero zeco merged into a single great lake[11] of an area of 1031 km^2. Banggong Co overflew further east to Tagutuqingin 30 km away from the present beach of Banggong Co[10], and flooded to west to make itself become one of the origins of the Indian River. Meanwhile, for headward erosion and/or water overflow, the Huanghe River ran through Zoige Palaeolake[28], and the upstream water system pattern like the present, had come into being. The total lake area of the Tibetan Plateau is estimate at least up to 150000 km^2, 3.8 times of the present, the lake supply coefficients were 3—10, equivalent to those in South Tibet at present.

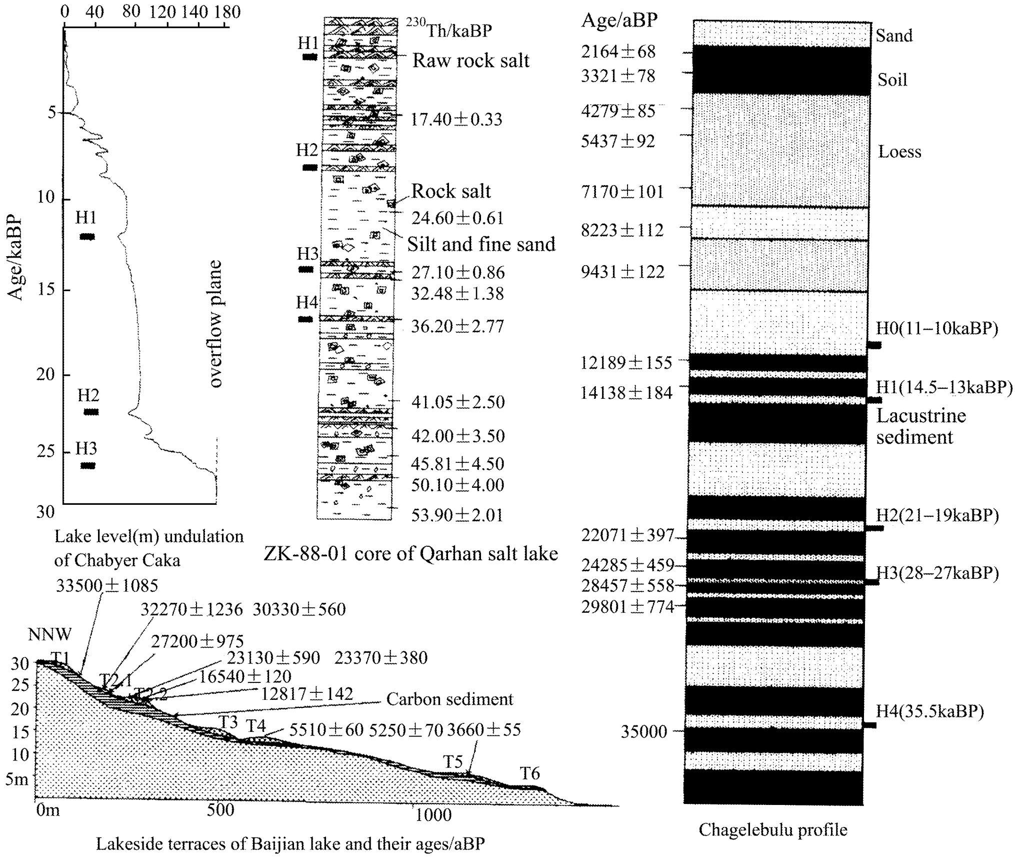

Fig. 3. Correlation of climate records from Qarhan salt lake (Huang et al., 1987, Zhang et al., 1993)[24,25], Chabyer Caka (Zheng et al., 1989)[11], Badain Jaran Desert (Gao et al., 1998)[29] and Baijian Lake (Pachur et al., 1995)[17], and their Heinrich events.

3 Correlation of climate records

There are seven lithologic, biologic and ice core climate records put here together to compare with episodes of massive iceberg releasing (Heinrich events[5]) at the North Atlantic Ocean during the last glaciation. These climate records are the abundance variablity of *N.Pachyderma* (s.) in core SDP609 (50° N, 25° W)[36], TOC(%) of 111KL core from Arabian Sea (23° 06′N, 66° 29′E)[7], $\delta^{18}O$ records from Guliya ice core in the Tibetan Plateau (35.6° N, 80.5° W)[37], lake level fluctuation of Chabyer Caka[11], lacustrine sediments of Qarhan salt Lake[24,25], lakeside terrace records from Baijian Lake[17] and lithologic sediment records from Chagelebulu (39° 53′N, 103° 18′E)[29] in the Badain Jaran desert to the north of the Tibetan Plateau (fig. 2).

N.Pachyderma (s.) is a planktic foraminifera which lives in water <10℃ and comprises about 95% of the fauna at summer temperature <5℃[36], and is abundant at Heinrich events.

At Heinrich events, the North Atlantic Ocean was in the cold conditions, and percent of TOC of 111KL core was in low stages, suggesting the summer monsoon weakened in Arabian Sea[7].

On the $\delta^{18}O$ curve of Guliya ice core, Heinrich events matched the low values of $\delta^{18}O$, coherent to low temperature stages, also showing a weakening summer monsoon stages.

Indicated by the other climate records, with alternating deposits from Qarhan Lake and lower and lower lake level from lakeside terraces in Chabyer Caka and Baijian Lake, between 40 kaBP and 10 kaBP, there was a gradual transition to dry conditions in broad-scale patterns, and mutli-cycles of sediment phases, which matched the climate instability shown by GRIP[4] and Guliya ice core[37]. At Heinrich events, the lake shrank markedly in Chabyer Caka, chemical rock salt sediments occurred in Qarhan Lake, and eolian deposit developed largely, which together indicated a response to a decrease in the local water budget for a negative balance of precipitation minus evaporation.

Generally speaking, Heinrich events were consistent with a weakening of Indian monsoon, perhaps almost across the entire Tibetan Plateau.

4 Causes of lake-expanding events

Corresponding to the Holocene moist and warm stage over the Tibetan Plateau, 9.0—5.0 kaBP lake-expanding event was nurtured by wet conditions in local basins for enhanced Indian Monsoon rainfall in large area of the east, center and south of the Tibetan Plateau.

With marked expanding at the present glacicer-existing basins, 13—11 kaBP lake-expanding event occurred in the warm stage of the late glacial period, between H1 and H0, suggesting that the glacial meltwater played an important role in sustaining high lake level. However, for high lake level stands that also occurred in some present non-glacial-existing basin, such as Gorren Co[12] in Kekexili District, the monsoon rain was estimated to start increasing over the Tibetan Plateau at 13—11 kaBP (fig. 4).

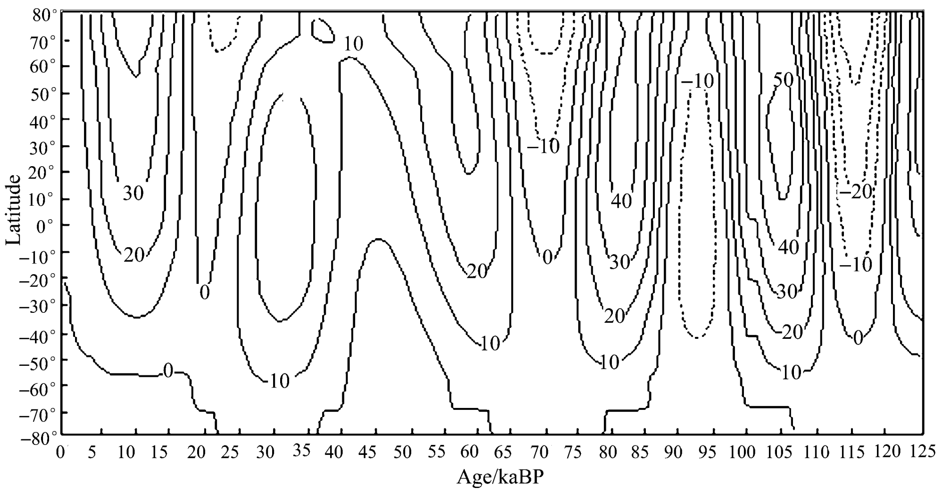

Fig. 4. Long-term variations of deviation (W/m^2) from the present day (1950) for insolation of July as a function of latitude[40,41].

From the above correlation of climate records, we realized that, at H2 and H1 stages, summer monsoon probably was in the weakest status between 21—13 kaBP, and the temperature is the lowest, which is in accord with the climate effect of further 3—6℃ drop in temperature from the already cold glacial climate shown in the Greenland ice cores[38]. In addition, evidence from west Kunlun Mountains[21] and Qiaogeli Peak in Karakorum Mountains[39] showed that just at that time there appeared the most extensive glacial advances of the last glacial maximum.

After H2, the globe fell into the last glacial maximum, which was in accord with the lowest solar radiation stage from the past 40 kaBP[40]. Ice core based evidence[37], However, displayed summer monsoon intensifying, which also was demonstrated by the increase in TOC in 111KL core[7]. Moreover, the increase in rain influenced by the westerly winds and the low precipitation for lower temperature over the local basin might also give a positive role in maintaining high lake level stands. In addition, the glacial meltwater should not be ruled out. This could be partly confirmed by the following example: the water level of Gozha Co with a mean annual temperature below −5℃ over basin at present, rose 14 m from 19 July to 28 August, 1987, measured by the Sino-Japanese Joint Expedition. This required a minimum of 3416×10^4 m^3 water, ignoring evaporation[21].

At 53—23 kaBP, pollen-based reconstruction of Tibetan vegetation exhibited systematic differences from the present: alpine steppe-forest shifted ca. 400 km further north and the alpine conifer forest extended ca. 400—800 km beyond their present west limits[41]. The ^{14}C date of fossil of vine, now only colonizing in tropical-subtropical area, is 36000 aBP found in laucstrine sediments from Nyingchi region[42], south of the Tibetan Plateau. In Qingshui River district, south of Qinghai Province, pollen-based analysis displayed, at 36000—34000 kaBP, the climate was far warmer and wetter than today[43].

Generally speaking, multi-proxy records from ice caps, lakes and pollen records show that it was warm and moist in some phase of 40—28 kaBP, and probably far warmer and moister than the Holocene warm and wet stage. For the vigorous evaporation of the tropical ocean with high solar radiation at earth orbital precessional cycle and enhanced airflow across equator, there existed an exceedingly strong summer monsoon climate over the Tibetan Plateau[41].

Certainly, large precipitation inspired by the strong summer monsoon is the main flourishing factor of high lake level stands. However, as the above-mentioned, for the existence of the north ice field in the Eurasia and North America during the Last Glacial Period, the westerlies shifted southward and flew over the warm North Atlantic Ocean between Heinrich events, which probably incurred more rainfall.

5 Discussion and conclusions

Heinrich events were the great armadas of icebergs flooding into the northern Atlantic Ocean during the last glaciation[5]. At these events, extensive sea-ice cover similar to that of present Arctic occurred in North Atlantic[44], and northward heat transport by the Atlantic thermohaline circulation was probably weakened greatly [44]. Imprints of Heinrich events have already been reported[44] in pollen record from North America, lake level from Africa, lake level and lacustrine sediments in the Tibetan Plateau, as mentioned above, and loess in northern China[45,46], suggesting these events were not only restricted to the Northern Atlantic region. Although the picture pattern may emerge only when our understanding of ocean circulation, ice sheet change, and the detailed climate system variability during the last glaciation is improved substantially, climate change of the Northern Hemisphere in the last glacial period is closely related with the heat release to atmosphere over the Atlantic Ocean, which was in association with the formation of deep water[44].

The Tibetan Plateau, as a huge-high unit, located in middle- to low-latitude regions, is sensitive to solar radiation[47]. And solar radiation was suggested to be a dominant factor in its climate change of time scale of stadial and interstadial cycle over the last glacial stage[37]. We noted in phase with the 23 kaBP-cycle of solar radiation, the lake-expanding events with a climate variation of warm and moist (40—28 ka)—cold and wet (19—15 kaBP)—warm and moist (13—5.0 kaBP) constitute a cycle of ca. 23 ka duration. Based on the analysis of weather systems on the Tibetan Plateau, Ding et al. suggested that the activity of the Tibetan high in winter is markedly related to other circulations, especially those in the westerlies, and when the westerly trough is located in the longitudinal range of 0—60° E, the rainfall is characterized by an excess over the western Sichuan Province, northwestern China, and northern China[48]. Thus, there is no doubt that westerly rainfall exerted an influence on the lake level change on the Tibetan Plateau, especially at the stage between Heinrich events in the last glacial period. At that stage, westerly winds flowing from the warmer and wetter North Atlantic Ocean, probably brought more moist air mass, and then led to more precipitation across the plateau. And especially at 19—15 kaBP, this precipitation played a more important role in fostering high lake level.

Although the association and interaction of westerly winds, the Tibetan high and the Tibetan low remains a matter of debate, from the above correlation of climate records, we suggested that Heinrich events gave a significant impact on the evolution of climate system over the Tibetan Plateau. H4 and H0 (Younger Dryas) happened at 35.5 kaBP and 11—10 kaBP, respectively, coincident with the high solar radiation stages, and incised the warm and moist period caused by the intensification of Indian summer monsoon. H3, with an age of 28—27 kaBP, occurring at the initial stage of the decrease in solar radiation of precessional cycle, shrank the enhanced summer monsoon for high solar radiation, and accelerated the end of the warm and moist stage of 40—28 kaBP. H2, with an age of 21—19 kaBP, in accord with the low solar radiation, speeded up the coming of the Last Glacial Period of the Tibetan Plateau. H1, with an age of 14.5—13 kaBP, occurring at the start point of the increase in solar radiation precessional cycle, hampered the intensification of Indian summer monsoon, and extended the Last Glacial Period.

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