

# Late Pleistocene lake and glaciation evolution on the northeastern Qinghai–Tibetan Plateau: a review

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**Abstract** Late Pleistocene paleoclimatic history on northeastern Qinghai–Tibetan Plateau (QTP) has been reconstructed mainly from lake sediments; however, data regarding dry–wet climate changes reported in this region are still not clear and controversial. Based on shoreline features and highstand lacustrine sediments around lakes on the QTP, high lake level histories in this paper were summarized and compared with paleoclimatic records from lake sediments, ice core and glaciation evolution surrounding mountains on the NE QTP during late Pleistocene. The results indicate that periods of high lake level occurred at MIS 5, MIS 3 and early-middle Holocene and most likely corresponding to warm and wet climate periods, while periods of low lake level existed in intervening intervals, corresponding to cold and dry climate periods, which most likely coincide with glacial advances surrounding high mountains. With an exception, no wide glacial advance in study area was found during MIS 3, possibly suggesting that effective moisture is lower than that in the other region of NE QTP in this period.

**Keywords** Lake and glaciation evolution · Northeastern QTP · Late Pleistocene

## Introduction

The northeastern Qinghai–Tibetan Plateau (NE QTP) is influenced by numerous climatic systems (such as Asian monsoon, Plateau monsoon and the Westerlies), which makes it sensitive to the globally climatic changes. Over the past 30 years, significant research efforts have been invested to investigate palaeoclimate change from lake cores (Chen and Bowler 1985, 1986, 1987; Chen et al. 1990; Herzschuh et al. 2005, 2006; Herzschuh 2006; Huang 1988; Huang et al. 1990; Ji et al. 2005, 2009; Kelts et al. 1989; Lister et al. 1991; Liu et al. 2007, 2008; Shen et al. 2005; Yang et al. 1995; Yu and Kelts 2002; Zhang 1987; Zhang et al. 1989, 1993, 1994, 2007; Zhao et al. 2007, 2008, 2010); however, dry–wet climate changes reported in this region are still not clear and controversial (Chen and Bowler 1986; Chen et al. 1990; Colman et al. 2007; Herzschuh et al. 2005, 2006; Hövermann and Süßenberger 1986; Madsen et al. 2008; Yang et al. 1995; Zhang 1987; Zhang et al. 1993; Zhang et al. 2007).

For example, Chen and Bowler (1985, 1986, 1987) concluded that the climate in the Qaidam Basin was relatively humid between 40 and 25 <sup>14</sup>C ka BP and that it became progressively drier and formed halite deposits after 25 <sup>14</sup>C ka BP in Qarhan region of eastern Qaidam Basin; until the last 9.0 <sup>14</sup>C ka BP, some new saline lakes have developed again over the Qarhan playas. Zhang et al. (2007) also reported that a uniform large lake was developed in the Qaidam Basin between 39.7 and 17.5 <sup>14</sup>C ka BP. Hydrological balance calculations indicate that annual precipitation is 150–350 mm/a in the period of 32–24 <sup>14</sup>C ka BP, the precipitation decreased to 50–150 mm/a between 21 and 15 <sup>14</sup>C ka BP and even less than 50 mm/a present in the Qaidam Basin (Hövermann and Süßenberger 1986).

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Lake terraces in the southern Qinghai Lake (Erlangjian section, +14 m above present lake level) confirmed that the lake has also expanded during 33.8–23.6  $^{14}\text{C}$  ka BP (Chen et al. 1990). Lake records of a sediment core from Qinghai Lake show that climate was very cold and dry in the Last Glacial Maximum (LGM) (during 18.0–16.9 cal. kyr BP) (see Table 1 for its age range), and started becoming warm and wet from late Glacial to middle Holocene (14.1–6.5 cal. kyr BP). Until late Holocene, the climate gradually became colder and drier (Ji et al. 2005, 2009; Liu et al. 2007; Shen et al. 2005). The history of the vegetation composition and ostracod assemblages of the Lake Luanhaizi from the NE QTP indicated that the climate conditions around 45 ka BP were similar to or even moister than present day, and the highest palaeomoisture (lake levels) existed in the early Holocene period (Herzschuh et al. 2005, 2006; Herzschuh 2006; Mischke et al. 2005).

These aforementioned results are basically consistent with the record of dust concentrations from the Dunde Icecap on the NE QTP. The dust concentrations of ice core is low before 30 ka BP; after that time the dust abruptly increases and the value is seven times that of >30 ka BP, until ~12 ka BP, when the value becomes low again (Thompson et al. 1989).

However, different palaeoclimatic variations in this region are reported over the past 50/40 ka. Zhang (1987), and Zhang et al. (1993) argued that the climate in the eastern Qaidam Basin was wet before 50 ka, corresponding to the deposition of lacustrine mud. After that, abundant halite sediments formed in the Qarhan region of eastern Qaidam Basin, which implies that the climate was very dry. Yang et al. (1995) also reported that drier and warmer conditions prevailed in the late Pleistocene, from 45 to 42 and 34 to 28 ka BP, with a dry and cold period from 19 to 11 ka. The climate was mainly dry and warm with a slightly wetter and warmer interval from 11 to 8 ka in the Qarhan region of eastern Qaidam Basin during the Holocene. These records imply that the climate in the eastern

Qaidam Basin shifted drier along with short-time wetter intervals during past 50/45 ka on the whole. Colman et al. (2007) also concluded that no high lake levels existed in the Qinghai Lake during MIS 3.

Therefore, this paper summarized high lake level histories based on shoreline features and highstand lacustrine sediments around lakes on the QTP, and then compared them with paleoclimatic records from lake sediments, ice core and glaciation evolution surrounding mountains on the NE QTP during late Pleistocene. The objectives of this study were to provide comprehensive evaluation of palaeoclimatic history and to understand possible mechanism in this critical region.

### Data sources and high lake level records

Lakeshore or highstand lacustrine sediments around lakes are direct geomorphic evidences to reflect lake-level fluctuation, as well as the change of effective moisture at geological time. Due to the absence of organic material within beach sediments for radiocarbon dating, few age results for lake level history were reported in previous works. The development of Optically Stimulated Luminescence (OSL) technique has facilitated the reconstruction of lake-level history in arid region (Madsen et al. 2008; Lee et al. 2009; Thomas et al. 2009). In recent years, more scholars reported the history of lake level on the QTP, based on OSL and U/Th age constraints (Fan et al. 2010a; Lee et al. 2009; Li et al. 2009; Liu et al. 2010; Madsen et al. 2008; Sun et al. 2010; Wang et al. 2008; Xue et al. 2010; Zhu et al. 2004).

Six lakes (Gahai Lake and Toson Lake, Qinghai Lake, Nam Co, Selin Co and Lop Nur, see Fig. 1) were selected to compare and discuss the history of lake level on the QTP, based on two criteria: (1) geomorphic evidences including shoreline features, lake terraces or highstand lacustrine sediments were investigated in these research; (2) a series of age constraints for these geomorphic evidences have been reported and they can cover Last Interglaciation.

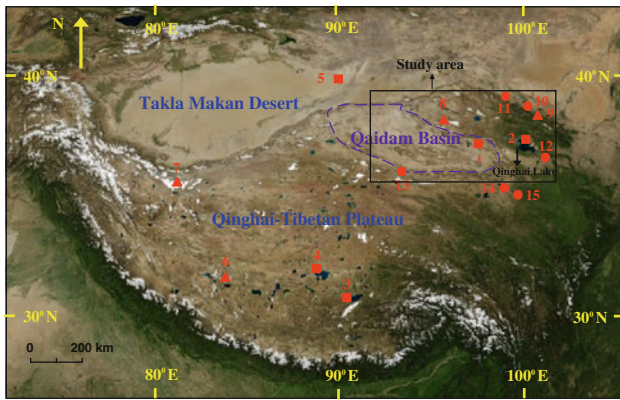
Highstand lacustrine sediments and beach ridges in Gahai Lake and Toson Lake were found based on field geomorphic investigation in 2010 (Figs. 2, 3, 4). Four samples were collected and their ages determined using OSL dating techniques (Table 2).

In addition, two high-resolution palaeoclimatic records (including Zabuye lake core and Guliya ice core) (site 6 and 7 in Fig. 1) were selected to compare with high lake levels and glacial advances from surrounding mountains on the NE QTP (site 10–15 in Fig. 1) (Owen et al. 2003a, 2003b, 2003c, 2006; Thompson et al. 1997; Zheng et al. 2007; Zhou et al. 2002).

**Table 1** Terms and age ranges for marine oxygen isotope stages (MIS)

	Marine oxygen isotope stage (MIS)	Age range (ka)
Holocene	1	12.1–present
Last glacial maximum (LGM)	2	24.1–12.1
	3	59.0–24.1
	4	73.9–59.0
Last interglaciation	5	129.8–73.9

Age ranges are from Martinson et al. (1987)



**Fig. 1** Map showing the location and paleoclimatic recording sites. High lake levels' study sites: 1 Gahai Lake and Toson Lake (in this paper); 2. Qinghai Lake (Liu et al. 2010; Madsen et al. 2008; Rhode et al. 2010); 3 Namco Lake (Zhu et al. 2004); 4 Selin Co (Li et al. 2009); 5 Lop Nur (Wang et al. 2008). Drilling core records: 6 Zabuye Salt Lake (Zheng et al. 2007); 7 Guliya Ice Core (Thompson et al. 1997); 8 Dundee Ice Cap (Thompson et al. 1989); 9 Luanhaizi Lake (Herzschuh et al. 2006). Glaciation records: 10 Laolongwan Valley, Laotugou Valley and Gangshiga Valley in the Qilian Shan (Owen et al. 2003a); 11 Bailang River Valley in the Qilian Shan (Zhou et al. 2002); 12 LaJi Shan (Owen et al. 2003b); 13 Burhan Budai Shan in the Kunlun Mountains (Owen et al. 2006); 14 Nianboyeze (Owen et al. 2003c); 15 Anyemaqen (Owen et al. 2003c). The square represents the study area. QTP is abbreviation of Qinghai–Tibetan Plateau

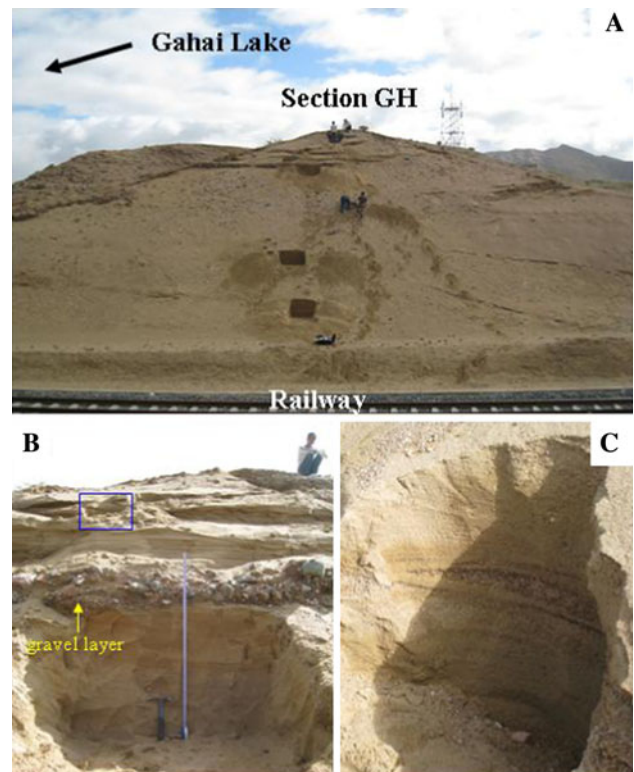
### Lake level changes and palaeoclimatic records on the QTP since late Pleistocene

#### Lake level changes on the QTP since late Pleistocene

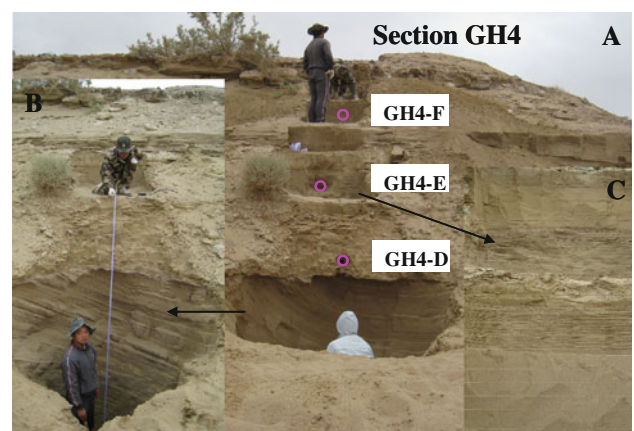
In a closed lake basin, lake-level fluctuation reflects the change of water balance on precipitation and evaporation, as well as dry–wet climate changes. In this paper, lake level records in Gahai Lake, Toson Lake, Qinghai Lake, Nam Co, Selin Co and Lop Nur were compared, which showed that most of these lakes are almost synchronous on the QTP (Fig. 5).

Gahai Lake and Toson Lake (site 1 in Fig. 1) are located in the northeastern Qaidam Basin, NE QTP. Highstand lacustrine sediments and shoreline features were found in the east of Gahai Lake and northwest of Toson Lake. Optically Stimulated Luminescence ages from lakeshore and highstand lacustrine sediments show that high lake levels existed in the 84–72, 63–55, 30 and 5.4 ka (Fan et al. 2010a, 2010b, 2010c).

Qinghai Lake (site 2 in Fig. 1) on the NE QTP is the largest saline lake in China. A number of paleoshorelines have been identified along the southern margin of the lake (such as Jiangxigou and Heimaha). Geomorphic evidences and OSL age results indicate that multiple periods of high lake level existed in the 110–70, 60–54 and 40 ka in Qinghai Lake (Liu et al. 2010; Madsen et al. 2008; Rhode

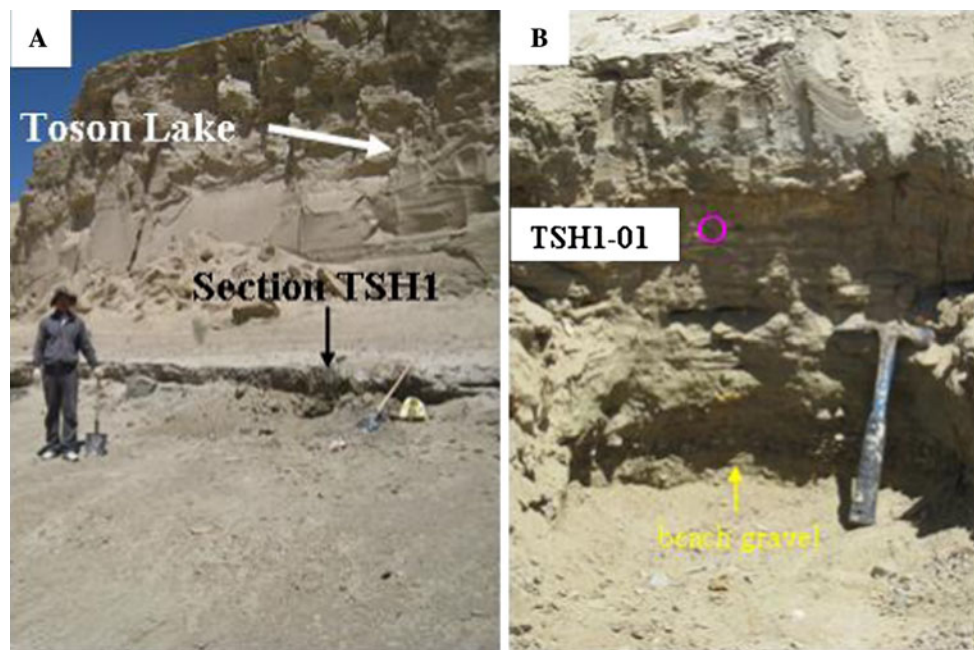


**Fig. 2** Pictures showing section GH and some details of the paleoshoreline deposits. a is the map of an outcrop, to the east of Gahai Lake, was exposed due to railway construction. The top of the section is about 25 above present lake level. b and c are typical of shoreline and beach deposits, which indicate that a large lake existed at Gahai Lake. Rectangle area in b is shown in detail in the c. The OSL ages above the gravel layer are 63–55 ka, while the OSL ages below the gravel layer is 82–73 ka in the b. Detailed description and discussion are seen in the paper by Fan et al. (2010a, b, c)



**Fig. 3** Pictures showing the section GH4, sampling locations and sediment characteristics in the east of Gahai Lake. A is entire picture of section GH4; B is the lower part of this section. C is upper part of this section, depositing horizontal-fine-bedding fine sands indicate that deep lacustrine sediments. Three samples (GH4–D–F) were collected in these stratigraphy





**Fig. 4** Pictures showing the section TSH1. One sample was collected above the beach gravels in the northwest of Toson Lake

et al. 2010).  $^{14}\text{C}$  ages from lake terraces show that high lake level also existed in 7.4–6.0 ka during Holocene (Chen et al. 1990).

Six lake terraces and highstand lacustrine sediments were found around Nam Co (site 3 in Fig. 1) in the northern QTP.  $^{14}\text{C}$  and U-series age results of lakeshore sediments around Nam Co indicate that ancient large lake existed since late Pleistocene. After 40 ka, the lake has broken up into several small lakes (Zhu et al. 2004).

Selin Co (site 4 in Fig. 1) in the central QTP has deposited four groups of beach ridges in the west and east shore of lake. OSL ages of beach ridges demonstrate that high lake levels occurred in the periods of 67.9, 30.4–18.6, 12.5–9.2 and 6.9 ka, respectively (Li et al. 2009). Other shorelines in northeastern bank of Selin Co and OSL ages indicate that high lake levels existed in the periods of 12.2, 6.3 and 2.3 ka, respectively (Xue et al. 2010).

Lop Nur (site 5 in Fig. 1), in the eastern Tarim Basin, is to the north of the QTP. Three lacustrine terraces on the northern and northeastern shore indicate past high lake levels. The results show that high lake levels occurred at 130–90 ka, ~30 and 7.5–7.0 ka, respectively (Wang et al. 2008). High lake level records in Lop Nur are also similar to other lakes on the QTP.

The results obtained by comparing these lake-level records of lakes on the QTP and north of QTP (in Fig. 5), show that high lake level periods of most lakes on the QTP occurred during MIS 5, MIS 3 and early-middle Holocene. However, there is an exception for high lake levels in Selin Co, an OSL age for the highest/oldest beach ridge group in

southeast side of Selin Co is  $67.9 \pm 2.4$  ka, corresponding to the early stage of the Last Glaciation (MIS 4) (Li et al. 2009). The other beach ridge group in southeast and southwest side of Selin Co produces three OSL ages of  $30.4 \pm 2.9$ ,  $27.4 \pm 1.5$  and  $18.6 \pm 1.7$  ka (Li et al. 2009), corresponding to late MIS 3 and LGM, respectively. High lake levels in Selin Co during MIS 4 and LGM are asynchronous with those in Nam Co, Qinghai Lake, Gahai Lake on the QTP.

When we compared in detail the age constraints for shorelines in Selin Co with that of other lakes on the QTP, we found that part of these ages are basically consistent within error. For example, the age ( $67.9 \pm 2.4$  ka) of highest lake level in Selin Co is close to two ages of  $73.7 \pm 6.7$  and  $73.0 \pm 6.0$  ka reported from terrace or beach ridge of Qinghai Lake and Gahai Lake on northeastern QTP, respectively (Fan et al. 2010a; Rhode et al. 2010). Two OSL ages ( $30.4 \pm 2.9$  and  $27.4 \pm 1.5$  ka) of secondary lake level is also close to age constraints of Qinghai Lake and Toson Lake on NE QTP (Fan et al. 2010c; Liu et al. 2010). Just one age of  $18.6 \pm 1.7$  ka was reported and implied that high lake level occurred in LGM; geomorphic elevations also revealed higher lake level in LGM (+57 m above present lake surface), higher than that in late MIS 3 (+43–46 m above present lake surface). The results seem to confound our knowledge that (1) if the lake level is higher during LGM than that during late MIS 3, beach ridges formed in late MIS 3 would be eroded or destroyed when lake level rose again in LGM; (2) if high lake level occurred in LGM (corresponding to dry and cold

**Table 2** Sample information, environment radioactivity and OSL dating results

Lab code	Sample ID	Depth (m)	Grain size (µm)	Water content (%)	U (ppm)	Th (ppm)	K (%)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	De (Gy)	Aliquot number	OSL age (ka)
ISL-Lum-051	GH4-D	18.65	38–63	20 ± 5	2.82 ± 0.25	10.8 ± 0.37	1.95 ± 0.05	0.037 ± 0.01	2.87 ± 0.21	240 ± 7	11	84 ± 7
ISL-Lum-052	GH4-E	17.60	88–125	15 ± 5	0.97 ± 0.17	5.11 ± 0.30	1.86 ± 0.05	0.040 ± 0.01	2.26 ± 0.18	183 ± 9	12	81 ± 8
ISL-Lum-053	GH4-F	14.20	88–125	15 ± 5	1.42 ± 0.19	6.78 ± 0.30	1.94 ± 0.05	0.053 ± 0.01	2.54 ± 0.20	188 ± 10	12	74 ± 7
ISL-Lum-060	TSH1-1	0.40	38–63	15 ± 5	1.75 ± 0.20	5.87 ± 0.29	2.12 ± 0.06	0.309 ± 0.04	2.91 ± 0.21	15.6 ± 0.7	12	5.37 ± 0.45

climate), how to maintain water balance between evaporate and precipitation in Selin Co; (3) more geomorphic evidences and age constraints of lakes can confirm the presence of high lake level and cluster contemporary lake level period. Therefore, more age constraints for beach ridges are needed in future work.

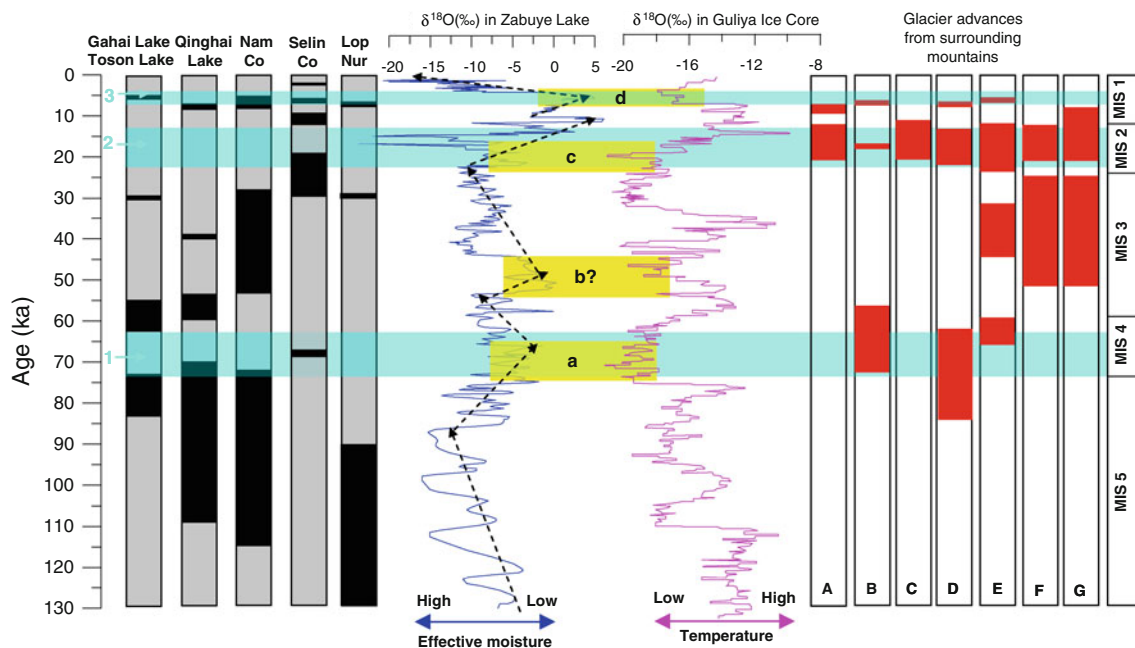
Palaeoclimatic records on the QTP since late Pleistocene

Two high-resolution palaeoclimatic records (including Zabuye lake core and Guliya ice core) were selected to compare with high lake levels on the QTP. An 83-m core obtained from Zabuye Salt Lake on the northern QTP was reported to cover the last 128 ka, based on radiocarbon, U-series disequilibrium and Electron Spin Resonance (ESR) dating methods (Zheng et al. 2007). The δ<sup>18</sup>O curve of authigenic calcium–magnesium carbonate derived from the core shows a very high correlation with oxygen isotope changes in Guliya ice core on the QTP, confirming these palaeoclimatic records during the last 128 ka were synchronous in the arid regions of the QTP (Zheng et al. 2007). Previous studies show that the δ<sup>18</sup>O value of authigenic calcium–magnesium carbonate formed in lake is a good indicator to reflect effective moisture or regional precipitation (Gu et al. 1993; Liu et al. 2007). The lower δ<sup>18</sup>O value of carbonate in these records reveals high effective moisture or high precipitation in study area; the higher δ<sup>18</sup>O value of carbonate indicates low effective moisture in reverse.

The Guliya ice core obtained from west Kunlun Mountains, with an elevation of 6,200 m, in the northern QTP. The δ<sup>18</sup>O record in the Guliya ice core indicates clearly close correlation between the temperature variation and the solar activity (Yao et al. 1997). Therefore, the δ<sup>18</sup>O variation in the Guliya ice core is more suitable to study the atmospheric temperature changes on the QTP during the 125 ka. The more positive δ<sup>18</sup>O values in the record imply that the temperature is higher since late Pleistocene (Thompson et al. 1997; Yao et al. 1997).

*The last interglacial period*

Palaeoclimate records from Guliya ice core and Zabuye lake core indicate that the climate on the whole is warmer and wetter during MIS 5 than MIS 3 and Holocene, though there is a great shift of both temperature and moisture at ~85 ka (Thompson et al. 1997; Yao et al. 1997; Zheng et al. 2007; see Table 1 for its age range). The average δ<sup>18</sup>O values in Guliya ice core, especially at peaks of ~120, 100 and 80 ka, are obviously more positive, implying that the climate is warmer during MIS 5 (Thompson et al. 1997). The temperature reconstructed



**Fig. 5** Comparison with high lake levels, lake sediments, ice core records and glacier evolution since late Pleistocene on the northeastern Qinghai–Tibetan Plateau. The black and gray bars in lake-level history represent high and low lake levels, respectively. The number 1–3 represent the dry–cold climate period, corresponding to *a*, *c* and *d* in the  $\delta^{18}\text{O}$  value of carbonate from Zabuye Salt Lake and Guliya Ice Core. The A–G is the evidence of glacier advances in the surrounding mountains on the northeastern QTP. A is Laolongwan

Valley, Laotugou Valley and Gangshiga Valley in the Qilian Shan (Owen et al. 2003a); B is Gangshiga Valley in the Qilian Shan (Zhou et al. 2002); C is LaJi Shan (Owen et al. 2003b); D is north slope of Burhan Budai Shan in the Kunlun Mountains (Owen et al. 2006); E is south slope of Burhan Budai Shan in the Kunlun Mountains (Owen et al. 2006); F is Nianboyeye (Owen et al. 2003c); G is Anyemaqen (Owen et al. 2003c). The arrow shows the high and low effective moisture in  $\delta^{18}\text{O}$  records from Zabuye lake core

from oxygen isotope data in three warm sub-stages (corresponding to MIS 5a, 5c and 5e) is 3, 0.9 and 5°C above present temperature (Yao et al. 1997). The average  $\delta^{18}\text{O}$  values of authigenic carbonate from Zabuye lake core are more negative and reach the minimum value at ~85 ka during MIS 5, which suggests the climate is wetter, especially in late MIS 5 (Zheng et al. 2007). The results, confirmed by the loess records from XiNing Basin on the NE QTP, reported that strong summer monsoon brings more precipitation during MIS 5 (Lu et al. 2004).

Widely high lake levels reported in Qinghai Lake (110–70 ka), Gahai Lake (84–72 ka) and Nam Co (115–70 ka) on the QTP favored that the climate is rather humid during MIS 5. Therefore, similar results from high lake levels and palaeoclimate records indicate that the climate is warmer and wetter on the QTP during late MIS 5.

#### The last glacial period

The last glacial period (corresponding to MIS 4, 3, 2) is the coldest period on the earth during late Pleistocene. The temperature reconstructed from Guliya ice core decreases by 12°C from warm stage of MIS 5 to MIS 4 and basically reaches the extent of LGM during MIS 4 (Yao et al. 1997).

The average  $\delta^{18}\text{O}$  value from Zabuye lake core reaches  $-5\text{‰}$  and is close to the average abundance of oxygen isotope in MIS 2, which implies that dry and cold climate prevails during MIS 4. No wide age constraints for high lake levels were found on QTP in this stage and only one age was reported in Selin Co, that there is large lake during MIS 4.

MIS 3 is a relatively warm interstadial stage in last glacial period. The temperature reconstructed from Guliya ice core is abnormally high and approximately reaches the extent of the Last Interglaciation (Yao et al. 1997). The effective moisture from Zabuye lake core is high in MIS 3; it is higher especially in late MIS 3 than the early Holocene (Zheng et al. 2007). Similar records also reported that the climate is warmer and wetter during 40–30 ka BP (corresponding to late MIS 3) (Shi et al. 1999, 2001). Pollen-based reconstruction of QTP vegetation shows that alpine steppe-forests were shifted ca. 400 km further north and the alpine conifer forest extended ca. 400–800 km beyond their present western limits. The temperature was 2–4°C higher and precipitation was 40% to cover 100% higher than today during 40–30 ka BP (Shi et al. 2001). High lake levels reported in Qinghai Lake (60–54 ka, ~40 ka), Gahai Lake (63–55 ka, ~30 ka), Nam Co (~40 ka) and

Selin Co (30–27 ka) also emphasize that the climate is humid during MIS 3.

The late period of Last Glaciation (corresponds to MIS 2) is dry and cold climate conditions. The temperature evidenced by Guliya ice core decreases to the lowest point in LGM; after that it began gradually rise until the transition between latest glacial period and Holocene. The effective moisture is gradually decreasing in LGM, abruptly increasing after ~15 ka BP. The result is consistent with aeolian sand records in southeastern margin of Qaidam Basin, which reported that extensive desert appeared in the period of 21–15 ka BP, and aeolian sand was alternately stabilized and mobilized in several intervals of 15–10 ka BP (Zeng et al. 2003). In addition, wide sand accumulation events on the QTP also confirmed that arid conditions prevail in the period of 21–16 ka (Lai et al. 2009).

### *The Holocene period*

Paleoclimatic records from Guliya ice core and Zabuye lake core show that the climate is relatively warm and wet in the periods 10.0–6.0 ka (corresponding to early-middle Holocene) and 4.0–0 ka (corresponding to late Holocene); however, geomorphic evidences of beach ridges in Selin Co demonstrated that lake level is gradually dropping and effective moisture gradually decreases from early Holocene to late Holocene (Xue et al. 2010). This is consistent with climate patterns which proposed that humid climate characterized the early Holocene, and drier climate prevailed during the late Holocene on NE QTP (Lister et al. 1991; Shen et al. 2005; Zhao et al. 2009; Zheng et al. 2009).

Lister et al. (1991) reported that substantial lake-level rises probably characterized the periods ~10.2–9.8, 9.5–8.5, 8.3–7.2 ka BP and ~6.8 yr BP, based on the oxygen isotope record for ostracoda from lake core in Qinghai Lake. Shen et al. (2005) analyzed multi-proxy including pollen, TOC, TN and  $\delta^{13}\text{C}$  of organic matter from a sediment core at Qinghai Lake and reported that climate was warm and wet period from 14.1 to 6.5 cal ka BP and came to its end at about 4.5 cal ka BP. After that, the climate gradually became colder and drier. Zhao et al. (2009) have concluded that vegetation was characterized by steppe desert, steppe or desert in the northern QTP, indicating a wet climate in the early and mid-Holocene until 6.0–4.5 ka. Zheng et al. (2009) reconstructed vegetation covers of Gahai Lake in Qaidam Basin during three periods of 6.0, 2.5 and 0 ka BP and reported that the climate is wetter during 6.0 ka BP and that the latter two periods are dry.

Age constraints of beach ridges and terraces in Toson Lake, Qinghai Lake, Nam Co, Selin Co and Lop Nur

suggest that high lake levels during Holocene occurred in 7.5–7.0, 7.4–6.0, 6.9, 6.3 or 5.4 ka, corresponding to middle Holocene (Chen et al. 1990; Fan et al. 2010c; Li et al. 2009; Wang et al. 2008; Xue et al. 2010; Zhu et al. 2004). Lake level records from Lagkor Tso on northern QTP show that the highest lake level occurred in 5.2 ka, after which the lake started shrinking during Holocene (Lee et al. 2009). The results of lake level are consistent with palaeoclimatic records on the QTP during Holocene.

By comparing high lake levels with palaeoclimatic records from Zabuye lake core and Guliya ice core on the QTP in Fig. 5 we found that periods of high lake level are almost synchronous on the QTP, corresponding to warm and humid climate conditions since late Pleistocene. In addition, effective moisture reconstructed by authigenic carbonate from Zabuye lake core shows its periodical variation since late Pleistocene. In last interglacial period, its fluctuation increases and reaches the maximum degree at ~85 ka, corresponding to periods of high lake level during MIS 5. After that, it obviously decreases and ends at ~65 ka, corresponding to glacier advances during MIS 4. It clearly increases and decreases again during MIS 3. High effective moisture corresponds to high lake levels, while low effective moisture corresponds to low lake levels. Until the late period of last glacial period, the effective moisture fluctuates frequently and decreases to the minimum degree, corresponding to wide glacier advances on the NE QTP. After that, the effective moisture is increasing in the early-middle Holocene and late Holocene. Few ages for beach ridges during late Holocene were reported at present; the palaeoclimatic records imply that effective moisture is slightly high during late Holocene. The effective moisture on the QTP was increasing at several intervals; however, the aridity has been increased on the whole since late Pleistocene. The results correspond to strong aeolian activity and the development of salt lakes on the QTP (Lai et al. 2009; Sun et al. 2007; Zhang et al. 1993; Zheng et al. 1998; Zeng et al. 2003).

### **Lake and glacier evolution on the northeastern QTP since late Pleistocene**

Lake and glacier developed on the QTP are good materials to study regional climate changes. A number of lake basins, glacier from high mountains and aeolian sediments are widely distributed on the NE QTP; therefore, it is an ideal laboratory to investigate lake and glacier evolution, and to examine their links in this region.

The Burham Budai Shan of the Kunlun Mountains lies in the south margin of Qaidam Basin. It preserved a number of ice-contacted fans associated with moraines. Based on field mapping, geomorphic and sedimentological



analysis, OSL and CRN (terrestrial cosmogenic radionuclide surface exposure) dating results define at least three glacial advances in the northern side and southern side of Burhan Budai Shan. On the northern side of the range approximately 10 km east of the Golmud–Lhasa highway, these advances date to penultimate/early last glacial cycle, the LGM/Lateglacial and Holocene, while on the south side of the range (south of the town of Xidatan), they date back to the penultimate glacial cycle, MIS 3, and possibly the LGM, Lateglacial or Holocene (Owen et al. 2006).

Many moraines and terraces were preserved in south slop valleys in the Lenglong Ling Mountains of the southwestern Qilian Shan. Zhou et al. (2002) concluded that four glacial advances existed in the Gangshiga valley of south Lenglong Ling Mountains, including MIS 4, 2, Neoglaical and the LIA (Little Ice Age), according to ESR dating results and previous  $^{14}\text{C}$  ages. Owen et al. (2003a) also investigated the moraines and terraces of the Laolongwan Valley, Laotugou Valley and Gangshiga Valley in the Lenglong Ling Mountains, and these advances dated to 18.4–15.7 and 10.2–9.5 ka in Laolongwan Valley, 19.5–12.7 and 7.3 ka in Laotugou Valley, 20.3–13.2 and 8.4–7.9 ka in Gangshiga Valley based on CRN dating.

La Ji Shan lies in the southeast of Qinghai Lake, NE QTP. Field investigation and CRN dating define that glacial advances have been existed during MIS 2 (Owen et al. 2003b).

By comparing the glacier advances on the Qilian Shan, Burham Budai Shan in the Kunlun Mountains and LaJi Shan on the northeastern QTP, we found that most glacier advances had occurred in the early stage of Last Glacial, LGM/Lateglacial and Holocene since late Pleistocene. These glacier advances also correspond to periods of low lake level (corresponding to 1, 2, 3 in Fig. 5) and coincide with positive  $\delta^{18}\text{O}$  value of authigenic carbonate from Zabuye Slat Lake and negative  $\delta^{18}\text{O}$  value of Guliya Ice Core, implying that three glacier advances existed in the dry–cold climatic periods on the NE QTP (corresponding to a, c, d in Fig. 5). The dry and cold climate conditions may induce strong evaporation in the lake basin and further make the lake level drop. On the contrary, the water vapor was brought to high elevation by evaporation and formed much snow on the high mountains around lake. It also accumulates positive mass balance to expand the extent of glacier. Therefore, the records between lake and glacier provide a framework that suggests links between climatic amelioration, deglaciation and high lake level.

In addition, there is a dry–cold climate period during middle MIS 3 (corresponding to b in Fig. 5) according to  $\delta^{18}\text{O}$  records from Zabuye Salt Lake and Guliya Ice Core. Low lake level is also found in the Gahai Lake and Toson Lake, Qinghai Lake and Lop Nur in this time. MIS 3 (ca.

25–65 ka) could be divided into three sub-stages in China. MIS 3a, MIS 3b and MIS 3c periods are 25–40, 40–55 and 55–65 ka, respectively (Xu et al. 2010). MIS 3b (44–54 ka) is a relative cold period, and many glacier advances were reported in middle and low latitudes (Shi and Yao 2002). However, no wide glacier advance in study area was found during MIS 3. It was only preserved in the south of NE QTP, including south slop of Burhan Budai Shan, Nianboyeze and Anyemaqen (Owen et al. 2003c, 2006). Owen et al. (2003c) argued that glacier advance during MIS 3 was synchronous throughout the south Asian monsoon-influenced regions of high Asia and that monsoon precipitation is vital in controlling the timing and pattern of glacial advances in these regions (Owen et al. 2003c; Xu et al. 2010).

Why did not glacier advance occur during MIS 3 on the NE QTP? The possible cause is low effective moisture in this period. The result is also consistent with the low palaeomosture reconstructed from Lake Luanhaizi on the NE QTP (Herzschuh et al. 2005). Low effective moisture induces negative mass balance and produces small extent of glacier during MIS 3. While wide glacier advance existed in the LGM/Lateglacial in study area and might have eroded more geomorphic evidences of former glaciers. Therefore, no geomorphic evidences of glacier advance during MIS 3 were found in the Qilian Shan, LaJi Shan and north Burham Budai Shan in the Kunlun Mountains on the NE QTP. The result possibly implies that the effective moisture is lower than other region of NE QTP.

## Conclusions

1. By comparing between age constraints of shorelines and highstand lacustrine sediments, we found that high lake levels occurred at MIS 5, MIS 3 and early-middle Holocene on the NE QTP.
2. Paleoclimatic records from lake core and ice core and lake-level history of lakes provide a framework that suggests links between climatic amelioration, deglaciation and high lake levels.
3. No wide glacier advance in study area was found during MIS 3 on the NE QTP, which possibly implies that the effective moisture is lower than other region of NE QTP.

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