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Geomorphic and chronometric evidence for high lake level history in Gahai Lake and Toson Lake of north-eastern Qaidam Basin, north-eastern Qinghai–Tibetan Plateau

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ABSTRACT: Palaeoshorelines, highstand lacustrine sediments and lakeshore terraces are preserved around saline lakes in the arid Qaidam Basin. Previous research indicates that the chronology of a mega-paleolake in the Qaidam Basin during the late Pleisotocene is controversial. Here we report quartz optically stimulated luminescence (OSL) age estimates of highstand lacustrine sediments, shoreline features and geomorphic exposures that contribute to a revision of the lake level history of Gahai and Toson lakes in the north-eastern Qaidam Basin, on the northeastern Qinghai–Tibetan Plateau (QTP) margin. The results imply that: (i) high lake levels at Gahai and Toson lakes based on quartz OSL dating occurred at 85–72, 63–55, 31, 5.4 and 0.9–0.7 ka, probably corresponding to periods of warm and wet climate; (ii) periods of high lake levels are almost synchronous with other lakes on the QTP (e.g. Qinghai and Namco lakes), with the highest late Pleistocene levels occurring during Marine Oxygen Isotope Stage 5; and (iii) highstand phases on the QTP are out of phase with those of low-latitude lakes in the southern hemisphere, possibly driven by solar insolation variability in the low-latitude region. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: Gahai Lake; high lake level; north-eastern Qinghai–Tibetan Plateau; OSL dating; Qaidam Basin; Toson Lake.

Introduction

The north-eastern Qinghai–Tibetan Plateau (QTP) (Fig. 1A) is influenced by numerous climatic systems (such as the East Asian and Indian monsoons, and the Westerlies), making it sensitive to global climatic changes. The Qaidam Basin is the largest arid basin in the region (1.2×10^5 km^2) and is surrounded by the Kunlun Mountains to the south, the Altun Mountains to the west and the Qilian Mountains to the north and east. With the 'high mountain and low basin' topography (Yuan *et al.*, 1983), it has developed 27 salt lakes, many of which were once linked to form a 'megalake', and deposits of thick salt beds and abundant brine resources are common (Chen and Bowler, 1986). In recent decades, significant research efforts have been undertaken to study the evolution of many of these salt lakes (Chaka, Qarhan, Taijinai, Kunteyi, Daliangtan, etc.) (e.g. Chen and Bowler, 1986; Huang and Cai, 1987; Huang and Chen, 1990; Zhang, 1987; Liang and Huang, 1995; Yang *et al.*, 1995; Liu *et al.*, 2008; Li *et al.*, 2010). Some geomorphic evidence and chronological data for late Pleistocene high lakeshore sediments have been recovered (e.g. Chen and Bowler, 1986; Huang and Cai, 1987; Ma, 1996; Owen *et al.*, 2006; Zhang *et al.*, 2007; Fan *et al.*, 2010; Mischke *et al.*, 2010; Sun *et al.*, 2010), but the chronology of a megalake in this basin remains controversial.

Different explanations have been put forward for the chronology of high lake levels in the Qaidam Basin. Based on field geomorphic investigation, topography and satellite image mapping, Chen and Bowler (1986) suggested that two large shorelines were preserved along the margins and pediments of the basin. Under the constraints of contemporary dating they speculated that the earliest megalake [$\sim$2800 m above sea level (a.s.l.)] was formed during the early Pleistocene, and that a late megalake ($\sim$2700 m a.s.l.) formed at 38.6–28.6 ^{14}C ka BP. This was based on radiocarbon dating of three shells from the 'Shell Bar' in the eastern Qaidam Basin to 28 630 $\pm$ 670, 35 100 $\pm$ 900 and 38 600 $\pm$ 680 ^{14}C ka BP (Huang and Cai, 1987).

Based on geomorphic field investigations and sedimentological analyses, multiple palaeoshorelines to the north of Lenghu in the north-western Qaidam Basin were identified (Ma, 1996). Age estimates of 31.7 $\pm$ 0.08 ^{14}C ka BP on bulk carbonate in lake marl and a thermoluminescence (TL) age of 62.7 $\pm$ 12.5 ka on underlying beach sand within a beach section, 45 m above the present Lenghu Lake, were obtained. A TL age of 50.5 $\pm$ 6.5 ka was also determined on beach sand within the highest terrace, 40 m above Chaka Lake in the eastern Qaidam Basin. Similarly, an age of 33.0 $\pm$ 0.1 ^{14}C ka BP on bulk carbonate from the Shell Bar was reported (Ma, 1996). Zhang *et al.* (2007) investigated the depositional conditions of the Shell Bar in detail and reported that no depositional reworking was evident throughout the entire section. Based on 48 ages based on organic matter (including residual and humic acids of organic matter), fossil shells and surface salt crystals, they concluded that a uniform megalake developed in the Qaidam Basin between 39.7 and 17.5 ^{14}C ka BP.

While this research indicates high late Pleistocene lake levels in the Qaidam Basin occurred during Marine Isotope Stage (MIS) 3, the interpretation is based mostly on conventional ^{14}C and TL ages and a different chronology for these high lake levels has recently emerged that is based on quartz optically stimulated luminescence (OSL), U-series and electron spin resonance (ESR) dating. Owen *et al.* (2006) demonstrated that a large lake existed prior to $\sim$ 30 ka, based on OSL dating of surface exposure sediments from extensive incised alluvial fans along the southern margins of the Qaidam Basin. After 30 ka, shrinkage of the palaeolake probably led to a lowering of base level and incision of the streams into valley fills. Fan *et al.* (2010) reported seven OSL ages of 82–55 ka from a section consisting of lacustrine and shoreline deposits east of Gahai Lake (site 1 in Fig. 1A) in the north-eastern Qaidam Basin that is

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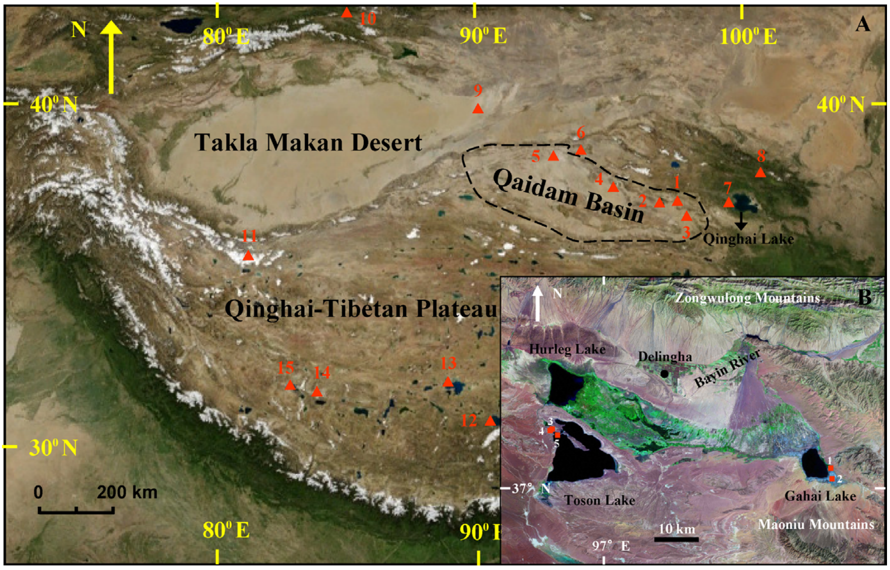

Figure 1. Map showing sampling location and palaeoclimatic records. (A) Map showing location of study area and recording sites of high lake levels since the late Quaternary: 1, Gahai Lake (this study); 2, Toson Lake (this study); 3, Chaka Salt Lake (Ma, 1996); 4, Xiao Qaidam Lake (Sun *et al.*, 2010); 5, Lenghu Lake (Ma, 1996); 6, Sugan Lake (Zhang *et al.*, 2009); 7, Qinghai Lake (Chen *et al.*, 1990; Lister *et al.*, 1991; Shen *et al.*, 2005; Madsen *et al.*, 2008; Liu *et al.*, 2010; Rhode *et al.*, 2010); 8, Luanhaizi Lake (Mischke *et al.*, 2005); 9, Lop Nur (Wang *et al.*, 2008a); 10, Manas Lake (Fan *et al.*, 2012); 11, Tianshuihai Lake (Zhou and Zhu, 2002; Li *et al.*, 2008); 12, Namco Lake (Zhu *et al.*, 2004); 13, Selin Co (Li *et al.*, 2009); 14, Zabuye Salt Lake (Zheng *et al.*, 2007); 15, Lagkor Co (Lee *et al.*, 2009). (B) Satellite image showing sampling locations (red rectangles) from Gahai Lake and northwest to Toson Lake: 1, GH4; 2, GH5; 3, TSH1; 4, TSH2 sections; 5, surface lacustrine sample (TSH-surface). This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

~24 m above the present lake. They argued that lake levels in Gahai Lake higher than at present occurred in both at 82–73 ka (corresponding to late MIS 5) and at 63–55 ka (roughly early MIS 3). Two higher lake levels in Xiao Qaidam Lake (site 4 in Fig. 1A) were also investigated: one at ~12 m and dated to ~11–3 ka and another at >40 m and dated to ~51–37 ka based on quartz OSL (Sun *et al.*, 2010). A new study from Shell Bar argued that the bar is not related to a lake, but rather represents a stream deposit (S. Mischke, Z.P. Lai and C.J. Zhang, unpublished data).

Thus, the question remains: did high lake levels in the Qaidam Basin occur during the late Pleistocene during MIS 5, late MIS 3 or both? Here we present new quartz OSL age estimates for highstand lacustrine sediments, shoreline features and geomorphic exposures to reconstruct the lake level histories of Gahai and Toson lakes, to further refine the timing of high lake levels in the Qaidam Basin and to understand the mechanism(s) underlying their formation.

Study region and the section

Gahai Lake (37°08′N, 97°33′E) and Toson Lake (37°04′–37°13′N, 96°50′–97°03′E) are located at the north-eastern edge of the Qaidam Basin on the north-eastern QTP (site 1 in Fig. 1A). To the north lie the Zungwulong Mountains, and to the south are the Maoniu Mountains. Hurleg and Toson lakes lie in the western portion of this Qaidam sub-basin, and the two lakes were once connected to Gahai Lake to the east (Fig. 1B). Gahai and Hurleg lakes are surrounded mostly by late Quaternary alluvial and lacustrine sand, silt and clay, while Toson Lake is bounded by Tertiary fine-grained deposits with limited groundwater storage capacity (Yi *et al.*, 1992). This region has an extremely arid desert climate. Mean annual precipitation at the Delingha climate station (2928 m a.s.l.), *c.* 25 km north of Gahai Lake, is 160–170 mm, and most precipitation falls as rain during the summer months. Based on climate averages for the period 1971–2000, annual temperature is 4 °C (January: –10.6 °C; July: 16.5 °C) and annual evaporation is about 2000–2200 mm. Modern vegetation in this region is dominated by desert plant communities, consisting mainly of Chenopodiaceae, Ephedra, Nitraria and Asteraceae (Zhao *et al.*, 2008).

Gahai Lake is now a saline lake, fed mostly by groundwater, with no permanent inflow streams (Wang and Dou, 1998), while Hurleg Lake is now a freshwater lake, fed mainly by Bayin River flow from the northern mountains and is situated upstream of Toson Lake. Hurleg Lake discharges through a small outlet stream to Toson Lake and the latter is also a closed-basin saline lake.

Sections and sample collection

In 2008, we investigated an outcrop a few kilometres east of Gahai Lake that was exposed by railway construction. The section comprised lacustrine and shoreline deposits about 13 m thick. Seven OSL samples (GH-01–07) were systematically collected from top to bottom in the section (Fan *et al.*, 2010) (Fig. 2). To provide additional geomorphic and chronometric data, we recently re-investigated the exposed shoreline history of Gahai and Toson lakes. Four sections (GH4: 37°07′55″N, 97°35′16″E; GH5: 37°06′21.8″N, 97°36′07.6″E; TSH1: 37°11′38.9″N, 96°52′35.9″E; TSH2: 37°11′37.2″N, 96°52′35.5″E) were selected for dating and 16 samples for OSL dating were collected from the four localities (Figs 3–6). The stratigraphic description of the four sections and a modern sample are given in the Supporting information, Appendix S1. A modern lacustrine sample (TSH-surface) was collected from Toson Lake to check luminescence clock-zeroing assumptions. Samples were collected by driving iron tubes (6 cm diameter, 20 cm long) into the freshly prepared sections. The ends of each tube were covered by a thick black cloth when the tube was filled with sediment, and then wrapped with opaque plastic tape.

Sample preparation and measurement techniques

To extract approximate grains for equivalent dose measurement, grains of 88–250 μm from paleoshoreline samples and grains of 38–63 μm from lacustrine samples were prepared to extract and purify quartz followed the methods described by Fan et al. (2010). Pure quartz grains that showed no obvious infrared stimulated luminescence (IRSL) signals were detected using X-ray diffraction (Fig. 7f). Equivalent doses (D_e) were determined using the improved single aliquot regenerative-

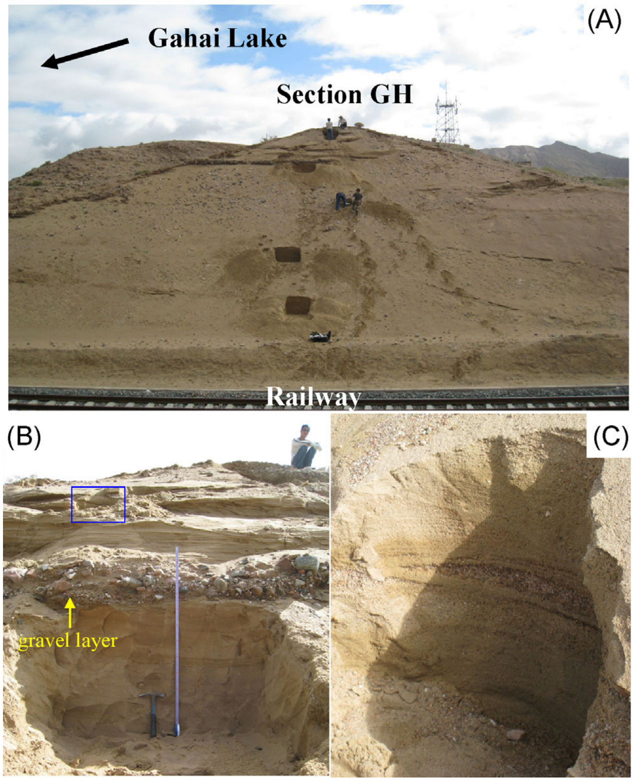

Figure 2. Photographs of section GH and details of the palaeoshoreline deposits. (A) Outcrop to the east of Gahai Lake; (B,C) typical details of shoreline and beach deposits, which indicate that a large lake existed at Gahai Lake. Detailed description and discussion are given by Fan *et al*. (2010). This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

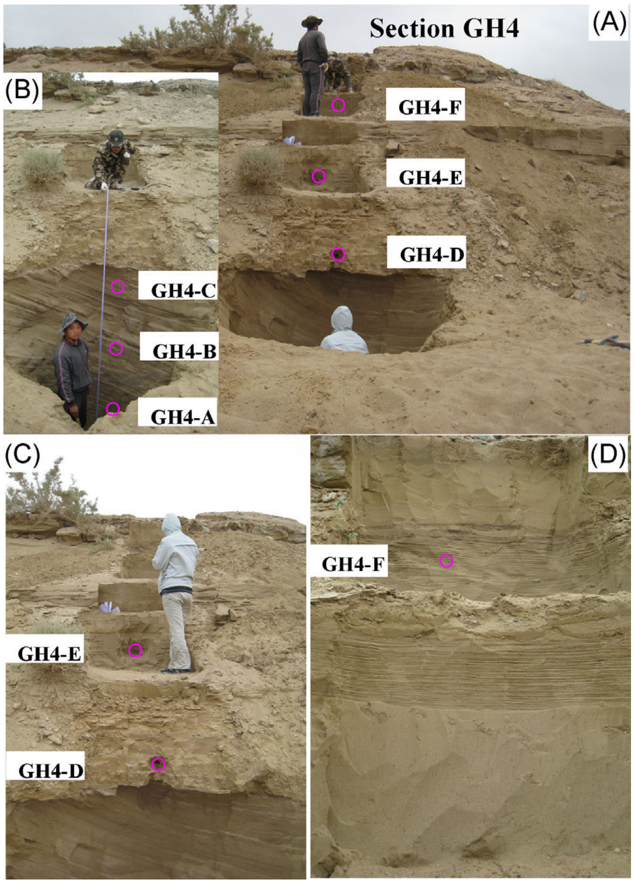

Figure 3. Photographs of section GH4: sampling locations and stratigraphic features. (A) Entire section; (B,C,D) sampling locations and stratigraphic features. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

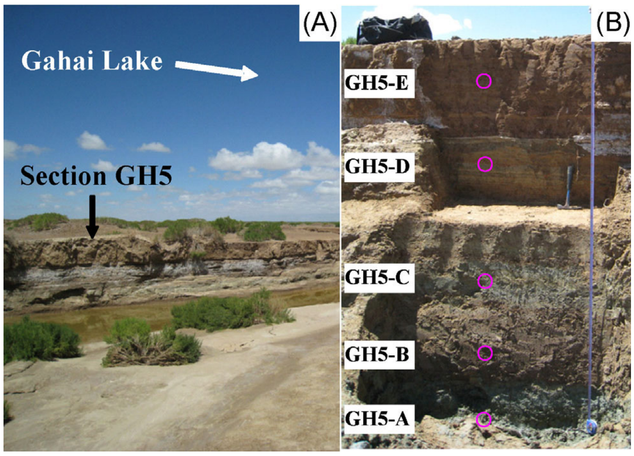

Figure 4. Photographs of section GH5. (A) Entire section; (B) sampling locations and lithological characteristics. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

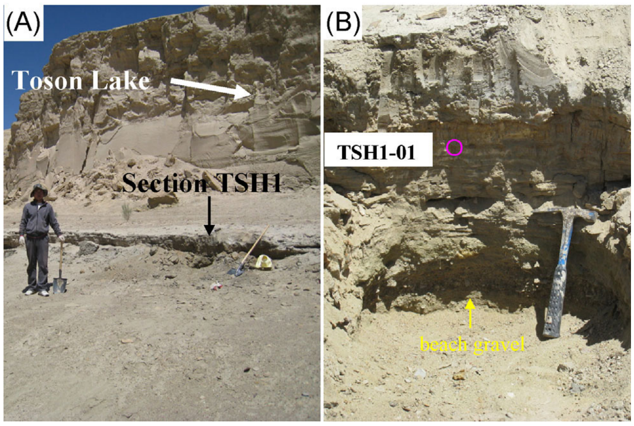

Figure 5. Photographs of section TSH1. (A) Palaeoshoreline around Toson Lake; (B) sampling locations and stratigraphic characteristics. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

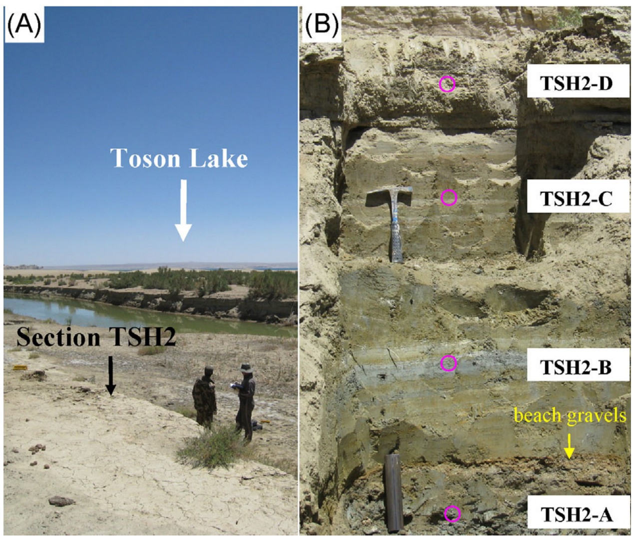

Figure 6. Photographs of section TSH2. (A) Entire profile; (B) stratigraphic characteristics and sampling locations. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

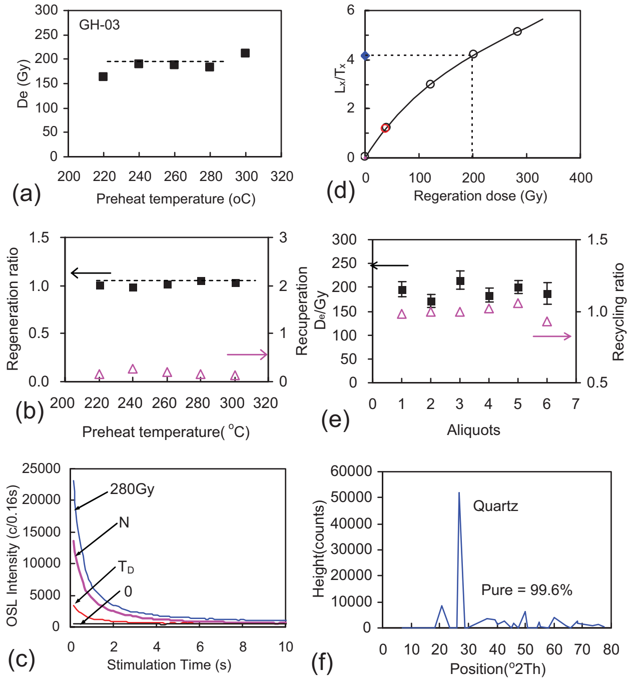

Figure 7. (a, b) Preheat temperature plateau test results; (c) OSL decay curves; (d) growth curve; (e) dose recovery test results; (f) XRD results of purified quartz grains before D_e measurement for sample GH-03. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

dose (SAR) protocol (Wintle and Murray, 2006) on an automated Risø TL/OSL DA-20 reader equipped with a beta source. OSL was stimulated at 130 °C for 40 s by blue LEDs ($\lambda = 470 \pm 20$ nm, ~50 mW · cm^{-2}), and 90% diode power was used. The OSL signals were detected by a 9235QA photomultiplier tube through a 7.5-mm-thick U-340 detection filter. To choose an appropriate preheat temperature on D_e, a preheat plateau test was carried out on sample GH-03 using 88–125 μm quartz grains between 220 and 300 °C at increments of 20 °C. The results indicate that there are no effects of preheat temperature on on D_e at least between 220 and 280 °C. Therefore, we selected a preheat temperature of 260 °C for 10 s in the middle of the plateau region, a cut–heat of 220°C for 10 s and a test dose of 27 Gy for the D_e measurement (Fig. 7a,b). Figure 7(c,d) show OSL decay curve and a growth curve for sample GH-03, respectively. To check overall performance of the SAR protocols for D_e determination (Murray and Wintle, 2003), a laboratory dose recovery test was conducted using sample GH-03 (Fig. 7e). Six aliquots were exposed to blue LED stimulation at 130 °C for 100 s to remove charge acquired during burial, and each aliquot was then given a laboratory dose of 202 Gy. The aliquots were then measured using SAR to obtain their D_e values, giving an average of 192 ± 16 Gy. Thus, the ratio of the measured to given dose is 0.95 ± 0.08, implying that experimental parameters of SAR measurements are appropriate for Gahai Lake samples. These conditions were then employed for determination of D_e values.

The concentrations of uranium, thorium and potassium were determined using neutron activation analysis at the China Institute of Atomic Energy in Beijing. The 'α value' for 38–63 μm quartz grains was taken as 0.035 ± 0.003 (Lai *et al.*, 2008). The water content is calculated based on moisture mass/dry mass (Aitken, 1985) and an error of 5% was estimated for all samples. The cosmic ray dose rate was estimated according to Prescott and Hutton (1994).

Results and interpretation

OSL dating results and other information for 17 samples from sections GH4, GH5, TSH1 and TSH2 and TSH-surface are given in Supporting information Table S1. All ages were in the range 85 ± 7 to 0.7 ± 0.1 ka. At each section, most ages are in stratigraphic order within error except for four ages from GH4-A–C and GH5-E samples.

Although three ages (76–79 ka) (GH4-A–C) at the bottom of section GH4 are younger than those of overlying sediments, they are basically consistent within error. In addition, these ages from section GH4 are consistent with those ages from section GH, adding confidence to the acceptability. Based on OSL ages and stratigraphic evidence from the two sections, there was an ancient large lake between 85 and 72 ka, at least ~12 m above modern Gahai Lake.

An OSL age of 31 ka was dated to the bottom of TSH2, implying that the palaeolake level of Toson Lake during late MIS 3 was higher than at present. Overlying beach gravels indicate that lake level fell after this period; lake level rose again until the early Holocene based on two ages (10 and 9.1 ka) at the top of this section.

An OSL age (5.4ka) from the top of section TSH1 shows that Toson Lake highstands, ~ 4 m above the modern lake surface, occurred during the mid-Holocene.

Four OSL ages were dated from section GH5. Stratigraphic and sedimentological features show that the upper yellow clay layer of the section is not lacustrine in origin, and resembles modern alluvial sediments. Therefore, high lake levels occurred at 2.0 and 0.9–0.7 ka based on other OSL ages and stratigraphic sequences.

Combining geomorphic exposures of beach sediments, lithological changes of lacustrine sediments and OSL ages in the four sections, high lake levels at Gahai and Toson lakes are dated to 85–72, 63–55, 31, 5.4 and 0.9–0.7 ka.

Discussions

High lake level history and other palaeoclimatic records in the study area

MIS 5 lake level history

OSL dating results yielded five ages of 82–73 ka and three ages of 85–74 ka in sections GH and GH4, respectively. No higher geomorphic evidence of lacustrine deposition was found and OSL chronology and shoreline geomorphology suggest that the highest ancient large lake preserved in the Delingha sub-basin formed during late MIS 5 (85–72 ka). Similar high lake level records have also been reported from other parts of the QTP and its adjacent regions (Zhu *et al.*, 2004; Li *et al.*, 2008; Madsen *et al.*, 2008; Wang *et al.*, 2008a; Liu *et al.*, 2010; Rhode *et al.*, 2010; Zhang, 2010; Fan *et al.*, 2012). For example, Qinghai Lake (site 7 in Fig. 1A) is located on the north-eastern QTP margin east of Gaihai Lake and has a lake history similar to that in the Delingha sub-basin. A large number of high palaeoshorelines have been identified along the southern margin of the lake, and OSL dating results suggest that high lake levels ~20–66 m above that of the modern lake occurred at ~110–75 ka (late MIS 5) (Madsen *et al.*, 2008; Liu *et al.*, 2010; Rhode *et al.*, 2010). Tianshuihai Lake (site number 11 in Fig. 1A; 35°30′N, 79°30′E), 4800–4900 m a.s.l., is located in the north-western QTP. Five lacustrine terraces were identified and the highest lake terrace, 90–100 m above the present lake, has a TL age of 110 ka (with no dating details) (Li *et al.*, 2008). Namco Lake (site number 12 in Fig. 1A; 30°30′N, 89°45′E) is located in the southern QTP and U-series, ^{14}C and ESR dating suggest a large lake was present there at ~115–40 ka (Zhu *et al.*, 2004).

Selin Co (site 13 in Fig. 1A; 88.5–89.4°E, 31.5–32.1°N) is near Namco Lake, and three palaeoshorelines have been identified around this lake. An OSL age of 69.7 ± 2.4 ka on a sample from the highest beach ridge was obtained (Li *et al.*, 2009).

Lop Nur (site 9 in Fig. 1A; 40°30′N, 90°30′E) is to the north of the QTP. Three lacustrine terraces are found 35–40 m above the present salt bed and OSL dating indicates that high lake levels existed between 138 and 90 ka, with highest levels occurring at ~90 ka (Wang *et al.*, 2008a). Manas Lake (site 10 in Fig. 1A) is also to the north-west of the QTP. OSL ages and geomorphic evidence of lacustrine sediments, ~20 m above the present lake bed, suggest that high lake levels occurred during and before ~66 ka, probably corresponding to MIS 5 (Fan *et al.*, 2012).

Huangqihai Lake is located in the eastern QTP, on the margin of the reach of the East Asian Monsoon. Luminescence dating and geomorphic investigations indicate that higher lake levels, 57 m above the present surface, existed at 97–71 ka (Zhang, 2010).

In addition, palaeoclimatic records from the QTP indicate that the climate was warmer and wetter during the last interglacial. A 910-m lacustrine core (Ck-6) taken from Qarhan Salt Lake indicates that the organic content was higher in MIS 5 than in other periods during the late Pleistocene, suggesting higher vegetation cover and effective moisture in this period (Huang and Chen, 1990). The Guliya ice cap is in the western Kunlun Mountains in the northern QTP, and $\delta^{18}O$ records from an ice core collected there reflect atmospheric temperature changes on the QTP. Average $\delta^{18}O$ values during MIS 5, especially peaks at ~120, ~100 and ~80 ka, are more positive than the rest of the record, implying the climate was warmer during MIS 5 (Thompson *et al.*, 1997). In addition, the loess records in Xining Basin confirm that high precipitation occurred during MIS 5 (Lu *et al.*, 2004). These results are also confirmed by $\delta^{18}O$ records of autogenetic carbonate derived from an 83-m lacustrine core in the Zabuye Salt Lake on the northern QTP (Zheng *et al.*, 2007), which are good indicators of effective moisture or regional precipitation on the QTP (Liu *et al.*, 2007). The average $\delta^{18}O$ values of authigenic carbonate from the Zabuye lake core are negative and reach a minimum value at ~85 ka during MIS 5, which suggests the climate was wetter, especially during late MIS 5 (Zheng *et al.*, 2007). Thereafter it clearly decreases and increases again during MIS 3 and the early–middle Holocene. Although average $\delta^{18}O$ values increase at several intervals, the effective moisture has been decreasing since late Pleistocene. The $\delta^{18}O$ values of lacustrine carbonates since 130 ka from a Tianshuihai Lake core also indicate an overall increasing $\delta^{18}O$ trend and decreasing effective precipitation (Zhou and Zhu, 2002). Therefore, effective moisture is the key factor in influencing palaeoclimatic changes, including lake level change on the QTP.

In summary, these high lake level records on the QTP and palaeoclimatic proxies imply that there was high effective moisture on the north-eastern QTP during MIS 5.

MIS 3 lake level history

Geomorphic evidence and OSL ages from section GH demonstrate that an ancient large lake, ~24 m above the present Gahai lake surface, was preserved between 63 and 55 ka (corresponding to early MIS 3). Another OSL age of 31 ka (corresponding to late MIS 3) from a lacustrine layer in section TSH2 was also obtained. We found no further geomorphic evidence during late MIS 3 at Gahai and Toson lakes, so lake level elevation during this period is not particularly clear. The lithology and OSL ages from section TSH2 indicate that lake level of Toson Lake was lower during late MIS 3 than that of Gahai Lake at 63–55 and 85–72 ka.

Many high lake level records have also been reported in the QTP and adjacent areas, e.g. Qaidam Basin: > 30 ka (Owen *et al.*, 2006); Xiao Qaidam Lake: 51–37 ka (> 40 m) (Sun *et al.*, 2010); Qinghai Lake: 60–54 ka (~56 m) (Liu *et al.*, 2010); Namco Lake: 54 ka (38–48 m), 41–32 ka (18–36 m) (Zhu *et al.*, 2004); Selin Co: 30–27 ka (43–46 m) (Li *et al.*, 2009); Lop Nur: 30 ka (~7 m) (Wang *et al.*, 2008a); Manas Lake: 38–27 ka (~20 m) (Fan *et al.*, 2012); Huangqihai Lake: 45–34 ka (~6 m) (Zhang, 2010).

In summary, the lake level records from the present study are similar to those from other parts of the QTP, north-west of the QTP and East Asian Monsoon area mentioned above, all showing higher lake levels during early MIS 3 or late MIS 3.

However, high lake levels on the QTP during MIS 3 have been variously explained (Colman *et al.*, 2007; Madsen *et al.*, 2008; Lai *et al.*, 2010). Based on lacustrine carbonate $\delta^{18}O$ records from a drill core, Colman *et al.* (2007) concluded that no high lake levels existed in the Qinghai Lake during MIS 3. Madsen *et al.* (2008) argued that MIS 3 highstands are much lower than the MIS 5 Lake and uncertain but may have been at or below postglacial elevation based on OSL dating and geomorphic exposures. Lai *et al.* (2010) summarized that the highest lake level existed during MIS 5, and the lake level during early MIS 3 was ~6–8 m above modern lake level and ~2–4 m above Holocene highstands. Lake level during late MIS 3 was even lower, ~2 m above modern levels based on luminescence ages and geomorphic evidence at Qinghai Lake, Xiao Qaidam Lake in the north-eastern QTP and other lakes in the western Tengger Desert. This discrepancy may highlight that either no palaeoshorelines or beach ridges were preserved around lakes in this period, or there is spatial heterogeneity of hydrology balance in different lakes.

MIS 1 lake level history

OSL dating results and stratigraphic interpretation from TSH1 and TSH2 suggest that the highest lake level during the Holocene existed at 5.4 ka. Similar high lake level records have also been reported in the QTP and adjacent region. For example, Lagkor Co: 5.2 ka (Lee *et al.*, 2009); Qinghai Lake: 7.4–6.0 ka (11–14 m) (Chen *et al.*, 1990), 8–5 ka (~10 m) (Liu and Lai, 2010); Selin Co: 6.9 ka (~10 m) (Li *et al.*, 2009); Linggo Co: 9–6 ka (~4 m) (Pan *et al.*, 2012); Huangqihai Lake: 11–7 ka (~8–9 m) (Zhang *et al.*, 2011); Baijian Lake: 7.3–6.5 ka (~14 m) (Long *et al.*, 2010). These higher lake levels are supported by Holocene wet climate records of many lakes or sections in the QTP, for example from Qinghai Lake: 10.2–9.8, 9.5–8.5, 8.3–7.2 and 6.8 ka (Lister *et al.*, 1991); 14.1–6.5 ka (Shen *et al.*, 2005); 10–6 ka (Liu *et al.*, 2007); Gahai Lake: 6.0 ka (Zheng *et al.*, 2009); Luanhaizi Lake: Early and Mid-Holocene (Mischke *et al.*, 2005).

Luminescence dating and lithology characteristics from GH5 indicate the latest high lake level occurred at 0.9–0.7 ka, corresponding to the 'Medieval Warm Period' (800–1300 AD) (Cronin *et al.*, 2003). This is consistent with the highest effective moisture from Gahai Lake in the north-eastern Qaidam Basin (Zhao *et al.*, 2010), low salinity from Sugan Lake in the north-western Qaidam Basin (Zhang *et al.*, 2009) and high precipitation from tree ring records in the eastern Qaidam Basin (Shao *et al.*, 2006).

Mechanism for Late Pleistocene high lake level history in north-eastern QTP

These high lake level records at Gahai Lake and Toson Lake in the north-eastern Qaidam Basin since the late Pleistocene are mostly synchronous with other lakes (such as Selin Co, Qinghai Lake and Namco Lake, see Fig. 8a–c) on the QTP, north of QTP

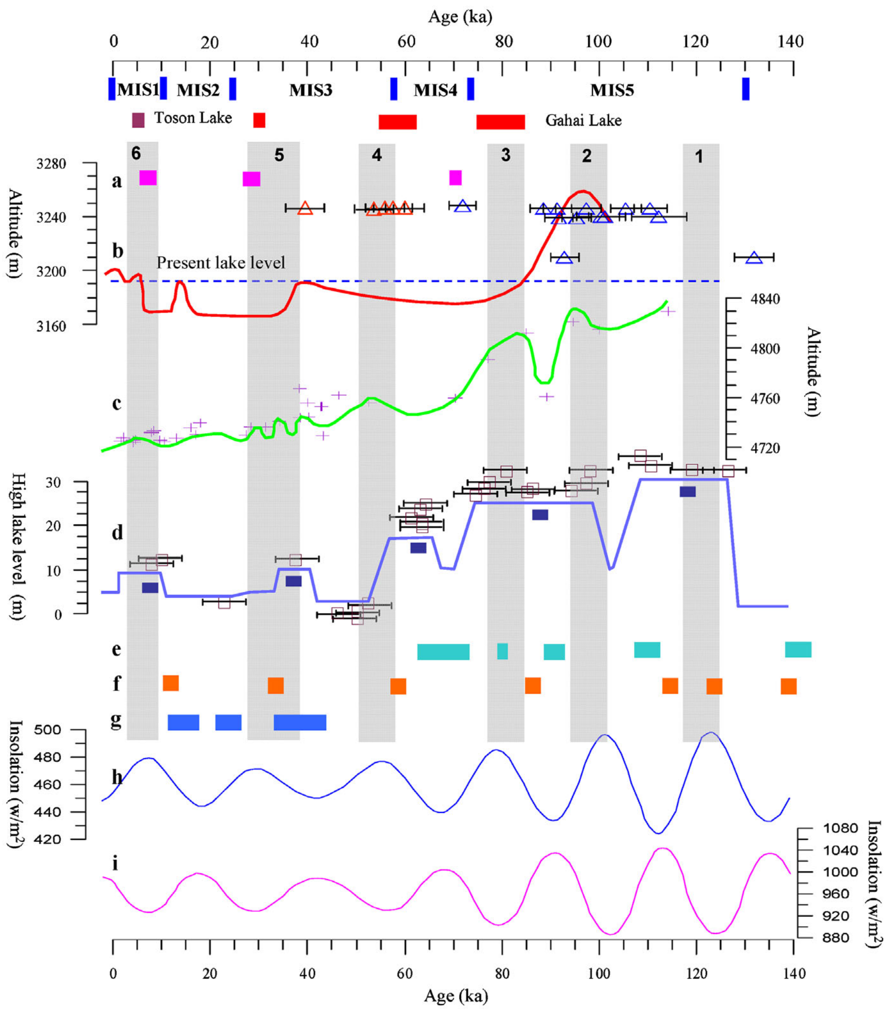

Figure 8. Comparison of high lake level histories from the northern and southern hemisphere since the Late Quaternary: a, Selin Co (Li *et al.*, 2009); b, Qinghai Lake (Madsen *et al.*, 2008; Liu *et al.*, 2010; Rhode *et al.*, 2010); c, Namco Lake (Zhu *et al.*, 2004); d, Eyre Lake (Magee *et al.*, 2004); e, Naivasha Lake (Trauth *et al.*, 2001); f, Ngami Lake (Burrough *et al.*, 2007); g, Chilwa Lake (Thomas *et al.*, 2009); h, summer solar insolation at 25°N (Berger, 1978); i, January solar insolation at 20°S (Berger and Loutre, 1991). Numbers 1–6 represents high lake level periods on the QTP since 130 ka. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

(such as Lop Nur and Manas Lake) and east of QTP (Huangqihai Lake), corresponding to a warm and wet climate period of the Last Interglacial, interstadial of the Last Glacial, Mid–Holocene Climatic Optimum and Medieval Warm Period. All geomorphic and chronometric evidence indicates that the highest lake level on the QTP occurred during MIS 5.

Previous researches revealed that effective moisture on the north-east QTP is dominantly transported by the South Asian summer monsoon from the Indian Ocean (Shi *et al.*, 2001; Liu *et al.*, 2007) and East Asian summer monsoon from the west Pacific Ocean (Shen *et al.*, 2005). Strong summer monsoon will bring considerable effective precipitation, while weak summer monsoon will result in aridity of the study area. In recent years, significant studies have obtained many high-resolution stalagmite records (such as Dongge Cave and Hulu Cave) reconstructing the Asian summer monsoon as well as precipitation change in the monsoon region (Wang *et al.*, 2008b; Yuan *et al.*, 2004). The $\delta^{18}O$ stalagmite records show that much precipitation induced by the Asian summer monsoon occurred during the interglaciation or interstadial intervals and dominated by ~20-ka procession cycles since the late Pleistocene. The result is also consistent with high lake level history (Qinghai Lake, Gahai Lake and Toson Lake) on the north-east QTP. A strong Asian monsoon may have brought much precipitation into the lakes' catchment areas and formed lake highstands. In addition, we also found that the periods of high lake level are almost synchronous with high solar insolations at 25°N (Berger, 1978) (Fig. 8–c, g). The result implies that increasing temperature on the QTP induced by high solar insolation from low latitude regions in the northern hemisphere also contributed to melt snow/ice water from high mountains, supplying water to the closed lake basin.

Comparison and teleconnection of high lake level history in the study area with that from low–latitude region in the southern hemisphere

It is interesting to compare the high lake level history on the QTP with other lakes from low-latitude regions of the southern hemisphere. Many records of high lake level in the southern hemisphere have been reported for the period since 140 ka (Trauth *et al.*, 2001; Magee *et al.*, 2004; Burrough *et al.*, 2007; Thomas *et al.*, 2009), for example: Eyre Lake (28°30′S, 137°28′E; Fig. 8d) (Magee *et al.*, 2004), Naivasha Lake (0°55′S, 36°20′E; Fig. 8e) (Trauth *et al.*, 2001), Ngami Lake (20°30′S, 22°40′E; Fig. 8f) (Burrough *et al.*, 2007) and Chilwa Lake (Fig. 8g) (Thomas *et al.*, 2009). By comparison with highstand phases of these lakes, we found that they are synchronous changes and are dominated by a ~20-ka procession cycle (Fig. 8d–g). At the same time, the lake level fluctuations from these lakes are consistent with solar insolation variations at 20°S. Trauth *et al.* (2001), Magee *et al.* (2004) and Burrough *et al.* (2009) argued that highstand phases at Naivasha Lake, Makgadikgadi Lake and Eyre Lake are controlled by a locally intensified monsoon driven by solar insolation variations.

In comparing high lake level records of lakes between the northern and southern hemisphere, we found that high lake level periods on the QTP are out of phase with those of low-latitude lakes in the southern hemisphere. This might have resulted from out-of-phase solar insolation in the low-latitude region either side of the equator (Fig. 8h,i) (Berger and Loutre, 1991), because solar insolation increases the pressure gradient between continent and ocean and enhances local monsoons (such as the Asian Monsoon, Australian Monsoon and African Monsoon), together with an increased moisture supply from the warming tropical ocean. In addition, the cross-equatorial air streams driven by the monsoon and trade winds may have had an influence on climatic changes in both hemispheres. A high-resolution continental record from Heqing core, near the south-eastern edge of the QTP, demonstrates that interhemispheric forcing is important in driving Indian Summer Monsoon variability at the glacial–interglacial time scale as well (An *et al.*, 2011). Therefore, solar insolation variability in the low-latitude region might be the factor most influencing monsoon and lake level changes. Numerical simulations of atmospheric circulation patterns and geological records have also suggested that the Asia Monsoon responds in a strong, coherent fashion to changes in the distribution of solar radiation of the precession cycle (Clemens and Prell, 1990; Prell and Kutzbach, 1992).

Although we obtained rough and partial data of high lake levels at Gahai Lake and Toson Lake on the north-eastern Qaidam Basin, they are mostly consistent with those of other lakes from the QTP, north of the QTP and east of the QTP, indicating an overall humid period during interglacial or interstadial stages. Similarly, this paper highlights the contrast of highstand records between the northern and southern hemisphere and provides evidence that lake level fluctuation might be driven by solar insolation variability in the low-latitude region. On the one hand, high solar insolation enhanced monsoon activity and brought much precipitation into inland lakes; on the other hand, high solar insolation increased earth surface temperature and melted much ice/snow from the high mountains into the closed lake basin. Although we have no conclusive highstand evidence at Gahai Lake and Toson Lake during late MIS 3, an OSL age of 31 ka from the lacustrine sediments in TSH2 indicates that lake level was lower than during MIS 5 and early MIS 3. Further geomorphic investigation and precise dating are needed.

Conclusions

The north-eastern Qaidam Basin is a hyper-arid area of the Qinghai–Tibetan Plateau. Previous research has indicated that there was a mega-palaeolake during the late Pleistocene, reflecting relatively humid climatic condition in the basin. Based on geomorphic exposures and OSL dating, we make the following conclusions:

1. High lake levels at Gahai Lake and Toson Lake based on OSL dating occurred at 85–72, 63–55, 31, 5.4 and 0.9–0.7 ka; these probably correspond to warm and wet climate periods of the Last Interglacial, interstadial of the Last Glacial, mid-Holocene Climatic Optimum and Medieval Warm Period, respectively.
2. The high lake level periods at Gahai Lake and Toson Lake are almost synchronous with those of other lakes (Qinghai Lake, Namco Lake and Selin Co) on the QTP, and the highest lake level since late Pleistocene existed during MIS 5.
3. Highstand phases of lakes on the QTP are out–of–phase with those of low–latitude lakes in the Southern Hemisphere, which might be driven by solar insolation variability in the low–latitude region.
4. No other geomorphic or chronometric evidence of beach deposits indicative of high lake levels during late MIS 3 have been found in the study area; only an OSL age of 31 ka from the lacustrine sediments was obtained, indicating that the lake level during this period was lower than during MIS 5 and early MIS 3. Further investigation and precise dating are needed to reconstruct the lake level history in the north-eastern QTP.

Supporting information

Additional supporting information can be found in the online version of this article:

Appendix S1. Supplementary sections.

Table S1 Sample information, environmental radioactivity and OSL dating results.

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Abbreviations. a.s.l., above sea level; ESR, electron spin resonance; MIS, Marine Isotope Stage; OSL, optically stimulated luminescence; QTP, Qinghai–Tibetan Plateau; SAR, single aliquot regenerative-dose; TL, thermoluminescence.

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