Lake-level fluctuations since the Last Glaciation in Selin Co (lake), Central Tibet, investigated using optically stimulated luminescence dating of beach ridges

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Received 17 May 2009
Accepted for publication 23 October 2009
Published 23 November 2009
Online at stacks.iop.org/ERL/4/045204

Abstract
This paper presents a preliminary study on lake-level fluctuations since the Last Glaciation in Selin Co (lake), Central Tibet, by dating four groups of beach ridges using optically stimulated luminescence (OSL). The highest/oldest beach ridge group (>100 m higher than the current lake level) is dated back to 67.9 ± 2.4 ka BP, corresponding to the early stage of the Last Glaciation (marine isotope stage (MIS) 4). This date further supports that no plateau-scale ice sheet covered the Tibetan Plateau during the Last Glaciation. The other three groups produce OSL ages of 30.4 ± 2.9 to 18.6 ± 1.7, 12.5 ± 1.6 to 9.2 ± 0.5, and 6.9 ± 0.2 ka BP respectively, most likely corresponding to cold or wet climate periods of the late stage of the Last Glaciation (MIS 2), deglaciation, and Holocene Hypsithermal. On the plateau scale, these four beach ridge groups are almost synchronous with advances or standstills of Himalayan glaciers, indicating similar climate controls across the central and southern Tibetan Plateau, and being consistent with the conclusion, obtained from nearby ice core records, that this area is affected by the South Asia monsoon. Furthermore, beach ridges are also synchronous with fluvial terraces in the northern Tibetan Plateau, implying common driving forces during their formation. Therefore, some terraces may be formed as a result of climate events rather than being of tectonic origin.

Keywords: Selin Co, beach ridges, Tibetan Plateau, OSL dating, MIS

1. Introduction

Beach ridges are common landforms along the shoreline of oceans and lakes. Various processes have contributed to the formation of beach ridges such as wash (Johnson 1919), settling lag, blown (Otvos 2000, Hesp 2005) and storm tides (Tanner 1995a, Taylor and Stone 1996). Beach ridges are dominated by wave deposition (Johnson 1919), or by the combination of both wave and aeolian deposition.
roots in the sample (Tanner 1993, Kilian et al. 1983, Brooke et al. 2008). In addition, they can also be used to identify co-seismic deformations (Keller 2001).

There are many beach ridges around lakes in Central Tibet that are commonly referred to as ancient shorelines or terraces in the Chinese literature (e.g. Li 2000, Li et al. 2001, Jia et al. 2001a, 2001b, Zhu et al. 2002, Jia et al. 2003, Zhu et al. 2004a, 2004b, Zhao and Li 2006, Zheng et al. 2006). These ridges represent paleo lake levels, which are critical for the understanding of lake level–climate interaction, sediment production and delivery, as well as tectonic uplift of the Tibetan Plateau. Therefore, extensive studies have been conducted associated with beach ridges and many data and arguments have been published (e.g. Li 2000, Li et al. 2001, Jia et al. 2001a, 2001b, Zhu et al. 2002, Jia et al. 2003, Zhu et al. 2004a, 2004b, Zhao and Li 2006, Zheng et al. 2006). However, controversy still exists about the relationship between climate (especially the glacial–interglacial cycle) and the formation of beach ridges. For example, Jia et al. (2001a) suggested that beach ridges in the Tibetan Plateau have been formed since 40 ka BP and represent four periods of higher lake levels of 40–28, 19–15, 13–11 and 9–5 ka BP. Dai (2002) reported much older beach ridges (terracettes) of 98.5 ± 7.3 and 72.1 ± 5.5 ka BP from Yang Lake of the northern Tibetan Plateau. Due to the lack of absolute age constraints, different explanations are proposed for the formation mechanism of beach ridges, including monsoon precipitation, wetting, glacier melting, and others. Therefore, absolute dating of beach ridges is of critical importance for improving our understanding of lake-level history and the formation mechanism of beach ridges in this critical area.

Several methods including 14C, U-series, and luminescence techniques have been or have the potential to be used to constrain beach ridge ages. 14C dating usually requires organic carbon, which is commonly taken from peat or organic materials in the lowland of adjacent ridges due to the lack of organic material in beach ridge deposits (Lichter 1995). However, it is not a direct measure of beach ridge age. In addition, sometimes it is difficult to find a suitable sample because it usually needs to be taken from the very bottom (several meters deep) of the ridge interval with the possibility of incorporating modern roots in the sample. As an indication of relict shorelines corresponding to long-term stable water levels and sufficient sediment supply, they have been used to reconstruct various paleo-environmental parameters such as sea/lake levels (Stapor 1982), sediment delivery rates, and climatic conditions (Rhodes et al. 1980, Chappell et al. 1983, Brooke et al. 2008). In addition, they can also be used to identify co-seismic deformations (Keller 2001). In addition, they can also be used to identify co-seismic deformations (Keller 2001).

These rivers provide enough sediment for the development of shoreline and beach ridges. Satellite images (http://glef. umiacs.umd.edu/data/landsat/) and digital elevation models (DEMs) indicate many sets of beach ridges, in the form of groups, distributed around the lake, especially along the southeast and southwest coasts due to the topography, wind direction and sediment supply. In the field we identified seven beach ridge groups that include >40 individual ridges on the southwest coast (figure 1(c)) and on the southeast coast, near parallel ridges extend >20 km further perpendicular to the shoreline (figure 1(d)).

### 2. Study area

The Selin Co is located in the central Tibetan Plateau (88.5–89.4°E, 31.5–32.1°N) with a surface area of >1830 km². It is the second largest lake in central Tibet (figure 1, the largest one being Nam Co, 130 km away to the southeast). The lake basin has no remarkable tectonic control and several major rivers in the plateau flow into the lake for water and sediment supply. The Zagen Zangbo (river) to the west is the largest endorheic river in the drainage basin (15315 km²) of Tibet with a length of 355 km. The Zajia Zangbo to the north is the longest (409 km) endorheic river in Tibet with a drainage area of 14850 km². The Ali Zangbo and Boqu Zangbo are located on the southwest and the east, with total lengths of 245 km and 85 km, and drainage areas of 7145 km² and 1360 km² respectively.

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### 3. Material and method

#### 3.1. Field work

As an initial study, the primary goal is to test the feasibility of using OSL to date beach ridge and, if this is possible, to reconstruct the lake-level fluctuation and spatio-temporal pattern of beach ridge formation in this area. Based on satellite image interpretation and field investigations, we constructed two survey lines from the southwest (L1) and southeast (L2) coasts for sample collection (figures 1(c) and (d)). These two survey lines cross-cut most beach ridges identified in the field. The locational information (latitude, longitude and altitude) for each sample site was recorded using GPS handheld units.
improve the accuracy of the measurement (especially in the altitude), we used two GPS units (MobileMapper 7.01, Thales Company, France, www.unistrong.com/ProductLine/detail.aspx?procode=MobileMapper) to determine the sample location using a differential GPS (DGPS) technique. The designed accuracy of the GPS unit is <1.0 m with a single reference-station DGPS, and 2.0–3.0 m with a WAAS (i.e. wide area augmentation system, a wide area DGPS). In the field, we set one GPS unit as the reference-station at a fixed location, and the other unit as the mobile station to perform the measurement. However, the reference-station data for L1 were lost during the data-processing. Fortunately, we were able to use the WAAS data to calibrate the measurement. The WAAS-based results for L1 have a position dilution of precision (PDOP) mean of 4.58 (754 sites, median of 4.43). For L2, both reference and mobile station data are available, and the DGPS results produce a PDOP mean of 4.15 (1245 sites, median of 2.63) in altitude. We believe that the accuracy of the altitude measured for these two survey lines is <5.0 m. The measurement of two survey lines from different sides of the lake allows us not only to date beach ridges but also to compare the elevation difference of beach ridges from both sides that have similar ages.

In each survey line we only sampled representative beach ridges in each group by digging a profile (pit) on the top of the ridge about 50–70 cm in depth. The structure and texture of the ridge profile were carefully examined before taking the sample. Typically, we can identify two layers (figure 2) in each profile. The upper yellow layer (U-layer) appears structureless without obvious sorting and bedding. The grain size of the sediment is finer (silt) with scattered rock fragments. The thickness of this upper layer increases with increasing distance from the current shoreline. We interpret this as local sediment reworked by wind (aeolian sediment). The lower layer (L-layer) comprises clear beddings (5–10 mm) of different grain sizes, colors and compositions. The grain size of the lower layer varies from sand to pebble but lacks silt–clay size grains.
Figure 2. A photo showing a ridge profile, sampling location and depth. The profile can be divided into an upper aeolian layer (U-layer) and a lower beach layer (L-layer). ➀ Aeolian sediment (sand-silt) with a thickness of \( \sim 15 \) cm. ➁ Gravel–sand layer, \( \sim 15 \) cm. ➂ Gravel sediment with gravel–sand layers, \( \sim 10 \) cm. ➃ Mid-fine sand layer, \( \sim 5 \) cm (sample 09 was collected here). ➄ Sand–gravel layer, \( > 10 \) cm.

The sediment is well sorted and is interpreted as of beach ridge origin. To constrain the age of the beach ridge, we sampled finer sediments (silt–sand) close to the top of the lower layer. We believe that this would provide a ‘real’ formation age of the beach ridge. For beach ridges with only coarser sediment (usually larger than sand) it is hard to sample finer silt–sand sediment. Alternatively, we collected samples from the bottom of the upper layer (samples 11 and 12). Although the dating of covered top aeolian sediments would not provide a direct measure of the age of formation of the beach ridge, we hoped it would provide a minimum age constraint for the beach ridge. In addition, it is also possible to evaluate whether dating the bottom of covered aeolian sediments would provide a valid age constraint for the beach ridge by comparing them with nearby dates measured directly from beach ridge sediments. One sample (05) was collected from the upper layer of a groove profile between beach ridges due to the difficulty of sampling directly from the beach ridges (we sampled the beach ridges twice, but all attempts failed). Another sample (08) was taken from the bottom (80 cm deep) of a sand dune to constrain the age of the underlying beach.

The samples were taken using black plastic tubes (length \( \sim 20 \) cm, diameter \( \sim 5 \) cm) (figure 2). The tubes were sealed immediately using aluminum foil and tape to retain moisture and avoid daylight exposure. In total, 13 samples were collected from two survey lines including nine from beach ridges, three from the upper aeolian layers and one from a sand dune.

3.2. Laboratory analysis

OSL sample preparation and measurement were performed in the Chronological Laboratory, Institute of Crustal Dynamics, Chinese Earthquake Administration, following the procedures of Lu et al (1987) and Forman (1991). Generally speaking, younger samples need more stringent OSL zeroing requirement (bleaching). For water-lain sediments, there may be considerable grain-to-grain variability in the extent of bleaching (Walker 2005). Therefore, we only measured the OSL signal of finer grains (4–11 \( \mu m \)), which is easier for bleaching than coarser ones. The sample was extracted under subdued red light in a darkroom. The two ends of the sample tube were first cut away to avoid potential daylight exposure during the sampling process. For each sample, 30 g of sediment was sieved to isolate the fraction of \(<63 \mu m\) for U, Th, and K analysis. The remainder was dried under 40°C, sieved to isolate the fraction of \(<90 \mu m\), and treated with 30% H\(_2\)O\(_2\) and 30% HCl to remove carbonates and organics. The sample was refined to fine silt size (4–11 \( \mu m \)) using sedimentation procedures based on Stokes law. The polymineral fraction of four samples (04, 05, 12, and 13) was immersed in H\(_2\)SiF\(_6\) (30%) for 3–4 days in an ultrasonic bath to separate pure quartz, followed by a treatment with 10% HCl to remove any fluorides produced. The purity of the separated quartz was tested by IR stimulation to make sure there was no obvious contamination by feldspar. Nine of the samples did not produce enough 4–11 \( \mu m \) polymineral fraction (<100 mg) for quartz separation. We used the whole polymineral grain for the further analysis. Finally all 13 samples (quartz or polymineral grains) were deposited on 9.7 mm diameter stainless steel discs to make multiple-grain aliquots.

The measurements were performed using a Daybreak 2200 automated OSL reader equipped with a combined blue (470 ± 5 nm) and infrared (880 ± 60 nm) LED unit, and a \(^{90}\)Sr/\(^{90}\)Y beta source (0.04651 Gy s\(^{-1}\)) for irradiation. Both IR and blue stimulation intensities are about 45 mW cm\(^{-2}\).
The OSL signal is detected by an EMI9235QA photomultiplier and a 3 mm U-340 glass filter. The simplified multiple aliquot regenerative-dose protocol (SMAR) (Wang et al. 2005) was employed to estimate the equivalent dose ($D_e$). In this study, 20 aliquots were used for each sample. The SMAR conditions (preheating at 260°C for 10 s, cut-heat at 220°C for 10 s) were applied to all aliquots. IR luminescence measurements were performed at 100°C for 10 s, cut-heat at 220°C, and blue stimulation at 215°C. The $D_e$ value was estimated by interpolating the sensitivity-corrected natural OSL onto the growth curve. As well as 10–12 of 20 aliquots for natural aliquots (N), another 6–8 regeneration doses were used, including a zero dose. Infrared stimulation was performed for 300 s at 60°C before 100 s blue light stimulation, which can remove the influence of feldspar for polymineral fine grains. A recent comprehensive study (Zhou et al. 2009) validated this method. This procedure yields two $D_e$ values: the IRSL $D_e$ and post-IR OSL $D_e$. The latter is adopted because of the anomalous fading of the luminescence signals from feldspars.

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U and Th concentrations were determined using thick-source alpha counting (TSAC). K content was analyzed using the anomalous fading of the luminescence signals from feldspars. The in situ water content was determined by weighing the sample before and after drying. However, all samples were dried. Based on field investigations, profile features, and previous studies of similar areas, an estimate of 10% (Lai et al. 2009, Fan et al. 2009) water content was adopted. Using the conversions of U, Th, and K contents and dose rates of different minerals (Aitken 1985), the environmental dose rate for all samples can be determined. Finally, based on $D_e$ and environmental dose rate, the post-IR OSL date for each sample can be calculated. The results are listed in table 1.

4. Results and discussions

4.1. OSL ages of beach ridges

No OSL signals were detected in two samples (06 and 08) (not listed in table 1). Eleven dates were obtained from polynilonic post-IR OSL. Based on spatial distribution and measured OSL ages (table 1), we group dated beach ridges into four groups starting from the coast—BG1, BG2, BG3, and BG4, respectively. The OSL ages of these four groups suggest that they correspond to four climate stages: Holocene, Hypsithermal, deglaciation, the late stage of the Last Glaciation (marine isotope stage 2 (MIS2)), and the early stage of the Last Glaciation (MIS 4) (table 1).

The highest beach ridge group (BG4) is up to 4641 m above sea level (a.s.l.), >100 m higher than the current lake level (4540 m a.s.l.) and 40 to 60 m higher than the second-highest beach ridge group (BG3). Sample 13 taken from this group was dated back to 67.9 ± 2.4 ka, similar to an age of 72.1 ± 5.5 ka reported from a terrace of the Yang Lake, northern Tibetan Plateau (Dai 2002). We believe that this indicates a plateau-wide event corresponding to the early stage of the Last Glaciation (MIS 4). This date provides additional support that no plateau-scale ice sheet covered the Tibetan Plateau during the Last Glaciation, which has been tested widely using terrestrial cosmogenic nuclide (TCN) surface exposure dating of glacial deposits from high mountains (Schäfer et al. 2002, Owen et al. 2005, 2009a).

The second-highest beach ridge group (BG3) is about 4583–4598 m a.s.l. (43–58 m above the current lake level). Three samples (01 and 02 from the southwest side, and 10 from the southeast side) produce OSL ages of 18.6 ± 1.7 to 30.4 ± 2.9 ka, indicating that BG3 corresponds to the late stage of the Last Glaciation (MIS 2). This group corresponds to a period that is widely identified as a high lake-level period around lakes on the Tibetan Plateau (40–14 ka) (Li 2000, 2001a, 2001b, 2003). In addition, beach ridges on different lake sides have approximately the same elevations, implying no obvious tectonic tilting in this area since at least MIS 2.

The third group (BG2) is about 4571–4580 m a.s.l. (31–40 m above the current lake level). Three samples (03 and 04 from the southwest side, and 09 from the southeast side) produce OSL ages of 9.2 ± 0.5 to 12.5 ± 1.6 ka. Therefore, BG2 corresponds to the time of last deglaciation. It correlates to another period (13–11 ka) of high lake level identified widely across the plateau (Jia et al. 2001a). It probably correlates to the Preboreal Oscillation and Greenland Holocene (GH) events (GH 1 is about 11.2 ka BP and GH 2 ~8.2 ka BP) of the Northern Hemisphere (Bjork et al. 1996, Alley et al. 1997, Bell and Walker 2005). The GH 2 event has been widely identified in lacustrine records in the Tibetan Plateau, such as in Zabuye Lake (Zheng et al. 2007) and Yang Lake (a terrace of

### Table 1: OSL dating and height of beach ridges around Selin Co.

| Line/sample No | Location (°E’/N°) | Altitude (m) | Height to lake (m)* | Equivalent dose (Gy) | Dose rate (Gy/ka) | Age (ka) | Materials | Beach ridge group | Climate stage |
|----------------|------------------|-------------|---------------------|----------------------|-----------------|----------|-----------|-----------------|--------------|
| SW-L1/07       | 88.66/31.70      | 4550        | 10                  | 16.6 ± 0.4           | 2.4             | 6.9 ± 0.2 | L-layer   | BG1             | Hypsithermal |
| SW-L1/05       | 88.67/31.70      | 4564        | 24                  | 8.0 ± 1.2            | 4.2             | 1.9 ± 0.3 | U-layer   | BG2             | Deglaciation |
| SW-L1/04       | 89.33/31.68      | 4571        | 31                  | 25.5 ± 1.4           | 2.8             | 9.2 ± 0.5 | L-layer   | BG2             | Deglaciation |
| SW-L1/03       | 88.67/31.69      | 4580        | 40                  | 20.6 ± 1.4           | 2.1             | 9.6 ± 0.7 | L-layer   | BG2             | Deglaciation |
| SW-L1/02       | 88.67/31.68      | 4586        | 46                  | 50.6 ± 2.7           | 1.9             | 27.4 ± 1.5 | L-layer   | BG3             | MIS 2        |
| SW-L1/01       | 88.68/31.68      | 4597        | 57                  | 56.9 ± 5.3           | 3.1             | 18.6 ± 1.7 | L-layer   | BG3             | MIS 2        |
| SE-L2/09       | 89.33/31.68      | 4571        | 31                  | 32.7 ± 4.1           | 2.6             | 12.5 ± 1.6 | L-layer   | BG2             | Deglaciation |
| SE-L2/10       | 89.34/31.68      | 4583        | 43                  | 82.3 ± 7.9           | 2.7             | 30.4 ± 2.9 | L-layer   | BG3             | MIS 2        |
| SE-L2/11       | 89.36/31.67      | 4598        | 48                  | 30.1 ± 0.5           | 3.2             | 9.6 ± 0.2  | U-layer   | BG3             | MIS 2        |
| SE-L2/12       | 89.38/31.67      | 4617        | 77                  | 4.8 ± 0.4            | 3.3             | 1.5 ± 0.1  | U-layer   | BG3             | MIS 3(2)     |
| SE-L2/13       | 89.41/31.67      | 4641        | 101                 | 227.4 ± 8.0          | 3.4             | 67.9 ± 2.4 | L-layer   | BG4             | MIS 4        |

* Calculated based on the current lake level of 4540 m above sea level (a.s.l.). SW, southwest side; SE, southeast side.
11 does produce a relatively older age of 9. Therefore, the OSL age from the upper aeolian sediment. Therefore, the OSL age from the upper aeolian layer can only provide a minimum age constraint but with very limited information about the ‘real’ age of the beach ridge.

### 4.2. Relationship with other environmental records

Four ice cores have been collected in the Tibetan Plateau—the Dunde, Guliya, Puruogangri, and Dasuopu ice cores (Thompson et al. 1997, 2000, 2006, Yang et al. 2006). The Puruogangri ice core, 300 km north of Selin Co, reveals that the influence of the South Asia monsoon could extend to >300 km north of Selin Co during the early Holocene (Thompson et al. 2000, 2006). The Guliya ice core, 800 km northwest of Selin Co, provides the longest local climate record covering the period to the late Pleistocene (>500 ka). Comparing OSL ages to the Guliya ice core record, the formation of beach ridges in Selin Co is well correlated to cold or wet climate events (figure 3, table 2). BG4 is within the early stage (75–58 ka) of the Last Glaciation (MIS 4). BG3 is related to the late stage (32–18 ka) of the Last Glaciation (MIS 2). The BG3 formation period overlaps with a plateau-wide high lake-level period of 40–28 ka (Li 2000). Traditionally, this period has been interpreted to represent an interglacial stage of the Last Glaciation (MIS 3). However, based on the fact that BG3 dates are fully overlapped with the late stage of the Last Glaciation in the Guliya ice core record, we believe that it is more reasonable to assign this as MIS 2. The interval between BG3 and BG4 is

![Figure 3. Correlation between beach ridges of Selin Co and the Guliya ice core record.](image-url)

**Table 2.** Chronological correlation of beach ridges in Selin Co with other environmental records (ka BP).

| Proxies       | Locations                  | BG1          | BG2          | BG3          | BG4          | References                        |
|---------------|----------------------------|--------------|--------------|--------------|--------------|-----------------------------------|
| Beach ridge   | Selin Co                  | 6.9 ± 0.1    | 12.5–9.2     | 30.4–18.6    | 67.9 ± 0.5   | This study                        |
|               | Yang Lake                  | 8.5 ± 0.7    | 13.1–11      | 40–28        | 72.1 ± 5.5   | Dai (2002)                        |
|               | Tibet and Qinghai         | 9–5          | 13–11        | 19–15        | 75–58        | Jia et al (2001a)                 |
| Ice core      | Guliya                     | 16–10        | 32–18        | 21–24        | >41          | Thompson et al (1997)             |
| Himalaya moraines | South slope              | 10.1 ± 0.4   | 23.9 to 17   | >27–24       | 68.1         | Owen et al (2009b)                |
|               | North slope                | 7.1–6.8      | 17–14(?)     | >27–24       | >41          | Owen et al (2009b)                |
| Terrace       | Tultanhuja river           | 5.4 ± 0.4    | 12.1 ± 0.8   | 68.4 ± 5.2   | Zhang (2003) |
|               | Yajiquan river             | 5.7 ± 1.3    | 10.4 ± 1.6   | 46.4 ± 5.3   | Li (2003)    |
|               | Yajiquan river             | 6.5          | 12.8         | 57.5         | Chang et al (2005)                |
|               | Ateatekan river            | 12.6         | 22 ± 1       |             | Jia (2002)    |
|               | Kunlan river               | 10.9         | 22 ± 1       |             | Jia (2002)    |
|               | Hatu river                 | 11.4         | 22 ± 1       |             | Jia (2002)    |
|               | Halaguole river            | 10.4         | 22 ± 1       |             | Jia (2002)    |
|               | Jinshui river              | 5.7 ± 0.4    | 22 ± 1       |             | Jia (2002)    |

OSL: Age determined by OSL, TL: Age determined by TL. a14C. c Others. e10Be.

8.5 ± 0.7 ka BP determined by TL (Dai 2002). This suggests that lakes across the northern and central Tibetan Plateau had similar lake-level fluctuations during this period.

The lowest group (BG1) is about 4550 m a.s.l. (≈10 m above the current lake level). One sample (07) produces an age of 6.9 ± 0.2 ka, corresponding to the Holocene Hypsithermal (about 6 ka BP). This event is widely identified in various environmental records in the Northern Hemisphere, for example a wet event around the Mediterranean Sea (Bell and Walker 2005) and southern Sweden (Harrison and Digerfeldt 1993) during the early/middle Holocene and the expansion of lakes in North America (Webb et al. 1993). All samples taken from the upper aeolian layer produce significantly younger ages than their corresponding beach ridge groups. Sample 05 from BG2 produces an age of 1.9 ± 0.3 ka, much younger than OSL ages measured from beach ridges (9.2 ± 0.5 to 12.5 ± 1.6 ka). Sample 12 from BG3 produces a similar age of 1.5 ± 0.1 ka as sample 05, whereas it is significantly younger than corresponding OSL ages from beach ridge sediment (18.6 ± 1.7 to 30.4 ± 2.9 ka). Sample 11 does produce a relatively older age of 9.6 ± 0.2 ka, but this is still younger than corresponding ages measured from beach ridge sediment (18.6 ± 1.7 to 30.4 ± 2.9 ka). This is probably caused by the time-lag of the aeolian activity or the alternation of erosion and deposition of the upper aeolian sediment. Therefore, the OSL age from the upper aeolian layer can only provide a minimum age constraint but with very limited information about the ‘real’ age of the beach ridge.
about 37.5–49.2 ka, roughly corresponding to a 43 ka cycle (Shi et al 2006) in the ice core record, and the difference between the start time of BG2 and BG3 is about 20 ka, likely corresponding to a 20 ka cycle (Shi et al 2006). Although BG2 (12.5–9.2 ka) is warmer than MIS 2, it is still a colder period, during which the cold and dry YD Event (11–10 ka BP) has been revealed by at least 20 study sites over the Tibetan Plateau (Shen et al 1996). The BG1 age corresponds to the Holocene Hypsithermal, the wettest period in the Holocene. In general, the formation of beach ridges around Selin Co is correlated to cold (for BG 4, 3, and 2) or wet climate (for BG1) events indicated by regional ice core records.

OSL dating of beach ridges in Selin Co correlates well with glacial fluctuations recorded from the southern Tibetan Plateau and the Himalayas, where climate is controlled by the South Asia monsoon. TCN and OSL dating of glacial deposits (Owen et al 2009b) reveals at least six stages of glacier advances/standstills in the Rongbuk Valley on the north slope of Mount Everest. Two stages, Jilong (24–27 ka BP) and Samdupo (7.1–6.8 ka BP), are correlated with BG3 (MIS 2) and BG1 (Hypsithermal) of Selin Co. Owen et al (2009b) also re-calculated past TCN and OSL dates from the south slope of Mount Everest. New chronology indicates three glacial advance/standstill stages of 68.1, 23.9–17, and 10.1 ± 0.4 ka, corresponding to BG4, BG3, and BG2 respectively.

He dating (Gayer et al 2006) showed that glaciers of the Mailun Valley in central Nepal were stabilized until ~7 ka BP, corresponding to BG1. These data suggest that the formation of beach ridges in Selin Co is synchronous with glacial advances/standstills in the southern Tibetan Plateau and Himalayas since the Late Glaciation, dominated by the South Asia monsoon. This indicates that the influence of the South Asia monsoon extended to the central and northern Tibetan Plateau during the Last Glaciation, agreeing well with the conclusion from the Puruogangri ice core record (Thompson et al 2000, 2006).

There is a long-standing debate about the origins (climate versus tectonic) of the fluvial terraces in the Tibetan Plateau (Chang et al 2005). Table 2 lists some terraces in the northern Tibetan Plateau. It seems there are good correlations between the formation period of fluvial terraces and beach ridges in Selin Co. Terrace T3 of the Tulanhujia River is 68.4 ± 5.2 ka, corresponding to the formation period of BG4. Terrace T2 (22 ± 1 ka) of Jinshui River is correlated to the BG3 period. Some terraces were formed during BG2, for instance the Tulanhujia (T2, 12.1 ± 0.8 ka), Yaziquan (T2, 10.4 ± 1.6, 12.5 ka), Ateakan (T3, 12.6 ± 0.9 ka), Kunlun (T2, 10.9 ± 0.5 ka), Hatu (T3, 11.4 ± 1.3 ka), and Halagoule (T2, 10.4 ± 1.4 ka) rivers (Wang 2003). The T1 terraces of the Tulanhujia, Yaziquan, and Jialu rivers are about 5.4 ~ 6.5 ka, approximately corresponding to the BG1 period. In conclusion, there exists synchronism between beach ridges and fluvial terraces in the northern Tibetan Plateau. Therefore, it seems that climate is the common agent for the development of both beach ridges and fluvial terraces. This provides an additional means to evaluate the role of tectonic and climatic influences in the formation of fluvial terraces and offers a new approach for identifying and separating origins for different fluvial terraces.

The formation of beach ridges requires a stable lake level combined with adequate sediment supply, lateral current and gentle relief (Tanner 1995b). It is expected that both cold and wet climates would lead to an increase in glacier area and volume. In detail, long-term glacier advance/standstills should form till deposits of great dimensions, and lead to increases of both water and sediments in the river system. Such hydrologic and sedimentary conditions have favored the development of beach ridges and the filling of river valleys. Once glaciers retreated, the established equilibrium broke and corresponding landforms such as terraces, beach ridges and moraines were formed. This hypothesis is supported by the beach ridge data in Selin Co. These beach ridges were mainly formed during periods of cold events such as MIS4, MIS2, YD or wet events such as the Holocene Hypsithermal, when glaciers advance or stand still. Owen et al (2009b) and Gayer et al (2006) suggested that glacial fluctuations in the Himalayas were controlled by fluctuation of global temperature during the Late Pleistocene, whereas since the Holocene control has been by change in annual precipitation. This trend is consistent with the formation of beach ridges in Selin Co, indicating that different geographical units such as lakes, glaciers and rivers have similar responses to climate change.

4.3. Lake-level fluctuations

OSL dating of beach ridges suggests that lake level in Selin Co has continually dropped since the Last Glaciation; a similar trend has been identified from other lakes across the Tibetan Plateau. Based on measured beach ridge elevations and the 90 m shuttle radar topography mission (SRTM) DEM (http://srtm.csi.cgiar.org), lake surface areas for different BGs have been interpreted. Results indicate that the lake surface area was about 5.7 times bigger than the current lake area during the formation of BG4 (67.9 ± 2.4 ka, MIS 4). Then, it dropped continually to 3.0–4.0 times the current lake surface area during the formation of BG3 (30.4 ± 2.9 to 18.6 ± 1.7 ka, MIS 2), 2.6–2.8 times during the formation of BG2 (12.5 ± 1.6 to 9.2 ± 0.5 ka) and 1.3–1.5 times during the middle Holocene (BG1, 6.9 ± 0.2 ka) (figure 4). This reflects a trend of continuous drying of this area since the Last Glaciation. However, we also find an anomaly. On the southwestern coast, the highest beach ridge dated from sample 01 (18.6 ± 1.7 ka) is about 10 ka younger than the nearby lower beach ridge of sample 02 (27.4 ± 1.5 ka). A similar anomaly was also reported in other lakes. For example, Jia et al (2003) reported that lake level during the last glacial maximum (LGM) (15.5 ± 1.2 ka) was higher than old lake level formed about 24 ka BP from Zigetang Co (~130 km east of Selin Co).

Sample 01 and 02 were taken from two close parallel beach ridges, both of them well-preserved. The reversed age pattern suggests the possibility that a beach ridge can be formed at a higher lake level without destroying older beach ridges. Comparison between the field GPS recorded shoreline (June, 2008) and the shoreline identified from the Landsat ETM image of September 1999 indicates that the shoreline advances outward about 400–500 m and lake level rises about 4 m on the southwest coast. The lowest group of beach
Figure 4. Lake-level fluctuations of Selin Co since the Last Glaciation: (a) MIS 4 (BG4); (b) MIS 2 (BG3); (c) Deglaciation (BG2); (d) Holocene Hypsithermal (BG1); and (e) current lake level.

ridges identified from the satellite image of September 1999 has been submerged under the current water level. This lake-level variation is probably due to dry and wet seasons, but most likely reflects the fact that glacial meltwater (Yao et al. 2007) and precipitation (Li et al. 2007) have significantly increased in central Tibet in the last decade because of global warming. The possibility of preserving old low lake-level beach ridges provides a unique opportunity to identify more complicated climate signals by dating all beach ridges in this area. However, since we just have one sample date for this anomaly, it may also indicate an error in OSL dating and further study is necessary.

5. Conclusions

OSL dating of four beach ridge groups provides improved understanding of the formation of beach ridges and lake level–climate interaction in Selin Co, central Tibet, since the Last Glaciation. These four ridge groups were most likely formed during cold or wet climate periods and correspond to MIS 4 (67.9 ± 2.4 ka), MIS 2 (30.4 ± 2.9 to 18.6 ± 1.7 ka), deglaciation (12.5 ± 1.6 to 9.2 ± 0.5 ka) and Holocene Hypsithermal (6.9 ± 0.2 ka) stages, with a height of >100, 40 to 60, 30 to 40, and 10 m above the current lake level, respectively. The development of beach ridges in the central Tibetan Plateau since the early stage of the Last Glaciation further supports that no plateau-scale ice sheet covered the Tibetan Plateau during the Last Glaciation.

The formation periods of beach ridges are almost synchronous with advances or standstills of Himalayan glaciers, indicating similar climate controls across the central and southern Tibetan Plateau. This is consistent with the evidence obtained from nearby ice core records that this area is affected by the South Asia monsoon. Furthermore, beach ridges are also synchronous with fluvial terraces in the northern
Tibetan Plateau, implying common driving forces during their formation. Therefore, some fluvial terraces may be formed as a result of climate events rather than being of tectonic origin.

Lake level has continually dropped since the Last Glaciation, representing a trend of continuous drying in this area since then. However, an anomaly is observed indicating the possibility of preserving low lake-level old beach ridges that have not yet been destroyed during the formation of late high lake-level beach ridges. It may be possible to identify more complicated climate signals if all these beach ridges can be dated. This requires more detailed studies in the future.

Acknowledgments

This study is supported by the Natural Sciences Foundation of China (NSFC 40771029, 40971013, 40730101) and the Research Board of the University of Missouri, grant no. RB 07-50. We thank two anonymous reviewers for valuable comments which helped to improve this manuscript. We also appreciate suggestions and discussions provided by Professors Liping Zhou and Zhongping Lai.

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