Full length article

Luminescence chronology and palaeoenvironmental significance of limnic relics from the Badain Jaran Desert, northern China

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ARTICLE INFO

Keywords:
Badain Jaran Desert
Limnic relics
Late Quaternary
K-feldspar pIRIR dating
Quartz OSL dating

ABSTRACT

The Badain Jaran Desert in northern China is well known for the highest mega-dunes on Earth and unique alternating megadune–lake landform, and various formation mechanisms have been proposed. Although the relics of interdune lakes are generally considered as good palaeoenvironmental records, their evolutions and relevance to palaeoenvironment change are poorly understood due to limited age control. In this study, quartz optically stimulated luminescence (OSL) and K-feldspar post-infrared infrared stimulated luminescence (pIRIR) were used to establish a chronological framework for limnic relics in order to reconstruct the evolution of interdune lakes. Our results indicate that limnic relics were deposited in MIS 5 and MIS 1, due to a lake level transgression and humid environmental condition. During the Holocene, humid conditions occurred at early to middle Holocene, immediately preceded and followed by aridity. The last 600 years have been characterized by high rates of aeolian activity. Based on field observation and luminescence ages, we propose that climate fluctuations since the Late Pleistocene have played a pivotal role in the formation of the unique landform assemblages.

1. Introduction

The Badain Jaran Desert (BJD) in northern China contains the highest megadunes on Earth and a unique alternating megadune–lake landscape. At the present day, the region is in the transitional zone between the Asian summer monsoon and the Westerlies, and the desert environment is influenced by both wind systems (Chen et al., 2008). Several mechanisms have been proposed for the formation of the alternating megadune–lake landscape, including control of underlying morphology (Lou, 1962; Sun and Sun, 1964; Tan, 1964), climate changes which leads to fixation, reactivation and ultimate formation of megadunes (Wang, 1990; Dong et al., 2004), groundwater which maintains the mega-dune landscape (Chen et al., 2004a), and wind erosion to form interdune lake basins during arid periods (Wang et al., 2016b). The influence of climate change has been studied extensively in recent years and it is now regarded as one of the key megadune–lake formation factors (Yang, 2000, 2001; Yang and Williams, 2003; Yang et al., 2003, 2010; Li et al., 2015b, 2015c; Wang et al., 2015, 2016a; Liu et al., 2016).

Previous chronological studies have shown that the climate of the BJD fluctuated at both orbital and millennial scales since the Late Pleistocene (Fig. 1). Yan et al. (2001a, 2001b, 2001c) dated a fossilized
The Holocene, based on 14C dating of various materials from interdune suggested that lakes in and adjacent to the study area expanded during acted as a cementing agent in dune construction. Several studies have megadune growth periods took place in humid climate, when water sand layers in the dune hills, Liu et al. (2016) proposed that main patterns based on optically stimulated luminescence (OSL) ages of wet dated to 7–2015b, 2015c). The results revealed that ∼62% of the Holocene samples were dated to 7–5 Cal ka BP and ∼38% were dated to 4–2 Cal ka BP over the Alxa Plateau, while in the BJD all Holocene samples were dated to 7–5 Cal ka BP (Li et al., 2015c). In a study of megadune growth patterns based on optically stimulated luminescence (OSL) ages of wet sand layers in the dune hills, Liu et al. (2016) proposed that main megadune growth periods took place in humid climate, when water acted as a cementing agent in dune construction. Several studies have suggested that lakes in and adjacent to the study area expanded during the Holocene, based on 14C dating of various materials from interdune palaeolake sediments (Yang and Williams, 2003; Yang et al., 2003, 2010, 2011; Yang and Scuderi, 2010; Hartmann and Wünnemann, 2009; Li et al., 2010; Wang et al., 2016a). OSL dating of lacustrine sediments demonstrated the existence of lakes during MIS5 (Bai et al., 2011; Fan et al., 2014), while a drill core from the eastern shore of Lake Ximuertu, a salt lake in the centre of the BJD, suggests that the area was lake dominated during MIS5, but with increased aeolian activity (Wang et al., 2015).

Previous studies in the BJD have shown that the area experienced dramatic environmental changes during the Late Quaternary. However, the interdune lake evolution in the BJD remains unknown, partly because the strong wind erosion has resulted in gaps in the sedimentary records and the scattered interdune lake basins were also strongly influenced by the fast migration of the sands around the lake basins. Additionally, most of the reported chronologies have used 14C dating as the primary dating method, which is only useful for deposits younger than ∼45 ka (Pigati et al., 2007), even only useful within ∼20 ka when using inorganic materials from arid areas in which case ages older than 25 ka are saturated (Lai et al., 2014; Song et al., 2015). The other reported chronologies rarely cover MIS5 and are also limited and unsystematic (Fig. 1). The situation of limited age control hinders the understanding of the evolution and palaeoenvironmental significance of interdune lakes in the BJD. This study provides a chronology of lacustrine sediments, based on 21 ages from seven profiles in lake shorelines and limnic relics, which allows a more systematic and nuanced analysis of their palaeoenvironmental significance and evolution in the Late Pleistocene.

2. Geological and physiographical setting

The BJD lies on the western part of the Alxa Plateau in northern China, covering an area of ca. 5.22 × 10^4 km^2 (Zhu et al., 2010). The BJD is surrounded by mountains on three sides (Fig. 2), with the Heli, Beida and Longshou mountains to the south and the Zongnai Mountains to the east. In the southeast, the Yabulai Mountains separate the Baidan Jaran from the Tengger Desert. To the west and north is the alluvial/lacustrine plain formed by the Heihe River in which Gurinai Oasis located (Wang et al., 2015). The elevation of the BJD gradually decreases from approximately 1800 m in the southeast to 1000 m in the northwest (Dong et al., 2004). Lying at the northwestern range of the East Asian Summer Monsoon (EASM), the region is characterized by the typical arid landscape of the monsoon–westerly wind transitional zone (Chen
et al., 2003), and is sensitive to climate change. At the present day, the climate of the BJD is classified as extreme continental, with cold winters and very low precipitation (< 90 mm, mainly falling from June to August and decreasing from the southeast to the northwest). Annual potential evaporation (> 2500 mm) and mean annual temperature (9.5–10.3 °C) increase from south to north as elevation decreases. Mean annual wind speed, which ranges from 2.8 to 4.6 m s$^{-1}$, also increases from south to north, with the strongest winds in April and May (Dong et al., 2004). Based on a modified Penman Equation approach, combined with weather data from CE 1961 to 2001 from the margins, Yang et al. (2010) re-estimated the mean annual evaporation from lake surfaces and dune slopes in the BJD, and suggested that the mean annual evaporation is ca. 1040 mm from the lake surface and ca. 100 mm from land surfaces in the southeastern part of the desert. Both of the values are much lower than previously published in literature. The dominant winds are from the northwest, northeast, and southwest (Zhang et al., 2015).

The BJD is known for the highest megadunes in the world and its unique alternating megadune–lake landscape. Dong et al. (2004) estimated that over 60% of the desert is occupied by megadunes, of which 42.1% are > 300 m high, 38.2% between 200 and 300 m and 19.7% < 200 m. The primary dune types are compound transverse and compound star (Dong et al., 2004). The tallest megadune, Bilutu Peak, is a compound transverse dune with a height of ~450 m (Liu et al., 2016). Currently there are more than 100 lakes in the BJD (Zhu et al., 1980; Yang et al., 2010; Wang et al., 2016a), with a total area of about 22.30 km$^2$ including six exceeding 1 km$^2$ and 46 between 0.1 and 1 km$^2$ (Yang et al., 2010). Most of the lakes are concentrated in the southeast of the desert (Fig. 2). The interdune depressions contain a large number of seepage lakes with no surface runoff, which vary considerably in terms of area and salinity (Hofmann, 1996; Yang and Williams, 2003).
3. Profiles and luminescence dating sampling

For this study, detailed ground survey and luminescence dating sampling was conducted over a three-year period in the southeastern BJD (Fig. 2). This area was chosen for study as it is where the highest concentration of lakes occurs. The main types of sediment in the southeastern desert include aeolian, sinter, gyttja and lacustrine. Field observations and interpretation of shorelines in ETM+ imagery by Yang et al. (2010) showed the areas of lake surface have been significantly expanded in the past, and some completely desiccated at present. We sampled sediments associated with past lakes, found on palaeoshorelines and in dry lake basins, to provide evidence of paleoenvironmental changes. 21 luminescence samples were collected from seven sections from different lake basins to provide a systematic chronology (Fig. 3).

The Yindeertu Lake (YDE) section (Fig. 3a) was located at the east shoreline of the lake, in the southeastern BJD (Fig. 2), which covers an area of 1.57 km². The YDE section mainly comprises of aeolian vegetation sand dune, dark brown swamp (gyttja) and caesious lacustrine sediments (Fig. 6). The Tonggutu playa (TGT) section (Figs. 3b and 6) was located on a quasi-sinter platform of the playa, near the southern edge of the BJD (Fig. 2). The section is mainly composed of sinter (covered on the top) and lacustrine sediments. Sections WMJL-1 and WMJL-2 are located at Womenjilin playa (Fig. 2). The WMJL-1 section (Fig. 3g) is mainly composed of vegetated dune sand and lacustrine sediments (Fig. 6). The WMJL-2 section (Fig. 3d) is mainly composed of lacustrine sediments (Fig. 6). Sections XNRT-1 and XNRT-2 are located in the east of Xinuooertu playa (Fig. 2). Section XNRT-1 (Fig. 3f) comprised sinters overlying alternating caliche and lacustrine sediments. Section XNRT-2 (Fig. 3e) was located about 50 m above water level and the OSL sample was obtained from well-cemented lacustrine sediment at a depth of 30 cm (Fig. 6). The BLT section (Fig. 3c) was located northwest of Bilutu Lake, which is separated from Yindeertu Lake by Bilutu Peak (Fig. 2) and mainly composed of caesium lacustrine sediments with some rusty stripes (Fig. 6). More detailed information of all the aforementioned sections and the sampling depths in each section are listed in Table 1 and shown in Fig. 6. Large and clear figures for each section in Fig. 3 are provided online as supplementary materials (Figs. S1–S7).

All samples were collected by hammering steel tubes into freshly cleaned vertical sections (dug to a depth of original sediments). The tubes were then covered with aluminium foil, sealed with opaque tape and wrapped with a black plastic bag to avoid light exposure.

4. Luminescence dating

4.1. Sample preparation and measurement techniques

In the luminescence dating laboratory of Qinghai Institute of Salt Lakes, Chinese Academy of Sciences, the unexposed middle part of each OSL tube was used to extract quartz and potassium feldspar (K-feldspar) for equivalent dose (Dq) determination under red light. Samples from the middle part of the tubes were treated with 10% HCl and 30% H2O2 to remove carbonates and organics, respectively. Grain-size fractions of 38–63 or 90–125 μm was extracted by wet sieving upon availability. Heavy liquids with densities of 2.62, 2.75, and 2.58 g/cm³ were used to separate the quartz and K-feldspar for 90–125 μm fraction. The 38–63 μm fraction was etched by 35% H3SiF6 for about two weeks to remove feldspars (Lai and Wintle, 2006; Lai et al., 2007a; Roberts, 2007). The 90–125 μm fraction was treated with 40% HF for 45 min to remove feldspars and the alpha-irradiated outer layer (~10 μm). The treated quartz grains was washed with 10% HCl to remove fluoride precipitates. The purity of quartz grains was checked by infrared (830 nm) stimulation, and any samples with obvious infrared stimulated luminescence signals were retreated with H3SiF6 or HF to remove feldspar contamination and avoid Dq underestimation (Duller, 2003; Lai and Brickner, 2008). The pretreated grains were then mounted on the centre (~0.7 cm diameter) of stainless steel discs (~0.97 cm diameter) with silicone oil. Material at the tube ends was reserved for measurement of U, Th and K concentrations by neutron activation analysis in the China Institute of Atomic Energy in Beijing. The elemental concentrations were converted into an annual dose rate according to Aitken (1985). For the 36–63 μm grains, the alpha efficiency value was taken as 0.035 ± 0.003 (Lai et al., 2008). The cosmic ray dose rate was estimated for each sample as a function of depth, altitude and geomagnetic latitude (Prescott and Hutton, 1994). For K-feldspar dose rates, a K concentration of 12.5 ± 0.5% and Rb concentration of 400 ± 100 ppm was assumed (Huntley and Baril, 1997). A water content of 20 ± 5% was used to calculate ages for Holocene paleolake shoreline sediments given that a generally stable lake environment existed in most periods of the Holocene, based on a previous study in adjacent areas (Li et al., 2017). A water content of 15 ± 5% was used as the life-average water content for MIS5 and MIS3 limnic relic samples, given that a dry environment resulted in a reduced water content during the last glacial period (Li et al., 2017). For samples from current sand dunes, a water content of 10 ± 5% was used to calculate ages based on a previous megadune study (Liu et al., 2016). The dosimetry data for quartz OSL and K-feldspar pIRIR dating of all samples are shown in Table 2.

All the measurements were carried out on an automated Riso TL/OSL-DA-20 reader equipped with blue diodes (λ = 470 ± 20 nm) and IR diodes (λ = 830 nm). Luminescence was stimulated by blue LEDs at 130 °C for 40 s, and detected with a 7.5 mm thick U-340 filter (detection window 275–390 nm) in front of the photomultiplier tube.

4.2. Luminescence characteristics and Dq determination

Preheat plateau tests were conducted on samples YDE-2 (gyttja) and YDE-5 (lacustrine sediments), and a preheat plateau was clearly identified from 240 to 280 °C in both samples (Fig. 4a and d). Preheat was at 260 °C for 10 s for natural and regenerative doses, and second preheat was at 220 °C for 10 s for test doses. Signals of the first 0.64 s stimulation were integrated for growth curve construction after background subtraction (last 10 s).

The SAR-SGC method (Lai and Ou, 2013), a combination of SAR protocol (Murray and Wintle, 2000) and the Standard Growth Curve (SGC) method (Roberts and Duller, 2004; Lai, 2006; Lai et al., 2007a, 2007b; Yu and Lai, 2012), was employed to determine the equivalent

Table 1

<table>
<thead>
<tr>
<th>Sections</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
<th>Typing of section lithology</th>
<th>Above modern basin floor (a.m.h.f) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YDE</td>
<td>39°50’57.9&quot;</td>
<td>102°27’13.1&quot;</td>
<td>1193</td>
<td>Shorelines around modern lake basin</td>
<td>20</td>
</tr>
<tr>
<td>BLTsu</td>
<td>39°50’33.18&quot;</td>
<td>102°29’30.1’9&quot;</td>
<td>1211</td>
<td>Shorelines above modern lake basin</td>
<td>15</td>
</tr>
<tr>
<td>XNRT1</td>
<td>39°57’15.48&quot;</td>
<td>102°50’23.26&quot;</td>
<td>1160</td>
<td>Shorelines above modern lake basin</td>
<td>20</td>
</tr>
<tr>
<td>XNRT2</td>
<td>40°10’54.72&quot;</td>
<td>101°44’48.06&quot;</td>
<td>1160</td>
<td>Shorelines above modern lake basin</td>
<td>15</td>
</tr>
<tr>
<td>TGT3</td>
<td>39°34’49.42&quot;</td>
<td>102°25’48.86&quot;</td>
<td>1224</td>
<td>Quasi-sinter platform around shorelines of dried lake basin</td>
<td>15</td>
</tr>
<tr>
<td>WMJL2</td>
<td>39°57’15.48&quot;</td>
<td>101°50’22.26&quot;</td>
<td>1211</td>
<td>Shorelines around dried lake basin</td>
<td>3</td>
</tr>
<tr>
<td>WMJL1</td>
<td>39°35’9.9&quot;</td>
<td>102°17’1.26&quot;</td>
<td>1210</td>
<td>Dried lake basin</td>
<td>2</td>
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</tbody>
</table>
In this study, an individual SGC was constructed for each sample based on the average of the growth curves which were measured with the SAR protocol. Twelve aliquots were then measured to obtain the values of test-dose-corrected natural signals only, and each of the values was matched in the SGC to obtain a De. For all samples, the final De is the mean of all SAR Des and SGC Des. Fig. 5b and d show typical OSL decay curves for YDE-2 and YDE-5, respectively, which indicate that the OSL signals were from the fast component. Fig. 5a and c show the growth curves of samples YDE-2 and YDE-5, respectively.

Dose recovery tests (Murray and Wintle, 2003), which can validate the SAR procedure, were performed on samples YDE-2, and YDE-5, and six aliquots of each sample were tested. The ratios of the average measured dose (13.90 Gy and 97.84 Gy) to the given dose (14.90 Gy and 105.90 Gy) suggested that the SAR protocol is suitable for De determination in this study.

Recuperation was calculated by comparing the sensitivity-corrected OSL signal of 0 Gy to the sensitivity-corrected natural signal to check the thermo-transferred signals. In this study, recuperations for different preheat temperatures were less than 2% of the natural signal, which is negligible (Fig. 4c and f). The ‘recycling ratio’ was introduced to check

<table>
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<tr>
<th>Sample ID</th>
<th>Elevation (m)</th>
<th>Depth (cm)</th>
<th>Grain size (μm)</th>
<th>K (%)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
<th>Water content (%)</th>
<th>De (Gy)</th>
<th>Dose rate (Gy/ka)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YDE-1</td>
<td>1193</td>
<td>35</td>
<td>90–125</td>
<td>1.51 ± 0.05</td>
<td>4.10 ± 0.14</td>
<td>1.13 ± 0.06</td>
<td>10 ± 5</td>
<td>0.96 ± 0.15</td>
<td>2.06 ± 0.14</td>
<td>0.47 ± 0.08</td>
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<td>90–125</td>
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<td>4.46 ± 0.16</td>
<td>1.48 ± 0.07</td>
<td>20 ± 5</td>
<td>15.90 ± 0.51</td>
<td>1.92 ± 0.13</td>
<td>8.30 ± 0.61</td>
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<td>YDE-3</td>
<td>1193</td>
<td>110</td>
<td>90–125</td>
<td>1.72 ± 0.06</td>
<td>5.68 ± 0.19</td>
<td>1.20 ± 0.06</td>
<td>20 ± 5</td>
<td>17.92 ± 0.71</td>
<td>2.06 ± 0.14</td>
<td>8.72 ± 0.68</td>
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<td>5.62 ± 0.19</td>
<td>1.50 ± 0.07</td>
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<td>21.18 ± 1.12</td>
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<td>3.17 ± 0.11</td>
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<td>106.03 ± 2.70</td>
<td>2.30 ± 0.15</td>
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<td>30</td>
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<td>2.93 ± 0.13</td>
<td>1.29 ± 0.07</td>
<td>15 ± 5</td>
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<td>1.74 ± 0.12</td>
<td>95.45 ± 8.46</td>
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<td>4.72 ± 0.17</td>
<td>7.01 ± 0.19</td>
<td>20 ± 5</td>
<td>207.64 ± 9.02</td>
<td>2.14 ± 0.13</td>
<td>116.83 ± 9.46</td>
</tr>
<tr>
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<td>30</td>
<td>38–63</td>
<td>2.05 ± 0.06</td>
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<td>4.73 ± 0.15</td>
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<td>16.44 ± 0.19</td>
<td>3.45 ± 0.24</td>
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<td>1.54 ± 0.05</td>
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<td>163.38 ± 6.23</td>
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<td>264.64 ± 12.11</td>
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<td>6.45 ± 0.17</td>
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<td>13.77 ± 0.29</td>
<td>3.32 ± 0.23</td>
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<td>7.55 ± 0.22</td>
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<td>1.30 ± 0.07</td>
<td>20 ± 5</td>
<td>1.94 ± 0.10</td>
<td>1.94 ± 0.13</td>
<td>0.53 ± 0.06</td>
</tr>
<tr>
<td>WMLJ2-2</td>
<td>1210</td>
<td>100</td>
<td>90–125</td>
<td>1.50 ± 0.05</td>
<td>4.20 ± 0.15</td>
<td>1.47 ± 0.07</td>
<td>15 ± 5</td>
<td>1.41 ± 0.06</td>
<td>2.34 ± 0.17</td>
<td>0.60 ± 0.05</td>
</tr>
</tbody>
</table>

![Fig. 4. Results of preheat plateau tests, recuperation and recycling ratio for YDE-2 (left) and YDE-5 (right). The equivalent dose (De) of each data point is the mean of four aliquots. The final chosen preheat temperature for quartz OSL dating in this study was 260 °C.](image-url)
for sensitivity change correction (Murray and Wintle, 2000), and for most aliquots, the recycling ratios fall into the acceptable range of 0.9–1.1 (Fig. 4b and e). The details of K-pIRIR dating were provided as supporting information (Appendix S1) due to the word limitation.

4.3. Dating results

Sample ages were obtained by dividing $D_0$ by the dose rate. The calculated ages for all samples are listed in Table 2. The $D_0$ values of samples from section TGT3 and XNRT2-1 are close to or larger than the 2$D_0$ values ($D_0$ refers to the characteristic saturation dose). This means their quartz OSL ages are close to or beyond the saturation level. In order to avoid the underestimation and check the reliability of the chronologies, K-pIRIR dating was also applied on sample YDE-3, YDE-5 and XNRT2-1. We also tried to obtain the K-pIRIR ages of TGT3 section, but failed to extract enough K-feldspar to measure. As a result, the calculated quartz OSL ages are used as minimum ages for this section. The $D_0$s of YDE-3 and YDE-5 are less than their 2$D_0$ values, which representing unsaturated ages. The results showed that the quartz OSL age of sample YDE-3 is similar to the K-pIRIR age within the error, while the quartz OSL ages of sample YDE-5 and XNRT2-1 are younger than their K-pIRIR ages.

Although the OSL $D_0$s of XNRT2-1 and BLThu1-1 are almost the same, their $D_0$ values are very different. The OSL $D_0$ of BLThu1-1 (166.51 ± 8.94 Gy) is less than its 2$D_0$ value (~240 Gy), while the OSL $D_0$ of XNRT2-1(163.38 ± 6.23 Gy) is beyond the 2$D_0$ value (~128 Gy). This is why the OSL age of XNRT2-1 was regarded as minimum, while the OSL age of BLThu1-1 was accepted and not regarded as minimum in the study. Consequently, the aforementioned reliable ages are used to discuss the environmental conditions.

As shown in Fig. 6, the ages of lacustrine sediments, gyttja and aeolian sediments in the BJD concentrate mainly in the early and middle Holocene and MIS3. In this study, only two samples were quartz OSL dated to MIS3. The quartz OSL age of XNRT2-1 is saturated and K-pIRIR dated to MIS5, while the quartz OSL age of YDE-5 is unsaturated and also K-pIRIR dated to MIS5. This severely limited our discussion about the paleoenvironment during MIS3 in the BJD. Thus, the palaeoenvironment during MIS3 in the BJD still need further study.

5. Discussion

The occurrence of lacustrine and gyttja deposits in the YDE section (Fig. 3a) demonstrate that the area wetlands was much larger in the past, indicating a more humid environment in the region. The hiatus between caesious lacustrine sediments and dark brown gyttja implies an abrupt change in environmental conditions, which might be related to aeolian and lacustrine geomorphic dynamics. Drier conditions prevailed during the hiatus, leading to an increase in aeolian activity that not only terminated sedimentation in the section, but also initiated the wind erosion of previous sediments. The loss of material through erosion explains why the ages of 8.3 ± 0.6 ka and 73.4 ± 2.6 ka cannot represent the end time of the humid environment while the age of...
10.7 ± 0.9 ka can feasibly represent the start time of the humid environment (it also represents the end time of the dry environment). The age of 0.5 ± 0.1 ka, obtained from dune sand at the top of the section, represents the most recent activation of aeolian sand.

In sections WMJL and XNRT1 (Fig. 3c–e), the lacustrine chronology demonstrates that the two playas were much larger in area than today between 7.0 ± 0.5 to 3.6 ± 0.3 ka. The ages from lacustrine and gyttja deposits in the middle part of section YDE and sections WMJL and XNRT1 suggest that the BJD environment was humid during the early and middle Holocene (10.7 ± 1.0 to 3.6 ± 0.3 ka). The ages from the top part the YDE and WMJL1 sections (Fig. 3a and c), which is mainly composed of vegetated dunes or modern aeolian sediments, indicate high rates of aeolian activity during the last 600 years. The age of 0.5 ± 0.1 ka from the top of the lacustrine unit in the WMJL1 section (Fig. 6) was discarded as it was so close to the lacustrine surface that the luminescence signal was bleached by the sunshine and also mixed by the covered aeolian sand. This is roughly consistent with historical records within the Ejina Basin, which is near the BJD, was dry from the end of the Yuan Dynasty (1271–1368 CE) to the beginning of the Ming Dynasty (1368–1644 CE) (Liu, 1992), and also roughly consistent with the absence of shoreline features dating to younger than ~0.8 ka implies the Gaxun Nur paleolake dried up after ~0.8 ka, with only seasonal lakes remaining in the basin (Li et al., 2017). The high rates of aeolian activity during the last 600 years are also in accordance with the relatively dry periods revealed from a 2000 year geochemical record from the BJD (Ma et al., 2009).

Palaeolimnological relics indicative of a widespread humid palaeoenvironment appeared in the desert. Usually the more weakly cemented materials on the margins of the lake are more easily eroded by wind, leaving the more well-cemented component in situ. Shorelines representing high lake levels associated with humid climate stages are preserved around current lakes and some were dated by luminescence. In section XNRT2, lacustrine terraces composed of silty-fine sand (Fig. 3e) represent a humid palaeoenvironment around 137 ± 9 ka. Caesious lacustrine sediments at the bottom of the YDE section (Fig. 3a) formed before 73 ± 3 ka. Hence, the age shows that lacustrine sediments in sections XNRT2 and YDE were formed during MIS5 without error. The OSL ages of palaeolimnological relics in sections BLThu and TGT (Fig. 3g and b) show that the lacustrine sediments were formed at least between 117 ± 10 to 96 ± 9 ka, corresponding to MIS5. Although one age from the bottom of YDE section is problematic, the other ages from TGT, BLThu and XNRT2 sections reveal that at least some of the lacustrine sediments in the BJ formed during MIS5.

5.1. Holocene climate in the BJD

A number of studies published in the last decade or so have shed light on the Holocene environment of the BJD. The findings of Yang and Scuderi (2010), based on a radiocarbon chronology of interdune lacustrine deposits, showed that the high lake levels in the basins of the BJD indicate higher moisture availability during the middle Holocene (8–4 Cal ka BP), followed by a drier late Holocene. A more recent study of interdune lake relics by Wang et al. (2016a) demonstrated that while many lakes reached their maximum water level in the middle Holocene between 8.6 and 6.3 Cal ka BP, there was also expansion of lakes during the early Holocene, with limnic peat dated to between 11 and 10 Cal ka BP, and lake retreat or desiccation about 3.5–0 Cal ka BP. In an analysis of a 310 m drill core obtained from the desert centre, Wang et al. (2015) suggested that lacustrine material in the upper part of the core represented lake re-appearance during the warm and humid Holocene climate. However, research in the north of the BJ by Chen et al. (2003), based on the radiocarbon chronology of a core from Juyanze Lake, shows a more complicated picture, with a distinct mid Holocene drought between 7 and 5 Cal ka BP and two periods of lake expansion at 7 and 5–3 Cal ka BP. Hydrological changes in the eastern Juyanze basin reflect reconstructed Holocene climate history, with wet alternations in the early Holocene (10.7–7.6 Cal ka BP), dry phases in the mid Holocene (7.6–5.4 Cal ka BP) and wet conditions in the mid to late Holocene (5.4–1.5 Cal ka BP) (Hartmann and Wünnemann, 2009). The frequency of calcareous root tubes 14C dating results were interpreted on the millennial scale as a proxy for effective moisture, and the frequency of the 14C dating results reveal that all Holocene samples, from the Badain Jaran Desert, were dated to 7–5 Cal ka BP (Li et al., 2015b, 2015c). However, climate reconstructions from south of the BJD show a different pattern. A radiocarbon chronology from Zhuyeze suggests that the early Holocene (11.0–7.4 Cal ka BP) was relatively arid, a humid environment prevailed during the mid Holocene (7.4–4.7 Cal ka BP), while arid conditions prevailed again during the late Holocene (4.7–0 Cal ka BP) (Li et al., 2009). These findings are supported by an OSL chronology from Zhuyeze, Long et al. (2012), which also shows a warm and dry early Holocene (9.5–7.0 ka), cool and humid mid Holocene (7.0–4.8 ka), and an increasingly arid late Holocene (since 4.8 ka). A radiocarbon chronology and other indexes from loess stratigraphy at Chagelebulu, on the southern fringe of the Badain Jaran (Gao et al., 2006) also confirm the overall trends, with loess accumulation between 9.4 and 8.2 Cal ka BP and 7.2–4.3 Cal ka BP, and palaeosol development between 3.3 and 2.2 Cal ka BP.

Although there is broad agreement between the above studies, the precise timing of the initiation and termination of each climatic stage varies between different dating methods and indexes of geochemistry in different sections. In this study, the age of YDE-4 in the YDE section indicates humid environment initiation at 10.67 ka and continuation during the early Holocene (10.7 ± 1.0 to 8.3 ± 0.6 ka). The youngest lacustrine sediment, in section WNJL1, implies the termination of aridity in the BJD around 3.6 ± 0.3 ka. In summary, this study shows that environment in the BJD was humid in the early and middle Holocene (10.7 ± 1.0 to 3.6 ± 0.3 ka), with aridity prior to 10.7 ka and since 3.6 ka, respectively.

In a synthesis of literatures published prior to the early 1990s, Shi et al. (1993) concluded that both the temperature and precipitation were high in China between 8.5 and 3.0 ka. However, An et al. (1993 and 2000) argued that effective precipitation peaked at 9 Cal ka BP in monsoon areas of northern and northwestern China, and that precipitation declined and aridity increased thereafter. In a study of the western part of the Chinese Loess Plateau, An et al. (2003) showed that wetland/swamp layers formed between 9.0 and 3.8 Cal ka BP, indicating a humid climate in that period. A pollen-based, well-dated ~20-yr-resolution quantitative precipitation reconstruction from an alpine lake on the Central Loess Plateau provide a robust EASM variation records since last deglaciation, which clearly showed humid in mid-Holocene (7.8–5.3 ka), relative humid in early Holocene (14.7–7.0 ka), and dry in late Holocene (since ~3.3 ka) in monsoonal East Asia (Chen et al., 2015). A study of loess and aeolian sand from the eastern Qaidam Basin also indicates a humid climate between 8.0 and 4.5 ka and relative aridity between 4.5 and 0.5 ka (Yu and Lai, 2012). The aeolian signature from lacustrine sediments of the Qaidam Basin in northeastern Qinghai-Tibetan Plateau indicates that extremely arid and relative shallow-water environment ended at about 12.5 ka (An et al., 2012). It is plausible that the climate during the early and middle Holocene (10.7–3.6 ka) was humid even in the transition zone of the Westerlies and the East Asian monsoon. In summary, the luminescence ages of lacustrine sediments in the BJ reported in this study are consistent with the general trends of reported Holocene monsoon variations in east and south Asia. This would also be consistent with the Holocene high lake levels and pan-lake period in the BJ reported by Wang et al. (2016a). Minor differences in the chronologies of the gyttja layers may be attributed to the floating interdune lake basin and the different dating methods.

5.2. Late Pleistocene climate in the BJD

Most previous work on the climate of the BJD has focused on the
6. Conclusions

This paper reports luminescence chronologies for limnic relics located in the core area of the BJD, which differ from most previous research in the region focusing on the desert margins and adjacent areas. Based on systematic geomorphological observations and luminescence dating, we established a primary chronological framework for interdune lake deposits and concluded that:

(1) Limnic relics of interdune lakes of the BJD can be used as a good record of environment change. However, the migration of the lake depocenter limited their potential as the long-term and continuous climate information archives.

(2) The BJD experienced a humid and lacustrine environment in the early and middle Holocene (10.7 ± 1.0 to 3.6 ± 0.3 ka), with arid condition prevailing immediately prior to 10.7 ka and since 3.6 ka. Aeolian processes have been more active during the last 600 years.

(3) Our luminescence chronologies from the limnic sediments suggest that the BJD had experienced a humid and lakes dominated environment during MISS. Our data extends the dating results of previous $^{14}$C chronologies from 30 to 40 ka in the desert to ages of 90–100 ka.

Acknowledgements

This work was funded by Chinese Academy of Geological Sciences (CAGS) Basal Research Fund Special Funds (Nos. YYWF201525, YYWF201618), the “Strategic Priority Research Program” of the Chinese Academy of Sciences (Climate Change: Carbon Budget and Relevant Issues, Grant No. XDA05120501), NSFC (Nos. 41571006 and 41761144073) and Natural Science Foundation of Shandong Province (ZR2015JL015). We are immensely benefited from the comments and suggestions by two anonymous reviewers. The authors also thank Dr. Xiangjun Liu for valuable suggestions while writing the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jseaes.2019.03.024.

References


