The luminescence dating chronology of a deep core from Bosten Lake (NW China) in arid central Asia reveals lake evolution over the last 220 ka

Li, Guoqiang; Duan, Yanwu; Huang, Xiaozhong; Buylaert, Jan-Pieter; Peng, Wei; Madsen, David B.; Rao, Zhiguo; She, Linlin; Xie, Haichao; Chen, Fahu

Published in:
Boreas

Link to article, DOI:
[10.1111/bor.12209](https://doi.org/10.1111/bor.12209)

Publication date:
2016

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Li, G., Duan, Y., Huang, X., Buylaert, J-P., Peng, W., Madsen, D. B., Rao, Z., She, L., Xie, H., & Chen, F. (2016). The luminescence dating chronology of a deep core from Bosten Lake (NW China) in arid central Asia reveals lake evolution over the last 220 ka. *Boreas*, 46, 264-281. <https://doi.org/10.1111/bor.12209>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 The luminescence dating chronology of a deep core from Bosten Lake (NW
2 China) in arid central Asia reveals lake evolution over the last 220 ka

3

4 GUOQIANG LI, YANWU DUAN, XIAOZHONG HUANG, JAN-PIETER BUYLAERT,
5 WEI PENG, DAVID B MADSEN, ZHIGUO RAO, LINLIN SHE, HAICHAO XIE,
6 JIANHUI CHEN AND FAHU CHEN

7

8 Li, G., Duan, Y., Huang, X., Buylaert, J.-P., Peng, W., Madsen, D.B., Rao, Z., She, L., Xie,
9 H., Chen, J. & Chen, F.: The luminescence dating chronology of a deep core from Bosten Lake
10 (NW China) in arid central Asia reveals lake evolution over the last 220 ka

11

12 The lacustrine deposits of lakes in arid central Asia (ACA) potentially record palaeoclimatic
13 changes on orbital and suborbital timescales, but such changes are still poorly understood due
14 to the lack of reliable chronologies. Bosten Lake, largest freshwater inland lake in China is
15 located in the southern Tianshan Mountains in central ACA. A 51.6 m deep lacustrine
16 succession was retrieved from the lake and thirty luminescence dating samples from the
17 succession were used to establish a chronology using multi-grain quartz OSL and K-feldspar
18 post-IR IRSL (pIRIR₂₉₀) dating. Quartz OSL ages were only used for samples from the upper
19 part of the core. The K-feldspar luminescence characteristics (dose recovery test, anomalous
20 fading test, first IR stimulation temperature plateau test) are satisfactory and from the
21 relationship between the quartz OSL, IR₅₀ and pIRIR₂₉₀ doses we infer that the feldspar
22 signals are likely to be well-bleached at deposition. Bacon age-depth modelling was used to
23 derive a chronology spanning the last ~220 ka. The chronology, lithology and grain-size
24 proxy record indicate that Bosten Lake formed at least ~220 ka ago and that lake levels

fluctuated frequently thereafter. A stable deep lake occurred at ~220, 210-180, ~165, 70-60, 40-30 and 20-5 ka, while shallow levels occurred at ~215, 180-165, 100-70, 60-40 and 30-20 ka. Bosten Lake levels decreased by at least ~29 m and possibly even have dried up between at ~160 and ~100 ka. We suggest the lake level fluctuations in the lakes of arid central Asia may not respond directly to climatic changes and may be affected by a number of complex factors.

Guoqiang Li (gqli@lzu.edu.cn), Yanwu Duan, Xiaozhong Huang, Wei Peng, David B. Madsen, Zhiguo Rao, Linlin She, Haichao Xie, Jianhui Chen and Fahu Chen, Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China; Jan-Pieter Buylaert, Technical University of Denmark, Center for Nuclear Technologies, DTU Risø Campus, Building 201, Frederiksborgvej 399, DK-4000 Roskilde, Denmark, and Nordic Laboratory for Luminescence Dating, Department of Geoscience, Aarhus University, DTU Risø Campus, DK-4000 Roskilde, Denmark.

The arid central Asia (ACA) is located at the central mid-latitude Eurasian continent, where present climate is primarily under the influence of the Westerlies and Siberian high systems (Wang & Ding, 2008). Many palaeoclimate records have been obtained recently from ACA. In particular, studies of lake sediments show significant variations in effective moisture (precipitation to evaporation ratio, P/E) during the Holocene (e.g. Chen *et al.* 2008; Rudaya *et al.* 2008). Chen *et al.* (2008) reviewed the lacustrine records in ACA and concluded that the westerly-dominated ACA experienced synchronous and coherent moisture changes characterized by a dry early Holocene and a moister mid-late Holocene, and suggested that the effective moisture history in the ACA was broadly out-of-phase with that in monsoonal Asia. Reduced water vapor advection, related to decreased westerly wind intensity and less upstream evaporation, is thought to have caused the dry climate during the early Holocene in ACA (Jin *et al.* 2012). More recently published lacustrine records indicate that the regionally-averaged moisture index from Xinjiang has climbed persistently since ~10 cal ka BP and that the period between ~4 and 0 cal ka BP was the optimal Holocene moisture period (Feng *et al.* 2013). They suggest that Holocene moisture variations in central ACA (i.e., Xinjiang) were controlled by winter temperature variations in the North Atlantic region. Cheng *et al.* (2012) reported a 500,000 year oxygen isotope ($\delta^{18}\text{O}$) record from stalagmites in Kesang Cave from the Tianshan Mountains and suggested that possible incursions of Asian summer monsoon rainfall or related moisture into the Kesang site and/or adjacent areas during high insolation times may play an important role in changing the orbital-scale hydrology of the region.

From the above it is clear that the ACA climate changes on orbital and suborbital timescales and the mechanisms behind climate changes are still under debate. Widely distributed lakes in the high mountains of ACA have well preserved Quaternary lacustrine sediments which

potentially can provide continuous high-resolution records for terrestrial environmental and climatic variation on orbital and sub-orbital timescales. However, a reliable chronology is critical for using these lacustrine records, and reliable age estimates for lacustrine deposits from ACA on orbital timescales remain unavailable thereby leading to difficulties in reliably correlating climatic records in this region to those in adjacent climatic regimes.

We drilled and retrieved a 51.6 m lacustrine sediment succession (core BST12B) from Bosten Lake in the southern Tianshan Mountains, central ACA. We here describe the lithology of the core in detail, as well as grain-size distributions measured at 10 cm intervals. Thirty luminescence samples were collected at ~1.5 m intervals, and the quartz optically stimulated luminescence (OSL) and K-feldspar post-IR IRSL (pIRIR) dating luminescence characteristics of these samples were investigated. The chronology of the drill core was established by using a Bacon age depth model (Blaauw & Christen 2011) on the quartz OSL and K-feldspar pIRIR ages that were considered reliable. These investigations allow the establishment of the first pIRIR dated chronology for a Northern Hemisphere Mid-to-Late Pleistocene lacustrine sequence. In combination with chronology, lithology and proxy index of grain size, the evolution of Bosten Lake over past ~220 ka is discussed.

Absolute chronologies for lacustrine successions

Radiocarbon dating is the most commonly used method for establishing chronologies of lacustrine deposits (Hatté *et al.* 2001; Pessenda *et al.* 2001). However, ^{14}C datable materials (e.g., plant residuals and charcoal) are not always available in ACA lake sediments and using ^{14}C dating is limited to samples less than 40-50 ka. The quartz OSL dating using a single-aliquot regenerative dose (SAR) procedure is now widely applied to date Late Pleistocene sediments

(Murray & Olley 2002; Wintle & Murray 2006; Wintle 2008). During the past few years, attempts have been made to apply quartz OSL dating to loess in ACA (Song *et al.* 2012; Yang *et al.* 2014; Li *et al.* 2015). However, the dating of older loess (>50 ka) using quartz OSL is limited by the early saturation of the quartz OSL signal (Buylaert *et al.* 2007; Chapot *et al.* 2012). In northern China this method is generally limited to the dating of deposits younger than ~60 ka (Li *et al.* 2014). Recently developed K-feldspar dating (Thomsen *et al.* 2008; Thiel *et al.* 2011; Buylaert *et al.* 2012), utilizing a post IR signal stimulated at high temperature of 290 °C (pIRIR₂₉₀) after IR measurement at low temperature of 50 °C, can be used to date late Pleistocene samples back to ~600 ka (in their study corresponding to the equivalent dose (D_e) values of ~600 Gy), which is a viable alternative for sediments in which the quartz OSL signal is insensitive or saturated. Recently, the K-feldspar pIRIR₂₉₀ signal was applied to reconstruct the lacustrine chronology for the PASADO core 5022-1D from the maar lake of Laguna Potrok Aike, Argentina (Buylaert *et al.* 2013). A K-feldspar pIRIR chronology based on 27 samples has shown a good agreement with independent age control, and then a robust age-depth model for this core was established. It should be noted that 18 of 47 samples were overestimated due to poor bleaching (internally identified using differential bleaching rates of IR₅₀ and pIRIR₂₉₀ signals). Li & Li (2011) proposed a multi-elevated-temperature post-IR IRSL (MET-pIRIR) protocol utilizing IRSL signals measured by progressively increasing the stimulation temperature from 50 to 300 °C in steps of 50 °C. The MET-pIRIR ages obtained at signals above 200 °C were consistent with independent ages and no fading correction was required (Li & Li 2011). MET-pIRIR dating has been successfully applied to various sedimentary samples from China deposited in the last ~130 ka (Li & Li 2011; Fu *et al.* 2012), and age estimates in agreement with independent ages were obtained for samples up to ~300 ka (Li & Li 2012a). A comparison of

MET-pIRIR dating and pIRIR dating of a series of samples indicates that these two methods can generate similar ages (Thomsen *et al.* 2012; Li & Li 2012b). An advantage of the two-step pIRIR protocol over MET-pIRIR is that the pIRIR signal is usually brighter and measurement time is shorter (Thomsen *et al.* 2012).

Study area

Bosten Lake (86°40'–87°26' E, 41°56'–42°14' N, 1051 m a.s.l.) is the largest freshwater inland lake in China. It is located in the lower intermontane Yanqi Basin in the southern Tianshan Mountains (Fig. 1). Bosten Lake is about 55 km from east to west and about 25 km from south to north, covering an area of ~1100 km². The average water depth in the lake is 10 m, with a maximum depth of 17 m (Xiao *et al.* 2010). The lake receives water from a catchment area of ~56000 km², with the Kaidu River as its main tributary (Wünnemann *et al.* 2006). The Yanqi Basin is surrounded by the Elbin-Alagou Mountains and its pediments in the north (part of the Tianshan) and by the Kuruktag Mountains in the south. A widespread active dune field, with complex dunes up to 100 m high, has developed on the pediment plain between the Kuruktag Mountains and the lake. The annual mean runoff of all drainages has been calculated to be $3.95 \times 10^8 \text{ m}^3 \text{ a}^{-1}$, and the Kaidu River provides more than 85% of this total input (Wünnemann *et al.* 2006). The Konqi River, located only ~10 km away from the Kaidu River, drains Bosten Lake and flows further south towards the Tarim Basin (Mischke *et al.* 2006).

Bosten Lake is located in a typical temperate arid region and meteorological records from Yanqi County indicate that the mean annual precipitation is ~70 mm in the Bosten area (Huang *et al.* 2010). However, rainfall is much higher in the upper catchment and may exceed 400 mm in the highest ranges of the eastern Tianshan Mountains. The most precipitation occurs during

spring and summer and is carried by Westerlies from Atlantic, Mediterranean and Caspian area (Aizen *et al.* 2006). During the winter, the Siberian high dominates the climate in the region and the precipitation is minor (Chen *et al.* 2008). Potential annual evaporation in Bosten Lake is as high as 2000 mm. Mean annual air temperature in the lake region is ~8 °C, and winds come mainly from the southwest. From higher to lower altitudes, there are four distinct zones of regional vegetation: a snow and ice zone above 3800 m a.s.l. with no visible plants, an alpine cushion to meadow zone at 3800–2800 m a.s.l., a steppe and desert steppe zone at 2800–1600 m a.s.l., and a desert vegetation zone at 1600–1050 m dominated by *Iljinia regelii*, *Ephedra przewalskii*, and *Salsola* sp. (Huang *et al.* 2010).

Material and methods

Core drilling and sampling

Core BST12B (42°00'42.9" N, 87°09'17.3" E, 1051 m a.s.l.) was drilled using a machine drilling system on ice covering the lake surface during the winter of 2011. We retrieved a 51.6 m long lacustrine succession from the center of the lake at a water depth of 9.2 m (the locality of the core is shown in Fig. 1). The lithology and the OSL sampling positions are shown in Fig. 2. The cylindrical core, with a diameter of 13 cm, was split in half, and half of the core was reserved for OSL dating. All OSL samples were collected from the core tubes under subdued red light. Only the inner part of the core sample was used for dose rate and D_e measurements to avoid contamination from potentially light-exposed material and smearing of the core barrel. The OSL samples were stored in a cold room with constant temperature of 4 °C to avoid a change in water content. The other half of the core was used for sediment description and proxy indexes analysis.

Sample preparation and measurement for luminescence dating

OSL sample preparation followed the methods described in Aitken (1998). All raw samples were treated with 10% HCl and 20% H₂O₂ to remove carbonate and organic matter, respectively. The samples were then sieved in water to extract the 125-90, 90-63, and 38-63 µm grain size fractions. Heavy liquids with densities of 2.62, 2.75 and 2.58 g cm⁻³ were then used to separate the quartz and K-feldspar rich fractions of each sample. The quartz-rich extract was treated with 40% HF for 80 to 120 min to remove the remaining feldspar grain contamination and outer layer irradiated by alpha particles. The K-feldspar grains were treated with 10% HF for 40 min to remove the outer layer irradiated by alpha particles. Finally, all samples were treated with 1 mol L⁻¹ HCl for 10 min to remove fluorides created during the HF etching. The coarse-grained quartz grains were mounted in a ~7 mm diameter circle using silicone oil on stainless steel discs (9.8 mm diameter); each aliquot contains several thousands of grains. The coarse-grained K-feldspar grains were mounted in a ~2 mm diameter circle on stainless steel discs.

Luminescence signals were measured using an automated Risø TL/OSL-DA-20 reader (Bøtter-Jensen *et al.* 2010) equipped with blue LEDs (470 nm, ~80 mW cm⁻²) and IR LEDs (870 nm, ~135 mW cm⁻²). Laboratory irradiation was carried out using ⁹⁰Sr/⁹⁰Y sources mounted on the reader. The quartz OSL signal was detected through two 3 mm thick Hoya U-340 filters and a double single aliquot regenerative (SAR) protocol (Banerjee *et al.* 2001, Table 1) was used to determine the quartz luminescence characteristics and measure D_e values. The quartz OSL signal was derived from the first 0.32 s integral of the initial decay curves minus an early background (0.32-0.96 s) to minimize the influence of slow and medium components (Cunningham & Wallinga 2010). The IRSL signal was detected using a photomultiplier tube with the IRSL passing through Schott BG-39 and Corning 7-59 filters. A K-feldspar pIRIR dating protocol

based on Thiel *et al.* (2011) was applied to the K-feldspar fractions (Table 1). Signals from test doses of at least 30% of the pIRIR₂₉₀ D_e were used to correct sensitivity changes (Yi *et al.* 2016). For both pIRIR₂₉₀ and IR₅₀ measurement, the first 2 s integral of the initial decay curves minus backgrounds estimated from the last 20 s integral of the 200 s stimulation were used for D_e calculation.

The environmental dose rate was calculated from the measurements of radioactive element concentrations in the sample. For all OSL samples, ~5 g of each sample were ground to <4 µm using an agate mortar. The uranium (U), thorium (Th) concentrations and potassium (K) content were determined using Neutron Activation Analysis (NAA). All results were converted to beta and gamma dose rates according to the conversion factors of Guérin *et al.* (2011). The observed water content (% by dry weight) and, for sandy sediments, the saturated water content were measured in the laboratory. The dose rate from cosmic rays was calculated according to Prescott & Hutton (1994). The internal dose rate of K-feldspar grains was calculated assuming a K content of 12.5±0.5% (Huntley & Baril 1997) and Rb content of 400±100 ppm (Huntley & Hancock 2001).

Grain-size analysis

A total of 520 grain-size samples were collected from core BST12B at 10 cm intervals. The samples were pretreated with 10 ml 30% H₂O₂ to remove organic matter and 10 ml 10% HCl with heating to remove carbonates. Deionized water was then added and each sample suspension was kept for 24 h to remove acidic ions. Finally, the sample residue was dispersed with 10 ml of 0.1 mol L⁻¹ (NaPO₃)₆ using an ultrasonic vibrator for 10 min to facilitate dispersion (Peng *et al.* 2005). Grain sizes were measured using a Malvern Master Sizer 2000. The measurement range is

202 0.02 and 2000 μm and the mean measurement error is $\sim 2\%$.

203

204 Results and discussion

205 *Lithology*

206 The lithology of BST12B can be divided into seven units from bottom to top (Fig. 2):

207 Unit 1 (51.6-50.5 m): brown silt and clayey silt.

208 Unit 2 (50.5-46 m): primarily grey-brown medium-to-fine sand. Yellowish interbedded
209 brown silt and clay occur at depths of 50-49 m. Snails occur at depths of 48.67-47.93 m and
210 50.5-50.17 m, while charcoal fragments were identified at the depth of 49.81 m.

211 Unit 3 (46-31.5 m): blue-grey clay with horizontal bedding. Grey-brown to yellowish-
212 brown silt layers occur occasionally in this unit. A 40 cm thick layer of coarse sand is present at
213 the depth of 41 m. Snails occur at the depth of 38.72-38.32 m

214 Unit 4 (31.5-22.7 m): throughout this unit the sediment gradually changes from silt to silty
215 sand and sand. From 31.5-28.5 m the sediments consist of light yellowish clayey silt to yellowish
216 brown silt. Grey to yellowish fine sand occurs at depths of 28.52-24.81 m, with snails occurring
217 at 28.03-27.44 m. Grey-brown medium-to-coarse sand is interbedded with yellowish brown clay
218 at depths of 24.84-22.82 m.

219 Unit 5 (22.7-20.2 m): primarily blue-grey clayey silt, with a thick uncompact silt layer
220 containing snails at the depth of 22.60-22.48 m.

221 Unit 6 (20.2-13.5 m): grey-brown coarse sand alternating with grey-yellowish medium-fine
222 sand. Blue-grey silty clay containing snails is found at depths of 15.22-14.91 and 19.63-19.21 m.

223 Unit 7 (subdivided in 6 subunits): sandy clay interbedded with sand. Unit 7a (13.5-11 m),
224 unit 7c (8.0-6.0 m) and unit 7e (4.1-1.5 m) are light-yellow to blue-grey clayey silt, while

yellowish brown medium-to-coarse sand, blue-grey fine sand and blue-grey silt occur at depths of 11-8.0 m (unit 7b), 6.0-4.1 m (unit 7d) and 1.5-0 m (unit 7f), respectively. Numerous snails are present between 0.80-1.21 m.

Quartz OSL characteristics

Seven coarse-grained quartz samples (Table 3) from the top of the BST12B core were used for D_e measurements. The purity of the quartz extracts was checked using an OSL IR depletion ratio (Duller 2003), and the average OSL IR depletion of the all aliquots is 0.82 ± 0.01 (Fig. 3A). In order to minimise the influence of feldspar inclusions, a double SAR quartz protocol (Banerjee *et al.* 2001) was used to measure quartz D_e for these OSL samples. A dose recovery test was conducted on sample Bst12b-488 to check the suitability of the measurement protocol (Murray 1996). The aliquots were bleached by two 40 seconds blue LEDs stimulations at room temperature, with 10 ks of storage at room temperature between the two stimulations. A beta dose of 102 Gy was then given in the reader. The measured to given dose ratio was 1.08 ± 0.06 ($n = 3$) suggesting that a SAR protocol with a preheat temperature of 260 °C and a second preheat of 220 °C after the test dose is suitable to measure the D_e of the quartz fraction. As shown in Fig. 4A for an aliquot of sample Bst12b-488, the initial signal for a regeneration dose of 127 Gy was only ~890 counts 0.16 s^{-1} (stimulation power of blue diodes 80 mW cm^{-2}). The quartz OSL signal of samples from Bosten Lake is dim in comparison to quartz signals from other parts of China (e.g., hundred thousand initial counts for a 6 mm aliquot of a sample of similar dose from the Gobi Desert of Mongolia, Jin *et al.* 2015). Similar to standard calibration quartz OSL signal, the OSL signals of sample Bst12b-488 decrease rapidly during the first second of stimulation (Fig. 4A), indicating that the OSL signal is dominated by the fast component, a prerequisite for

reliable dose measurements using SAR (Wintle & Murray, 2006). The mean recycling ratio value for all measured aliquots are 0.983 ± 0.020 and the recuperation of all aliquots are less than 5% of natural signal ($n = 97$), indicating that the test dose signal corrects adequately for sensitivity changes during the different SAR cycles. The dose response curve (DRC) can be readily fitted using a single saturation exponential (Fig. 3B). At least 12 aliquots for each sample were measured. The D_e values, dose rates and the calculated quartz OSL ages are listed in Table 3.

Luminescence characteristics of K-feldspar

Decay and dose response curves. – Decay curves for the uppermost sample (Bst12b-110) and the lowermost sample (Bst12b-5120) are illustrated in Fig. 4C and Fig. 4D, respectively. The IR_{50} signals are typically less bright than the $pIRIR_{290}$ signals, consistent with observations from other parts of the world (e.g. Thomsen *et al.* 2008; Thiel *et al.* 2011). The DRCs of the IR_{50} and $pIRIR_{290}$ signals for the two samples (Bst12b-5120 and Bst12b-2896, Fig. 4E and Fig. 4F respectively) can be well represented using single exponential saturation functions. Different DRC shapes were observed when different test doses were applied (Fig 3C and 3D). When a low test dose of ~ 38 Gy ($\sim 6\%$ of natural D_e) is applied, the DRC shapes of the IR_{50} and $pIRIR_{290}$ signals are different and the calculated saturation characteristic dose (D_0) for the $pIRIR_{290}$ signal is only ~ 200 Gy. However, when a large test dose of ~ 340 Gy ($\sim 58\%$ of natural D_e) is applied, the DRC shapes of the IR_{50} and $pIRIR_{290}$ signals are similar and the calculated D_0 increases to 350 Gy. Qin & Zhou (2012) investigated the dependence of D_0 and D_e on test dose size for 45-63 μm polymineral samples from the central Loess Plateau of China. They found that the D_0 of the dose response curve increases monotonically when the test dose is increased from ~ 5 to $\sim 37\%$, a

trend similar to that found in the samples from Bosten Lake. They also found that D_e values do not change significantly when the test dose is larger than ~25% of the natural D_e and attribute this to a reduction of the importance of a thermally transferred signal to the test dose pIRIR signal. Yi *et al.* (2016) have extensively tested the D_e and dose recovery dependence on test dose size. They found for small test doses (<15%), the dose recovery ratio is significantly greater than unity. In contrast, large test doses (>80%) yield ratios lower than unity. The best dose recovery ratios ($\pm 5\%$ of unity) are found when the test dose ranges between ~15-80% of the total dose. They conclude that the test dose size is a parameter that should be routinely considered in pIRIR dating; they found that for their samples from NE China a test dose between ~15% and 80% of the dose to be measured is appropriate. In this study, we have adopted a test dose of ~30% of the D_e . All IR₅₀ and pIRIR₂₉₀ D_e s from the drill core samples are less than $2 \times D_0$ (690 ± 50 Gy), indicating that natural signals lie below the saturation level on the DRCs.

Internal SAR tests. – The suitability of the pIRIR dating succession was also checked using a dose recovery test. First, we bleached 8 aliquots of the youngest K-feldspar sample (Bst12b-110) for 56 h under sunlight (4 hours per day, 14 days in June 2014 in Lanzhou, China). After sunlight bleaching, the residual dose for K-feldspar was measured using 4 aliquots and the pIRIR succession given in Table 1. Another set of bleached aliquots was given a beta dose of 381 Gy in the reader and measured with the same succession. The calculated residual doses for the pIRIR₂₉₀ and IR₅₀ signals are 3.67 ± 0.23 Gy and 0.33 ± 0.04 Gy, respectively. These residual doses are less than 1% of the given dose of 381 Gy and are thus negligible. The measured to given dose ratios are 0.94 ± 0.04 and 0.72 ± 0.05 for the pIRIR₂₉₀ and IR₅₀ signals, respectively. These analyses indicate that the employed dose measurement protocol is suitable for measurement of the

pIRIR₂₉₀ signal of our samples. The dose recovery for IR₅₀ signal measured from pIRIR dating
 protocol is low (e.g., 0.72 ± 0.05), but this is not necessarily a good predictor of inaccurate
 measurement of D_e . Previous study indicates that IR₅₀ D_e values measured as part of the pIRIR₂₉₀
 protocol (Table 1) were very close to the IR₅₀ D_e values measured with a preheat of 250 °C and a
 single IR stimulation SAR protocol with better dose recovery (Buylaert *et al.* 2012). In any case,
 the IR₅₀ signals measured as part of the pIRIR₂₉₀ protocol and resulting IR₅₀ D_e values were not
 used for age calculation but only for checking the bleaching of the pIRIR₂₉₀ signal; a systematic
 underestimation of the IR₅₀ doses compared to the pIRIR₂₉₀ will not induce more scatter in the
 IR₅₀ to pIRIR₂₉₀ plot but only change the shape of the fitted curve. The average SAR pIRIR₂₉₀
 recycling ratio (165 aliquots from 27 samples) is 0.995 ± 0.002 (Fig. 3B) and recuperation is <5%
 of the sensitivity corrected natural signal (inset Fig. 3B). We conclude that the luminescence
 characteristics of the pIRIR₂₉₀ signal are satisfactory.

Laboratory measurements of pIRIR₂₉₀ signal stability. – The IR₅₀ signal of K-feldspar samples
 stimulated at ambient temperatures suffers from anomalous fading (Spooner 1994). This is
 usually quantified by the g -value to represent the luminescence signal loss per decade of
 normalized storage time (Aitken 1985). In contrast, the pIRIR signal can be used to reduce the
 fading rates (Thomsen *et al.* 2008). Laboratory fading tests were conducted on K-feldspar
 samples Bst12b-1070 (183 ± 3 Gy) and Bst12b-2706 (500 ± 8 Gy). A single-aliquot measurement
 protocol with storage after dosing and preheating was used to measure the g values (Auclair *et al.*
 2003) (protocol given in Table 1). In this experiment, decay in the sensitivity-corrected
 pIRIR₂₉₀ signals (L_x/T_x) as a function of storage time at room temperature was measured. A
 given dose of 508 Gy and test dose of 152 Gy for sample Bst12b-2706, and a given dose of 191

Gy and a test dose of 63 Gy for sample Bst12b-1070 were used. The same laboratory dose was given repeatedly with different delay periods between the end of the 320 °C preheat and the start of the subsequent IRSL measurement. The g values were normalised to a t_c of 2 days (Huntley & Lamothe 2001).

The decay of the IR_{50} and $pIRIR_{290}$ signals for samples Bst12b-1070 and Bst12b-2706 as a function of storage time (t) is shown in Fig. 5A, B. The g_{2days} values are $0.88 \pm 0.24\%/decade$ ($n = 3$) and $1.24 \pm 0.21\%/decade$ ($n = 6$) for the $pIRIR_{290}$ signals of samples Bst12b-1070 and Bst12b-2706, respectively. The g values of $pIRIR_{290}$ signals have been measured for a wide variety of samples from around the world (Buylaert *et al.* 2012; average g_{2days} $1.44 \pm 0.03\%/decade$, $n = 128$). They found good agreement of $pIRIR_{290}$ ages with independent age controls and suggested that it is possible that these apparent laboratory fading rates are in fact a measurement artefact. In this study we do not correct the $pIRIR$ ages in accordance with other published work (e.g. Buylaert *et al.* 2012; Roberts 2012; Colarossi *et al.* 2015). In contrast to the $pIRIR_{290}$ signal, the IR_{50} signal is more prone to fading (e.g. Thomsen *et al.* 2008; Li & Li 2011). The g values of the IR_{50} signal for samples Bst12b-1070 and Bst12b-2706 are 2.07 ± 0.58 and $1.76 \pm 0.75\%/decade$, respectively, slightly higher than the $pIRIR_{290}$ signals for both samples. Because of the poor dose recovery and higher fading rates of the IR_{50} signals and the model assumptions inherent to any fading correction (Morthekai *et al.* 2008) we do not use this signal for age determination.

As a further test for stability we measured a first-IR stimulation plateau (Buylaert *et al.* 2012). Prior IRSL stimulation temperatures were increased from 50 to 250 °C in 50 °C intervals and then the $pIRIR D_e$ was measured at 290 °C. As shown in Fig. 5C, the $pIRIR D_e$ shows no obvious change with variations of the prior IR stimulation temperatures suggesting that a prior IRSL stimulation at 50 °C is sufficient to remove the unstable part of the signal. However, it is

possible that the oldest samples in our lake succession (D_e values >500 Gy) are slightly underestimated the true sedimentation ages due to signal instability (Li & Li, 2012b; Yi *et al.* 2016).

Residual doses. – In order to test the bleachability of the pIRIR₂₉₀ signals, 24 sand-sized K-feldspar samples with varying D_e s (one aliquot per sample) were exposed in 56 h of full sunlight (4 hour per day, 2 weeks, Lanzhou, China) and in 112 h (4 hour per day, 4 weeks, Lanzhou, China), and then the residual doses were measured. The measured residual dose data are summarized in Table 4 and illustrated in Fig. 6. It can be seen that there is a trend between the residual doses and the D_e values for both the IR₅₀ and pIRIR₂₉₀ signals after 56 h bleaching. This has been reported previously (Sohbati *et al.* 2011; Buylaert *et al.* 2012). Doubling the bleaching time to 112 h reduces the residual signal even more and the residual dose becomes independent of the D_e ; from these data we extrapolate a residual dose of 0.31 ± 0.11 Gy and 2.36 ± 0.15 Gy for IR₅₀ and pIRIR₂₉₀, respectively. The residual doses for IR₅₀ signal are much smaller than those of the pIRIR₂₉₀ signal for after both 56 h and 112 h bleaching. It should be noted that the determination of the dose present at deposition is very difficult to quantify accurately in the laboratory (Kars *et al.* 2014). We have subtracted these residual doses from the measured D_e values. Fortunately most of our samples have D_e values that are significantly larger than the residual dose estimated here (Table 2). Only for the top samples with a very low D_e (8 Gy) this subtraction has made a significant difference to the age.

Differential bleaching of IR₅₀ and pIRIR₂₉₀ signals. – The K-feldspar IRSL signal is reset by daylight (bleached) more slowly than the quartz OSL signal (Godfrey-Smith *et al.* 1988;

Thomsen *et al.* 2008) and the pIRIR signal stimulated at high temperature bleaches more slowly than the IRSL signal stimulated at ambient temperatures (Buylaert *et al.* 2012; Murray *et al.* 2012; Kars *et al.* 2014). Although it has been confirmed that bleaching of the pIRIR signal can be achieved in nature (Buylaert *et al.* 2011; Reimann *et al.* 2011, 2012; Chen *et al.* 2013), the bleaching of pIRIR signals in lacustrine deposits still needs to be carefully checked. One way to examine whether or not the pIRIR₂₉₀ signal is likely to have been fully bleached is to compare it with other luminescence signals that have different sensitivities to daylight (Murray *et al.* 2012; Buylaert *et al.* 2013). It has been shown that the IR₅₀ signal bleaches more rapidly in sunlight than do the pIRIR signals stimulated at elevated temperature (e.g., pIRIR₂₂₅ and pIRIR₂₉₀) (Buylaert *et al.* 2012; Murray *et al.* 2012). Buylaert *et al.* (2013) developed a new criterion based on known relative bleaching rates of the IR₅₀ and pIRIR₂₉₀ signals, and the relationship between resulting D_es was successfully used to identify and reject poorly bleached samples from a Potrok Aike Lake, Argentina drill core. The established chronology using selected pIRIR ages was in good agreement with independent ¹⁴C ages.

The IR₅₀ D_e values are plotted against the pIRIR₂₉₀ D_e values in Fig. 7. All the data points lie on a smooth curve (solid line in Fig. 7) below the line of slope unity, consistent with the effects of IR₅₀ signal instability. Except for one sample (Bst12b-2446), all of the data points lie less than 10% away from the solid line (along the x-axis) and fall within one standard deviation of the line (dashed line). This indicates that the IR₅₀ and pIRIR₂₉₀ signals of the lacustrine K-feldspar samples from the drill core were likely well-bleached before deposition. The pIRIR₂₉₀ age of sample (Bst12b-2446) is consistent with the pIRIR ages of the samples below and above and so this sample was also accepted.

Dose rate and pIRIR age calculations

The U, Th and K concentrations, water content and calculated total dose rate to K-feldspar are listed in Table 2, while the calculated total dose rate to quartz grains is listed in Table 3. The observed radionuclide concentrations for K-feldspar samples from different depths of the drill core are summarized in Table 2 and illustrated in Fig. 8. Except for the high dose rate of sample Bst12b-4115 at 41.15 m, there is little variation in total dose rate with depth for all these samples, which suggests that the radioactive disequilibrium possibly has not affected dose rate of sediment after burial. On the other hand, the average U, Th and K concentration of K-feldspar samples from core BST12B are ~2 ppm, ~10 ppm, and ~2% K, respectively. Using an average 30% water content, the U decay chain nuclides contributed dose rate is ~13 % of the total dose rate of coarse grained K-feldspar sample. This suggests that the impact of uranium disequilibrium on total dose rate of coarse-grained K-feldspar is small and would not obviously change the age framework. The exact reason for the high dose rate of sample Bst12b-4115 is still unclear and needs further study. As a result, Bst12b-4115 is not used in deriving a chronology. Fig. 8 illustrates the observed water content (expressed as weight %) ($W_{in-situ}$) for all 30 samples from the drill core, and it can be seen that water content varies between ~9 and ~25%, except for a high water content of ~38 % at 1.1 m near the surface and a low water content of ~0.2% at the depth of 5.33 m. The low water content of ~0.2% for the 5.33 m sample is probably caused by unexpected water loss after sampling. The measured saturation water content varies between ~16-34% (Fig. 8). The observed water content is systematically smaller than the saturation water content, and may be possibly caused by water loss during core transportation, OSL sampling and OSL samples storage. The saturation water contents were used for external dose rate calculation. The $W_{in-situ}$ of ~38% for the sample at 1.1 m was considered acceptable given that near surface

oversaturation continually occurred after burial. The internal dose rates of $0.427 \pm 0.020 \text{ Gy ka}^{-1}$ for 90-125 μm and $0.212 \pm 0.01 \text{ Gy ka}^{-1}$ for 38-63 μm were used for K-feldspar grains based on a K content of $12.5 \pm 0.5\%$ (Huntley & Baril, 1997) and Rb content of $400 \pm 100 \text{ ppm}$ (Huntley & Hancock, 2001). The IR_{50} and pIRIR_{290} D_e values, radionuclide concentrations, water content (in situ and saturated), total dose rates and calculated pIRIR_{290} ages are given in Table 2.

Grain size distribution

The sediments in core BST12B can be divided into 4 grades of grain size: sand (63 – 2000 μm), silt (4 – 63 μm) and clay (<4 μm). Percentages of different content fractions reflect different sedimentary environments (Lerman 1978). Changes with depth in sand, silt and clay of the BST12B core are shown in Fig. 2.

Comparison between quartz OSL and K-feldspar pIRIR ages

Quartz OSL ages for 7 samples from the top of the core are illustrated in Fig. 9 to compare with their K-feldspar pIRIR_{290} ages. The quartz OSL ages for the three samples at the depth of 4.88, 5.33 and 7.46 m are consistent with their pIRIR ages, providing confidence in the reliability of the pIRIR ages and the completeness of bleaching of the pIRIR_{290} signal. The quartz OSL ages for four samples at depths of 8.89, 10.76, 13.64 and 15.94 m vary between ~35 and ~56 ka, and are systematically smaller than the K-feldspar pIRIR ages (Table 3). This may be caused by underestimation of quartz OSL ages for samples older than 50-60 ka in the northern China. The quartz OSL ages underestimation for sample older than 50 ka from northern China has been observed by others (Buylaert *et al.* 2007; Chapot *et al.* 2012; Yi *et al.* 2015; Li *et al.* 2016). This is possibly caused by the inconsistency of laboratory-generated dose response curve and natural-

generated dose response curve at high dose zone (Chapot *et al.* 2012). The quartz OSL ages for these four samples are discarded from the age model because they are likely underestimated.

The chronology of the Bosten Lake drill core

As shown in the previous section the pIRIR₂₉₀ signal is suitable for dating Bosten Lake samples. In Fig. 9A the pIRIR₂₉₀ D_e values of the samples from the top 20.2 m generally increase with depth, providing further evidence that the K-feldspar samples from the drill core have not been affected by poor bleaching. Incomplete bleaching would be very unlikely to produce a smooth dose-depth relationship. Only the pIRIR₂₉₀ age for sample Bst12b-1860 (65±5 ka) at 18.6 m is out of stratigraphic order, and may possibly be caused by dose rate problems given that the D_e's smoothly increased with depth over the interval 16-20 m. This age is thus rejected for chronological modelling.

The pIRIR ages at depths of 19.74 and 20.64 m are 95±7 and 178±13 ka, respectively, suggesting an obvious age gap between these closely spaced samples (Fig. 9B). This gap may be the result of deflation of the lacustrine deposits after a period of lake desiccation or it may be due to a very slow deposition rates. The twelve pIRIR ages for K-feldspar samples at depths between 20.6-32.6 m vary between 155±10 and 198±14 ka. Although the data are dispersed, there seems to be a weak increase in age with depth over this depth interval. We could not retrieve reliable ages for samples between 32.7-44.2 m due to a lack of coarse-grained K-feldspar in the silty clay and clay sediments at these depths. Only one sample from the depth of 41.15 m (sample Bst12b-4115) has a computed D_e. However, its pIRIR age is unreliable due to dose rate overestimation.

The quartz OSL and K-feldspar pIRIR dating produced individual ages at distinct depth intervals in the drill core record. An age-depth model that can be used to interpolate between

these discrete ages was established by using Bacon age-depth modelling (Blaauw 2010; Blaauw & Christen 2011). Age-depth models are reconstructed separately for the top 20.2 m and for 20.2-51.6 m, based on 3 quartz OSL ages and 28 K-feldspar pIRIR ages and the reconstructed age-depth model is shown as a dashed line in Fig. 9B. The grey shading illustrates the 95% confidence interval in the age-depth model estimated from Monte Carlo age-depth simulations.

Bosten Lake evolution during the late Pleistocene

The Bacon age depth model for the BST12B core shows that the lacustrine deposits at the bottom of the core date to ~220 ka. We did not reach bedrock below the lacustrine sediments and this age is a minimum estimate of when Bosten Lake initially began to form.

The Bacon age-depth model indicates that the sediments at depths of 51.6 to 20.2 m in the core were deposited from ~220 to ~160 ka, generally corresponding to MIS 7 (243-191 ka, Lisiecki & Raymo 2005) and early MIS 6 (191-130 ka, Lisiecki & Raymo 2005). As shown in Fig. 2, deep-water lacustrine clayey silt- and silt- dominated sediments occur at 51.6-50.6 m (lithology unit 1), 36-31.5 m (lithology unit 3) and 22.7-20.2 m (lithology unit 5). The grain-size frequency distributions of samples from these three units are characterized by a distinctive peak at around 15 to 20 μm and two very smooth peaks at around 0.3 and 400 μm , although a few samples in lithology unit 3 are characterized by three smooth peaks at around 0.4, 10 and 60-70 μm (Fig. 10A, C, E). These size ranges are typical of lacustrine deposits (Ying *et al.* 2008), indicating stable deep lake environment occurred in Bosten Lake at ~220, 210-180 and ~165 ka. Lithology unit 2 (50.5-46 m of the core) consists mainly of shallow lacustrine clayey sand or near-shoreline sand (Fig. 2). Snails occur at depths of 48.67-47.93 m and 50.64-50.17 m, and charcoal is present at the depth of 49.81 m. The grain size frequency distributions of samples

from this unit are characterized by a distinctive peak at $\sim 300 \mu\text{m}$ and a very smooth peak at 10 to $20 \mu\text{m}$ (Fig. 10B). Lithological unit 4 (31.5-22.7 m of the core) is yellowish sand alternating with silt, with mean grain size and sand gradually increasing from the bottom to the top of this unit (Fig. 11). The grain size frequency distributions of samples from this unit have very different peak characteristics with distinctive peaks varying from 8 to $200 \mu\text{m}$ (Fig. 10D), and snails occur in the middle of this unit (28.03-27.44 m). These lithological characteristics suggest that units 2 and 4 reflect a shallow lake environment with frequent lake level fluctuations dated to ~ 215 and 180-165 ka.

An age gap of ~ 60 ka between 160-100 ka is present at the depth of ~ 20.2 m in the core, suggesting the lake dried out and was subject to pronounced deflation during late MIS 6 and early MIS 5 (130-71 ka, Lisiecki & Raymo 2005). If that was the case, water levels may have dropped rapidly to at least below ~ 1022 m, ~ 29 m lower than the modern water level of ~ 1051 m. This age gap corresponds to the transicion of Penultimate Glaciation to last interglaciation. The reason why the lake level quickly decreased or even the lake dried out is still unclear and need further study.

Lithological Unit 6 (20.2-13.5 m) consists of brown to yellowish sand interbedded with silt. The grain size frequency distributions of samples in unit 6 are characterized by one distinctive peak at around $200 \mu\text{m}$ and a very smooth peak at around $10 \mu\text{m}$. A few samples have three smooth peaks at 10, 40 and $200 \mu\text{m}$ or a distinctive peak at around $10 \mu\text{m}$ (Fig. 10J). Snails are present at the top and bottom of this unit (15.22-14.91 and 19.63-19.21 m). Together these characteristics indicate a generally shallow lake environment of ~ 100 -70 ka in Bosten Lake.

Lithological unit 7 (top of 13.5 m) is clayey silt alternating with sand and was deposited after ~ 70 ka. The grain size frequency distributions of samples from this unit are characterized by a

distinctive peak at around 10-30 μm in Unit 7a (Fig. 10G). Samples in Unit 7c are characterized by distinctive peak at around 10-30 μm and two smooth peaks at around 20 and 150 μm (Fig. 10I). The grain size frequency distributions of samples in Unit 7e are similar in character to that in Unit 7a, consisting of a distinctive peak at around 10 μm and two very smooth peaks at around 0.5 and 300 μm , although a few samples are characterized by two smooth peaks at around 15 μm and 70 μm (Fig. 10K). The grain size frequency distributions of samples in Unit 7f are characterized by one smooth peak at around 20 μm or two smooth peaks at 10 and 100 μm (Fig. 10L). However, the top 0.4 m of the core may have been disturbed during the drilling process. Units 7a, 7c, and 7e are deep lacustrine deposits, suggesting high levels of Bosten Lake during the periods 70-60, 40-30 and 20-5 ka. Lithological units 7b and 7d consist mainly of shallow lacustrine sand deposited at 60-40 and 30-20 ka, respectively. The grain size frequency distributions of samples in units 7b and 7d are characterized by a distinctive peak at around 300 μm and a very smooth peak at around 20 μm . A few samples have two smooth peaks at around 10 and 200 μm in unit 7b, while few samples have one smooth peak at around 40 to 50 μm in unit 7d (Fig. 10H, J). These analyses indicate shallow lake environments occurred at 60-40 and 30-20 ka. As shown in Fig. 11, the stable deep lake periods generally correspond to a high clay and silt component, and low sand component. This is likely due to the location of the drill core site far from the lake shoreline, with higher lake levels resulting in an expansion of the lake margins.

We obtained only one pIRIR Holocene age of ~ 3 ka at the depth of the 1.1 m. The top 0.4 m of the deposits may not be reliable due to turbulence caused by the drilling system. As a result, we were unable to retrieve a reliable Holocene record from core BST12B. Chen *et al.* (2008) drilled and studied four intact Holocene lacustrine successions (see 2, 3, 4, 5 in Fig. 1) and the

chronology of these successions has been established by using AMS dating results of the plant remains and lacustrine organic materials. The chronology of these successions suggests that eolian sand was deposited in Bosten Lake during the early Holocene, and that a lacustrine environment occurred at the beginning of middle Holocene (~8 cal. ka BP). A relatively high lake level occurred 6.2-1.5 cal. ka BP.

In summary, a stable deep lacustrine environment was present at Bosten Lake at ~220, 210-180, ~165, 70-60, 45-30 and 20-5 ka, while shallow lake levels occurred at ~215, 180-165, 100-70, 60-40, 30-20 ka. The lake possibly dried out between ~160 and ~100 ka, with strong wind erosion occurring in the region. These high and low lake level variations are, however, inconsistent with the $\delta^{18}\text{O}$ records of stalagmites from Kesang Cave in Tianshan Mountains. Also, it is hard to correlate the lake level fluctuations to the Marine Isotope stages deduced from benthic foraminifera $\delta^{18}\text{O}$ values (Lisiecki & Raymo 2005). Thus, we suggest lake level fluctuations in the lakes of arid central Asia (e.g., Bosten Lake) may not respond directly to climatic changes and may be affected by a number of complex factors (e.g. shifting of the inflow rivers of the lake, and glacier advances and retreats).

Bosten Lake apparently dried up between ~160 and ~100 ka, corresponding to mid-late MIS 6 to early MIS 5, spanning periods of penultimate glaciation and last interglaciation. The quick lake level drop might have been caused by a combination of factors including lake basin geomorphological changes and shifts in river inflow rates. The precipitation in the region is carried by westerlies, and the north-southward variation of the westerlies on orbital and suborbital timescale can cause the precipitation variations and lake level fluctuations (Liu *et al.* 2015). In that case, the of climatic changes in the region is likely much different to that in East Asia characterized with cycles of moisture interglacials and dry glacials (Sun *et al.* 2006). Also,

the glacier advances and retreats in the Tianshan Mountains area may have contributed to lake level fluctuations. Andreas (2010) drilled a 93.6 m deep sediment core in Niederweningen in the Wehntal, Northern Switzerland, establishing a chronology using anomalous fading corrected IRSL ages, and discovered a clear age gap in the drill core covering most of MIS 6. It was suggested that a possible glacier advance and erosion of the lake sediments during MIS 6 may have caused this age gap. The driving forces of the lake level fluctuations and lake evolution in arid central Asia need a further study.

Conclusions

We investigated the luminescence characteristics of quartz and K-feldspar from a 51.6 m deep drill core collected at Bosten Lake in the Tianshan Mountains of central ACA. Quartz SAR dating was applied to 7 OSL samples from the top of the core, while the K-feldspar pIRIR dating was successfully employed for 30 samples to establish a chronology for the core. Dose recovery tests indicate pIRIR dating is suitable for lacustrine samples from Bosten Lake. The agreement between pIRIR₂₉₀ ages and quartz OSL ages for samples <40 ka and a smooth relationship in the IR₅₀ D_e-pIRIR₂₉₀ D_e plot suggest that K-feldspars from the lacustrine deposits were well-bleached before burial. The quartz OSL ages for four samples that older than ~40 ka are systematically smaller than the K-feldspar pIRIR ages, which is probably due to quartz OSL age underestimation at doses approaching ~100 Gy. A robust chronology was established by Bacon age-depth modelling using 3 quartz OSL ages and 28 pIRIR ages. A combination of chronology, lithology and grain-size analysis indicates that Bosten Lake formed at at least ~220 ka and that water levels fluctuated frequently after that. A stable deep lake occurred at ~220, 210-180, ~165, 70-60, 40-30 and 20-5 ka, while shallow levels occurred at ~215, 180-165, 100-70, 60-40 and

30-20 ka. Bosten Lake levels decreased by at least ~29 m and possibly the level even dried up between ~160 and ~100 ka. Lake level fluctuations in the lakes of arid central Asia (e.g., Bosten Lake) may not respond directly to climatic changes and may be affected by a number of complex factors, which requires further studies.

Acknowledgements. - We thank two anonymous reviewers whose comments improved the manuscript, and Prof. Jan A. Piotrowski for English language improvement. This study was supported by the NSFC grant No. 41571181, 41302143, 41130102 and 41171168.

References

- Aitken, M.J. 1985: *Thermoluminescence Dating*. 359 pp. Academic, New York.
- Aitken, M.J. 1998: *An Introduction to Optical Dating*. 267 pp. Oxford University Press, Oxford.
- Aizen, V.B., Aizen, E.M., Fujita, K., Takeuchi, N., Nikitin, S.A. & Joswiak, D.R. 2006: Climatic and atmospheric circulation pattern variability from ice-core isotope/geochemistry records (Altai, Tien Shan and Tibet). *Annals of Glaciology* 43, 49-60.
- Züger, A., 2010: Climatic and environmental changes during the transition from the Penultimate Glaciation into the Last Interglacial (MIS 6-5e): a case study from Niederweningen, Switzerland. Master thesis. <http://csold.unibe.ch/students/theses/msc/45.pdf>
- Auclair, M., Lamothe, M. & Huot, S. 2003: Measurement of anomalous fading for feldspar IRSL using SAR. *Radiation Measurements* 37, 487–492.
- Banerjee, D., Murray, A.S., Bøter-Jensen, L. & Lang, A. 2001: Equivalent dose estimation using a single aliquot of polymineral fine grains. *Radiation Measurement* 33, 73–94.
- Blaauw, M. 2010: Methods and code for classical age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5, 512-518.
- Blaauw, M. & Christen, J. 2011: Flexible paleoclimate age-depth models using an autoregressive gamma

process. *Bayesian Analysis* 6, 457-474.

Bøtter-Jensen, L., Thomsen, K.J. & Jain, M. 2010: Review of optically stimulated luminescence (OSL) instrumental developments for retrospective dosimetry. *Radiation Measurements* 45, 253–257.

Buylaert, J. P., Huot, S., Murray, A. S., Van den haute, P. 2011: Infrared stimulated luminescence dating of an Eemian (MIS 5e) site in Denmark using K-feldspar. *Boreas* 40, 46–56.

Buylaert, J.P., Jain, M., Murray, A.S., Thomsen, K.J., Thiel, C. & Sohbati, R. 2012: A robust feldspar luminescence dating method for Middle and Late Pleistocene sediments. *Boreas* 41, 435-451.

Buylaert, J.P., Murray, A.S., Gebhardt, A.C., Sohbati, R., Ohlendorf, C., Thiel, C., Wastegard, S. & Zolitschka, B. 2013: Luminescence dating of the PASADO core 5022-1D from Laguna Potrok Aike (Argentina) using IRSL signals from feldspar. *Quaternary Science Reviews* 71, 70-80.

Buylaert, J.P., Murray, A.S., Thomsen, K.J. & Jain, M. 2009: Testing the potential of an elevated temperature IRSL signal from K-feldspar. *Radiation Measurements* 44, 560-565.

Buylaert, J.P., Vandenberghe, D., Murray, A.S., Huot, S., De Corte, F. & Van den haute, P. 2007: Luminescence dating of old (>70 ka) Chinese loess: a comparison of single-aliquot OSL and IRSL techniques. *Quaternary Geochronology* 5, 9-14.

Chapot, M.S., Roberts, H.M., Duller, G.A.T. & Lai, Z.P. 2012: A comparison of natural- and laboratory-generated dose response curves for quartz optically stimulated luminescence signals from Chinese Loess. *Radiation Measurements* 47, 1045-1052.

Chen, F.H., Yu, Z.C., Yang, M.L., Ito, M., Wang, S.M., Madsen, D.B., Huang, X.Z., Zhao, Y., Sato, T., Birks, H.J.B., Boomer, I., Chen, J.H., An, C.B. & Wünnemann, B. 2008: Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history. *Quaternary Science Reviews* 27, 351–364.

Chen, Y.W., Li, S.H. & Li, B. 2013: Residual doses and sensitivity change of post IR IRSL signals from potassium feldspar under different bleaching conditions, *Geochronometria* 40, 229-238.

Cheng, H., Zhang, P., Spötl, C., Edwards, R.L., Cai, Y., Zhang, D., Sang, W., Tan, M. & An, Z. 2012: The climatic cyclicity in semiarid-arid Central Asia over the past 500 000 years, *Geophysical Research Letters* 39, L01705.

- Colarossi, D., Duller, G.A.T., Roberts, H.M., Tooth, S. & Lyons, R. 2015: Comparison of paired quartz OSL and feldspar post-IR IRSL dose distributions in poorly bleached fluvial sediments from South Africa, *Quaternary Geochronology* 30, 233-238.
- Cunningham, A.C. & Wallinga, J. 2010: Selection of integration time intervals for quartz OSL decay curves. *Quaternary Geochronology* 5, 657-666.
- Duller, G.A.T. 2003: Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiation Measurements* 37, 161-165.
- Wang, W. & Feng, Z.D. 2013: Holocene moisture evolution across the Mongolian Plateau and its surrounding areas: A synthesis of climatic records. *Earth-Science Reviews* 122, 38-57.
- Fu, X., Li, B. & Li, S.H. 2012: Testing a multi-step post-IR IRSL dating method using polymineral fine grains from Chinese loess. *Quaternary Geochronology* 10, 8-15.
- Godfrey-Smith, D.L., Huntley, D.J. & Chen, W.H. 1988: Optically dating studies of quartz and feldspar sediment extracts. *Quaternary Science Reviews* 7, 373-380.
- Guérin, G., Mercier, N., & Adamiec, C. 2011: Dose-rate conversion factors: update. *Ancient TL* 29, 5-8.
- Hatté, C., Pessenda, L.C., Lang, A., Paterne M., 2001. Development of accurate and reliable ¹⁴C chronologies for loess deposits: application to the loess sequence of nussloch (Rhine valley, Germany). *Radiocarbon* 43, 611-618.
- Huang, X.Z., Zhou, G., Ma, Y.L., Xu, Q.H. & Chen, F.H. 2010: Pollen distribution in large freshwater lake of arid region: a case study on the surface sediments from Bosten Lake, Xinjiang, China. *Frontiers of Earth Science* 2, 174-180.
- Huntley, D.J. & Baril, M.R. 1997: The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating. *Ancient TL* 15, 11-13.
- Huntley, D.J. & Hancock, R.G.V. 2001: The Rb contents of the K-feldspar grains being measured in optical dating. *Ancient TL* 19, 43-46.
- Huntley, D.J. & Lamothe, M. 2001: Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating. *Canadian Journal of Earth Sciences* 38, 1093-1106.
- Jin, L.Y., Chen, F.H., Morrill, C., Otto-Bliesner, B.L. & Rosenbloom, N. 2012: Causes of early Holocene

desertification in arid central Asia. *Climate Dynamics* 38, 1577-1591.

Jin, M., Li, G., Li, F., Duan, Y., Wen, L., Wei, H., Yang, L., Fan, Y. & Chen, F. 2015: Holocene shorelines and lake evolution in Juyanze Basin, southern Mongolian Plateau, revealed by luminescence dating. *The Holocene* 25, 1898-1911.

Kars, R.H., Reimann, T., Ankjaergaard, C. & Wallinga, J. 2014: Bleaching of the post-IR IRSL signal: new insights for feldspar luminescence dating. *Boreas* 43, 780-791.

Lerman, A. 1978: *Lakes: Chemistry, Geology and Physics*. 356 pp. Springer-Verlag, New York.

Li, B. & Li, S.H. 2011: Luminescence dating of K-feldspar from sediments: a protocol without anomalous fading correction. *Quaternary Geochronology* 6, 468–479.

Li, B. & Li, S.H. 2012a: Luminescence dating of Chinese loess beyond 130 ka using the nonfading signal from K-feldspar. *Quaternary Geochronology* 10, 24–31.

Li, B. & Li, S.H. 2012b: A reply to the comments by Thomsen et al. on “Luminescence dating of K-feldspar from sediments: A protocol without anomalous fading correction”. *Quaternary Geochronology* 8, 49–51.

Li, G., Jin, M., Wen, L., Zhao, H., Madsen, D.B., Liu, X., Wu, D. & Chen, F. 2014: Quartz and K-feldspar optical dating chronology of eolian sand and lacustrine sequence from the southern Ulan Buh Desert, NW China: Implications for reconstructing late Pleistocene environmental evolution. *Palaeogeography Palaeoclimatology Palaeoecology* 393, 111–121.

Li, G., Wen, L., Xia, D., Duan, Y., Rao, Z., Li, F., Jia, J., Zhao, H. & Chen, F., 2015. Quartz OSL and K-feldspar pIRIR dating of a loess/paleosol sequence from arid central Asia, Tianshan Mountains, NW China. *Quaternary Geochronology* 28, 40-53.

Li, G., Rao, Z., Duan, Y., Xia, D., Wang, L., Madsen, D.B., Jia, J., Wei, H., Qiang, M., Chen, J. & Chen, F. 2016: Paleoenvironmental changes recorded in a luminescence dated loess/paleosol sequence from the Tianshan Mountains, arid central Asia, since the Penultimate Glaciation. *Earth and Planetary Science Letters* 448, 1-12.

Liu, X., Rao, Z., Zhang, X., Huang, W., Chen, J. & Chen, F., 2015: Variations in the oxygen isotopic composition of precipitation in the Tianshan Mountains region and their significance for the Westerly circulation. *Journal of Geographical Sciences* 25, 801-816.

- 676 Lisiecki, L.E. & Raymo, M.E. 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$
 677 records. *Paleoceanography* 20, PA1003.
- 678 Mischke, S. & Wünnemann, B. 2006: The Holocene salinity history of Bosten Lake (Xinjiang, China) inferred
 679 from ostracod species assemblages and shell chemistry: Possible palaeoclimatic implications. *Quaternary*
 680 *International* 154/155, 100-112.
- 681 Morthekai, P., Jain, M., Murray, A. S., Thomsen, K. J. & Bøtter-Jensen, L. 2008: Fading characteristics of
 682 martian analogue materials and the applicability of a correction procedure. *Radiation Measurements* 43,
 683 672–678.
- 684 Murray, A.S. 1996: Developments in optically stimulated luminescence and photo-transferred
 685 thermoluminescence dating of young sediments: Application to a 2000-year sequence of flood deposits.
 686 *Geochimica et Cosmochimica Acta* 60, 565-576
- 687 Murray, A.S. & Olley, J.M. 2002: Precision and accuracy in the optically stimulated luminescence dating of
 688 sedimentary quartz: a status review. *Geochronometria* 21, 1–16.
- 689 Murray, A.S., Thomsen, K.J., Masuda, N., Buylaert, J.P. & Jain, M. 2012: Identifying well-bleached quartz
 690 using the different bleaching rates of quartz and feldspar luminescence signals. *Radiation Measurements*
 691 47, 688-695.
- 692 Peng, Y.J., Xiao, J.L., Nakamura, T., Liu, B.L. & Inouchi, Y. 2005: Holocene East Asian monsoonal
 693 precipitation pattern revealed by grain size distribution of core sediments of Daihai Lake in Inner
 694 Mongolia of north-central China. *Earth and Planetary Science Letters* 233, 467 – 479.
- 695 Pessenda, L.C.R, Gouveia, S.E.M. & Aravena, R. 2001: Radiocarbon dating of total soil organic matter and
 696 humin fraction and it's comparison with ^{14}C age of fossil charcoal. *Radiocarbon* 43, 596–601.
- 697 Prescott, J.R. & Hutton, J.T. 1994: Cosmic ray contributions to dose rates for luminescence and ESR dating:
 698 Large depths and long-term time variations. *Radiation Measurements* 23, 497–500.
- 699 Qin, J.T. & Zhou, L.P. 2012: Effects of thermally transferred signals in the post-IR IRSL SAR protocol.
 700 *Radiation Measurements* 47, 710-715.
- 701 Reimann, T, Tsukamoto, S, Naumann, M. & Frechen, M. 2011: The potential of using K-rich feldspars for
 702 optical dating of young coastal sediments-A test case from Darss-Zingst peninsula (southern Baltic Sea

coast). *Quaternary Geochronology* 6, 207–222.

Reimann, T. & Tsukamoto, S. 2012: Dating the recent past (<500years) by post-IRSL feldspar-Examples from the North Sea and Baltic Sea coast. *Quaternary Geochronology* 10, 180-187.

Roberts, H.M. 2012: Testing Post-IR IRSL protocols for minimising fading in feldspars, using Alaskan loess with independent chronological control. *Radiation Measurements* 47, 716-724.

Rudaya, N., Tarasov, P., Dorofeyuk, N., Solovieva, N., Kalugin, I., Andreev, A., Daryin, A., Diekmann, B., Riedel, F., Tserendash, T. & Wagner, M. 2008: Holocene environments and climate in the Mongolian Altai reconstructed from the Hoton-Nur pollen and diatom records: a step towards better understanding climate dynamics in Central Asia. *Quaternary Science Reviews* 28, 540-554.

Spooner, N.A. 1994: The anomalous fading of infrared stimulated luminescence from feldspars. *Radiation Measurements* 23, 625-633.

Sohbati, R., Murray, A.S., Buylaert, J.P., Ortuño, M. & Cunha, P.P. 2011: Luminescence dating of Pleistocene alluvial sediments affected by the Alhama de Murcia fault (southeastern Betics, Spain) – a comparison between OSL, IRSL and post-IR IRSL ages. *Boreas* 41, 250-262

Song, Y.G., Li, C.X., Zhao, J.D., Cheng, P. & Zeng, M.X. 2012: A combined luminescence and radiocarbon dating study of the Iii loess, Central Asia. *Quaternary Geochronology* 10, 2-7.

Sun, Y.B., Chen, J., Clemens, S.C., Liu, Q.S., Ji, J.F. & Tada, R. 2006: East Asian monsoon variability over the last seven glacial cycles recorded by a loess sequence from the northwestern Chinese Loess Plateau. *Geochemistry Geophysics Geosystems* 7, Q12Q02.

Thiel, C., Buylaert, J.P., Murray, A., Terhorst, B., Hofer, I., Tsukamoto, S. & Frechen, M. 2011: Luminescence dating of the Stratzing loess profile (Austria) – Testing the potential of an elevated temperature post-IR IRSL protocol. *Quaternary International* 234, 23–31.

Thomsen, K.J., Murray, A.S., Jain, M. & Bøtter-Jensen, L. 2008: Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. *Radiation Measurements* 43, 1474-1486.

Thomsen, K.J., Murray, A.S., Jain, M. & Buylaert, J.P. 2012: Re ‘Luminescence dating of K-feldspar from sediments: a protocol without anomalous fading correction’ by Bo Li and Sheng-Hua Li. *Quaternary Geochronology* 8, 46–48.

- Wang, B. & Ding, Q.H. 2008: Global monsoon: dominant mode of annual variation in the tropics. *Dynamics of Atmospheres and Oceans* 44, 165–183.
- Wintle, A.G. 2008: Luminescence dating: where it has been and where it is going. *Boreas* 37, 471–482.
- Wintle, A.G. & Murray, A.S. 2006: A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating. *Radiation Measurements* 41, 369–391.
- Wünnemann, B., Mischke, S. & Chen, F.H. 2006: A Holocene sedimentary record from Bosten Lake, China. *Palaeogeography Palaeoclimatology Palaeoecology* 234, 223–238.
- Xiao, M., Wu, F.C., Liao, H.Q., Li, W., Lee, X.Q. & Huang, R.S. 2010: Characteristics and distribution of low molecular weight organic acids in the sediment porewaters in Bosten Lake, China. *Journal of Environmental Sciences-China* 22, 328–337.
- Yin, Z.Q., Qin, X.G., Wu, J.S. & Ning, B. 2008: Multimodal grain-size distribution characteristics and formation mechanism of lake sediments. *Quaternary Sciences* 28, 345–353 (in Chinese with English abstract).
- Yang, S.L., Forman, S.L., Song, Y.G., Pierson, J., Mazzocco, J., Li, X.X., Shi, Z.T. & Fang, X.M. 2014: Evaluating OSL-SAR protocols for dating quartz grains from the loess in Ili Basin, Central Asia. *Quaternary Geochronology* 20, 78–88.
- Yi, S., Buylaert, J.P., Murray, A.S., Thiel, C., Zeng, L. & Lu, H.Y. 2015: High resolution OSL and post-IR IRSL dating of the last interglacial–glacial cycle at the Sanbahu loess site (northeastern China). *Quaternary Geochronology* 30, 200–206.
- Yi, S., Buylaert, J.-P., Murray, A. S., Lu, H., Thiel, C. & Zeng, L. 2016: A detailed post-IR IRSL dating study of the Niuyangzigou loess site in northeastern China. *Boreas*, doi: 10.1111/bor.12185.

Figure and Table captions

Fig. 1. Map of Bosten Lake and surrounding areas. Drill core localities are shown as squares with associated numbers: 1-BST12B, 2-BST04H, 3-BST04C, 4-BSTC-01 and 5-XBWu46. The green lines represent the Kaidu and Kongque rivers, the main recharge and discharge rivers, respectively. The dashed line in the inset represents the modern Asian summer monsoon limit (Chen *et al.* 2008).

Fig. 2. Lithology of core BST12B at Bosten Lake, OSL sample codes, and associated luminescence age estimates.

Fig. 3. A. Histogram of OSL IR depletion ratio for all aliquots of quartz samples as listed in Table 3. B. Histogram summarising the recycling ratios for all measured aliquots using quartz OSL dating. The inset shows a histogram of the recuperation values for all quartz aliquots. C. Histogram summarising the recycling ratios for all measured aliquots using pIRIR dating. The inset shows a histogram of the recuperation values for all measured aliquots.

Fig. 4. Luminescence characteristics of decay and growth curves for quartz and K-feldspar samples from the drill core: A. Decay curves of the natural signal, and regeneration doses of 95.33 Gy and 0 Gy for the quartz sample Bst12b-488. B. Fit growth curves for quartz sample Bst12b-488 using an exponential function. C. Decay curves of the IRSL and pIRIR signals for the youngest sample Bst12b-110. D. Decay curves of the IRSL and pIRIR signals for the oldest sample Bst12b-5120. E. Growth curves of the IRSL and pIRIR signals for an old sample (Bst12b-2896) when a small test dose of ~38 Gy was applied (~6% of D_e). F. Growth curves of the IRSL and pIRIR signals for an old sample (Bst12b-5120) when a large test dose of ~340 Gy was applied (~58% of D_e).

Fig. 5. A. Anomalous fading of the IR₅₀ signal and pIRIR₂₉₀ results for sample Bst12b-1070. B. Anomalous fading of the IR₅₀ signal and pIRIR₂₉₀ results for sample Bst12b-2706. C. Dependence of D_e on prior IR stimulation temperature from 50 to 250 °C in 50 °C intervals for sample Bst12b-1070. Three aliquots were measured at each temperature. Error bars represent one standard error.

Fig. 6. Residual doses of the pIRIR₂₉₀ and IR₅₀ signals for samples from different depths of the core after 56 h of sunlight bleaching (A) and 112 h of sunlight bleaching (B).

Fig. 7. IR₅₀ D_e plotted against pIRIR₂₉₀ D_e values for all samples from the core. The solid line represents a single saturating exponential function of the form $y = a(1 - \exp(-x/b))$ ($y = 535.7(1 - \exp(-x/274.9))$) fitted to the data represented by the solid symbols. The dash-dotted line is derived from the solid line by multiplying the pIRIR₂₉₀ co-ordinates of the line by 1.1. Error bars represent one standard error (see Table 2).

Fig. 8. Summary of dosimetric information. ‘Dose rate’ is the total field dose rate of sand-sized K-feldspar grains. Analytical data are provided in Table 2. The black squares are the observed water contents and the red circles are the saturation water contents. The saturation water content was used for dose rate calculations.

Fig. 9. A. pIRIR D_es for samples from different depths in core BST12B. B. pIRIR ages at different depths in core BST12B using a reconstructed Bacon age-depth model (red dashed line) derived from 3 quartz OSL age and 28 K-feldspar pIRIR ages. The grey shading indicates the model's 95% probability interval.

Fig. 10. Grain-size frequency distribution curves for samples from different lithological units of core BST12B.

Fig. 11. The mean grain sizes of the clay, silt, and sand components of core BST12B during the past ~253 ka, and their relationship to climatic stalagmite record at Kesang Cave (Cheng *et al.* 2012) and benthic foraminifera $\delta^{18}\text{O}$ record from core LR04 (Lisiecki & Raymo 2005). Low $\delta^{18}\text{O}$ values indicate a warmer climate and vice versa. The grey shade indicates stable deep lake periods.

Table 1. K-feldspar pIRIR₂₉₀ dating protocol and quartz post-IR OSL dating protocol.

Table 2. K-feldspar pIRIR₂₉₀ dating results. Saturated water content was employed for dose rate determinations except that the observed water content of ~38% for sample Bst12b-110 was applied to dose rate calculation. The absolute uncertainty on the water content is 8%.

Table 3. Quartz OSL dating results for samples from the top of the drill core.

Table 4. Summary of the residual doses of the pIRIR₂₉₀ and IR₅₀ signals after 2 weeks (56 h, 14 days, 4 hours per day) and after one month (112 h, 28 days, 4 hours per day) of sunlight bleaching for 24 samples from the drill core.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Step	pIRIR K-feldspar protocol (Thiel <i>et al.</i> 2011)	Observed	Double SAR quartz protocol (Banerjee <i>et al.</i> 2001)	Observed
1	Give dose D_i		Give dose D_i	
2	Preheat at 320 °C for 60 s		Preheat at 260 °C for 10 s	
3	IRSL, 200 s at 50 °C	L_{X1}	IRSL, 100 s at 50 °C	
4	pIRIR, 200 s at 290 °C	L_{X2}	OSL, 100 s at 125 °C	L_X
5	Give test dose		Give test dose	
6	Preheat at 320 °C for 60 s		Preheat at 220 °C for 10 s	
7	IRSL, 200 s at 50 °C	T_{X1}	IRSL, 100 s at 50 °C	
8	pIRIR, 200 s at 290 °C	T_{X2}	OSL, 100 s at 125 °C	T_X
9	IRSL, 100 s bleaching at 325 °C		Return to 1	
10	Return to 1			

Sample No.	Depth (m)	Grain size (µm)	Ali quots	pIRIR ₂₉₀ D _e (Gy)	IR ₅₀ D _e (Gy)	U (ppm)	Th (ppm)	K (ppm)	Observed W.C. (%)	Saturation W.C. (%)	Dose Rate (Gy ka ⁻¹)	IR ₅₀ age (ka)	pIRIR ₂₉₀ age (ka)
Bst12b-110	1.10	90-125	5	7.2±0.2	4.9±0.1	1.60±0.08	5.81±0.20	1.84±0.06	38	29	2.43±0.09	2.0±0.1	3.0±0.2
Bst12b-353	3.53	63-90	6	46±1	29±1	2.79±0.11	5.71±0.19	1.71±0.06	15	31	2.50±0.10	12±1	18±1
Bst12b-488	4.88	90-125	4	68±2	46±1	1.86±0.08	9.23±0.28	1.67±0.06	9	23	2.78±0.12	17±1	24±2
Bst12b-533	5.33	90-125	6	92±1	61±1	1.51±0.08	6.98±0.23	1.96±0.06	0.2	23	2.82±0.12	22±2	33±2
Bst12b-746	7.46	90-125	4	116±2	77±1	1.71±0.08	7.74±0.26	2.02±0.06	13	28	2.83±0.12	27±2	41±3
Bst12b-889	8.89	90-125	6	155±2	112±2	2.79±0.10	7.67±0.25	1.88±0.06	14	21	3.05±0.13	37±3	51±4
Bst12b-1070	10.70	90-125	4	183±3	114±2	1.07±0.06	3.91±0.15	2.08±0.06	14	20	2.71±0.12	42±3	68±5
Bst12b-1364	13.64	90-125	8	201±3	137±1	1.16±0.06	4.54±0.16	2.21±0.06	15	16	2.96±0.13	46±3	68±5
Bst12b-1594	15.94	90-125	4	200±5	133±2	1.72±0.08	5.99±0.20	1.87±0.06	13	23	2.70±0.12	49±3	74±5
Bst12b-1860	18.60	90-125	4	211±3	138±3	1.60±0.08	8.18±0.25	2.29±0.07	16	19	3.25±0.15	42±3	65±5
Bst12b-1974	19.74	90-125	4	286±6	188±5	2.33±0.09	10.1±0.28	1.91±0.06	11	25	3.01±0.13	62±4	95±7
Bst12b-2064	20.64	90-125	10	462±7	243±5	1.42±0.08	4.71±0.17	1.81±0.06	14	19	2.59±0.12	94±7	178±13
Bst12b-2223	22.23	63-90	4	484±6	256±5	2.88±0.11	10.8±0.30	1.92±0.06	25	27	3.01±0.13	85±6	161±11
Bst12b-2310	23.10	63-90	4	514±14	261±9	2.46±0.10	9.75±0.27	1.86±0.06	23	28	2.82±0.12	93±7	183±13
Bst12b-2372	23.72	90-125	8	417±5	242±3	1.51±0.08	4.20±0.16	2.08±0.06	20	24	2.70±0.12	90±6	155±10
Bst12b-2446	24.46	90-125	4	552±12	247±4	2.64±0.10	10.5±0.29	2.00±0.06	20	25	3.16±0.13	78±5	174±12
Bst12b-2555	25.55	90-125	8	457±7	254±3	1.58±0.08	6.84±0.23	1.91±0.06	20	19	2.82±0.13	90±6	161±11
Bst12b-2706	27.06	90-125	6	500±8	255±3	1.55±0.08	6.93±0.23	1.76±0.06	15	24	2.72±0.12	94±6	183±13
Bst12b-2797	27.97	90-125	4	500±25	261±9	2.02±0.09	13.2±0.36	1.91±0.06	17	29	3.06±0.13	86±6	164±13
Bst12b-2896	28.96	90-125	8	600±13	320±5	2.76±0.11	10.2±0.30	1.95±0.06	21	29	3.04±0.12	106±7	198±14
Bst12b-2956	29.56	90-125	4	513±11	265±5	2.67±0.10	9.50±0.27	1.84±0.06	21	27	2.93±0.12	90±6	175±12
Bst12b-3053	30.53	90-125	8	585±14	319±7	2.95±0.11	10.8±0.31	2.00±0.06	21	23	3.28±0.14	97±7	178±13
Bst12b-3260	32.60	38-63	2	632±19	309±5	3.26±0.12	11.8±0.33	1.97±0.06	23	20	3.22±0.13	96±9	197±16
Bst12b-4115	41.15	90-125	8	547±12	264±4	2.91±0.11	18.4±0.48	2.51±0.07	19	26	3.99±0.13	66±5	138±10
Bst12b-4419	44.19	90-125	6	630±11	319±5	3.56±0.13	9.97±0.29	1.65±0.06	21	22	3.00±0.12	106±8	210±15
Bst12b-4590	45.90	90-125	6	649±8	313±3	3.46±0.12	11.0±0.31	2.24±0.07	22	35	3.20±0.13	98±7	203±13
Bst12b-4768	47.68	90-125	6	546±3	294±5	2.92±0.11	10.7±0.31	1.84±0.06	11	27	2.98±0.12	99±7	183±12
Bst12b-5054	50.54	90-125	4	577±10	287±8	2.12±0.09	8.84±0.26	1.93±0.06	14	27	2.80±0.12	102±8	206±14
Bst12b-5057	50.57	90-125	6	637±14	330±3	3.00±0.11	8.08±0.26	1.55±0.05	19	28	2.66±0.12	125±10	240±16
Bst12b-5120	51.20	90-125	4	612±12	294±7	1.88±0.08	7.83±0.24	1.83±0.06	18	28	2.68±0.13	110±8	229±15

Sample No.	Grain size (μm)	Aliquots	Quartz OSL D _e (Gy)	U (ppm)	Th (ppm)	K (%)	Water content (%)	Cosmic ray (Gy ka ⁻¹)	Dose rate (Gy ka ⁻¹)	Quartz OSL age (ka)
Bst12b-488	90-125	14	57±3	1.86±0.08	9.23±0.28	1.67±0.06	23	0.06	2.34±0.02	24±2
Bst12b-533	90-125	15	63±4	1.51±0.08	6.98±0.23	1.96±0.06	23	0.05	2.38±0.02	26±3
Bst12b-746	90-125	14	90±6	1.71±0.08	7.74±0.26	2.02±0.06	28	0.05	2.39±0.02	38±4
Bst12b-889	90-125	19	90±5	2.79±0.10	7.67±0.25	1.88±0.06	21	0.04	2.60±0.02	35±3
Bst12b-1070	90-125	13	97±5	1.07±0.06	3.91±0.15	2.08±0.06	20	0.04	2.27±0.02	43±4
Bst12b-1364	90-125	9	97±6	1.16±0.06	4.54±0.16	2.21±0.06	16	0.03	2.52±0.02	38±4
Bst12b-1594	90-125	13	126±7	1.72±0.08	5.99±0.20	1.87±0.06	23	0.03	2.26±0.01	56±5

Sample No.	Depth (m)	Residual dose pIRIR ₂₉₀ (56 h bleaching) (Gy)	Residual dose IR ₅₀ (56 h bleaching) (Gy)	Residual dose pIRIR ₂₉₀ (112 h bleaching) (Gy)	Residual dose IR ₅₀ (112 h bleaching) (Gy)
Bst12b-110	1.10	3.81±0.08	0.38±0.02	2.30±0.08	0.38±0.03
Bst12b-353	3.53	6.99±0.18	0.63±0.03	2.40±0.08	0.32±0.02
Bst12b-488	4.88	11.06±0.28	0.89±0.03	2.27±0.08	0.53±0.04
Bst12b-533	5.33	10.80±0.27	0.89±0.03	2.47±0.08	0.26±0.01
Bst12b-746	7.46	13.09±0.34	1.39±0.05	2.56±0.08	2.25±0.15
Bst12b-889	8.89	13.34±0.35	1.15±0.03	3.44±0.09	0.24±0.03
Bst12b-1070	10.70	16.40±0.40	1.52±0.05	2.39±0.08	0.53±0.04
Bst12b-1364	13.64	17.92±0.45	1.65±0.05	3.50±0.09	1.72±0.03
Bst12b-1594	15.94	17.54±0.50	1.91±0.06	2.69±0.09	0.27±0.03
Bst12b-1860	18.60	18.18±0.46	2.04±0.07	2.75±0.08	0.40±0.03
Bst12b-1974	19.74	17.38±0.41	2.20±0.08	5.06±0.19	0.37±0.02
Bst12b-2064	20.64	17.41±0.44	3.94±0.13	3.96±0.14	0.57±0.03
Bst12b-2372	23.72	25.04±0.61	2.93±0.08	2.57±0.08	0.45±0.03
Bst12b-2555	25.55	25.42±0.65	2.80±0.08	3.14±0.10	0.44±0.09
Bst12b-2706	27.06	24.79±0.68	3.43±0.09	3.05±0.09	0.58±0.05
Bst12b-2797	27.97	22.70±0.62	3.15±0.10	3.65±0.19	0.54±0.03
Bst12b-2896	28.96	20.97±0.54	3.05±0.09	3.73±0.12	0.33±0.03
Bst12b-3053	30.53	23.38±0.62	3.05±0.09	3.74±0.12	1.02±0.03
Bst12b-4115	41.15	24.53±0.62	3.56±0.10	2.99±0.11	1.08±0.07
Bst12b-4419	44.19	22.62±0.62	5.34±0.17	3.08±0.11	0.61±0.03
Bst12b-4590	45.90	28.22±0.69	3.94±0.10	3.91±0.10	0.53±0.04
Bst12b-4768	47.68	25.42±0.65	3.94±0.10	3.84±0.10	0.29±0.03
Bst12b-5057	50.57	38.13±1.28	6.36±0.15	3.85±0.11	0.39±0.03