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Research paper

# OSL and ESR dating of glacial deposits and its implications for glacial landform evolution in the Bogeda Peak area, Tianshan range, China

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A B S T R A C T

The Bogeda Peak area is the largest center of modern glaciation in the eastern Tianshan range in China. Four moraine complexes and associated fluvioglacial deposits are well preserved in the valleys, indicating multiple Quaternary glaciations in this region. Optically stimulated luminescence (OSL) and electron spin resonance (ESR) dating were used to determine the ages of the glacial tills and associated sediments in the Gubanbogeda and Heigou valleys. A total of eighteen samples were collected from moraines and fluvioglacial deposits. Fourteen samples were dated using OSL with a single-aliquot regenerative-dose (SAR) protocol, and the other four samples were analyzed by ESR dating of germanium (Ge) centers in quartz grains, which are sensitive to both sunlight and grinding. The results indicate that the fluvioglacial deposits are more suitable for OSL dating than the tills. Most ages show good agreement with the geological setting and field investigations, and the OSL and ESR ages are consistent with each other for the samples collected from the fourth set of moraines. Based on the ages as well as geomorphic and stratigraphic, the first and second moraine complexes of the Bogeda Peak area were deposited during the Little Ice Age (LIA) and Neoglaciation respectively. The low and high glacial terraces of the third set of moraines in the Gubanbogeda and Heigou valleys were deposited during marine oxygen isotope stages (MIS) 2 and 4. The fourth set of moraines has MIS 6 ages associated with the penultimate glaciation.



## 1. Introduction

Mountain glaciers are sensitive climatic markers that usually advance or retreat rapidly with changes in temperature and/or precipitation. The response of these glaciers to climate directly influences glacial erosion, sediment transport and deposition. As a result, spectacular landscapes have been produced in areas of mountain glaciations, and these landscapes contain important information on past climate change and landform evolution. Successions of multiple moraines that record glacial advance and retreat are common, providing a potential opportunity to investigate the nature of past glacier fluctuations as a part of paleoenvironmental reconstructions. In tectonically active regions, these studies can also provide potential information on the history of uplift (Shi et al., 2006).

Dating glacial landforms is a fundamental component for studying the landform evolution and for paleoenvironmental reconstructions. In recent decades, several new dating techniques, including cosmogenic radionuclides (CRN: e.g., Koppes et al., 2008; Li et al., 2011), electron spin resonance (ESR: e.g., Zhou et al., 2002; Yi et al., 2002; Zhao et al., 2006, 2010) and optically stimulated luminescence (OSL: e.g., Owen et al., 2002; Spencer and Owen, 2004; Ou et al., 2010), have been developed, refined and widely applied, and these dating techniques can potentially provide constraints on the ages of glacial sediments and landforms. This has allowed conventional mapping and relative dating studies to be augmented by quantitative dating techniques, which has allowed for significant advances in research on Quaternary glaciation in China (Shi et al., 2006, 2011).

The Tianshan range is a major, tectonically active mountain system in Central Asia. During Quaternary glacial–interglacial cycles, the Tianshan range was extensively and repeatedly glaciated, and landforms from multiple glaciations are well preserved in valleys, basins and on piedmonts. Studies of these landforms can provide insight into temporal and spatial variation of glacier extent

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and behavior, as well as contribute to paleoenvironmental reconstructions in the Tianshan range. Quaternary glacial landforms and moraines in the Bogeda Peak area have been studied extensively since the 1980s (Zheng and Wang, 1983; Zheng and Zhang, 1983). However, previous researchers were not able to closely constrain the ages of the glacial landforms and sediments because of the lack of well developed dating techniques at that time. Our current study focuses on determining the glacial chronology of the Bogeda Peak area using OSL and ESR dating of glacial landforms and sediments. This paper describes the Quaternary glacial landforms and sediments on the south slope of Bogeda Peak, presents dating results, and uses the timing of glaciations to provide a conceptual framework for Quaternary glaciations in this part of the eastern Tianshan range.

## 2. Regional setting

The Bogeda range (43°10′ ~ 44°05′N, 87°40′ ~ 91°35′E) is an important part of the eastern segment of the Tianshan range, and extends about 330 km west to the east and about 40–70 km north to south, covering ~$2 \times 10^4$ km$^2$ (Wu et al., 1983). Two major basins, Tulufan and Zhuiger, occur along the south and north piedmont, and the Bogeda Peak area is the largest center of modern glaciation in the eastern segment of the Tianshan range. Glacier meltwater provides a vital resource for the oases and agriculture in this area.

The climate of the Tianshan range is dominated by mid-latitude westerlies, with precipitation directly influenced by the westerly circulation. The average annual precipitation above 4000 m is about 670 mm, and the average annual temperature is less than −9 °C in the Bogeda Peak area (Wu et al., 1983). Mountain ridges are between 3000 and 5000 m in elevation, and there are 469 active glaciers in this area with a modern equilibrium-line altitude (ELA) between 3740 and 3850 m (Lanzhou Institute of Glaciology and Geocryology, CAS, 1987). Currently-active glaciers include hanging, cirque, single valley and compound valley form with a total area of about 214 km$^2$ and an ice volume of about 10 km$^3$. The largest glacier is Shanxing (No. 5Y725B10), with an area of 10.27 km$^2$, an ice volume of about 0.99 km$^3$, and a terminus at 3330 m asl. Its meltwater flows into the Gubanbogeda River to the south and the Sangong River to the north.

## 3. Glacial landforms

Moraines that were deposited at the margins of modern glaciers during retreat over the past several decades are very distinct in the Bogeda Peak area. They have fresh glacial tills with well striated boulders. Four other major sets of moraines are present from the terminuses of the modern glaciers to an altitude of about 2200 m asl, and are seen particularly clearly on the south slope of Bogeda Peak (Fig. 1). Two valleys, the Gubanbogeda River valley and Heigou River valley were the focus of the work presented here.

### 3.1. Gubanbogeda river valley

Four major moraine complexes are preserved in the Gubanbogeda River valley and the first moraine complex occurs several hundred meters beyond the modern glacial landforms. This moraine complex consists of 3 or 4 end moraines with heights of 5–10 m, and the tills are fresh and unweathered.

The second set of moraines occurs between 0.3 and 4 km down valley from modern glaciers, and parts of the end moraine were buried or destroyed by later glacial advances. These moraines have incipient weathering and support pioneering plant species. Several meters of fluvioglacial deposits and 3 m lacustrine sediments were preserved on the outer side of the southwest margin of the second set of moraines. The distinct feature of the lacustrine sediments suggests that a short-lived glacial lake developed here.

The third moraine complex occurs between 3300 and 2500 m asl on both sides of the Gubanbogeda River and includes two glacial

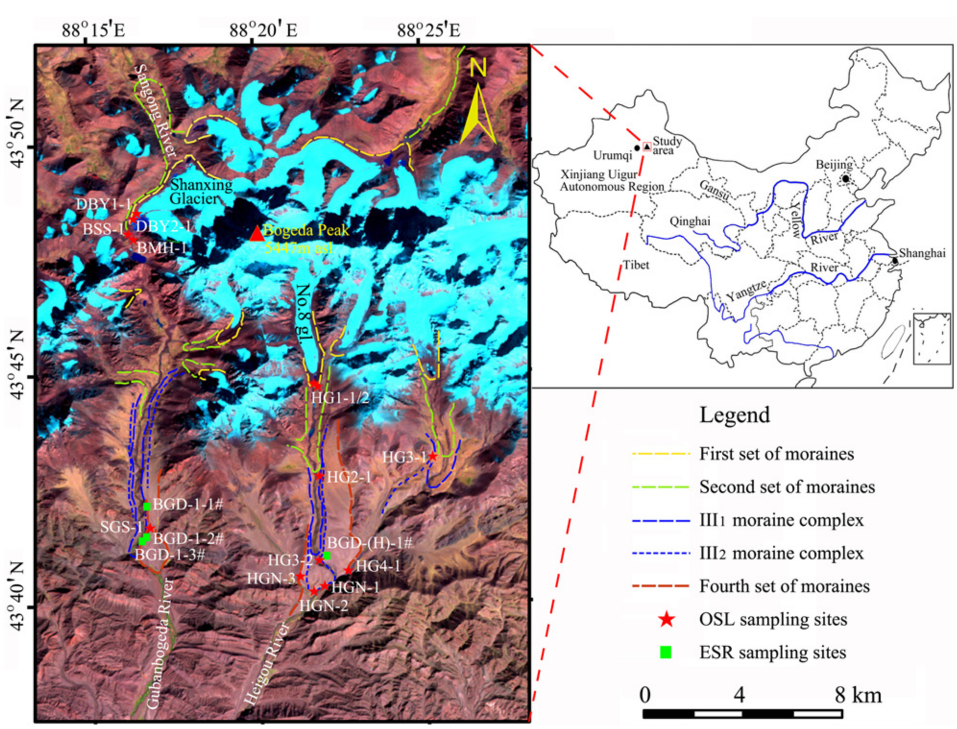


**Fig. 1.** Landsat ETM + image and the sampling sites in the Gubanbogeda river valley and Heigou river valley, Bogeda Peak area, Tianshan range.

terraces ($III_1$ and $III_2$). The $III_1$ moraine complex is about 20–30 m above the river and extends about 8 km from an altitude of about 3200 to 2500 m asl. Only a lateral moraine about 50 m above the river remains of $III_2$. Dolerite boulders, 2–3 m in diameter, are present on the surface of the moraines, and the surfaces of some boulders are covered by a 2–3 mm thick calcium carbonate coating. The till of the third moraines includes dolerite, limestone, slate and sandstone clasts.

The fourth moraine complex consists of a small glacial plateau beyond the third set of moraines. The till here is 50–100 m thick and occurs about 100 m above the river. There is also a high lateral moraine, extending about 2.5 km from about 3400 to 3100 m asl on the east side of the Gubanbogeda River, on the basis of depositional relationships, appears to have been deposited at the same time as the glacial plateau. The till of the fourth moraine complex includes dolerite, slate and sandstone lithologies and is compacted and semi-cemented with calcium carbonate suggesting that it dates to a much older glacial advance.

Distinctive erosional landforms are well developed and preserved above 3300 m asl in the Gubanbogeda River valley, including roche moutonnées, polished bedrock, horns, arêtes, cirques and other features.

### 3.2. Heigou River valley

Four major moraine complexes are also preserved in the Heigou River valley (Fig. 1), and the first moraine complex is an end moraine, ~500 m in front of the terminus of glacier No. 8. This end moraine dams up a small glacial lake (~0.05 $km^2$) and the lake outlet is incised 5–7 m in to the moraine. The tills of the first moraine complex are fresh and unweathered with no soil or vegetation development.

The second moraine complex occurs 0.5–4 km beyond the terminus of glacier No. 8. The Heigou River cuts through the outmost and largest end moraine on the east side in a gorge that is 20–30 m deep. Several meters of lacustrine sediments are visible along the river within this moraine complex, indicating that there were periods when glacial lakes were dammed up by moraines.

The third moraine complex in the Heigou River valley extends 4–9 km beyond the terminus of glacier No. 8 and also includes two glacial terraces ($III_1$ and $III_2$), similar to that of the Gubanbogeda River valley. The lower glacial terrace ($III_1$ moraine complex) is about 3 km long, 100–150 m wide, and 20–30 m above the current river. The higher glacial terrace ($III_2$ moraine complex) is about 5 km long, ranges in width up to 200 m, and is about 50–70 m above the river.

The fourth moraine complex occurs on both sides of the Heigou River. However, only high lateral moraines have been preserved. On the east side of the valley a 3.5 km lateral moraine has been preserved between 3300 and 2800 m asl. On the west side till is found from 3050 to 2400 m asl along a 4 km stretch of the valley. The main lithology of tills of the fourth moraine complex is dolerite and boulders 1–3 m in diameter are present on the surface of the lateral moraine.

## 4. Methods and results

Samples for luminescence and ESR dating were collected from natural or man-made sections (S1). The OSL samples were collected using metal tubes and the ESR samples in opaque plastic bags to ensure that they were not exposed to light. The OSL samples were analyzed in the OSL chronology laboratory at the Qinghai Institute of Salt Lakes, Chinese Academy of Sciences (CAS), Xining. The ESR samples were pretreated in the OSL chronology laboratory at the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), CAS, Lanzhou, and were analyzed in the chronology laboratory at the Institute of Geology, China Earthquake Administration, Beijing. The concentrations of U and Th and the contents of K were determined by neutron activation analysis (NAA) at the China Institute of Atomic Energy, Beijing.

### 4.1. OSL dating

The samples in the metal tubes were sub-sampled under safe laboratory light. The outer 2–3 cm of each end was removed and the interior were chemically treated and then sieved to collect the 38–63 μm fraction which was then treated following the procedures described by Lai et al. (2009) and Ou et al. (2010). The chosen fraction was etched with 35% hydrofluorosilicic acid ($H_2SiF_6$) for about 2 weeks to dissolve feldspars and then with 10% HCl to remove fluoride precipitates. Samples with obvious IRSL (infrared stimulated luminescence) signals were re-treated with fluorosilicic acid to avoid age underestimation (Lai and Brückner, 2008). The purity of treated quartz grains was checked by IR stimulation to ensure that feldspar contamination had been efficiently removed. Quartz grains were then mounted on the center of the stainless steel discs (10 mm in diameter) using silicone oil.

OSL measurements were performed on a Risø TL/OSL-DA-20 reader. To keep any residual IRSL signals from affecting the equivalent dose ($D_e$) estimation, a post-IR dating procedure was applied. The quartz discs were stimulated by infrared stimulation for 100 s at 0 °C before blue light stimulation (using double-SAR protocol by Banerjee et al., 2001). A preheat temperature plateau test for a representative sample (HG2-1) was carried out and 260 °C (10 s) was selected as the preheat temperature for our measurements. Stimulation by blue LEDs ($\lambda = 470 \pm 20$ nm) lasted for 40 s at 130 °C. The OSL signal was detected by a 9235QA photomultiplier tube through a 7.5 mm thick Hoya U-340 detection filter. Fig. 2 shows typical OSL decay curves for sample HG2-1 for natural dose (N), test dose (TD = 11.1 Gy), and regeneration doses of 88.8 Gy and 0 Gy. The curves show that the OSL signal decreases very quickly in the first second of stimulation, indicating that the signal is fast component dominant. For most aliquots, the recycling ratios were acceptable, implying that the test dose corrected for sensitivity changes appropriately. For some older glacial samples, the growth curves were still growing with doses greater than 300 Gy, indicating that the OSL signals were not saturated. Therefore, $D_e$s of less than 300 Gy could be determined.

For several samples, the decay curve of the 0 Gy regeneration dose shows a small thermal transfer signal. Previous studies

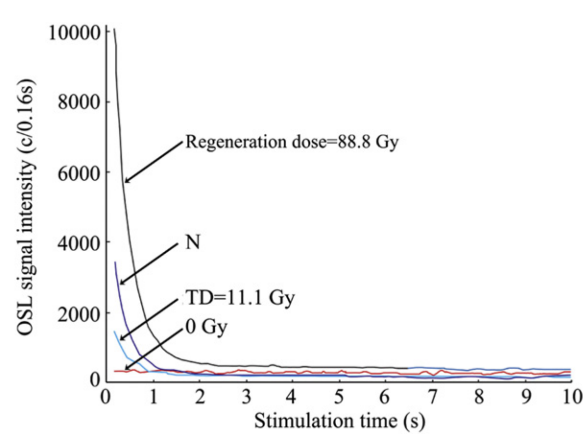


**Fig. 2.** OSL decay curves of natural dose (N), test dose (11.1 Gy), regeneration dose of 88.8 Gy and 0 Gy for sample HG2-1.

indicate that the effect of thermal transfer is significant for glacigenic sediments due to their low sensitivity (Richards, 2000). This effect is reflected by the ratio of the corrected OSL of the zero dose cycle ($L_0/T_0$) to the natural dose cycle ($L_N/T_N$). However, the values of the $(L_0/T_0)/(L_N/T_N)$ ratio for most aliquots are below the rejection level (Spencer and Owen, 2004; Wintle and Murray, 2006; Bøe et al., 2007). Therefore, the effect of thermal transfer on the $D_e$ is at an acceptable level for our samples.

$D_e$s were determined using both the single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000) and the standardized growth curve (SGC) methods (Roberts and Duller, 2004; Lai, 2006; Lai et al., 2007). For every sample, 6 aliquots were used for $D_e$ determination using the SAR protocol, and the SGCs were constructed using the SAR data (Fig. 3). Then, 16–18 additional aliquots were prepared and measured for the natural ($L_N$) and test dose ($T_N$) under the same conditions as those for the SAR procedure. The test dose corrected natural OSL signal level ($L_N/T_N$) was then matched with the SGC to obtain a $D_e$ value. The $D_e$s determined by SGC and SAR protocols are in agreement. The final $D_e$ is the mean of SAR $D_e$s and SGC $D_e$s.

### 4.2. ESR dating

For ESR dating, the Ge centers were chosen as dating signals because prior work has shown that the signal intensity of Ge centers in quartz grains exposed under natural room light does not decrease (Walther and Zilles, 1994; Rink, 1997). Schwarcz (1994) suggested that the samples can be prepared in normal laboratory light. Therefore, ESR samples were treated under natural room light conditions in this study. The sample preparation procedures followed Zhao et al. (2006, 2009). The prepared samples were divided into nine aliquots (about 250 mg each) and were irradiated with different artificial doses. ESR spectra were measured with an EMX1/6ESR Bruker spectrometer in the chronology laboratory at the Institute of Geology, China Earthquake Administration, Beijing. The measurement conditions and parameters were as follows: room temperature; X-band; microwave power: 2.021 mW; modulation amplitude: 0.1 mT; central magnetic field: 352.5 mT; sweep width: 5 mT; frequency: 9.852 GHz; modulation frequency: 100 kHz; time constant: 40.96 ms; and sweep time: 10.486 s. Typical ESR spectra of the glacial quartz grains are shown in Fig. 4. A least-squares analysis was used to fit the data points on the basis of different

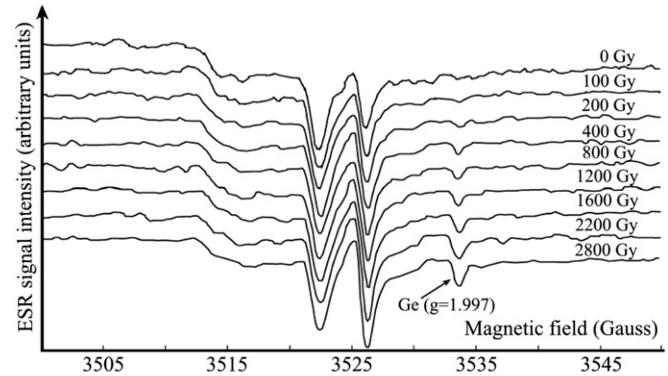


**Fig. 4.** Typical ESR spectra of the glacial quartz grain samples at room temperature.

artificial irradiation doses and their corresponding signal intensities. A linear-fit extrapolation was used to obtain $D_e$ (Fig. 5).

The annual dose rate ($D$) was estimated from the concentrations of U and Th and the contents of K, water content and the cosmic ray contribution which was estimated and calculated following the formulas of Prescott and Hutton (1994).

The OSL and ESR ages were calculated using the following equation:

$$T = \frac{D_e}{D}$$

where $D_e$ is the equivalent dose and the $D$ is the annual dose rate. The details of the sampling sites, the dating results and correlated parameters are listed in Table 1 (S2).

## 5. Discussion

### 5.1. Resetting OSL and ESR signals in glacial environments

In OSL and ESR dating it is assumed that the signal in mineral grains was resetted during the last process of sediment reworking, transportation and deposition. For OSL dating, the glaciogenic sediments are considered to be partially bleached (Duller, 1994, 2006) and previous studies have suggested that the fluvioglacial

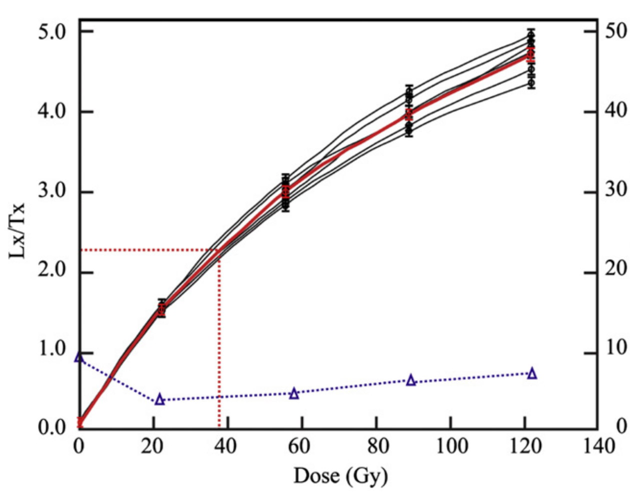


**Fig. 3.** Growth curves of six aliquots for sample HG2-1 and the curve of the constructed SGC (middle red line). The standard error for the regenerative-dose points is shown as empty triangles (right-hand $y$-axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

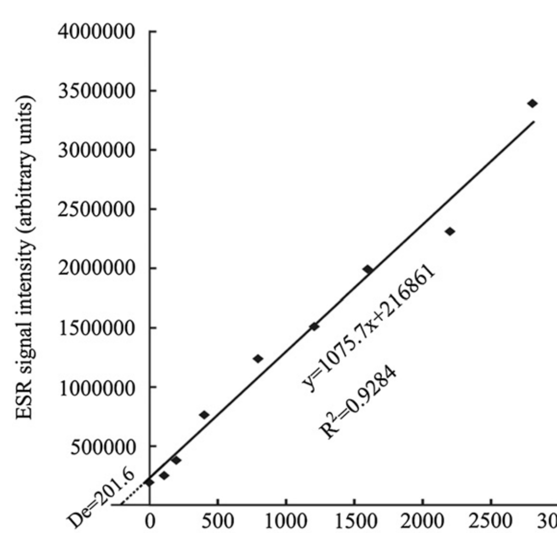


**Fig. 5.** Best-fit line between artificial radiation doses and ESR signal intensity (BGD-1-1).

deposits are more suitable for OSL dating than the glacial tills (Fuchs and Owen, 2008; Thrasher et al., 2009). Unexpected and inconsistent dates for till samples DBY2-1 (88.3 ± 5.3 ka), HG1-1 (34.9 ± 2.8 ka) and HG1-2 (123.2 ± 18.2 ka) collected from fresh, unweathered end moraines close to modern glaciers and the date for HG3-2 (187.7 ± 12.9 ka) collected from the third moraine complex (Fig. 1) confirms concerns about using OSL on tills. However, the signals of these four samples do not show saturation, suggesting that it might still be possible to date them with an appropriate dating strategy, such as single-grain dating techniques (Duller, 2006). The other ten samples are all from fluvioglacial deposits or sand lenses which were sandwiched within glacial tills. The dating results of these samples are consistent with their geological settings.

One method suggested for the detection of partially bleached sediments is the use of frequency histograms (Murray et al., 1995; Olley et al., 1998, 1999; Bøe et al., 2007; Ou et al., 2010). When plotting the $D_e$ values as histograms, well-bleached sediments have narrow and almost normal distribution, whereas, partially bleached sediments have a broad distribution and are skewed toward the larger $D_e$ values (Duller, 2004; Fuchs et al., 2007). Strongly skewed distributions reflect a small number of poorly bleached grains within a dominantly bleached sample (Olley et al., 1999; Fuchs et al., 2007). The $D_e$ frequency histograms obtained for our samples from fluvioglacial deposits and sand lenses have a narrow and nearly symmetric shape (Fig. 6), indicating that sufficient bleaching of the glacial quartz grains occurred. Samples collected directly from moraines have broad $D_e$ value distributions, indicating that minerals in glacial tills were poorly bleached in this area.

For ESR dating, the previous studies have shown that Ge centers are sensitive to sunlight, UV-light and grinding, and that these mechanisms could bleach sediments effectively (Buhay et al., 1988; Walther and Zilles, 1994; Rink, 1997; Ye et al., 1998). Subglacial and englacial clasts are subject to grinding during the downslope movement of alpine glaciers and high silt contents in glacial deposits as well as microscopic studies of till quartz grains suggest that abrasion and crushing are very prevalent in subglacial sediment transport (Yi, 1997). Therefore, sunlight and grinding could have bleached Ge centers in the quartz grains found in glacial till.

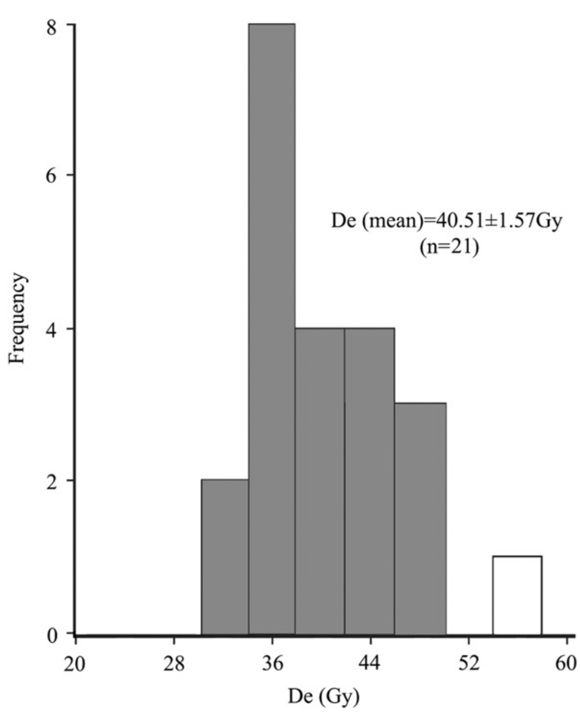


**Fig. 6.** $D_e$s histogram of the sample HG2-1. The empty column (aliquot with abnormal high dose) is excluded when calculating the average $D_e$.

### 5.2. Glacial sediment sequences

Glacial landforms in the Bogeda Peak area provide a promising opportunity for understanding local environmental variations, and dating provides a temporal framework for examining the rates of landscape evolution. In addition, it is believed that the $\delta^{18}O$ records of marine sediments or ice cores can be used as climatic proxies for comparison to records of continental glaciations. A comparison of the dating results in the Gubanbogeda and Heigou valleys and the other records demonstrate complex and long history of landscape evolution in this area (Fig. 7).

Glacier fluctuations in the Bogeda Peak area appear to be similar to those at the headwaters of the Urumqi River valley during the Holocene (Zheng and Zhang, 1983). Based on the degree of weathering, soil and vegetation development, Zheng and Zhang (1983) suggested that the first moraine complex beyond the terminuses of modern glaciers in the Urumqi River valley and the Bogeda Peak area was deposited during the Little Ice Age (LIA) (glacial advances in the cold periods since the 16th century). Considering that the dominant atmospheric circulation of the Tianshan range impacts both the Urumqi River valley and the Bogeda Peak area, and the lichenometrical results (1538 ± 20a AD, 1770 ± 20a AD and 1871 ± 20a AD) obtained on the moraines from the headwaters of the Urumqi River (Chen, 1989), it is reasonable to suggest that the first set of moraines in the Bogeda Peak area was deposited during the LIA.

The fluvioglacial deposits beyond the second set of moraines date to 1.3 ± 0.1 ka (BSS-1) and 1.6 ± 0.3 ka (BMH-1) (S1). This moraine complex was composed of several end moraines. Based on the field investigation and considered the stratigraphic and geomorphic relationships between the fluvioglacial deposits and the moraines, these fluvioglacial deposits were deposited during the period of the second moraine complex. Therefore, we conclude that the second moraine complex were deposited along the Neoglaciation (the largest glacial advances occurred during the last 3–4 ka in the western China (Shi et al., 2006, 2011)), and during this period, both the Shanxing glacier and the glacier No.8 extended for about 4 km beyond their current terminuses positions.

A sample from a sand lense in the low glacial terrace of the third moraine complex in the Heigou River valley was dated to 24.4 ± 1.7 ka (HG2-1) (Fig. 1), which is equivalent to marine oxygen isotope stage (MIS) 2 (Fig. 7a, b). Thus we conclude that the $III_1$ moraine complex in the Gubanbogeda River valley was deposited during a late period of the last glaciation. Based on geomorphic and stratigraphic relationships, we also conclude that erosional landforms such as roche moutonnées, polished bedrock and the other erosional features in the Gubanbogeda River valley between 3300 m asl to 3400 m asl were formed during this period.

Two samples collected from the $III_2$ moraine complex were dated to 78.0 ± 6.8 ka (HGN-1) and 85.0 ± 12.4 ka (HGN-2) and one sample collected from a tributary in the east was dated to 75.4 ± 7.1 ka (HG3-1). All these dates place the moraine deposition during late MIS 5 (MIS 5a). According to the $\delta^{18}O$ record in the Guliya ice core, MIS 5 (75 ∼ 125 ka BP) has been divided into 5 substages (MIS 5a, MIS 5b, MIS 5c, MIS 5d and MIS 5e). As the temperature during MIS 5a was about 3 °C higher than present (Yao et al., 1997) was impossible for glacier to extend and be well developed during MIS 5a. Referring to the glacial sequences in the other parts of the Tianshan range (Zhao et al., 2006, 2010) and the dating results, the $III_2$ moraine complex deposition could be assigned to the early period of the last glaciation, which

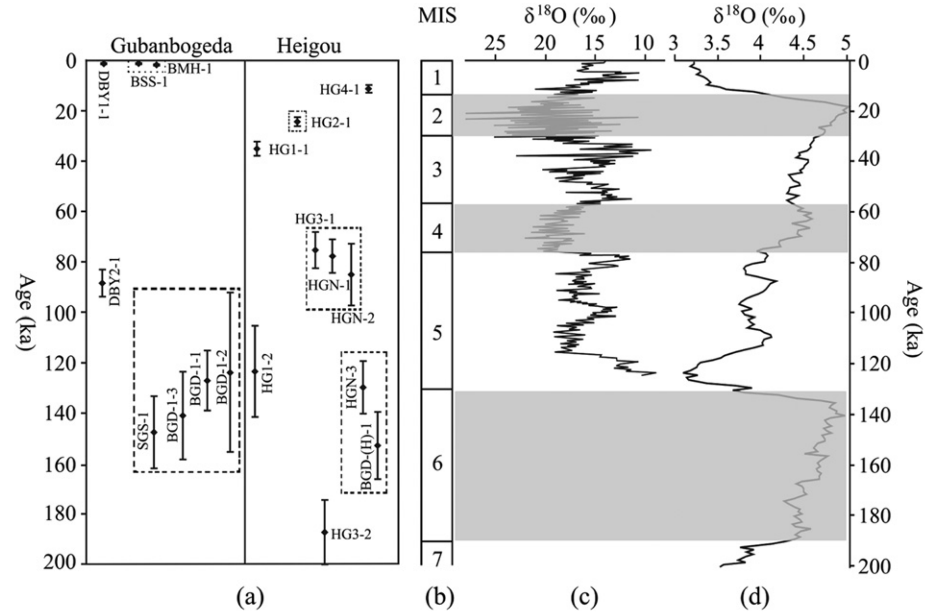


**Fig. 7.** A comparison of Quaternary glacial chronology in the Bogeda Peak area with different records. (a) dating results and their errors; (b) marine oxygen isotope stage (MIS); (c) the $\delta^{18}O$ record of the Guliya ice core (modified after Yao et al., 1997); (d) the $\delta^{18}O$ record of the 57 globally distributed benthic sediments (modified after Lisiecki and Raymo, 2005).

corresponding to MIS 4. The paleoclimate and paleoenvironment literatures in China indicate that the climate was cold and dry during glacial period (Shi, 2000; Shi et al., 2006), whereas, the humidity of MIS 4 was higher than that of MIS 2 in the western China, especially in westerly circulation areas (Shi, 2000). Perhaps, the dominate factor for glacier development was precipitation in this area during this period. The glacial landforms suggest that an extensive glacial advance occurred in the early period of the last glaciation rather than during the global Last Glacial Maximum ($LGM_G$). According to the extent of glacial landforms, the paleoglacier extended at least 7 km in the Heigou River valley and 14 km in the Gubanbogeda River valley, and a large compound valley glacier was developed during this event.

There are seven ages for the fourth set of moraine complex. Four ages were obtained for samples from the fourth set of moraines in the Gubanbogeda River valley. The dates are 147.8 ± 14.4 ka (SGS-1, OSL), 127.4 ± 12.1 ka (BGD-1-1, ESR), 123.9 ± 31.6 ka (BGD1-2, ESR), 141.1 ± 17.3 ka (BGD1-3, ESR). Three dates for samples from the oldest moraine complex in the Heigou River valley are 130.0 ± 10.4 ka (HGN-3, OSL), 11.2 ± 1.4 ka (HG4-1, OSL) and 152.9 ± 13.2 ka (BGD(H)-1, ESR). The age for HG4-1 is not consistent with the geological setting, indicating that this sample was reworked.

The dating results demonstrate that a large glacial advance occurred during MIS 6 (Fig. 7). As there were several stages of glaciation after this event, during which there was extensive glacial erosion, this suggests that the landscape during the MIS 6 glaciation would have been quite different from the present landscape. According to the previous studies in other parts of the Tianshan range, the oldest glaciations occurred in MIS 12 (Zhou et al., 2002; Zhao et al., 2006, 2009). Therefore, more work should be done in the Bogeda Peak area, especially on the north slope of it, to search for oldest glacial evidence.

## 6. Conclusion

Glacial tills and associated fluvioglacial sediments of the Bogeda Peak area, Tianshan range, China, were dated using OSL and ESR dating techniques. Results from samples of fluvioglacial and till deposits show that the SAR protocol was appropriate for $D_e$ determination of fluvioglacial deposits and that OSL did not work to date glacial tills in this study because the signals in quartz grains was not completely bleached. Consistent OSL and ESR ages for the oldest moraine complex demonstrate that these two dating techniques could be used to complement each other.

In the Bogeda Peak area, the first major moraine complex down valley from the current glacier is composed of 3 or 4 end moraines and was deposited during the LIA. The second set of moraines is Neoglacial in age. The lower and higher glacial terraces ($III_1$ and $III_2$ moraine complexes) in the Heigou River valley and the Gubanbogeda River valley were deposited during the late and early periods of the last glaciation, respectively, and are equivalent in age to MIS 2 and 4, respectively. The fourth and most extensive moraine complex was deposited during MIS 6.

## Acknowledgements

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## Appendix A. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.quageo.2012.03.004.

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