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Optically stimulated luminescence dating of young glacial sediments from the eastern Qinghai-Tibetan Plateau

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Abstract: Poor bleaching is a significant problem for Optically Stimulated Luminescence (OSL) dating of glacial sediments. Five young glacial samples (including two modern analogues) from different depositional settings were collected beyond the Yingpu Glacier in the eastern Qinghai-Tibetan Plateau. D_e was determined using different OSL methods. The luminescence characteristics and dating results showed that the large aliquot quartz Blue Stimulated Luminescence (BSL) is more applicable than polymineral infrared stimulated luminescence (IRSL) method. Small aliquot quartz BSL results showed poor luminescence properties due to low luminescence sensitivity of quartz in this area. The dating results also indicated that glaciofluvial samples deposited close to ice margin (~40 m and ~700 m) and supraglacial debris dominated lateral moraine samples are relatively well-bleached, whereas samples from ground moraine and low terminal moraine were poorly bleached, probably due to containing subglacial and englacial debris. The residual doses of glaciofluvial and lateral moraine crest samples were below a few Gy and age overestimations were below a few hundred years. The ground moraine and low terminal moraine samples had residual doses as high as ~110 Gy, and ages were overestimated by ~15-17 ka.

Keywords: Glacial sediments; Optically stimulated luminescence; Quartz; Residual age; Qinghai-Tibetan Plateau

Introduction

The Qinghai-Tibetan Plateau is the most glaciated region outside the polar area. Widely-distributed mountain glacial landforms in the plateau provide valuable archives for the reconstruction of palaeoglaciation and palaeoclimate. Optically stimulated luminescence (OSL) is one of the few techniques that are applicable for Quaternary glaciation dating. Over the last two decades, this method has been increasingly applied for dating glacial landforms in this region (Hu et al. 2015; Hu et al. 2014; Ou et al.

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2015; Ou et al. 2014; Rhodes 2000; Rhodes and Bailey 1997; Rhodes and Pownall 1994; Richards et al. 2000a,b; Spencer and Owen 2004; Tsukamoto et al. 2002; Wang et al. 2013; Xu et al. 2009; Zhang et al. 2012 a,b; Zhang et al. 2014; Zhao et al. 2012; Zhao et al. 2013 a,b; Zhao et al. 2009). However, the applicability of OSL dating of glacial sediments still remains controversial, especially that partial bleaching is known as one of the most outstanding problems (Duller 2008; Fuchs and Owen 2008; Houmark-Nielsen 2008; Klasen et al. 2007; Lukas et al. 2007; Ou et al. 2012; Richards 2000; Spencer and Owen 2004; Thrasher et al. 2009a; Tsukamoto et al. 2002). Analyzing young samples is one of the best ways to assess the bleachability of OSL signal of glacial landforms, especially modern analogues. In recent years, we investigated some young glacial samples in the Yingpu Valley in the eastern Qinghai-Tibetan Plateau (Ou et al. 2014) and the source area of the Urumqi River in Tianshan (Ou et al. 2015). However, these samples were all measured using large aliquot quartz blue stimulated luminescence (BSL) method. When large aliquot method is applied, signals from thousands, even tens of thousands of grains were averaged. Incomplete bleaching, if any, is likely to be obscured by the effects of averaging (Duller 2008). In contrast, single grain or small aliquot methods, provide an opportunity to further investigate incomplete resetting of luminescence signal, or to distinguish poor- and well-bleached grains (Duller 2008). However, low luminescence signal of quartz from glacial sediments makes the application of single or small aliquot methods of quartz difficult. In this study, five young glacial and glaciofluvial samples from the Yingpu Valley in the eastern Qinghai-Tibetan Plateau, which were previously measured using large aliquot quartz BSL methods (Ou et al. 2014), were re-measured using small aliquot quartz BSL and polymineral infrared stimulated luminescence (IRSL) methods. Luminescence properties of sediments from different depositional settings and applicability of different OSL methods will be discussed.

1 Regional Setting and Samples

Yingpu Glacier is a valley glacier located in the northern slope of the Queer Shan Mountains in the northwestern part of the Hengduan Mountains, eastern Qinghai-Tibetan Plateau (Figure 1). It currently terminates ~10 km south of Zhuqing Village, Dege County, Sichuan Province. The glacier is now terminates at an altitude of ~4700 m at 32°03′39.0′′ N, 98°50′36.7′′ E. Several Neoglacial (~4-1 ka), Little Ice Age (LIA, ~16th-19th century) and modern moraines and small outwash plains are distributed in the U-shaped valley beyond the glacier (Figure 1). The last glaciation and older moraines are located outside the U-shaped valley (Lehmkuhl 1998; Li and Feng 1984;

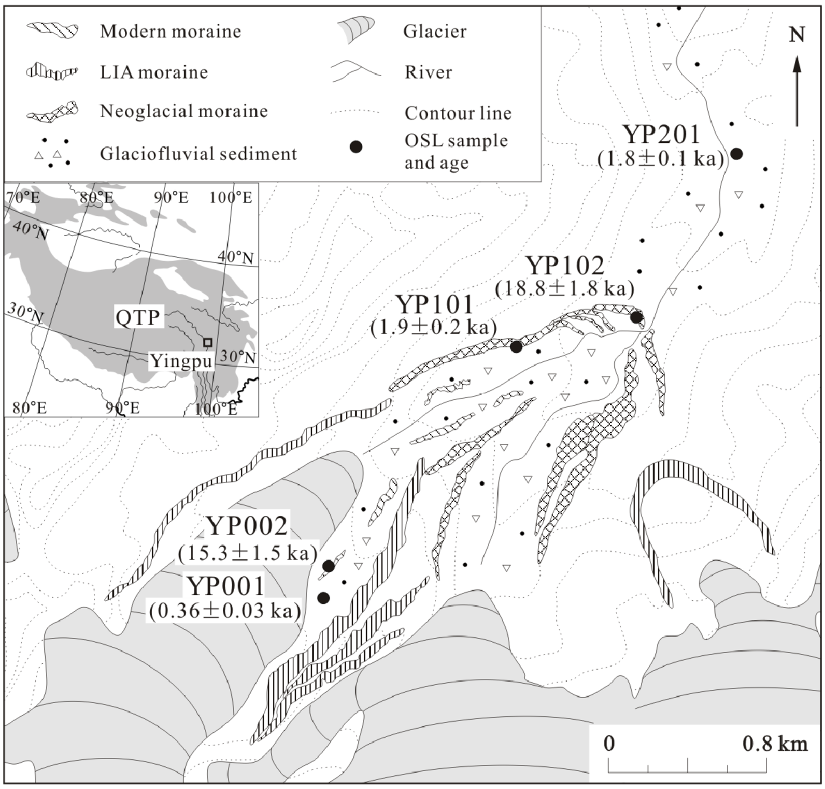

Figure 1 Location of study area, sampling sites (with their large aliquot quartz BSL ages) in front of the Yingpu Glacier (QTP is short of the Qinghai-Tibetan Plateau) (modified from Ou et al. 2014).

Ou et al. 2014).

Five samples were collected beyond the Yingpu Glacier (Figure 1; Figure 2). Sample YP001 (Figure 2a) is taken from a small distal ice marginal sandur to the east of the snout of the west branch of the glacier. The sample site is ~40 meters from the ice. The sample was collected from an interbedded ~8 cm silt layer in the recent unconsolidated sand deposits, at a depth of ~20 cm beneath the surface. Sample YP002 (Figure 2a) was collected from a recent un-vegetated ground moraine which is 2-10 m in height and ~200 m in length. It is mostly composed of loose sands and granite gravels. According to field observation, this ground moraine was formed during the recent retreat of the Yingpu Glacier. The sample site is ~40 m meters to the east of the snout of the west branch of the Yingpu Glacier and ~160 m to the north of YP001. Sample YP101 (Figure 2b; d; e) was collected from the top of a ~80 m high lateral moraine, which is covered by a thin soil layer and sparse herbosa and undershrub. It is mostly composed of granite gravels and coarse sands. Sample YP102 (Figure 2b, 2e) was taken from the top of a low terminal moraine (~20 m in height). It is mainly composed of sands and granite gravels. This terminal moraine exhibits similar sedimentological characteristics to that of the lateral moraine which YP101 was collected from. The moraines of YP101 and YP102 belong to different sub-moraines of the same moraine complex which were supposed to be formed during the Neoglacial (~4-1 ka, see Table 1) (Li and Feng 1984; Ou et al. 2014). Sample YP201 (Figure 2b, 2c, 2e) is glaciofluvial sediments mainly composed of silt and sand. It was collected from an outwash terrace which is linked to the above mentioned Neoglacial moraine complex. The sampling sites of YP101, YP102 and YP201 are ~800 m, ~1400 m and ~2100 m respectively in front of the snout of the west branch of the Yingpu Glacier.

2 Methods

2.1 Sample preparation

All samples were collected by driving steel tubes (30 cm long and 6 cm in diameter) into the fresh section. In the luminescence dating

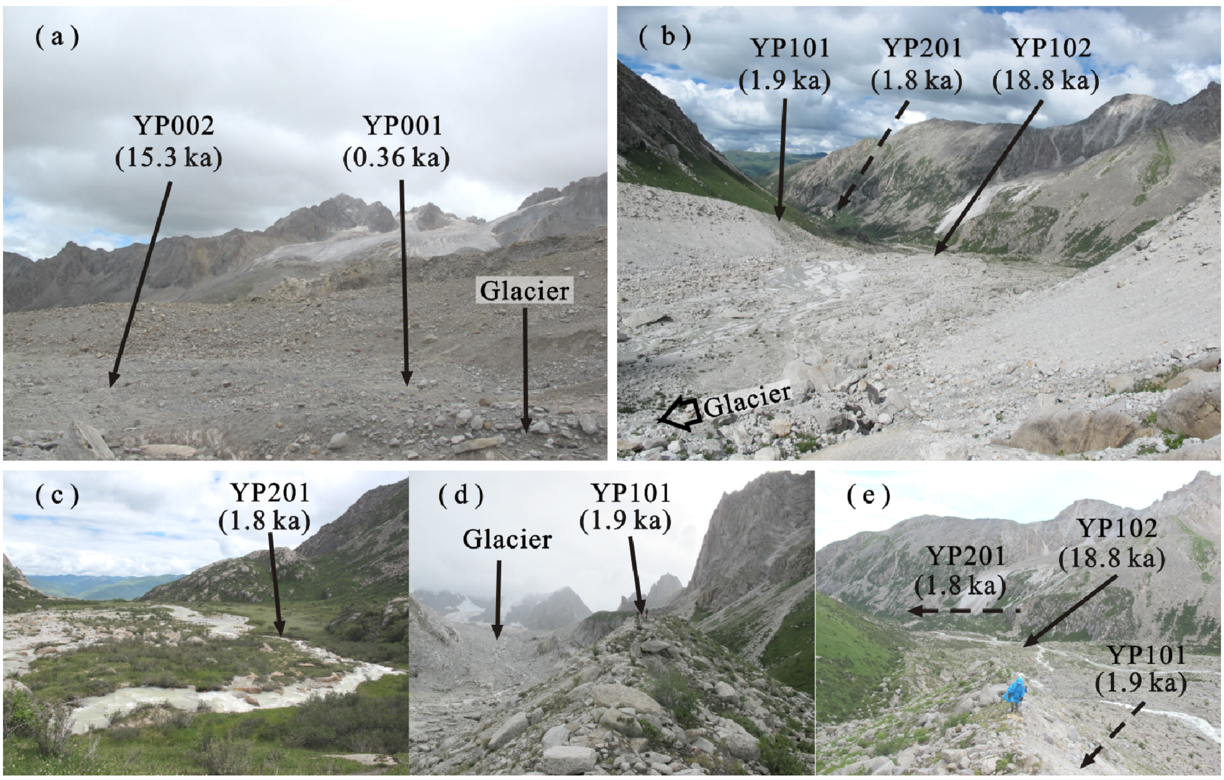

Figure 2 Glacial landforms and sediments in front of the Yingpu Glacier, the sampling sites and large aliquot quartz BSL ages.

Table 1 Optically Stimulated Luminescence (OSL) dating results

Sample ID	Depositional setting	Expected age	Depth (m)	K (%)	Th (ppm)	U (ppm)	W (%)	Dose rate (Gy/ka)	D_e (Gy)	Age (ka)	n (measured /accepted)	Methods*
YP001	Sandur, glaciofluvial	Modern	0.2	4.01±0.12	49.86±1.1	10.51±0.35	25±5	8.5±0.6	3.1±0.2	0.36±0.03	36/34	6 mm, Q, BSL
									2.1±0.4	0.25±0.05	24/22	2 mm, Q, BSL
								9.9±0.6	30.0±0.6	3.0±0.2	24/24	6 mm, P, IRSL
YP002	Ground moraine	Modern	0.4	4.03±0.11	33.29±0.73	5.42±0.23	15±5	7.4±0.5	113.2±7.7	15.3±1.5	36/35	6 mm, Q, BSL
									49.5±3.8	6.7±0.7	24/24	2 mm, Q, BSL
YP101	High lateral moraine	Neoglacial (~4-1 ka)	0.8	3.65±0.11	40.78±0.9	5.47±0.24	15±5	7.6±0.5	14.6±1.1	1.9±0.2	36/36	6 mm, Q, BSL
									9.9±1.2	1.3±0.2	24/23	2 mm, Q, BSL
								8.7±0.6	61.6±1.0	7.1±0.5	24/24	6 mm, P, IRSL
YP102	Low terminal moraine	Neoglacial (~4-1 ka)	0.5	3.55±0.1	32.93±0.72	4.9±0.22	15±5	6.8±0.5	128.1±8.7	18.8±1.8	36/36	6 mm, Q, BSL
									66.7±5.7	9.8±1.1	24/23	3 mm, Q, BSL
YP201	Outwash terrace, glaciofluvial	Neoglacial (~4-1 ka)	0.7	3.42±0.1	55.73±1.23	11.64±0.4	20±5	9.3±0.6	16.5±0.5	1.8±0.1	36/36	6 mm, Q, BSL
									9.7±0.6	1.1±0.1	24/24	2 mm, Q, BSL
								10.9±0.7	22.8±0.3	2.1±0.1	24/24	6 mm, P, IRSL

Notes: * Q = quartz; P = polymineral; BSL=Blue Stimulated Luminescence (BSL). The 6 mm quartz BSL data are from Ou et al. 2014.

laboratory, the samples were treated with 10% HCl and 30% H_2O_2 to remove carbonates and organics, respectively. The fraction of 38-63 μm was extracted by sieving. Some materials from three of five samples were separated for polymineral IRSL measurement. The other materials, which were used for quartz BSL measurement, were etched for about two weeks with 30% hydrofluorosilicic acid (H_2SiF_6) to remove the feldspar grains, followed by 10% HCl for 30 minutes to remove any fluoride precipitates. The purity of quartz grains were monitored by infrared irradiation. Quartz grains which showed obvious IRSL signals were retreated with hydrofluorosilicic acid again. For large aliquot measurement, samples were mounted on the center ~6 mm of stainless steel discs (10 mm in diameter) by silicone oil, while for small aliquot measurement, samples were only covered the center 2 or 3 mm of the discs.

2.2 Measurement procedures

Three methods were applied for D_e determination and comparison: large aliquot quartz BSL (measured previously in Ou et al. (2014)), small aliquot quartz BSL and large aliquot polymineral IRSL (only for the selected three samples: YP001, YP101 and YP201). All the measurements were carried on an automated Risø TL/OSL-DA-20 reader equipped with calibrated $^{90}Sr/^{90}Y$ beta radiation source (dose rate 0.1487 Gy/s). The SAR-SGC procedures (Lai and Ou 2013) i.e. single aliquot regenerative-dose (SAR) protocol (Murray and Wintle 2000) plus the standardized growth curve (SGC) protocol (Lai 2006; Roberts and Duller 2004), was used for all samples. Detailed description of the SAR-SGC method could be found in Ou et al. (2014) or Lai and Ou (2013). The mean value of SAR and SGC is taken as final D_e.

For quartz BSL measurement, stimulation was carried out using blue LEDs (λ = 470±20 nm) for 40 s at 130°C. Ninety percent diode power was used for all of the samples. The OSL signal was detected by a 9235QA photomultiplier tube through a 7.5 mm thick Hoya U-340 detection filter. A preheat at 260°C for 10 s and a cut-heat at 220°C for 10 s was used. The first 0.64 s of the signal was integrated for growth curve construction, and the last 8 s for background. For polymineral IRSL measurement, infrared LEDs (λ = 870±40 nm) were using for stimulation for 100 s at 130°C. Ninety percent diode power was used for all of the samples. Signal was detected by a 9235QA photomultiplier tube through a 7.5 mm thick Hoya U-340 detection filter. A preheat at 220°C for 10 s and a cut-heat at 200°C for 10 s was used. The first 1.6 s of the signal was used in later calculations, with a background subtraction over the last 20 s.

The concentrations of U, Th, and K were measured by Neutron Activation Analysis. Water content was estimated according to measurement in lab and field observation. Cosmic dose rates were calculated according to Prescott and Hutton (1994), considering the altitude, latitude, longitude, and the depth and density of the overburden sediments at each site. The alpha efficiency was taken as 0.035 ± 0.001 for quartz (Lai et al. 2008) and 0.1 ± 0.003 for polymineral.

3 Results

The combined preheat plateau and dose recovery test was carried out to evaluate the suitability of SAR protocol for both large aliquot quartz BSL and polymineral IRSL. A set of 20 aliquots of quartz or polymineral from sample YP201 were bleached with blue or infrared LED for 100 or 200 seconds at room temperature. A laboratory beta dose (16.5 Gy or 22.8 Gy) which is close to natural dose was then given, followed by SAR measurements with 5 different preheat temperatures (220°C - 300°C or 180 °C - 260°C with an interval of 20°C, four aliquots for each temperature) and a cut heat of 220°C or 200°C. The given dose could be reproduced within a temperature range of 220 °C - 280°C or 200 °C -260°C (Figure 3a, c). Recycling ratios are consistent with unity for preheat temperatures 220°C - 260°C or 180°C - 260°C (Figure 3b, d). The thermal transfer effect rises when temperatures become higher (Figure 3b, d). Finally, the preheat temperature of 260°C and 220°C were chosen for BSL and IRSL measurement, respectively.

3.1 Large aliquot quartz BSL

Figure 4 shows growth curves and SGC construction of different methods for sample YP101, as well as decay curves of natural dose (N), test dose (TD), a regeneration dose (R) and zero dose (0). The BSL signal was quickly bleached to

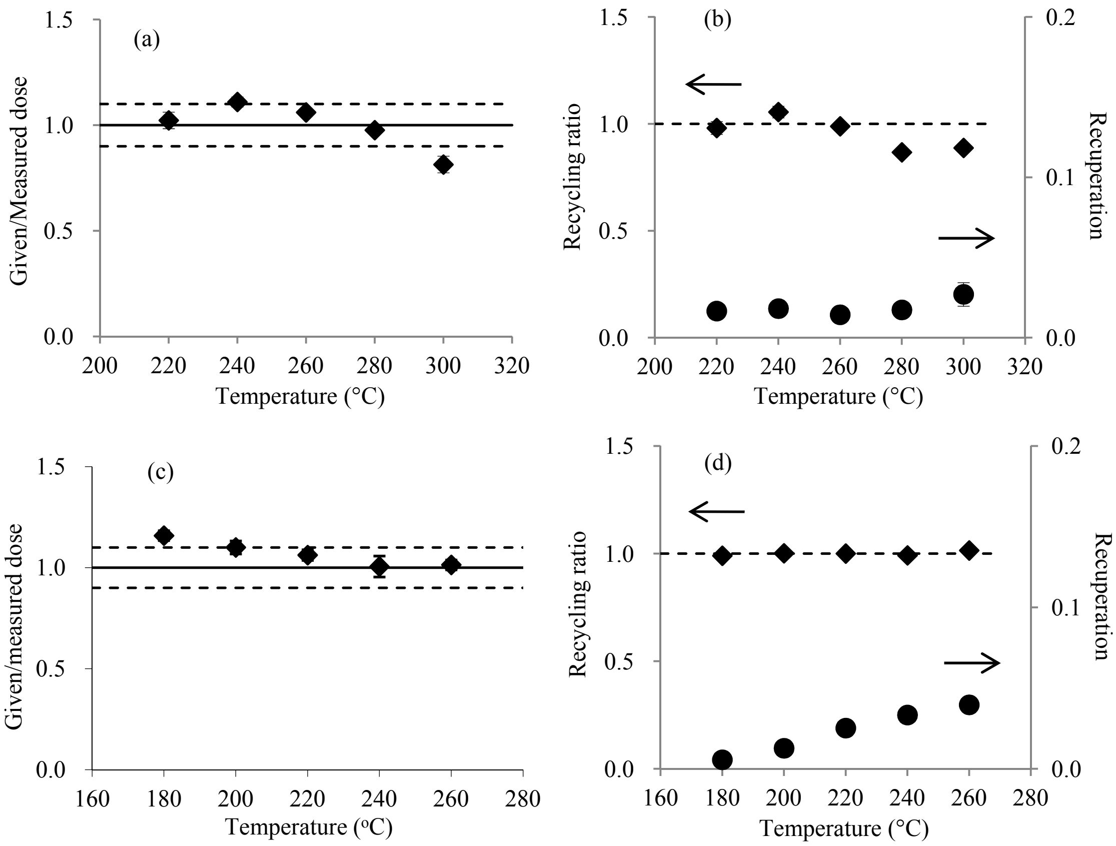

Figure 3 Combined test of preheat plateau and dose recovery, recycling ratio and recuperation of sample YP201 (a and b: large aliquot quartz BSL; c and d: large aliquot polymineral IRSL).

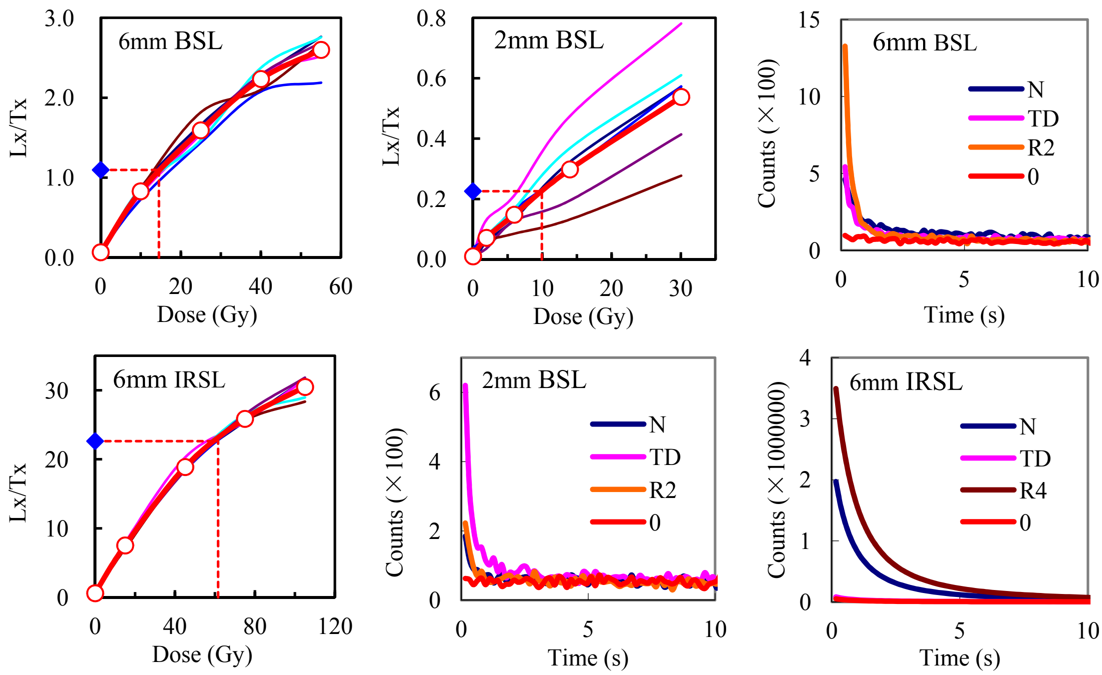

Figure 4 Growth curves and SGC construction (upper) and decay curves (lower) of sample YP101 using three different methods (6mm aliquot quartz BSL, 2mm aliquot quartz BSL and 6mm aliquot polymineral IRSL). Upper: growth curves for each of six aliquots (fine solid lines) and SGC (red heavy line) which denotes the average of the six growth curves. Lower: decay curves of natural dose (N), test dose (TD), a regeneration dose (R) and zero dose (0).

background within about one second, suggesting that the quartz grains are dominated by the fast component signal. The decay curves also indicate that OSL signals of large aliquot quartz are low, but still acceptable. Most of the recycling ratios are consistent with unity (0.9-1.1). Sample YP001 shows relatively low recycling ratios (range between 0.69-0.95, with an average of 0.82). The decay curve of the 0 Gy dose shows small thermal transfer. All the (L_0/T_0) / (L_N/T_N) ratios are low, with an average value of 6.80%, indicating the contribution of thermal transfer to D_e is quite limited.

3.2 Small aliquot quartz BSL

For the small aliquot quartz BSL measurement, most of the recycling ratio is beyond the range of 0.9-1.1. Most of the thermal transfer effects are below 10% except sample YP001 (41.3%). The decay curves indicate very low signal intensity (Figure 4). Growth curves of different aliquots look significant diverging (Figure 4). In this case it is difficult for SGC construction and D_e determination. D_es of different aliquots are relatively scattered (Figure 5). Sample YP002 and YP102 show much wider D_e distribution than the other samples. Overdispersion (OD) values of all the samples range from 22.4 to 50.6% (Figure 5).

3.3 Large aliquot polymineral IRSL

Typical polymineral (feldspar) IRSL properties are showed in Figure 4. The signal is much brighter but decays more slowly to background than quartz. The recycling ratios are highly consistent (0.97-1.02). The effects of thermal transfer are very low (2.2%-3.1%). Different aliquots show similar growth curves and D_es.

OSL ages of different methods with their D_es and dose rate information are given in Table 1.

4 Discussions

4.1 Comparison of different methods

It is well-known that feldspar IRSL bleaches more slowly than quartz OSL (Aitken 1998; Godfrey-Smith et al. 1988; Houmark-Nielsen 2008). Combined quartz and feldspar studies on glacial sediments from Hunza and Chitral in Himalaya area indicated that quartz data were in closer agreement with independent chronology, and feldspars were poorly bleached (Owen et al. 2002; Spencer and Owen 2004). In this study, it is showed that ages of large aliquot polymineral IRSL>large aliquot quartz BSL>small aliquot quartz BSL (Figure 6, Table 1). For those samples (YP001, YP101 and YP201) which are supposed to be better bleached (see section 4.2), the dating results of different methods seems close to the expected ages, although the IRSL ages of YP001 and YP101 are still overestimated by 3-6 ka (Figure 6, Table 1). The polymineral IRSL D_es are ~6-50 Gy higher than quartz BSL, which means ~0.3-6 ka

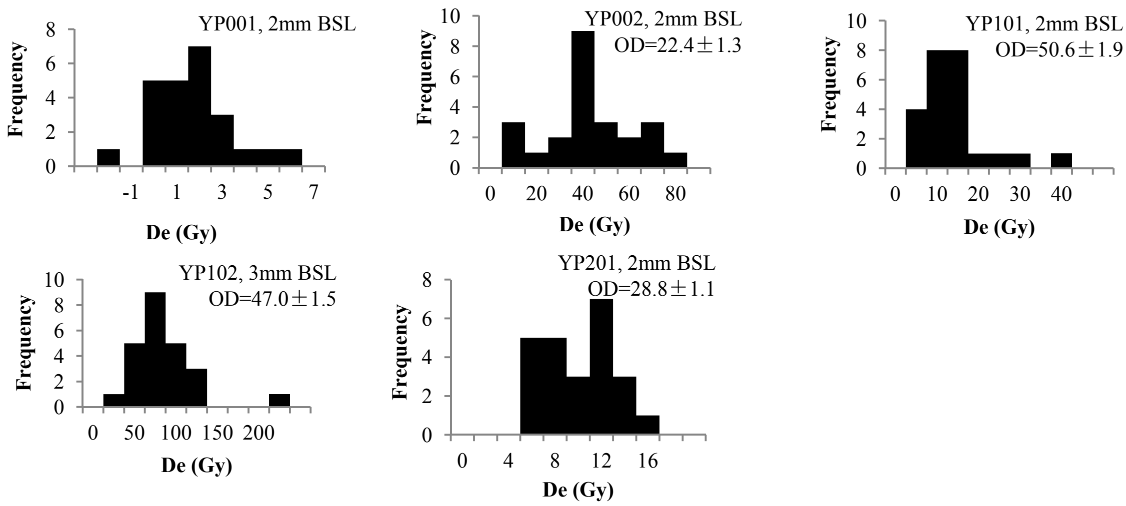

Figure 5 Histograms of D_e distribution determined by quartz small aliquot method.

older in age. Combined quartz and feldspar luminescence studies on glacial sediments from the Hunza and Chitral valleys in northern Pakistan also indicated that the feldspar ages were significantly higher than the corresponding quartz ages (Owen et al. 2002; Spencer and Owen 2004). Feldspar IRSL signal seems more difficult to be reset in this area, consistent with the widely accepted conclusion (Aitken 1998; Godfrey-Smith et al. 1988). Things will probably more complicated if partial-bleaching effect superimposed by abnormal fading of feldspar (Aitken 1998). Therefore, quartz is probably a better choice for dating glacial sediment than feldspar.

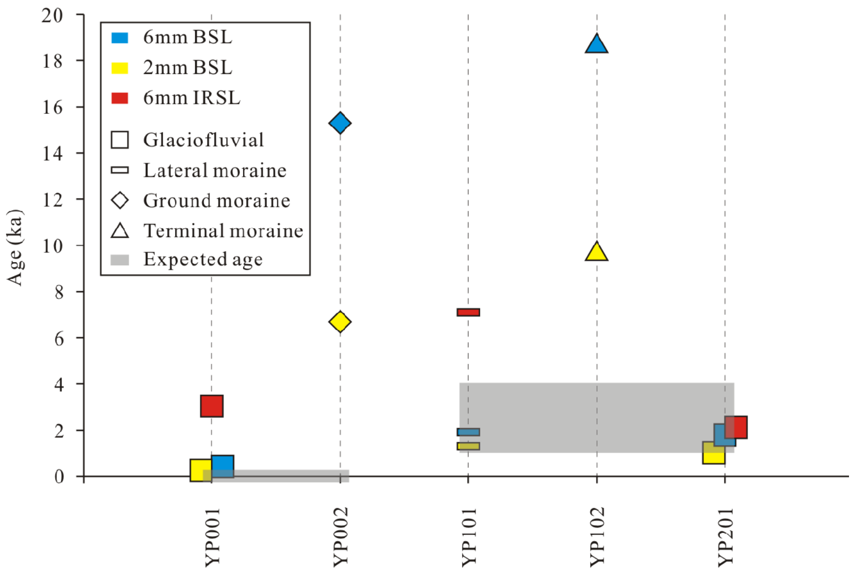

Figure 6 Comparison of ages of different methods and from different depositional settings.

For the better bleached samples (YP001, YP101 and YP201), the difference between large aliquot and small aliquot BSL is small. Large aliquot BSL D_es are 0.96-6.77 Gy greater than small aliquot BSL D_es, which means 0.11-0.7 ka older. While for those poorer bleached samples (YP002 and YP102), the large aliquot quartz BSL D_es are significant (~60 Gy) higher than small aliquot quartz BSL, which means much older (~9 ka) in age. However, high residual doses (~50 Gy) still occur when small aliquot was conducted. Poor bleached samples are unable to be distinguished by the D_e distributions and OD values (Figure 5). It seems that medium grain small aliquot method cannot completely solve the partial bleaching problem, probably because the 2 or 3 mm aliquot still contains thousands of medium grains. Less grains in an aliquot, even single grain method, could probably distinguish the heterogeneous bleaching grains. But the dim quartz of the young glacial sediments in this area hinders the application of these methods. According to the quartz BSL dating results, the ages of small aliquot method seems younger and closer to the true ages. However, due to low luminescence signal, the growth curves and D_es of small aliquots are more scattered (Figure 4). It is difficult to build a convincing SGC and get accurate age. In the following text, the discussion is based on the ages of large aliquot quartz BSL method.

4.2 Comparison of different depositional settings

It is well known that glacial sediments are difficult to be well-bleached (Alexanderson and Murray 2012b; Duller 2008; Fuchs and Owen 2008; Houmark-Nielsen 2008; Klasen et al. 2007; Lukas et al. 2007; Richards 2000; Spencer and Owen 2004; Thrasher et al. 2009a; Tsukamoto et al. 2002). There are many factors influence the resetting of OSL signal, such as sediment source, its position in the glacier ice, sedimentary process, transport distance and depositional setting (Alexanderson and Murray 2012b; Fuchs and Owen 2008; Houmark-Nielsen 2008; King et al. 2013, 2014; Lukas et al. 2007; Ou et al. 2015; Richards 2000; Thrasher et al. 2009b).

The expected ages (Table 1; Figure 6) of the five samples in the Yingpu Valley could be estimated according to field observation and previous studies (Li and Feng 1984; Ou et al. 2014). The OSL data indicate that residual ages vary with different depositional settings (Figure 6). Glaciofluvial and lateral moraine samples show low residual ages whereas ground moraine and terminal moraine samples show significant higher residual ages. Both of samples YP001 and YP002 are modern deposits collected very close (~40 m) to the ice margin, with expected age close to zero. But D_e of YP002 (ground moraine) is ~110 Gy higher and the age is ~15 ka older than YP001 (glaciofluvial). Sample YP101 and YP102 were collected respectively from a lateral moraine and a terminal moraine of the Neoglacial moraine complex with estimated age of ~4-1 ka. Sample YP201 is from an outwash terrace linked to this moraine complex. It was deposited ~700 m beyond the former (Neoglacial) glacier, as deduced from the geomorphological context. Samples YP101 and YP201 show consistent OSL ages. However, D_e of YP102 is ~110 Gy higher and the age is ~17 ka older than YP101 and YP201. It could be seen from Figure 6 that OSL ages of glaciofluvial (YP001 and YP201) and lateral moraine sample (YP101) are agree with their expected ages. These samples were relatively well-bleached. In contrast, OSL ages of ground moraine (YP002) and terminal moraine samples (YP102) are significantly higher than their expected ages. Their OSL ages even older than or similar with the Lateglacial moraines (12.2±1.1-16.6±1.3 ka) ~5 km downstream outside the Yingpu Valley (Ou et al. 2014). This is obviously against the geomorphological context. Therefore, these two samples were regarded as incompletely bleached.

Glacial debris are transported on top of (supraglacial), beneath (subglacial), or within (englacial) a glacier, and released as various kinds of tills, to form glacial landforms, such as terminal moraine, lateral moraine, ground moraines, lodgement moraines and hummocky moraines. Some finer debris are released and transported by melt water, and deposited as glaciofluvial or glaciolacustrine sediments, which might experience more chance of light exposure (Fuchs and Owen 2008; Houmark-Nielsen 2008; Richards 2000). In contrast, tills are normally more difficult to be bleached due to shorter daylight exposure during transport and deposition (Duller 2006; Fuchs and Owen 2008; Tsukamoto et al. 2002).

The effective of resetting of OSL signal of glaciofluvial sediments depends on turbidity, water depth, the number of depositional and erosional cycles before final deposition and transport distance (Houmark-Nielsen 2008; Richards 2000). In the Arctic region, frequent reworking of sediments and continuous daylight in summer (the melt season) increase the possibility of bleaching of glaciofluvial samples, although the long polar night may mitigate against this point (Alexanderson and Murray 2012a). It was indicated that the further the sediments were transported, the residual OSL ages seem to be smaller (Alexanderson and Murray 2012a; Houmark-Nielsen 2008). In Engelskbukta Bay, Svalbard, Alexanderson and Murray (2012a) reported a ~12 Gy dose for a glaciofluvial sample ~100 m from present glacier margin, whereas ice-distal samples were more or less completely bleached. Glaciofluvial sediments within 2 km of the ice margin from a glacier in southern Norway showed low residual ages range from zero to 4.06±1.04 ka (King et al. 2013). In the Basongcuo catchment near the eastern Himalayan syntaxis, young OSL ages (1.3±0.3~4.2±0.4 ka) of a glaciofluvial sand lens from a LIA lateral moraine were obtained (Hu et al. 2015). These ages were overestimated but the residual ages are low (~1-4 ka). In the source area of the Urumqi River, Tianshan, some modern and LIA glaciofluvial sediments deposited close to the ice were investigated and relatively low residual OSL ages were reported (Ou et al. 2015). A modern glaciofluvial bar sample (~150 m beyond the glacier snout) yielded an OSL age of 2.0±0.2 ka. A glaciofluvial lens sample from a LIA lateral moraine showed an OSL age of 1.6±0.1 ka, with residual age of ~1.4 ka. But a modern glaciofluvial lens embedded in a ground moraine near the glacier showed a surprisingly high OSL age of 20.6±2.7 ka (Ou et al. 2015). In this study, two glaciofluvial samples deposited close to modern or former ice margin have low residual OSL ages, indicating very rapidly bleaching of OSL signal in this area. In the low latitude high altitude region such as the Himalaya-Tibetan Plateau, sediments are usually deposited in high-energy environment. This results in high turbidity and high sediment loads of meltwater which reduce the possibility of sufficient exposure to light (Richards 2000). However, two glaciofluvial samples in this study were collected from silt or sand layers, which reflect lower energy flow regime and thus raise the possibility of bleaching (Thrasher et al. 2009b). Furthermore, in the Himalaya-Tibetan region, there are several factors in favour of bleaching such as high solar incident angle, high UV intensities, and ice melting mainly occurs in daytime in summer (Richards 2000). These make rapidly bleach of glaciofluvial sediments possible even after only short transport distances.

For moraine samples, the bleachability of OSL signal varies with different kinds of tills they are composed of. Different kinds of tills possess different chances to be bleached, depends on the position of the debris in the glacier ice. Supraglacial debris probably have a high chance to be exposure to daylight because they are transported on the surface of glacier (Richards 2000; Tsukamoto et al. 2002). In contrast, subglacial englacial debris are unlikely to get sufficient light exposure (Houmark-Nielsen 2008; Richards 2000; Tsukamoto et al. 2002). For low moraine and ground moraine, the source of the debris may be complicated. Ground moraine was formed during glacier retreating. When glacier retreating, all the debris (supraglacial, englacial and subglacial) carried by ice will be dumped without sorting. Low moraine (including lower part of moraine) is also likely consisted of various kinds of debris. The englacial and subglacial debris raise the risk of age overestimation. This explains the high residual ages of samples from the ground moraine (YP002) and low terminal moraine (YP102). In contrast, sample YP101 was collected at the top of a ~80 meters high lateral moraine, it is supposed to be dominated by supraglacial sediments, thus shows very low residual OSL age. In the Himalaya area, where the dominant transport path is supraglacial, and deposition is predominantly by subaerial debris flows and meltwater streams, reliable ages have been obtained from quartz from ice contact sediments (Benn and Owen 2002; Richards 2000; Spencer and Owen 2004; Tsukamoto et al. 2002). In Basongcuo, a modern supraglacial sediment sample from a lateral moraine was dated to ~0.2 (fine grain) to ~0.7 (medium grain) ka, suggesting that the sediment was not completely bleached but the residual ages are not very high (Hu et al. 2015). In the source area of the Urumqi River, relatively low residual ages (~0-3.7 ka) were obtained for young lateral moraine samples, whereas samples from subglacial tills, terminal moraines, ground moraines (including the interbedded glaciofluvial lens), and hummocky moraines showed high residual ages (~7.7-29.6 ka) (Ou et al. 2015). This study confirms again that lateral moraine sediments (supraglacial debris dominated) are more likely to be well-bleached than terminal moraines and ground moraines which might contain subglacial and englacial debris.

5 Conclusions and Implications for Quaternary Glacial Landform Dating

For young glacial quartz in this area, it is too dim to apply small aliquot BSL method for D_e determination. The polymineral IRSL method is also not a good choice due to slower bleaching of feldspar (and abnormal fading might further complicates the dating results). For the well-bleached young samples, it seems that large aliquot quartz BSL method is more applicable. For the Pleistocene glacial sediments, signals might be higher and also much brighter as grains might had experienced multiple burial-exposure cycles. In this case, small aliquot or single grain BSL method could be applied to distinguish incompletely bleach.

Relatively low residual doses and ages were obtained for 3 of 5 young glacial samples. Glaciofluvial samples deposited close to ice margin (~40 m and ~700 m) and supraglacial debris dominated lateral moraine crest sample are relatively well bleached. The residual doses are below several Gy and age overestimations below several hundred years. In contrast, samples from a ground moraine and a low terminal moraine are insufficiently bleached, probably due to mixture of subglacial and englacial debris. The residual doses are as high as ~110 Gy and ages could be overestimated by ~15-17 ka.

This study shows potential of application of OSL dating on old (e.g. Pleistocene) glacial landforms in this area. Several hundred years of overestimation is negligible for Pleistocene glacial sediments. Furthermore, sediments might be carried longer by the expanded glacier during Pleistocene Glaciation, increasing the potential of grains undergoing sufficient exposure to sunlight. High incident angle of sunlight and UV flux in the Qinghai-Tibetan Plateau makes rapidly resetting of OSL signal of quartz grains possible.

Glacial sediments are, however, very complex and it is unlikely that all grains were fully reset during transportation and sedimentation. Therefore, sampling sites should be carefully selected in the field. Glaciofluvial and upper part of lateral moraines are recommended for sampling. In contrast, ground moraines, low terminal moraines, which may contain subglacial and englacial debris, should be avoided.

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References

Aitken MJ (1998) An introduction to optical dating. Oxford University Press, Oxford, United Kingdom.

Alexanderson H, Murray AS (2012a) Luminescence signals from modern sediments in a glaciated bay, NW Svalbard. Quaternary Geochronology 10: 250-256. DOI: 10.1016/j.quageo.2012.01.001

Alexanderson H, Murray AS (2012b) Problems and potential of OSL dating Weichselian and Holocene sediments in Sweden. Quaternary Science Reviews 44: 37-50. DOI: 10.1016/j.quascirev.2009.09.020

Benn DI, Owen LA (2002) Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains. Quaternary International 97-8: 3-25. DOI: 10.1016/S1040-6182(02)00048-4

Duller GAT (2006) Single grain optical dating of glacigenic deposits. Quaternary Geochronology 1: 296-304. DOI: 10.1016/j.quageo.2006.05.018

Duller GAT (2008) Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. Boreas 37: 589-612. DOI: 10.1111/j.1502-3885.2008.00051.x

Fuchs M, Owen LA (2008) Luminescence dating of glacial and associated sediments: review, recommendations and future directions. Boreas 37: 636-659. DOI: 10.1111/j.1502-3885.2008.00052.x

Godfrey-Smith D, Huntley DJ, Chen WH (1988) Optical dating studies of quartz and feldspar sediment extracts. Quaternary Science Reviews 7: 373-380. DOI: 10.1016/0277-3791(88)90032-7

Houmark-Nielsen M (2008) Testing OSL failures against a regional Weichselian glaciation chronology from southern Scandinavia. Boreas 37: 660-677. DOI: DOI 10.1111/j.1502-3885.2008.00053.x

Hu G, Yi CL, Zhang JF, et al. (2014) Optically stimulated luminescence dating of a moraine and a terrace in Laohugou valley, western Qilian Shan, northeastern Tibet. Quaternary International 321: 37-49. DOI: 10.1016/j.quaint.2013.12.019

Hu G, Yi CL, Zhang JF, et al. (2015) Luminescence dating of glacial deposits near the eastern Himalayan syntaxis using different grain-size fractions. Quaternary Science Reviews 124: 124-144. DOI: 10.1016/j.quascirev.2015.07.018

King GE, Robinson RAJ, Finch AA (2013) Apparent OSL ages of modern deposits from Fåbergstølsdalen, Norway: implications for sampling glacial sediments. Journal of Quaternary Science 28: 673-682. DOI: 10.1002/jqs.2666

King GE, Robinson RAJ, Finch AA (2014) Towards successful OSL sampling strategies in glacial environments: deciphering the influence of depositional processes on bleaching of modern glacial sediments from Jostedalen, Southern Norway. Quaternary Science Reviews 89: 94-107. DOI: 10.1016/j.quascirev.2014.02.001

Klasen N, Fiebig M, Preusser F, et al. (2007) Luminescence dating of proglacial sediments from the Eastern Alps. Quaternary International 164-165: 21-32. DOI: 10.1016/j.quaint.2006.12.003

Lai ZP (2006) Testing the use of an OSL Standardised Growth Curve (SGC) for De determination on quartz from the Chinese Loess Plateau. Radiation Measurements 41: 9-16. DOI: 10.1016/j.radmeas.2005.06.031

Lai ZP, Ou XJ (2013) Basic procedures of optically stimulated luminescence (OSL) dating. PROGRESS IN GEOGRAPHY 32: 683-693. DOI: 10.11820/dlkxjz.2013.05.001 (in Chinese)

Lai ZP, Zoller L, Fuchs M, et al. (2008) Alpha efficiency determination for OSL of quartz extracted from Chinese loess. Radiation Measurements 43: 767-770. DOI: 10.1016/j.radmeas.2008.01.022

Lehmkuhl F (1998) Extent and spatial distribution of Pleistocene glaciations in eastern Tibet. Quaternary International 45-46: 123-134. DOI: 10.1016/S1040-6182(97)00010-4

Li JJ, Feng ZD (1984) Quaternary Glaciation Relics in Hengduan Mountains (in Chinese), In: Li JJ, Zhang LY, Feng ZD (eds.), Evolution of mountain glaciers and the Quaternary glaciation. Journal of Lanzhou University (monograph), Lanzhou, China. pp 61-72.

Lukas S, Spencer JQG, Robinson RAJ et al. (2007) Problems associated with luminescence dating of Late Quaternary glacial sediments in the NW Scottish Highlands. Quaternary Geochronology 2: 243-248. DOI: 10.1016/j.quageo.2006.04.007

Murray AS, Wintle AG (2000) Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32: 57-73. DOI: 10.1016/S1350-4487(99)00253-X

Ou XJ, Lai ZP, Zeng LH, et al. (2012) OSL dating of glacial sediments from the Qinghai-Tibetan Plateau and its bordering mountains: a review and methodological suggestions. Journal of Earth Environment 3: 743-756. DOI: 10.7515/JEE201202001

Ou XJ, Lai ZP, Zhou SZ, et al. (2015) Optical dating of young glacial sediments from the source area of the Urumqi River in Tianshan Mountians, northwestern China. Quaternary International 357. DOI: 10.1016/j.quaint.2014.08.053

Ou XJ, Lai ZP, Zhou SZ, et al. (2014) Timing of glacier fluctuations and trigger mechanisms in eastern Qinghai-Tibetan Plateau during the Late Quaternary. Quaternary Research 81: 464-475. DOI: 10.1016/j.yqres.2013.09.007

Owen LA, Kamp U, Spencer JQ, et al. (2002) Timing and style of Late Quaternary glaciation in the eastern Hindu Kush, Chitral, northern Pakistan: a review and revision of the glacial chronology based on new optically stimulated luminescence dating. Quaternary International 97-98: 41-55. DOI: Pii

S1040-6182(02)00050-2
Rhodes EJ (2000) Observations of thermal transfer OSL signals in glacigenic quartz. Radiation Measurements 32: 595-602. DOI: 10.1016/S1350-4487(00)00125-6
Rhodes EJ, Bailey RM (1997) The effect of thermal transfer on the zeroing of the luminescence of quartz from recent glaciofluvial sediments. Quaternary Science Reviews 16: 291-298. DOI: 10.1016/S0277-3791(96)00100-X
Rhodes EJ, Pownall L (1994) Zeroing of the OSL Signal in Quartz from Young Glaciofluvial Sediments. Radiation Measurements 23: 581-585. DOI: 10.1016/1350-4487(94) 90103-1
Richards BWM (2000) Luminescence dating of Quaternary sediments in the Himalaya and High Asia: a practical guide to its use and limitations for constraining the timing of glaciation. Quaternary International 65-66: 49-61. DOI: 10.1016/S1040-6182(99)00036-1
Richards BWM, Benn DI, Owen LA, et al. (2000a) Timing of late Quaternary glaciations south of Mount Everest in the Khumbu Himal, Nepal. Geological Society of America Bulletin 112: 1621-1632. DOI: 10.1130/0016-7606(2000)112<1621: TOLQGS>2.0.CO;2
Richards BWM, Owen LA, Rhodes EJ (2000b) Timing of Late Quaternary glaciations in the Himalayas of northern Pakistan. Journal of Quaternary Science 15: 283-297. DOI: 10.1002/ (SICI)1099-1417(200003)15:3<283::AID-JQS525>3.0.CO;2-X
Roberts H, Duller GAT (2004) Standardised growth curves for optical dating of sediment using multiple-grain aliquots. Radiation Measurements 38: 241-252. DOI: 10.1016/j.radmeas. 2003.10.001
Spencer JQ, Owen LA (2004) Optically stimulated luminescence dating of Late Quaternary glaciogenic sediments in the upper Hunza valley: validating the timing of glaciation and assessing dating methods. Quaternary Science Reviews 23: 175-191. DOI: 10.1016/S0277-3791(03)00220-8
Thrasher IM, Mauz B, Chiverrell RC, et al. (2009a) Luminescence dating of glaciofluvial deposits: A review. Earth-Science Reviews 97: 133-146. DOI: 10.1016/j.earscirev.2009. 09.001
Thrasher IM, Mauz B, Chiverrell RC, et al. (2009b) Testing an approach to OSL dating of Late Devensian glaciofluvial sediments of the British Isles. Journal of Quaternary Science 24: 785-801. DOI: DOI 10.1002/Jqs.1253
Tsukamoto S, Asahi K, Watanabe T, et al. (2002) Timing of past glaciations in Kanchenjunga Himal, Nepal by optically stimulated luminescence dating of tills. Quaternary International 97-98: 57-67. DOI: 10.1016/S1040-6182(02) 00051-4
Wang J, Pan BT, Zhang GL, et al. (2013) Late Quaternary glacial chronology on the eastern slope of Gongga Mountain, eastern Tibetan Plateau, China. SCIENCE CHINA Earth Sciences 56: 354-365. DOI: 10.1007/s11430-012-4514-0
Xu X, Yang J, Dong G, et al. (2009) OSL dating of glacier extent during the Last Glacial and the Kanas Lake basin formation in Kanas River valley, Altai Mountains, China. Geomorphology 112: 306-317. DOI: 10.1016/j.geomorph.2009.06.016
Zhang B, Ou XJ, Lai ZP (2012a) OSL ages revealing the glacier retreat in the Dangzi valley in the eastern Tibetan Plateau during the Last Glacial Maximum. Quaternary Geochronology 10: 244-249. DOI: 10.1016/j.quageo.2012.01.013
Zhang W, He MY, Li YH, et al. (2012b) Quaternary glacier development and the relationship between the climate change and tectonic uplift in the Helan Mountain. Chinese Science Bulletin 57: 4491-4504. DOI: 10.1007/s11434-012-5283-z
Zhang W, Liu B, Li Y, et al. (2014) Late Pleistocene Glaciations on Qianhu Mountain, Northwest Yunnan Province, China. Geografiska Annaler: Series A, Physical Geography 96: 417-429. DOI: 10.1111/geoa.12041
Zhao J, Lai Z, Liu S, et al. (2012) OSL and ESR dating of glacial deposits and its implications for glacial landform evolution in the Bogeda Peak area, Tianshan range, China. Quaternary Geochronology 10: 237-243. DOI: 10.1016/j.quageo.2012.03. 004
Zhao J, Yin X, Harbor JM, et al. (2013a) Quaternary glacial chronology of the Kanas River valley, Altai Mountains, China. Quaternary International 311: 44-53. DOI: 10.1016/j.quaint. 2013.07.047
Zhao JD, Liu SY, He YQ, et al. (2009) Quaternary glacial chronology of the Ateaoyinake River Valley, Tianshan Mountains, China. Geomorphology 103: 276-284. DOI: 10.1016/j.geomorph.2008.04.014
Zhao JD, Yin XF, Harbor JM, et al. (2013b) Quaternary glacial chronology of the Kanas River valley, Altai Mountains, China. Quaternary International 311: 44-53. DOI: 10.1016/j.quaint. 2013.07.047