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Cosmogenic nuclide constraints on glacial chronology in the source area of the Urumqi River, Tian Shan, China

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ABSTRACT: Cosmogenic nuclide surface exposure dating of boulders and erratics provides new constraints for a glacial chronology in the source area of the Urumqi River, Tian Shan, China. ^{10}Be exposure ages of 15.0 ± 1.3–17.1 ± 1.5 ka from the Upper Wangfeng (UWF) moraines agree well with their previous relative age assignments to marine isotope stage (MIS) 2, but are younger than published AMS ^{14}C and electron spin resonance (ESR) ages (from 22.8 ± 0.6 to 37.4 ka). This difference may result from variations in techniques, or could reflect the impact of surface erosion and sediment/snow cover on surface exposure dating. ^{10}Be ages from the Lower Wangfeng (LWF) moraines (18.7 ± 1.8 and 16.2 ± 1.5 ka) are indistinguishable from the UWF exposure ages, but are significantly younger than previously reported thermoluminescence (TL) and ESR ages (37.7 ± 2.6–184.7 ± 18 ka). Either these two groups were formed during the same period (MIS 2) and there are problems with TL and ESR ages, or the moraines were of very different ages and the similar exposure ages result from different degrees of degradation. Erratics on rock steps and a drumlin along >8 km of the main glacial valley above the UWF have internally consistent and slightly decreasing ^{10}Be exposure ages indicating glacier retreat >2.5 m a^{-1} after MIS 2 and before middle or late Holocene glacier re-advances. This retreat rate is similar to rates observed from modern glaciers.

KEYWORDS: ^{10}Be dating; alpine glaciers; Asian glaciation; landform evolution; Tian Shan.

Introduction

The high mountains and plateaus of Central Asia are critical areas for understanding Quaternary glaciations and the interactions between climate systems such as the Westerlies and the Asian monsoon (Benn and Owen, 1998; Owen *et al.*, 2005, 2008; Owen, 2009). Reconstructing glacial chronologies in this region plays a key role in understanding spatial and temporal fluctuations of glaciers in response to climate change. However, dating glacial deposits and landforms can be challenging because the timescale of ^{14}C dating (<50 ka) is insufficient to provide more than minimum-limiting ages for many glacial events and there is often a paucity of organic matter for ^{14}C dating in glacial deposits and landforms.

The development of several dating techniques provides new opportunities to constrain the ages of glacial deposits/landforms. Techniques now increasingly being used include accelerator mass spectrometry (AMS) ^{14}C of pedogenic carbonates (e.g. Yi *et al.*, 2004), electron spin resonance (ESR) (e.g. Yi *et al.*, 2002; Zhao *et al.*, 2006), thermoluminescence (TL) (e.g. Li, 1995), optically stimulated luminescence (e.g. Owen *et al.*, 2006) and terrestrial cosmogenic nuclide (TCN) surface exposure dating (e.g. Gosse and Phillips, 2001). However, each technique has limitations and measures some slightly different proxy for time related to a period of glaciation.

TCN surface exposure dating has recently been used to make significant progress in improving constraints on glacial chronologies in Central Asia (e.g. Owen *et al.*, 2003, 2005, 2006, 2008; Abramowski *et al.*, 2006; Seong *et al.*, 2007; Koppes *et al.*, 2008). However, active erosion and degradation, surface instability and weathering, and possible complications due to sediment and snow cover result in potentially large uncertainties in TCN dating. Thus, in some cases it is hard to test hypotheses about the timing and synchroneity of events relying solely on TCN dating. Multiple dating techniques with detailed geomorphic studies are necessary to refine the ages of glacial deposits/landforms and to evaluate potential impacts of surface erosion and landform degradation on TCN dating and to develop a robust understanding of the chronology of glacial landform development in an area.

The source area of the Urumqi River, Tian Shan, China, is one of the most intensively studied areas of glacial geomorphology in the world because of its spectacular landforms and the presence of a major research station in the valley since 1959. Glacial landforms and deposits in this area have been studied extensively (e.g. Cui, 1981a, b; Wang, 1981a, b; Chen, 1989; Li, 1995; Li *et al.*, 2001a, b; Yi *et al.*, 2002, 2004; Zhao *et al.*, 2006; Kong *et al.*, 2009), and multiple techniques have been used to provide a glacial chronology, including ^{14}C, lichenometry, AMS ^{14}C, ESR, TL and ^{10}Be. However, controversy still exists about the ages of glacial landforms and deposits, and additional techniques and ages are needed to constrain the chronology of glacial events and improve the understanding of glacier–climate interactions in this critical area of Central Asia.

This paper reports ^{10}Be exposure ages of moraines that were thought to be deposited during the Last Glaciation (defined as equivalent to the Wisconsinan in North America and the Würm in Europe) and erratics distributed along the glacial valley. In addition to helping to determine the glacial chronology and glacier-retreat pattern during the Last Glaciation, this approach allows us to examine the relationships between TCN dating and results from other methods.

Study area, geological setting and previous work

The source area of the Urumqi River is on the northern slope of Kalawucheng Mountain, Central Tian Shan (Fig. 1). The highest peak, Tianger Peak (43.7° N, 86.49° E), is about 4486 m a.s.l. The modern snowline is about 4000–4100 m a.s.l. Although modern glaciers are limited to cirque glaciers, hanging glaciers

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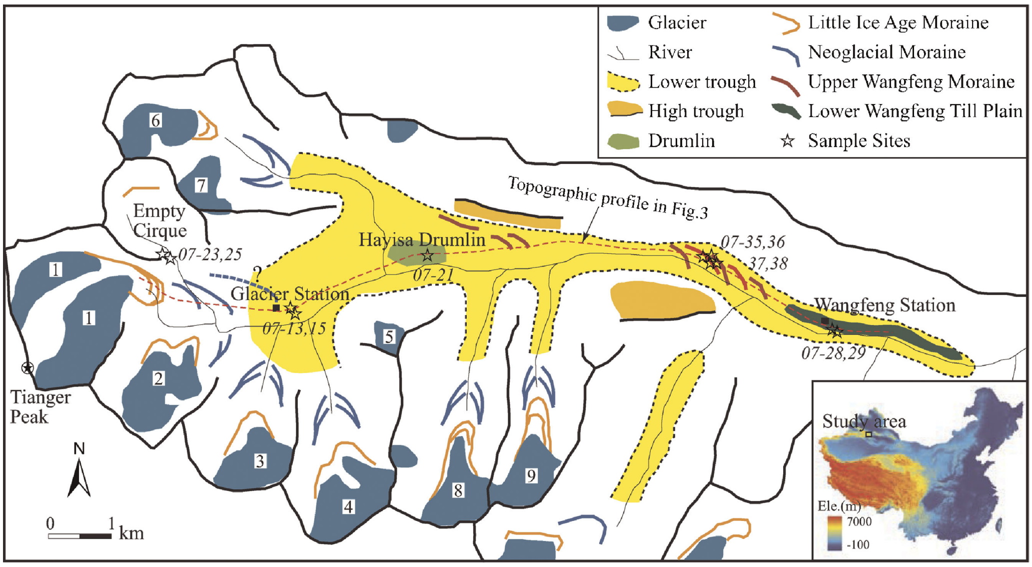

Figure 1. Geomorphology of the source area of the Urumqi River, Tian Shan, China. Numbers 1–9 inside each glacier represent the coding scheme used for the glaciers in this area. A question mark near the Glacier Station indicates the debate about the age of the lateral moraine. A topographic profile (red dashed line) from the terminus of Glacier No. 1 to the Wangfeng Station is shown in Fig. 3. This figure is available in colour online at wileyonlinelibrary.com.

and small valley glaciers, abundant glacial landforms, erratics and deposits are distributed along the valley more than 10 km downstream from modern glaciers.

This area is particularly well known because of the presence of double troughs in glaciated valleys (Cui, 1981a; Li *et al.*, 2001a, b). The higher troughs are believed to have formed during marine isotope stage (MIS) 8 and the lower troughs during MIS 6 and 2 (Wang, 1981b). Within these troughs, five groups of glacial moraines have been identified (Fig. 1). The first group includes three lateral–end moraines a few hundred metres away from the terminus of Glacier No. 1. Boulders on moraines are little weathered and no soil or vegetation has developed. Lichenometric ages of 1538 ± 20, 1777 ± 20 and 1871 ± 20 AD (Chen, 1989), and calibrated AMS ^{14}C ages of 416 ± 146 and 428 ± 127 cal a BP (Yi *et al.*, 2004) for these moraines indicate that they were formed during the Little Ice Age (LIA). [All ^{14}C ages were calibrated using CALIB 6.0 (Reimer *et al.*, 2009) and ^{10}Be ages were re-calculated by applying the Lal (1991) and Stone (2000) time-dependent model using the CRONUS Earth 2.2 calculator (Balco *et al.*, 2008; http://hess.ess.washington.edu/math/) under the assumption of zero erosion. Both original and calibrated/re-calculated data are listed in the online Supporting information, Table S1.] The second group of moraines is between the LIA moraines and the Glacier Station. Boulders of this group are slightly weathered and there is a thin layer and grass on the top of the moraines. The ^{14}C ages of 6.5 ± 0.1, 4.6 ± 0.2 and 4.4 ± 0.2 cal ka BP (Zheng and Zhang, 1983) suggest that they were formed during the middle–late Holocene (Neoglaciation). A lateral moraine close to the Glacier Station yielded AMS ^{14}C ages of 7.5 ± 0.1 and 1.8 ± 0.1 cal ka BP from the inner and outer layers of coating, with a much older age of 23.5 ± 0.2 cal ka BP from the till matrix (Yi *et al.*, 2004). These ages suggest that it may be a relic moraine formed during the Last Glaciation. Recent work by Kong *et al.* (2009) produced four ^{10}Be ages of 10.2 ± 1.1–21.6 ± 2.2 ka from surface boulders at this site; the wide range of ages may reflect considerable post-depositional reworking or potential nuclide inheritance of some boulders.

Two groups of moraines are found in the lower trough further down the main valley (Fig. 1). The Upper Wangfeng (UWF) moraine group extends from the Hayisa Drumlin (HD) to the Wangfeng Station and includes a series of subdued moraine ridges. The morphology of the moraines is still visible, although it is significantly less distinct than LIA and Neoglacial moraines. A thin layer of grey soil and about 50 cm of loess are commonly found covering the top of the moraines, and granite/gneiss boulders are scattered on the moraine surfaces. Previous studies identified two layers of till in a moraine profile exposed in a road cut. The lower till is believed to have been formed by subglacial processes and has a consolidated texture and high silt content (Cui, 1981b). The upper till is looser and coarser with low silt content and has been interpreted as a supraglacial melt-out till (Cui, 1981b). Wang (1981b) obtained a ^{14}C age of 10.3 ± 0.5 cal ka BP from the loess on the top of the till and a ^{14}C age of 18.0 ± 0.8 cal ka BP for an inorganic carbonate coating in the till and concluded that this moraine group was formed during MIS 2. Yi *et al.* (2004) reported two calibrated AMS ^{14}C ages of 22.8 ± 0.6 and 27.9 ± 0.5 cal ka BP for carbonate coating from the upper and lower tills, respectively. Yi *et al.* (2002) reported ESR ages of 37.4 and 27.6 ka for these two tills. Zhao *et al.* (2006) provided an ESR age of 35 ± 3.5 ka for this moraine group. Kong *et al.* (2009) provided three ^{10}Be ages from 15.9 ± 1.4 to 20.9 ± 2.0 ka for boulders on these moraines. Together, these ages suggest that the UWF moraine group was formed during MIS 2, although Zhao *et al.* (2006) suggested that this moraine group may be formed during MIS 3b.

The Lower Wangfeng (LWF) moraine group is found in a 3.5-km-long U-shaped valley downstream from the Wangfeng Station and terminates at about 2900 m a.s.l. (Fig. 1). There are no other glacial landforms present between the UWF and LWF moraine groups; however, an over-thrust unconformity between these two moraine groups was identified by Wang (1981b), indicating that these moraine groups formed during different periods of glaciation. Around the Wangfeng Station, the modern river cuts down through the till into the bedrock exposing a total till thickness of >100 m. The surface of the LWF moraines is very subdued, suggesting that it may have experienced significant degradation. The age of this moraine group was constrained by ESR and TL dating, but controversy still exists. Based on a TL age of 37.7 ± 2.6 ka for fluvial sediments covered by the till, Li (1995) concluded that the till was deposited during the late stage of the Last Glaciation, similar to the UWF. Yi *et al.* (2002) suggested that the LWF moraine group was formed during MIS 4 based on four ESR ages of 54.6–72.6 ka. Zhao *et al.* (2006) identified a lower MIS

6 section based on three ESR ages (171.1 ± 17–184.7 ± 18 ka) close to the till bottom.

The oldest moraine in this area is called the High Wangfeng (HWF) moraine group and is found in the remnants of high troughs about 200–300 m above the river bed. The original moraine surface has been destroyed, and only about 10 m of till is left and preserved in the high trough bottom. ESR ages (459.7 ± 46 and 471.1 ka) suggest that the HWF moraine group was formed during MIS 12 (Zhou *et al.*, 2001; Zhao *et al.*, 2006). However, Kong et al. (2009) obtained five much younger ^{10}Be ages of 5.5 ± 0.7–17.3 ± 2.2 ka on moraine boulders and suggested a possibility that this moraine group was left behind by tributary side valley glacial retreat during the Last Glaciation.

In addition to these moraine groups, there are also other landforms in the valley that help in understanding glacial chronology in this area. An empty cirque (EC) is located to the north-east of Glacier No. 1 (Fig. 1). There are no modern glaciers inside the cirque but erratics and a thin layer of till occur on the cirque outlet rock step (ECRS). No absolute ages have been obtained to constrain the age of the till or the erratics in the cirque. It has been suggested that the till on the ECRS was formed during the mid-Holocene (Neoglaciation) (Cui, 1981b) or during the late stage of the Last Glaciation (Wang, 1981a).

Another impressive rock step occurs a few hundred metres below the Glacier Station and close to the Weather Station and has been named the Weather Station Rock Step (WSRS). This rock step occurs at the confluence of several tributary glaciers. Some large erratics (2-3 m high) are present on the top of the rock step, presumably remnants from glacial retreat. About 1.5 km down from the WSRS, there is a streamlined landform called the HD. Compact lodgment till with high silt content is found around the exposed bedrock core. A sample collected from 3 m below the surface yields an ESR age of 45.9 ka BP, much older than expected, suggesting that the till may have formed during MIS 3b and subsequently survived several late-glacial events without being reworked (Yi *et al.*, 2002). Granite and gneiss erratics are scattered on top of the till and bedrock surface.

Sample collection, preparation and measurement

Major focuses for sample collections were: (i) on the UWF and LWF moraine groups that can be used to determine glacial chronology and provide comparisons with other dating results; and (ii) erratics distributed along the valley to examine the retreat pattern of the last glacial cycle. Rock samples of up to 4 cm depth were collected from the top surfaces of selected boulders located on top of the moraine/till or rock step and drumlin. These locations were chosen to minimize the potential impact of overburden shielding and toppling on cosmogenic nuclide concentrations. All samples were taken from gneiss and granite boulders. A GPS unit was used to record sample location and altitude. Surrounding mountain slopes and dip angles of the sampled surface were measured to determine the topographic shielding factor for each sample.

Two samples (07-28 and -29, see Fig. 2A) were collected for the LWF moraine group (Fig. 1). It was hard to find large

Figure 2. Photographs of sample sites. (A) Sample 07-28 from the LWF moraine group; (B) sample 07-35 from the UWF moraine group; (C) sample 07-21 from the HD; (D) sample 07-15 from the WSRS; (E) sample 07-23 from the ECRS; (F) sample 07-25 from the ECRS. This figure is available in colour online at wileyonlinelibrary.com.

boulders on top of this moraine group, so we sampled the two largest gneiss boulders we could find (about 40 × 40 × 30 cm and 50 × 30 × 30 cm). Four samples (07-35, -36, -37 and -38, see Fig. 2B) were collected for the UWF moraine group. All boulders sampled are >0.5 m high. One erratic sample (07-21, Fig. 2C) on top of the HD bedrock surface was sampled from a quartz vein of a boulder >0.5 m high. Two samples (07-13 and -15; see Fig. 2D) were collected on top of the WSRS from two gneiss erratics >1 m high. We also collected two erratic samples on top of the ECRS. One sample (07-23, Fig. 2E) was collected from a granite erratic >0.5 m high and another (07-25, Fig. 2F) was taken from a relatively small granite erratic (40 × 30 × 20 cm).

Sample preparation was performed in the cosmogenic nuclide laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Approximately 30-60 g pure quartz was separated for each sample following the procedures of Kohl and Nishiizumi (1992). The quartz was then dissolved in HF and HNO_3 and spiked with ~0.7 mg ^{9}Be carrier. AMS measurements were carried out at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab) based on revised ICN standards (Nishiizumi *et al.*, 2007). $^{10}Be/^{9}Be$ ratios were measured by AMS and corrected by full chemistry procedural blanks (4.82×10^{-15}) and converted to ^{10}Be concentrations. [Quartz mass, ^{9}Be carrier mass and AMS $^{10}Be/^{9}Be$ ratios of these samples are given in supporting Table S2.] All ^{10}Be exposure ages were calculated by applying the Lal (1991) and Stone (2000) time-dependent model using the CRONUS Earth 2.2 calculator (Balco *et al.*, 2008; http://hess.ess.washington.edu/math/) under the assumption of zero erosion (Lal, 1991). The renormalized ^{10}Be production rate at sea level in high latitudes of this calculation is 4.39 ± 0.37 atom g^{-1} a^{-1} (http://hess.ess.washington.edu/math/) and the ^{10}Be half life is 1.36 ± 0.07 Ma (Nishiizumi *et al.*, 2007). Topographic shielding was calculated based on Dunne *et al.* (1999) and a thickness correction was determined based on Gosse and Phillips (2001) using a rock density of 2.7 g cm^{-3} and a cosmic ray attenuation coefficient of 160 g cm^{-2}.

Results and discussion

The results are listed in Table 1 and are shown graphically in Fig. 3; only the minimum exposure age under an assumption of zero surface erosion (Lal, 1991) is given for each sample.

^{10}Be exposure ages of UWF and LWF moraines

Four samples (07-35, -36, -37, -38) from the UWF moraines yield minimum ^{10}Be exposure ages from 15.0 ± 1.3 to 17.1 ± 1.5 ka (Table 1, Fig. 3). Based on studies around Tian Shan and the Tibetan Plateau (Abramowski *et al.*, 2006; Seong *et al.*, 2007; Koppes *et al.*, 2008), a maximum erosion rate of 3 mm ka^{-1} at the boulder surface can be used to constrain a conservative maximum exposure age for each sample. However, because this adjustment increases exposure ages by <5%, we simply report minimum exposure ages here. These ages are consistent with three ^{10}Be ages reported by Kong *et al.* (2009) from 15.9 ± 1.4 to 20.9 ± 2.0 ka. As discussed in many studies (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003; Briner *et al.*, 2005; Abramowski *et al.*, 2006; Putkonen and O'Neal, 2006; Koppes *et al.*, 2008; Putkonen *et al.*, 2008), ^{10}Be surface exposure ages of moraine boulders are affected by several factors such as moraine degradation and boulder exhumation, inheritance, boulder surface erosion, and snow/sediment cover. Most of these factors, except nuclide inheritance, tend to reduce the nuclide accumulation at the boulder surface and hence underestimate the formation age of the moraine. Briner *et al.* (2005) proposed that surface exposure ages more likely represent the age of the moraine stabilization rather than the timing of ice retreat from a moraine position. Therefore, an "oldest-age method" is more suitable in the determination of the moraine formation age, especially where there is no clear evidence of inheritance. Our data from the UWF moraines support this method. All samples were from gneiss/granite boulders that are different in lithology from nearby bedrock (schist). These boulders were transported several kilometres by glaciers from the area close to modern glaciers where the local lithology is gneiss/granite. This indicates a reduced possibility of inheritance for these boulders. Therefore, the oldest age of 20.9 ± 2.0 ka (Kong *et al.*, 2009) in this dataset is more close to the formation age of the UWF moraines, and the clustering of boulder ages around 16 ka probably corresponds to a period of moraine stabilization after ice retreat from the moraine position.

Our measured ^{10}Be exposure ages are younger than ages determined by AMS ^{14}C and ESR. Yi *et al.* (2004) performed AMS ^{14}C dating of inorganic carbonate coating and obtained ages of 22.8 ± 0.6 cal ka BP for the upper till and 27.9 ± 0.5 cal ka BP for the lower till. The difference between the ages of these two layers was interpreted as indicating that the lower till (subglacial) was deposited a few thousand years earlier than the

Table 1. Measured ^{10}Be concentrations and calculated apparent exposure ages at the headwater of the Urumqi River, Tian Shan, China

Sample ID	Location, type*	Latitude (°N)	Longitude (°E)	Altitude (m)	Thickness (cm)	Topographic and thickness correction†	^{10}Be concentration ($\times 10^{5}$ atoms g^{-1})‡	Minimum ^{10}Be exposure age (ka)§
07-13	WSRS, Erratic	43.114	86.847	3520	2.0	0.966	8.51 ± 0.40	15.9 ± 1.5
07-15	WSRS, Erratic	43.114	86.847	3520	2.0	0.966	8.35 ± 0.19	15.6 ± 1.4
07-21	HD, Erratic	43.119	86.867	3429	3.0	0.951	8.26 ± 0.31	16.4 ± 1.5
07-23	ECRS, Erratic	43.119	86.825	3831	2.0	0.962	9.97 ± 0.21	15.7 ± 1.4
07-25	ECRS, Erratic	43.119	86.824	3832	3.0	0.954	9.00 ± 0.42	14.3 ± 1.4
07-28	LWF, Boulder	43.110	86.945	3005	2.5	0.924	7.13 ± 0.30	18.7 ± 1.8
07-29	LWF, Boulder	43.110	86.945	3006	2.5	0.924	6.15 ± 0.25	16.2 ± 1.5
07-35	UWF, Boulder	43.119	86.920	3192	2.0	0.939	6.60 ± 0.11	15.3 ± 1.3
07-36	UWF, Boulder	43.119	86.920	3186	2.0	0.939	7.39 ± 0.13	17.1 ± 1.5
07-37	UWF, Boulder	43.119	86.920	3183	3.5	0.927	7.01 ± 0.18	16.5 ± 1.5
07-38	UWF, Boulder	43.119	86.920	3179	3.0	0.931	6.37 ± 0.14	15.0 ± 1.3

*WSRS, Weather Station Rock Step; HD, Hayisa Drumlin; ECRS, Empty Cirque Rock Step; LWF, Lower Wangfeng Group; UWF, Upper Wangfeng Group. †Topographic shielding correction calculated according to Dunne *et al.* (1999). Thickness correction calculated according to Gosse and Phillips (2001) with a rock density of 2.7 g cm^{-3} and a cosmic ray attenuation coefficient of 160 g cm^{-2}. ‡ ^{10}Be concentrations were measured by PRIME Lab, Purdue University, based on revised ICN standards (Nishiizumi *et al.*, 2007). § ^{10}Be minimum exposure ages are calculated by applying the Lal (1991) and Stone (2000) time-dependent model using the CRONUS Earth 2.2 calculator (Balco et al., 2008; http://hess.ess.washington.edu/math/) under the assumption of zero erosion (Lal, 1991).

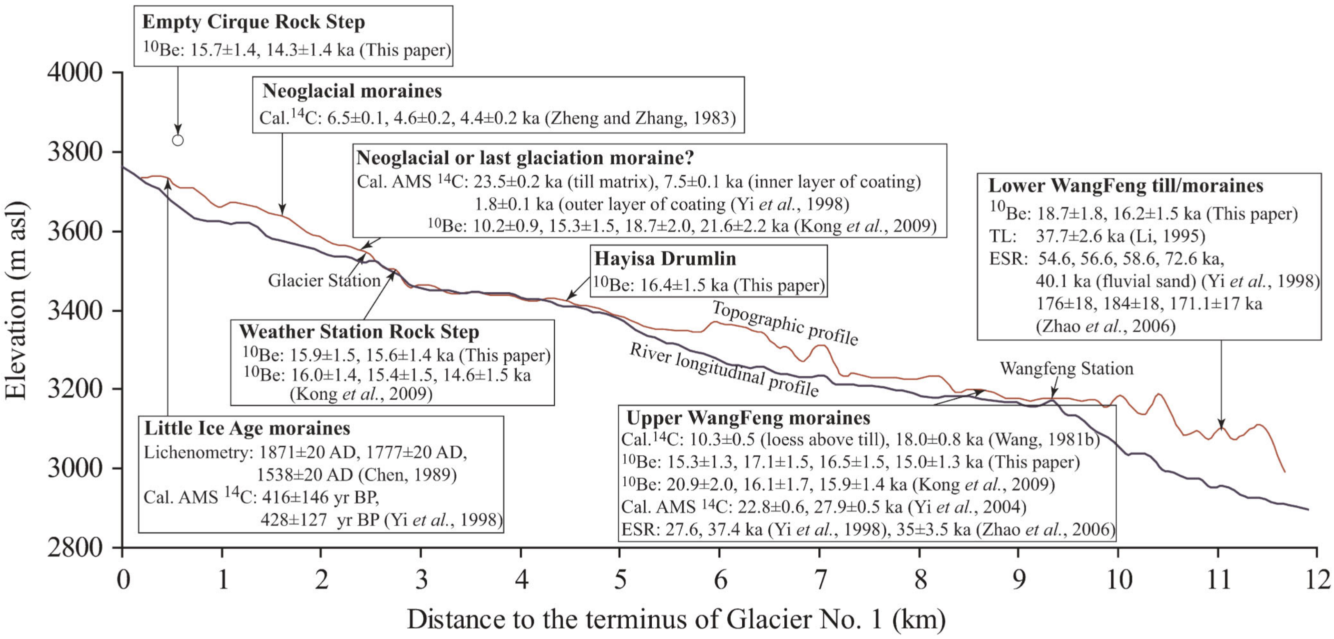

Figure 3. Different dating techniques and the ages of moraines and related sediments. The Urumqi River longitudinal profile cuts mostly into bedrock or bedrock with a thin layer of glacial deposits. The topographic profile (location indicated in Fig. 1) includes glacial deposits along the valley: the Little Ice Age and Neoglacial moraines from the modern glaciers to the Glacier Station, the UWF moraines from the HD to the Wangfeng Station, and the LWF moraines near the Wangfeng Station. There are few glacial deposits between the Glacier Station and HD.

upper supraglacial melt-out till. As the targets of the ^{10}Be exposure dating are boulders from the moraine surface, ^{10}Be ages should be compared with the age from the upper till (22.8 ± 0.6 cal ka BP). The slight difference (~1.9 ka) between ^{10}Be and AMS ^{14}C ages may result from variations in the techniques, or could reflect the impact of surface erosion and sediment/snow cover on ^{10}Be dating. Thus, ^{10}Be results confirm that the UWF moraines were formed during MIS 2.

A contrasting view of the age of the UWF moraines is provided by published ESR data. Yi *et al.*'s (2002) ESR ages of 37.4 ka for the upper till and 27.6 ka for the lower till are reversed, but the age of the lower till is consistent with the AMS ^{14}C result (27.9 ± 0.5 cal ka BP). Zhao *et al.* (2006) provided an ESR age of 35 ± 3.5 ka, similar to the upper till age (37.4 ka) measured by Yi *et al.* (2002) and they argued that the UWF moraines were formed during MIS 3b. One way to resolve the difference between ^{10}Be and ESR ages is to consider the possibility that ESR ages from the upper supraglacial till may reflect incomplete resetting of the ESR signal, and thus are the maximum-limiting ages that are not inconsistent with a MIS 2 age. However, an ESR age of 27.6 ka from the lower subglacial till is still older than ^{10}Be surface exposure ages.

In considering disparities between ^{10}Be exposure and ESR ages, it is important to consider what each technique is actually dating in a glacial event. TCN dating measures time since the surface has been exposed due to glacier retreat, and is typically used to provide minimum ages of glacial landforms/deposits. ESR dates the formation of glacial till as a result of subglacial crushing and abrasion sufficient to reset the ESR signal, usually representing a maximum age for the end of a glacial event. Implicit in comparing ages from these two methods is an assumption that the formation of till (ESR) and the end of the glaciation (TCN) are somewhat contemporaneous. However, it is possible that the material in a particular till might have been reset for ESR early and even preserved from previous events. ^{10}Be and ESR ages from another site (HD) may reflect this explanation. The ^{10}Be age of the erratic on the HD surface yields an exposure age of 16.4 ± 1.5 ka, representing the time of glacial retreat, whereas the ESR age from 3 m below the lodgment till surface at the same location yields a significantly older age of 45.9 ka (Yi *et al.*, 2002). Yi *et al.* (2002) believed that the till was deposited during several glacial cycles from an early stage of the Last Glaciation.

The age of the LWF moraine group is constrained by two boulder samples that yield ^{10}Be exposure ages of 18.7 ± 1.8 and 16.2 ± 1.5 ka, consistent with ages on the UWF but significantly younger than ages measured by TL and ESR for the LWF deposits (Fig. 3). The large difference between ^{10}Be and TL/ESR ages cannot be accounted for by corrections for boulder surface erosion and possible sediment or snow covers in ^{10}Be ages. A high boulder surface erosion rate of 3 mm ka^{-1} increases the exposure age only of the order of 5%.

Our limited ^{10}Be results do not resolve the debate over the timing of the LWF moraines; rather, they suggest more possibilities for understanding the formation and chronology of the LWF moraines. Here, we consider two possible hypotheses to explain ^{10}Be exposure ages and the difference between exposure, ESR and TL ages. The first possibility is that the LWF and UWF surfaces were exposed almost at the same time and that both relate to a period of continuous retreat after MIS 2. In this case, the differences between ^{10}Be and TL/ESR results are due to the fact that they date different aspects of a glacial event, and may also reflect incomplete resetting in ESR dating. We note that ESR ages for the LWF vary widely: Yi *et al.* (2002) provided ESR ages of 54.6–72.6 ka, whereas Zhao *et al.* (2006) provided significantly older ESR ages of 171.1 ± 17–184.7 ± 18 ka from the lower portion. It seems plausible that these ages reflect deposition of LWF till throughout the Last Glaciation, with most recent exposure after MIS 2 retreat measured by ^{10}Be ages (18.7 ± 1.8 ka).

Another plausible hypothesis is that the LWF moraine group is significantly older than measured ^{10}Be apparent ages because the feature has experienced significant degradation since it was exposed. Moraine degradation and its impact on surface exposure dating of moraine boulders have been studied in many areas (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003; Briner *et al.*, 2005; Abramowski *et al.*, 2006; Putkonen and O'Neal, 2006; Koppes *et al.*, 2008; Putkonen *et al.*, 2008). Hallet and Putkonen (1994) developed a moraine degradation model that predicts an increase in the range of TCN exposure ages with increasing moraine ages. A conservative analysis of moraines in western North America found that the maximum depth of moraine degradation is about 25% of the final height of the moraine (Putkonen and O'Neal, 2006). In the Aksu Valley, western Tian Shan, Abramowski *et al.* (2006) concluded that a majority of ^{10}Be samples are affected by moraine degradation. Fu and Yi (2009) found a strong correlation between glacier length and moraine height for Holocene moraines, but a poor relationship for older moraines due to moraine degradation.

In this area, the UWF and LWF moraines are all subdued compared with LIA and Neoglacial moraines. The difference between these two moraine groups is that the morphology of the UWF moraines is still visible and can be identified in the field, whereas the morphology of the LWF moraines is difficult to identify. This contrast presumably relates to different degrees of degradation, which might relate to differences in apparent ^{10}Be ages, or could reflect differences in degradation susceptibility. With the current data available, we cannot rule out either hypothesis. The wide range in ages reported for the LWF and differences between ^{10}Be and ESR ages indicate that further studies are necessary to resolve the debate about the formation age of these important landforms.

Glacial retreat patterns and rates after MIS 2

^{10}Be exposure ages from erratics are generally used to provide constraints for the timing of local deglaciation (Fabel *et al.*, 2002, 2004), and thus ^{10}Be ages from the HD, WSRS and ECRS can be used to examine local glacial retreat rates after MIS 2. The erratic on the top of HD yields an exposure age of 16.4 ± 1.5 ka, two erratics on the WSRS yield ^{10}Be ages of 15.9 ± 1.5 and 15.6 ± 1.4 ka, and two erratics on the ECRS yield ^{10}Be ages of 15.7 ± 1.4 and 14.3 ± 1.4 ka. These ages are all younger than MIS 2. Although these ages are broadly consistent with exposure ages of the UWF moraines close to the Wangfeng Station (>8 km from ECRS samples), the central values represent a pattern of slight decrease in ^{10}Be ages upstream from the UWF moraines and suggest a glacier retreat rate of >2.5 m a^{-1} after MIS 2 (Fig. 4). This rate is comparable with the observed 4.0–4.5 m a^{-1} retreat rate of Glacier No. 1 over the last 40 years (Li *et al.*, 2003).

^{10}Be exposure ages of erratics on the ECRS (15.7 ± 1.4 and 14.3 ± 1.4 ka) are the first published quantitative age constraints for the EC and suggest that the tributary glacier retreated into the cirque during the late-glacial and before the Holocene. It also indicates that any late glacial advances within the Holocene were confined to the cirque and did not extend out into the main valley. ^{10}Be exposure ages from the WSRS erratics (15.9 ± 1.5 and 15.6 ± 1.4 ka) are consistent with Kong *et al.*'s (2009) ^{10}Be ages of 10.2 ± 1.1–21.6 ± 2.2 ka from the moraine near the Glacier Station. The erratics on the WSRS are very close to this moraine, and in the field appear to be part of a former extension of the moraine into the centre of the main glacial valley. However, Kong *et al.*'s (2009) ^{10}Be ages from this moraine show relatively large variability (Fig. 4). Plotting their results and the new ages in this study together allows us to evaluate the potential causes of this large variability. The youngest age (10.2 ± 1.1 ka) is an outlier that may result from exhumation of the boulder that was sampled. The oldest age

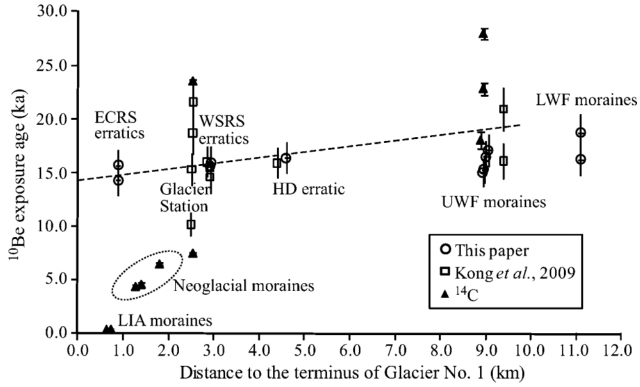

Figure 4. Glacial retreat pattern upstream from the LWF and UWF moraines after MIS 2. The distance was determined from the river longitudinal profile (Fig. 3). A trend of slightly decreasing ^{10}Be ages upstream from the UWF moraines (dashed line) suggests an ice retreat rate of >2.5 m a^{-1} after MIS 2. This figure also shows the relatively large variability of ^{10}Be ages reported by Kong *et al.* (2009) for a lateral moraine around the Glacier Station (see text for detail) and the middle–late Holocene glacial advances (Neoglacial and LIA moraines) dated by ^{14}C in the main valley.

(21.6 ± 2.2 ka) is the oldest value in the whole dataset (even older than ages of the UWF moraines >6 km down the valley); it may therefore be an outlier reflecting prior exposure of the boulder. Given that this sample was from a lateral moraine, there is a greater chance to incorporate boulders into the moraine from the valley side; such boulders may have been exposed on the valley side prior to their incorporation into the moraine.

Based on ice core records from the Tibetan Plateau, Thompson *et al.* (2005, 2006) proposed a hypothesis for asynchronous Northern Hemisphere glaciation implying that the ice cover on much of the plateau was limited during the late part of the last glacial cycle when the high-latitude northern ice sheets were expanding. They also argued from ice core records that the ice cover on the plateau must have disappeared in the latest Pleistocene and then re-accumulated in the early to mid-Holocene subsequent to the Northern Hemisphere insulation maximum (~9 ka). The glacial retreat pattern identified in this area is consistent with this hypothesis. We observed a very fast late-glacial retreat before the Holocene (Fig. 4) and the ECRS location (Fig. 1) was exposed by this retreat prior to >14 ka, suggesting that during the late-glacial period glaciers had retreated at least to the positions marked by the termini of modern glaciers, and may even have disappeared entirely. The lack of early Holocene deposits suggests possible limited glacial expansion during this phase and reworking of any deposits by more extensive expansion during the middle or late Holocene. In addition, the rapid retreat pattern observed in this area is also consistent with observations in the Alay-Turkestan Range (Abramowski *et al.*, 2006), the Teskey Ala-Too Range and the AtBashy Range in Kyrgz Tian Shan (Narama *et al.*, 2009) where glaciers advanced several kilometres down valley during MIS 2. However, Koppes *et al.* (2008) also observed a restricted glacial expansion in Kyrgz Tian Shan, with only cirque glacier advances in MIS 2. Further studies are necessary to assess fully the patterns of glacier–climate interaction in the Tian Shan and other mountains of Central Asian.

Conclusions

We used ^{10}Be exposure ages from boulders on the top of moraines and erratics along glacial valleys to constrain moraine ages and glacial retreat rates during the Last Glaciation at the headwater of the Urumqi River, Tian Shan, China. ^{10}Be ages of the UWF moraines are 15.0 ± 1.3–17.1 ± 1.5 ka, consistent with previous reported ^{10}Be ages that these moraines were formed during MIS 2. However, ^{10}Be ages are younger than the ages determined by AMS ^{14}C and ESR, probably due to the potential impacts of surface erosion and sediment/snow cover on surface exposure dating, as well as the fact that each technique measures a slightly different aspect of the glacial event.

Our ^{10}Be ages of the LWF moraines (18.7 ± 1.8 and 16.2 ± 1.5 ka) are similar to the UWF ages, but significantly younger than ages measured by ESR. Either the two moraine groups were formed during the same period (MIS 2) and the ESR ages reflect incomplete resetting of the ESR signal and/or possible older events in the lower till, or the ESR data reflect the age of the moraines and ^{10}Be ages reflect differing degrees of moraine degradation.

Our ^{10}Be ages from erratics on rock steps and a drumlin distributed along >8 km of the main glacial valley indicate a glacier retreat rate of >2.5 m a^{-1} after MIS 2. This rate is comparable with observed modern glacier retreat rates over the past 40 years. The timing and rate of glacial retreat is consistent with ice core studies on the Tibetan Plateau that suggest ice cover on the plateau had probably disappeared during the latest Pleistocene and then re-accumulated in the early Holocene. However, there is no evidence of early Holocene glacial advances identified in this area, and it appears most likely that any evidence would have been later destroyed by more extensive ice advances in the middle or late Holocene.

Supporting information

Additional supporting information can be found in the online version of this article:

Table S1. Available numerical dates/ages of moraines at the source area of Urumqi River, Tian Shan, China

Table S2. Sample information including latitude, longitude, altitude, quartz weight, ^{9}Be carrier mass, and AMS ^{10}Be / ^{9}Be ratios

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Abbreviations. AMS accelerator mass spectrometry; EC empty cirque; ECRS EC outlet rock step; ESR electron spin resonance; HD Hayisa Drumlin; HWF High Wangfeng; LIA Little Ice Age; LWF Lower Wangfeng; MIS marine isotope stage; PRIME Purdue Rare Isotope Measurement (Lab); TCN terrestrial cosmogenic nuclide; TL thermoluminescence; UWF Upper Wangfeng; WSRS Weather Station Rock Step.

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