Quaternary Research 78 (2012) 590–597

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

The late Pleistocene glaciation in the Bogchigir Valleys (Pamir, Tajikistan) based on ^{10}Be surface exposure dating

Ines Röhringer [a], Roland Zech [b,*], Uwe Abramowski [a], Pjotr Sosin [c], Ala Aldahan [d], Peter W. Kubik [e], Ludwig Zöller [a], Wolfgang Zech [a]

[a] *Chair of Geomorphology, University of Bayreuth, Bayreuth, Germany*
[b] *Geological Institute, ETH Zurich, Zurich, Switzerland*
[c] *Tajik Academy of Agriculture, Dushanbe, Tajikistan*
[d] *Department of Earth Sciences, Uppsala University, Uppsala, Sweden*
[e] *Laboratory of Ion Beam Physics, ETH Zurich, Zurich, Switzerland*

ARTICLE INFO

Article history:
Received 4 February 2012
Available online 25 September 2012

Keywords:
Quaternary
Cosmogenic nuclides
Paleoclimate
Westerlies
Monsoon

ABSTRACT

Glacial chronologies from the Pamir may not only provide insights into past changes in temperature, but also into past changes in precipitation related to the northern-hemispheric westerlies and the monsoonal circulation. We present 18 new exposure ages from the Bogchigir Valleys that complement and refine our previous studies in these valleys. The most extensive dated glaciation in the area occurred ~100 ka, during Marine Oxygen Isotope Stage (MIS) 5, and indicates increased precipitation likely from both the westerlies and the monsoonal circulation. A subsequent glacier advance, which deposited characteristic 'chukur' moraine lobes, occurred at ~80–75 ka. Circumstantial evidence points to glacial advances at ~65 and 40 ka, the latter likely also documenting increased monsoonal moisture supply during MIS 3. Less extensive glacial advances occurred during MIS 2 at ~28 and 24 ka and reflect the aridization trend during the course of the last glacial cycle. Deglaciation started ~21 ka, interrupted by minor stillstands or readvances at ~16 and 12 ka. Local calibration sites and glacier-climate modeling would be very helpful to reduce the systematic methodological uncertainties (still at least 10%) and to draw more detailed paleoclimatic conclusions.

Introduction

Mountain glacier fluctuations are closely linked to temperature and precipitation changes. Geomorphological mapping and dating of moraines and other glacial landforms therefore provide an important tool for the investigation of past climate changes. Great progress has been made in physical dating techniques over the last few decades, above all in using terrestrial cosmogenic nuclides for surface exposure dating (SED). This new technique allows the reconstruction of glacial chronologies in arid mountain regions, where organic material for radiocarbon dating is scarce and therefore age control has long been virtually absent. An impressive number of studies has meanwhile been conducted throughout the Himalayan–Tibetan orogen (Owen et al., 2008; Owen, 2009; Scherler et al., 2010; Chevalier et al., 2011; Heyman et al., 2011). However, glacial chronologies from the Pamir, situated in the westernmost part of the Himalayan–Tibetan orogen, are still sparse and controversial.

The first numerical ages of moraines in this area based on ^{10}Be SED were published by Zech et al. (2005a,b) and Abramowski et al. (2006). Zech et al. (2005a,b) recognized several glacial stages in the Lake Yashilkul area north of the Bogchigir Range. The oldest dated glacial advance unambiguously occurred early during the last glacial cycle, during Marine Oxygen Isotope Stage (MIS) 5 or 4, and thus documents an early *local* last glacial maximum (*local* LGM). The exact timing remains unclear because of large systematic methodological uncertainties mainly related to the local production rate. A subsequent, less extensive glaciation is documented by characteristic hummocky moraine lobes that are locally called 'chukurs' and that can be interpreted as dead-ice terrain. This glaciation could not be dated unequivocally because available exposure ages scatter widely. Zech et al. (2005a,b) argued that the oldest ages (~70–50 ka) are closest to the actual moraine deposition age and that ^{10}Be exposure ages that are too young reflect long-lasting ice decay and geomorphological surface instability. Abramowski et al. (2006), on the other hand, pointed out that it cannot be excluded that the hummocky moraine lobes were deposited during MIS 2, i.e. synchronous with the *global* LGM, and that exposure ages that are too old may be the result of inheritance (pre-exposure).

The objectives of the present study are to (i) contribute to the above controversy by refining the existing glacial chronologies in the Bogchigir Valleys, (ii) investigate the extent of the MIS 2 glaciation in particular, and (iii) date recessional moraines farther upvalley in order to constrain the timing of deglaciation. We should acknowledge here

---

* Corresponding author.
E-mail address: godotz@gmx.de (R. Zech).

0033-5894/$ – see front matter © 2012 University of Washington. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yqres.2012.09.002

that with 18 new exposure ages our studies may still be considered to be at reconnaissance level. This reflects the time-consuming and expensive nature of the ^{10}Be analyses, but our results may help identifying key sites for future, more detailed studies.

Geographical setting

Situated in a climatic transition zone, the Pamir is a key location for identifying the interaction between mid-latitude westerlies, the Indian summer monsoon and the Siberian High (Benn and Owen, 1998; Aizen et al., 2001, 2009). Under today's climatic conditions, moisture supply to the Pamir is mainly coupled to cyclones traveling along the westerly jet stream and advecting moisture from the Caspian Sea, the Mediterranean and the Gulf of Persia (Bohner, 2006). The influence of the Indian summer monsoon ends south of the NW-Himalaya, only occasionally reaching the Hindukush and Karakoram (Weiers, 1995) (Fig. 1a).

Our study area is located south of Lake Yashilkul (37.8°N, 72.8°E, 3720 m asl, above sea level) in the southwestern Pamir (Fig. 1b) and marks the geomorphologic and climatic transition zone between the more humid, heavily dissected western Pamir and the arid, plateau-like eastern Pamir (~4000 m asl, <100 mm/yr, UNEP, 2002). The cold and dry climate conditions only support scarce semi-desert to mountain-steppe vegetation (UNEP, 2002). South of Lake Yashilkul the Bogchigir Range rises to 5700 m asl and has a glaciated area of ~100 km^2 (Wissmann, 1959). The valleys of the Great Bogchigir and Orto Bogchigir-I drain northwards into the lake (Fig. 1c). At present, the glacier tongues in both valleys descend to 4540 m asl and the ELA is approximately 4970 m asl (Wissmann, 1959). Geologically, the Bogchigir Range belongs to the south-western Pamir Crystalline series, which consists of Precambrian metamorphic rocks and Mesozoic and Paleogene granites (Burtman and Molnar, 1993).

Material and methods

Stratigraphy and sampling locations

Four generations and types of moraines can be distinguished in our research area at Lake Yashilkul. First, the stratigraphically oldest moraines are situated at the southwestern bank of Lake Yashilkul (*M1*, *M1**, Figs. 2a, 3a,b. Note that all new sampling sites are labeled with asterisks). These E–W trending lateral moraines are ~1 km long, have a relatively subdued topography, and are ca. 100 m (*M1*) and 50 m (*M1**) above the main valley floor. *M1* was dated by Zech et al. (2005a) to between 101.6 ± 6.4 ka and 85.8 ± 4.6 ka (n = 7). Note that these and all other previously published exposure ages presented in this manuscript have been recalculated to take into account the ongoing methodological improvements and to allow direct comparison between all ages (see also 'exposure age calculation' below and Table 2). In order to determine whether *M1** documents a younger glacier advance we collected two samples from the lower moraine wall *M1**, which had not been sampled previously.

Second, extensive and well-preserved hummocky moraine lobes (chukurs) cover the lower parts of the Orto Bogchigir-I and Great Bogchigir Valleys and extend into Lake Yashilkul (Figs. 1b, 2). Boulder samples from the outer moraine crest of the chukur *M2* from the Orto Bogchigir-I (Figs. 2a, 3a) yielded seven exposure ages between 74.6 ± 2.9 ka and 15.9 ± 1.0 ka (Zech et al., 2005a). The corresponding chukur in the Great Bogchigir Valley (*BO1*) was dated by Abramowski et al. (2006) to between 79.6 ± 4.3 ka and 36.1 ± 2.0 ka (n = 5). Given the wide exposure age scatter on these deposits and the resultant ambiguous interpretation, we collected additional samples from the outermost moraine in the lower Great Bogchigir Valley (*BO1**, Fig. 2b), paying particular attention to large, stable and un-eroded boulders for sampling.

Third, a series of nested lateral moraines can be identified at about 4000–4200 m asl in the lower parts of the valleys. They form N–S trending ridges up to 200 m above the valley floor. Zech et al. (2005a) dated the upper part of a single-crested lateral moraine in the Orto Bogchigir Valley to 28.5 ± 1.3 ka–28.1 ± 1.9 ka (n = 3, *M4*, Fig. 2a) and speculated that two lateral moraines slightly farther downvalley document separate, older glacial advances at 64.6 ± 2.7 ka (n = 2, but the younger exposure age of 57.3 ± 2.3 was rejected as outlier due to erosion or post-depositional exhumation) and 40.2 ± 1.9 ka (n = 1, *M3*). Abramowski et al. (2006) dated a lateral moraine in the neighboring Great Bogchigir Valley to between 23.5 ± 1.1 ka and 22.4 ± 1.0 ka (n = 4, *BO2*, Fig. 2b). We now have additionally sampled the latero-terminal moraine *BO3** (Figs. 2b,

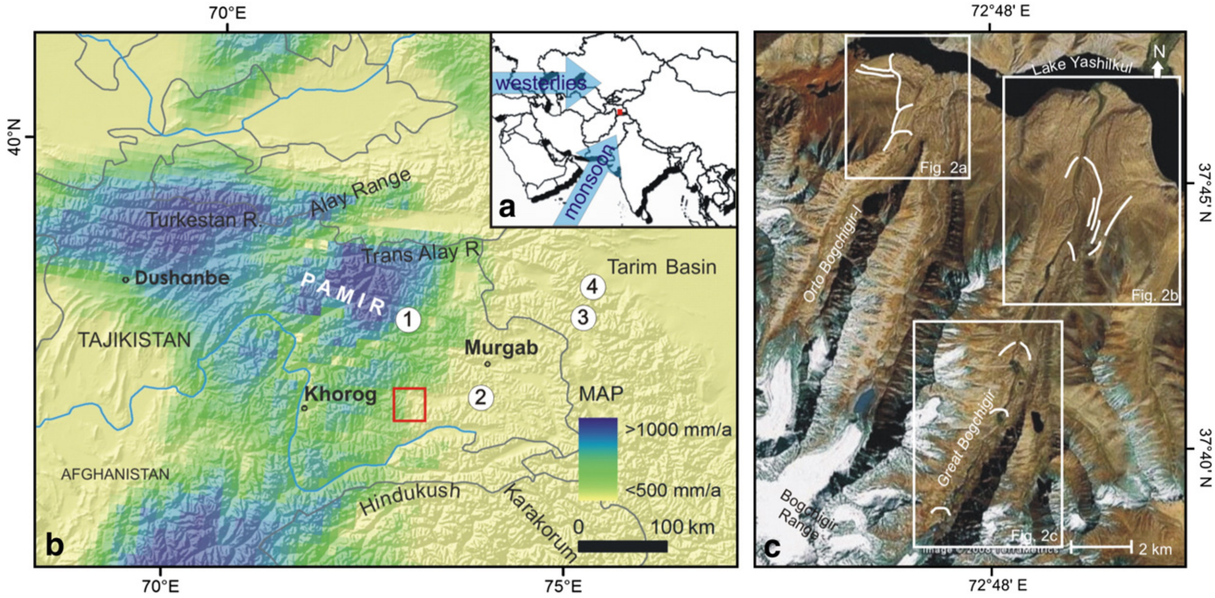

Figure 1. Geographical setting of the Pamir. a) Atmospheric circulation patterns influencing the Pamir. b) Mean annual precipitation (MAP). The red rectangle marks the study area and the encircled numbers other sites discussed in the text: 1 Tanymas Valley (Abramowski et al., 2006), 2 Uchkol and Gurumdi Valleys (Abramowski et al., 2006), 3 Muztag Ata/Kongur Shan (Seong et al., 2009), 4 Kongur Mountain (Wang et al., 2011). c) Google Earth image of the study area southwest of Lake Yashilkul. The white lines mark the dated moraines, and the white rectangles denote the detail plots shown in Figs. 2a–c.

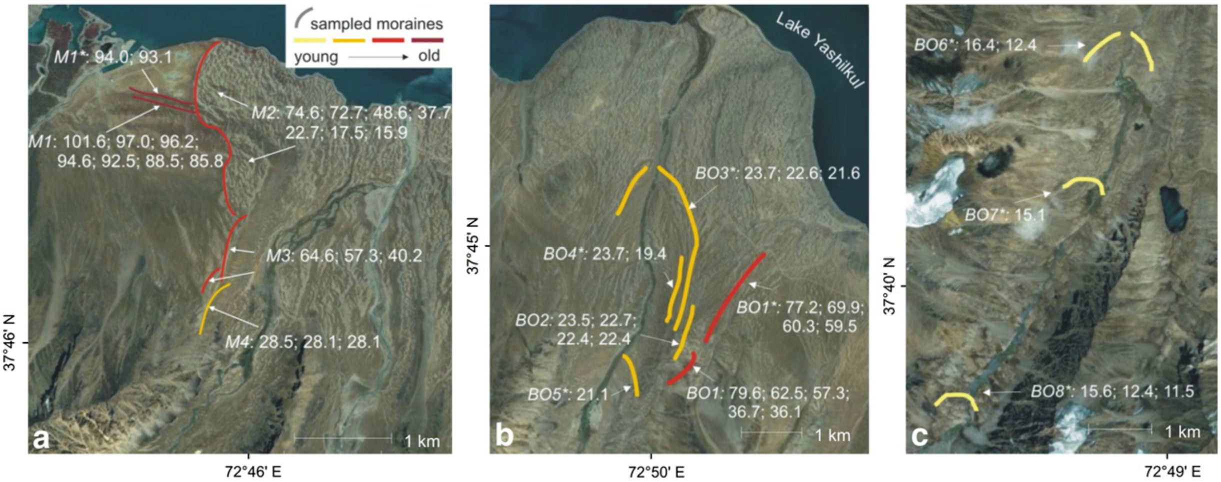

Figure 2. Detail plots of the sampling sites, exposure ages obtained in this study (*M1**, *BO3**–*BO8**) and those recalculated from Zech et al. (2005a,b: *M1*–*M4*) and Abramowski et al. (2006: *BO1*, *BO2*). a) The lower part of the Orto Bogchigir-I Valley, b) the lower part of the Great Bogchigir Valley, and c) the upper reaches of the Great Bogchigir Valley.

3c), as well as the moraines *BO4** and *BO5**, which document the first recessional stages of the deglaciation (Figs. 2b, 3c,d).

Fourth, approximately 20–m-high terminal moraines farther upvalley above 4200 m asl represent younger recessional stages. Samples were collected from two latero-terminal moraines (*BO6**, Figs. 2c, 3e, *BO7**, Fig. 2c) and from boulders on a roche moutonnée (*BO8**, Figs. 2c, 3f), which is located ~800 m from the present-day glacier terminus.

Sampling, laboratory procedures, and exposure age calculation

Field work was carried out in 2007 in the valleys of the Great Bogchigir and the Orto Bogchigir-I (Fig. 1b). We sampled 1–5 cm thick chips from the flat top of large granitic boulders. To minimize the risk of boulder instability and age underestimation, we preferred to sample large boulders firmly embedded in the till, thickly covered by desert varnish, and showing little evidence of rock surface erosion. Sample location and elevation were obtained using a GPS (Global Position System) receiver. Surface inclination of the boulders and shielding from surrounding topography was measured with an inclinometer. All relevant sample data are provided in Table 1.

Laboratory analyses were carried out partly at the laboratory of the Chair of Geomorphology, University of Bayreuth, and partly at the cosmogenic isotope laboratory of the University of Uppsala (Table 1). After crushing and sieving the samples, the 250–700 µm fraction was repeatedly leached with 5% HF and concentrated HNO_3 in order to isolate the quartz grains. A Franz magnetic separator was used for further mineral purification. Separation of the beryllium was conducted according to a slightly modified scheme of Ivy-Ochs (1996): ^{9}Be carrier was added before the quartz was dissolved in 48% HF. In order to remove fluorides and boron, the dissolved samples were fumed off with 65% HNO_3 and 32% HCL, respectively. The beryllium was then purified using anion and cation exchange columns, and oxidized in a furnace at 850°C. The BeO was mixed with Cu powder

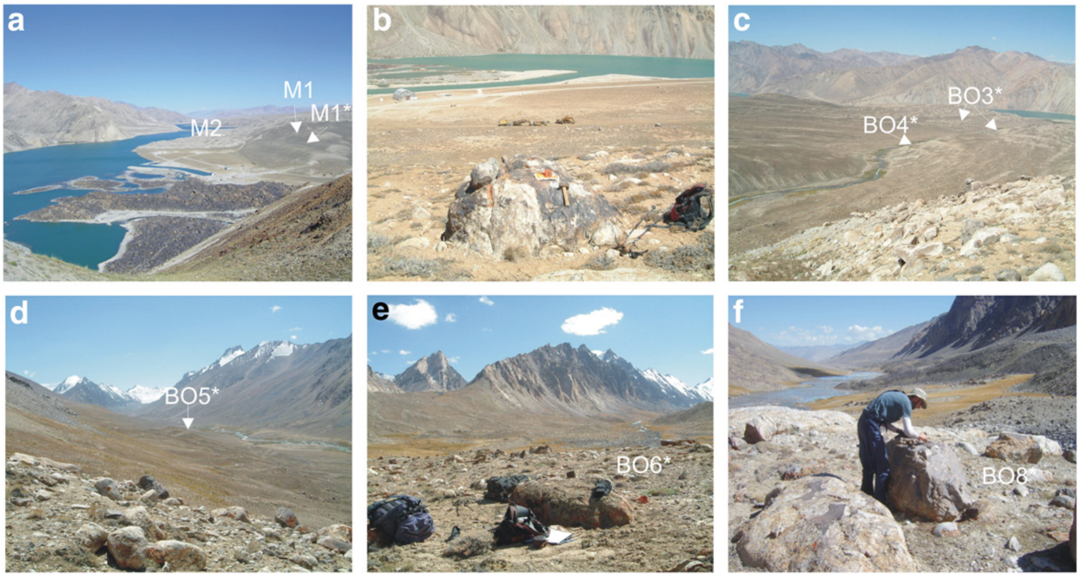

Figure 3. Glacial landforms in the study area. (a) View east along Lake Yashilkul to the latero-terminal moraines *M1*, *M1** and the hummocky moraine lobe *M2*. (b) Sampled boulder on the MIS 5 moraine *M1**. (c) View north along the lower Great Bogchigir Valley and to the global LGM moraines *BO3** and *BO4**. (d) View south into the upper reaches of the Great Bogchigir Valley and to the recessional moraine *BO5**. (e) View south over the sampled boulder from the recessional moraine *BO6**. (f) View north across the youngest sampled moraine *BO8**.

Table 1
Sample data, ^{10}Be concentrations, and exposure ages calculated without erosion and 3 mm/ka erosion, respectively.

Moraine number[a]	Sample ID	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Sample thickness (cm)	Sample density (g/cm^3)	Topographic shielding	^{10}Be (10^4 atoms/g SiO$_2$)	No-erosion exposure age (ka)	3 mm/ka exposure age (ka)
Orto Bogchigir Valley										
*M1**	OB21	37.785	72.752	3788	2	2.7	0.99	467.42 ± 27.14[b]	74.0 ± 4.8	93.1 ± 8.3
*M1**	OB22	37.784	72.756	3791	1	2.7	0.99	475.98 ± 18.84[b]	74.7 ± 3.3	94.0 ± 5.7
Great Bogchigir Valley										
*BO1**	BT101	37.741	72.847	4091	2	2.7	0.99	383.95 ± 21.55[b]	51.2 ± 3.2	60.3 ± 4.6
*BO1**	BT103	37.744	72.848	4054	3	2.7	0.99	369.04 ± 15.98[c]	50.5 ± 2.5	59.5 ± 3.5
*BO1**	BT104	37.745	72.850	4031	5	2.7	0.99	447.46 ± 26.65[b]	64.0 ± 4.3	77.2 ± 6.6
*BO1**	BT105	37.746	72.851	4013	2	2.7	0.99	419.07 ± 15.28[c]	59.0 ± 2.4	69.9 ± 3.6
*BO3**	BT91	37.748	72.841	4069	4	2.7	1.00	147.22 ± 6.86[b]	21.4 ± 1.0	22.6 ± 1.2
*BO3**	BT92	37.746	72.840	4084	1	2.7	1.00	159.82 ± 8.48[b]	22.4 ± 1.2	23.7 ± 1.4
*BO3**	BT93	37.746	72.841	4084	4	2.7	1.00	141.73 ± 7.16[c]	20.5 ± 1.1	21.6 ± 1.2
*BO4**	BT62	37.741	72.837	4126	3	2.7	0.99	158.91 ± 9.11[b]	22.4 ± 1.3	23.7 ± 1.5
*BO4**	BT63	37.744	72.837	4080	1	2.7	0.99	129.45 ± 6.64[c]	18.6 ± 1.0	19.4 ± 1.1
*BO5**	BT52	37.732	72.829	4095	3	2.7	0.99	140.27 ± 8.62[b]	20.2 ± 1.3	21.3 ± 1.4
*BO6**	BH51	37.697	72.811	4220	2	2.7	0.99	115.78 ± 6.22[b]	15.8 ± 0.9	16.4 ± 0.9
*BO6**	BH53	37.698	72.811	4217	3	2.7	0.99	86.45 ± 6.91[c]	12.0 ± 1.0	12.4 ± 1.0
*BO7**	BH31	37.682	72.807	4275	1	2.7	0.98	109.48 ± 5.89[b]	14.6 ± 0.8	15.1 ± 0.9
*BO8**	BH12	37.649	72.780	4451	3	2.7	0.96	118.68 ± 7.75[b]	15.0 ± 1.0	15.6 ± 1.1
*BO8**	BH13	37.649	72.780	4451	2	2.7	0.96	95.41 ± 3.78[c]	12.0 ± 0.5	12.4 ± 0.5
*BO8**	BH14	37.649	72.780	4449	4	2.7	0.96	87.00 ± 4.09[c]	11.2 ± 0.5	11.5 ± 11.5

Note: 1σ uncertainties reflect the propagated analytical uncertainties, i.e. the AMS measurement uncertainties corrected for the analytical blanks. The blank values were ^{10}Be/^{9}Be = 0.034×10^{-12} for Bayreuth and ^{10}Be/^{9}Be = 0.015×10^{-12} for Uppsala. All measured ratios were normalized to the ETH house standard S555.

[a] Moraine number referring to the text and Figures 2–4.

[b] BeO-extraction was carried out at the University of Bayreuth.

[c] BeO-extraction was carried out at the cosmogenic isotope laboratory of the University of Uppsala.

and pressed into targets. Ratios of ^{10}Be/^{9}Be nuclides were measured at the accelerator mass spectrometry (AMS) in the Laboratory of Ion Beam Physics, ETH Zurich, Switzerland. Measured ratios were normalized to the ETH house standard S555. The typical analytical error of the AMS measurement was 3–5%.

Exposure age calculations were performed using the CRONUS online calculator version 2.2 (Balco et al., 2008) and the time-dependent production rate scaling model of Lal (1991) and Stone (2000). The effects of tectonic uplift and snow cover were neglected because paleo-uplift rates for the Pamir are poorly constrained and snowfall is low, respectively. We present our ages assuming constant erosion rates of 3 mm/ka for each bolder. It was argued that this assumption ignores the fact that rock surface erosion affects boulders randomly, not systematically, and that generally boulders with no or little signs of erosion are sampled (Zech, 2012). However, similar 'corrections' are commonly made based, for example, on boulder erosion rate estimates in the Karakoram and the European Alps (Owen et al., 2002; Kubik and Ivy-Ochs, 2004). Note that assuming zero boulder surface erosion, an age of 20 ka may underestimate the true age by ~4%, an age of 50 ka by ~13%, and an age of 90 ka by ~24% (Table 1). Another noteworthy source of systematic uncertainty is the fact that the reference production rate, the most appropriate scaling model, and the method of geomagnetic correction are still a matter of contention (Staiger et al., 2007; Balco et al., 2008; Sato et al., 2008; Putnam et al., 2010; Lifton, 2011). The exposure ages presented here may therefore require re-calculations as further methodological improvements are being made.

Concerning the interpretation of the exposure ages, we follow the view that boulder erosion and exhumation are more probable processes than prior exposure, and that the oldest exposure age of a set of samples collected from a moraine therefore likely provides a minimum estimate for the true deposition age of a moraine (Putkonen and Swanson, 2003; Briner et al., 2005; Heyman et al., 2011).

Equilibrium Line Altitudes (ELAs) and Equilibrium Line Altitude depressions (ΔELAs) were calculated as glacial elevation indices using the Toe to Headwall Altitude Ratio method (THAR) and placing the former ELAs at mid proportion between the terminal moraine and the base of the headwall (THAR 0.5) (Benn and Lehmkuhl, 2000).

Results and discussion

Glacial chronology of the Bogchigir Valleys

The local LGM

The two samples from the lateral moraine *M1** yielded exposure ages of 94.0 ± 5.7 ka and 93.1 ± 8.3 ka (Table 1, Figs. 2a, 3a, b). Within measurement uncertainties, these ages are indistinguishable from those from moraine *M1* (101.6 ± 6.4 ka to 85.8 ± 46 ka) (Zech et al., 2005a). This indicates that *M1* and *M1** belong to the same moraine generation. The scattering of the exposure ages of *M1* and *M1** is relatively low, indicating that these moraine surfaces are well preserved and that boulder exhumation and moraine degradation were not significant. The available exposure ages suggest that the Yashilkul/Gunt Valley was completely filled by ice during MIS 5 at ~100 ka. The ELA for this former glacier was at ~4600 m, a depression of 370 m relative to the modern ELA.

Glaciation during late MIS 5/4, MIS 4 and MIS 3

In the lower part of the Great Bogchigir Valley, four samples from the right outermost lateral moraine *BO1** (Fig. 2b) yielded exposure ages between 77.2 ± 6.6 ka and 59.5 ± 3.5 ka (Table 1). These results are particularly important because they suggest that the wide range of exposure ages for *BO1* (79.6 ± 4.3 ka to 36.1 ± 2.0 ka, n = 5, Fig. 2b) (Abramowski et al., 2006) can be explained with boulders that are too young due to post-depositional processes. The older boulders on a moraine are accordingly closer to the actual deposition age than the younger ones. With this knowledge in mind, the dating results from *BO1** and *BO1* are also in good agreement with the oldest exposure age of 74.6 ± 2.9 ka for the hummocky moraine lobe *M2* in the Orto Bogchigir-I Valley (Zech et al., 2005a). These consistent results corroborate the morphological and stratigraphical correlation of *BO1**, *BO1* and *M2*, and support the hypothesis that the chukurs were deposited well before the global LGM, namely around the MIS 5–4 transition.

Equivocal evidence for glacier advances during MIS 4 and probably again during MIS 3 comes from the exposure ages of the *M3* moraines

(Zech et al., 2005a) (Fig. 2a). The two boulders from the outer part of *M3* are 64.6 ± 2.7 ka and 57.3 ± 2.3 ka, while a single exposure age of 40.2 ± 1.9 ka is interpreted tentatively to date the inner part of *M3*. Meltwater activity may have eroded the corresponding terminal moraine complexes, because they could not be clearly identified in the field. In contrast, in the Great Bogchigir Valley several less pronounced lateral moraine walls can be denoted between *BO3** and Lake Yashilkul, which merge gradually into the hummocky moraine lobe (Fig. 2b). These walls were considered prone to ice-decay-induced long-lasting geomorphological instability and therefore not suitable for SED. It thus remains speculative whether glacier readvances occurred at ~65 ka and ~40 ka in both Bogchigir Valleys.

Glaciation during the global LGM

Three exposure ages suggest a deposition time between 23.7 ± 1.4 ka and 21.6 ± 1.2 ka for *BO3** (Fig. 2b). This is in agreement with two exposure ages from the adjacent lateral moraine *BO4** (23.7 ± 1.5 ka and 19.4 ± 1.1 ka), as well as four (recalculated) ages for *BO2* ranging from 23.5 ± 1.1 ka to 22.4 ± 1.0 ka (Abramowski et al., 2006). These results confirm that the glaciation of the Great Bogchigir Valleys was less extensive during MIS 2 than during MIS 5 and MIS 4. The respective ELA was at ~4740 m, i.e. the ELA depression was only ~270 m.

Zech et al. (2005a) interpreted three exposure ages of ~28 ka from the lateral moraine *M4* in the Orto Bogchigir-I Valley (Fig. 2a) as documenting a glacier advance during the global LGM. Stratigraphically *M4* correlates with *BO2*, and we speculate that the Bogchigir glaciers may have advanced two times during MIS 2, around 28 ka and 24 ka, and that deposits from each advance have been preserved in only one of both valleys.

Deglaciation

A single boulder from the latero-terminal moraine *BO5** yielded an age of 21.3 ± 1.4 ka (Fig. 2b). The close proximity to the moraines *BO3** and *BO4** indicates rapid ice retreat and moraine stabilization already shortly after the MIS 2 advance at ~24 ka. The recessional moraine *BO6** farther upvalley yielded exposure ages of 16.4 ± 0.9 ka and 12.4 ± 1.0 ka, and *BO7** yielded another age of 15.1 ± 0.9 ka (Figs. 2c, 3e). Both recessional moraines were thus deposited during a phase of glacier stagnation or minor readvance during the late glacial. The ELA for the recessional wall *BO6** was ~4810 m, resulting in an ELA depression of 160 m.

The uppermost sampling location *BO8** (Figs. 2c, 3f) yielded three exposure ages of 15.6 ± 1.1 ka, 12.4 ± 0.5 ka and 11.5 ± 0.6 ka. As the oldest age is, within uncertainties, still stratigraphically consistent with the exposure ages from *BO6** and *BO7**, we cannot exclude that this location became ice free already at ~15 ka. Alternatively, the oldest boulder might contain inherited nuclides, and the exposure age of 12.4 ± 0.5 ka might more closely date the timing of ice retreat from this location. This would then document an ice retreat after a second minor stillstand or readvance during the late glacial. In either case, the Great Bogchigir glacier did not advance beyond *BO8** during the Holocene, and given the respective ELA of ~4925 m, Holocene ELA depressions were not more than ~45 m.

Comparison with other glacial chronologies from the Pamir and adjacent mountain ranges

The early local LGM

Our results suggest that the Bogchigir glaciers reached their last glacial maximum extent during MIS 5, and that several subsequent glacier advances (~80–75 ka, and possibly also ~65 and 40 ka) were more extensive than the glaciation during the global LGM. This corroborates previous studies in the region. Recalculated exposure ages from the Tanymas Valley, north-central Pamir (Fig. 1a) show that moraine *TK* was deposited already around 97.4 ± 5.7 ka (oldest age, n = 5, Fig. 4c) (Abramowski et al., 2006). Approximately 80 km east of the Bogchigir Valleys, an extensive glaciation in the Uchkol and Gurumdi Valleys (Fig. 1a) also occurred during MIS 5 (Fig. 4c, oldest age *UK2*: 89.7 ± 5.3 ka, n = 5, oldest age *GU1*: 85.7 ± 3.8 ka, n = 6) and had very similar ELA depressions (ΔELA: ~380 m) compared to the local LGM in the Bogchigir Valleys (Abramowski et al., 2006).

Unfortunately, assigning ages to the subsequent glacier advances in these valleys, which might be synchronous to the deposition of the well-preserved chukurs in the Yashilkul area (*M2*, *BO1*, *BO1**) is challenging because of the wide scatter in exposure ages. Correlations therefore remain speculative. Moraine *GU2* in the Gurumdi Valley, for example, might document a glaciation during MIS 4 (oldest age: 65.6 ± 4.4 ka, n = 5, Abramowski et al., 2006) coinciding with the older part of the *M3* moraine in the Orto Bogchigir-I Valley (recalculated age: 64.6 ± 2.7 ka, Zech et al., 2005b).

Seong et al. (2009) dated glacial landforms ~130 km further north-east, in the north- and westward-draining valleys of the Muztag Ata and Kunlun Shan (Fig. 1a). They suggested that the Subaxh Glacial Stage represents one or more glaciations early during the last glacial cycle and/or penultimate glacial cycle. Given the wide scatter of the surface exposure ages of the Subaxh Stage, it is difficult at present to correlate it directly with the glacial stages in the Yashilkul area. Nevertheless, the exposure age below the Yanbuk glacier on moraine m2B (recalculated age: MUST_92: 82.7 ± 4.1 ka, Fig. 4c), as well as from the Kodak Valley on m2G (recalculated age: KONG_30: 70.4 ± 2.3 ka) indicate that glacial advances in the Muztag Ata and Kunlun Shan might correspond to the MIS 5 and 4 glaciations in the Bogchigir Valleys. Further evidence for a local LGM during MIS 5 comes from the Kongur Shan Valleys, where electron spin resonance (ESR) was applied to date the moraine platform above the Upper Gaizi Village to between 87 ± 9 ka and 66 ± 7 ka (GZ-01, GZ-04) (Wang et al., 2011). In a very recent study, Owen et al. (2012) provided convincing evidence for an early local LGM also in the Tashkurgan Valley (Chinese Pamir). Published exposure ages for the Tashkurgan stage there range from 25 to 87 ka (average: 73 ± 7 ka, n = 9, Kuzigun Valley), from 65 to 76 ka (average: 68 ± 5 ka, n = 4, Jialongqiete Valley), from 53 to 84 ka (average: 65 ± 11 ka, n = 7, Dabudaer Valley), and from 44 to 62 ka (average: 54 ± 8 ka, n = 5, Kuzigun Valley). Note that for a direct comparison these ages would need to be corrected as well assuming a rock surface erosion of 3 mm/ka, which would make them significantly older (75 ka would, for example, become ~95 ka).

Glaciation during MIS 3

Exposure ages from the Uchkol and Gurumdi Valleys also document glacial advances during MIS 3. Recalculated ages for moraine *UK4* range from 31.4 ± 1.4 ka to 15.4 ± 1.0 ka, for *GU3* from 48.7 ± 2.3 ka to 19.4 ± 0.9 ka, and for *GU4* from 32.1 ± 2.8 ka to 21.8 ± 1.1 ka (Fig. 4c) (Abramowski et al., 2006). In the Ting Valley, Kongur Shan, recalculated ages for m2H are between 33.6 ± 1.0 ka and 20.2 ± 0.5 ka (Seong et al., 2009) (Fig. 4c). Wang et al. (2011) dated a moraine of the Upper Gaizi Village platform (GZ-12 to GZ-14: 49 ± 6 ka to 41 ± 4 ka) and the hummocky moraines on the western slope of Kongur Mountain (KXW-05, KXW-07, GGE-2 to GGE4: ~48 ± 5 ka to 36 ± 3 ka) to mid-MIS 3. Owen et al. (2012) interpreted the Hangdi stage in the Tashkurgan Valley to document an early MIS 2 advance, but that their oldest ages would partly allow interpreting the respective moraines to be late MIS 3 (Kuzigun Valley: 22 to 25 ka, average: 24 ± 1 ka, n = 4; Jialongqiete Valley: 13 to 30 ka, average: 26 ± 2 ka, n = 10; South Tashkurgan Valley: 13 to 35 ka, average: 24 ± 9 ka, n = 6; erosion rate correction would make the ages 1 to 3 ka older).

Some of the above glacial advances may correlate with the inner part of moraine *M3* in the Ortho Bogchigir I (Fig. 2a), but it is also likely that many of the advances did not occur exactly synchronously. Nevertheless, and despite the fact that we were not able to date MIS 3 moraines in the Great Bogchigir Valley, there is reasonable evidence

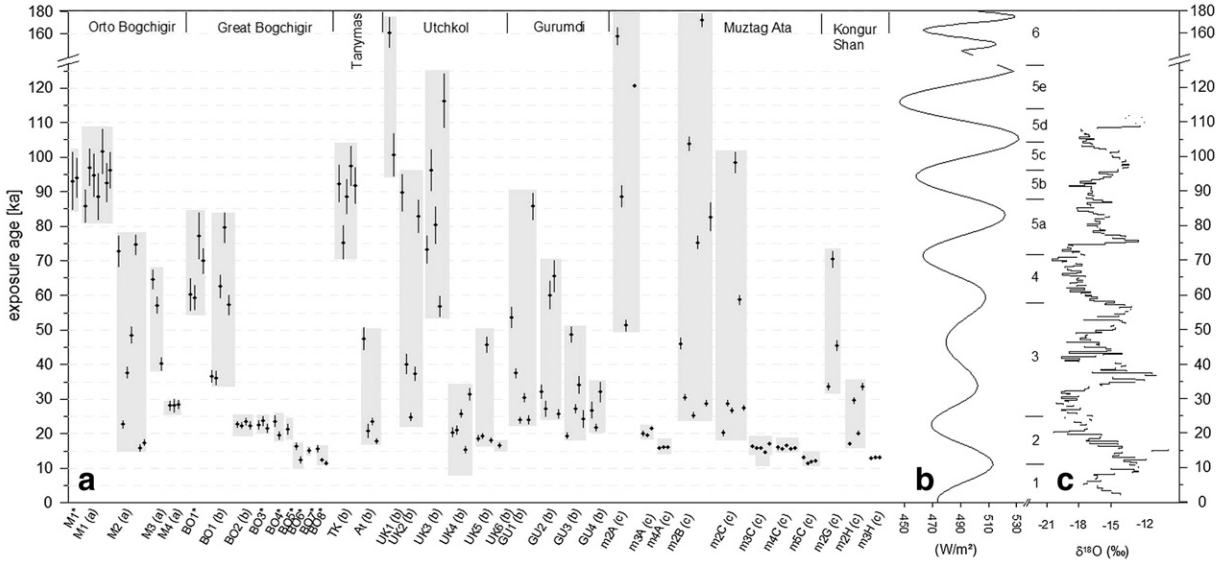

Figure 4. Paleoclimate context and correlation: a) Own and recalculated exposure ages. The asterisks denote own ages, 'a' ages from Zech et al. (2005a), 'b' ages from Abramowski et al. (2006), and 'c' ages from Seong et al. (2009). b) Marine Oxygen Isotope Stages (MISs) and 30°N June insolation (Berger and Loutre, 1991). c) The $\delta^{18}O$ record from the Guliya ice cap in the Kunlun Shan (Thompson et al., 1997).

that regional climate conditions during MIS 3 were favorable for glaciation, at least for more extensive glacial advances than during MIS 2.

Glaciation during the global LGM and the late glacial

Our results suggest that the Bogchigir glaciers advanced two times during the global LGM (*BO4*: ~23.7 ± 1.4 ka, *M4*: ~28.5 ± 1.3 ka). An advance similar to the younger of these two is suggested by the recalculated data from the Ailuitek Pass area, north-central Pamir. Excluding the oldest exposure age as influenced by inheritance, the terminal moraine *AT* there was deposited ~23.5 ± 1.0 ka (n = 3, Fig. 4c) (Abramowski et al., 2006). In the Uchkol Valley, the glaciers seem to have been restricted already to the upper reaches of the valley (*UK5* and *6*, Fig. 4c) (Abramowski et al., 2006). A MIS 2 glacial advance has also been dated in the Kartamak Valley with a recalculated age of ~26.8 ± 0.7 ka (m2C, MUST-64) (Seong et al., 2009), and in the Tashkurgan Valley (see Handgi stage above and the Kuzigun stage; Kuzigun Valley: 15 to 24 ka, average: 19 ± 4 ka, n = 4; Jialongqiete Valley: 3 to 23 ka, average: 19 ± 4 ka, n = 7; Owen et al., 2012).

Glacier oscillations in the Bogchigir Valleys were restricted in extent to within a few hundred meters to a few kilometers of the contemporary glaciers during the late glacial. This was also observed in the northern and eastern Pamir mountain ranges (Abramowski et al., 2006) as well as in the eastern Muztag Ata and Kongur Shan massifs (Seong et al., 2009). Seong et al. (2009) also suggested that after the global LGM, glacier advances in western Tibet likely responded to Northern Hemisphere climate oscillations on millennial time scales. For the late glacial our dating results from the Great Bogchigir Valley might corroborate this notion, as stillstands or readvances were dated to ~16 ka and tentatively to ~12 ka, i.e. correlating with the Heinrich-I and Younger Dryas cooling events. One has to acknowledge, however, that in the absence of local calibration cites, the methodological uncertainties of surface exposure dating are still on the order of at least ~10%, so that such conclusions remain speculative.

Paleoclimatic implications

Our updated glacial chronology for the Bogchigir Valleys corroborates the previous findings that the glacier extents in the Pamir became successively more restricted during the course of the last glacial (Zech et al., 2005a; Abramowski et al., 2006). One may be tempted to correlate the glacier advances at ~100 ka, 80–75 ka, (65 ka, 40 ka), 28 ka and 24 ka with northern hemisphere and global temperature minima during MIS 5b, 4 and 2 as recorded in polar ice cores, marine sediments, and the $\delta^{18}O$ record from the Guliya ice cap in the Kunlun Shan (Thompson et al., 1997) (Fig. 4a). The temperature minima roughly coincide with minima in northern hemispheric summer insolation (Berger and Loutre, 1991) (Fig. 4b) and glacier mass balances are certainly sensitive to summer insolation and temperature.

However, the systematic methodological uncertainties are quite large especially for ages beyond MIS 3, namely at least ~10%, and this is not yet considering the different approaches to account (or not account) for rock surface erosion (see Tables 1 and 2). Moreover, one should keep in mind that glacier mass balances become particularly sensitive to changes in precipitation and cloud cover in more arid regions (Kull et al., 2008; Rupper and Roe, 2008). On the one hand, this precipitation-sensitivity can explain the successively more restricted glacial extent in the Pamir during the last glacial cycle with increasing aridity. This aridization trend that has also been observed for Siberia (Svendsen et al., 2004; Zech et al., 2011) and the Tien Shan (Koppes et al., 2008; Narama et al., 2009; Zech, 2012) and can be attributed to a strengthening of the Siberian Anticyclone and a blocking of the westerly moisture supply. On the other hand, precipitation increases could explain glacial advances asynchronous with temperature minima. During MIS 3, for example, the 30°N summer insolation was high and the Indian summer monsoon was strengthened. This is recorded by high lake level stands and pollen records from the Tibetan Plateau (Shi et al., 2001; Herzschuh, 2006) and could have favored the MIS 3 glacial advances particularly in the most arid central Pamir (Uchkol and Gurumdi).

The age control for the MIS 5 glacial advances in the Pamir is still too uncertain to exactly determine whether they occurred synchronously and in phase with MIS 5b. It cannot be excluded that the local LGM occurred already during MIS 5d, which would be in agreement with findings from the Lake Baikal region (Karabanov et al., 1998) and northeast Siberia (Zech et al., 2011) and emphasize the role of low obliquity for glacier mass balances. In any case, we suggest

Table 2
Previously published exposure data from the Bogchigir Valleys (recalculated).

Moraine number	Sample ID	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Sample thickness (cm)	Sample density (g/cm^3)	Topographic shielding	^{10}Be (10^4 atoms/g SiO$_2$)	No-erosion exposure age (ka)	3 mm/ka exposure age (ka)
Orto Bogchigir Valley (Zech et al., 2005a)										
M1	YE11	37.782	72.757	3815	2	2.7	1.00	447.83 ± 16.26	69.4 ± 2.8	85.8 ± 4.6
M1	YE12	37.783	72.757	3815	5	2.7	1.00	482.10 ± 16.97	76.7 ± 3.0	97.0 ± 5.4
M1	YE14	37.782	72.758	3820	3	2.7	1.00	481.26 ± 20.33	75.0 ± 3.6	94.6 ± 6.2
M1	YE15	37.782	72.758	3815	3	2.7	1.00	454.88 ± 22.83	71.1 ± 4.0	88.5 ± 6.7
M1	YE16	37.783	72.758	3815	3	2.7	1.00	509.77 ± 19.99	79.8 ± 3.5	101.6 ± 6.4
M1	YE17	37.782	72.759	3830	2	2.7	1.00	479.07 ± 19.00	73.7 ± 3.3	92.5 ± 5.6
M1	YE18	37.782	72.759	3830	2	2.7	1.00	494.83 ± 17.39	76.1 ± 3.0	96.2 ± 5.3
M2	YE21	37.791	72.763	3755	3	2.7	1.00	376.58 ± 15.93	61.0 ± 2.9	72.7 ± 4.4
M2	YE23	37.790	72.762	3755	4	2.7	1.00	125.37 ± 5.22	21.5 ± 0.9	22.7 ± 1.0
M2	YE25	37.789	72.761	3755	4	2.7	1.00	209.47 ± 7.23	34.6 ± 1.3	37.7 ± 1.6
M2	YE29	37.787	72.761	3770	5	2.7	1.00	268.10 ± 10.03	43.1 ± 1.8	48.6 ± 2.4
M2	YE20	37.787	72.761	3770	1	2.7	1.00	394.17 ± 10.72	62.3 ± 1.9	74.6 ± 2.9
M2	YE37	37.775	72.766	3960	5	2.7	1.00	96.51 ± 5.91	15.3 ± 0.9	15.9 ± 1.0
M2	YE30	37.777	72.767	3945	5	2.7	1.00	105.83 ± 4.80	16.8 ± 0.8	17.5 ± 0.8
M3	YE34	37.771	72.764	4035	4	2.7	1.00	392.40 ± 11.81	54.8 ± 1.8	64.6 ± 2.7
M3	YE35	37.771	72.764	4020	4	2.7	1.00	351.87 ± 10.62	48.9 ± 1.7	57.3 ± 2.3
M3	YE36	37.771	72.764	4005	4	2.7	1.00	256.59 ± 9.51	36.8 ± 1.5	40.2 ± 1.9
M4	YE31	37.767	72.762	4040	6	2.7	1.00	178.40 ± 7.18	26.4 ± 1.1	28.1 ± 1.3
M4	YE32	37.768	72.762	4040	5	2.7	1.00	179.52 ± 10.82	26.4 ± 1.7	28.1 ± 1.9
M4	YE33	37.768	72.762	4040	4	2.7	1.00	183.37 ± 7.08	26.7 ± 1.1	28.5 ± 1.3
Great Bogchigir Valley (Abramowski et al., 2006)										
BO1	BO11	37.735	72.838	4250	1	2.7	0.99	269.80 ± 10.20	33.77 ± 1.4	36.7 ± 1.7
BO1	BO12	37.735	72.838	4225	3	2.7	0.99	257.60 ± 11.60	33.25 ± 1.6	36.1 ± 2.0
BO1	BO13	37.735	72.838	4240	3	2.7	0.99	425.30 ± 16.00	52.95 ± 2.2	62.5 ± 3.2
BO1	BO14	37.736	72.838	4240	2	2.7	1.00	526.00 ± 19.70	65.44 ± 2.7	79.6 ± 4.3
BO1	BO17	37.736	72.838	4230	2.5	2.7	1.00	395.80 ± 14.90	48.86 ± 2.1	57.3 ± 2.9
BO2	BO21	37.738	72.839	4180	1.5	2.7	1.00	159.50 ± 6.20	21.50 ± 0.9	22.7 ± 1.0
BO2	BO24	37.739	72.839	4170	2	2.7	1.00	156.00 ± 5.90	21.24 ± 0.8	22.4 ± 0.9
BO2	BO28	37.740	72.840	4130	4.5	2.7	1.00	157.70 ± 6.40	22.28 ± 0.9	23.5 ± 1.1
BO2	BO29	37.740	72.841	4120	2	2.7	1.00	152.20 ± 6.40	21.24 ± 0.9	22.4 ± 1.0

that both the westerlies and the monsoonal circulation were more effective in advecting moisture to the Pamir during MIS 5 and thus triggered the extensive early glaciation.

Conclusions

SED using *in situ* produced cosmogenic ^{10}Be in the Bogchigir Valleys suggests that glacier advances occurred at ~100 ka, 80–75 ka, (65 ka, 40 ka), 28 ka and 24 ka. The early local LGM during MIS 5, when the main Yashilkul/Gunt Valley was filled by ice, can only be explained with substantially increased precipitation, possibly advected by both the westerlies and an enhanced monsoonal circulation. The subsequent glacial advances, which reached the main valley and deposited the characteristic 'chukur' moraine lobes, likely occurred at the MIS 5/4 transition, but the methodological uncertainties prevent a robust interpretation concerning the role of low temperatures (MIS 4) and/or increased precipitation (MIS 5). Evidence for glacial advances during MIS 3 remains circumstantial in the Bogchigir Valleys, yet previously published and recalculated exposure ages from moraines in the central Pamir suggest increased precipitation from the westerlies and/or the monsoonal circulation. Two glacial advances occurred at ~28 and 24 ka, i.e. during MIS 2, and deglaciation was on its way by ~21 ka, although probably interrupted by periods of stagnation or minor readvances around 16 and 12 ka.

As mentioned above, glacial chronologies from the Pamir and the adjacent mountain ranges can provide valuable information about past changes in temperature, as well as precipitation derived from the westerlies and the monsoonal circulation. One needs to acknowledge, however, that both the large scatter of exposure ages, particularly on chukur moraines, and the remaining systematic uncertainties in the method make it challenging to correlate moraines between valleys and to establish detailed and robust chronologies. Obviously, a local calibration site would be extremely helpful. Moreover, further dating efforts should focus on stable lateral moraines and be conducted in the more humid western and northern Pamir, as well as in the arid central and southern Pamir for comparison, in order to more precisely investigate the climatically controlled differences in timing. On top of that, future studies would probably greatly benefit from combining dating and glacier-climate modeling, which might help to further disentangle the role of low temperature, increased precipitation and its seasonality.

Acknowledgments

We thank the German Research Foundation for funding (DFG project ZE 154/63-1), and Ari Matmon, an anonymous reviewer, and editors Alan Gillespie and Lewis Owen for comments and suggestions.

References

Abramowski, U., Bergau, A., Seebach, D., Zech, R., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2006. Pleistocene glaciations of Central Asia: results from Be-10 surface exposure ages of erratic boulders from the Pamir (Tajikistan), and the Alay-Turkestan range (Kyrgyzstan). Quaternary Science Reviews 25, 1080–1096.
Aizen, E.M., Aizen, V.B., Melack, J.M., Nakamura, T., Ohta, T., 2001. Precipitation and atmospheric circulation patterns at mid-latitudes of Asia. International Journal of Climatology 21, 535–556.
Aizen, V.B., Mayewski, P.A., Aizen, E.M., Joswiak, D.R., Surazakov, A.B., Kaspari, S., Grigholm, B., Krachler, M., Handley, M., Finaev, A., 2009. Stable-isotope and trace element time series from Fedchenko glacier (Pamirs) snow/firn cores. Journal of Glaciology 55, 275–291.
Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. Quaternary Geochronology 8, 174–195.
Benn, D.I., Lehmkuhl, F., 2000. Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. Quaternary International 65, 15–29.
Benn, D.I., Owen, L.A., 1998. The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion. Journal of the Geological Society 155, 353–363.
Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10, 297–317.

Bohner, J., 2006. General climatic controls and topoclimatic variations in Central and High Asia. Boreas 35, 279–295.

Briner, J.P., Kaufman, D.S., Manley, W.E., Finkel, R.C., Caffee, M.W., 2005. Cosmogenic exposure dating of late Pleistocene moraine stabilization in Alaska. Geological Society of America Bulletin 117, 1108–1120.

Burtman, V.S., Molnar, P., 1993. Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir. Geological Society of America: Special Paper, 281, 76 p.

Chevalier, M.-L., Hilley, G., Tapponnier, P., Van Der Woerd, J., Liu-Zeng, J., Finkel, R.C., Ryerson, F.J., Li, H., Liu, X., 2011. Constraints on the late Quaternary glaciations in Tibet from cosmogenic exposure ages of moraine surfaces. Quaternary Science Reviews 30, 528–554.

Herzschuh, U., 2006. Palaeo-moisture evolution in monsoonal Central Asia during the last 50,000 years. Quaternary Science Reviews 25, 163–178.

Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W., 2011. Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. Earth and Planetary Science Letters 302, 71–80.

Ivy-Ochs, S., 1996. The dating of rock surfaces with ^{10}Be, ^{26}Al and ^{36}Cl, with examples from Antarctic and the Swiss Alps. Diss.ETH No.11763, Zuerich, 197 pp.

Karabanov, E.B., Prokopenko, A.A., Williams, D.F., Colman, S.M., 1998. Evidence from Lake Baikal for Siberian glaciation during oxygen-isotope substage 5d. Quaternary Research 50, 46–55.

Koppes, M., Gillespie, A.R., Burke, R.M., Thompson, S.C., Stone, J., 2008. Late Quaternary glaciation in the Kyrgyz Tien Shan. Quaternary Science Reviews 27, 846–866.

Kubik, P., Ivy-Ochs, S., 2004. A re-evaluation of the 0–10 ka ^{10}Be production rate for exposure dating obtained from the Köfels (Austria) landslide. Nuclear Instruments and Methods in Physics Research B 223–224, 618–622.

Kull, C., Imhof, S., Grosjean, M., Zech, R., Veit, H., 2008. Late Pleistocene glaciation in the Central Andes: temperature versus humidity control — a case study from the eastern Bolivian Andes (17°S) and regional synthesis. Global and Planetary Change 60, 148–164.

Lal, D., 1991. Cosmic-ray labeling of erosion surfaces — in situ nuclide production-rates and erosion models. Earth and Planetary Science Letters 104, 424–439.

Lifton, N.A., 2011. Potential resolution of discrepancies between scaling models for *in situ* cosmogenic nuclide production rates. INQUA meeting, abstract #1554. Bern.

Narama, C., Kondo, R., Tsukamoto, S., Kajiura, T., Duishonakunov, M., Abdrakhmatov, K., 2009. Timing of glacier expansion during the Last Glacial in the inner Tien Shan, Kyrgyz Republic by OSL dating. Quaternary International 199, 147–156.

Owen, L.A., 2009. Latest Pleistocene and Holocene glacier fluctuations in the Himalaya and Tibet. Quaternary Science Reviews 28, 2150–2164.

Owen, L.A., Finkel, R.C., Caffee, M.W., Gualtieri, L., 2002. Timing of multiple late Quaternary glaciations in the Hunza Valley, Karakoram Mountains, northern Pakistan: defined by cosmogenic radionuclide dating of moraines. Geological Society of America Bulletin 114, 593–604.

Owen, L.A., Caffee, M.W., Finkel, R.C., Seong, Y.B., 2008. Quaternary glaciation of the Himalayan–Tibetan orogen. Journal of Quaternary Science 23, 513–531.

Owen, L.A., Chen, J., Hedrick, K.A., Caffee, M.W., Robinson, A.C., Schoenbohm, L.M., Yuan, Z., Li, W., Imrecke, D.B., Liu, J., 2012. Quaternary glaciation of the Tashkurgan Valley, Southeast Pamir. Quaternary Science Reviews 47, 56–72.

Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. Quaternary Research 59, 255–261.

Putnam, A.E., Schaefer, J.M., Barrell, D.J.A., Vandergoes, M., Denton, G.H., Kaplan, M.R., Finkel, R.C., Schwartz, R., Goehring, B.M., Kelley, S.E., 2010. *In situ* cosmogenic ^{10}Be production-rate calibration from the Southern Alps, New Zealand. Quaternary Geochronology 5, 392–409.

Rupper, S., Roe, G., 2008. Glacier changes and regional climate: a mass and energy balance approach. Journal of Climate 21, 5384–5401.

Sato, T., Yasuda, H., Niita, K., Endo, A., Sihver, L., 2008. Development of PARMA: PHITS-based analytical radiation model in the atmosphere. Radiation Research 170, 244–259.

Scherler, D., Bookhagen, B., Strecker, M.R., Von Blanckenburg, F., Rood, D., 2010. Timing and extent of late Quaternary glaciation in the western Himalaya constrained by Be-10 moraine dating in Garhwal, India. Quaternary Science Reviews 29, 815–831.

Seong, Y.B., Owen, L.A., Yi, C.L., Finkel, R.C., 2009. Quaternary glaciation of Muztag Ata and Kongur Shan: evidence for glacier response to rapid climate changes throughout the Late Glacial and Holocene in westernmost Tibet. Geological Society of America Bulletin 121, 348–365.

Shi, Y.F., Yu, G., Liu, X.D., Li, B.Y., Yao, T.D., 2001. Reconstruction of the 30–40 ka BP enhanced Indian monsoon climate based on geological records from the Tibetan Plateau. Palaeogeography, Palaeoclimatology, Palaeoecology 169, 69–83.

Staiger, J., Gosse, J., Toracinta, R., Oglesby, B., Fastook, J., Johnson, J.V., 2007. Atmospheric scaling of cosmogenic nuclide production: climate effect. Journal of Geophysical Research 112 (B02205), 1–8.

Stone, J.O., 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research, Solid Earth 105, 23,753–23,759.

Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., et al., 2004. Late quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1229–1271.

Thompson, L.G., Yao, T., Davis, M.E., Henderson, K.A., Mosleythompson, E., Lin, P.N., Beer, J., Synal, H.A., Coledai, J., Bolzan, J.F., 1997. Tropical climate instability: the last glacial cycle from a Qinghai–Tibetan ice core. Science 276, 1821–1825.

UNEP, 2002. Vital maps and graphics on climate change, Tajikistan. www.grida.no/enrin/htmls/tadjik/vitalgraphics/eng/html/climate.htm.

Wang, J., Zhou, S., Zhao, J., Zheng, J., Guo, X., 2011. Quaternary glacial geomorphology and glaciations of Kongur Mountain, eastern Pamir, China. Science China Earth Sciences 54, 591–602.

Weiers, S., 1995. Zur Klimatplogie des NW-Karakorum und angrenzender Gebiete. Bonner Geographische Abhandlungen 92, 156.

Wissmann, H.V., 1959. Die heutige Vergletscherung und Schneegrenze in Hochasien. Akademie der Wissenschaften und der Literatur, Abhandlungen der Mathematisch-Naturwissenschaftlichen Klasse 14, 306.

Zech, R., 2012. A Late Pleistocene glacial chronology from the Kitschi-Kurumdu Valley, Tien Shan (Kyrgyzstan), based on ^{10}Be surface exposure dating. Quaternary Research 77, 281–288.

Zech, R., Abramowski, U., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2005a. Late Quaternary glacial and climate history of the Pamir Mountains derived from cosmogenic Be-10 exposure ages. Quaternary Research 64, 212–220.

Zech, R., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2005b. Evidence for long-lasting landform surface instability on hummocky moraines in the Pamir Mountains from surface exposure dating. Earth and Planetary Science Letters 237, 453–461.

Zech, W., Zech, R., Zech, M., Leiber, K., Dippold, M., Frechen, M., Bussert, R., Andreev, A., 2011. Obliquity forcing of Quaternary glaciation and environmental changes in NE Siberia. Quaternary International 234, 133–145.