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A late Pleistocene glacial chronology from the Kitschi-Kurumdu Valley, Tien Shan (Kyrgyzstan), based on ^{10}Be surface exposure dating

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ABSTRACT

Surface exposure dating has become a helpful tool for establishing numeric glacial chronologies, particularly in arid high-mountain regions where radiocarbon dating is challenging due to limited availability of organic material. This study presents 13 new ^{10}Be surface exposure ages from the Kitschi-Kurumdu Valley in the At Bashi Range, Tien Shan. Three moraines were dated to ~15, 21 and >56 ka, respectively, and corroborate previous findings that glacial extents in the Tien Shan during Marine Oxygen Isotope Stage (MIS) 2 were limited compared to MIS 4. This likely documents increasingly arid conditions in Central Asia during the last glacial cycle. Morphological evidence in the Kitschi-Kurumdu Valley and a detailed review of existing numeric glacial chronologies from the Tien Shan indicate that remnants of the penultimate glaciation (MIS 6) are preserved, whereas evidence for MIS 5 glacier advances remains equivocal. Reviewed and recalculated exposure ages from the Pamir mountains, on the other hand, reveal extensive MIS 5 glacial extents that may indicate increased monsoonal precipitation. The preservation of MIS 3 moraines in the Tien Shan and the southern Pamir does not require any monsoonal influence and can be explained alternatively with increased precipitation via the westerlies.

Introduction

Glacial chronologies from around the world provide valuable insights into past climate changes (Gillespie and Molnar, 1995; Thackray et al., 2008; Ehlers et al., 2011). Increasing evidence suggests, for example, that late Pleistocene glacier advances varied regionally and that the *local* last glacial maximum (LGM) did not everywhere coincide with the temperature minimum during the *global* LGM (~26–19 ka: Clark et al., 2009; Mix et al., 2001), which is often explained with past changes in precipitation. However, the full potential of past glacier fluctuations for paleoclimate reconstructions remains to be utilized and is mostly limited by the availability of robust glacial chronologies.

Although radiocarbon dating has long been successfully applied in relatively humid regions, where datable organic material could be found, the glacial mass balances in such regions are mainly sensitive to temperature changes. Thus glaciers there generally reached their maximum extents in phase with the global LGM, eroding sedimentological and geomorphological evidence of earlier glacier fluctuations, and the obtainable paleoclimatic information is relatively limited. Glacial mass balances in more arid regions, on the other hand, are more sensitive to precipitation changes and cloud cover (Kaser, 2001; Kull et al., 2008; Rupper et al., 2009), and respective glacial chronologies may allow reconstructing past changes in atmospheric circulation and related amounts of precipitation (e.g. Zech et al., 2008). Establishing reliable glacial chronologies in arid regions has been challenging due to the lack of organic material for radiocarbon dating. Only the recent developments of alternative dating techniques, such as surface exposure dating and optically stimulated luminescence (OSL), provide the necessary tools for such studies.

The Tien Shan and Pamir mountains are located in the transition zone between the westerlies and the monsoon (Figure 1), and the enhanced precipitation sensitivity of the glacial mass balances in the arid parts of Central Asia make this region a suitable location to study past changes in precipitation and atmospheric circulation patterns. Prior results from the Tien Shan have revealed that the glaciers there reached their maximum extents early during the last glacial cycle during Marine Oxygen Isotope Stage (MIS) 3 to 5, but also that regional differences may exist (Narama et al., 2007; Koppes et al., 2008; Narama et al., 2009; Zhao et al., 2009). Given the limited datasets available so far, it remains unclear whether these proposed differences are real and reflect variable, site-specific sensitivities of glacial mass balances to past changes in temperature and precipitation, respectively.

The aim of this study is to contribute to the glacier and climate reconstruction in the Tien Shan by establishing a numeric glacial chronology (at reconnaissance level) for the Kitschi-Kurumdu Valley in the At Bashi Range, Kyrgyzstan, based on ^{10}Be surface exposure dating. Subsequent detailed comparison with existing numeric chronologies from the Tien Shan and the Pamir mountains shall then shed light on regional synchronies and asynchronies, in order to finally infer and discuss past climate changes.

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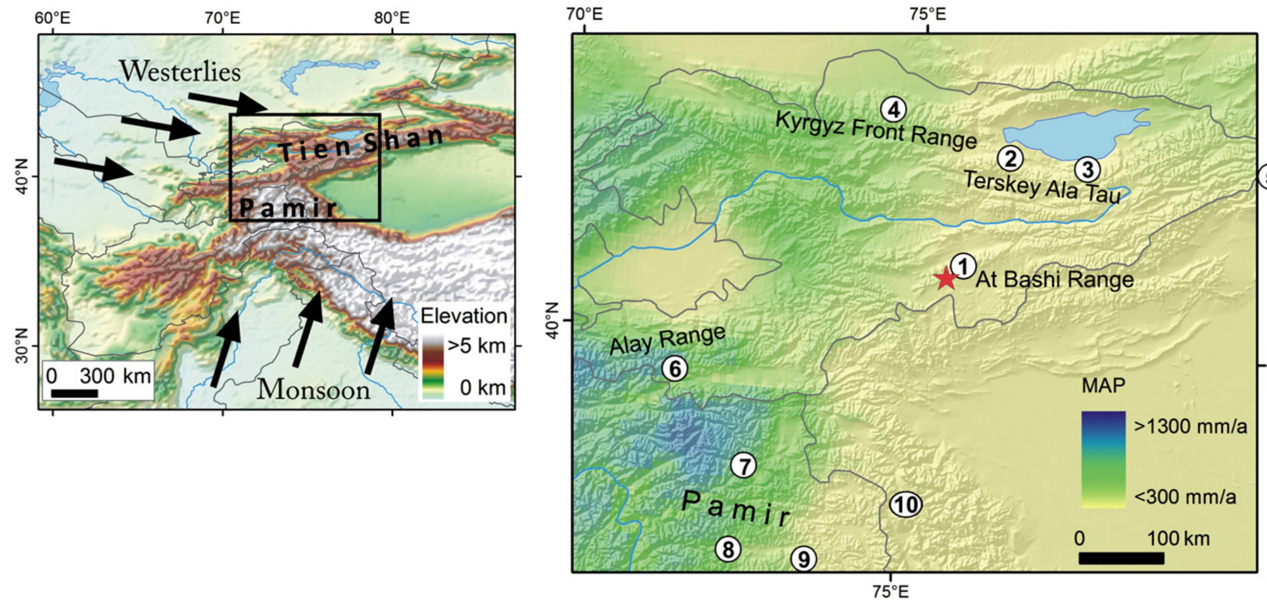

Figure 1. Geographical setting of the study area. The red star indicates the location of the Kitschi-Kurumdu Valley, the encircled numbers are other sites discussed in the text and listed in Fig. 5.

Material and methods

The Tien Shan is a roughly 1500 km long east–west oriented mountain range and marks the northwestern boundary of the Central Asian orogen. Its northern and western parts form an orographic barrier against the prevailing westerlies, which advect moisture from the Atlantic and the Mediterranean region, so that precipitation there can exceed 1000 mm/a (Figure 1). The seasonality of precipitation is controlled by the Siberian High that blocks the westerlies in winter. Spring and fall are thus the seasons when disturbances along the westerlies' storm track cause rainfall maxima (Aizen et al., 1995, 2001). The interior and particularly the southern parts of the Tien Shan, on the other hand, are extremely dry, with mean annual rainfall less than 300 mm (Figure 1). Here, precipitation falls mainly in summer related to heating and convection. This should not be confused with monsoonal precipitation; the Indian and Asian summer monsoons do not reach the Tien Shan today.

The study area is the Kitschi-Kurumdu Valley in the At Bashi Range (Figures 1, 2). This partly glaciated range reaches altitudes of ~4800 m asl (above sea level) and separates the At Bashi Basin to the north (~2100 m asl) and the Aksai Basin to the south (~3500 m asl). Peak altitudes in the south-facing Kitschi-Kurumdu headwaters reach ~4500 m, but despite low mean annual temperatures (~−10°C at 4150 m asl, Koppes et al., 2008), the valley is not glaciated at present due to the very arid conditions. Glacial deposits, such as distinct lateral and latero-frontal moraines, as well as '*tschukurs*' (characteristic moraine lobes with undulating dead-ice terrain) document past climate conditions more humid and/or colder than today. Solifluction features, including block glaciers, are common in the At Bashi Range and also occur in the upper reaches of the Kitschi-Kurumdu.

In order to establish a glacial chronology for the Kitschi-Kurumdu Valley, moraines were mapped and large, stable granitic boulders sampled for ^{10}Be surface exposure dating. Approximately ~0.5–1 kg chips of the upper 2–3 cm from the flat top of each boulder were obtained using hammer and chisel. All boulders were documented by photography (see supplementary material), and the exact geographical locations were determined using a hand-held GPS. Laboratory analyses of 13 samples were carried out following standard procedures (Ivy-Ochs, 1996). In brief, this involved separation of quartz, addition of ^{9}Be carrier and dissolution in HF, chromatographical purification of beryllium, precipitation and oxidation, and AMS measurement of the ^{10}Be over ^{9}Be ratio at ETH Zurich, Switzerland.

Exposure ages were calculated using the CRONUS-Earth Online Calculator (Balco et al., 2008). All relevant sample data and the ^{10}Be concentrations are provided in Table 1. Topographic shielding for all samples is negligible, but corrections were made for sample thickness. Snow and vegetation cover can likely be neglected due to the dry climatic conditions and the scarce vegetation cover. Calculations assume zero rock surface erosion, because generally well-preserved boulders are preferentially sampled for surface exposure dating. Moreover, assuming a specific constant erosion rate in the calculations may erroneously suggest that exposure ages can be corrected for in fact randomly occurring, non-constant erosion. Respective calculations merely provide sensitivity tests as to how a boulder and its exposure age may have been affected.

All exposure ages in the text are based on the time-dependent scaling model Lal (1991) / Stone (2000) because it brings the currently available calibration dataset into tighter agreement than the more recently developed neutron monitor-based models and those may thus not provide more accurate results (Lifton, 2011). Nevertheless, for the sake of completeness, Table 2 provides exposure ages calculated with all currently available scaling models. Note that the CRONUS calculator does not take into account that the currently adopted reference production rate is likely overestimated by more than ~10% (Putnam et al., 2010; Kaplan et al., 2011). This needs to be kept in mind in the paleoclimatic discussion, as the exposure ages presented here may increase ~10% when calculated with future versions of the CRONUS calculator.

For the interpretation of surface exposure ages the 'oldest age model' should be applied, i.e. the oldest boulder that is not a statistical or stratigraphical outlier is the best available estimate of the deposition age of a moraine (Briner et al., 2005; Zech et al., 2005a; Dortch et al., 2010). Principally, it is possible that a boulder contains inherited cosmogenic nuclides from an earlier exposure ('pre-exposure' or 'inheritance'), and that a boulder thus yields an anomalously old exposure age. Generally, however, the probability for inheritance is low (<3%) (Putkonen and Swanson, 2003; Heyman et al., 2011). Too young exposure ages, on the other hand, are relatively likely to occur due to common post-depositional geomorphological processes, such as denudation, boulder exhumation, boulder toppling and rock surface erosion. Especially in cold and arid regions melting of debris-covered ice takes thousands of

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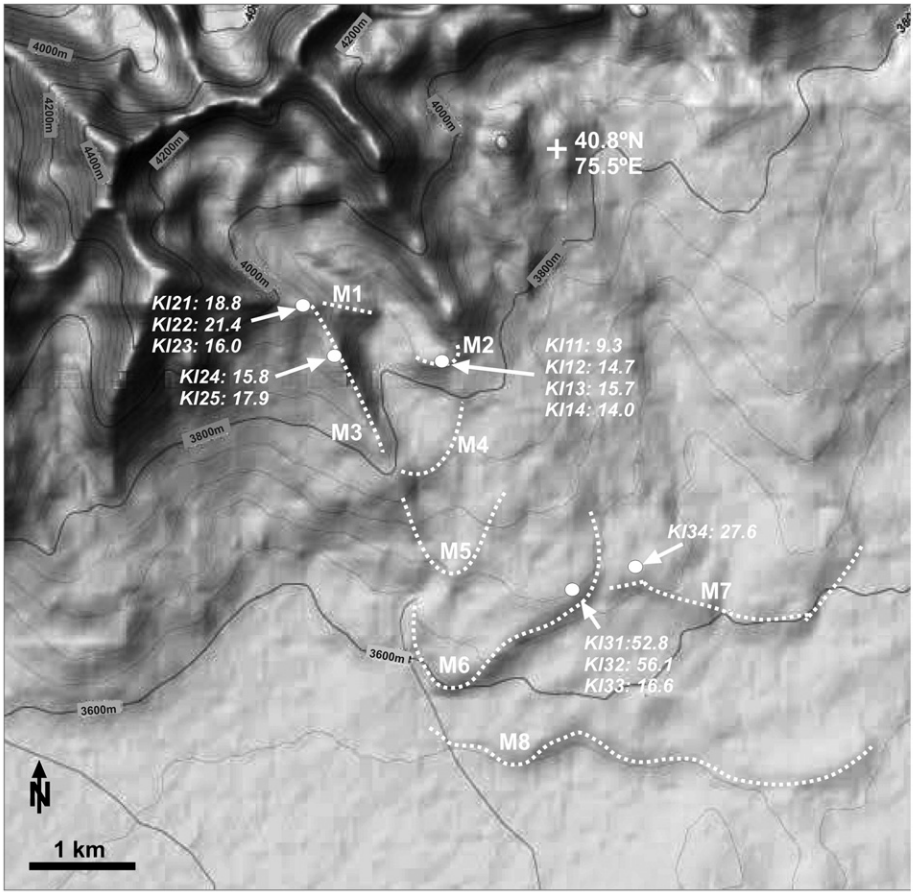

Figure 2. Google map terrain image from the Kitschi-Kurumdu Valley, showing the moraine stratigraphy (M1 to M8) and the exposure ages (in ka) obtained.

years, and long-lasting ice-decay may be responsible for very wide ranges of exposure ages as suggested for tschukurs in the Pamir (Zech et al., 2005a). In such cases, the application of the oldest age model probably provides a minimum estimate for the beginning of the ice retreat rather than for the timing of the glacial advance itself.

Results and discussion

Stratigraphy and exposure ages

The youngest sampled feature (M2) is a latero-frontal moraine at 3870 m asl (Figures 2, 3a,b). Four exposure ages yield 9.3 ± 0.9 ka (KI11), 14.7 ± 1.4 ka (KI12), 15.7 ± 1.4 ka (KI13) and 14.0 ± 1.4 ka (KI14) (Table 2). The three older ages agree reasonably well within the dating uncertainties, while KI11 is probably too young and has been affected by post-depositional processes. M2 thus documents a late glacial advance at ~15 ka. Morphologically, M2 likely documents a slightly more extensive advance than the remnants of a right-lateral moraine (M1) that leads to the onset of the prominent lateral moraine M3 at 3990 m asl (Figures 2, 3b,c).

Five exposure ages from M3 range from 15.8 ± 1.4 ka (KI24) to 21.4 ± 2.0 ka (KI22). Applying again the 'oldest age' model and assuming that the younger exposure ages are due to post-depositional processes, M3 likely documents a glacial advance in the Kitschi-

Table 1
Sample data.

Sample	Latitude ° N	Longitude ° E	Altitude m	Flag	Thickness cm	Density g/cm^3	Shielding	Erosion rate cm/yr	^{10}Be at/g	1σ
KI11	40.7827	75.4876	3870	std	3	2.7	1	0	618,693	25,441
KI12	40.7827	75.4876	3870	std	3	2.7	1	0	986,706	35,415
KI13	40.7826	75.4869	3870	std	3	2.7	1	0	1,054,226	32,225
KI14	40.7826	75.4869	3870	std	3	2.7	1	0	933,846	44,665
KI21	40.7874	75.4728	3990	std	3	2.7	1	0	1,357,544	47,407
KI22	40.7874	75.4728	3995	std	3	2.7	1	0	1,560,235	52,686
KI23	40.7871	75.4734	3980	std	3	2.7	1	0	1,139,210	36,319
KI24	40.7840	75.4763	3940	std	3	2.7	1	0	1,101,947	36,053
KI25	40.7838	75.4763	3940	std	3	2.7	1	0	1,255,321	42,133
KI31	40.7650	75.5025	3725	std	3	2.7	1	0	3,487,281	105,091
KI32	40.7650	75.5025	3725	std	3	2.7	1	0	3,688,019	144,202
KI33	40.7644	75.5024	3720	std	3	2.7	1	0	1,028,063	40,639
KI34	40.7666	75.5084	3708	std	3	2.7	1	0	1,750,840	53,109

Notes: A long term mean blank of 0.048E^{-12} ^{10}Be/^{9}Be has been subtracted from all measured AMS ratios to account for the ^{10}Be background. Samples are normalized to the laboratory house internal standard S555.

Table 2
Exposure age results in ka based on various scaling systems available in the CRONUS online calculator (vs. 2.2, assessed 12.01.2011).

Sample	Lal/stone constant	Desilet	Dunai	Lifton	Lal/stone time-dependent
KI11	9.2 ± 0.9	9.1 ± 1.1	9.4 ± 1.2	8.8 ± 0.9	9.3 ± 0.9
KI12	14.8 ± 1.4	13.9 ± 1.7	14.2 ± 1.7	13.6 ± 1.4	14.7 ± 1.4
KI13	15.8 ± 1.5	14.8 ± 1.8	15.0 ± 1.8	14.5 ± 1.5	15.7 ± 1.4
KI14	14.0 ± 1.4	13.2 ± 1.7	13.5 ± 1.7	13.0 ± 1.4	14.0 ± 1.4
KI21	19.1 ± 1.8	17.4 ± 2.2	17.5 ± 2.2	17.0 ± 1.8	18.8 ± 1.7
KI22	21.9 ± 2.1	19.7 ± 2.4	19.8 ± 2.4	19.2 ± 2.0	21.4 ± 2.0
KI23	16.1 ± 1.5	14.9 ± 1.8	15.1 ± 1.8	14.6 ± 1.5	16.0 ± 1.4
KI24	15.9 ± 1.5	14.8 ± 1.8	15.0 ± 1.8	14.5 ± 1.5	15.8 ± 1.4
KI25	18.1 ± 1.7	16.7 ± 2.1	16.8 ± 2.1	16.3 ± 1.7	17.9 ± 1.6
KI31	57.0 ± 5.3	47.8 ± 5.9	47.4 ± 5.8	45.7 ± 4.8	52.8 ± 4.8
KI32	60.4 ± 5.8	50.7 ± 6.4	50.1 ± 6.3	48.3 ± 5.2	56.1 ± 5.3
KI33	16.7 ± 1.6	15.7 ± 2.0	15.9 ± 2.0	15.4 ± 1.6	16.6 ± 1.5
KI34	28.7 ± 2.7	25.7 ± 3.2	25.7 ± 3.1	25.0 ± 2.6	27.6 ± 2.5

Kurumdu Valley at ~21 ka, i.e. in phase with the global LGM. This conclusion is independent of production-rate uncertainties. A correction of ~10% would result in only slightly older ages. Likewise, rock surface erosion is negligible. A constant erosion rate of 1 and 3 mm/ka, for example, would yield an exposure age of 21.8 and 22.6 ka for KI22, respectively. Morphologically, the global LGM terminal moraine is difficult to identify, because the surface morphology is very subdued. In Figure 2, M4 marks the possible former ice margin, while M5 might indicate an earlier (undated) stage.

Down-valley from M3 to M5, there is a gradual morphological transition towards a characteristic, undulating dead-ice terrain. It belongs to a tschukur, a moraine lobe that has a steep front of several tens of meters height (M6 in Figures 2 and 3d). Three samples from the tschukur front yielded exposure ages of 52.8 ± 4.8 ka (KI31), 56.1 ± 5.3 ka (KI32) and 16.6 ± 1.5 ka (KI33). Another exposure age of 27.6 ± 2.5 ka (KI34) comes from a boulder that was sampled on a slightly lower part of the tschukur (M7). M7 may document a separate, stratigraphically older advance than M6, or, more likely, a more or less simultaneous advance with ice confluence from the neighbouring valley (Figure 2). Either way, the wide range of exposure ages from M6 (and M7), the characteristic dead-ice terrain, and the extremely cold conditions suggest that melting of debris-covered ice probably took ten thousands of years. This strongly resembles conditions previously described in the Pamir (Zech et al., 2005a) and implies that even applying the oldest age model only yields a minimum age estimate for the beginning surface stabilization. M6 (and M7) was thus likely deposited by a glacial advance before ~56 ka. Assuming constant rock

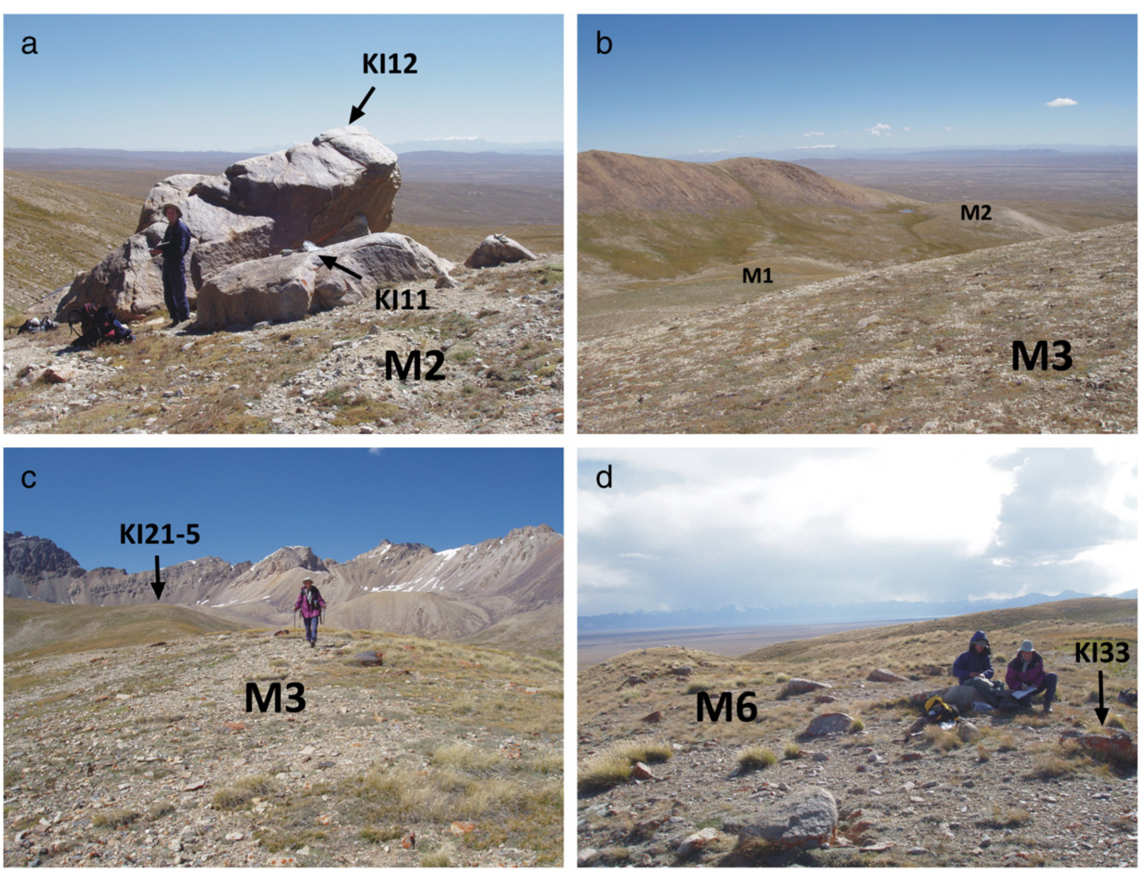

Figure 3. Photographs of a) sampled boulders KI11 and 12 on the late glacial moraine M2 (view east), b) moraines M1 and M2 (view east from onset of M3), c) the prominent right-lateral moraine M3 (view north into the debris-laden slopes in the headwaters of the Kitschi-Kurumdu Valley), and d) tschukur M6 and sample KI33 (view west into the Aksai Basin and towards Lake Chatyr Kul that is recognizable behind the pronounced tschukur front).

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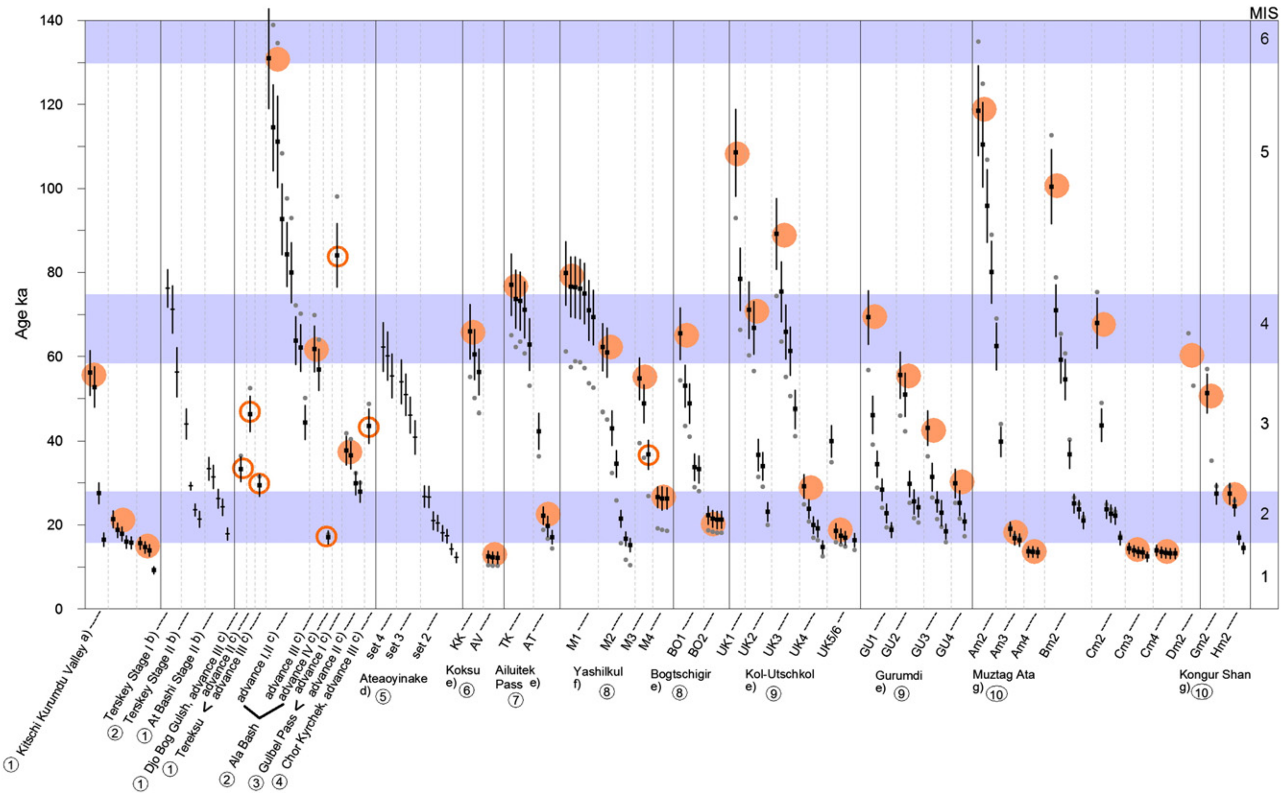

Figure 4. Comparison of the glacial chronology in the Kitschi-Kurumdu Valley with other numeric chronologies in the Tien Shan, Alay and Pamir. The encircled numbers below the site names mark the respective locations in Figure 1. Underlying red dots shall facilitate recognizing the inferred deposition ages applying the oldest age model. Where only a single age is available, ages are encircled. Black dots and error bars: exposure ages (recalculated) based on Lal (1991)/Stone (2000) and external uncertainties. Grey dots: ages as originally published. a) This study, b) Narama et al. (2007, 2009, OSL ages), c) Koppes et al. (2008), d) Zhao et al. (2009, ESR ages), e) Abramowski et al. (2006), f) Zech et al. (2005b), g) Seong et al. (2009, the 3 profile ages were not recalculated). The light blue bars mark MIS 2, 4, and 6.

surface erosion rates of 1 or 3 mm/a would result in exposure ages of 59.2 and 66.2 ka for the oldest boulder KI32. Adopting a new production rate would likewise yield significantly (~10%) older exposure ages.

An earlier and more extensive glacial advance must have occurred and deposited an older tschukur (M8), which is again characterized by an undulating topography and a distinct front. No suitable boulders for surface exposure dating could be sampled.

Comparison with other glacial chronologies from the Tien Shan

Given the limited number of exposure ages from the Kitschi-Kurumdu Valley, its glacial chronology shall be put into context with existing datasets (see Figure 4) before drawing any paleoclimatic conclusions. Note that all exposure ages reviewed in the following are recalculated and presented here using the scaling system Lal/Stone and zero rock surface erosion in order to ensure consistency and allow direct comparability.

In the neighbouring Djo Bog Gulsh Valley, Koppes et al. (2008) obtained one exposure age of ~33 ka from a moraine that they stratigraphically defined as local LGM (their advance III). A similar, second exposure age of ~29 ka comes from an advance III moraine in the Tereksu, a north-facing valley in the At Bashi Range. Both ages should be interpreted with caution, because only one boulder age is available from each feature, but they agree well with the age range for the 'At Bashi Stage II' (late MIS 3 to 2) defined by Narama et al. (2009). These authors have obtained five OSL ages from tills in four north-facing valleys ranging between 18 and 33 ka. The At Bashi Stage II thus also encompasses the 'global LGM advance' that could be dated in the Kitschi-Kurumdu Valley to ~21 ka. Narama et al. (2007, 2009) also presented OSL ages from till in north-facing valleys from the Terskey Ala Tau. Here, these authors correlated their Terskey Stage II with MIS 2 based on three OSL ages ranging from 21 to 29 ka, but they excluded a forth sample (sample T-2, 44 ka, in brackets in Figure 4) as outlier due to insufficient bleaching.

The >56 ka advance in the Kitschi-Kurumdu Valley falls well into the Terskey Stage I defined by Narama et al. (2009) and correlated with MIS 4-early MIS 3 based on three OSL ages ranging from 56 to 76 ka. The >56 advance thus likely belongs to the At Bashi Stage I, which was described, but not dated by Narama et al. (2009). Two exposure ages of 57 and 62 ka were obtained by Koppes et al. (2008) from the Ala Bash (Terskey Ala Tau) corroborating that the local LGM (their advance III) in that valley occurred during MIS 4, i.e. Terskey Stage I.

Reasonable evidence from the Kyrgyz Tien Shan also points to the existence of glacial advances between the At Bashi and Terskey Stages I and II. A single age of ~46 ka, for example, comes from an advance II moraine (defined as penultimate glaciation) in the Tereksu Valley, and an advance III moraine in Chor Kyrchek in the Kyrgyz Front Range yielded a single exposure age of 44 ka (Koppes et al., 2008). Moreover, four ages from near the Gulbel Pass range from 28 to 38 ka and suggest that the respective moraine, which was stratigraphically assigned to advance II (i.e. penultimate glaciation), likely just predated Terskey Stage II. Although speculative, moraine M5 in the Kitschi-Kurumdu Valley might also document a MIS 3 stage.

Glacial advances predating the At Bashi and Terskey Stages I have also been found in the Kyrgyz Tien Shan. In the Ala Bash Valley, nine exposure ages assigned to advance I and II range from 44 to 131 ka (Koppes et al., 2008), suggesting that penultimate glacial deposits (sensu MIS 6) can locally be preserved. At the Gulbel Pass, a moraine assigned to advance I (i.e. 'oldest glaciation') was dated by a single

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boulder to 84 ka, but again, conclusions drawn from single samples remain vague. Anyway, moraine M8 in the Kitschi-Kurumdu Valley may also document a glacial advance predating MIS 4.

The limited number of exposure and OSL ages makes it challenging to draw a robust detailed picture of the timing of past glaciation in the Kyrgyz Tien Shan. Nevertheless, the general pattern is in agreement with electron spin resonance (ESR) ages from the Ateaoyinake Valley in the Chinese Tien Shan (Zhao et al., 2009). There, the glacial advance during the global LGM (eight ESR ages from 12.3 to 27 ka for their second moraine set) was less extensive compared to an early local LGM dated with three ESR ages to between 55 and 62 ka (for their fourth set of moraine). Zhao et al. (2009) also described a third and fifth moraine set (four ages from 41 to 54 ka, and two ages of 134 and 220 ka, respectively), which may correspond to the MIS 3 and pre-MIS 4 advances in Kyrgyzstan.

Comparison with surface exposure chronologies from the Alay and Pamir

Three exposure ages from 56 to 66 ka suggest that the early local LGM in the Koksu Valley in the Alay Range may have occurred during MIS 4 (Abramowski et al., 2006) and could thus be correlated with the At Bashi and Terskey Stage I. The steep valley flanks further upstream are not favourable for preservation of moraines, so that apart from one recessional terminal moraine, dated with three boulders to ~12 ka, no further age control is available.

The early local LGM in the Ailuitek Pass area in the north-central Pamir was dated by Abramowski et al. (2006) with five boulders from a high lateral moraine to 63 to 77 ka. Taken at face value, these ages may also be interpreted to document a MIS 4 advance, but including only minor erosion corrections and/or adopting new reference production rates pushes these ages into MIS 5. Only one younger stage is preserved and dated in the Ailuitek Pass area. Three boulders from moraine sets in the valley bottom yielded ages of 17, 20 and 22 ka, and thus likely document a glacier advance in phase with the global LGM. A forth boulder with an exposure age of 42 ka was interpreted as outlier with inherited cosmogenic nuclides from previous exposure (Abramowski et al., 2006).

Further south in the Pamir, at Lake Yashilkul, the most extensive dated glaciation is documented by a lateral moraine, which yielded seven exposure ages between 69 and 80 ka (Zech et al., 2005b). As for the early LGM in the Ailuitek Pass area, these minimum ages point to an extensive glaciation during MIS 5, which can thus not be correlated with the At Bashi and Terskey Stage I. However, less extensive, but very prominent glacial deposits at Lake Yashilkul are massive tschukurs that extend out of the southern tributary valleys and reach far into the lake. Exposure ages range from 15 to 62 ka (Zech et al., 2005b), and from 33 to 66 ka in the neighbouring Bogtschigir Valley (Abramowski et al., 2006). This can again most plausibly be explained with long-lasting ice decay and landform surface instability due to thick supra-glacial debris cover (Zech et al., 2005a). Applying the oldest age model, these tschukurs were likely deposited during MIS 4 and can be correlated with the At Bashi and Terskey Stage I. In both valleys, global LGM moraines could be dated as well (~27 and 22 ka, respectively) corresponding to the At Bashi and Terskey Stage II in the Tien Shan. Zech et al. (2005b) additionally found preserved remnants of lateral moraines, tentatively dated to ~55 ka and 37 ka.

It is tempting to try correlating the full Yashilkul sequence with respective numeric ages from the Tien Shan and other study areas in the Pamir. In the Gurumdi Valley (southern Pamir), for example, the whole set of oldest ages from four moraines (~70, 56, 43 and 30 ka) (Abramowski et al., 2006) roughly matches the Yashilkul sequence (~62, 55, 37 and 27 ka). The 55 ka Yashilkul moraine is also in good agreement with four unpublished exposure ages from the nearby Tscholok Valley (Ines Roehringer, personal communication, 2011), and with the >56 ka early local LGM moraine in the Kitschi-Kurumdu Valley. The 37 ka Yashilkul moraine may tentatively be correlated with the 38 ka moraine at Gulbel, and with the 46 ka and 44 ka moraines in the Tereksu and Chor Kyrchek. Exposure ages from the Kol-Utschkol, southern Pamir (Abramowski et al., 2006), also match the emerging glacial pattern. There, a pronounced (less extensive) tschukur (UK4) can be interpreted as Stage II advance (five exposure ages ranging from 15 to 29 ka), and an older (more extensive) tschukur (UK2) yields an oldest age of ~71 ka, i.e. Stage I. Very weakly expressed moraine stages in between may have been deposited during MIS 3.

Interestingly, two older remnants of left-lateral moraines in the Kol-Utschkol yield oldest exposure ages of 89 ka (UK3) and 108 ka (UK1), respectively. They clearly predate MIS 4 and corroborate the findings from Lake Yashilkul and Ailuitek that the oldest datable glacial advances in the Pamir likely occurred during MIS 5 or even earlier. However, note that age differences between these advances seem to be too large to assign them to a single glacial stage. Comparison with published exposure ages from early LGM moraines in the Muztag Ata region (Seong et al., 2009) sheds some more light on this issue. There, oldest boulders at four sites yield minimum exposure ages of 118, 100, 68 and 51 ka. Given the large age ranges and the limited datasets, it currently seems impossible to establish a more detailed chronology for the pre-MIS 4 stages. Interestingly, although moraines roughly in phase with the global LGM were found in the Muztag Ata region (oldest ages of 19, 24?, and 28), evidence for MIS 3 moraines remains equivocal.

Synthesis and paleoclimate discussion

Three distinct moraines in the Kitschi-Kurumdu Valley could be dated to ~15 ka, 21 ka and >56 ka, and at least one older glacial deposit could be mapped. This corroborates prior studies that found an early local LGM in the Tien Shan. Detailed comparison with other numeric chronologies from the Tien Shan suggests that the most extensive glaciation during the last glacial cycle occurred during MIS 4 (At Bashi and Terskey Stage I). Evidence of MIS 5 stages remains equivocal, whereas at least locally MIS 3 and MIS 6 moraines are preserved.

In the adjacent Pamir mountains, on the other hand, there is reasonable evidence that the local LGM may have occurred already during MIS 5. Given the arid conditions and the resultant precipitation sensitivity of many glaciers in Central Asia, this difference could tentatively be interpreted to indicate increased monsoonal moisture advection to the Pamir during MIS 5. This speculation needs to acknowledge, of course, that currently available numeric glacial chronologies are still very scarce, and that systematic and random methodological uncertainties are quite large. It thus cannot be excluded that MIS 5 moraines in the Tien Shan have simply been missed so far, and likewise, all exposure ages presented here may be systematically too old, so that the early LGM in the Pamir may actually also be MIS 4 in age. This latter argument, however, seems rather implausible, because both the new, not yet adopted reference production rates and erosion rate corrections would lead to even older exposure ages.

Methodological uncertainties may also be the reason, why it is so challenging to precisely correlate the dated MIS 4, 3 and 2 moraines from one study area to the next. Even the global LGM advances, which can be dated relatively accurately, seem to differ locally by more than several thousand years. This suggests that minor age differences between corresponding moraines are real and reflect site-specific non-climatic factors, such as topography, bedrock, debris cover, glacial dynamics, etc.

In any case, the robust common feature in the Tien Shan and Pamir is that glaciation became successively more restricted from MIS 4 to 2. Already prior studies have inferred very arid conditions during MIS 2 from the limited glacier extents during the global LGM (Zech et al., 2005b; Abramowski et al., 2006; Narama et al., 2007; Koppes et al., 2008; Narama et al., 2009). This is in agreement with very limited ice sheet and glacier extents in Siberia (Svendsen et al., 2004; Stauch and Gualtieri, 2008; Zech et al., 2011) and likely points to (i) reduced moisture advection via the westerlies due to lee effects behind the massive Fennoscandian Ice Sheet in Europe, and (ii) blocking of the westerlies by a strong Siberian High. Arid conditions during MIS 2 also explain high dust-accumulation rates observed in the Central Asian and southern Siberian loess regions (Frechen and Dodonov, 1998; Chlachula, 2003; Frechen et al., 2005).

It should be pointed out that the currently available luminescence ages from the loess regions seem to date the onset of the 'MIS 4' dust accumulation to only ~60 ka, i.e. strictly speaking to the MIS 4/3 transition rather than the MIS 5/4 transition. Methodological limitations might explain this apparent discrepancy, but further research should clarify this issue, because although the glacial chronologies suggest more humid conditions during MIS 4 compared to MIS 2, it is generally assumed that MIS 4 was already relatively arid compared to much more humid conditions during MIS 5 (as reflected in the strongly developed 'Eemian' paleosols).

Finally, concerning the climatic conditions during MIS 3, the existence of respective moraines both in the Tien Shan and the Pamir indicates increased precipitation that could compensate for the presumably slightly warmer interstadial conditions. MIS 3 glacial advances in the Karakoram and the Himalayas (Owen et al., 2002; Finkel et al., 2003; Owen et al., 2008) have been explained with a strengthening of the monsoon system at that time. However, it remains questionable whether the monsoon reached the Pamir and Tien Shan at that time. It may have not, because (i) MIS 3 advances in the southern Pamir don't seem to have been more extensive relative to the MIS 3 moraines in the Tien Shan, and they may be fully missing in the Muztag Ata region (ii) there is no evidence for moraines in the southern Pamir that would indicate a glacier response to the strengthening of the monsoon during the early Holocene, and (iii) evidence from the loess–paleosols shows that the westerlies advected more humidity during MIS 3, so there is also no need to infer any influence of the monsoon to explain the MIS 3 glacial advances.

Conclusions

Surface exposure dating in the Kitschi-Kurumdu Valley allowed establishing a new numeric glacial chronology, which supplements and largely corroborates prior studies about past glaciation in the Tien Shan. The distinction between At Bashi and Terskey Stages I and II, which correspond to MIS 4/early MIS 3 and late MIS 3/MIS 2, is supported by respective moraine ages of >56 and ~21 ka. A detailed review of existing numeric chronologies in the Kyrgyz Tien Shan indicates that undated moraines in the Kitschi-Kurumdu Valley may correspond to MIS 6 and MIS 3. Evidence for MIS 5 stages in the Tien Shan remains equivocal, as does evidence for systematic regional differences in glacial chronologies.

A quite intriguing difference, however, could be found when comparing results from the Tien Shan with existing chronologies from the Pamir. The MIS 5 moraines there are tentatively interpreted to document the influence of monsoonal precipitation during the last interglacial, whereas no such influence is evident since. The MIS 3 moraines in the Tien Shan and southern Pamir can be better explained with more moisture advection via the westerlies than the monsoon.

The above paleoclimatic conclusions are relatively robust against methodological dating uncertainties, but more studies are needed to establish more precise and complete stratigraphies and chronologies. In particular, the remaining systematic uncertainties of surface exposure dating need to be addressed. This requires local independent age control, e.g. from radiocarbon or OSL dating, but also further reference calibration sites worldwide and a better understanding of the physics behind cosmogenic radiation and nuclide formation.

A final conclusion addresses the lack of studies that combine establishing glacial chronologies with glacier-climate modelling. Such an approach might greatly help disentangling the effects of changing temperature and precipitation over time and should compare sites situated in (i) more humid parts of Central Asia with dominant influence of the westerlies, (ii) humid parts in the Hindu Kush with dominant influence of monsoonal precipitation, and (iii) the arid core of the southern Pamir and southeastern Tien Shan.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.yqres.2011.11.008.

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