Palaeoglaciology of the northeastern Tibetan Plateau

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"The assumption that one finds snow and ice everywhere in Tibet is not true"

Heinrich Harrer: Seven years in Tibet (1953)

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Cover: Central Bayan Har Shan seen from the upper Galala Valley
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ABSTRACT

This study concerns the palaeoglaciation of the northeastern Tibetan Plateau, with emphasis on the Bayan Har Shan (Shan = Mountain) in the headwaters of Huang He (Yellow River). To reconstruct past glacier development multiple techniques, including remote sensing, field investigations, cosmogenic exposure dating, and numerical modelling have been employed. Analysis of the large-scale geomorphology indicates that glacial erosion has been dominant in the elevated mountain areas on the low-relief plateau, whereas fluvial erosion outpaces glacial erosion along the plateau margin. Landform and sediment records yield evidence for multiple local glaciations, restricted to the highest mountain areas, and a maximum glaciation beyond the mountain front. Absence of data supporting the former presence of proposed ice sheets, plateau-wide or regional, tentatively indicates that no ice sheet glaciation occurred on the northeastern Tibetan Plateau. Cosmogenic exposure dating of boulders, surface pebbles, and sediment sections in central Bayan Har Shan indicates that its record of past glaciations predates the global Last Glacial Maximum (LGM). Based on a world-wide analysis, yielding that wide age disparity within apparent exposure age datasets is most likely caused by post-glacial shielding processes, the Bayan Har Shan exposure ages constrain four periods of glaciation with minimum ages of 40-65 ka, 60-100 ka, 95-165 ka, and undetermined oldest stage. Similar to Bayan Har Shan, the plateau-wide distribution of boulders with pre-LGM exposure ages close to present-day glaciers shows that its LGM glaciers were generally not much larger than today. The results of a high resolution glacier model applied to nine regions across the plateau indicates that temperature depressions of 2-4 K are enough to expand glaciers beyond their global LGM extent, implying that during periods of Northern Hemisphere glaciation the Tibetan Plateau was not much colder than today or became exceedingly dry.

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This thesis consists of a summary and five papers:

Paper I
Heyman J, Hättestrand C, Stroeven AP, 2008. Glacial geomorphology of the Bayan Har sector of the NE Tibetan Plateau. *Journal of Maps* 2008, 42-62.
[Map in pdf format on enclosed CD]

Paper II
Stroeven AP, Hättestrand C, Heyman J, Harbor J, Li YK, Zhou LP, Caffee MW, Alexanderson H, Kleman J, Ma HZ, Liu GN, 2009. Landscape analysis of the Huang He headwaters, NE Tibetan Plateau – patterns of glacial and fluvial erosion. *Geomorphology* 103, 212-226.

Paper III
Heyman J, Stroeven AP, Alexanderson H, Hättestrand C, Harbor J, Li YK, Caffee MW, Zhou LP, Veres D, Liu F, Machiedo M, 2009. Palaeoglaciation of Bayan Har Shan, northeastern Tibetan Plateau: glacial geology indicates maximum extents limited to ice cap and ice field scales. *Journal of Quaternary Science* 24, 710-727.

Paper IV
Heyman J, Stroeven AP, Harbor J, Caffee MW, submitted. Boulder cosmogenic exposure ages as constraints for glacial chronologies. *Earth and Planetary Science Letters*.
[Supplementary material on enclosed CD]

Paper V
Heyman J, Stroeven AP, Caffee MW, Hättestrand C, Harbor J, Li YK, Alexanderson H, Zhou LP, Hubbard A, manuscript. Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: the case of a missing LGM expansion.
[Supplementary material on enclosed CD]

Co-authorship

Paper I: Heyman mapped the glacial geomorphology, based on initial mapping by Hättestrand and Stroeven, and prepared the manuscript.

Paper II: Hättestrand and Stroeven mapped the geomorphology, performed analyses, and wrote the first draft of the manuscript. Heyman, Harbor and Li contributed with analyses and final manuscript preparations.

Paper III: Heyman planned and conducted all aspects of the study during two consecutive field seasons, following a reconnaissance field study by Stroeven, Caffee, Harbor, Hättestrand, and Li. Heyman wrote the manuscript.

Paper IV: Heyman compiled the exposure age and deglaciation reconstruction age datasets, developed the boulder exhumation model, and wrote the manuscript.

Paper V: Heyman supervised cosmogenic nuclide sample selection, conducted parts of the geochemistry work, lead the data analysis, performed the glacier modelling, and wrote the manuscript.

All co-authors have been invited to contribute to field work, data analysis and manuscript preparation, and have contributed to a few or all of these aspects.

Introduction

The Tibetan Plateau is an exceptional topographic feature, located above 4000 m a.s.l., hosting the highest mountains in the world, and with an area similar in size to Greenland (Fig. 1a). The rise of the plateau, caused by the India-Eurasia collision, altered large-scale climate systems including the Asian monsoon and has been suggested to have induced global cooling by erosion, chemical weathering, and declined atmospheric CO_2 (Raymo and Ruddiman, 1992; An et al., 2001; Harris, 2006). The Tibetan Plateau mountain ranges host a large part of the glaciers located outside the polar areas (Dyurgerov and Meier, 2005) and the plateau is commonly termed the third pole (Qiu, 2008). The meltwater from the glaciers on the Tibetan Plateau feed some of the largest rivers in the world providing water to more than 1.3 billion people (Xu et al., 2007), and the glacier development in the Tibetan Plateau region is therefore of utmost importance. As one piece of the glacier evolution puzzle, studies of former glaciation of the Tibetan Plateau may yield key information on the dynamics and response of past glaciers to climate variation (cf. Owen et al., 2009b).

The Quaternary glacial evolution of the Tibetan Plateau has been investigated for more than a century with widely different interpretations of the extent and timing of former glaciers (e.g. Kuhle, 1985; Derbyshire et al., 1991). Early studies reported the presence of glacial landforms and deposits in mountain regions of the Tibetan Plateau and noted an absence of glacial traces for extensive low-relief plateau areas (e.g. Huntington, 1906; Tafel, 1914; Hedin, 1922; Ward, 1922; Norin, 1925; Trinkler, 1930). Since the early 1980s, Matthias Kuhle has insistently argued for extensive glaciation with a plateau-wide ice sheet present during the global last glacial maximum (LGM) c. 20 ka (Kuhle, 1985, 1988, 1998, 2004; Fig. 1b). While this idea has sparked interest in the glacial history of the Tibetan Plateau and a lively debate (e.g. Zheng, 1989; Rutter, 1995), the Tibetan global LGM ice sheet hypothesis has been subject to severe criticism (Derbyshire et al., 1991; Zheng and Rutter, 1998; Lehmkuhl and Owen, 2005; Owen et al., 2008). Regarding the *extent* of past glaciations, geomorphological and sedimentological studies have repeatedly shown that glacial landforms and sediments are restricted to higher mountain areas indicating formation by alpine-style valley glaciers and ice-fields (e.g. Burbank and Kang, 1991; Derbyshire et al., 1991; Shi et al., 1992; Rutter, 1995; Lehmkuhl, 1998; Lehmkuhl et al., 1998; Zheng and Rutter, 1998; Lehmkuhl and Owen, 2005). As for the *timing* of glaciations, an extensive dataset with cosmogenic exposure ages and additional luminescence dating have shown that over at least the last few glacial cycles (the last few hundred thousand years) no plateau-scale ice sheet has covered the Tibetan Plateau (e.g. Phillips et al., 2000; Richards et al., 2000; Brown et al., 2002; Schäfer et al., 2002; Owen et al. 2003, 2005, 2006a, 2006b, 2008, 2009a; Chevalier et al., 2005; Zech et al., 2005; Abramowski et al., 2006; Colgan et al., 2006; Schaefer et al., 2008; Seong et al., 2009; Paper V).

On a plateau-scale, a restricted glacial extent reconstruction has been presented in the Quaternary glacial distribution map (Li et al., 1991; Fig. 1c) with c. 20% of the area above 2000 m a.s.l. formerly ice covered. For the northeastern Tibetan Plateau this reconstruction includes a regional scale ice sheet of 95000 km^2 covering the Bayan Har Shan (Shan = Mountains) in the headwaters of the Huang He (Yellow River) – the Huang He ice sheet. While the idea of a Huang He ice sheet was supported and further elaborated on by Zhou and Li (1998) based on proposed widespread glacial landforms and sediments, Lehmkuhl et al. (1998) and Zheng and Rutter (1998) argued for past glaciation restricted to the highest mountains and opposed the existence of a former Huang He ice sheet. The palaeoglaciology of the Bayan Har Shan, with previous spatial reconstructions including alpine-style glaciers as well as ice sheets and without chronological constraints, forms the core issue of this thesis.

The chronology of former glaciations on the Tibetan Plateau has been investigated using multiple dating techniques for a large number of sites. A number of radiocarbon constraints for Holocene and prior glacier advances have been reported from multiple sites on the Tibetan Plateau (Yi et al., 2007, 2008), but the technique has been limited by the scarcity of organic material. With the progress of new dating techniques such as cosmogenic exposure dating (e.g. Phillips et al., 2000; Schäfer et al., 2002; Owen et al., 2005, 2008), luminescence dating (e.g., Richards, 2000), and electron spin resonance dating (e.g. Zhao et al., 2009) the temporal range of the chronological tools has been extended. However, these techniques are all hampered by the physical and geological principles they rest on and the dates must typically be interpreted with care. Hence, although significantly more than 1000 dates from the Tibetan Plateau have been presented (Paper IV), it is for most areas still impossible to define the exact timing of past glaciations (cf. Owen et al., 2008).

This study was initiated to help resolve the glacial history of the northeastern Tibetan Plateau. With widely different spatial reconstructions of former glaciers and an absence of

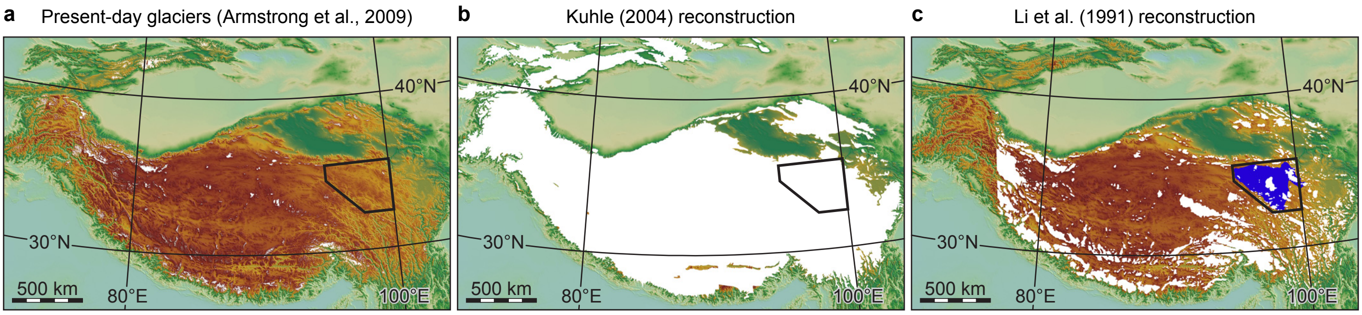

Figure 1. The Tibetan Plateau with present-day glaciers and two palaeoglaciological reconstructions. The black box marks the Bayan Har Shan study region (Fig. 2). (a) Present-day glaciers from the GLIMS project (note that not all glaciers have been mapped in the western region). (b) A plateau-wide ice sheet proposed by Kuhle (2004). (c) The glacial reconstruction from Li et al. (1991) with restricted glaciation (white) and a regional ice sheet (blue) over the Bayan Har Shan area.

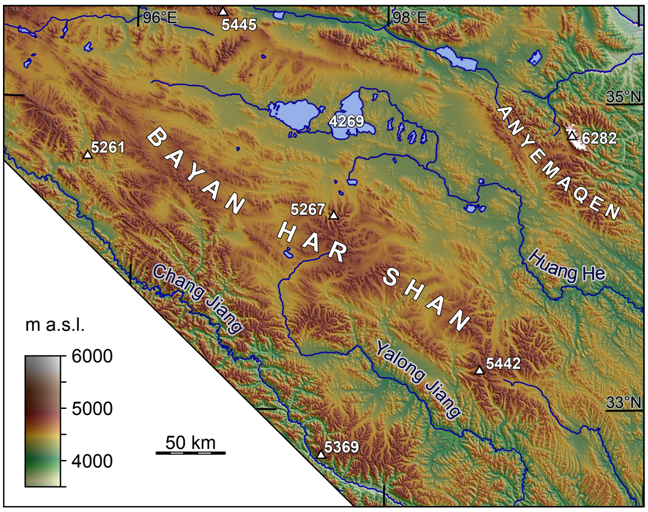

Figure 2. The Bayan Har Shan study area. See Figure 1 for location on the plateau.

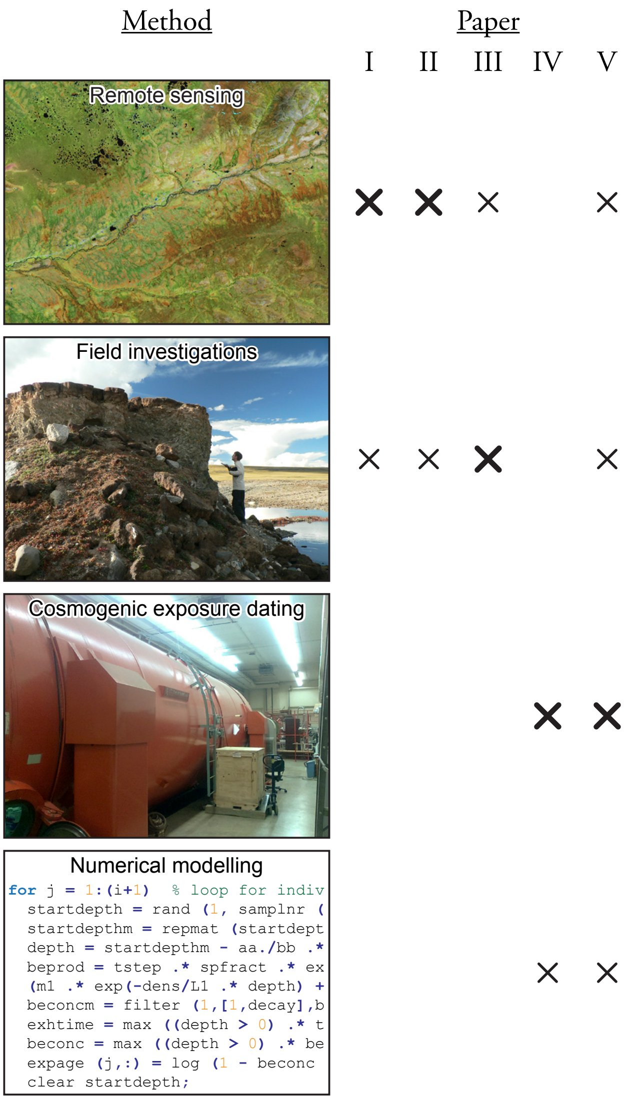

Figure 3. The methodology and their importance to Papers I to V. Thick crosses mark the main method for each paper. Field investigation photo: Helena Alexanderson.

chronological constraints, the palaeoglaciology of the Bayan Har Shan has remained elusive. The project has been an attempt to employ spatial reconstruction techniques previously successfully used for the Fennoscandian and Laurentide ice sheets (e.g. Kleman et al., 1997, 2006) and to couple this with chronological constraints using cosmogenic exposure dating (e.g. Fabel and Harbor, 1999; Gosse and Phillips, 2001). The main objective of this study is the spatial and temporal evolution of past glaciers on the northeastern Tibetan Plateau, with special emphasis on the Bayan Har Shan. Two questions can summarize this objective:

How extensive have past glaciers in Bayan Har Shan been and when did they exist?

This study further explores the effectiveness of glacial and fluvial erosion over landform evolution timescales, geological uncertainties and interpretation strategies for boulder cosmogenic exposure dating, and palaeoclimate implications of the Tibetan Plateau glacial geology.

Bayan Har Shan study area

Bayan Har Shan is a NW-SE trending mountain range of c. 500 by 150 km in the northeastern corner of the Tibetan Plateau (Fig. 2). The mountain range forms a low relief alpine landscape reaching above a gentle plateau surface of c. 4300 m a.s.l. The highest peaks in the central Bayan Har Shan reach c. 5200 m a.s.l. and the relief from valley floor to interfluve is typically less than 300 m. Bayan Har Shan forms the water divide between the Huang He, with its source area along the northern side of the Bayan Har Shan range, and the Chang Jiang (Yangtze River) passing the southern side of Bayan Har Shan. While the mountain areas are characterized by glacial erosional landforms such as U-shaped valleys and troughs, the lower-lying intervening plateau areas are characterized by extensive fluvial plains and gentle hills marked by weathering and fluvial erosion. In central Bayan Har Shan the mean annual temperature is c. -4°C and the annual precipitation is c. 400 mm (Hijmans et al., 2005).

Methodology

Four main methods have been employed in this study; (i) remote sensing, (ii) field investigations, (iii) cosmogenic exposure dating, and (iv) numerical modelling. Their importance to Papers I to V is illustrated in Figure 3.

Remote sensing has enabled comprehensive mapping of large-scale glacial landforms for an extensive area of the northeastern Tibetan Plateau. The SRTM elevation model (Jarvis et al., 2009) of c. 90 m resolution and Landsat ETM+ satellite imagery (GLCF, 2009) of c. 15 m resolution have been used. In addition, Google Earth has been frequently utilized primarily for 3D visualization. Field investigations in the Bayan Har Shan, including detailed work on sedimentary sections and recording presence/absence of glacial deposits, yield detailed point data for the investigated areas. Three fieldworks have been carried out in the Bayan Har Shan during 2005-2007. Combined, remote sensing and fieldwork investigations form the basis for the spatial reconstruction of former glacial extents.

Cosmogenic exposure dating (Fabel and Harbor, 1999; Gosse and Phillips, 2001; Balco et al., 2008), enables quantification of the time a rock surface has been exposed to the atmospheric flux of cosmic rays. Cosmogenic nuclides accumulate in quartz as a result of bombardment by cosmic rays with spatially and temporally varying production rates. The concentration of cosmogenic nuclides can be measured and, with a known production rate history and a few assumptions on the geological history of the sampled surface, converted to a time of exposure. Cosmogenic exposure dating has been frequently used for dating glaciations because glaciers typically strip the ground and leave rock surfaces free of cosmogenic nuclides (starting from an exposure age of zero) after deglaciation. For the Bayan Har Shan study, ^{10}Be exposure dating of glacial boulders, surface pebbles, and sediment section profiles have been employed. Cosmogenic exposure dating provides the temporal constraints for reconstructing past glaciations.

In this study two numerical models of different types have been used. First, a Monte Carlo simulation (Metropolis and Ulam, 1949) of boulder exhumation towards the surface has been developed, yielding boulder exposure ages as a result of random deglaciation age and random initial boulder depth. Second, a high resolution glacier mass balance and 3D ice flow model (Hubbard et al., 1998) has been applied, yielding glacier evolution as a result of input climate data. The numerical modelling yields quantitative data for idealized states and enables testing of key assumptions.

Presentation and summary of papers

Paper I

Heyman J, Hättestrand C, Stroeven AP, 2008. Glacial geomorphology of the Bayan Har sector of the NE Tibetan Plateau. *Journal of Maps* 2008, 42-62.

In this paper we present a glacial geomorphological map of the Bayan Har Shan. Using remote sensing techniques we mapped glacial valleys/troughs, marginal moraines/moraine remnants, glacial lineations, hummocky terrain, and meltwater channels in a c. 450 by 350 km (Fig. 2; 136 500 km^2) area of the northeastern Tibetan Plateau. The glacial landforms are concentrated to elevated mountain regions with a striking absence of glacial landforms in extensive lower-lying plateau areas. In addition, the mapping project reveals a complete absence of landforms commonly found in palaeo-ice sheet areas, such as glacial lineation swarms, ribbed moraines, and eskers. The mapped glacial geomorphology forms the basis for spatial reconstructions of former glacial extent in Bayan Har Shan (Papers III and V). The glacial landform record indicates former alpine-style glaciation with valley glaciers and ice fields centered on the highest regions, but lends no support to the former existence of a plateau-wide or a regional ice sheet.

Paper II

Stroeven AP, Hättestrand C, Heyman J, Harbor J, Li YK, Zhou LP, Caffee MW, Alexanderson H, Kleman J, Ma HZ, Liu GN, 2009. Landscape analysis of the Huang He headwaters, NE Tibetan Plateau – patterns of glacial and fluvial erosion. *Geomorphology* 103, 212-226.

In this paper we perform an analysis of the large-scale geomorphology of Bayan Har Shan and evaluate the relative importance of glacial and fluvial erosion in forming the landscape. Based on remote sensing, we present a three-piece classification with glacial landscapes formed by glacial erosion, relict upland surfaces with plains and hills with gentle slopes, and fluvial landscapes dominated by sharp V-shaped valleys formed by fluvial incision of the Huang He and Chang Jiang. In the elevated mountain areas of Bayan Har Shan U-shaped glacial valleys which are wider and deeper than adjacent fluvial valleys indicate that, integrated over time, glacial erosion has been more effective than fluvial erosion. Along the plateau margin, however, this relationship is reversed with dramatic fluvial rejuvenation of the relict upland surface as well as of glacial valleys. The outline of the relict upland surface closely mimics the outline of the proposed Huang He ice sheet. This spatial coincidence, in conjunction with a reclassification of valleys previously interpreted as formed by glacial erosion, indicates that the regional ice sheet may be based on a misinterpretation of a low-relief relict upland surface.

Paper III

Heyman J, Stroeven AP, Alexanderson H, Hättestrand C, Harbor J, Li YK, Caffee MW, Zhou LP, Veres D, Liu F, Machiedo M, 2009. Palaeoglaciation of Bayan Har Shan, northeastern Tibetan Plateau: glacial geology indicates maximum extents limited to ice cap and ice field scales. *Journal of Quaternary Science* 24, 710-727.

In this paper we present geological field data from the Bayan Har Shan. We performed detailed sedimentological investigations at key locations to distinguish glacial from non-glacial deposits based on identification of well established glacial characteristics. We mapped glacial deposits, including glacial sediments and erratic boulders, across an extensive area and, in addition, we recorded locations with an absence of glacial traces. Similar to large-scale glacial landforms (Paper I, Paper II), glacial deposits are concentrated to elevated mountain regions. However, in multiple locations glacial deposits occur in a zone beyond large-scale glacial erosional landforms, indicating limited glacial erosion under the peripheral zones of the most extensive palaeo-glaciers. Using the record of glacial deposits (field data) in conjunction with mapped glacial landforms (remote sensing) we present a map of glacial traces representing a minimum interpretation of the most extensive glaciation. The glacial geological record indicates maximum glaciation larger than any present-day ice mass apart from the Antarctic and Greenland ice sheets, with local ice fields/ice caps covering entire mountain ranges. However, absence of glacial traces in extensive lower-lying areas suggests that the palaeo-glaciers did not merge to form a regional or plateau-scale ice sheet.

Paper IV

Heyman J, Stroeven AP, Harbor J, Caffee MW, submitted. Boulder cosmogenic exposure ages as constraints for glacial chronologies. *Earth and Planetary Science Letters*.

In this paper we evaluate cosmogenic exposure dating of glacial boulders and the interpretation alternatives related to geological uncertainties. Exposure of the landscape to cosmic rays prior to glaciation may yield boulder exposure ages that are older than deglaciation, and partial shielding from cosmic rays subsequent to deglaciation, for example as a result of moraine degradation or boulder erosion, yield exposure ages that are younger than deglaciation. To address this issue we used a meta-analysis approach, compiling a dataset of 1848 ^{10}Be exposure ages from glacial boulders from the Tibetan Plateau, from areas covered by the Laurentide and European ice sheets during the global LGM, and from present-day glaciers and their late Holocene moraines (recent glaciers) worldwide. The recent glacier boulder dataset and the palaeo-ice sheet boulder dataset, the latter representing maximum likelihood situations, have a modest amount of prior exposure, indicating that prior exposure is of limited importance. The exposure age pattern of the extensive Tibetan Plateau boulder dataset was compared to the output of a simple boulder exhumation model, with remarkable conformity indicating that post-glacial shielding can explain a large part of the exposure age distribution. In summary, the study implies that post-glacial shielding is far more important than prior exposure, and we conclude with the recommendation that, in the absence of other evidence, boulder exposure ages should be viewed as minimum limiting deglaciation ages.

Paper V

Heyman J, Stroeven AP, Caffee MW, Hättestrand C, Harbor J, Li YK, Alexanderson H, Zhou LP, Hubbard A, manuscript. Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: the case of a missing LGM expansion.

In this paper we use 67 new ^{10}Be measurements from boulders, surface pebbles, and depth profiles from Bayan Har Shan to constrain the timing of former glaciations. We measured ^{10}Be exposure ages of 39 glacial boulders, 13 surface pebble samples, and 15 samples from four sediment sections. The apparent exposure ages range from 3.1 ka to 128.7 ka with wide age disparity within morphostratigraphic groups as well as within individual sites. Based on the study presented in Paper IV, the wide age spread is explained by post-glacial shielding with the maximum exposure ages yielding minimum limiting ages for the glaciations. This interpretation conforms to the fact that moraine ridges are subtle (presumably due to moraine degradation) and to the cosmogenic nuclide data of three sediment sections indicating limited prior exposure. Classifying the samples into four morphostratigraphic groups we used the maximum boulder exposure age of each group as a minimum limiting age of glaciation and presented a four-stage time slice glacial reconstruction for Bayan Har Shan. Including the uncertainty of ^{10}Be production rates in the area, the youngest glacial stage, with glaciers less than 10 km long, has a minimum age of 40-65 ka. Two more extensive glaciations, in size similar to half present-day Barnes ice cap and half present-day Vatnajökull, have minimum ages of 60-100 ka and 95-165 ka. The maximum glaciation, with a Bayan Har ice field slightly larger than the two present-day Patagonian ice fields together, are temporally constrained by the younger glaciations with a minimum age of 95-165 ka. All four groups, including samples from moraines formed by glaciers only a few kilometers long, pre-date the global LGM at c. 20 ka. The missing LGM expansion in central Bayan Har Shan is corroborated by a high resolution numerical glacier model which, when glaciers are expanded to moraines dated to the global LGM in Anyemaqen (Fig. 2), produces no glaciers in central Bayan Har Shan.

Palaeoclimate implications derived by 3D glacier modelling

The present-day climate of the Tibetan Plateau is characterized by large seasonal temperature variation and precipitation brought by two climate systems: the south Asian monsoon and the mid-latitude westerlies (Benn and Owen, 1998; Böhner, 2006). For most of the Tibetan Plateau the major part of the precipitation is brought by the summer monsoon and the winters are dry. The summer monsoon precipitation is released along the southern and eastern margin with decreasing precipitation towards the north and west. Due to the seasonality of the precipitation, many glaciers in the southern and eastern regions have both maximum accumulation and ablation during the summer season. In the far northwestern areas winter precipitation brought by the mid-latitude westerlies exceed summer precipitation.

Although a large number of studies have focused on the timing and control of glacier development on the Tibetan Plateau (e.g. Benn and Owen, 1998; Schäfer et al., 2002; Owen et al., 2005, 2008) and a growing body of research has presented palaeoclimate proxy data (e.g. Thompson et al., 1997, 2006; Mischke et al., 2008), few studies report quantitative palaeoclimate data. Shi (2002) reported an LGM cooling of 6-9 K for the Tibetan Plateau based on proxy data and Mark et al. (2005) reported a mean LGM temperature depression of 7.5 K for Himalaya based on snowline estimates. Climate simulation studies have reported LGM temperature depressions of 2-13 K (Liu et al., 2002), 6 K (Böhner and Lehmkuhl, 2005), and 1.8-6.4 K (Ju et al., 2007). Reduced precipitation during the global LGM is indicated by proxy data (Herzschuh, 2006) and climate simulations with strongest effects in the areas influenced by the summer monsoon (Liu et al., 2002; Böhner and Lehmkuhl, 2005; Ju et al., 2007).

An outcome of the Bayan Har Shan project, as well as many other cosmogenic exposure age studies from the Tibetan Plateau (cf. Paper IV), is that most glaciers have remained restricted for at least the last 20-50 ka. Of all boulders from the Tibetan Plateau dated by ^{10}Be measurements a large majority are located close outside present-day glaciers or the headwall of the parent glacier (Fig. 4). Out of 162 sites (mostly moraine ridges) with maximum boulder ^{10}Be exposure ages predating 20 ka (CRONUS Lm scaling; Paper IV), as many as 97 sites are located less than 10 km from a present-day ice margin or the inferred headwall of the parent glacier, indicating that even pre-LGM glaciers have been limited in extent. This circumstance presents an opportunity to constrain the palaeoclimate by numerical modelling based on climate data. By using a glacier

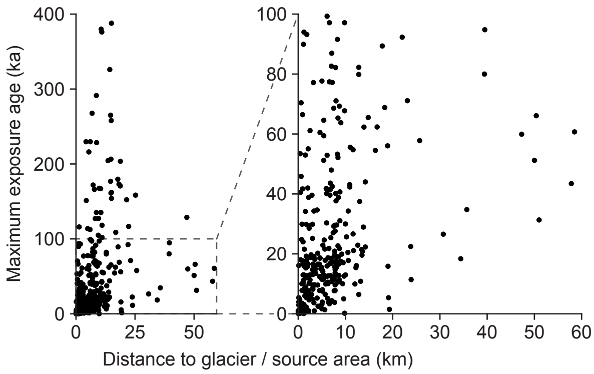

Figure 4. Maximum boulder ^{10}Be apparent exposure age (cf. Paper IV) for all dated sites (mostly moraine ridges; n = 343) on the Tibetan Plateau and the distance to their parent glacier or parent glacier headwall. A majority of the boulders, also of those pre-dating the global LGM at c. 20 ka, are located within 10 km of present-day glaciers or their parent glacier headwalls. See Figure 5 for location of dated boulders.

model forced by climate data and topography, the climate perturbations expanding glaciers over sites with chronological constraints can be derived.

Here I present data from a set of glacier model runs across the Tibetan Plateau. I have used a high resolution higher order numerical model of glacier ice flow forced by a positive degree day (Braithwaite, 2008) mass balance approach. For detailed information regarding the ice flow model, see Hubbard et al. (1998) and Hubbard (1999, 2000). The model domain is 200 by 200 grids in a cartesian latitude-longitude projection with a resolution of 15 seconds (c. 380 by 460 m for the Tibetan Plateau). The model topography is based on the SRTM elevation data (Jarvis et al., 2008) and the input climate data is derived from the WorldClim data with present-day mean monthly temperature and precipitation (Hijmans et al., 2005). For each domain the same key parameters for mass balance and ice flow calculations are used (Table 1). Glacier flow is modelled as internal deformation only and thus, in the model no basal sliding occurs.

The model was used for 9 domains from where cosmogenic exposure ages have been reported (Fig. 5) and run forward for 5000 years with static climate perturbations. Apart from the Bayan Har domain, present-day glaciers occur in all domains against which the model can be tested. For each domain the following five experiments (three for Bayan Har lacking present-day glaciers) were performed;

(1) Stepwise (0.1 K) temperature perturbations to attain a best fit to present-day glaciers.
(2) Stepwise (0.1 K) temperature perturbations to expand glaciers over sites with boulder ^{10}Be exposure ages.
(3) Stepwise (0.1 K) temperature perturbations with a 50% reduction of the present-day precipitation to expand glaciers over sites with boulder ^{10}Be exposure ages.
(4) Stepwise (10%) precipitation perturbations to expand glaciers over sites with boulder ^{10}Be exposure ages.
(5) Stepwise (10%) precipitation perturbations with temperature perturbations derived from experiment 1 to expand glaciers over sites with boulder ^{10}Be exposure ages.

The output of experiment 1 indicates the accuracy of the input data and the modelling approach. Experiments 2-5 yield climate constraints for past glacial extents and reveal the sensitivity to temperature and precipitation perturbations.

The result of the modelling is presented in Figures 6 and 7. The best fit to present-day glaciers (experiment 1) is achieved with temperature perturbations between +0.5 and -2.0 K, with an average of -0.7 K. To expand glaciers over the dated boulders, temperature depressions of 1.9-5.2 K (experiments 2-3) or precipitation perturbations of 190-1800% (experiments 4-5; multiplication by 1.9 to 18.0) are required. The average temperature shift between experiments 1 and 2 (present-day glaciers and glaciers covering dated boulders) for all domains is -2.2 K, and the maximum shift is -3.0 K. The average temperature shift between experiments 1 and 3 (present-day glaciers and glaciers covering dated boulders; 50% precipitation) is -3.0 K and the maximum shift is -3.7 K. The average precipitation perturbation expanding glaciers over the dated boulders is 780% for experiment 4 (temperature shift = 0 K) and 440% for experiment 5 (temperature shift based on best fit to present-day glaciers).

The ability of the model to reproduce present-day glaciers with temperature shifts of ±2 K lends credibility to the climate data and glacier model approach. However, several factors may yield erroneous results. The present-day climate data for the Tibetan Plateau, particularly for the central and western part, is based on interpolation of data from few weather stations (Hijmans et al., 2005). The positive degree day approach may miss important factors for the mass balance (cf. Rupper and Roe, 2008) and the static climate perturbations may misrepresent past climate (cf. Böhner and Lehmkuhl, 2005). Because the model employs the SRTM representation of the landscape as basal topography, the elevation of present-day glaciers is slightly overestimated in the model. While absence of basal sliding is supported by present-day glaciers on the Tibetan Plateau frozen to the bed (Thompson et al., 2006), glacially eroded U-shaped valleys indicate that basal sliding did occur under palaeo-glaciers. The absence of basal sliding implies initial glacier growth inertia with stronger climate perturbations needed for initial growth of glaciers. For some of the domains, in particular the low-relief Bayan Har (BH) and Tanggula (TGL), the inertia of glacier expansion leads to increased glacier thickness and increased accumulation which eventually result in more extensive glaciers than a model with basal sliding and more rapid ice flow would. However, in tests with the Bayan Har and the Tanggula domains including basal sliding and higher ice flow parameters counteracting the inertia-ice thickness-expansion effect, the sites with dated boulders became ice-covered with more modest climate perturbations because of the short distance to the glacier source areas. In summary, the simplicity of the model setup and the uncertainty of the input data imply that the model output should be interpreted with care. Considering the ice flow lacking basal sliding, the climate shifts expanding glaciers over dated boulders (experiments 2-5) should likely rather be interpreted as maximum perturbations relative to present-day climate.

The model temperature perturbations for glacier growth are relatively low, also with reduced precipitation (experiments 2 and 3), and indicate sensitivity to temperature shifts. The precipitation perturbations for glacier growth are relatively high and vary significantly with relatively minor temperature perturbations (experiments 4 and 5), indicating more modest importance of precipitation shifts. These results are in agreement with previous studies suggesting that temperature variation is the main driver of glacier change (Oerlemans, 2005; Rupper et al., 2009).

The temperature constraints on glacier growth derived from the glacier modelling indicate more modest cooling than previously published temperature reconstructions for the LGM (e.g. Shi, 2002; Mark et al., 2005; Braconnot et al., 2007; Ju et al., 2007). The glacial geology of the Tibetan Plateau, including

Table 1
Key model parameters for the mass balance and ice flow model.

Parameter	Value
Domain size	200 x 200 grids
Grid resolution	15 seconds
Degree day factor	4.1 mm d^{-1} K^{-1}
Lapse rate	-0.006 K m^{-1}
Flow parameter	3.03 x 10^{-17} s^{-1} kPa^{-3}
Model time	5000 years
Time step	0.05-0.5 years

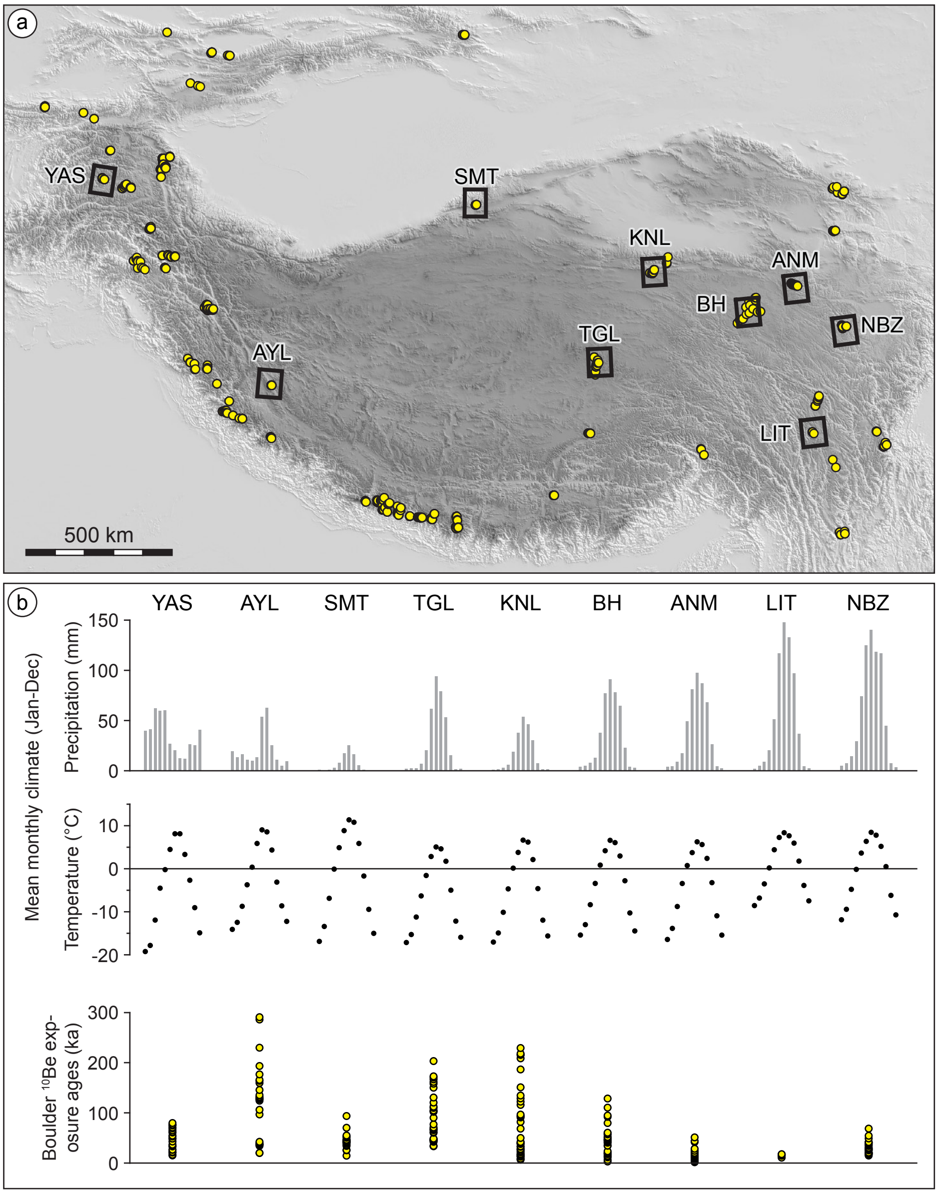

Figure 5. (a) Map of the Tibetan Plateau with locations of all boulders dated by ^{10}Be exposure dating (Paper IV) and the nine domains where the glacier model (Figs. 6 and 7) has been applied. (b) Average climate data (Hijmans et al., 2005) for each domain and the exposure ages within the domains (Paper IV). Original publications for the exposure age data: YAS (Zech et al., 2005; Abramowski et al., 2006); AYL (Chevalier et al., 2005); SMT (Mériaux et al., 2004); TGL (Schäfer et al., 2002; Owen et al., 2005; Colgan et al., 2006); KNL (Owen et al., 2006b); BH (Paper V); ANM (Owen et al., 2003); LIT (Schäfer et al., 2002); NBZ (Owen et al., 2003). See Figure 6 for proper names of the domains.

an extensive exposure age dataset (Figs. 4 and 5), indicates that during the global LGM glaciers were generally not much larger than today. The glacier modelling experiments, with consistent temperature depressions for nine domains across the plateau (Figs. 6 and 7), indicate that the Tibetan Plateau LGM climate (and older) was therefore not much colder than today or exceedingly dry (cf. Herzschuh, 2006).

Summary and outlook

Using multiple methods, the palaeoglaciology of the northeastern Tibetan Plateau has been examined. The entire glacial record of central Bayan Har Shan appears to be significantly older than the global LGM, implying that when extensive ice sheets developed over North America and Europe the Bayan Har Shan looked similar to today. This is in agreement with results from other regions of the Tibetan Plateau where global LGM glaciers were not much larger than today (Fig. 4). The Tibetan Plateau exposure age dataset and the outcome of the glacier modelling experiments present an interesting contrast regarding the Tibetan Plateau palaeoglaciology. While modest cooling seems to be enough to produce significant glacier expansion, the geological data shows that glaciers have remained surprisingly restricted over long time spans.

The geological record of Quaternary glaciations on the Tibetan Plateau, including glacial landforms and sediments as well as chronological datasets, is spatially and temporally extensive. The width of the record entails difficulties for comprehending the full picture of former glaciations, but it enables studies of a wide field of former environments. In

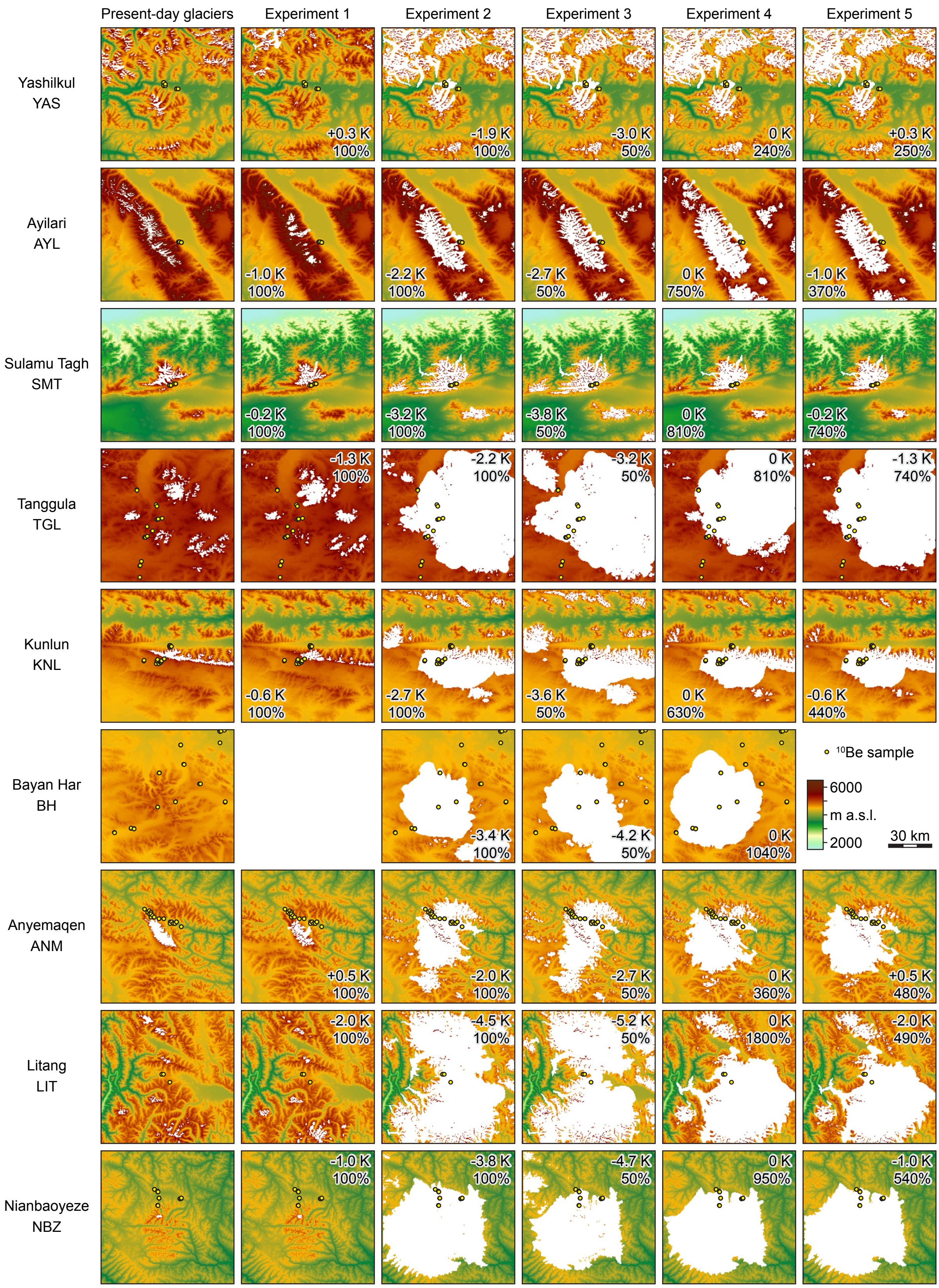

Figure 6. Present-day and modelled glaciers (experiment 1-5) for the nine domains. Temperature (K) and precipitation (%) perturbations are given for each experiment. The Bayan Har domain lacks present-day glaciers and experiments 1 and 5 were therefore not performed for this domain. See Figure 5 for location of the domains.

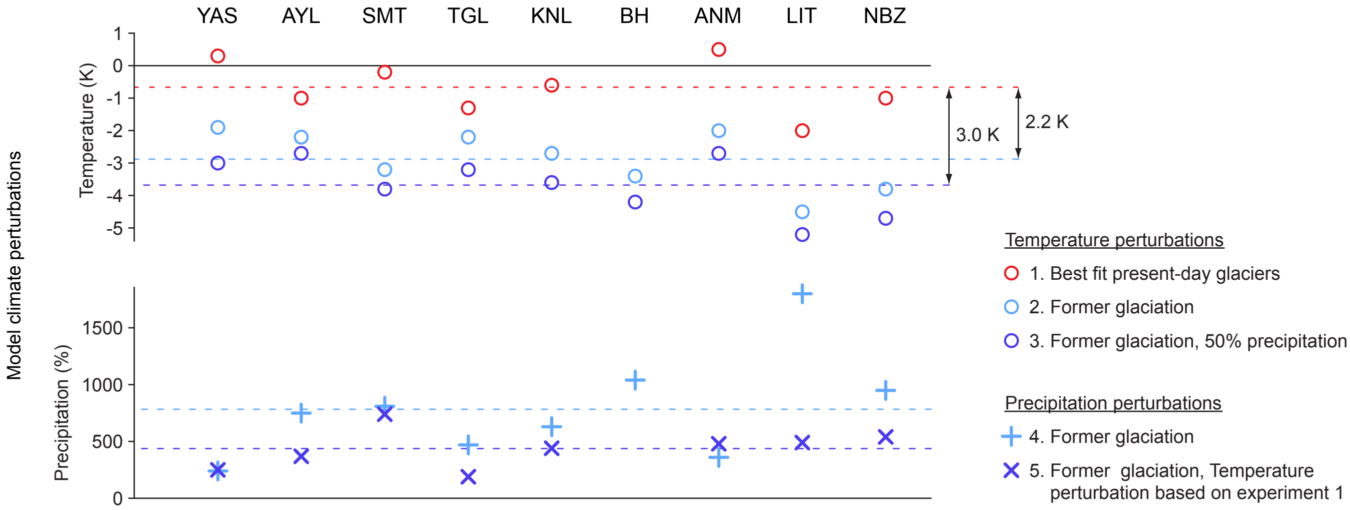

Figure 7. Climate perturbations from the five experiments (1-5) performed on the nine domains. Dashed lines mark the average value of each experiment. See Figure 5 for locations of the domains, and Figure 6 for the modelled glaciers and proper domain names.

comparison to the northern hemisphere palaeo-ice sheets, which during their LGM expansions erased most traces of earlier glaciations (cf. Kleman et al., 1997, 2006), the limited extent of LGM glaciation on the Tibetan Plateau yield an opportunity of insight into earlier glaciations. Former glaciations on the Tibetan Plateau remain elusive with a large number of issues still to be resolved. The glacial geomorphology is for large areas still not recorded (cf. Paper I). With the accessibility of satellite data, detailed geomorphological records can be produced for extensive areas. The glacial chronological record for the Tibetan Plateau is extensive, but large uncertainties hamper the possibility to pinpoint the timing of former glaciations (cf. Owen et al., 2008). To narrow the uncertainty of the cosmogenic exposure age dataset (Owen et al., 2008; Paper IV), production rate calibration for sites on the Tibetan Plateau would be highly advantageous. Further, comparison of data from multiple dating techniques may help limiting the uncertainties related to sample geological history. Finally, the glacial geological record can be used to constrain palaeoclimate reconstructions. Togehter with new high resolution climate datasets (e.g. Hijmans et al., 2005; Böhner, 2006), the glacial geological record provides a key boundary condition for palaeoclimate modelling studies which should ultimately be coupled with temporally continuous palaeoclimate proxy records (e.g. Thompson et al., 1997; Herzschuh, 2006).

Conclusions

The main conclusions of this thesis are;

- Glacial landforms and sediments are concentrated to elevated mountain regions of the northeastern Tibetan Plateau, indicating former glaciation controlled by altitude. A wide array of large-scale glacial landforms, including glacially eroded valleys, moraines, and glacial lineations, testify of multiple glaciations with alpine-style glaciers. Glacial sediments, including erratic boulders, occur some distance beyond the large-scale glacial landforms and indicate a maximum glaciation more extensive than any present-day ice mass apart from the Antarctic and Greenland ice sheets. An absence of glacial imprint indicates limited glacial erosion under the peripheral regions of the maximum palaeo-glacier. Extensive lower-lying plateau areas lack all traces of glaciation and may never have been glaciated. No evidence has been found in support of any past ice sheet, neither a plateau-wide ice sheet nor a regional ice sheet.

- Wide U-shaped glacial valleys in the mountain areas indicate glacial erosion surpassing fluvial erosion integrated over glacial time spans. Along the plateau margin fluvial incision is consuming glacial landforms with knickpoint retreat into a low relief relict upland surface, indicating a reversed relationship with higher rates of fluvial erosion.

- Meta-analysis of worldwide glacial boulder ^{10}Be exposure ages, including cosmogenic inheritance quantification for northern Hemisphere palaeo-ice sheet boulders, and boulder exhumation simulation for the Tibetan Plateau boulder dataset indicate that post-glacial shielding is generally more important than prior exposure. Because of the direct relationship between the potential for post-glacial shielding and the deglaciation age, the likelihood of post-glacial shielding increases with deglaciation age. In the absence of other evidence, cosmogenic boulder exposure ages should be interpreted as minimum ages.

- Exposure ages of boulders, surface pebbles, and sediment sections from central Bayan Har Shan indicate that all dated landforms, including moraines formed by glaciers just a few kilometers long, are significantly older than the global LGM at c. 20 ka. Three morphostratigraphic units of marginal moraines formed by valley glaciers in central Bayan Har Shan have minimum deglaciation ages in the time spans (^{10}Be production rate dependent) 40-65 ka, 60-100 ka, and 95-165 ka. The age of the most extensive glaciation is constrained by the three more restricted and morphostratigraphically younger glacial stages, with a minimum age of 95-165 ka.

- The distribution of boulders pre-dating the global LGM close outside present-day glaciers indicate that the Tibetan Plateau glaciers were generally not much larger than today during the global LGM. A high resolution glacier model forced by climate perturbations and used for nine locations across the Tibetan Plateau indicates that the climate shifts needed to expand glaciers over boulders pre-dating the global LGM are not very large. To produce more extensive glaciers than were present during the LGM it is enough to lower the temperature by 2-4 K.

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