国际第四纪联合会第四纪冰川研讨会:

从高亚洲到全球山地冰川的时代与性质

INQUA workshop on Timing and nature of mountain glaciation, from High Asia to the World

Exploring aspects of climate change, glaciation, and landscape evolution

14-22 September, 2006

Xining and the Tibetan Plateau, China

Organized by

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Hosted by

Institute for Tibetan Plateau Research and the Qinghai Institute for Salt Lakes (Chinese Academy of Sciences)

Sponsored by

INQUA Working Group on Timing and Nature of Mountain Glacier Advances

INQUA Working Group on Quaternary Glaciations and Chronology in Monsoonal Asia

US National Science Foundation

National Science Foundation of China

Workshop Rationale

Mountain glaciers and their deposits represent important archives of past climatic information. Mountain glaciers are highly sensitive to fluctuations in temperature and precipitation and, thus, the record of glacier growth and retreat constrains those climatic variables. Data from widespread locales indicate that the timing of mountain glacier maxima and subsidiary advances varied widely. That variability reflects important paleoclimatic processes. As additional chronologic data are generated, particularly with rapidly increasing usage of cosmogenic and luminescence techniques and improved resolution of AMS radiocarbon dating, it is essential to design a conceptual framework for evaluating the temporal and spatial distribution of mountain glacier fluctuations and to identify areas where critical data are insufficient. Similarly, variability in the nature and timing of mountain glacier expansions modulates their influences on landscape evolution. The spatial and temporal relationships of erosion and uplift in orogenic belts is a topic of considerable current debate.

Because mountain glaciers are influenced by regional, not global, climatic processes, mountain glacier fluctuations can be expected to vary strongly across the globe. Indeed, numerous studies have demonstrated just such variability. For example, many mountain glacier systems reached their maximum Late Pleistocene positions (i.e., their greatest ice extent in the time period of 125,000 to 10,000 yr BP) around the time of the Northern Hemisphere ice-sheet maximum, ca. 21,000 yr BP (e.g., Ehlers and Gibbard, 2004a, 2004b, 2004c). Conversely, other mountain glacier systems appear to have reached their maximum Late Pleistocene positions before the ice-sheet maximum, in, for example, the tropical Andes (Smith et al., 2005), Tibet, (Owen et al., 2003, 2005), Alaska, USA (Briner et al., 2005), Washington, USA (Thackray, 2001), New Zealand (Shulmeister et al., in review), and Mediterranean Europe (Hughes et al., 2006). Other mountain glacier systems reached their maximum ice extent or near maximum extent after the 21,000 yr BP ice-sheet maximum, at, for example, Nanga Parbat, Pakistan (Phillips et al., 2000), and in parts of the northwestern United States (e.g., Licciardi et al., 2001; Thackray et al., 2004). Variations in precipitation delivery to glacier systems often have been cited as important influences on these "asynchronous" fluctuations, and for some ice-sheet synchronous advances as well (e.g., Shulmeister et al., 2005). It is clear from many examples that considerable variability exists in the timing of mountain glacier fluctuations around the globe, and that a variety of paleoclimatic processes are responsible for the variability. Thus, regional patterns of mountain glacier chronologies represent a relatively untapped opportunity to enhance understanding of paleoclimatic processes.

This workshop is endorsed and funded by the International Quaternary Union, the US National Science Foundation, the National Science Foundation of China, and other organizations. The major goals of this working group are to compile existing data on mountain glacier fluctuations and to propose new research to produce rigorous tests of hypotheses regarding dominant influences on those fluctuations.

To date, there has been no thorough synthesis of the variability in timing of Late Pleistocene mountain glacier fluctuations, although two recent compilation efforts have aided this project. A recent effort edited by Ehlers and Gibbard (2004a, 2004b, 2004c) compiled a wealth of information on glacier fluctuations. That effort emphasized glacier fluctuations around the last ice-sheet maximum (ca. 21,000 yr BP), and did not incorporate a synthesis of fluctuations between regions. A recent project headed by Mark and Harrison (Harrison, 2005, and Mark et al., 2005) focused specifically on tropical glaciers around the Northern Hemisphere ice-sheet maximum. Our effort differs, in that we focus on the entire glacial cycle, ca. 115,000 to 10,000 ka. Furthermore, this effort addresses asynchrony of glacier advances between regions as well as synchrony. Our efforts, in fact, meld with and build upon the results of the aforementioned compilation efforts: Gibbard is a collaborator on the INQUA project, and we anticipate archiving the data from this proposed compilation effort in the SNOWLINE database begun through the Mark and Harrison effort (described in Mark et al, 2005).

We have several goals for this workshop and following activities. Firstly, we aim to produce a compilation including an in-depth review and discussion of the existing knowledge. Secondly, a specific goal of the workshop is to formulate a series of testable hypotheses regarding mountain glacier-climate interactions and a plan for focused research projects. Thirdly, the workshop format and its associated investigation of nearby field sites will be ideal for building collaborative relationships between researchers from several countries. There have been no recent meetings or workshops on this topic so we hope this stimulate reviewed interest in mountain glaciation. Certainly mountain glaciers are a topic of substantial interest at major scientific conferences (e.g., Geological Society of America, International Quaternary Union), but this workshop has specific research goals, not a simple reporting of scientific results.

Finally, we aim to discuss issues of glaciers and landscape evolution. Significant debate exists over the importance of mountain glaciers versus other processes, such as fluvial erosion and mass movement, in shaping mountain landscapes. While data from the Himalaya (Brozovic et al., 1997) and the Andes (Montgomery et al., 2001), for example, suggest that glacial erosion limits topography, data from the Cascades (Kelsey et al., 1994, Schmidt and Montgomery, 1995) suggest topography is limited by rock strength or uplift rates respectively. Furthermore, in a more empirical study, Spotila et al. (2004) compared denudation rates to tectonic influx in the Chugach-St. Elias Mountains of southeast Alaska. Long-term denudation rates were found to be an order of magnitude less than the short-term values set forth by Hallet et al. (1996) who examined sediment yields from glaciated catchments to determine glacial erosion rates. Currently, the questions of what limits topography and of the role of glaciers in orographic belts, both spatially and temporally, and variations of denudation rates over time remain unanswered. A stratigraphic and temporal framework is essential to answer these questions and to help quantify and assess the role and importance of mountain glaciers in landscape evolution. The results promised by the workshop in Tibet, therefore, have important implications for helping to quantify and understand the dynamics of mountain landscapes and for addressing questions such as the role of glaciers in limiting topography. Furthermore, the Himalaya-Tibet orogen is one of the best natural laboratories for examining the links between glaciation and tectonics because it has some of the highest rates of tectonic deformation, large climatic gradients and glacial systems that vary from high activity maritime to continental cold-based glaciers. The Himalayan-Tibetan region, therefore, has the potential to help answer the complex problems posed by the links between these processed and systems.

The workshop also aims to help stimulate debate and new research initiatives into the links between glacial geology, climate, tectonics and landscape evolution and the dynamics of mountain processes.

Specific objectives of the Workshop:

1) **Assess global variability in the timing of Late Pleistocene mountain glacier fluctuations**
2) **Evaluate the role of glaciation in denudation and landscape evolution**
2) **Initiate new research to fill critical data gaps**
3) **Build international collaborative relationships.**

Organization of meeting

The three-day assembly in Xining will comprise a series of working sessions addressing the following topics:

1) Results of mountain glacier fluctuation data compilations for each of several regions.
3) Formation and testing of hypotheses regarding climatic mechanisms (e.g., monsoonal variability, westerly flow variability, orbitally induced temperature variations) responsible for variability in mountain glacier chronologies.
3) Examination of the links between climate, glaciation, erosion and landscape evolution.
4) Planning of focused projects to test hypotheses regarding climate-glacier-erosion-landscape evolution relationships.

Experts have been identified to compile and summarize key research findings on these topics. Each will present a keynote lecture lasting for 20 minutes and followed by 10 minutes of discussion. An hour-long discussion session will follow each set of topics. This will be moderated by an expert on the topic. The moderator will provide a framework for the discussion and will help mediate the debate. In addition to the moderator, an expert has been invited to compile a written record of the session.

Oral poster presentations will be held at the end of Days 1 and 2. These will comprise a 10 minute-long formal presentation at the participant's poster. The posters will highlight case studies and important new developments pertinent to mountain glaciation and landscape evolution. It is hoped that these sessions will stimulate informal debate.

On the last day of the meeting, the participants will divide into specialty groups to compile a document summarizing the discussion, results and future strategies for each topic. Each group will be lead by the moderator of the specific topic. The participants will reconvene at the end of the three-day meeting in Xining to hear a summary of the compilation of each the specialty groups. These summaries will help form the basis of two research papers that will be published as part of compilation volumes in *Journal of Quaternary Science* and *Geomorphology*. A workshop report will also be prepared for *EOS* and *Quaternary Perspectives*

The visit to field research areas on the Tibetan Plateau will cap the workshop. The principal purposes of this field excursion will be to investigate the nature of Tibetan Plateau glacial records, to discuss issues of snowline calculation and dating control for glacial sequences, to discuss influences of monsoonal variation on glacier fluctuations, and to examine the nature of landscape evolution of the plateau. These issues and others will lie at the heart of subsequent proposals for focused research projects. It is also hoped that the field excursion will provide ample opportunity for informal discussions of the topics presented in Xining.

Results of the workshop and follow-up activities will be disseminated by several means. First, we anticipate edited journal volumes, in *Journal of Quaternary Science* and *Geomorphology,* which will include papers on each regional compilation, on proposed paleoclimatic mechanisms, and on plans for research. Second, the compiled data themselves will be archived as a web database. The structure of this database is yet to be determined, but the criteria of the database are 1) detailed geographic coordinates, snowline elevations, timing of major glacial advances; 2) inclusion of rating of data quality; 3) compatibility with widely available Geographic Information System software; 4) web accessibility. We are investigating the feasibility of integrating the compilation database with the SNOWLINE database (Mark et al., 2005). Alternatively, the compilation database may be archived as a stand-alone database. Third, the results of the workshop and subsequent research will form the basis of one or more sessions at the XVII INQUA Congress in Cairns, Australia, in August, 2007, and will be presented at other professional meetings as well.

The overall results of this workshop and subsequent research will be two-fold. First, the process will yield a much-improved understanding of mountain glacier history, glacier-climate linkages, and influences of glaciation and related processes on landscape evolution.. Second, the process will enhance international collaboration, between scientists from several countries. The specific involvement of young professionals and students in the workshop and other group research activities will ensure that those scientists develop collaborative ties at an early stage in their careers.

Organizing committee

The workshop organizing committee includes:

- **Glenn Thackray**, chair, Idaho State University
- **Lewis Owen**, University of Cincinnati
- **Chaolu Yi** and **HuaLiang Chen**, Chinese Academy of Sciences, Institute of Tibetan Plateau Research
- **Zhou Shangzhe**, College of Geographical Science, South China Normal University, Guangzhou, China

Participants

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Jason Briner	University at Buffalo
Marc Caffee	Purdue University
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PROGRAM
In Xining

Day	Session	Convenor	Speaker	Region/Topic	Time
Day 0-evening (8/13/06)	Welcoming reception and ice breaker	Thackray, Chaolu Yi			7-9 PM
Day 1-morning (8/14/06)	Load presentations for Day 1				7:30-8 AM
	1. Opening remarks	Thackray	Thackray Ma Haizhou Liu Xiaohan Wang Jian		8-8:30
	2. Central Asia	Owen	Shi Chaolu Yi Shangze Zhou Lehmkuhl Koppes	Tibet Monsoon Asia Mongolia W. Cn Asia	8:30-10:30
	Coffee Break	Group Photograph			10:30-11:00
	3. Sub-tropics	Sharma	Owen Yang Xu	Himalaya Gurla Mandata SE Tibet	11-12
	Lunch				12:00-1:30
Day 1-afternoon	4. Tropics	Chaolu Yi	Smith Mark	S. America Africa	1:30-2:30
	Discussion – Tropical chronologies	Moderator: Owen Recorder: Yi			2:30-3:30
	Coffee Break				3:30-4:00
	Poster Presentations I	Chaolu Yi			4:00-5:00
	Load presentations for Days 2 and 3				5:00-5:30
	Poster Presentation II	Thackray			5:30-6:30
	Dinner				7:00-8:00

Day 2-morning (8/15/06)	5. Southern Mid-latitudes	Thackray	Rother Fink Kaplan	New Zealand Australia S America	8:00-9:30
	Coffee Break	Visit to exhibition of Ins. of Saline Lake			9:30-10:00
	6. Northern Mid-latitudes (continued)	Kaplan	Hughes Thackray Clark Licciardi Leonard	Mediterranean Northwest US Southwest US Yellowstone ice cap Southern Rocky Mountains	10:00-12:00
	Coffee Break				12:00-12:15
Day 2-afternoon	Discussion – Mid-latitudes chronologies	Moderator: Thackray Recorder: Smith			12:15-1:00
	Lunch to go	Owen & Ma Haizhou		La Ji field trip	1:00-7:00
	Dinner				7:30

Day 3-morning (8/16/06)	7. High Latitudes	Kaufman	Briner Gualtieri Licciardi	Alaska Russia Iceland	8:00-9:30
	Discussion – High latitudes chronologies	Moderator: Gualtieri Recorder: Kaufman			9:30-10:30
	Coffee Break				10:30-11:00
	8. Climate, Glaciers, denudation and Landscape Evolution I	Owen	Stroeven Schoenbohm	Huang He ice sheet Plateau uplift	11:00-12:00
	Lunch				12:00-1:00
	8. Climate, Glaciers, denudation and Landscape Evolution II	Caffee	Anderson Koppes	Mountain glacier erosion Glacier erosion rates	1:00-2:00
	Coffee Break				2:00-2:30
	Climate, Glaciers, denudation and Landscape Evolution	Anderson	Montgomery Marston Caffee ZhangXinBao	Outburst floods and incision Fluvial incision in Himalaya Old landscapes Periglaciation	2:30-4:30
	Discussion: Landscape evolution	Moderator: Marston Recorder: Schoenbohm			4:30-5:30
	NSF projects		Ellis		5:30-6:00
	Dinner				7:00

Evening of Sept 19	**Document preparation Break up into small groups**	**Moderators and recorders lead each group**			
Evening of Sept 20	**Reconvene and present highlights from each group**				

Abstracts

Toward models of glacial landscape evolution

Robert S. Anderson, Dylan Ward, and Mark A. Kessler
Institute for Arctic and Alpine Research (INSTAAR) and Department of Geological Sciences
University of Colorado

Glaciers are efficient engines of erosion. They can both incite large-scale changes in the topographic relief of mountains, and can greatly impact the fluvial system downstream by delivering large quantities of sediment. Before we can understand the full array of landscape responses to glacial occupation, we must understand the glaciers themselves. I will illustrate the toolkit we have assembled to address these problems, drawing upon examples from alpine settings in the Sierras, the Colorado Rockies, and in Alaska.

Both field efforts and theoretical work suggest that glacial erosion will scale as ice discharge, as long as the base of the glacier is temperate. Analytic models of glacial ice discharge patterns show maximum ice discharge at the ELA for any specified mass balance pattern. One can extend this analysis to both more topologically complicated glacial valleys, and to realistically variable climate, leading to predictions of long-term patterns of glacial valley erosion.

To extend such analytic models, we use a 2D numerical glacial model to explore the expected pattern of glacial occupation of a realistic alpine topography as a precursor to modeling the evolution of the glacial headwaters. Only when we incorporate realistic orographic precipitation patterns can we reproduce the details of the Sierran glacial footprint, matching LGM terminal moraines on both west and east sides of this large-scale mountain range. We note that during advance and retreat of glaciers in these valleys, there are times during which many tributary valleys are ice free, and side-glacial lakes would have formed that could potentially outburst. The glacial system therefore serves as a catastrophe machine in that it generates the potential for unleashing water discharges into the fluvial system that far exceed meterologically-derived floods. I will briefly summarize our work on outburst floods in the Kennicott Glacier in Alaska.

We employ the ^{10}Be concentrations in glacial polish sites along a 90-km long valley draining the San Juan icecap in SW Colorado to document the timing of glacial recession from that valley. We show that during the last glacial cycle enough subglacial erosion was accomplished to remove the entire inventory of radionuclides. The ^{10}Be concentration in polish therefore documents the age of ice recession past that point. The pattern suggests slow retreat, and hence slow ELA rise, that spans 17ka to 9 ka, a pattern that appears to hold in the Colorado Front Range as well.

Feedbacks in the glacial erosion system can lead to high relief in not only the tips of alpine landscapes (summarized in the Teflon peaks hypothesis), but in the fjorded margins of continents subjected to repeated occupation by ice sheets. I will briefly address the components of these feedbacks, their implications, and the tools needed to quantify them in the real world.

Glaciation in Alaska from 5e to YD

Jason Briner and Darrell Kaufman
University at Buffalo and Northern Arizona University

Unlike other high-latitude areas of North America, much of Alaska was never glaciated. Despite the vastness of its unglaciated area, Alaska's mountainous terrain generated a mass of glacier ice on par with all the rest of the western United States combined. Most of the ice comprised the northwestern extension of the Cordilleran Icesheet, but dozens of ranges across the state also supported mountain glaciers. Because most of Alaska was not glaciated, these glaciers were free to expand onto adjacent lowlands where they left a rich record of multiple moraines, including a series of older moraines that escaped erosion by the relatively restricted glacial expansion during the last local glacial maximum (LLGM).

Detailed glacial-geologic mapping and accurate chronologies are available for only a few parts of Alaska. The available data show that the maximum advance during last glaciation (Wisconsin glaciation; 115-10 ka) is older than the useful range of radiocarbon dating. Drift of this 'penultimate' advance overlies or encloses the widespread Old Crow Tephra (OCT; ~140 ka). Cosmogenic exposure dating of moraine boulders in three separate mountain ranges across the state point to an age between 60 and 50 ka. In the Bristol Bay area of southwestern Alaska, luminescence ages provide maximum-limiting ages of about 70 ka for lava-baked sediment underlying penultimate drift. Nearby, however, luminescence ages and glacial-geologic evidence indicate that the penultimate drift was deposited when eustatic sea level was relatively high, perhaps during marine isotope stage (MIS) 5d. In the northeastern Alaska Range, in contrast, published studies document penultimate drift draped with OCT, suggesting the absence of an extensive middle/early Wisconsin advance. However, central-Alaskan loess stratigraphy shows MIS 4 loess activity on par with intense loess activity during the LLGM.

LLGM moraines are widespread in Alaska, and most mountain ranges host a four-fold sequence of relatively fresh, sharp-crested or hummocky moraines. The moraines have been mapped in many locations, but only a few have been dated. The most robust chronologies are from the Brooks Range (northern Alaska), the Alaska Range (central Alaska), and the Ahklun Mountains (southwestern Alaska). Radiocarbon ages from the Brooks Range, mainly from outwash sequences, constrain the LLGM from 27 to 13 ka (all ^{14}C ages reported in cal yr BP), with the maximum phase occurring ~26 ka; eight ^{10}Be ages from the northeastern Brooks Range support the age of the maximum advance. Radiocarbon ages from the Alaska Range constrain a sequence of four moraines to between 27 and 11 ka; the maximum advance culminated ~21 ka, consistent with four ^{10}Be ages of 19.7 ± 1.6 ka. In the Ahklun Mountains, the arrival to, and the retreat from, the LLGM position is tightly constrained by continuous lake sediments to between 24 and 22 ka. Following several minor fluctuations, late Wisconsin glaciation in Alaska concluded with a late-glacial advance represented by several small, single-crested vegetated moraines a few kilometers downvalley of extant ice in many alpine settings. Although securely dated at 12-11 ka in the Ahklun Mountains by nine cosmogenic exposure ages and basal lake sediments, a widespread advance during the Younger Dryas has yet to be revealed.

Although spatially sparse, the existing chronologies in Alaska show some spatial heterogeneity in timing of the LLGM. Glaciers retreated from their LLGM moraines by ~25 ka in northern Alaska, and by ~22 to ~20 ka in central and southern portions of the state. The maximum advance of the last glacial cycle in most places apparently occurred around the MIS 4/3 boundary, which may have resulted from more abundant moisture during this time compared to the LLGM.

Cosmogenic nuclides in arid environments: erosion rates and exposure histories of landforms

Marc W. Caffee
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Cosmic-ray-produced (cosmogenic) nuclides are routinely used to obtain exposure chronologies for a variety of landforms. Alternatively, cosmogenic nuclides can be used to quantify the rates of erosion on scales ranging from individual bedrock surfaces to regional basins. Samples taken from arid environments, where removal of surface material is reduced, offer near-unique scientific opportunities. Specifically, cosmogenic nuclides have now been measured in a number of arid to semi-arid environments: Antarctica; Atacama Desert, Chile; Namibia; Australia; and others. A common feature of these measurements is the relatively high concentration of cosmogenic nuclides in both bedrock and clasts. Minimum model exposure ages from these areas range from > 100 Kyr to > 1 Myr. Interpreted as limiting maximum erosion rates, the cosmogenic nuclide concentrations correspond to erosion rates ranging from ~2 m/Myr to < 0.2 m/Myr. In less arid environments, the inexorable effects of erosion, in a relatively short time (< 100 Kyr), dominate the inventory of cosmogenic nuclides, obscuring older events. Arid and semi-arid mountainous landscapes likewise afford outstanding opportunities to apply cosmogenic nuclides for both chronological and erosion rate studies. Cosmogenic nuclides have been extensively on the Tibetan Plateau, for example, where they have been used to reconstruct glacial chronologies, constrain slip-rates, and characterize different erosional regimes.

Wisconsin Glaciation in Oregon, California, and the Great Basin

Dr. Douglas Clark
Western Washington University

The mountains of the southwestern U.S preserve abundant late-Pleistocene moraine sequences. In some ranges, such as the Sierra Nevada, these deposits have been studied extensively and have abundant, if somewhat controversial, age constraints. In others, such as the South Cascades of Oregon and the desert ranges of the Great Basin, much less is know both about the extent and ages of the deposits. In general, the deposits appear to be dominated by moraines related to MIS 2 and MIS 6, with intervening advances generally not preserved. However, some locations in the Sierra Nevada indicate large advances during MIS 4 or 5. In addition, some locations preserve deposits that are either late MIS 3 or early MIS 2. Together, these deposits suggest that, at least locally, climatic conditions in the region favored large glacier advances even when global ice volumes were modest. Maximum advances throughout the maritime ranges indicate snowline lowering of roughly 900 m relative to modern, whereas inland ranges may have experienced somewhat reduced snowline depressions.

The Sierra Nevada has arguably the longest history of glacier investigation in the western U.S., dating back to the mid-1800's. Most of this work has focused on the steep eastern slope of the range, because the deposits are much better preserved than on the western slope. Recent numeric dating has attempted to place firm constraints on the ages of these deposits. Early $^{40/39}$Ar and P-wave velocity dating by Gillespie (1982) indicated major advances during MIS 2 and 6 (termed the Tioga and Tahoe I, respectively), but also an extensive intervening advance, presumably MIS 4 (Tahoe II). More recent CRN exposure dating at Bloody Canyon by Phillips et al. (1990) suggested there had been advances during MIS 5 (120-110 ka) and MIS 4 (70-60 ka), in addition to MIS 2 (24-20 ka). Reassessment of field relationships cast doubt on the MIS 5 advance, but leaves open the possibility of large advances between 70-50 ka and between 35-20 ka (Phillips et al., 1996; Bursik and Gillespie, 1993). Perhaps the most complete record of glacier advances in the region comes from playa lake sediments downstream of the moraines. In particular, Owens Lake sediments show strong peaks in outwash between 55-40 ka and again between ~28-17 ka (Benson et al., 1996). Recently, a core from Grass Lake Bog near Lake Tahoe records the initial onset of retreat of the Tioga glacier there, placing it at 20 ka, followed by total collapse of the Sierran glaciers by ~16 ka. Only minor late-glacial advances occurred between 14-13 ka. Modeling of the coupled glacial and lake records (Plummer, 2002) suggests that the LGM advances in the Sierra were largely controlled by a temperature depression of ~6 C, accompanied by precipitation increase of 25-50%.

Moraines of small valley glaciers in the San Bernardino Mountains of Southern California appear to record only the late LGM (~21-17 ka) and later events (Owen et al., 2003). However, interpretation of the climate forcing is similar to that in the Sierra.

Age and climate constraints on late-Pleistocene glaciation in the South Cascades and Great Basin ranges are thin at best. In central Oregon, moraines indicate that modest ice caps blanketed the larger Cascade volcanoes during MIS 2; these moraines are correlated to the LGM in Washington (22-18 ka; Scott, 1990), with glacial snowlines ~700-900 m lower than present. However, the best age constraints for moraines in the state come from the Wallowa Mountains in northeastern Oregon (Licciardi et al., 2004), with the LGM occurring 22-20 ka, followed by retreat after 17 ka. Pre-LGM moraines have not been dated in the region. Only the highest ranges in the Great Basin supported late-Pleistocene glaciers, dominantly cirque and small valley glaciers, often with extensive debris cover. Minimal age constraints suggest that the timing of advances broadly followed those in the Sierra Nevada and Cascades, but these are largely based on correlation rather than independent numeric ages. The strong effects of the Sierra/Cascade rainshadow and local effects of Pleistocene lakes (Lahontan and Bonneville) make the glacial records in these regions potentially more complex than in the maritime ranges.

Glacial Pellets at Terminal of the Glacier № 1, Upper Urumqi River, Tian Shan of NW China: Genesis, Provenance and Implication

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A special type of glacial pellets is found at terminal of glacier No.1, Tian Shan, Xinjiang, NW China. Their nature, genesis, material provenance and implications have been discussed in detailed in this study. The grain size analysis, geochemical and other data shows that the pellets' material is originated from atmospheric input. A two-stage model of pellets formation is proposed, and used to explain the particular concentric structure of pellets. Some evidences shows that Pellets' material can be preserved as stratigraphical records. Therefore, the glacial pellets may have significance for understanding of large-scale recycling of finer materials between desert and glacial systems by means of atmospheric transportation.

The environmental significance of the subglacial deposits at Qiangyong Glacier, Tibet

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Subglacially-formed debris-rich chemical deposits were found both on bedrock surface and in bedrock crevice on the edge of Qiangyong Glacier, one of the continental glaciers in Tibet. Grain size distribution, internal structures and chemical components of the chemical deposits were analyzed. It can be inferred that the temperature of some part of the ice-bedrock interface is closed to melt point and there exists pressure melting water under Qiangyong Glacier. Debris, especially those from continental aerosols, can release Ca^{++} in the water. At the lee-side of obstacles on glacier bed the CO_2 in the melt water might escape from the water and the melt water might refreeze due to the dramatically reduced pressure, making the enrichment and precipitation of $CaCO_3$. The existence of subglacial melting water and the process of regelation under Qiangyong Glacier indicates that sliding could contribute some proportion to the total movement of Qiangyong glacier and it belongs to multiplex cold-temperate glaciers.

The chronology of mountain glaciation in northeast Russia and Kamchatka

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The paleogeography of the Bering Strait region has had a significant effect on the extent, style and chronology of glaciation in northeast Russia throughout the last glacial cycle. In the past, parts of the East Siberian and Bering Seas were emergent, thus having a continental climatic effect on the region. Regional climate patterns are affected by the confluence of the Siberian High and the Aleutian Low. Winters are stormy, cold and dry with temperatures ranging from -5 to -30ºC and precipitation of 75-100 mm. Summers are mild with average temperatures of 5 to 15 ºC and precipitation of 100-150 mm. The northern and high alpine areas consist of continuous permafrost, while the lowlands and southern areas have discontinuous permafrost. Vegetation in northeast Russia and the alpine regions of Kamchatka is broadly defined as tundra, while Kamchatka's lowlands are characterized by *Betula-Larix* forest. The geology of northeastern Russia consists of accreted oceanic terranes of Proterozoic to early Cretaceous volcanics, metamorphosed sedimentary rocks and unconsolidated Quaternary sediments. Kamchatka's mountain ranges consist of relatively young (30-40 ka) volcanic calderas with basalt, andesite, dacite and rhyolite. Non-volcanic Quaternary sediments occur as isolated patches in alpine areas and lowlands of Kamchatka.

The principle factors controlling glaciation can be broken down into global and regional. Global factors include: low insolation, high sea levels, warm oceans, cold continents, and meridional heat transport. Regional factors include: moisture availability, migration of the Aleutian Low, sea ice cover of the Arctic Ocean, effects of continental ice sheets to the west, and changes in North Pacific sea surface temperatures.

Both numerical and relative dating techniques have been employed in northeast Russia and Kamchatka to evaluate the chronology of glaciation. Specifically in Kamchatka geomorphology, tephrachronology and radiocarbon dating have been used to constrain the age of the LGM to 21-10 ka. In northeast Russia a variety of dating techniques have been used, but the most solid chronology comes from ^{10}Be, ^{26}Al and ^{36}Cl exposure age dating of erratics on moraines. The age of the LGM in northeast Russia is 26-15 ka. Evidence for two older glaciations in these regions exists, however, their timing is not well constrained.

In general, the older glaciations were the most extensive in this region, with the general trend towards less extensive glaciations throughout the Pleistocene and into the Holocene. This pattern is broadly consistent with the pattern of glaciation in Alaska. Our understanding of the chronology of mountain glaciation in northeast Russia and Kamchatka could be enhanced by improvements to the pre-LGM and Holocene glacier records, the use of tephrachronology, and a better knowledge of the capacity of westerly winds to carry moisture across Siberia.

Mediterranean glaciation during the last cold stage

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The Mediterranean mountains contain sedimentary records of glaciation during multiple cold stages from the Middle to Late Pleistocene. The glacial records of Mediterranean mountains are key toward understanding cold stage atmospheric circulation over Europe, North Africa and the Near East. Also, the glacial record provides important insight into environmental conditions in mountains which are thought to have been areas of biotic refugia through multiple Pleistocene cold stages. Furthermore, the Mediterranean mountains were some of the first areas to be occupied by modern humans during the last cold stage.

In several areas, glacier-climate reconstructions for the local glacier maxima of the last cold indicate that temperatures were depressed by 5-10˚C and precipitation was similar to modern values. More specifically, glacier-climate conditions in the central and eastern Mediterranean appear to have been analogous with glaciated maritime areas, such as Norway. These findings are at odds with palaeobotanical evidence from long lacustrine sequences in Italy and Greece, since these records indicate a dry steppic environment during the height of glacial cycles – including the last global glacial maximum (LGM). However, arboreal species are known to have been able to survive in wetter mountain refugia, but even these areas are considered to have been much drier than at present. Thus, it is very unlikely that the former glacier maxima in the Mediterranean mountains coincided with the most severe arid phase of climate indicated in palaeobotanical sequences, which at several sites has been correlated with the global LGM.

Geochronological evidence from the Mediterranean region – as well as other locally-glaciated European mountain areas - supports a theory of asynchronous ice advance compared with global ice volume. For example, geochronological evidence for an early Würmian glacial maximum has been documented in the Cantabrian Mountains of Spain (^{14}C), the Pyrenees (^{14}C), the Massif Central (^{14}C), the Vosges (^{14}C), the Italian Apennines (^{14}C), as well as in the Pindus Mountains, Greece (U-series). Ages of local glacier maxima vary from region to region, with some preceding the global LGM by just a few thousand years and others by tens of thousands of years. However, very recent results from a cosmogenic dating (^{10}Be) programme in the Pyrenees questions earlier geochronologies based on radiocarbon dating. Nevertheless, the overall evidence in the Mediterranean mountains strongly points to early local glacier maxima during the last cold stage – preceding the global LGM.

The small glaciers in the Mediterranean mountains would have responded rapidly to climate change, in contrast to the extensive ice sheets that covered the Alps and northern Europe. The small mountain glaciers of the Mediterranean are likely, therefore, to have grown and decayed much faster and reached their maximum extent before the large ice sheets. The rapid response of mountain glaciers to climate change and increased aridity in southern Europe around the time of global glacial maxima may explain the evidence for an early glacial maximum in areas characterised by mountain glaciation during the last glacial stage. Mediterranean mountain glaciers are likely to have formed and reached maxima during *intermediate* rather than severe stadial phases of glacial cycles - during periods of sustained moisture supply. Furthermore, given their potential for rapid response to climate change, Mediterranean mountain glaciers are likely to have oscillated in response to millennial to inter-annual climate changes as a result of short term perturbations in North Atlantic circulation. This is reflected across the Mediterranean by a several re-advances following the local glacier maxima, including during Heinrich Event I and the Younger Dryas.

Glacial and climate history of the Southern Andes during the Late Quaternary Period

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Patagonia has one of the longest most complete glacial landform records on Earth, especially outside Antarctica. On the wet west side of the Andes radiocarbon dating is possible, but south of ~42˚S the record often begins only at the last termination or late glacial period. On the dry east side, fossil organic matter is lacking but cosmogenic nuclide dating has excellent potential for reconstructing glacial chronologies. Two main areas of focus for cosmogenic dating have been around the Lago Buenos Aires (LBA) region, 46˚S, and from Torres del Paine to Tierra del Fuego, ~50 to 54˚S. Cosmogenic nuclide chronologies have been established for the last two glacial cycles, including the marine isotope stage 6 glaciation, last glacial maximum (LGM), late glacial interval and early Holocene Period. These data complement radiocarbon-based chronologies along southernmost Patagonia, especially on the west side of the Andes.

At LBA, following a stage 6 glaciation, ca. 150-140 ka, the next recorded glacial period is during stage 2. There is no stage 4 glaciation recorded, despite a major peak in Patagonian-derived dust reaching Antarctica at this time. Most likely, the stage 4 glacial deposits were overrun and removed by ice during the more prominent stage 2 LGM advances. A major implication is that not only did major ice advances in the southern mid-latitudes coincide in timing with Northern Hemisphere ice expansions during at least the last ~150,000 yrs, but the relative magnitude of areal extent during stages 6, 4, and 2 was similar as well.

The LGM is well represented by moraines in southern Patagonia and cosmogenic dating works well east of the mountains due to low erosion rates. At LBA, the last glacial period is dated from 23 to 16 ka. Ice was at its maximum extent prior to 22 ka and at least five moraines were deposited in less than 10 kyr. In the Strait of Magellan, the southern Patagonian ice sheet was expanded between ~25 and 17.6 ka with maximum ice extent achieved ~25-24 ka. The Late Glacial period is between ~14 and 10.7 ka, and varies in structure slightly depending on the location. The cosmogenic nuclide data are in good agreement with ^{14}C-based chronologies. These are also times of peak Patagonian-derived dust to the Antarctic continent.

Broadly, the chronologies for the LGM are similar between the two regions. At LBA, the earliest and latest moraines are slightly younger than those in the Strait Magellan, which perhaps can be attributed to local effects such as greater continentally. The earliest LGM advances in Magellan, and also in the Chilean Lake District, are not observed at LBA, perhaps also due to local topography. Modeling simulations of the ice extent suggest about 6˚C of cooling, a slight drying east of the Andes, and >750m snowline depression in southern Patagonia during the LGM.

I infer the Patagonian records, coupled with nearby ocean records, proxy for major movements of the former air-ocean fronts such as the westerlies. The Magellan record is strikingly similar to nearby ocean records including of sea ice extent. Some of the paleo movements occurred in step with global glacial maximum climate changes. For example, an overall LGM timing between ca. 25 and 16 ka, a maximum ice extent prior to 22 ka, and deglaciation 16-18 ka is in phase with cosmogenic-nuclide based glacial chronologies for North America and Europe, despite a maximum in Southern Hemisphere insolation during this time period. The similar mid-latitude glacial history in both hemispheres implies that a global climate forcing mechanism, such as atmospheric cooling, synchronizes the ice age climate on orbital time scales. However, at least on the millennial scale, the climate of the southern ocean also plays a key role in Patagonian environmental change.

Late Pleistocene glaciation in the Tien Shan Mountains, western Central Asia

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The Tien Shan mountains of Kyrgyzstan contain abundant evidence of extensive late Pleistocene alpine glaciation. The Tien Shan extends over 1500 km in a northeasterly trending arc from the western boundary of Kyrgyzstan through Xinjiang and as far east as Mongolia, and represents the northernmost impact of the continental convergence of the Indian and Asian plates. Like the Himalaya, the Tien Shan comprises many separate smaller ranges, with peaks reaching 7000 m. and supporting over 6000 modern glaciers.

The dominant climatic signatures in western Central Asia include orographic thunderstorms in summer, a cold, dry Siberian high pressure cell in winter, and westerly cyclonic storms that cross the Kazakh steppe from the North Atlantic and eastern Mediterranean in spring and fall. The Kyrgyz Tien Shan parallels these cyclonic storm tracks, and lies just south of the modern day jet stream. As such, the setting of the Tien Shan provides an extreme continental 'end-member' for comparing the timing and magnitude of the major late Pleistocene glacial advances worldwide. Unlike in more maritime settings, glaciations throughout the Quaternary in this region must have been driven less by temperature fluctuations than by the availability of moisture, from distant sources, to the range.

I will discuss results from geomorphic mapping and ^{10}Be cosmogenic radionuclide exposure-age dating conducted on moraine sequences in six drainages along and across the Kyrgyz Tien Shan, and compare them to similar exposure age dating in ranges to the west, south and east. Our results indicate that there were multiple "maximum" advances of roughly similar magnitude and equilibrium line (ELA) depressions in several of the drainages, but the timing of these advances differed significantly across the range. Glaciers advanced to their maximum positions around 90 ka and again around 65 ka in the eastern past of the Kyrgyz Tien Shan, and at around 50 ka and 35 ka in the western and southern parts of the range. The magnitude of glacial advances also varied across the range, with ELA depressions for the local maximum advance, during marine oxygen isotope stage (MIS) 3, decreasing dramatically from over 1350 m. in the north, to only 400 m. in the south. These advances mirror the timing and magnitude of major glacial advances in the Pamir, Alay and Kunlun ranges further to the west and south, and in the Xinjiang Tien Shan and Qilian Shan to the east.

Just as significantly, and contrary to findings in the ranges to the west and east of the Kyrgyz Tien Shan, no evidence has been found of a major glacial advance during MIS 2. Most glacier advances during MIS 2 were restricted to cirques and upper valleys in the vicinity of extant glaciers. Because of this, the glacial record from earlier in the Pleistocene has been well-preserved. The geomorphology and CRN ^{10}Be dates suggest the Kyrgyz Tien Shan was precipitation starved during MIS-2, when winter thermal high-pressure systems diverted the jet stream and westerly storm tracks to the south of the range. These results highlight the sensitivity of glaciation in western Central Asia to the location and intensity of westerly storm tracks across the southern Russian steppes.

Dynamic influences on glacier erosion rates: examples from Alaska and Patagonia

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A vibrant dimension of the current thinking on landscape evolution is the potential impact of climate change on erosion rates due to differences in efficiency of glacial and non-glacial erosion processes. The climate-sensitive rate and spatial distribution of erosion can be as important as the tectonic environment in determinng the size, morphology and structural development of mountain ranges, by controlling exhumation. The "snow buzzsaw" hypothesis, which infers that relatively rapid erosion in glacial and periglacial environments effectively limits the elevation of mountain ranges, is intriguing but requires solid data that glacial and periglacial erosion is, in fact, more rapid than fluvial erosion under similar precipitation regimes and geologic settings, and is able to keep pace with rock uplift. To understand the evolution of mountain systems, many of which are glaciated and were considerably more so during the Quaternary, a more precise understanding of the impact of glaciers in the landscape is needed.

A growing database of measured glacial and fluvial erosion rates indicates that glaciers are indeed quite efficient at eroding and transporting material. Some of the highest reported glacial erosion rates, however, are receiving heightened scrutiny, for they significantly exceed long term regional exhumation rates. Two issues are likely to contribute to these high rates, which are measured primarily from temperate tidewater glaciers. First, contemporary sediment yields measured in recently deglaciated fjords may have been overestimated by failing to account for the input of non-glacially derived material, as the over-steepened landscape relaxes in response to the removal of ice. Second, and more significantly, sediment yields in the past century may be exceptionally high because the tidewater glaciers measured have been anomalously dynamic and erosive during a period of rapid, sustained thinning and retreat. These contemporary erosion rates are likely to be substantially higher than erosion rates averaged over the entire glacial-interglacial cycle.

To investigate these influences, I will present findings from seismic measurements of sediments in front of two Alaskan tidewater glaciers, Muir Glacier (Glacier Bay) and Tyndall Glacier (Icy Bay), and two glaciers in Chilean Patagonia, San Rafael Glacier (North Patagonian Icefield) and Marinelli Glacier (Cordillera Darwin). All of the glaciers were in rapid retreat during the latter part of the 20th century. Post-glacial sediment contributions from recently deglaciated tributary valleys were identified from historical photographs and seismic facies and compared to glacial input into the fjords. Using a numerical model of glacimarine sedimentation to quantify the annual sediment flux from the glaciers, we have found a strong correlation emerging between glacial retreat rates and glacial sediment yields. This implies that most contemporary sediment yield data from retreating tidewater glaciers, at least in temperate environments such as Alaska, may correspond to recent erosion rates that are a factor of 3.5 ± 1.5 higher than in the long term.

I will also discuss preliminary glacier modeling using NCEP-NCAR climate reanalysis data to reconstruct the flux of ice into the glaciers, which can be compared to the erosion rate to understand the influence of ice dynamics on the rate of glacier erosion. The intent is to use the relationship between decadal-scale, climate-dependent glacier dynamics and the rate of glacial erosion to interpret climate signals in the rich late Cenozoic sedimentary record preserved on high latitude continental shelves.

The distribution of Pleistocene glaciations along a North-South transect in Central Asia (from Mongolia towards the Tibetan Plateau)

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The current state of research concerning the timing and distribution of Late Pleistocene ice for Mongolia and central and northern Tibet is summarized. To show the variations in the ice extent, the modern and Late Pleistocene equilibrium-line altitudes (ELAs) for this area are presented in cross-sections. The ELAs are relatively low in the more humid outermost ranges of the arid and semiarid regions of Central Asia and are rising towards the central part of Mongolia and the Tibetan Plateau, respectively. The limited extent of present and Pleistocene glaciers in the eastern part of the Russian Altai and in the Mongolian Altai is the result of reduced precipitation from west to east. This results in a rise of present and Pleistocene ELAs towards the east. A similar situation can be observed for the north-eastern part of the Tibetan Plateau: The present and Pleistocene ELAs rise towards the interior of the Tibetan Plateau. However, in all these areas this was more pronounced during the Pleistocene than today. In addition, the evidence of a Pleistocene ice sheet in the source area of the Huanghe will be discussed. According to the authors opinion there are only mountain glaciation during the Late Pleistocene. The basins show evidence for permafrost and periglacial processes followed by alteration of higher lake levels and aeolian sedimentation. There is an essential lack of absolute dating in this particular region. The current state of research show, that most Late Pleistocene glacier advances in Mongolia take place in the MIS 2 and 4. Recent data from the Russian Altai suggest a main glacier advance between 20 and 28 ka.

Late Pleistocene Glaciation of the Southern and Middle Rocky Mountains, USA: Climatic Controls, Chronology, and Paleoclimate

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The southern and middle Rocky Mountains encompass the highest topography in the conterminous United States. Due to their low latitude and strong continentality, however, they supported less extensive Late Pleistocene glaciers than ranges to the north and west. Late Pleistocene glaciation was generally limited to cirque and valley glaciers, although small ice-field/outlet-glacier complexes developed in several ranges, the largest in the Yellowstone area. Modern glaciation is limited to small cirque and niche glaciers in topographically favored locations. This paper summarizes the chronologic and paleoglaciological results of many workers in the region.

The Late Pleistocene glacial chronology of the southern and middle Rocky Mountains is based on radiocarbon and CRN ages from at least twelve ranges, and appears generally consistent with global ice volume records. However, some topics of uncertainty remain and there appear to be at least two local exceptions to regional synchrony. The extent of glaciation late in marine isotope stage (MIS) 5 is not clear, as moraines with apparent MIS 5 ages may in fact date from MIS 6. These moraines indicate a glaciation slightly more extensive than MIS 2 glaciation, so *if* they were deposited during MIS 5 they would indicate anomalously extensive glaciation at that time. Any MIS 4 glaciation must have been less extensive than subsequent MIS 2 glaciation. MIS 2 glaciation culminated in local last glacial maximum (LGM) ice stands that are surface-exposure dated between 23 and 16 ka, mostly between 22 and 18 ka. In the North Yellowstone area and in the Wasatch and Uinta Ranges of Utah, the local LGM occurred between 18 and 16 ka, a few thousand years after maxima elsewhere in the region. Moraines of a small Late Glacial readvance are preserved in many areas. Where these have been dated, they appear to have been deposited during the Younger Dryas interval.

Lateness of the local LGM of the North Yellowstone glacier complex has been attributed to moisture starvation during the global LGM, due to the southward migration of the jet stream and the polar front, followed by increased precipitation after the global LGM as the jet migrated back northward. The delayed local LGM of the Utah ranges appears to be most directly a response to precipitation enhancement related to the maximum high stand of pluvial Lake Bonneville immediately upwind. Timing of the Bonneville high stand was itself probably a response to the changing position of the jet. Paleoglaciological studies indicate that in addition to influencing the timing of the glacial advance in local ranges, precipitation enhancement from Lake Bonneville influenced the LGM extent and mass balance of these glaciers. Glaciers in both the Wasatch and Uinta ranges were significantly larger, with lower ELAs, and likely higher mass flux, than would have been the case as a result of regional climate change alone without the more local effects of lake-enhanced precipitation. On a more regional scale, however, paleoELA studies suggest the persistence of general modern wind patterns and moisture sources at the LGM.

Quaternary glaciation in Africa: key chronologies and climatic implications

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Africa embodies Earth's largest continental tropical landmass that symmetrically spans the equator, providing an unequaled latitudinal expanse over which to investigate the geomorphologic record of Quaternary glaciations. Four principal highland regions have been recognized as containing possible evidence for Quaternary glaciations (Osmaston and Harrison, 2005[1]), and there are at least two unexplored sites with adequate elevation to have also sustained glaciers. To date, very few glacial chronologies exist with absolute age control. However, each glaciated region is situated in a different climatic context, and improved geomorphologic mapping with more radiometric dates will elucidate important information about past climatic dynamics. In this presentation I will review the best chronological data available in each site, the patterns of past glacial extent, and some paleoclimatic implications derived from complementary data.

The best African glacial chronologies come from equatorial East Africa, where the geomorphologic record shows several phases of Quaternary glaciations. The three highest mountains (Kilimanjaro, Kenya, Rwenzori) reach over 5000 m.a.s.l. and are currently glacierized. Moraines have been dated with radiocarbon in each of these locations to the LGM. 122 boulders on Kenya and Kilimanjaro have yielded ages from in situ cosmogenic ^{36}Cl that limit ages of older moraines to >360 kyr BP. Large variations in paleoglacier extent by aspect suggest strong precipitation gradients and local controls on glacial mass balance. Correlative paleoclimate records depict a dry, cold LGM and highly variable humidity conditions during the late glacial that hint at interhemispheric linkages. Rapid recent deglaciation is noted on all the mountains, with some recent contention in the literature regarding climatic forcing and the role of aridity in this thermally homogeneous region. The solar-paced shifting of the inter-tropical convergence zone (ITCZ) results in a dual-peaked seasonal precipitation regime with the majority of precipitation falling in April-May. The region features anomalously low precipitation for the latitude, suggesting strong influences by coastal winds. Climatic teleconnections featuring the pressure fields across the Indian Ocean have been shown as crucial to controlling interannual humidity flux.

Ethiopia features a high volcanic plateau from which at least three of ten mountains rising above 4 km have evidence for low latitude (4-15°N) glaciations. Radiocarbon dates provide minimum age control for late glacial (>12 ka) and Holocene (>4.2 ka) moraines. Climate variability is controlled largely by the ITCZ. In the Atlas Mountains of NW Africa, at least three glaciations have been proposed, featuring high intra-regional variations and gradients in reconstructed equilibrium line altitudes (ELAs). There are no absolute dates. Climate is strongly moderated by the seasonal monsoon, and offshore ocean sediment records have great potential for expanding the paleoclimate interpretation of improved geomorphic mapping and chronology. The Drakensberg Mountains of South Africa contain equivocal evidence of glaciation that lacks a consensus interpretation.

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[1] Osmaston H.A. and S.P. Harrison, 2005. The Late Quaternary glaciation of Africa: A regional synthesis. *Quaternary International* **138-139**, 32-54.

Deformation and Denudation Associated with the Main Central Thrust (MCT) Shear Zone: Examples from the Garhwal Himalaya, India, and Manaslu-Ganesh Himals, Nepal

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The Main Central Thrust (MCT) has been identified as a dominant crustal-thickening mechanism in the Himalaya, responsible for post Miocene deformation, producing extreme relief when concurrent with rapid river incision and mass wasting. Advances in numerical dating of episodes of deformation and denudation create exciting opportunities to more closely document the timing of landscape forming events in high mountain areas. In this presentation, I will discuss examples from studies of the Garhwal Himalaya in northwest India, and the Manaslu-Ganesh Himals in central Nepal.

The Himalayan Main Central Thrust (MCT) is a shear zone several kilometers thick that separates high grade gneisses of the Greater Himalayan crystallines from Lesser Himalayan metasedimentary rocks. The MCT zone is bounded by major thrust faults, and was traditionally thought to have been inactive since the early Miocene (approx. 22 Ma). Recent earthquake activity and other evidence now counter this claim. Th-Pb ion microprobe ages of monazite (Catlos et al. in-press) have established that the MCT was reactivated during the Pliocene in the Garhwal. The distribution of monazite ages within the Lesser Himalaya along the Bhagirathi River suggest that the duplex in northwest India developed from ~4 to ~1 Ma, versus from ~15 to ~3 Ma in central Nepal.

Recent MCT deformation would be expected to exert a strong influence on the spatial and temporal distribution of slope failures, the longitudinal profiles of rivers, and cross-valley topographic profiles. In the Garhwal Himalaya, Saha et al. (2002) developed a GIS model of slope failure hazards, demonstrating the importance of major thrust faults associated with the MCT, along with lithology, land cover, and slope angle. In the Manaslu-Ganesh Himals, slope failures were mapped during two field expeditions traversing a total of 430 km. The style and frequency of slope failures differs above/below the MCT zone and the frequency of slope failures varies inversely with distance from the MCT zone. Longitudinal profiles were created for tributaries of the Bhagirathi and Alaknanda rivers, extracted from 40-60m DEMs. Hodges et al. (2004) had completed a similar exercise for the Marsyandi River and its tributaries in central Nepal. In both regions, channel gradients become less steep downstream (south) of the MCT. Topographic profiles were created for several valley sections in the Garhwal from the 40-60 meter DEMs. Cross-valley topographic profiles are decidedly more convex near the MCT zone.

Cosmogenic isotope dating was used to date rock strath terraces along the Bhagirathi, Alaknanda, and Maldakini rivers in the Garhwal Himalaya. Rates of incision were calculated at 3.6 to 34 mm/a. Our rates of incision (mean = 15 mm/a) were higher than reported by Barnard et al. (2001) of ~4 mm/y for Alaknanda drainage and ~7 mm/y by Pratt-Sitaula and Burbank (2004) in Marsyandi drainage of central Nepal.

Evidence for Holocene megafloods down the Tsangpo River gorge, Southeastern Tibet

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Lacustrine and alluvial terraces and sediments reflect the extent of two Holocene glacially dammed lakes immediately upstream of the Tsangpo River gorge at the eastern syntaxis of the Himalaya. The larger lake covered almost 2850 km^2, with a maximum depth of 680 m and contained an estimated 835 km^3 of water; the smaller lake contained an estimated 81 km^3 of water. Radiocarbon dating of wood and charcoal yields conventional radiocarbon ages of 8860±40 BP and 9870±50 BP for the higher set of lake terraces, and 1220±40 BP and 1660±40 BP for sediments from the lower terraces. Catastrophic failure of the glacial dam that impounded the larger lake would have released an outburst flood down the gorge of the Tsangpo River with an estimated peak discharge of 5×10^6 $m^3 s^{-1}$. The erosive potential represented by the unit stream power calculated for the head of the gorge during such a catastrophic lake breakout implies that post-glacial megafloods down the Tsangpo River were among the most erosive events in recent Earth history. Our evidence for immense late-glacial lakes at Namche Barwa show that monsoon-driven valley glacier advances dammed even the largest Himalayan rivers, and repeatedly created unstable glacier-dammed lakes that would have generated some of the most erosive events in recent Earth history. Hence, immense outburst floods could well have played an important role in carving the deepest valley on Earth and, more generally, the development of the spectacular topography of the Himalaya and other high, glaciated ranges.

Late Quaternary glaciation in the Himalaya and Tibet

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The mountains of the Himalaya and Tibet are the most glaciated region outside of the Poles and they have an important influence on regional and global environmental change. Glaciation in this region is controlled by two major climatic systems: the mid-latitude westerlies and the South Asian monsoon. In addition, significant interannual climatic variability in the region is associated with El Nino Southern Oscillation. Furthermore, glaciation is strongly influenced by topographic constrains. Yet despite the regional and global importance of glaciation in High Asia, the dynamics, extent and timing of glaciation in this region is poorly understood and defined. To test the relative importance of the difference climatic systems and topographic constrains on glaciation and the associate hydrological changes, we have been systematically examining the glacial and associated geology throughout the region, and dating landforms and sediments using cosmogenic radionuclide (CRN) surface exposure and optically stimulated luminescence (OSL) dating. To date, we have undertaken detailed studies in mountains of Chitral, Swat, Nanga Parbat, Hunza Valley, K2 area of the Central Karakoram, Lahul, Ladakh, Zanskar, Garhwal, Nanda Devi, Langtang, Khumbu, Northern slopes of Everest, Mustagata-Kongar, Gurla Mandata, Gonga Shan, Gangdise, Nyainqentangulha, Tangula, Kunlun, Nianbaoyeze, Anyemaqen, La Ji and Qilian Shan. This has included detailed mapping, together with ~1000 numerical dates on moraines and associated landforms, that define the extent and timing of glaciation. Published CRN dates have recently been reassessed using new production rate data to test synchronuity of glaciation throughout the region and to test the forcing factors. The best chronologies for the eastern region are provided by the valleys to the north and south of Everest, while for the western regions the mountains of the Karakoram and Mustagata-Kongur provide the best chronologies. These studies suggest that the regional patterns and timing of glaciation throughout the region reflect temporal and spatial variability in the south Asian monsoon and, in particular, regional precipitation gradients. As a consequence, old (pre-Last Glacial) moraines and/or tills are more readily preserved in regions of greater aridity, such as central and westernmost Tibet. In contrast, within regions with greater rainfall as a result of the strong influence of the monsoon, such as the southern slopes of the Himalaya and eastern Tibet, the preservation potential of pre-Lateglacial moraine successions is extremely poor because of the associated high erosion rates. Furthermore, glaciation in such regions during the early Holocene insolation maximum was probably more extensive than earlier in the last glacial cycle (and specifically at the global LGM), and thus any evidence of older moraines has been destroyed by subsequent glacial advances. It is therefore likely that glaciation throughout Tibet and the Himalaya is strongly influenced by orography that, in turn, strongly influences climate. Understanding these factors and patterns are essential for helping to establish regional glacial chronologies.

Cosmogenic ^{10}Be dating of moraine in Tianshan, Central Asia

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The Tianshan mountain area is located towards the center of the Eurasian continent and is one of the driest regions in the world. Studies of glacial history in this region are especially important because it is far from the climatic key area of the North Atlantic and thus could be a better place to make connections between ocean, atmosphere and terrestrial systems. Relating glacial advances in the extreme-continental environment to abrupt climatic changes initiated in the North Atlantic area which cannot be attributed directly to orbital forcing may especially improve the fundamental understanding of the interrelations of distinct elements of the earth climate system as well as the mechanisms underlying abrupt climate changes.

Successions of well-preserved moraines are present in the Urumqi river head valley, Tianshan mountains, central Asia. These moraines are relics of glacial advances and retreats during the late Quaternary. By using ^{10}Be surface-exposure dating of moraine boulders, we determined the timing of glacial advances in this area to be: ~17,700 yr, ~12,400 yr and ~8,300 yr. The first age is coincident with deglaciation after the Last Glacial Maximum (LGM) and the last two glacial advances are most likely associated with abrupt climate events after the LGM: the Younger Dryas and the 8200-year cooling event. Our results suggest a relation of glaciations in the Tianshan mountains with climate changes in the North Atlantic. The occurrence of glacial advances during abrupt climate cooling periods in the remote Eurasian continent suggests rapid linkages between ocean, atmosphere and terrestrial systems.

Climate-Tectonic interactions and Landscape Dynamics on the margins of Continental Plateaus: Examples from the Andes and Tibet

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Continental plateaus, such as the Tibetan Plateau and the Altiplano-Puna plateau in the central Andes, are the result of exceptional tectonic and climatic conditions. As such, they are natural laboratories in which to study tectonic-climate interactions and landscape dynamics. In this presentation I will discuss three different examples from Tibet and the Andes.

Along the southern margin of the Puna Plateau in northwest Argentina, climate plays a dynamic role in the growth of the plateau. It is hypothesized that as crustal shortening causes mountains to grow, rivers draining the intermontane-basins are defeated by a combination of tectonic uplift and orographically driven aridification; internal drainage conditions allow the basins to fill with sediment over time, to gain elevation, and eventually to be incorporated into the topographically and hydrologically defined plateau. I will discuss basins flanking the southeast edge of the Puna Plateau which show evidence of partial filling during times of constricted or blocked drainage, followed by re-incision, and will also discuss the processes by which blocked basins can become reincorporated into the externally drained foreland.

In Yunnan Province, China, geomorphic observations led to the hypothesis that weak lower crust is flowing into this region from beneath the Tibetan Plateau, inflating crustal thickness in the southeast margin of the plateau, and causing isostatic uplift. As a response, the major rivers of the southeast margin, including the Yangtze, Mekong, Salween and Red Rivers, have incised deep gorges into a relict landscape now perched at high elevations. In particular, I will discuss new data which establishes the timing and magnitude of river incision along the Red River, which, together with existing thermochronologic data from closer to the Plateau, demonstrates southeast propagation of lower crustal material into the southeast margin of the Plateau

In the Pamir mountains of western China, in the footwall of the Kongur detachment, the correlation of the high peaks Kongur Shan (7719 m) and Muztagh Ata (7546m), large glaciers, exhumation of mid-crustal rocks and rapid cooling suggests the development of a system in which (1) erosion effectively removes material, driving advection of increasingly hotter, weaker rock, forming the gneiss domes which underlie the peaks, and (2) glaciers drive relief production and peak uplift, enhancing orographic precipitation, thus forming larger, more erosive glaciers. We suggest a scenario in which initial structural unroofing of the footwall, increased peak height and the resulting orographic focusing of precipitation may have led to increased glacial erosion. Glaciation would have been most significant in the south where the peaks were highest. The additional component of exhumation in the southern regions then drove greater structural exhumation, maintaining high topography and establishing a climate-moderated feedback loop. I will discuss ongoing research into this dynamic system.

Late Pleistocene Alpine Glaciation in the Uinta Mountains, northeastern Utah, U.S.A.: Trends in Equilibrium Line Altitudes, Variable Chronologies, and Local Moisture Sources

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The Uinta Mountains of northeastern Utah were glaciated repeatedly during the Pleistocene, and glacial deposits from the Smiths Fork and Blacks Fork glaciations (Pinedale and Bull Lake equivalents, respectively) are well preserved throughout the range. Reconstructions of Smiths Fork ice extents suggest that the central and eastern parts of the range contained discrete valley glaciers, ranging from 4 to 43 km in length. However, valleys in the extreme western end of the range, which is lower in elevation than the central part of the range, were occupied by outlet glaciers of the 685 km^2 Provo Ice Field. Equilibrium line altitudes (ELAs) in this part of the range were ca. 2600 to 2800 m asl, whereas ELAs in the central and eastern parts of the range were generally above 3000 m asl. This pattern of glaciation in the Uintas suggests that winter precipitation in western valleys nearest pluvial Lake Bonneville (~50 km upwind) was enhanced relative to valleys located farther east.

To test this hypothesis, we obtained cosmogenic ^{10}Be surface-exposure ages of several terminal moraines in the Uintas Mountains. Exposure ages from the southwestern Uintas reveal that ice in the Lake Fork valley remained at its maximum position until 16.8 ± 0.7 ka, nearly 2 kyr later than when glaciers in the neighboring Wind River Range and the Colorado Rocky Mountains began to retreat. These ages also indicate that the onset of ice retreat in the Uintas occurred at approximately the same time as the hydrologic fall of Lake Bonneville. These findings, along with the pattern of ELAs in the Uintas, suggest that although the lake and local glaciers were presumably responding the same regional climatic forcing, the presence of the lake amplified the extent of ice in areas immediately downwind, perhaps by providing lake-effect moisture to glacier accumulation zones.

At the western end of the range, however, ^{10}Be surface-exposure ages from moraine boulders deposited by the Bear River glacier, which flowed northward from the Provo Ice Field, indicate that the maximum ice extent was reached by 24.6 ± 2.5 ka (±2σ) and retreat began by ~21 ka. In addition, outlet glaciers in the Provo River drainage, flowing southwest from the ice field, reached their maximum extent by 21.9 ± 1.8 ka and likely began retreating by 19.0 ± 1.5 ka. Ice in the Lake Fork valley, which was not influenced by the dynamics of the Provo Ice Field, reached its maximum extent by 19.9 ± 1.0 ka. According to these ages, the peak of the last glaciation in the Bear River Valley occurred several thousand years prior to the global LGM and deglaciation began earlier in this valley than in the Provo and Lake Fork valleys. While this finding may reflect the complex dynamics of the Provo Ice Field, it may also reflect spatial variations in winter precipitation during the LGM in the Uintas. For example, southeasterly circulation in the vicinity of Lake Bonneville would have enhanced precipitation in the south-flowing Provo and Lake Fork valleys relative to the north-flowing Bear River valley. To set additional limits on the timing of deglaciation the western Uintas, we obtained paired measurements of ^{10}Be and ^{26}Al in samples from striated bedrock surfaces below the former ice flow center of the Provo Ice Field. These data suggest that deglaciation of the westernmost valleys in the Uinta Mountains was virtually complete by 15.8 ± 0.5 ka, and that in the western Uintas, glaciers likely did not readvance in response to the Younger Dryas cooling event.

Finally, we applied a physically-based, numerical mass- and energy-balance and glacier flow model to investigate the climate of the western Uinta Mountains during the LGM based on reconstructed ice extent. Modern climate data were used to calculate the mass- and energy-balance of the land surface within the modeling domain, and this output drives the ice flow model. Model simulations of Smiths Fork glaciers support that temperatures were 5.0 to 8.5 °C colder than present, and generally, glaciers received more precipitation when expanding to their maximum extent than glaciers farther east in the range. If our estimates for paleotemperatures are accurate, this finding also supports the hypothesis that precipitation in the western Uinta Mountains was enhanced by pluvial Lake Bonneville during the last glaciation.

Holocene Lake Lake Level Changes of Nam Co as a Reaction to Late Glacial Glacier Decay and Holocene Climate Change

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The Nam Co and its drainage basin are the largest and highest lake system in the central Tibetan Plateau. Nam Co covers a lake area of c. 1.870 km2. It is located in 4.600 m a.s.l. and its drainage basin covers an area of approx. 15.000 km2. In its southern drainage during last glaciation Nyainqentanglha Mountains (c. 7100 m a.s.l.) were covered by valley glaciers, presently showing still few remnants. The location on the plateau and its proximity to the intersection of the different air masses makes it an extreme sensitive area and thus well suited area to study past and present lake system response to Monsoon dynamics and, thus, climate change.

In the south of Nam Co, but around part of the lake a cliff line of 5-10 m height is recorded with its base 21 m above the present lake level. It is assumed that this cliff line marks the Younger Dryas up to earliest Holocene lake-level high after LGM glacier decay. Next to this, a minimum of additional twelve Holocene lake levels were recorded between this cliff line and the present lake level, preserved as beach ridges and cliffs. In the south of Nam Co the cliff line is repeatedly interrupted by u-shaped valleys. Incision took place after LGM with runoff fed by melt water of decaying glaciers. Channels were appointed to the wave cut platform of YD cliff as erosion surface. In the east of Nam Co aeolian deposits cover the cliff line. Here, the Younger Dryas cliff line and overlying aeolian sand were recently cut and v-shaped valleys were incised.
Today surface of Nam Co covers an area of 1855 km2. For the Younger Dryas cliff line base located in approx. 21 m above present lake level corresponding lake area totaled up to 20 % more than at present. Integration of topography points to a difference in lake volume of 43*1027 m3.

Various beach ridges generations along the Nam Co shoreline prove former lake level raised stands. Due to the glaciation history of the drainage Nam Co's early Holocene lake level changes are directly coupled to deglaciation processes. However, lake level changes are in general a direct response to regional water balance with beach ridges as their evidence, controlled by the annual precipitation-evaporation-ratio as well as on the time of the year precipitation appears and its magnitude and frequency.

MIS 3b (54~44 ka BP) Cold Period and Glacial Advance in Middle and Low Latitudes

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The records of Guliya ice core showed that there was a MIS 3b cold period between 54 and 44 ka BP，when temperature was 5℃ below present average. In contrast to this，temperatures in the warm period at MIS 3c (early) and MIS 3a (late) were 3℃ and 4℃ above present average, respectively. This has been proved to be consistent with the insolation changes caused by a precessional cycle of 23 ka and a significant global impact appeared between 65^{o} N and 60^{o}S. From preliminary analysis of literatures concerning well-dated glacier advances during the Last Glaciation，it has been found that MIS 3b cold period resulted in glacial advances at some 30 sites of 12 regions in Asia，Europe，North America, South America and Australia. In this paper the authors give a brief review to these sites. The plentiful precipitation during MIS 3b coupling with the suppressive effect of low temperature on ice ablation，glaciers advanced beyond the extent of cold-dry MIS 2 between 25 and 15 ka BP（LGM）. Several new dating methods，such as modified optically stimulated luminescence（OSL）method，infrared stimulated luminescence （IRSC）method，cosmogenic ^{3}He，^{10}Be，^{26}Al and ^{36}CI dating methods，Uranium series dating method，together with ^{14}C method，TL method，ESR method and fission track method，effectively improve the dating of several glacial advance during the Last Glaciation. Despite the importance of the records of Guliya ice core in defining the MIS 3b cold period，few data was held on glacial advance during that time in West China，further study is essential.

Mountain glaciation in the tropical Andes

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The tropical Andes host the majority of the world's remaining tropical glaciers and ice caps. While the modern retreat of tropical glaciers in the Andes has been widely attributed to anthropogenic climate change, fluctuations in Andean ice extent over the past 130,000 years [since Marine Isotope Stage (MIS) 5e] must reflect changes in climate arising from natural forcing mechanisms. Understanding the forcing mechanisms begins with recognizing patterns among Andean glacial records.

In several locations in the Peruvian Andes, ice advances during the local last glacial maximum (LLGM; MIS 3-2) were relatively small compared to previous advances. Surface exposure dating (^{10}Be) of boulders on moraines in valleys bordering the east side of the Junin Plain in central Peru (~11.0° S) showed that the LLGM advance was considerably smaller than advances that occurred prior to MIS 5e. After geomagnetic correction, the ^{10}Be ages suggest that glaciers in the Junin region stabilized at their LLGM extent ~32-28 thousand years before present (ka), retreated by ~21 ka, and either halted, or readvanced to, within ~1-2 km of their previous termini ~20-16 ka. Subsequent retreat appears to have been uninterrupted by any late-glacial readvances during the Antarctic Cold Reversal or Younger Dryas. Surface exposure ages (^{10}Be) have been also determined for boulders on three sets of moraines in several valleys in the Cordillera Blanca (9.4-9.8° S). Ages on the outer moraines were >400 ka. The two inner sets of moraines had exposure ages of ~29 and 16.5 ka, which have been interpreted as indicating two separate advances. In the deeply incised valleys of the Cordillera Huayhuash (~10.3° S), however, others have found that most preserved moraines dated by cosmogenic ^{10}Be have LLGM, late-glacial, and early Holocene ages; older moraines have not been identified thus far.

Well-preserved moraines marking the limits of extensive pre-LLGM glaciations appear to be less abundant in the Bolivian Andes than in Peru. In the Milluni Valley (~16.3° S), ^{10}Be ages of ~32-21 ka (the LLGM) were obtained on large lateral moraines comparable in size to the oldest moraines in the Junin region. Aerial photographs suggest that older moraines may be present outboard of the LLGM moraines, but the older moraines, if present, are difficult to discern in the field. Other workers using different geomagnetic correction methods have calculated slightly younger ^{10}Be ages (~20, 16 10, and 8 ka) on multiple moraine sequences in nearby regions in Bolivia. Well-dated moraine sequences are rare in Ecuador.

Several fundamental questions arise from the existing glacial chronologies in the tropical Andes. Why do we see an MIS 3 advance and an MIS 2 readvance or stillstand in Peru? Why were older glaciations more extensive than the LLGM in some areas of Peru, but possibly not in Bolivia? What are the relative roles of temperature and precipitation? Do precession-driven increases in insolation act primarily as a source of enhanced convection and storminess or as a force of increased ablation? What role has the position of the ITCZ played in glacial expansion in the tropical Andes?

Timing of Pleistocene glaciations in the Verkhoyansk Mountains, North-Eastern Siberia

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The Verkhoyansk Mountains are situated in NE Siberia between the Arctic Ocean and Central Yakutia. They extend over 1200 km from north to south and form a major barrier for the precipitation from the west. The climate is extremely continental. Studies concerning pleistocene glaciations are rare. Major work was done in 60^{th} and 70^{th} by several Russian scientists. They identified multiple glaciations in the Mountain system. The oldest one took place in the penultimate glacial cycle, while three major advances were during the last glacial, one in the early Weichselian (Zyryan), an other one during the interstadial at around 32ka (Karginsk), and the last one in phase with the global Last Glacial Maximum (gLGM, Sartan). The interstadial advance during MIS3 was a major advance with mountain glaciers of more than 200km in length. Age estimates from second half of the last glacial are based on radiocarbon dates from. In the late 90^{th} Grosswald & Hughes (1999; 2002) proposed a major ice sheet covering the whole of north-eastern Asia including the Verkhoyansk Mountains. This ice sheet was part of the pan-artic ice sheet situated on the arctic shelf.

New geomorphological mapping and IRSL dating revealed five glacial advances of mountain glaciations, but no indications for a major ice sheet. Formation of the terminal moraines took place between older than 120ka and 50ka. No terminal moraines can be attributed to the gLGM or the Karginsk around 32ka. The formation of glaciers in the Verkhoyansk Mountains seems to be related to the size of the ice sheets in northern Europe and Western Siberia.

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Grosswald, M.G. & T.J. Hughes (2002): The Russian component of an Arctic Ice Sheet during the Last Glacial Maximum. In: Quaternary Science Reviews **21**:121-126.

Surface exposure dating in the Shaluli Mountains, eastern Tibet: Evidence for an ice advance in Marine Isotope Stage 2

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Glacial landscapes mirror ice advances or ice cap expansions and thus, yield substantial paleoclimate information. It is widely accepted that no extensive ice cap covered the Tibetan Plateau during the global last glacial maximum (LGM). However, the spatial extent and the exact timing of regional glaciations within the last glacial cycle still need to be established in some areas. Especially in the monsoon influenced south eastern part of the Tibetan Plateau, where absolute datings of glaciogenic surface features are rare.

With in situ produced cosmogenic nuclide measurements (^{10}Be and ^{21}Ne) we dated a moraine succession at 4150 m above sea level in the northern Shaluli Mountain range, western Sichuan Province, China (99°45'E, 31°5'N). We sampled nine erratic boulders from three terminal moraines (three boulders per moraine) at a distance of about 12 km from the paleocatchment area, where no present-day glacier exists. The moraines are separated by less than 500 m. Adjacent to huge gravel deposits is the outermost sampled moraine, a relict of strong moraine degradation. The inner two walls are well preserved, about 20 m high and show clear ridge morphologies. Between each of these moraines additional smaller ridges exist. The innermost sampled moraine delimits the last terminal basin.

Measurements of cosmogenic ^{10}Be and ^{21}Ne were carried out on quartz separates from all samples (TSO 1–9). So far only ^{10}Be results are available, ^{21}Ne analysis is still in process. The moraine ages – derived from minimum ^{10}Be exposure ages (assuming no erosion) from the erratic boulders – are 19.8 ± 0.9 kyr for the outermost, 18.5 ± 0.9 kyr for the intermediate, and 18.0 ± 0.9 kyr for the innermost moraine. These results indicate (1) that a major ice advance occurred in the northern Shaluli Mountains during Marine Isotope Stage 2, and (2) that the dated moraine succession reflects rather an oscillating ice margin with an abrupt glacial retreat, than different glacial stages.

Geomorphology of the Huang He ice sheet area: towards a reconstruction of the glacial history of the northeastern Tibetan Plateau

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Recent terrestrial cosmogenic nuclide (TCN) studies on end moraines of the Tibetan Plateau have yielded a first synthesis of the timing of mountain glacier and ice field maximum extents at discrete times in the past. Although these allow important constraints on the presence of expanded ice on the plateau, they don't address the question of the presence of areally more extensive ice sheet configurations where mountain ice complexes from discrete mountain blocks coalesce to form larger bodies. Two ice sheets hypothesised to have covered parts of the Tibetan Plateau are the Tibetan ice sheet and the areally much more restricted Huang He ice sheet. In this study we have focussed on the hypothesised Huang He ice sheet area in the headwaters of the Huang He and Yangtze rivers on the north-eastern margin of the Tibetan Plateau.

Two mountain blocks from which ice might have emanated to inundate the plateau surface around it and form the ice sheet are the marginally-located Anyemaqen and centrally-located Bayan Har Mountains. Of these the Anyemaqen is located closer to the edge of the plateau, is higher, wetter, and is ornamented with glaciers today, which, according to TCN studies have been more extensive during marine oxygen isotope stages 3, 2, and 1.

Using Landsat 7 ETM+ satellite imagery we have mapped the glacial geomorphology of the entire hypothesised Huang He ice sheet area (50,000-70,000 km^2) and concentrated our TCN field sampling to its core area, the Bayan Har Mountains. The area displays widespread morphological evidence of glacial erosion and deposition, particularly around the higher mountain blocks. The erosional landforms include large-scale glacial troughs, U-shaped valleys and occasional lake basins, and small-scale lateral meltwater channels. The depositional landforms include primarily lateral and end-moraines, but also hummocky moraines and drumlins. Field inspection has yielded observations of tills and erratic boulders. Taken together, these traces comprise an impressive record of multiple large-scale erosional events as witnessed by cross-cutting relationships of glacial valleys and multiple glacier advances through the Bayan Har Mountain valleys, some of which terminated onto the plateau surface, by the presence of suites of end-moraines and associated meltwater traces.

The mapping exercise thus far has established a clear patchiness to the erosional imprint of ice in the uplands comprising the Huang He ice sheet area. Although the integrated imprint of erosion is clear and displays a pattern of topographically-forced selective linear erosion, the rates of glacial landscape change in the absence of TCN measurements remains unknown.

We note that except for the arguable presence of tills and the reported, but not confirmed, presence of erratics beyond the mountain fronts, we have not been able to establish firm evidence of ice coverage on the intervening plateau surfaces. Rather, many areas display a distinct non-glacial morphology with well-developed fluvial valley systems and basins infilled with alluvial deposits. This casts some doubt on the concept of the Huang He ice sheet, although one may argue that, if of considerable age, few glacial traces may have survived degradational processes. Moreover, we conclude that the break in slope between the youthful steep fluvial landscapes of the Huang He and Yangtze rivers and the relict gentle sloping surface of the Tibetan Plateau almost entirely coincides with the outline of the Huang He ice sheet bordering these rivers. This *could* be used to further question the reality of the Huang He ice sheet or, if indisputable further evidence can be uncovered in the years to come, the coincidence of borders *could* indicate that the ice sheet was larger but that evidence for this is now flowing down the rivers.

Finally, an ambitious TCN and OSL sampling campaign in the Bayan Har Mountains region with our colleagues from the USA (Caffee, Harbor, Li) and China (Zhou, Liu, Ma) will likely shed light on the timing of glacial advances through the dating of end moraines, erratics and till stratigraphies and establish contemporary landscape catchment erosion rates through the analysis of river bank sediment TCN concentrations.

Mountain Glacier Chronologies in the Northwestern United States and the Extent of Moisture Influences on Mountain Glaciation

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Mountain glacier chronologies from four mountain ranges in the northwestern United States, coupled with the chronology of the Puget Lobe of the Cordilleran ice sheet, reveal patterns of variable moisture influences on mid-latitude glaciation. While chronologic data exist for glacial sequences in many northwestern mountain ranges, this analysis focuses on five areas for which relatively robust chronologies exist.

In the Olympic Mountains, Washington (Thackray, 2001), geomorphic and stratigraphic evidence document six late Pleistocene advances constrained by radiocarbon chronology. The most extensive advance occurred between 54 and 125 ka, while a subsequent advance ca. 29-33 cal ca was nearly as extensive. Most importantly, the moraines correlative with the 21 cal ka Last Glacial (ice sheet) maximum (LGM) represent a 27 km retreat from maximum late Pleistocene positions. Coupled with local pollen data, this glacial record indicates a strong dependence of glaciers on abundant moisture.

A 36Clchronology from Icicle Creek, on the east side of the Cascade Range, reveals a partly similar chronology (e.g., Swanson and Porter, 1995). The most extensive advance occurred ca. 108 ka, with subsequent advances ca. 98 ka and 77-71 ka. All three advances were more extensive than the 20-18 ka advance correlative with the Last Glacial Maximum. Advances subsequent to the LGM occurred 15-18 ka, 13-14 ka and 13-12 ka.

The Puget Lobe of the Cordilleran ice sheet, which originated from coalesced mountain glaciers in the Canadian Coast Ranges and Rocky Mountains, reveals a simpler chronology. Porter and Swanson's (1998) detailed radiocarbon chronology shows that the Puget Lobe advanced rapidly between ca. 19 and 17 cal ka, and subsequently retreated dramatically between 17 and 16 cal ka. This culmination of this maximum advance postdated the LGM by ca. 4 ka. The ice sheet record likely integrates earlier climatic events into this broader advance.

Inland chronologies show contrasting patterns. In the Wallowa Mountains of northeastern Oregon (Licciardi et al., 2003), several hundred kilometers inland from the coastline, a 10Be chronology reveals ice advances more correlative with ice sheet maxima. The maximum late Pleistocene advance occurred ca. 22 ka, with a subsequent readvance ca. 17 ka. A late glacial advance culminated 11.3 ka. Further inland, the Sawtooth Mountains have produced an incomplete chronology that may be broadly correlative. Sherard (2006) describes a 10Be chronology at Redfish Lake that constrains an extensive ice advance ca. 19 ka, with a sequence of subsequent moraines ca. 17-14 ka. The maximum late Pleistocene advance remains poorly constrained. A late glacial advance occurred ca. 11.5 ka. Thackray et al. (2004) described a radiocarbon chronology that constrains moraine ages of ca. 17 and ca. 14 cal ka. They also suggested on the basis of moraine data that an older group of moraines was constructed at least 30 ka BP.

Together, these chronologies represent a complex regional response of glaciers to moisture availability and temperature depression. In the maritime Olympic and Cascade ranges, the LGM-correlative advance appears to have been limited by aridity, documented in pollen data and suggested by modeling results to reflect the development of dry, easterly ice sheet anticyclonic winds. Earlier, more extensive advances were likely driven by less severe temperature depression coupled with sustained moisture availability. In the inland Wallowa and Sawtooth Mountains, the LGM-correlative advance is extensive, suggesting that those regions were either unaffected by the anticyclone, or that the glaciers were less strongly influenced by reduced moisture availability. The 17 ka advance appears regionally consistent, documented in four of the five chronologies, and possibly present in the fifth (Olympic Mountains) as well. This advance was likely driven by reinvigoration of westerly moisture transport as the ice sheet anticyclone weakened.

In Situ Cosmogenic ^{10}Be dating of the Quaternary glaciations in the southern Mountain Shaluli on the Southeastern Tibetan Plateau

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It is generally considered that four times ice age happened during the Quaternary epoch on the Tibetan Plateau. However, the research on the chronology of the four times ice age is not substantially enough. The Mountain Shaluli on the Southeastern Tibetan Plateau is the typical place for plaeo-glacier study, because there are abundant Quaternary glacial remains there. This paper tries to discuss the ages of the Quaternary glaciations, based on the exposure dating of roche mountonnee、moraines and glacial erosion surfaces using *in situ* cosmogenic isotopes ^{10}Be. It is found that the exposure age of the roche mountonnee at Tuershan is 15 ka, corresponding to Stage 2 of the deep-sea oxygen isotope, suggesting that the roche mountonnee at Tuershan is formed in the last glacial maximum. The exposure age of glacial erosion surface at Laolinkou is 130-160 ka， corresponding to Stage 6 of the deep-sea oxygen isotope. The oldest end moraine at Kuzhaori may form at 421-766 kaBP, corresponding to Stage 12-18 of the deep-sea oxygen isotope. In accordance with the climate characteristic of stages 12,14,16 and 18 reflected by the deep-sea oxygen isotope, polar ice cores and loess sequence, the oldest end moraine at Kuzhaori may form at stage 12 or stage 16, the latter is more possible.

An assessment of the radiocarbon dating of glacial landforms in Tibet and the bordering mountains

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Radiocarbon dating was done on both organic and inorganic matter in glacial till in Tibet and surrounding mountains since the 1970s last century. We summarized these data and assessed their reliability to determine their timing and spatial variations. Based on these calibrated data, five Quaternary Glaciation stages were quite clearly present since the Last Glaciation Maximum. Little Ice Age, Stage III (1871±20AD), Stage II (1777±20AD), Stage I (1528±20AD); Neoglacial, Stage III (1.5-1.6 ka BP), Stage II (2.2-2.4 ka BP), Stage I (3.2-3.6 ka BP); Last Glaciation, Stage IV (12.6-13.4 ka BP), Stage III (17.5-25 ka BP). Dating data show that more glacial advances occurred in boring mountains than in inner Tibet. The timing of Quaternary glaciations in northern Tibet and bordering mountains are synchronized with the cooling events in northern hemisphere, while there were more glacial advances in the southern Tibet and bordering mountains since the Last Glaciation Maximum. The temporal and spatial variation in Quaternary glaciations are contributed to more precipitation around neighboring mountains than inner Tibet.

Asynchronous Glacial Chronologies in the Central Andes (15-40°S) and Paleoclimatic Implications

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We have established glacial chronologies along a N-S transect over the Central Andes using ^{10}Be surface exposure dating. Our results show that maximum glacial advances occurred asynchronously and reflect the varying influence and shifts of the major atmospheric circulation systems during the Late Quaternary: the tropical circulation in the north and the westerlies in the south.

In Bolivia (three research areas in the Cordillera Real and the Cordillera Cochabamba, ~15°S) glacial advances could be dated to ~20 and 12 ka BP. This is in good agreement with published exposure age data from moraines in Bolivia and Peru (provided that all ages are calculated following the same scaling system). Accordingly, the maximum glaciation there probably occurred roughly synchronous to the temperature minimum of the global Last Glacial Maximum (LGM) and the lateglacial cold reversals. Strict correlation with neither the Younger Dryas in the northern hemisphere, nor the Antarctic Cold Reversal is possible due to the current systematic exposure age uncertainties ~10%). Glacier-Climate-Modelling corroborates the sensitivity of the reconstructed glaciers to temperature changes, rather than precipitation.

On the contrary, there is good evidence for the dominant role of precipitation changes on the glacial chronologies in the lee of the Cordillera Occidental, i.e. on the Altiplano and further south. The pronounced lateglacial wet phase, which is well documented in lake transgression phases as far south as 28°S (→ tropical moisture source), seems to have caused glacial advances even at ~30°S. In two research areas in Chile at that latitude, we were able to date several lateglacial moraines. Besides, the maximum datable glaciation there occurred at ~30 ka BP. That is significantly earlier than the LGM (sensu strictu) and points to favourable climate conditions for glaciation at that time (particularly increased precipitation). We conclude that the westerlies were more intensive or shifted northward at ~30 ka BP. We have not yet been able to date LGM moraines as far south as ~40°, which would indicate the transition of precipitation- to temperature-sensitive glaciers. Instead, our preliminary exposure age chronology from Valle Rucachoroi ~39°S, Argentina) suggests that the maximum glaciation there occurred also at ~30 ka BP, but that the valleys became ice-free only by ~15 ka BP. Samples from moraines in the cirques are currently in progress and may document lateglacial re-advances.

Periglacial planation surfaces of the Tibet Plateau and its highland effects on cooling the earth

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Tibet Plateau has clear vertical geomorphology zoning and it consists of glacial zone of glacial mountains, periglacial geomorphology zone of the plateau surfaces , fluvial geomorphology zone of deeply dissected gorges . In plateau surface areas underlain mostly by soft rocks , tectonic uplifting rates are less than the maximum potential denudation rate of the rocks and terrain is under a dynamic equilibrium condition between tectonic uplifting and terrain denudation after initial planation stage . In the glacial mountain areas underlain mostly by hard crystalline rocks, tectonic uplifting rates are greater than the maximum potential denudation rate of the rocks and terrain is not under a dynamic equilibrium condition between tectonic uplifting and terrain denudation ,therefore, mountains are still growing up. The Tibet Plateau surfaces are planation products of freeze-thaw creep and earth flow under periglacial climate, therefore, spatial variation of the plateau surface elevation, that the elevation decreases from south to north and from west to east, is not only controlled by tectonics, but also climate. Tibet Plateau surfaces have always been in periglacial geomorphology zone since initial raising up to zone, and there has no giant ice cap existed in the plateau.

Part of the ground radiation absorbed by the atmosphere is radiated back toward the earth surface, a process called counterradiation. For this reason, the lower atmosphere acts a blanket that returns heat to the earth. This mechanism helps to keep the earth surface warm. The principle is described as greenhouse effect. For a certain latitude, the atmosphere at highland and low land receive same amount of solar radiation (shortwave), but longwave radiation from atmosphere to space at highland is greater than it at lowland because the atmosphere layer is much thinner at high land than it at low land and downward counterradiation at high land is much less. The high land is usually colder than the lower land If lateral energy transform in atmosphere is ignored, the difference of solar radiation between Tibet Plateau and Qiqihaer is 40×103 cal/cm2.yr ,which may represent the reduction of counterradiation due to uplifting of the plateau since Cenozoic Era. The plateau has an area of 2.3×106km2 and the counterradiation of the plateau have reduced by 9.2×1020 cal/cm2.yr ,which accounts for18％of the total solar radiation over the plateau, and 7.1×10-4 of the total solar radiation over the planet. Assuming that the counterradiation reduction due to uplifting of Tibet Plateau since Cenozoic Era accounts for 10% of the total reduction of all highland over the planet , the total reduction accounts for 7.1×10-3of the total solar radiation over the world. If the energy transported by atmospheric circulation from lowland to highland, the extent of highland contribution to counterradiation reduction should be much greater than the above value. The proposed hypotheses of highland effect on cooling the earth can be used to explain the relationships between three tectonic movements and their correspondent cold (glacial) periods since Phanerozoic eon : Coledonian movement ~ Ordovician/Silurian period ; Hercynian movement~ Carboniferous / Permian period ; Himalaya movement ~ Cenozoic Era.

Skylight effects of highland on the earth's heat energy delivery and cooling of the earth during Cenozoic Era

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Based on solar radiation equilibrium on the earth surface, "skylight effects of highland on the earth's heat energy delivery", resulted from reduction in inverse radiation of the atmosphere of highland by comparison of the atmosphere of lowland, are analyzed. The effects of the reduction of inverse radiation due to uplifting of Tibet Plateau to the solar radiation equilibrium on the earth surface are assessed. It is proposed that the cooling of the earth during Cenozoic Era may be caused by formation of the highlands of the low and middle latitudes on the earth.

Quaternary glacial sediments sequences in the Ateaoyinake River Valley, Tianshan Mountains

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Ateaoyinake River, located on the southern slope of the Tumer Peak in the western Tianshan Mountains in China, is the largest modern glaciation center. Six relative integrated sets of glacial tills formed in Quaternary glacial-interglacial cycles were well reserved in this valley. ESR dating (OSL dating technique as a supplementary method) of the glacial tills and outwashes was carried out using Ge centers in quartz grains. The dating results of them are 7.3±0.8ka BP (OSL, outwash sands), 12.3±1.2ka BP (OSL) and 15~29ka BP, 46~54ka BP, 56~65ka BP, 155.8±15.6ka BP and 234.8±23.5ka BP, 453.0±45.3ka BP respectively. Considering the dates and the principles of geomorphology and stratigraphy, they deposited in Neoglaciation, MIS2, 3b, 4, 6 and 12. The results of the third set of the glacial tills demonstrate that a larger glacier advance happened in MIS3b in this area, similar with the extent of the Last Glacial Maximum (MIS2). The glaciation that deposited the oldest glacial tills are called "Qingshantou Glacial Stage", the dating result of it consistent with the ages (459.7±46ka BP and 477.1ka BP) of the Gaowangfeng glacial tills at the headwaters of the Urumqi River, demonstrating that the western and the middle segments of the Tianshan Mountains were rising to a sufficient elevation and entered cryosphere at least in MIS12, resulting in development of the glaciers in that period.

Pleistocene Glaciations of the Yulong Mountains, Yunnan, China

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Yulong Mountains (27°10′～27°40′N,100°09′～100°20′E), situated in the north of Yulong County, Lijiang City, Yunnan Province and the southeast margin of the Tibetan Plateau, are the southernmost mountains with existing glaciers both in China and Eurasia. On the east, northeast and west feet of the mountains, there are series of relics of Pleistocene glaciations. Studying these glacial relics and reconstructing their evolutionary history are important to understand the uplift histories of the Hengduan Mountains and the Tibetan Plateau and the effects to climate and environmental changes, as well as the development of Jinsha River. It has also potential values for the protection of the tremendous resources of hydraulics and tourism in this area.

The authors surveyed, studied and mapped the Pleistocene glacial deposits along the eastern and western sides of the Yulong Mountains. We have analyzed calcareous cement deposits, using ESR, OSL and U-series dating methods, and classified them into remnants of four glaciations, i.e. the early-Middle Pleistocene Yulong Glaciation (0.7～0.6MaBP), the middle-Middle Pleistocene Ganhaizi Glaciation (0.53-0.45MaBP), the late-Middle Pleistocene Lijiang Glaciation (0.31～0.13MaBP) and the middle-late Late Pleistocen Dali Glaciation (0.075～0.01MaBP).

Results show that the Yulong Mountains area was a part of the united peneplain ranging from the Tibetan Plateau to the Yunnan-Guizhou Plateau, with an elevation of 500～1000m a.s.l. during Miocene. In Pliocene and the Early Pleistocene, the Yulong Mountains were uplifted and the Lijiang Basin, Daju Basin and Shigu Valley and other basins were subsided due to fault activities along the east and west sides of the Mountains. At this time, the ancient Jinsha River cut through the present valley. In the early Middle Pleistocene, the Yulong Mountains had uplifted to an elevation reaching snowlines, and giant piedmont glaciers of the Yulong Glaciation, the largest glaciation in this area, occurred to their east, west and northeast feet. Because of obstruction by moraines of the Yulong Glaciation, the Shigu Valley became a glacial-blocked lake, "Lake Shigu". Glaciers of the Ganhaizi Glaciation were possibly piedmont or valley ones, but much smaller than the Yulong Glaciation. During the two interglacial periods in the Middle Pleistocene，some tributaries of the Jinsha River were formed. In the late Middle Pleistocene, large-scale valley glaciers of the Lijiang Glaciation were developed in the tributaries of the Jinsha River and three fluvioglacial fans from the west feet of the Yulong Mountains had possibly entered into the Lake Shigu. In the Last Interglacial Period, water of the Lake Shigu was wholly discharged and then the present Jinsha River and their four terraces（5～15m， 15～25m， 25～35m and 40～50m，respectively）were formed. In the middle-late Late Pleistocene, valley glaciers of the Dali Glaciation were also developed in the tributaries of the Jinsha River, but their scales were much smaller than that of the Lijiang Glaciation.

Quaternary glaciations in the eastern Qinghai-Xizang plateau

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There exist rich Quaternary glacial traces in the eastern Tibetan plateau. We investigated Luding moraine and Mianning moraine and Daqingliangzi Moraine and Zagulao terraces and Haizishan moraine and Zheduoshan pass and Changtai glacial cap.There is an old glaciation 4.3Ma B.P. During Quaternary, there are five glaciations. The study of moraines and their geomorphic features, clear late Cenozoic glacial change, and define the paleoclimatic events. At last, it devote to past global change and the effect of plateau uplift.Near Luding county, there is 43-meter-thick gravel bed beneath Xigeda lacustrine. We researched gravel sedimental character and surface shape analysis of Quartz sands.It belongs to moraine. Through magnetostratigraphy dating, the gravel bed formed Cochiti event of Gibert Epoch, about 4.3Ma B.P. The glaciation is the oldest one in the eastern Asia.

In the eastern Luoji mount and south to Qionghai lake, there is 15-meter-thick gravel bed, which distribute in the pass between Zemu river and Ezhang river. The purple mud-gravel is covered by Daqingliangzi lacustrine.The gravels mainly came from western Luoji mount. Its sedimental features and SEM analysis of Quartz sands can explain that the mud-gravel is typical moraine. There exist an erosional face between the mud-gravel and Daqingliangzi lacustrine. We studied the magnetostratigraphy of the lacustrine. The beginning age of lacustrine is 2.14 Ma B.P, Therefore the Daqingliangzi moraine appeared the early stage of early Pleistocene, and earlier than 2.14 Ma B.P.

In the back mount of Xiancao village north to Mianning county, we found a mud-gravel. The Xiancao gravel bed is about 20-meter-thick, and grey-white clay-sand-gravel mixed sediment. We found scratch gravel and pressing fissure gravel. The gravels included granite boulder away from ten kilometers. The scanning electron microscope analysis of Quartz sands testifies the gravel is moraine. According to ESR dating, the Xiancao moraine' age is 101.2 to 128.8 Ma B.P., and belong to the middle stage of early Pleistocene.

We dated exposure age of ^{10}Be、^{26}Al and ^{21}Ne of the moraines in Tanggula mountain and Haizishan pass in Litang and Zheduoshan pass. First data of exposure age of moraines in the plateau were got. Three kinds of exposure ages are similar. According to the dating, there are two glaciations, one is formed during 16-80 ka BP, the other during 160-180 ka BP.

Near Lixian county, here are three level terraces in the north of Zagulao river, covered by loess. The three gravels belongs to moraines. We sampled in the bottom of these gravels to date. The upper terrace's ESR age is 691 ka B.P., the middle one 613 ka B.P., and the lower one 79 ka B.P. The three terraces represent two glaciations. The upper and the middle terraces are two stages of one big glaciation.

In the northern section of Shaluli mount, there grew an ice cap with an area of more than 2000 square kilometers. The ice cap locates between Ganzi and Baiyu county. We found lots of glacial traces, such as glacial lakes and glacial valley and side moraines and end moraines and polish surface and erratic boulders etc.. According to initial research, there are two stages of glaciations,the older glaciation and the last glaciation. During the last glaciation, there are six arc dikes of end moraines in the exit of Nalengcuo valley. The oldest end moraine's exposure age is 19 ka BP., then the six end moraines represent glacier retreat in different stages since last glaciation. It will be a typical district to study LG and LMG and YD in Tibetan plateau.

In a word, we established glaciations since late Cenozoic in eastern Qinghai-Xizang plateau. The oldest glaciation appeared 4.3 Ma B.P.. During Quaternary, there are five glaciations. The first one appeared earlier than 2.14 Ma B.P.The second one formed 101.2 to 128.8 Ma B.P.,and the third one 613-691 ka B.P., and the fourth one 160-180 ka B.P.. The last one is last glaciation. The glaciations in eastern plateau are typical and complete. The research will help us to understand the glaciations in plateau and its affection on global climate.

Cosmogenic radionuclide ^{10}Be exposure ages for Guxiang and Baiyu Glaciations in the southeastern Tibetan Plateau

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Guxiang and Baiyu Glaciations are two representative ones among the Tibetan Plateau glaciations suggested so far. They have been widely regarded as the model of other glaciations in the Tibetan Plateau and its surrounding mountains, but their numerical ages are unknown so far. The glacial boulders of Guxiang and Baiyu Glaciations are dated using cosmogenic radionuclide Be-10. The most extensive advance of the Guxiang Glaciation occurred during or before marine oxygen isotope stage 6 based on 4 Be-10 model exposure ages that range from 112.9±16.7 ka BP to 136.5±15.8 ka BP. This advance extended as far as tens of kilometers from its source to Guxiang Village and completely filled the Boduizangbu River Valley. The second most extensive glacial advance of Baiyu Glaciations occurred at the end of marine isotope stage 2 based on 8 Be-10 ages that range from 11.1±1.9 to 18.5±2.2 ka BP. This advance filled the Baiyugou Valley and Zhuxigou Valley and blocked the Boduizangbu River Valley.

Timing and nature of mountain glacier advances, from 5e to Younger Dryas

Exploring aspects of climate change, glaciation and uplift

Field Guide

Xining-Lhasa

Compiled by

Lewis A. Owen

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Late Quaternary glaciation of Tibet and the bordering mountains: a review

FRANK LEHMKUHL AND LEWIS A. OWEN

BOREAS

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Abundant glacial geologic evidence present throughout Tibet and the bordering mountains shows that glaciers have oscillated many times throughout the late Quaternary. Yet the timing and extent of glacial advances is still highly debated. Recent studies, however, suggest that glaciation was most extensive prior to the last glacial cycle. Furthermore, these studies show that in many regions of Tibet and the Himalaya glaciation was generally more extensive during the earlier part of the last glacial cycle and was limited in extent during the global Last Glacial Maximum (marine oxygen isotope stage 2). Holocene glacial advances were also limited in extent, with glaciers advancing just a few kilometers from their present ice margins. In the monsoon-influenced regions, glaciation appears to be strongly controlled by changes in insolation that govern the geographical extent of the monsoon and consequently precipitation distribution. Monsoonal precipitation distribution strongly influences glacier mass balances, allowing glaciers in high altitude regions to advance during times of increased precipitation, which are associated with insolation maxima during glacial times. Furthermore, there are strong topographic controls on glaciation, particular in regions where there are rainshadow effects. It is likely that glaciers, influenced by the different climatic systems, behaved differently at different times. However, more detailed geomorphic and geochronological studies are needed to fully explore regional variations. Changes in glacial ice volume in Tibet and the bordering mountains were relatively small after the global LGM as compared to the Northern Hemisphere ice sheets. It is therefore unlikely that meltwater draining from Tibet and the bordering mountains during the Lateglacial and early Holocene would have been sufficient to affect oceanic circulation. However, changes in surface albedo may have influenced the dynamics of monsoonal systems and this may have important implications for global climate change. Drainage development, including lake level changes on the Tibetan plateau and adjacent regions has been strongly controlled by climatic oscillations on centennial, decadal and especially millennial timescales. Since the Little Ice Age, and particularly during this century, glaciers have been progressively retreating. This pattern is likely to continue throughout the 21st century, exacerbated by human-induced global warming.

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The Tibetan Plateau and bordering mountains are the greatest glaciated tracks outside the Polar Region. They have a profound influence on regional and global atmospheric circulation and are therefore important for our understanding the dynamics of global environmental change (Ruddiman & Kutzbach 1989; Molnar & England 1990; Prell & Kutzbach 1992; Owen *et al*. 2002d). Changes in glaciation and hydrology in Tibet and the bordering mountains throughout the late Quaternary may have altered the input of fresh water into the seas and oceans adjacent to the Asian continent. This in turn could have had a major impact on ocean circulation and global climate, an impact analogous to effects of the melting of the Laurentide Ice Sheet on North Atlantic oceanic circulation towards the end of the Last Glacial (cf. Broecker *et al*. 1989). In particular, glaciation throughout Tibet and the bordering mountains was probably far more extensive during the Late Pleistocene than at present, and it is possible that when glaciers began to retreat during the termination of the last glacial cycle substantial amounts of meltwater produced new drainage systems feeding into the adjacent seas. Yet, despite its importance, the timing and extent of glacial advances are still highly debated. To investigate links between glaciation, hydrology and environmental change in the high mountains of Central Asia, and the possible relationship with global climate change, this article aims to synthesis new research and the current knowledge on the late Quaternary glaciation of Tibet and the bordering mountains (Fig. 1).

This paper extends work presented in a comprehensive bibliography produced by Barnard & Owen (2000), research papers (Owen & Lehmkuhl 2000; Owen & Zhou 2002) and summaries of the Global Mapping Project of INQUA on the glacial geology in central Asia (Ehlers & Gibbard 2004). We stress the importance of developing a modern framework for the geomorphic and sedimentological analysis of glaciogenic sediments and landforms in high mountain environments for the accurate reconstruction of former glaciers. We highlight the problems of dating glacial

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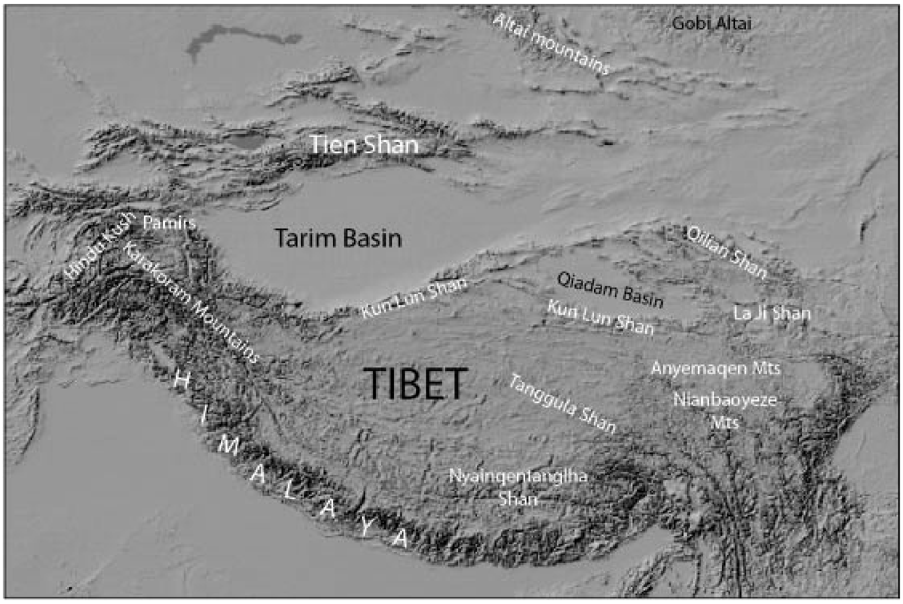

Fig. 1. The extent of the region covered by this article.

successions and encourage programmes for numerical dating in critical regions, as suggested by Benn & Owen (2002). Furthermore, we emphasis the problems of using and calculating equilibrium-line altitudes (ELAs) as a means of quantifying glaciation and reiterate the recommendations provided to help quantify the degree of glaciation using reconstructions of former glacier extent presented by Benn & Lehmkuhl (2000), Benn *et al*. (2005), Owen & Benn (2005). We also highlight the usefulness of other palaeoclimate proxy data, such as the loess, lacustrine, fluvial and palaeobotanical records. In particular, we highlight the importance of the lake record, especially because, during the Pleistocene, lakes in the western Tibetan Plateau covered an area four times the present extent ($\sim$80 000 km^2, vs. $\sim$20 000 km^2; Lehmkuhl & Haselein 2000). Such lake level changes could have profound effects on regional climate because of changes in albedo and precipitation.

Regional setting

Tibet and the bordering mountains formed as a consequence of the collision of the Indian and Eurasian continental plates initiated $\sim$50 million years ago. Geologically, the region is a complex assemblage of rocks of different ages that are still actively being deformed by the continued northward movement of the Indian continental plate at $\sim$50 mm/year (DeMets *et al*. 1994). The average altitude across the Himalayan–Tibetan region is $\sim$5000 m a.s.l. (Fielding 1996). The region stretches $\sim$2000 km and $\sim$1500 km in an east–west and north–south direction, respectively (Fig. 1). This mountain mass comprises a series of approximately east–west trending ranges that include, from south to north, the Siwaliks, Lesser Himalaya, Greater Himalaya, Transhimalaya, Nyaingentanglha Shan, Tanggula Shan, Bayan Har Shan, Kunlun Shan, Altun Shan and Qilian Shan. We include the Pamir, Tian Shan and Altai Mountains in our study region because they broadly border the Tibetan–Himalayan region to the west (Fig. 1).

These mountain ranges are influenced by four major climatic systems: the mid-latitude westerlies, the south Asian monsoon, the Mongolian high-pressure system and the El Nino Southern Oscillation (ENSO). The relative importance of each varies throughout the region, with the eastern end and the southern slopes of the Himalaya being the wettest (Fig. 2). The southern slopes of the Himalaya and the high mountains of eastern Tibet receive snowfall mainly in the summer monsoon season, whereas northern and western Tibet, and ranges such as the Karakoram Mountains, Pamir, Tian Shan and Altai, receive heavy snowfalls during the winter with moisture supplied from the mid-latitude westerlies and the Mongolian high pressure system (e.g. Böhner 1996). This snow supports ice caps and valley glaciers throughout Tibet and the bordering mountains. As a consequence, the region presently has the largest concentration of glaciers outside the Polar Regions ($\sim$126 200 km^2; Haeberli *et al*. 1989).

Major rivers, including the Indus, Ganges, Tsangpo-Bhramaputra, Mekong, Yangtze and Huanghe, drain the region. They are essentially fed by glacial melt-water and monsoon precipitation; they have discharges and they produce sediment loads that are among the highest in the world. Furthermore, these rivers are essential for the agricultural, industrial and domestic needs of approximately three-quarters of the world's population.

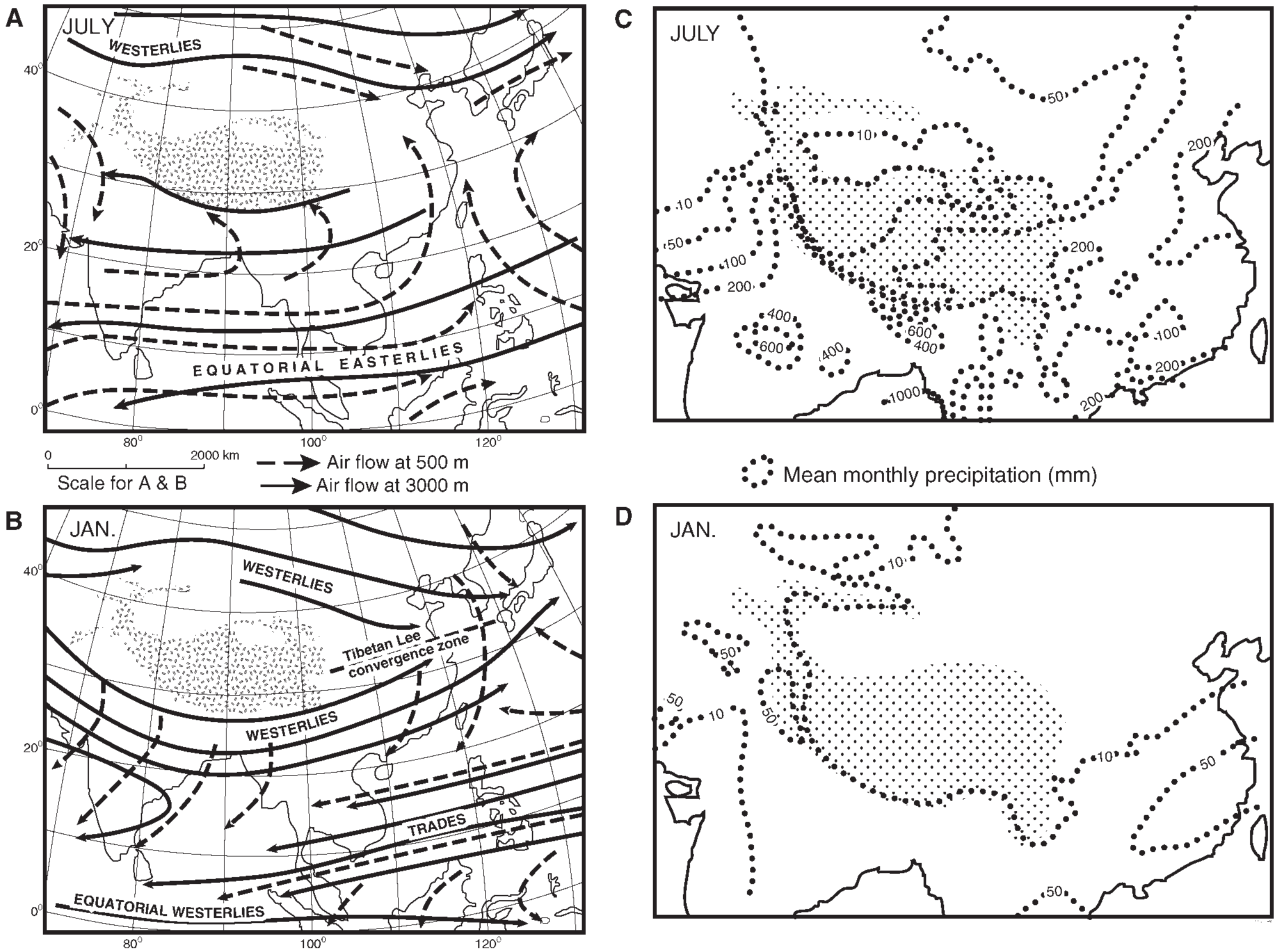

Fig. 2. Characteristic air circulation (A & B) and precipitation (C & D) over southern and central Asia. The Tibetan Plateau and bordering mountains above 5000 m a.s.l. are shown within the dotted areas. The solid lines in (A) and (B) indicate airflow at about 6000 m a.s.l. and 3000 m a.s.l., respectively, and the dashed lines airflow at about 600 m a.s.l. (C) and (D) show the strong N–E and E–W precipitation gradients (adapted from Owen *et al*. 1998 and Benn & Owen 1998).

Timing and extent of glaciation

Relative glacial chronologies have been developed throughout the Himalaya and Tibet using morphostratigraphy aided by relative weathering studies (e.g. Burbank & Kang 1991; Hövermann *et al*. 1993a, b; Hövermann & Lehmkuhl 1994; Lehmkuhl 1995a, b, 1997, 1998b; Owen *et al*. 1997; Lehmkuhl *et al*. 2000, 2002) and soil development (e.g. Bäumler *et al*. 1997; Guggenberger *et al*. 1998; Zech *et al*. 2000). Reconstructing palaeoenvironmental change from glacial geologic evidence in Tibet and the bordering mountains has been difficult because of the lack of organic material for radiocarbon dating, and the problems of correctly identifying the origin of highly dissected landforms. Numerous radiocarbon dates are available for the wetter parts of the Himalayan–Tibetan region, but most are limited to Holocene proglacial deposits that poorly define the timing of glaciation (Röthlisberger & Geyh 1985; Lehmkuhl 1995a, 1997). Newly developing techniques that include optically stimulated luminescence (OSL) and cosmogenic surface exposure dating are now allowing glacial successions throughout Tibet and the bordering mountains to be dated and correlated (Lehmkuhl *et al*. 2000, 2002; Phillips *et al*. 2000; Richards *et al*. 2000a, b; Owen *et al*. 2001, 2002a, b, c, 2003a, b, c, 2005; Schäfer *et al*. 2002; Tsukamoto *et al*. 2002; Finkel *et al*. 2003; Zech *et al*. 2003; Spencer & Owen 2004; fig. 3).

Tibet

Reconstruction of the extent of glaciation across the Tibetan Plateau has a long history (Klute 1930; Frenzel 1960; Kuhle 1985; Frenzel *et al*. 1992; Ono *et al*. 2004; Klinge & Lehmkuhl 2004). More recently, Chinese workers have compiled synthesis maps to show the probable extent of glaciation across the Tibetan Plateau (Shi *et al*. 1986, 1993; Liu *et al*. 1988; Shi 1988; Li *et al*. 1991; Shi 1992). In a series of articles, Kuhle (1985, 1986, 1987, 1988a, b, 1990a, b, 1991, 1993, 1995) hypothesized that an extensive ice sheet covered essentially the whole of the Tibetan Plateau during glacial times. The existence of an extensive ice sheet has been one of the most contentious glacial issues concerning Tibet over the past few decades. Numerous publications, however, discuss the evidence against an extensive ice sheet (Derbyshire 1987; Zheng 1989; Pu 1991; Shi 1992; Hövermann *et al*. 1993a, b; Lehmkuhl 1995a, 1998b; Rutter 1995; Lehmkuhl *et al*. 1998; Zheng & Rutter 1998; Zhou & Li 1998; Schäfer *et al*. 2002; Owen *et al*. 2003c) and it is now generally accepted that a large ice sheet did not cover the Tibetan Plateau, not at least during the past few glacial cycles (see more detailed discussion below).

One of the main reasons for the differing opinions on the distribution and extent of Pleistocene glaciations on and around the Tibetan Plateau is the lack of general agreement on terminology and stratigraphic division of the different end moraine sequences and till deposits in the various mountain areas (Lehmkuhl 1997). Some relative chronologies exist for mountain glaciations, but the timing of glacier oscillations is poorly understood due to the lack of known numerical ages on moraines. Even a common relative stratigraphy based on ELA depressions, such as the one developed for the European Alps, is not available. An evaluation of recent glacial geologic studies suggests that Li *et al*. (1991) provide the best reconstruction of the extent of glaciation for the entire Tibetan Plateau. Their map shows limited glaciation in the interior of the Tibetan Plateau but expanded ice caps and valley glaciers on its margins during the last glacial cycle. They also provide a reconstruction of the former extent of a small ice sheet in northeast Tibet during the penultimate glacial cycle. The lack of numerically dated glacial landforms, however, makes it difficult to test whether the glacial limits that they map are not diachronous. The exact details of the extent of glaciation at particular times during the Quaternary are therefore still highly debated.

In the Chinese literature, the last glaciation is commonly divided into two main stages. These are thought to represent glaciations that occurred during marine oxygen isotope stages (MIS) 2 and 4 and are separated by an interstadial that lasted from about 55 to 32 ka (e.g. Liu *et al*. 1985; Li & Pan 1989; Thompson *et al*. 1989, 1997; Zhang *et al*. 1991). Chinese workers such as Li & Shi (1992) and Li & Pan (1989) argue that the expanded ice caps and valley glaciers on the Tibetan Plateau during the last glacial began substantial retreat between 15 and 13 ka. Much of this work is summarized in Lehmkuhl (1995a), Owen *et al*. (1997) and Benn & Owen (1998). The summary articles emphasize, however, that the timing of glaciation is poorly defined because of the limited number of numerical dates that were undertaken in these studies and state that great care should be taken in making regional generalizations about the timing and extent of glaciation.

During the past decade, however, OSL and cosmogenic surface exposure dating has been providing new insights into the ages of glacial landforms and the timing of glaciation. Studies using these techniques are showing that glaciation was restricted in extent during the last glacial cycle in regions such as central Tibet. In particular, Lehmkuhl *et al*. (2000, 2002) have shown that the morphology of the northern Nyainqêntanglha Shan and Mt. Jaggang, as well as the surroundings of Lakes Siling Co and Dagze Co, has demonstrated that the extent of ice during the late Quaternary was very limited. A luminescence date of 89 ± 10 ka on aeolian silt that overlies the oldest terminal moraines on the northern slope of the Nyainqêntanglha Shan helped define the timing of the penultimate glaciation (Lehmkuhl *et al*. 2002). In addition, Schäfer (2000) and Schäfer *et al*. (2002) presented cosmogenic surface exposure dates from the Tanggula Shan, dating moraines to between 123 ka and 261 ka that were only a few tens of kilometers beyond the present ice margins. These data suggest that there was no extensive plateau glaciation around 20 ka and that there was no ice sheet over the whole of Tibet during the Late or Middle Pleistocene. Owen *et al*. (2005) confirmed the Schäfer *et al*. (2002) study by undertaking a more extensive examination of the Tanggula Shan and extending their work onto the eastern slopes of the Nyainqêntanglha Shan.

Studies on the glacial successions in the Anyemaqen and Nianbaoyeze mountains in NE Tibet using cosmogenic surface exposure dating methods suggest that glaciers in the more monsoon-influenced regions of Tibet advanced during times of increased insolation, such as MIS-3 and the early Holocene (Owen *et al*. 2003c). This suggests that increased moisture flux during these times created higher precipitation in the form of snow at high altitude, which in turn led to positive glacial mass balances and glacial advance. However, although precipitation would have been reduced during the insolation minima of MIS-2 (global Last Glacial Maximum: LGM), temperatures were low enough to lead to positive glacier mass balances, allowing glaciers to advance, albeit not as far as during MIS-3.

Lakes records (sediments and shorelines) in Tibet and the adjacent deserts support the view that higher moisture flux occurred during times of increased insolation. Summaries of fluctuations of late Quaternary lake levels in Tibet and the desert margins of central Asia are provided in Fang (1991), Gasse *et al*. (1991, 1996), Frenzel (1994), Pachur *et al*. (1995), Tarasov *et al*. (1996), Benn & Owen (1998), Qin & Yu (1998), Tarasov & Harrison (1998) and Wünnemann *et al*. (1998). A discussion of the relationship between lake level changes, mountain glacier fluctuations and desert margins, and regional palaeoenvironmental changes in Central Asia is reviewed in Lehmkuhl & Haselein (2000).

There is increasing evidence for limited glacier advances during MIS-2 (LGM) throughout the semi-arid and monsoon-influenced regions of Tibet (Schäfer *et al*. 2002; Owen *et al*. 2003a, b, c, 2005). Schäfer *et al*. (2002), for example, produced cosmogenic surface exposure ages on erratics from the eastern margin of the Tibetan Plateau (close to the city of Litang, 99°33′E, 30°15′E) indicating that valley glaciation was only 10 km away from the present glacier snout. These were dated between 14 ka and 30 ka and suggest that the main glacial advance was at 17000 ± 1000 yr BP. Similarly, in the Qilian Shan and Li Ji Mountains in NE Tibet, cosmogenic surface exposure and OSL ages support limited glacial advances during the LGM (<10 km long; Owen *et al*. 2003a, b). Likewise, on the Karola Pass in southern Tibet north of the Transhimalya, Owen *et al*. (2005) provide cosmogenic surface exposure ages on moraines that demonstrate a MIS-2 glacial advance <10 km in extent.

There are only a few published studies on the Lateglacial and Holocene fluctuations of mountain glaciers on the Tibetan Plateau and the surrounding areas (Pu 1991; Lehmkuhl 1997; Owen *et al*. 2003a, b, c, 2005). Glacier advances have been dated to about 15 ka in West Kunlun, in the Tian Shan and in the mountain areas surrounding the Qaidam Basin (Kang 1992; Shi 1992; Guo *et al*. 1995; Owen *et al*. 2003a). Several Chinese authors (e.g. Wang & Fan 1987) argue for Holocene glacier advances, but most do not differentiate between Lateglacial end moraines or ice marginal limits and the LGM (MIS-2) terminal moraines. Chronology is mainly based on radiocarbon dating of organic matter that overlies terminal moraines. These dates are minimum ages and consequently only a few Pleistocene and Holocene glacial advances have been dated with a sufficient degree of confidence. Beug (1987), Wang & Fan (1987) and Lehmkuhl (1995a) suggest that Early Holocene glaciers had approximately the same size as modern glaciers. However, recent cosmogenic surface exposure dating of moraines in the Anyemaqen, on the Karola Pass and Gonga Shan suggest that glaciers advanced several kilometers beyond their present positions during the Early Holocene with an ELA depression of approximately 100 m (Owen *et al*. 2003c, 2005). The Little Ice Age and Neoglacial moraines are defined by dates on wood and branches incorporated in moraines in southern Tibet (Arza glacier; Wang & Fan 1987) and, for example, in the Qilian Shan (Pu 1991). Pollen records show a cooler and moister period during the Late Holocene (e.g. Sun & Chen 1991; Schlütz 1999). Historical records suggest that brief cold and wet intervals occurred periodically throughout the Late Holocene. These have been reported from the Taklimagan desert (in the Tarim Basin; Fig. 1) at about 2000 years BP and during the Little Ice Age for example (Yang 1991; Yang *et al*. 2002).

The nature of glacial fluctuations since the Little Ice Age (17th to 19th centuries) is discussed in Su & Shi (2002). They show that the mean temperature of monsoonal temperate glaciers in China has increased by 0.8°C since the Little Ice Age and has resulted in a decrease that amounts to an equivalent of 30% of the modern glacier area, a loss of some 4000 km^2 of glaciated area. They predict that by the year 2100 the temperature in the monsoonal temperate glaciers of China will rise by 2.1°C and that the glacier area will decrease by 75% (~9900 km^2 loss of glaciated area). Furthermore, they predict that precipitation will decrease in the coming decades and that glacier retreat will accelerate, but they argue it is unlikely to exceed a loss of 80% of the total glaciated area. General circulation models for global warming, however, suggest that monsoon precipitation will increase in the coming years, which may lead to increased snowfall and positive glacier mass balances. Therefore, there is considerable uncertainty as to the future of Tibetan glaciers. However, there is little doubt that glaciers have been retreating and that glacier ice has been warming throughout the last century. Such conditions clearly pose a serious threat to the water resources and environment throughout Central Asia.

Himalaya and Transhimalaya

A comprehensive review of the Quaternary glacial history of the Himalaya was presented in Owen *et al*. (1998), and Owen *et al*. (2002a) evaluated studies of the extent of glaciation throughout the Himalaya during the global LGM (~18–24 ka) as part of the EPILOG (Environmental Processes of the Ice Age: Land, Ocean, Glaciers) program of IGBP/PAGES program IMAGES (International Marines Studies of Global Change). Further descriptions of the Quaternary glacial history of each Himalayan region are provided in Ehlers & Gibbard (2004). The new data highlighted in these publications show that the local last glacial maximum for most of the Himalaya occurred during the early part of the last glacial cycle. In most areas, this probably occurred during MIS-3. In contrast, during the global LGM, glaciation was generally restricted throughout most of the Himalaya and Transhimalaya, with glaciers advancing less than 10 km from contemporary ice margins. Furthermore, recent OSL and comsogenic radionuclide surface exposure dating by Richards *et al*. (2000b) and Finkel *et al*. (2003) in the Khumbu Himal supports the view that glacial advances were restricted (<5 km) during the global LGM (MIS-2), with the local last glacial maximum occurring in the earlier part of the last glacial cycle. Correlating numerical dating studies, Finkel *et al*. (2003) suggest that glaciations can

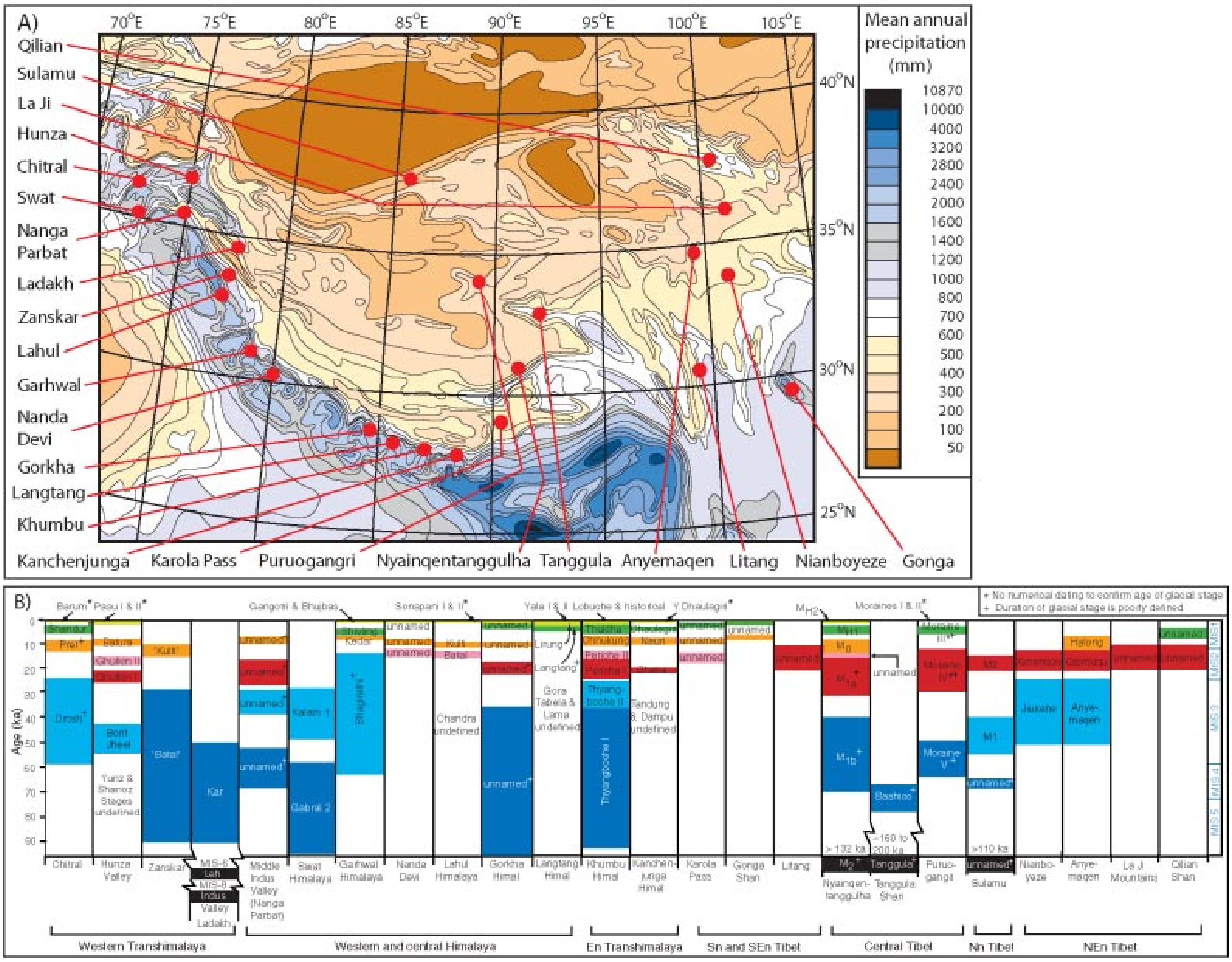

Fig. 3. The contemporary mean annual (A) precipitation across Tibet and the bordering regions showing (B) the locations and glacial chronologies that have reliable numerical dates in the Himalaya and Tibet (adapted from Owen *et al*. 2005). The color bars in (B) represent the likely duration of each glacial advance and the name of each glacial stage has been inserted into the box. An asterisk and cross after each name indicate that no numerical dating has been undertaken to confirm an age and the duration of the glacial is poorly defined, respectively. A tentative correlation is suggested by applying similar colors to the bars of the glacial stages that are likely synchronous. (MIS = marine oxygen isotope stage).

be broadly correlated along the Himalaya. This is summarized in Fig. 3.

The pattern of glaciation, however, appears to be different in the Hindu Kush at the far western end of the Himalayan–Tibetan orogen. Here, Owen *et al*. (2002c) showed that extensive valley glaciers extended to an altitude of ~1670 m a.s.l. during the LGM. Despite this study, most of the data help confirm the view of Benn & Owen (1998) that glaciation through the Himalayan–Tibet region was asynchronous with the Northern Hemisphere ice sheets, with the maximum glacial advances occurring during MIS-3 or MIS-5a to 5d (Owen *et al*. 2005). This asynchroneity is attributed to increased precipitation as snow at high altitudes due to a strengthened monsoon that penetrated further north into the Himalaya during times of increased insolation. In contrast, during times of lower insolation, particularly the global LGM (MIS-2), the influence of the monsoon was reduced, which in turn resulted in lower snowfall and snow accumulation and less extensive glaciation.

It has long been recognized that glaciers throughout the Himalaya and Transhimalayan regions have been retreating throughout the last century (Mayewski & Jeschke 1979; Mayewski *et al*. 1980), but the extent of retreat has not been adequately quantified. As discussed earlier with regard to Tibetan glaciers, it is difficult to assess the likely future trends due to global warming because of the complex feedbacks due to the predicted increase in monsoon precipitation and subsequent increased snowfall leading to possible positive glacier mass balances. Nevertheless, presently retreating glaciers pose serious threats to water resources on the Indian subcontinent as well as hazards such as those from glacial lake outburst floods (GLOFs) that are common as glaciers retreat (Richardson & Reynolds 2000).

Tian Shan and Altai Mountains

There are differing opinions concerning the extent of Late Pleistocene ice in the mountains north of the desert regions of Central Asia. Grosswald *et al*. (1994) and Grosswald & Kuhle (1994) present the view that an extensive ice sheet existed in these regions during the last glacial cycle. They argued that, in the Tian Shan, Late Pleistocene glaciers extended to the foothills, and mountain glaciers south of Lake Baikal terminated in the lake. They estimated LGM ELA depressions to be between 1150 and 1400 m for the Tian Shan, and about 1500 m for the mountains south of Lake Baikal. In contrast, Zech *et al*. (1996) and Heuberger & Sgibnev (1998) show clear evidence that glaciers were restricted to the Tian Shan mountain range and did not reach the foothills and had significantly lower ELA depressions than suggested by Grosswald *et al*. (1994) and Grosswald & Kuhle (1994).

The extent of Pleistocene glaciation in the Russian Altai is debated, but most researchers argue that valley glaciers reached Lake Teleski at 430 m a.s.l. (e.g. Baryshnikov 1992; Budvylovski 1993). The extent of ice was much greater in the western part of the Russian Altai than in the eastern region. In the eastern region, valley glaciers stretched down to the Kuray and Chuya Basins damming the main rivers and forming ice-dammed lakes, which produced the largest mega-floods (GLOFs) in the world (Baker *et al*. 1993; Rudoi 2002). In the eastern part of the Russian Altai and the Mongolian Altai there is evidence of two major Pleistocene glaciations of similar extent (Lehmkuhl 1998a; Klinge 2001; Klinge *et al*. 2003; Lehmkuhl *et al*. 2004). The limited extent of present and Pleistocene glaciers in the western part of the Russian Altai and in the Mongolian Altai is the result of reduced precipitation from west to east, which causes a rise of present and Pleistocene ELAs towards the east. There is an essential lack of numerical dating of glacial sediments in this particular region. Nevertheless, according to the present knowledge, most Late Pleistocene glacier advances in Mongolia and in the Russian Altai took place during MIS 2 and 4 (Grunert *et al*. 2000; Lehmkuhl *et al*. 2004).

Quantifying climate change from glacial geologic data

The most common method for reconstructing climate from glacial data is the use of glacier equilibrium lines. Benn & Lehmkuhl (2000) discuss the mass balance and glacier characteristics of glaciers in the high mountains of Asia and review the methods used to reconstruct former ELAs. They emphasize that methods of ELA reconstruction employed in low-relief environments are not always applicable in high mountains. Benn & Lehmkuhl (2000) argue that some of the methods of ELA estimation (e.g. terminus-to-headwall ratio: THAR) do not give true ELAs, and suggest glacial elevation indices (GEIs) as a more appropriate term, especially in the steep relief of the Himalaya and the Karakoram. Nonetheless, GEIs/ELAs are useful for reconstructing gradients across regions and for regional comparisons. Local and regional variations in ELAs are common in the mountains of Northern India, as shown by the work of Burbank & Fort (1985), Holmes & Street-Perrott (1989) and Sharma & Owen (1996). Nevertheless, these methods show that ELAs during Pleistocene glaciations dropped by between 300 to 500 m in the drier parts, and 600 to more than 1000 m in the wetter parts of the Tibetan Plateau and Himalaya. Figure 4 illustrates examples of present and Pleistocene glaciers and ELAs and can be used to help illustrate and semi-quantify the nature of glaciation in the high mountains of central Asia.

Profile A – A′ in Fig. 4 shows the distribution of present and Pleistocene ice from the Russian Altai in the west towards the Mongolian Altai in the east. The present ELAs in the Russian Altai and Mongolian Altai are between 2600 and 3100 m a.s.l. and between 3100 and 3600 m a.s.l., respectively (Bussemer 2001; Klinge 2001). The Late Pleistocene ELA is calculated to be ~2000 m a.s.l. in the eastern mountain ranges and >2800 m a.s.l. in the western parts of the Russian Altai. The ELA depression was >1000 m in the wettest parts of the western Russian Altai (today's annual precipitation: >1000 mm/a) and between 800 m and 500 m in the eastern part of the Russian Altai and in the Mongolian Altai, respectively (Lehmkuhl *et al*. 2004). This regional gradient of the ELAs was steeper during glacial times. Further to the east, in the Khangay, the ELA depression is again >1000 m (see below, profile C – C′). This may be the consequence of a strong monsoonal influence, which is also evident further east in the mountains of Northern China as the Qinling Shan or Wutai Shan (Lehmkuhl & Rost 1993; Rost 1998, 2000).

Profile B – B′ in Fig. 4 shows the increase in elevation of the ELA from the eastern margin towards the interior of the Tibetan Plateau for the Late Pleistocene (Lehmkuhl 1995a, 1998b). The Late Pleistocene ELA depression varies from between 800 m and 1000 m in the eastern part to 500 m in the western part of Tibet. There is a comparable increase of the modern and Late Pleistocene ELAs towards the plateau on the northern and northeastern flank; for example, from 3300 m a.s.l. in the Qinling Shan (34°15′N, 109°10′E) to 4150 m a.s.l. in the La Ji Shan (36°55′N, 101°E) (Lehmkuhl & Rost 1993; Rost 2000). This general increase in ELA corresponds with the decrease in precipitation from east to west, which was more pronounced during glacial times (cf. Lehmkuhl 1995a).

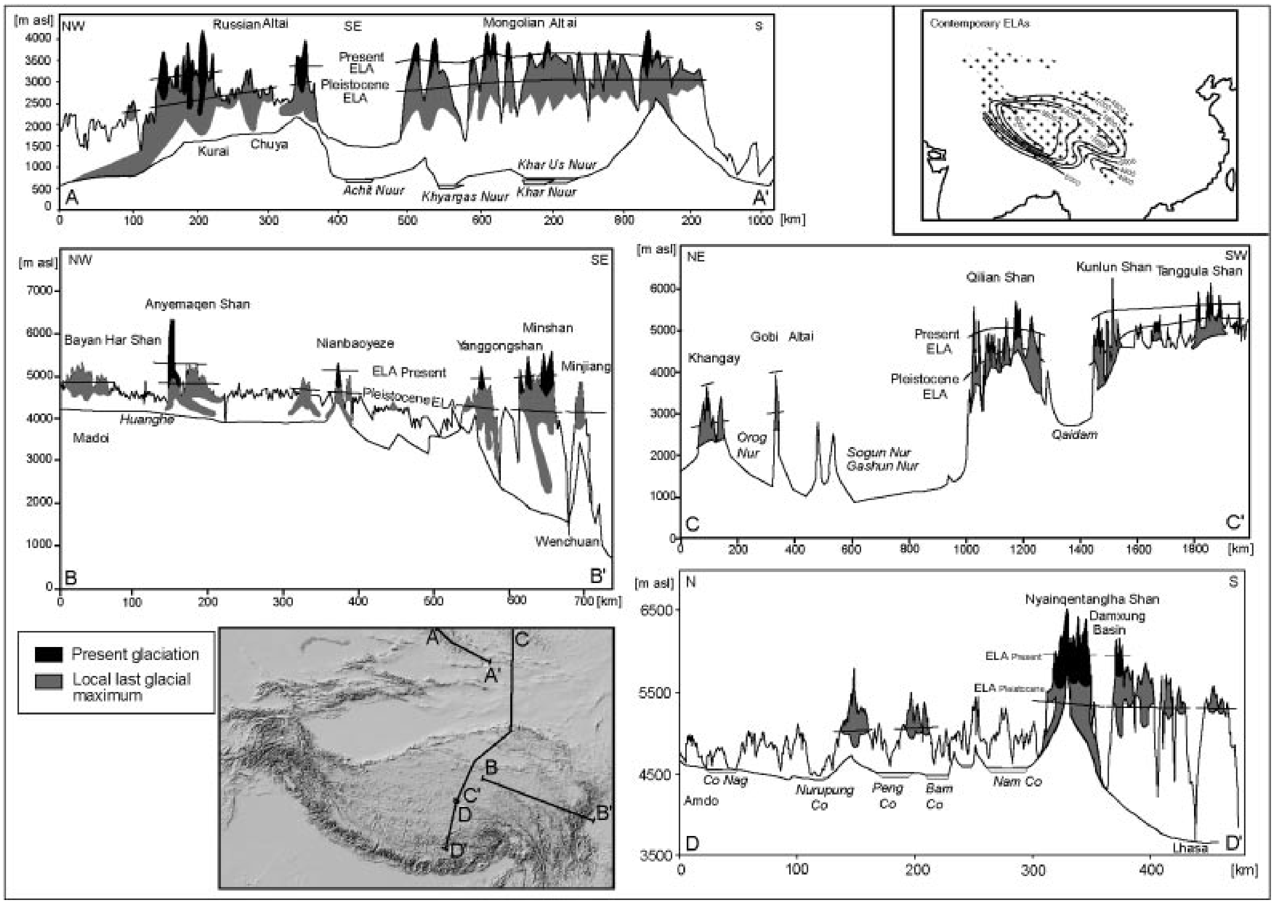

Fig. 4. Map with selected cross-sections of Central and High Asia, including the distribution of present and local last glacial maximum ice and the equilibrium line altitudes (ELAs). Cross-section A – A′ shows the distribution of present and local last glacial maximum ice and the ELAs from the Russian Altai to the Mongolian Altai (according to Klinge 2001 and Lehmkuhl 1999, 2002). Cross-section B – B′ shows the distribution of present and local last glacial maximum ice and the ELAs from the Khangay and Gobi Altai to the Tibetan Plateau (according to Lehmkuhl 1995, 1997b). Cross-section C – C′ shows the distribution of present and local last glacial maximum ice and the ELAs from the eastern fringe of the Tibetan Plateau (according to Lehmkuhl 1995, 1998b). Cross-section D – D′ shows the distribution of present and local last glacial maximum ice and the ELAs from southern Tibet (according to Lehmkuhl *et al*. 2000, 2002). The inset map in the top right corner shows the variation in contemporary regional snowlines across Tibet and the bordering mountains (adapted from Benn & Owen 1998).

In addition, fossil involutions (cryoturbation) and ice-wedge casts provide evidence for LGM permafrost in the Basin of Zoige (3400 to 3500 m a.s.l.) and on the southern shores of Qinghai Lake (Porter *et al*. 2001). Past temperatures can be estimated from these periglacial features and the existence of sand wedges indicates higher aridity – thus supporting the possibility that the ELA depression during the Late Pleistocene was between 600 and 800 m (Lehmkuhl 1998b).

The extent of late Quaternary glaciation from the mountains of Mongolia (Khangay and Gobi Altai) towards the northern, central and southern parts of the Tibetan Plateau is shown in Fig. 4. Presently, there are no glaciers in the central part of the Khangay and Gobi Altai (Profile C – C′ in Fig. 4). However, Lehmkuhl & Lang (2001) calculated the Pleistocene ELA to be between 2700 and 2800 m a.s.l. in the Khangay. Lehmkuhl (1998a) suggested that Quaternary glaciers were present in the Gobi Altai during glacial times. This suggests that the ELA depression in the Gobi Altai was ~1000 m.

On the northern slopes of the Qilian Shan in northeast Tibet, the modern ELAs are between 4600 and 5000 m a.s.l. and the Pleistocene ELA is ~3800 m a.s.l. (an ELA depression of ~1000 m; Lehmkuhl & Rost 1993; Hövermann *et al*. 1998). The modern ELA is 200 to 300 m lower in the outermost ranges of the Qilian Shan than in the innermost ranges (cf. Lehmkuhl 1992, 1995b, 1998b; Shi 1992). This pattern is also seen south of the Qaidam basin, from the Kunlun Shan in the north towards the Tanggula Shan in the south-central part of the Tibetan Plateau (profile C – C′ in Fig. 4). There is a sharp increase in elevation of the ELA from 4550 m a.s.l. in the innermost ranges of the Kunlun

Shan on the northern slope towards the Plateau to 4950 m a.s.l. on the southern slope. This is the only range that is presently glaciated. It has an ELA of ~5300 m a.s.l. and a Pleistocene ELA depression of ~600 m. At the marginal (outermost) northern range, Kuhle (1987) argues that the ELA depression during the Late Pleistocene was ~1000 m a.s.l. However, on the southern slope of the main range of the Kunlun Shan system, which is 70 km wide, glaciers advanced only a few kilometres from the Kunlun Pass to the interior of the Plateau to the south. There is no evidence to support Kuhle's (e.g. 1993) hypothesis that glaciers transported boulders 400 km north from the central Tanggula Shan (cf. Lehmkuhl 1995a, 1998b; Lehmkuhl & Hövermann 1996). In the Tanggula Shan, the modern ELAs are ~5700–5800 m a.s.l. and the Late Pleistocene ELA depression is between 500 and 600 m (Lehmkuhl 1998b). There is little difference between ELAs on the northern and southern sides of the Tanggula Shan. The general increase of modern and Late Pleistocene ELAs towards the plateau corresponds with the decrease in precipitation from north to south, which was more pronounced at the eastern margin during the ice age (cf. Lehmkuhl 1995a).

Profile D – D' (Fig. 4) shows that the present ELA in Southern Tibet is between 5800 and 6000 m a.s.l., with a Pleistocene ELA depression of 300 to 500 m in the drier parts of the Plateau, and 600 to 800 m in the wetter southern and southwestern mountain slopes of the Nyainqêntanglha Shan. Luminescence dates on aeolian silt that overlies the oldest terminal moraines on the northern slope of the Nyainqêntanglha Shan indicate an older glacier advance of the penultimate glaciation (89 ± 10 ka; Lehmkuhl *et al*. 2002). However, the geomorphology of the areas north of the Nyainqêntanglha Shan shows clear evidence that the extent of ice during the Late Pleistocene was limited (Lehmkuhl *et al*. 2000, 2002). In addition, the cosmogenic surface exposure ages presented by Schäfer (2000), Schäfer *et al*. (2002) and Owen *et al*. (2005) in the Tanggula Shan provide evidence for a slightly larger extent of ice during the penultimate glaciation.

Effects of surface uplift on glaciation

Controversy exists over the timing and rates of uplift throughout Tibet and the bordering mountains. The extension exhibited by normal and reverse faulting along Tibet's margins, volcanic activity in northeastern Tibet and palaeobotanical evidence in southern Tibet, however, suggests that much of Tibet probably reached its present elevation by ~13–14 Ma (Colman & Hodges 1995; Edwards & Harrison 1997; Blisniuk *et al*. 2001; Spicer *et al*. 2003). The mountain ranges that surround the Tibetan Plateau are generally much younger than 13 Ma and surface uplift rates are estimated to be a few mm/year (e.g. Zeitler *et al*. 2001). These uplift rates are usually defined using exhumation rates determined by fission track and mineral cooling ages, and incision rates determined from dating strath terraces and calculating contemporary sediment fluxes and volumes of deposited sediments (Collins 1998; Clift *et al*. 2001). Since the mountains produce positive relief, it is generally considered that the exhumation and incision rates must be less than or equal to the surface uplift rates. It is likely that current denudation is keeping pace with uplift and that the net gain in elevation is small. It is therefore highly unlikely that maximum uplift exceeds 10 mm/year and surface uplift is most likely in the order of ~1 mm/year in the actively growing mountain ranges.

Most of the late Quaternary glacial geologic studies in Tibet and the bordering mountains are limited to the last 100 000 years. A range of surface uplift rates between 1 and 10 mm/year suggests that the mountains have not uplifted >100 m since ~100 ka. In the most rapidly rising regions, such as Nanga Parbat, uplift could be in the order of several hundred metres to as much as a kilometre. In most regions, however, uplift is not considered to have greatly influenced the style of late Quaternary glaciation. The Ladakh Range of northern India may be an exception. Here, glaciation may have become dramatically more restricted over the past few hundred thousand years. Taylor & Mitchell (2000) and Bovard (2001) suggest that the Greater Himalaya and Pir Panjal to the south may have uplifted enough to restrict the northward penetration of the south Asian summer monsoon, reducing precipitation and glacial cover.

Conclusions

An understanding of the nature of late Quaternary glaciation in Tibet and the bordering mountains is still in its infancy. However, the application of modern geomorphic and sedimentological techniques, and the development of new dating techniques, such as cosmogenic surface exposure and OSL dating, have opened up the possibility for regional and temporal correlations across this vast region. Although the extent of former glaciers is relatively well known, in most regions it is still not known when glaciers advanced to particular positions. Nevertheless, at this stage we are able to conclude the following:

- In most regions of Tibet and much of the Himalaya, glaciation was most extensive earlier in the last glacial cycle, possibly MIS-3 or MIS-5a to 5d. Furthermore, glaciation was generally most extensive prior to the last glacial cycle. It is possible, however, that the behaviour of glaciers influenced by the different climatic systems was different at different times, and more detailed geomorphic and geochronological studies are needed to fully explore regional variations.

- There is a strong topographic control on glaciation, particularly in regions that have rainshadow effects. This is most evident from the strong regional variability in present and past ELAs.
- Glaciation was more extensive in monsoon-influenced regions, and was strongly controlled by changes in insolation that control the geographic extent of the monsoon and consequently precipitation distribution. This strongly influences glacier mass balances, allowing glaciers to advance during times of increased precipitation in high altitude regions, and these are associated with insolation maxima during glacial times.
- Tectonic uplift has had little effect on glaciation during the last glacial cycle, but may have been important in controlling differences in glacial styles and extent over many hundreds of thousands of years.
- Drainage development, including lake level changes, has been strongly controlled by climatic oscillations, particularly on millennial time scales. However, centennial and decadal fluctuations are also discernible.
- Changes in glacial ice volume after the global LGM were relatively small in the Tibet–Himalayan region compared to the Northern Hemisphere ice sheets. It is therefore unlikely that meltwater draining from Tibet and the bordering mountains during the Lateglacial and early Holocene would have been sufficient to affect oceanic circulation upon flowing into the adjacent oceans. However, changes in surface albedo may have influenced the dynamics of monsoonal systems and had implications for global climate change.
- Despite the relatively small volume of glacial ice that existed in this region during glacial times, Tibet and the bordering mountains presently have the greatest concentration of glaciers outside the Polar Regions. Since the Little Ice Age, and particularly during this century, glaciers have been progressively retreating. This pattern is likely to continue throughout this century, exacerbated by human-induced global warming.

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DAY 1 - STOP 1: LA JI MOUNTAINS
Lead by: Lewis Owen, Ma Haizhou and Marc Caffee

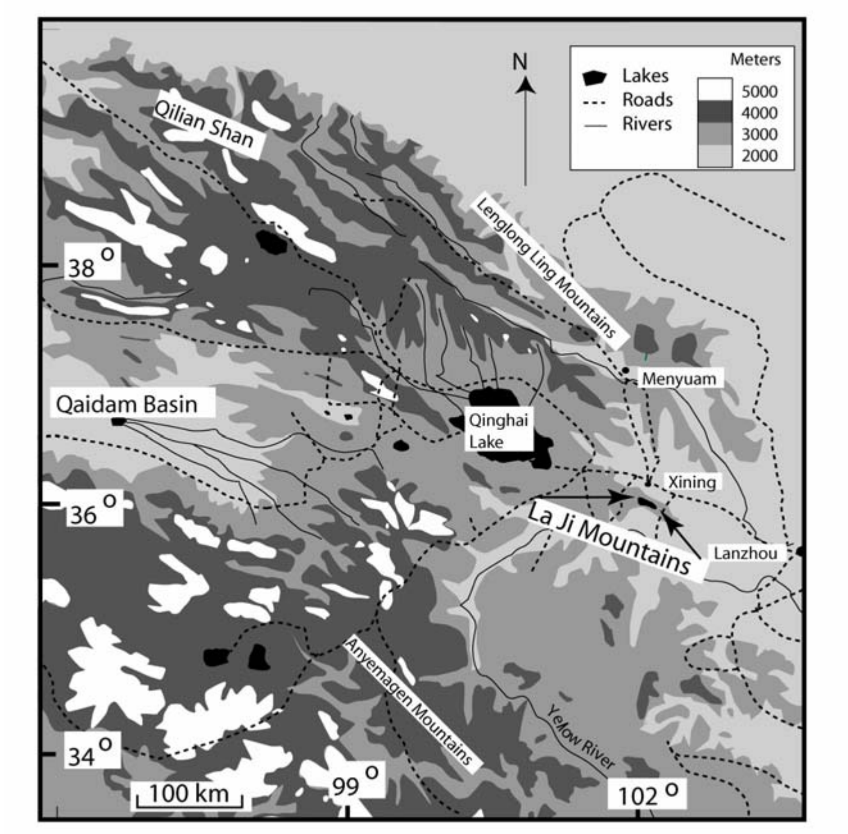
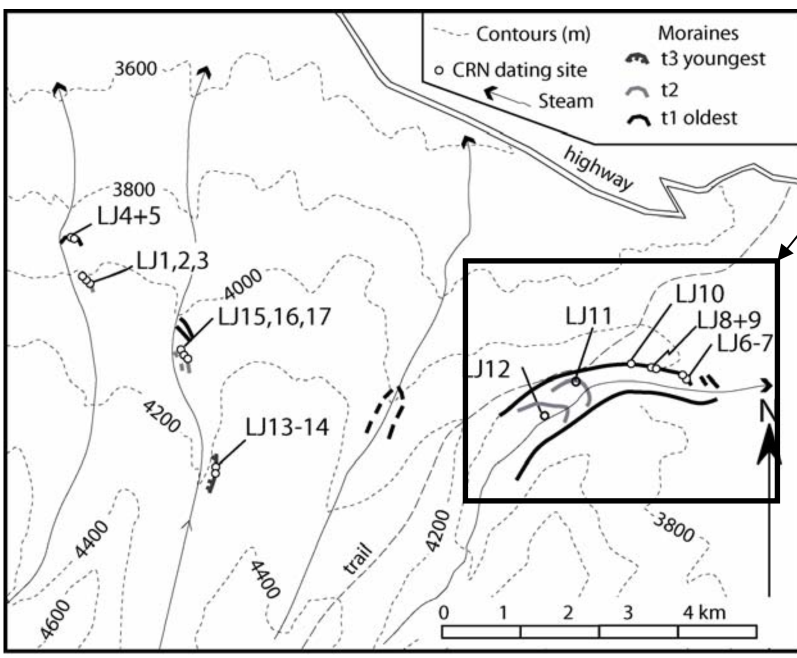


Figure 1.1: Location map for the La Ji Mountains

Figure 1.2: Google image of the La Ji Mountains.

The La Ji Mountains are situated on the northeastern edge of the Tibetan Plateau and rise to an elevation of 4898 m asl with a relative relief of ~ 1500 m (Fig. 1.1). The region is moderately influenced by the southeast Asian summer monsoon and has an annual precipitation of between 200-400 mm falling mainly during the summer months. No glaciers exist in the region today, but during exceptional years small snow patches persist throughout the summer at the highest elevations. The valleys along the northern edge of the La Ji Mountains are U-shaped in their lower reaches with steep bare rock walls at their heads. Granitic and gneissic lithologies dominate the core of the mountains and the lithologies within the moraine, pediment and fluvial sediments. Hummocky and latero-frontal moraines are present within and beyond the mouths of the north-easternmost valleys down to an elevation of 3900 m asl (Figs. 1.2 and 1.3). Three sets of moraines can be differentiated on the basis of morphostratigraphy, although the weathering characteristics of each set of moraines are similar. The moraine ridges are subdued and their surfaces are covered with a cm- to dm-thick layer of solum and turf. The boulders on the crests of the moraines are usually half buried and their surfaces are pitted to a depth of ~ 5-10 mm exhibiting moderate exfoliation. The best-preserved moraines are present in the north-easternmost valley (Figs. 1.3 and 1.4). An extensive latero-frontal moraine exists here, behind which an impressive suite of hummocky moraines and kettle holes are preserved. The southern margin of the hummocky moraines is marked by a steep scarp and associated debris aprons that mark a former ice margin. An extensive pediment surface exists beyond the glacial limits and is comprised of well-rounded boulders and cobbles covered by a thick organic-rich solum.



Area to be visited during the excursion. See Google image in Figure 1.4.

Figure 1.3: Locations of main moraines and area that will be examined during the field visit (adapted from Owen et al., 2003).

Mapping and terrestrial cosmogenic nuclides (TCNs) surface exposure dating (SED) of moraine successions in the La Ji Mountains was undertaken by Owen et al. (2003). They showed that glaciers existed in this marginal region of Tibet during the latter part of the global Last Glacial Maximum and during the Lateglacial. Their data suggests that temperatures were low enough and/or monsoon precipitation was sufficiently high to support one or more limited glacial advances between ~20 and 10 ka. Glaciation however was limited to glaciers of < 10 km in length and the estimated ELA depression was ~ 800 m. These results confirm studies throughout other regions of Tibet and the Himalaya that shows that glaciation was restricted during the latter part of the Last Glacial.

At this location we will examine the succession of moraines in the north-eastern most studied valley to discuss the nature and style of glaciation at the NE margin of Tibet and the validity of the TCN SED. The moraines in this area comprise impressive laterals with inset laterofrontal and hummocky moraines. Owen et al. (2003) dated these and moraines in adjacent valley using Be-10 TCNs and their results are shown in Figure 1.5. The dates provide ages that range between 9 to 21 ka, with two boulders providing significantly older ages of ~33 and 63 ka. The TCN surface exposure ages on individual moraines are not tightly clustered, but they do show that the moraines formed some time between the latter part of the LGM and/or during the Late Glacial or possibly the early part of the Holocene. Furthermore, the dating set shows no systematic difference between dated moraines that are morphostratigraphically older or younger than each other. Consequently, they did not assign the moraines to different specific climatostratigraphic periods. Nevertheless, it can be seen that the TCN surface exposure ages cluster, as a group, between 8 to 21 ka. This suggests that the moraines along the northern edge of the La Ji Mountains represent one or more glacial advances that occurred during the latter part of the global LGM and the Late Glacial or possibly the early part of the Holocene. The two oldest ages (LJ3 and LJ9) probably represent boulders that may have inherited TCNs from prior exposure. The youngest ages of ~ 8 – 10 ka (LJ4, 11, 15 and 16) appear to be stratigraphically inconsistent with their location on moraines that should be stratigraphically older than those up valley. These may represent toppled boulders and/or boulders that were exhumed late in their history.

Figure 1.4: Google images of moraines that will be examined during the field excursion.

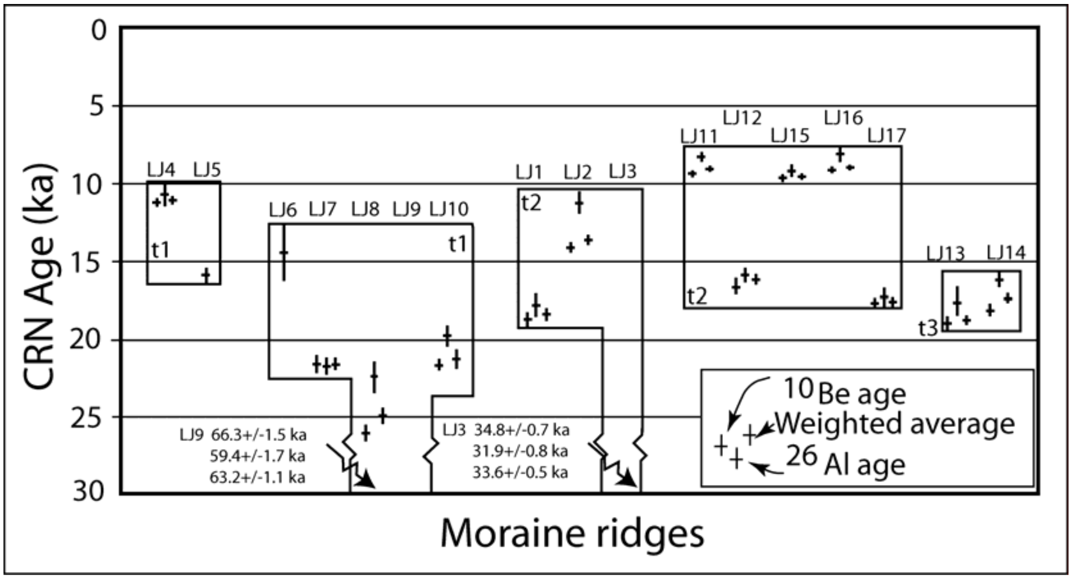


Figure 1.5: Be-10 terrestrial cosmogenic radionuclide surface exposure dates for the La Ji Mountains (after Owen et al., 2003).

DAY 1 – STOPS 2 TO 5: QUATERNARY GEOLOGY OF QINGHAI LAKE AREA

Steve Porter

Figure 2.1. Satellite image of n Qinghai Lake and adjacent cloud-capped Qinghai Nan Shan to south.

The next four stops will provide an opportunity to examine the Quaternary geology of the Qinghai Lake area (Fig. 2.1).

Stop 2. WEDGE FEATURE AND BAJADA STRATIGRAPHY
(Borrow pit across main road from Qinghai Huzhang Fang Hotel)
The pit exposes 2.5 m of alluvium (pebble-cobble gravel) capped by loess and a paleosol (Fig. 2.2). Details of the site are discussed by Porter *et al.* (2001). The gravel underlies a broad bajada surface (coalescing alluvial fans) former at the northern base of the Qinghai Nan Shan. Luminescence (IRSL) dates indicate that the exposed gravel was deposited between ca. 45,000 and 33,000 years ago during marine isotope stage (MIS) 3. Lenses of fine silt (loess) are interstratified with the gravel. Coarsening of the gravel to the south, as well as its overall lithology, indicate that it originated in nonglaciated stream valleys draining the northern slope of the range. Of particular interest is a wedge feature that penetrates the gravels and is overlain by the loess-paleosol section (Fig. 2). The wedge is interpreted as a fossil ice wedge. Its sediment fill consists of fine eolian sand, silt, and clasts from the wedge walls that fell into the depression when ice melted out. A luminescence date for a sample from the wedge fill indicates that the ice wedge was active prior to about 15,000 years ago, during last glacial age (MIS 2). An ice wedge at this site implies subfreezing temperatures and permafrost conditions. However, to generate an ice wedge, moisture is required, and this suggests that Qinghai Lake was present and perhaps seasonally unfrozen. Melting of the ice and subsequent filling of the wedge depression points to warming of the climate at the end of the glacial period.

Overlying the gravel and wedge fill is ca. 1.5 m of loess, within which is a paleosol that formed >8300 and <11,700 IRSL yr ago. In most sections, a paleosol is also developed in the top of gravel. The hiatus between the gravel and loess represents the interval from ca. 33,000 to 12,700 IRSL yr ago (i.e., it includes the last glaciation). The absence of late Malan loess (L1LL1) suggests that this was a cold, windy land surface during full-glacial time from which fine sediment was deflated

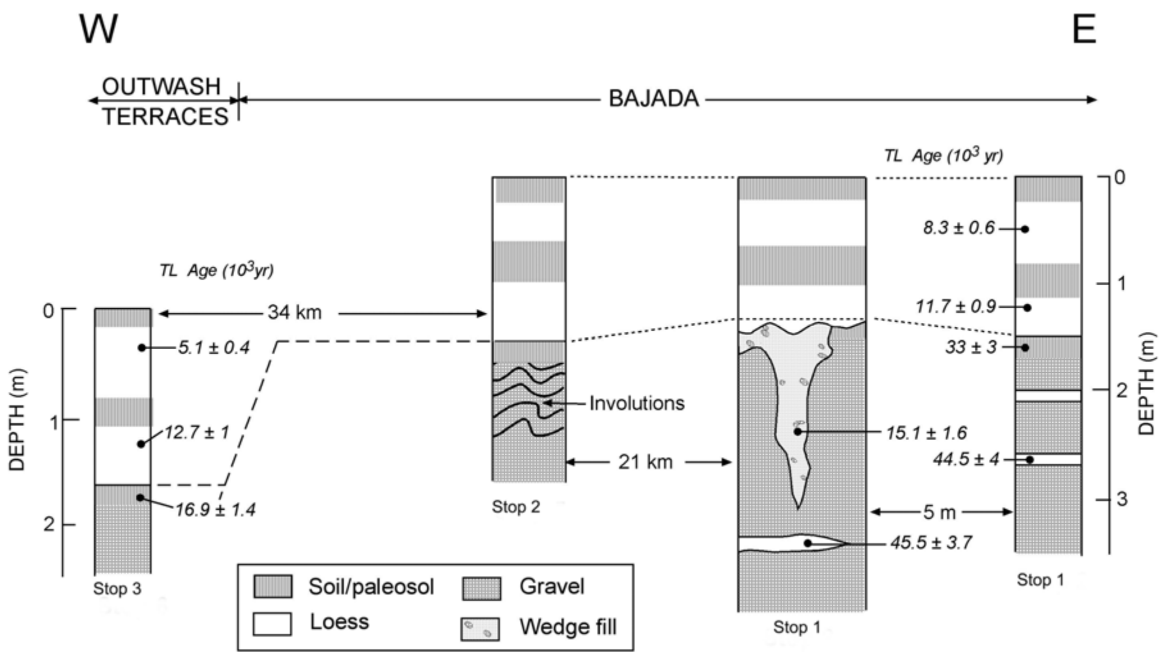


Figure 2.2: Stratigraphic sections along a 55-km transect along the base of the Qinghai Nan Shan.

HOLOCENE BEACH RIDGES

The most recent high stand and subsequent recession of the lake is marked by a wave-cut strandline along some reaches of the lake shore and by beach ridges along embayed sectors (Fig. 2.3). The highest strandline lies close to 9.5 m above present lake level. Although this high stand of Qinghai Lake has not yet been closely dated, absence of the early Holocene paleosol on beach ridges suggests that the high stand occurred during the middle Holocene,

Figure 2.3. Holocene beach ridge south of the eastern large spit. View is toward the QHF Hotel and the low, middle sector of the Qinghai Nan Shan.

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STOP 3: POSTGLACIAL LOESS AND CRYOTURBATED BAJADA GRAVEL

(Borrow pit ca. 500 m east of Jiaxigou)

This section is similar to that at Stop 2. However, the bedding of the bajada gravel is distorted (involutions) implying strong frost action during the last glaciation (Fig. 3.1). This frost action, i.e., cryoturbation, likely was synchronous with ice-wedge development at Stop 2.

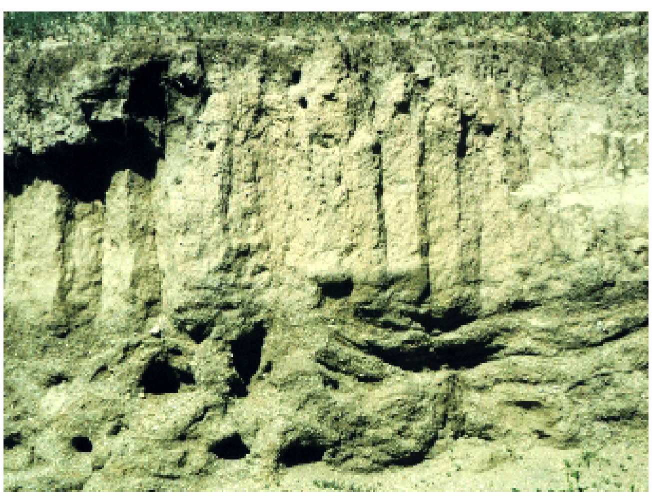

Figure 3.1. Columnar late-glacial loess 1.5 m thick overlies distorted bedding (involutions) in bajada gravels in a roadside borrow pit. The deformation is attributed to cryoturbation (disturbance by frost action). The deformation was likely contemporaneous with development of an ice wedge at Stop 1 (i.e., during the last glaciation).

GLACIERS OF THE QINGHAI NAN SHAN

The northern flank of the range is indented by cirques and glaciated valley heads excavated by small glaciers during the most recent glacial age(s) (Fig. 3.2). Most of the glaciers faced north to northeast and ranged in length from 1 to 5 km. The most recent glaciers (MIS 2) had an average equilibrium-line altitude (ELA) of 4250 ± 50 m. The cirques now are ice-free, but extrapolation of present ELAs from nearby glacierized mountains suggests that the present ELA lies at ca. 5000 m (Shi *et al*., 1992). Snowline depression during the last glaciation therefore may have been about 750 ± 50 m.

A well-developed soil is seen on the highest terrace remnant bordering the outwash fan below the glaciated valleys (Fig. 3.2). It is inferred to date to the last interglaciation (S1 paleosol, = MIS 5). If true, then the glaciers related to the terrace gravel likely formed during MIS 6.

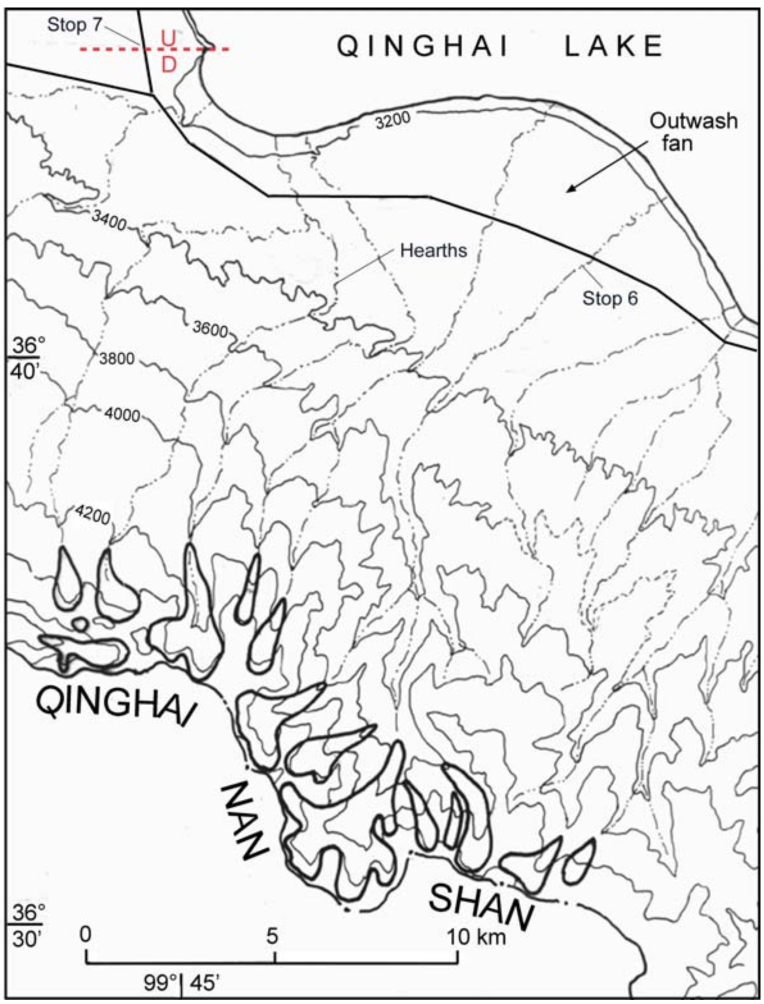

Figure 3.2. Glaciers along crest of western Qinghai Nan Shan and large outwash fan built by proglacial streams that drained them. Glaciers headed in cirque basins at altitudes of 4400-4500 m. The glaciers ranged in length from ca. 1 to 5 km and most faced between north and northeast. Two buried hearths were found in alluvium close to the mountain front near the head of the outwash fan.

STOP 4: STRATIGRAPHY OF OUTWASH TERRACE ON LARGE ALLUVIAL FAN
(Cutbank ca. 150 m above bridge over stream flowing down large alluvial fan)

A large alluvial fan heads in steep valleys that drain glaciated drainage basins along the western Qinghai Nan Shan (Fig. 3.2). At this locality, an IRSL date from the top of the exposed gravel (16,900 ± 1400 yr) indicates that fluvial sedimentation ended toward the close of the last glaciation . Hence, these gravels are much younger than surface gravel at Stops 2 and 3 and record deposition close to the time when the ice wedge at Stop 2 melted out at the glacial termination.

This terrace is second of three terraces identified on the fan, each believed to represent the distal meltwater deposits of alpine glaciers that advanced several times during the late Pleistocene. The terrace is capped by 1.5 m of loess, in the middle of which is a paleosol like that seen at Stops 2 and 3. Bracketing luminescence dates (12,700 and 5100 years) suggest that this soil may be early Holocene in age.

Alluvium exposed near the apex of the fan contains two buried hearths, charcoal from which dates 12,420 ± 170 to 11,510 ± 145 ^{14}C yr B.P. (ca. 14,500 to 13,500 cal yr B.P.) (Fig. 3.2). The hearths record the presence of humans at the range front during early postglacial time.

STOP 5: OVERVIEW OF WARPED SUMMIT EROSION SURFACE (en route Chaka Lake)

The western Qinghai Nan Shan, although deeply incised by glaciated valleys, preserves remnants of a broad, gentle upland surface that extends from the crest northward toward the lake (Figs. 5.1 and 5.2). The surface appears to be offset where several W-E-trending faults cross the range. It is cut across deformed bedrock and likely represents a warped pre-Quaternary surface that formed at a lower altitude.

Figure 5.1. Gentle upland surface at crest of range along road to Caka Lake. A thin cover of loess and colluvium mantles the surface, and is locally being eroded away.

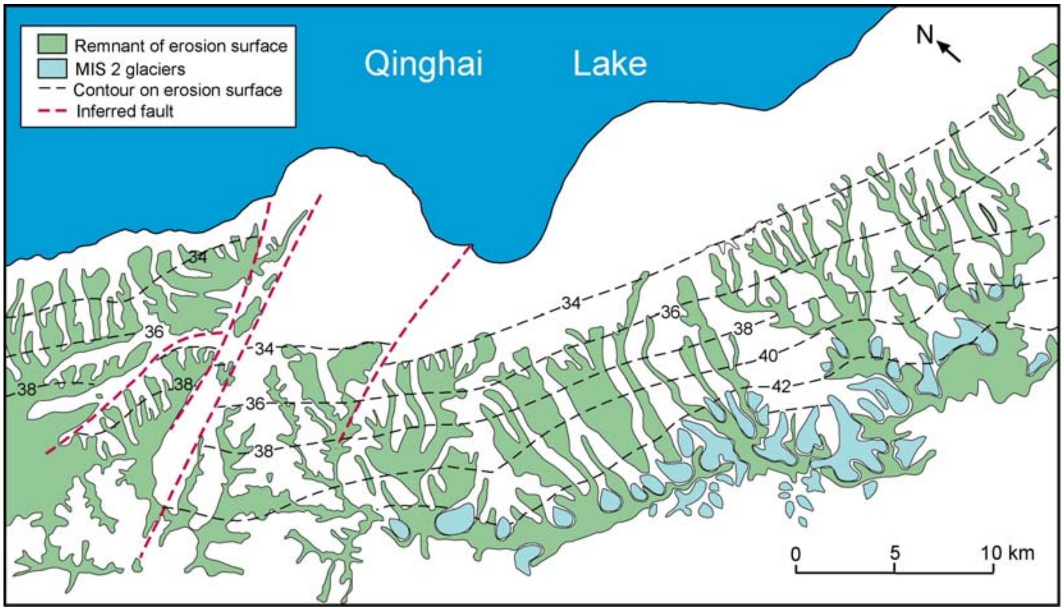

Figure 5.2. Remnants of an erosion surface preserved on the range crest and interfluves of the western Qinghai Nan Shan.

Owen, L.A., Spencer, J.Q., Ma Haizhou, Barnard, P.L., Derbyshire, E., Finkel, R.C., Caffee, M.W. and Zeng Yong Nian, 2003. Timing of Late Quaternary glaciation along the southwestern slopes of the Qilian Shan. Boreas, 32, 281-291.

Porter, S. C., Singhvi, A., An, Z.S., and Lai, Z. P., 2001. Luminescence age and palaeoenvironmental implications of a Late Pleistocene ground wedge on the northeastern Tibetan Plateau. Permafrost and Periglacial Processes, 12, 203-210.

Shi, Y. F., Zheng, B. X., and Li, S., 1992. Last glaciation and maximum glaciation in the Qinghai-Xizhang (Tibet) Plateau: a controversy to M. Kuhle's ice sheet hypothesis. Zeitschrift für Geomorphologie Supplement Band, 84, 19-35.

DAY 2: QAIDAM BASIN AND THE KUNLUN MOUNTAINS
Lead by: Lewis Owen and Marc Caffee

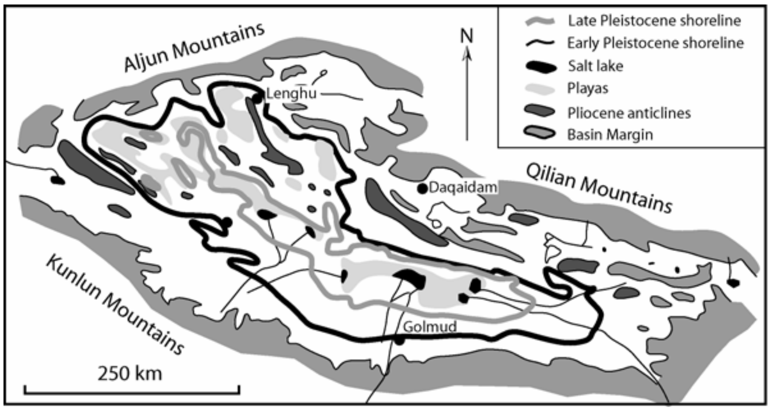

Figure 1.1: Outline of the Qaidam Basin showing the extent of early and late Pleistocene mega-lakes as proposed by Chen and Bowler (1986). The main detailed study areas within the Qaidam Basin are highlighted by the black boxes.

Overview

The Qaidam Basin in northern Tibet is one of the largest hyper-arid intermontane basins on Earth and is bounded to the north by the Aljun and Qilian Mountains and to the south by The Kunlun Mountains (Fig. 1.1). Alluvial fans, pediment surfaces, shorelines and a thick succession of sediments within the basin, coupled with moraines and associated landforms in the adjacent high mountain catchments of the Kunlun, Aljun and Qilian Mountains, record a complex history of Late Quaternary paleoenvironmental change and landscape evolution. The region provides an ideal natural laboratory to examine the interaction between tectonics and climate within a continent-continent collision zone and to quantify rates of landscape evolution as controlled by climate and the associated glacial and hydrological changes in hyper-arid and adjacent high altitude environments. Geomorphic mapping, analysis of landforms and sediments, and TCN surface exposure and optically stimulated luminescence dating by Owen et al. (2006) serve to define the timing of formation of Late Quaternary landforms along the southern and northwestern margins of the Qaidam Basin, and in the Burhan Budai Shan of the Kunlun Mountains adjacent to the basin on the south. These dates provided a framework that suggests links between climatic amelioration, deglaciation, lake desiccation and alluvial fan evolution. At least three glacial advances are defined in the Burham Budai Shan of the Kunlun Mountains. On the northern side of this range these occurred in the penultimate glacial cycle or early in the last glacial cycle, during the Last Glacial Maximum/Late Glacial and during the Holocene. On the south side of the range, advances occurred during the penultimate glacial cycle, MIS-3, and possibly the LGM, Late Glacial or Holocene. Several distinct phases of alluvial fan sedimentation are likewise defined. Alluvial fans formed on the southern side of the Kunlun Mountains prior to 200 ka. Ice-contact alluvial fans formed during the penultimate glacial and during MIS-3. Extensive incised alluvial fans that form the main valley fills north of the Burham Budai and extend into the Qaidam Basin are dated to ~30 ka. These ages suggest that there was a period of alluvial fan aggradation and valley filling that persisted until desiccation of the large lakes in the Qaidam Basin post ~30 ka led to base level lowering and active incision of streams into the valley fills. The continued Late Glacial and Holocene desiccation likely led to further degradation of the valley fills. Ice wedge casts in the Qaidam Basin date to ~15 ka, indicating significant Late Glacial climatic amelioration, while Holocene loess deposits north of the Burham Bdudai suggest that aridity has increased in the region since the early Holocene. From these observations, Owen et al. (2006) inferred that the major landscape changes within high glaciated mountains and their adjacent hyper-arid intermontane basins, such as the Kunlun Mountains and Qaidam Basin, occur rapidly over millennial timescales during periods of climatic instability.

We will examine many of these aspects throughout the day concentrating on the area shown in Figure 1.2.

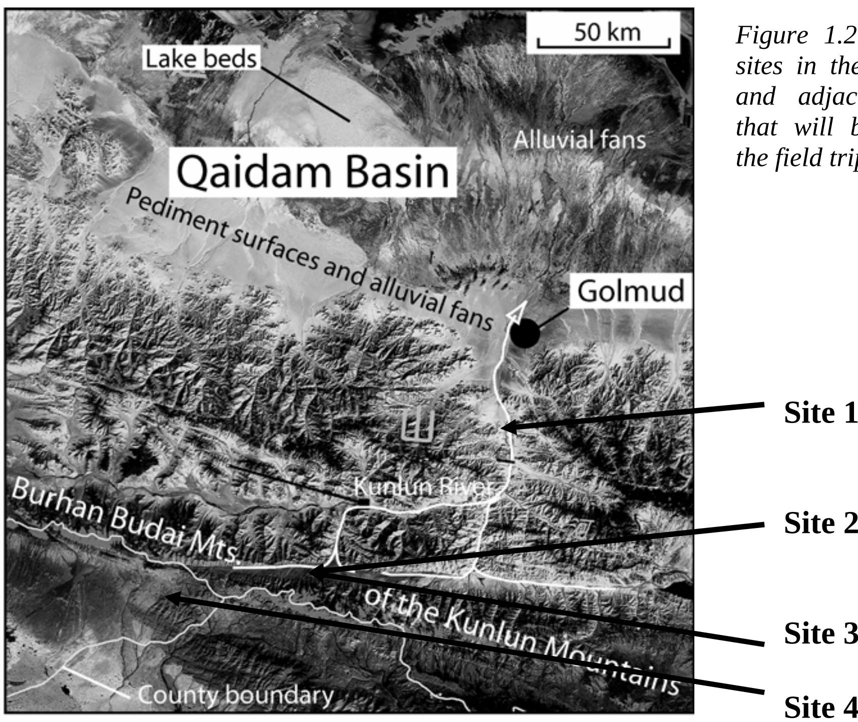

Figure 1.2. Location of study sites in the Kunlun Mountains and adjacent Qaidam Basin that will be examined during the field trip.

Stop 1: Golmud Fan and the Burhan Budai-Golmud drainage

The Lhasa-Golmud highway follows the main drainage (Kunlun River) of the Burhan Budai Shan from Xidatan to Golmud. Impressive alluvial fans are present along this drainage. These are incised to their heads, rising many tens above the contemporary drainage to form a notable valley fill and terrace-like landforms (Fig. 1.3). The alluvial fan surfaces coalesce and are almost continuous from Xidatan to Golmud eventually joining with the main bajada that stretches along the southern margin of the Qaidam basin. The alluvial fans comprise of crudely stratified meter and decimeter beds of fanglomerates and debris flow deposits, and in places stratified sands and silts are present representing shallow ponds/swamps (Fig. 1.4). Older highly dissected alluvial fans are present along several stretches of the valley, but these are many tens of meters above the dominant alluvial fans that form the main valley fill (e.g. 35°55’N/094°40’E).

Figure 1.3: Google Earth image of the main alluvial fan and drainage from the Kunlun Mountains south of Golmud.

The deep fan incision has extended into the bedrock at some locations. At 35°53’N/094°45’E, for example, 3-4 m-thick the alluvial fans cap bedrock that has been incised by more than 25 m to form impressive strath terraces. Owen et al. (2006) collected samples for SED from boulders on the alluvial fan surface, which date to between 30 and 40 ka. The alluvial fans along Burhan Budai-Golmud drainage that were dated by Owen et al. (2006) using SED and OSL techniques have ages that range from 43ka to 8 ka. The most distal alluvial fan surface that was dated had surface exposure ages that range between 43 and 33 ka and the same surface, ~ 50 km south, has a surface exposure age of ~32 ka (Fig. 1.4). This latter date is supported by an OSL date of 28.3 ± 2.8 ka on sediments within the alluvial fan. The fanglomerates at this site are capped with swamping/lacustrine silts and have an OSL age of 8.8 +/-0.8 ka. These are in turn overlain by loess.

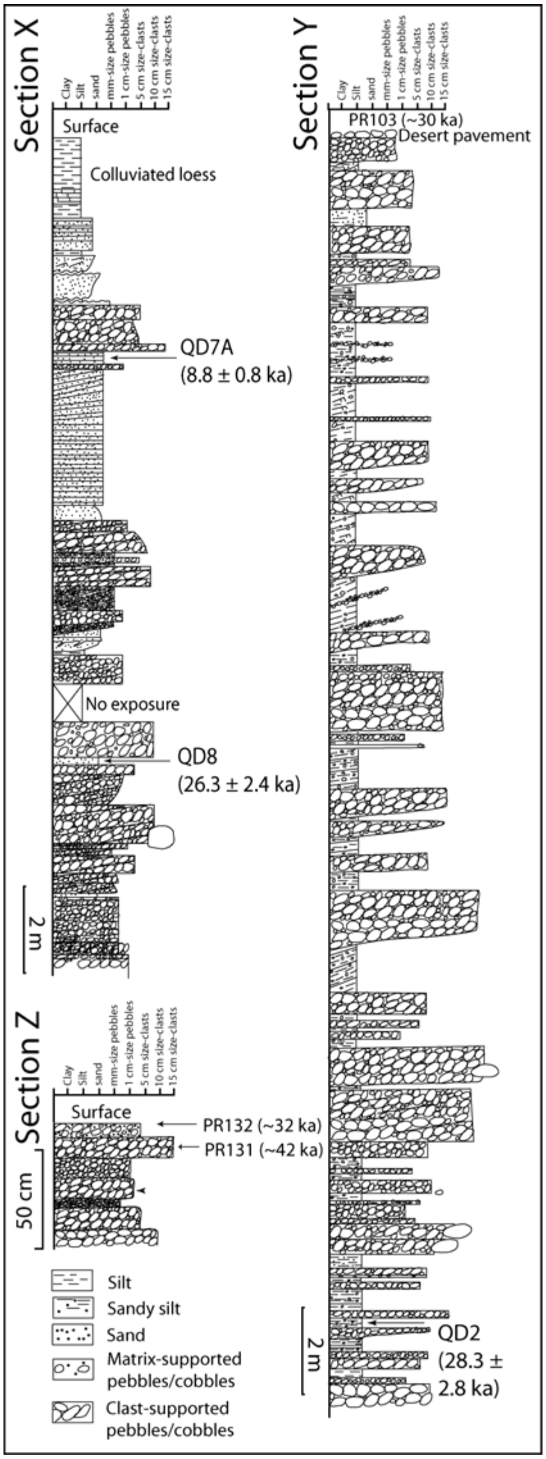

Fig.1.4. Graphic sedimentary logs through a discontinuous valley fill deposit ~50 km south of Golmud (36°04.749'N/094°48.325'E, 3245 m asl) (after Owen et al., 2006).

A discontinuous cap of loess, decimeters- to meters-thick, cap these alluvial fans and rock slopes throughout the valley. The thickest loess section that was examined by Owen et al. (2006) had a basal OSL date of 8.6 ± 0.7 ka.

These data suggest that the main alluvial fans which form the major component of the valley fills along the Burhan Budai-Golmud drainage were forming and infilling the valley during MIS-3 and that they became abandoned/incised prior MIS-2. Later sedimentation as shallow pond and loess probably occurred during and since the early Holocene.

Stop 2: North side of the Burhan Budai Shan

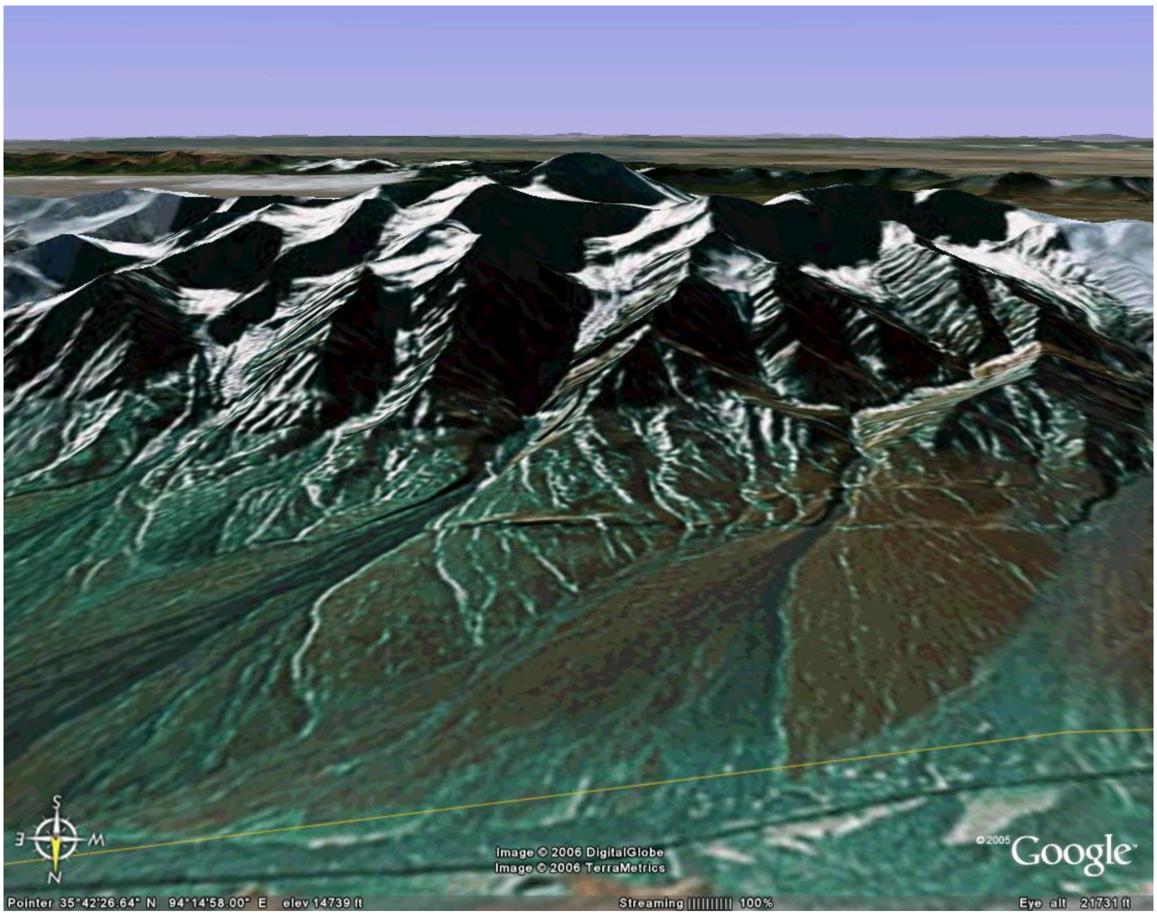

Figure 2.1: Google image of the north side of the Burhan Budai Shan

At this site we will examine the geomorphic evidence for active tectonics, fan development and glaciation. The north side of the Burhan Budai is bounded by the Kunlun fault (Figs 2.1 and 2.2.). On the basis of measured displacement of alluvial surfaces, whose surface ages were determined by cosmogenic Al-26 and Be-10 dating of quartz pebbles, and by radiocarbon dating of charcoal, Van der Woerd et al. (2002) determined Late Pleistocene–Holocene left-lateral slip-rates on several segments of the Kunlun Fault in northeastern Tibet. In the west, at three sites along the Xidatan–Dongdatan segment of the fault, near 94^{o}E, terrace riser offsets ranging from 24 to 110 m, with TCN ages ranging from ~1800 to ~8200 yr, yield a mean left-lateral slip-rate of 11.7±1.5 mm/yr. Field observations indicate minimum offsets of 9–12 m; this offset, when combined with the long-term slip-rate, indicates that great earthquakes (M~8) rupture this segment of the fault with a recurrence interval of 800–1000 yr. Van der Woerd et al. (2002) suggest that the slip-rates are constant, within uncertainty, throughout the 600 km of the Kunlun Fault that they studied, with an average slip-rate of 11.5±2.0 mm/yr. Extrapolating this rate to the reminder of the fault, they concluded that most (80 per cent) of the 300 morphological offsets measured in the field or on SPOT satellite images post-date the Last Glacial Maximum. Van der Woerd et al. (2002) suggested that the terraces they studied were deposited during a humid period in the Early Holocene Optimum (9–5 ka) and the formation of younger terraces reflects Late Holocene climate change.

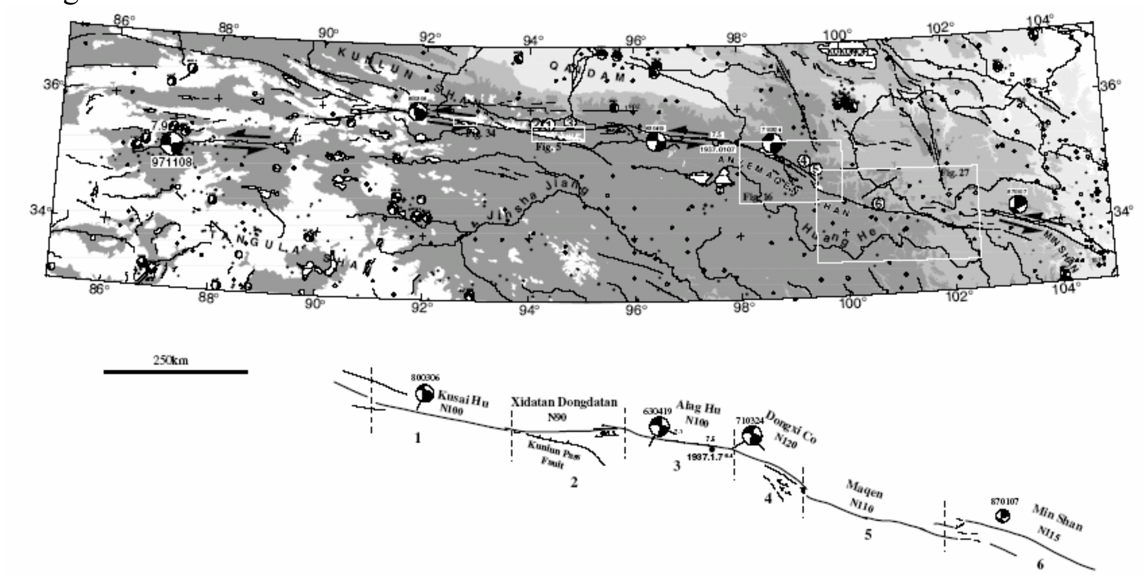

Figure 2.2. Large-scale segmentation of Kunlun Fault. From 91^{o}E to 105^{o}E, six segments are identified. Min Shan segment (103^{o}E to 105^{o}E) steps about 50 km to the north (after van der Woerd et al., 2002). West of 91^{o}E, several segments, with strikes between N70^{o}E and N140^{o}E, linked with normal faults form the broad western horsetail termination. Instrumental and historicalseismicity, filled and open circles, respectively, is shown for magnitude Ms>4. Focal mechanisms are from Molnar & Lyon-Caen (1989) and USGS. White boxes refer to figures, circled numbers to sites studied in the field.

Several sets of alluvial fans are present along the northern side of the Burhan Budai Shan forming a bajada (Fig. 2.1). These were mapped by Van der Woerd et al. (2002) and dated using SED methods. They showed that these formed during the Holocene and recognized five terraces at 8-9 ka, 5-6 ka, ~3 ka, ~2 ka and < 1.5 ka. Two sets of moraines are evident near the exit of the tributary valleys. The older higher moraine Owen et al. (2006) called M1 while the younger moraines they named M2 (Fig 2.2). The contemporary glaciers are only several kilometers from both these sets of moraines. In this region, the M1 moraine set is represented by subdued ridges near the exit of the tributary valley from the Burhan Budai Shan (Fig. 2.2). These rise more than fifty meters above the contemporary drainages. The younger set of moraines (M2) is represented by several subdued ridges that rise several tens of meters above the contemporary drainage. The outermost one (M2') can be traced to a shutter ridge that has been displaced by the Kunlun Fault. Surface boulders are not abundant on these surfaces and many may have been covered with a decimeter-thick layer of loess. However, Owen et al. (2006) attempted only to sample surface boulders that they believed were large enough to provide reliable dates, and in locations where, shielding from burial was not a problem. Samples for surface exposure dating (PR1 to PR10 and PR114 to PR117) were collected from each of the moraines and the shutter ridge (Fig. 2.2). In some of the valley, small sharp crested lateral moraines are present near the contemporary glaciers.

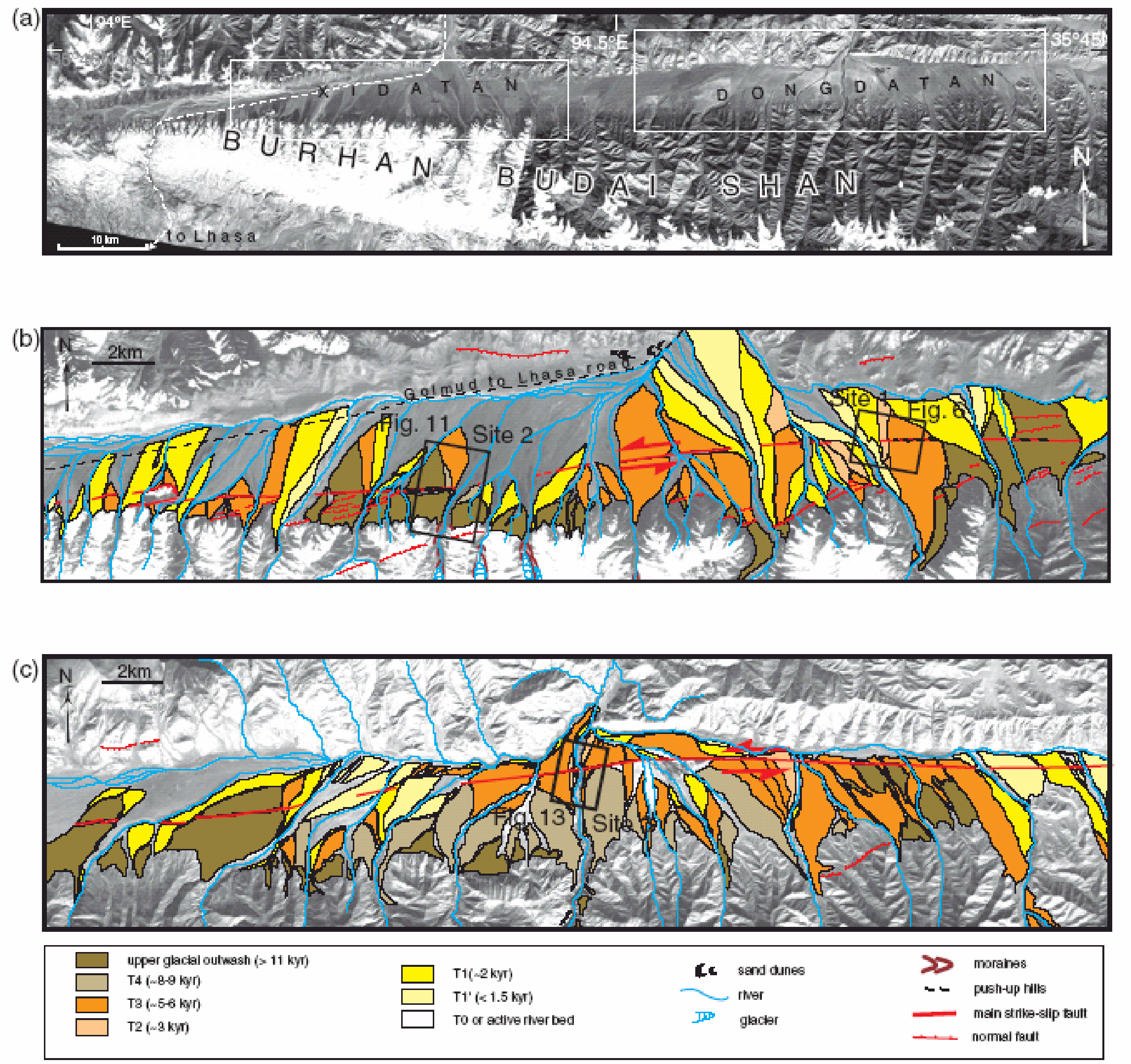

Figure 2.3. The alluvial fans and faults of the Burhan Budai range (after Van der Woerd et al., 2003). (a) SPOT image mosaic showing the Xidatan segment of the Kunlun Fault. White dashed line indicates the road from Golmud to Lhasa, which crosses the Burhan Budai range just north of Kunlun Pass. The main branch of Kunlun Fault strikes N80–90^{o}E, from the western end of Xidatan valley to the northeastern corner of Dongdatan valley. A clear trace of Kunlun Pass Fault is also visible south of the Burhan Budai ice-capped crest line. (b) Geomorphic map of alluvial fans and terraces cut by Kunlun Fault in central Xidatan. The fault trace is fairly continuous across bajada, except in the most recent alluvial surfaces where it vanishes. Discontinuous normal fault-scarps are visible north and south of the valley at the foot of ranges. Seven alluvial terrace levels can be distinguished and correlated on the basis of relative elevation, incision, and hence age, by combining field evidence with SPOT image analysis. (c) Geomorphic map of alluvial fans and terraces cut by Kunlun Fault in central Dongdatan.

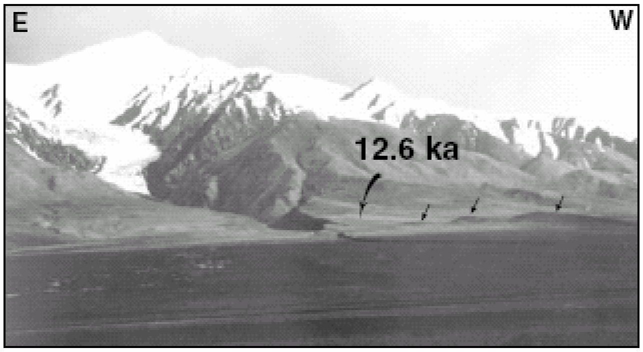

Figure 2.4. View, looking south at site (after Van der Woerd et al., 2002). The fault trace is marked by large pressure ridges on the left bank of the stream fed by melting glacier in the background. Snow- and ice-covered summits are ~6000m high, and the bajada in the foreground is ~4000 m a.s.l. The stream first formed a large fan after the onset of postglacial warming (~12 ka), and then deposited two inset terraces during entrenchment (~8.1- 6.2 ka).

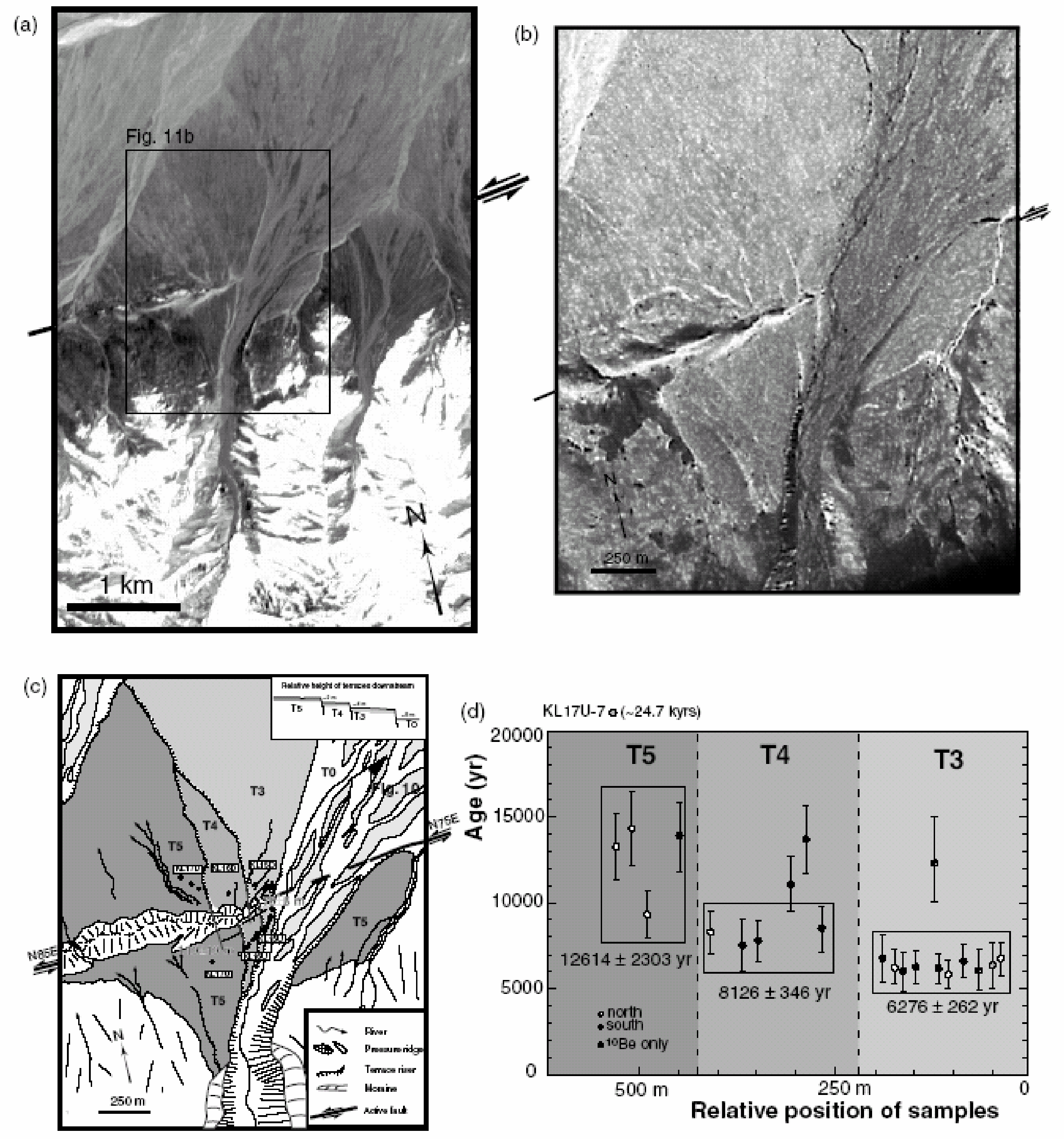

Figure 2.5 (previous page). Tectonic geomorphology of the site at Xidatan (after Van der Woerd et al., 2003) (a) Enlargement of panchromatic SPOT image of the site. The fault trace is marked by snow-covered pressure ridges on the old fan surface. This surface merges with the frontal moraine, which has been breached and deeply incised by the river. Incision has led to the formation of inset terraces that are offset several tens of meters by left-lateral movement on the fault. The black rectangle corresponds to part (b). (b) Enlargement of CORONA satellite images. (c) Schematic interpretation of images. Riser offsets were measured in the field and on CORONA and SPOT images. The fault trace is marked by large pressure ridges. Fist-size quartz pebbles were sampled on top of the main alluvial surfaces, south and north of the fault trace (grey and white circles, respectively). (d) Plot of sample ages, for each terrace, in relative position, from east to west. For each terrace level, samples were grouped and a mean age calculated (boxes and bold numbers).

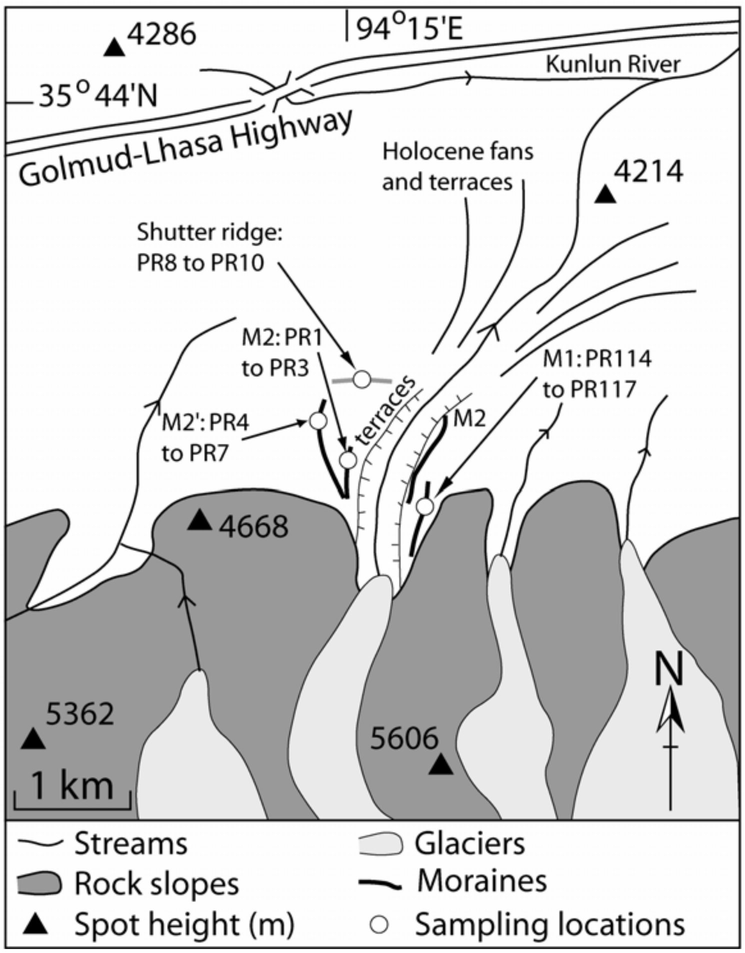

Figure. 2.6. Moraines and fans along the northern side of Burhan Budai Shan near Xidatan (after Owen et al., 2006).

On northern side of Burhan Budai Shan the oldest moraine (M1) that was dated has surface exposure ages which range from 116 to 68 ka, while the younger moraines have surface exposure ages that range from 23 ka to 6 ka (Owen et al., 2006)(Fig. 2.3).

Boulders on the shutter ridge have ages that range from 97 ka to 20 ka. The large spread of surface exposure ages might be the consequence of burial by aeolian silts and recent exhumation. The M1 moraines may represent an advance during the early part of the last glacial cycle or even during the penultimate glacial cycle. The M2 moraines are likely to represent an advance during the Last Glacial Maximum or Lateglacial. However, they may even represent a Holocene glacial advance, with the older dates representing derived boulders. The Holocene ages on the alluvial fans dated by Van der Woerd et al. (2002) suggest that there were significant climatic and hydrological cycles throughout the Holocene and many of the alluvial fans/terraces might have a paraglacial origin. The ages on the shutter ridge support the view that there was not an extensive trunk valley glaciation during the last glacial cycle. If there had been such a glaciation it would be difficult to explain the old surface exposure ages. The moraines near the present glacial have not been dated and their freshness suggests that they formed during the Late Holocene.

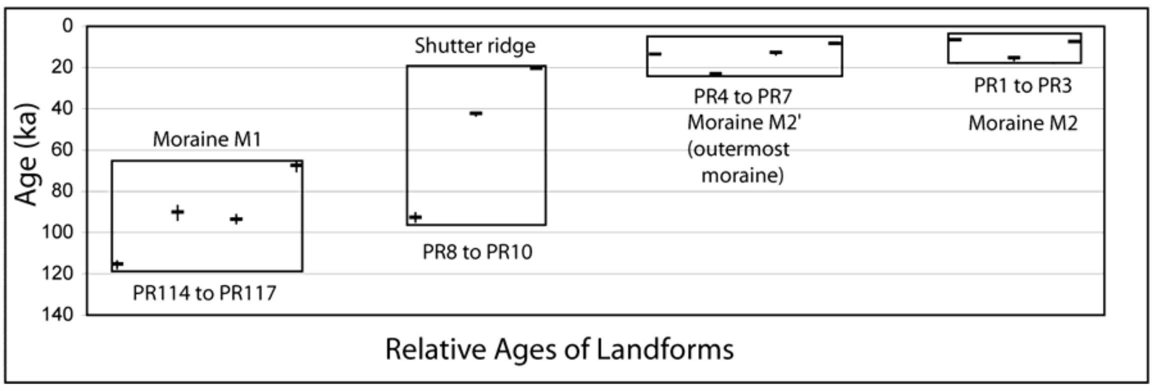

Fig. 2.7. Be-10 terrestrial cosmogenic radionuclide surface exposure dates for the landforms north of Burhan Budai Shan plotted by relative age of each landform (after Owen et al. 2006).

Stop 3: Ice Avalanches

On 14 November 2001, a magnitude 7.9 earthquake (Kokoxili) shook the Kunlun and produced a surface rupture that was >400 km long following approximately the trace of the Kunlun Fault (Fig. 3.1). Several giant ice avalanches were initiated by slope failure from ice caps due to the strong ground motion during the earthquake (Figs. 3.2 and 3.3). Van der Woerd et al. (2003) identified four giant ice avalanches on the north slope of the Burhan Budai Shan several kilometers east of the Kunlun Pass, and two on the south slope of the eastern Yuxi Feng, which is ~50 km west of the Kunlun Pass. These ice avalanches originated from steep-sided ice caps and progressed over and past the termini of outlet valley glaciers. In the Burhan Budai Shan, the ice avalanches comprised ice and snow that reached 2–3 km down valley beyond the snouts of the contemporary glaciers.

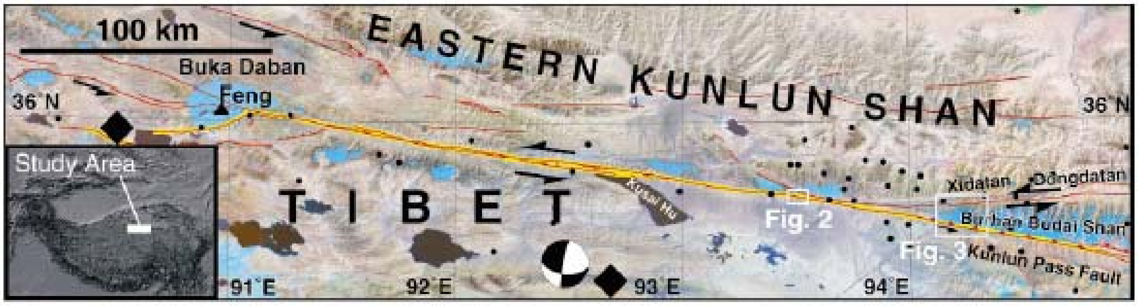

Figure 3.1. Map of ruptured Kusai Hu segment of Kunlun fault with Landsat image in background (after van der Woerd et al., 2003). Red lines are active faults and yellow lines are ruptured strands. Black diamonds show location of epicenter (west) and centroid with mechanisms (Harvard, 2001) of November 14, 2001 Kokoxili earthquake. Black dots are aftershocks (M≥5). The ice capped summits appear in light blue, lakes in black. Inset is location of study area within Tibet.

Detailed study of the largest ice avalanche (B2) shows that the initial movement over the contemporary glacier was turbulent in nature, having a velocity 35 m/s (Figs 3.3 – 3.5). Beyond the contemporary glacier, the ice avalanche was confined within steep valley walls and entrenched paraglacial fans. Before coming to rest, this ice avalanche moved as a Bingham plastic flow at a velocity of ≤21 m/s. These ice avalanches transported little rock debris, and it is thus unlikely that they are important in contributing to the landscape evolution of this region. Van der Woerd and colleagues visited the region in November 2003, two years after the 14 November 2001 earthquake that caused the avalanches. Unexpectedly, all the avalanches had already melted away except for a few icy patches in the shadows of the valley's flanks. Instead of several decades, as we had forecasted, only two years were enough to almost completely melt the avalanches, despite the high elevation and cold inter temperatures. The rapid disappearance of such volumes of ice and snow emphasizes the importance of remote sensing techniques in high mountainous regions to detect such events and make hazard studies. Yet, given the appropriate geologic and climatic conditions, ice avalanching may be an important process in the landscape evolution of high mountainous terrains. The frequency of such events is unknown, but such phenomena may become more common in the future as a consequence of increased glacier and slope instability caused by human induced climate change. Ice avalanches, therefore, likely constitute a significant geologic hazard in the near future.

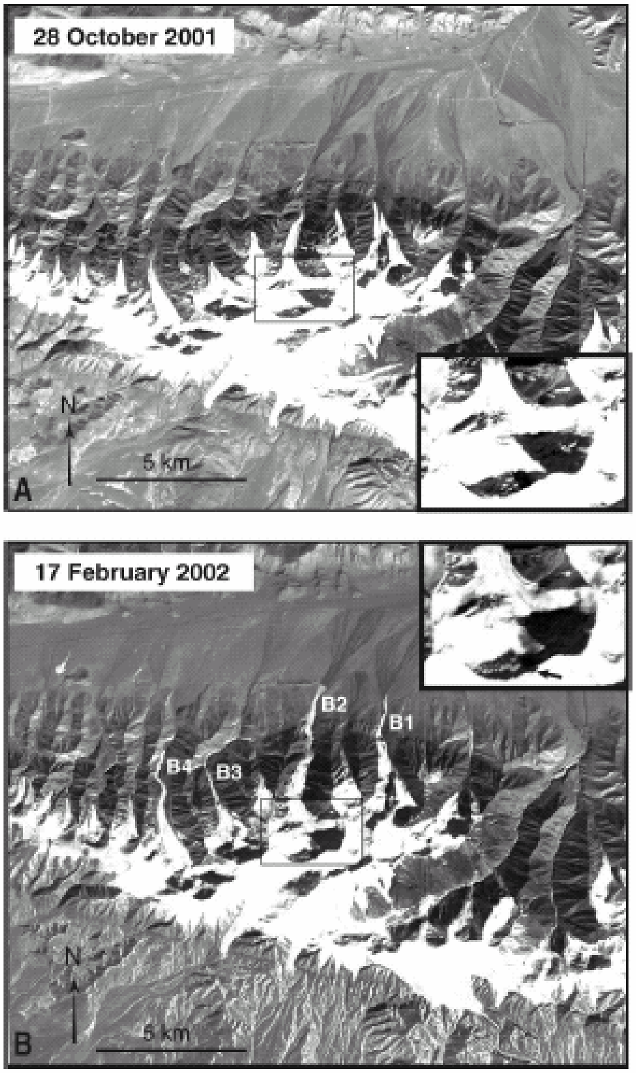

Figure 3.2. Comparisons between ASTER images of Burhan Budai Shan (after Van der Woerd et al. 2003). (A) Before Kokoxili earthquake (October 2001). (B) After Kokoxili earthquake (February 2002). Images show north-facing glacial cirques with steep valley walls. Insets show enlargement of upper glacial catchment area of ice avalanche B2 and its possible source at steep cliff of ice cap edge (arrow).

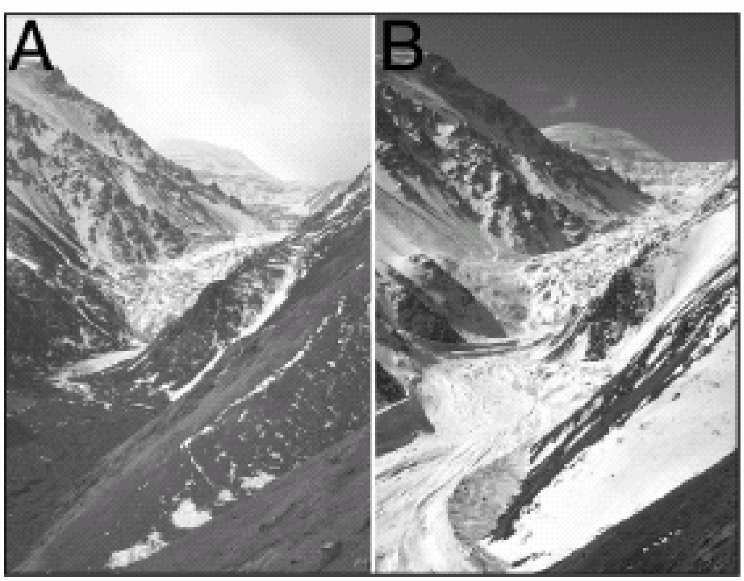

Figure 3.3. Views (looking south) at snout of glacier in Burhan Budai Shan over which ice avalanche B2 progressed (after Van der Woerd et al., 2003). Images were taken in (A) April 2001 and (B) April 2002.

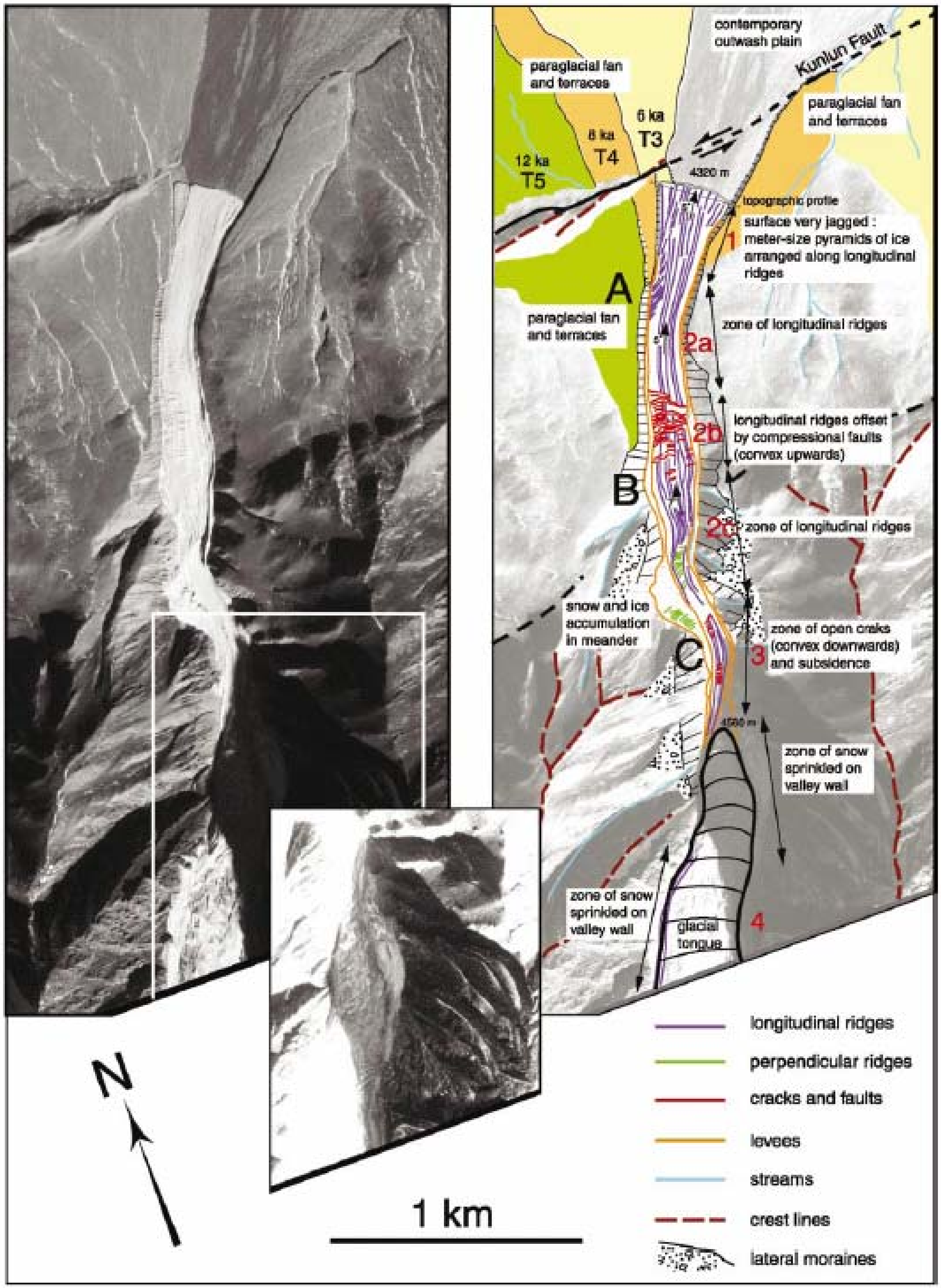

Figure 3.4. Ikonos image showing main surface characteristics of ice avalanche B2 and an interpretation supplemented with field observations (after Van der Woerd et al., 2003). A, B and C are sections where paleovelocity calculations were performed (see Table 2). Red numbers (1 to 4) refer to zones described in text. Inset enhances part of image remaining in shadow and shows undisturbed glacial tongue terminus.

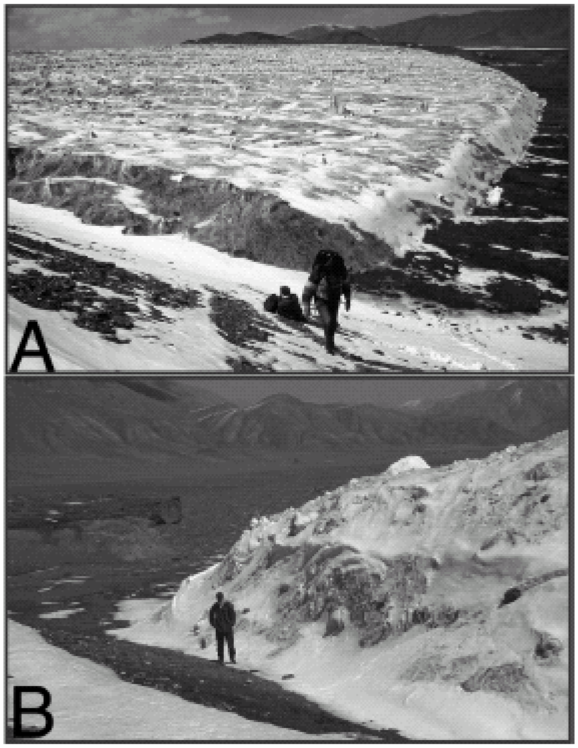

Figure 3.5. Views of snout of ice avalanche B2 in April 2002 (after Van der Woerd et al., 2003). (A) View looking west across snout. Note radiating nature of longitudinal ridges in this zone. (B) Steep front of ice avalanche.

Stop 4: South side of the Burhan Budai Shan

Extensive glacial outwash alluvial fans form a bajada along the southern side of the Burhan Budai Shan. At least three distinct sets of alluvial fans are present. The oldest comprises dissected alluvial fan remnants that rise 5 – 10 m above the younger onlapping alluvial fans. These Owen et al. (2006) called F1. The surfaces of these alluvial fans are relatively smooth and have scattered boulders up to 2 m in diameter. The surface boulders are generally weathered with pits up to several tens of centimeters in diameter and several centimeters deep. Boulders that appeared to be least weathered (e.g. few pits) were sampled for SED. The next set of alluvial fans is very extensive, radiating from the tributary glaciated valleys of the Burhan Budai Shan. The heads of these alluvial fans terminate in steep proximal faces that slope up valley and trace out broad arcs, which radiate from the tributary valleys. In the valley that Owen et al.'s (2006) studied in detail, the proximal slopes are traceable to a high lateral moraine (M1) that rises several tens of meters above the western side of the contemporary drainage, well beyond the main mountain front (Fig. 4.1). This relationship suggests that these landforms may have been ice-contact outwash fans. The surfaces of these fans are also relatively smooth and have scattered boulders, which exhibit similar degrees of weathering as the higher dissected fan remnants. Owen et al. (2006) therefore call these F2 ice-contact outwash fans. Samples for surface exposure dating were collected from both the moraine and outwash fan.

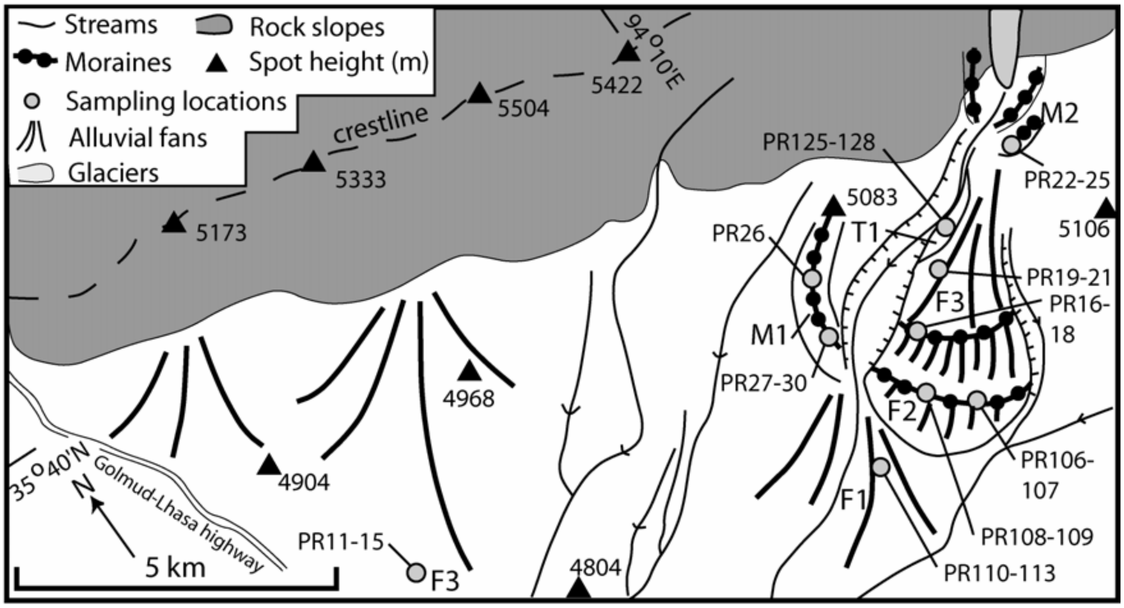

Figure 4.1. Moraines along the southern side of the Burhan Budai Shan. The fan surfaces are labeled F1 to F3, the moraines are M1 and M2, and the dated river terrace is T1 (after Owen et al., 2006).

The next set of alluvial fans, F3, has an undulating surface of subdued channels and levees and has a higher frequency of surface boulders than F1 and F2. Samples for SED were collected from boulders within the study valley and from a surface ~10 km to the west of the main study valley. In the valley Owen et al.'s (2006) studied, F3 originated at a latero-frontal moraine, which rises several tens of meters above the contemporary drainage within the tributary valley. Owen et al. (2006) collected a set of samples for surface exposure dating from this moraine.

Near the contemporary stream, F3 alluvial fan overlies a river terrace. This terrace rises several meters above the contemporary stream. In contrast to the outwash and ice-contact fans, it contains no surface boulders; however, well rounded cobbles are abundant. We collected cobble samples for surface exposure dating from this terrace and refer to it as T1. Morphostratigraphically, this was the youngest landform Owen et al. (2006) attempted to date in this study area. A younger moraine is present up valley of this moraine and encloses the contemporary glacier. However, this moraine was not dated.

The surface exposure ages for boulders on landforms on the southern side of the Burhan Budai Shan range from >235 ka to 12 ka, with a large number being well older than 100 ka. This suggests that many of the landforms that Owen et al. (2006) dated formed during or before the penultimate glacial cycle. Landforms of such antiquity are prone to erosion 4.2) and it is rare for boulders on their surfaces to remain stable through the whole history of the landform. These results in a large scatter of surface exposure ages on individual landforms, and the older ages in each data set are probably more indicative of the true age of the landform.

Such scatter of ages is evident for outwash fan F1 whose boulders have surface exposure ages which range from 236-188 ka. However, with the exception of one boulder (188 ka) all the other boulders are >200 ka. Given the likelihood that the boulders on this fan have undergone significant weathering the fan is likely to be much older than 200 ka.

Ice-contact fan F2 provides another example of the large scatter of surface exposure ages, which range from 123 ka to 238 ka. With the exception of one boulder (~26 ka), however, all the boulders on the F2 ice-contact fan surfaces are much older than 100 ka. This suggests that they formed during the penultimate glacial cycle. The moraine that is associated with these fans has surface exposure ages with an exceptionally large range (16-152 ka). Given the effect of weathering and toppling of boulders on a moraine crest, together with possible exhumation as the moraine degrades with time, the older ages in the data set suggest that it likely formed during the penultimate glacial cycle, coincident with the F2 ages that suggest formation during the penultimate glacial cycle.

Terrace T1 has surface exposure ages that range from 65 ka to 109 ka, which suggest that it formed during the early part of the last glacial cycle.

The scatter of surface exposure ages on outwash fan F3 dates in the distal area is large (33 ka to 82 ka), but much less for the study valley (27-38 ka). If PR12 (~82 ka) is excluded from the data set, the surface exposure ages cluster between 27 ka to 38 ka suggesting that these outwash fans formed during MIS-3.

M2 has surface exposure ages that range from 41 to 12 ka. Although we can not equivocally assign an age to this moraine, it is likely that this moraine formed during MIS-3, and it is associated with the F3 outwash fan.

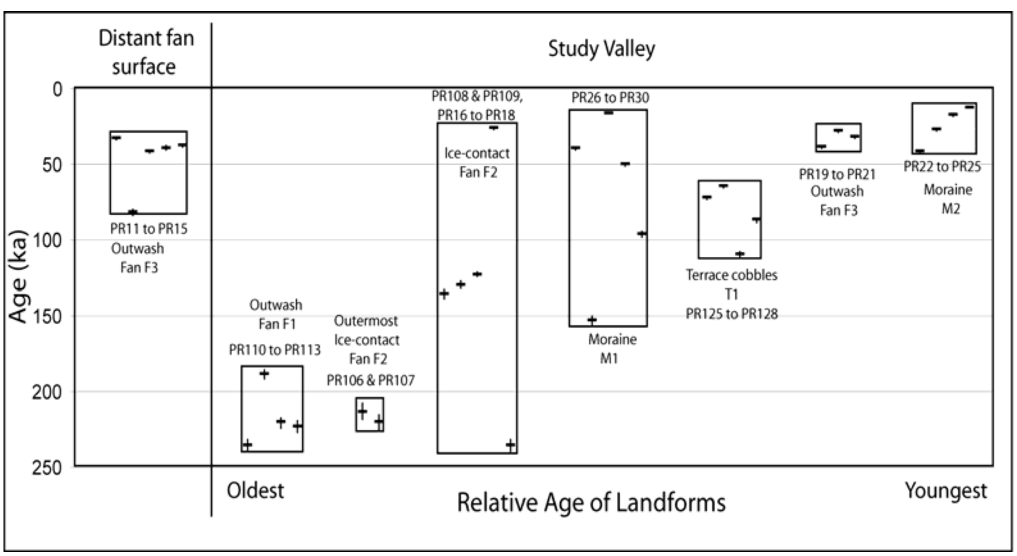

Figure 4.2. Be-10 terrestrial cosmogenic radionuclide surface exposure dates for the landforms south of Burhan Budai Shan plotted by relative age of each landform (after Owen et al., 2006).

Recent TCN surface exposure dating undertaken by Marc Caffee, Jon Harbor, Yingkui Li, and Arjen Stroeven on moraine boulders on the south side of the Burhan Badai Shan provide an Be-10 TCN age of between 42 and 63 ka for an old moraine and a provide 11.5 ka on a younger moraine (Table 4.1). These support the view that a major advance likely occurred during MIS-3. They use data to determine minimum erosion rates for the region (Table 4.1).

Table 4.1. Preliminary Be-10 TCN dates from the southern side of the Burhan Badai Shan

Sample number	Latitude/Longitude	Altitude (km)	Moraine	Age	Erosion rate (m/Myr)
TB04-17	35.65/94.04	4.91	Oldest	62600±4400	9.47±0.67
TB04-18	35.65/94.04	4.93	Oldest	43900±2900	13.58±0.90
TB04-20	35.65/94.04	4.92	Oldest	41600±2600	14.32±0.90
TB04-21	35.65/94.04	4.91	Oldest	53400±4100	11.13±0.86
TB04-04	35.63/94.21	5.10	Youngest	11500±2700	52.23±12.43

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Owen, L.A., Finkel, R. C., Ma Haizhou and Barnard, P.L. 2006. Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: a framework for examining the links between glaciation, lake level changes and alluvial fan formation. Quaternary International, 154-155, 73-86.

Van der Woerd, J., Owen, L.A., Tapponnier, P., Xiwei X., Kervyn, F., Finkel, R.C. and Barnard, P.L., 2004. Giant, M~8 earthquake-triggered, ice avalanches in the eastern Kunlun Shan (Northern Tibet): characteristics, nature and dynamics. Geological Society of America Bulletin, 116, 394-406.

Van der Woerd, Tapponnier, P., Ryerson, F.J., Meriaux, A.-S., Meyer, B., Gaudemer, Y., Finkel, R.C., Caffee, M.W., Zhao, G. and Xu, Z., 2002. Uniform postglacial slip-rate along the central 600 km of the Kunlun Fault (Tibet), from ^{26}Al, ^{10}Be, and ^{14}C dating of riser offsets, and climatic origin of the regional morphology. Geophysical Journal International, 148, 356-388.

DAY 3: TANGGULA SHAN
Lead by: Lewis Owen, Marc Caffee, Zhou Shangzhe & Jiangqiang Yang

Overview

The Tanggula Shan is an east–west trending mountain range in central Tibet (Fig. 1.1). The surrounding lowlands are semi-arid (540mma^{-1}), while the higher peaks of the Tanngula Shan receive up to 5700m ma^{-1} due to orographic effects during the summer monsoon season. The contemporary glaciers in this region are of cold continental type (Derbyshire, 1981; Pu et al., 1998; Su and Shi, 2002). Pu et al. (1998) showed that, for the Xiao Dongkemadi Glacier in the vicinity of the Tanggula Pass, the mean annual temperature and precipitation at the equilibrium line is ~9.8^{o}C and 560mm (at 5600m asl), respectively, and the basal ice temperature is ~7.5^{o}C.

Figure 1.1 Google image of the Tanggula Shan

The glacial geology of the region was originally described by Zheng and Jiao (1991) who produced a map of the Tanggula Pass showing evidence for at least three major glaciations (Fig. 1.2). They referred to these as the Tanggula Ice Age, the Zhajiazangbo Ice Age and the Bashico Ice Age and regarded them as representing 'extremely old', penultimate, and last glacial cycles, respectively. During the first two of these glaciations, glaciers and ice caps expanded into the forelands from the Tanggula Shan to form a continuous ice cap that, in the area around the Tanggula Pass, was ~90km and ~25km wide during the Tanggula and Zhajiazangbo Ice ages, respectively (Derbyshire et al., 1991; Zheng and Jiao, 1991). This produced extensive sheets of till and subdued terminal moraines. The extent of the glacial advance during the Bashico Ice Age was restricted to only several kilometres beyond the present ice margins. Schäfer et al. (2001) dated four glacial boulders on the Tanggula Pass using ^{10}Be, ^{26}Al, and ^{21}Ne surface exposure dating (Fig. 1.2). They showed that three boulders within the Tanggula glacial limit had ages of 181.3±5.7, 89.3±8.0 and 172.9±13.8 ka, while a boulder within the limit of the Bashico Ice Age had a surface exposure age of 72.1±6.2 ka. Owen et al. (2005) dated samples from boulders using ^{10}Be within the same regions as Schafer et al. (2001), as well as from moraines dating from the Zhajiazangbo Ice Age. This provided a test of the validity of the glacial ages based on the samples dated by Schäfer et al. (2001), as well as a means of examining the age of the previously undated intermediate glaciation, the Zhajiazangbo.

Using ^{10}Be TCN surface exposure dating, Owen et al. (2005) dated moraines of the Zhajiazangbo glacial which were well bracketed between the Tanggula and Bashico Glacial Stages at ~148±36 ka (mean age and the errors are quoted as 1σ for all the samples dated of the same glacial stage) and 68±26 ka, yet the SED ages range from >210 to <50 ka (118±73 ka) (Fig. 1.3). The young ages were attributed to extreme weathering (although care was taken to avoid any boulder that showed signs of significant weathering) or recent exhumation by erosion and/or frost heaving. The old ages were considered by Owen et al. (2005) to be boulders derived from older glacial events and/or ones that were not adequately eroded by glacial processes and therefore have inherited TCNs from prior exposure on hill slopes. Despite the scatter of ages, the data show that the Zhajiazangbo glaciation must have occurred during the early part of the last glacial cycle, the Tanggula Glacial prior to the last interglacial (the younger dates for samples PR58 and PR77 may well be the results of weathering or exhumation) and the Bashico Glacial probably during marine isotope stage (MIS) 4 or the latter part of MIS 5. Owen et al.'s (2005) data compare well with the surface exposure ages determined by Schäfer et al. (2001) for the five boulders in his study.

Owen et al.'s (2005) and Schäfer et al. (2001) Be-10 TCN ages were reconfirmed by Colgan et al. (2006) when they dated three boulders and a glacial striated rock surface from the north side of the Tanggula Shan. TCN ages of 41.4±4.3 ka and 66.8±7.1 ka were obtained for glacial boulders of the Zhajiazangbo glaciation. They also provided a Be-10 TCN age of 16.1±1.7 ka for striated bedrock and 31.9±3.4 ka for a boulder on a small moraine within a few miles of the contemporary Tanggula glacier. They argued, however, that four to seven boulders need to be dated to better determine the age of this younger glacial advance, which they called the Longxiazai phase. Their study reiterated earlier studies that show evidence for very limited glaciation during the global last glacial maximum.

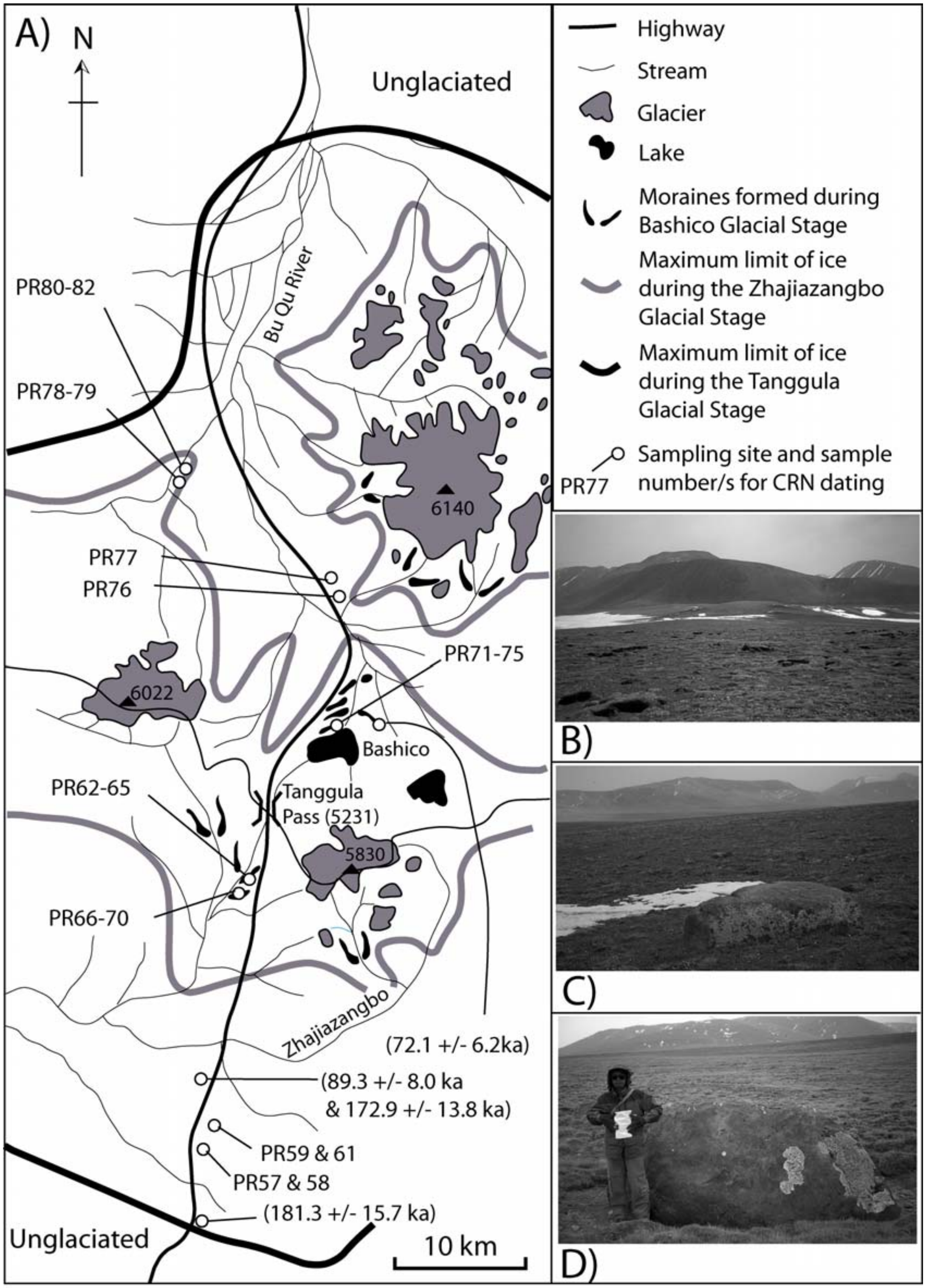

Figure 1.2: The glacial geology in the area around the Tanggula Pass after Owen et al. (2005). (A) Simplified geomorphic map of the Tanggula Pass showing the sites where we have obtained SEDs on moraines (modified from Benxingand Keqin, 1991). The dates in parenthesis were undertaken by Schäfer et al. (2001). (B) View of end moraines of the Bashico Glacial Stage south of the Tanggula Pass. (C, D) Typical glacial boulders on surface of moraines deposited during the Zhajiazangbo (C: boulder PR76) and Tanggula Glaciations and (D: boulder PR77).

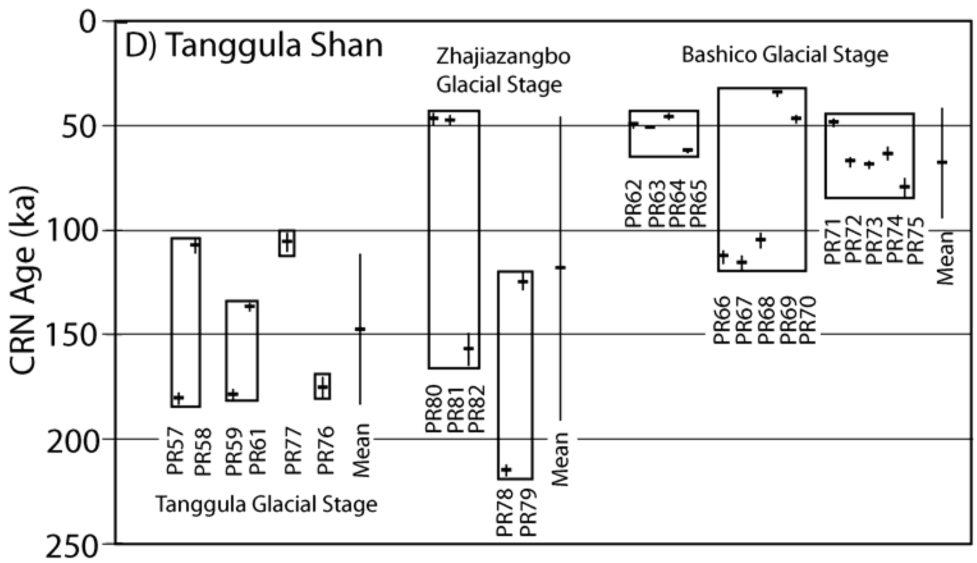

Figure 1.3: Be-10 SEDs for Tanggula Shan (after Owen et al., 2005)

Stop 1: North side of Bashico Lake

The first stop will examine the moraines north of Bashico Lake (Figure 1.4). These were dated by Owen et al. (2005) using ^{10}Be TCNs, which show they formed during the early part of the last glacial (Figs. 1.2 and 1.3).

Figure 1.4: Oblique Google image of Bashico Lake on the north side of Tanggula.

Stop 2: South side of Tanggula Pass
This stop will examine moraines on the SW side of the Tanggula Pass (Fig. 2.1). These were dated by Owen et al. (2005) to ~50ka and >100 ka (Figs. 1.2 and 1.3). At this location we shall discuss the uncertainties regarding TCN surface exposure dating methods.

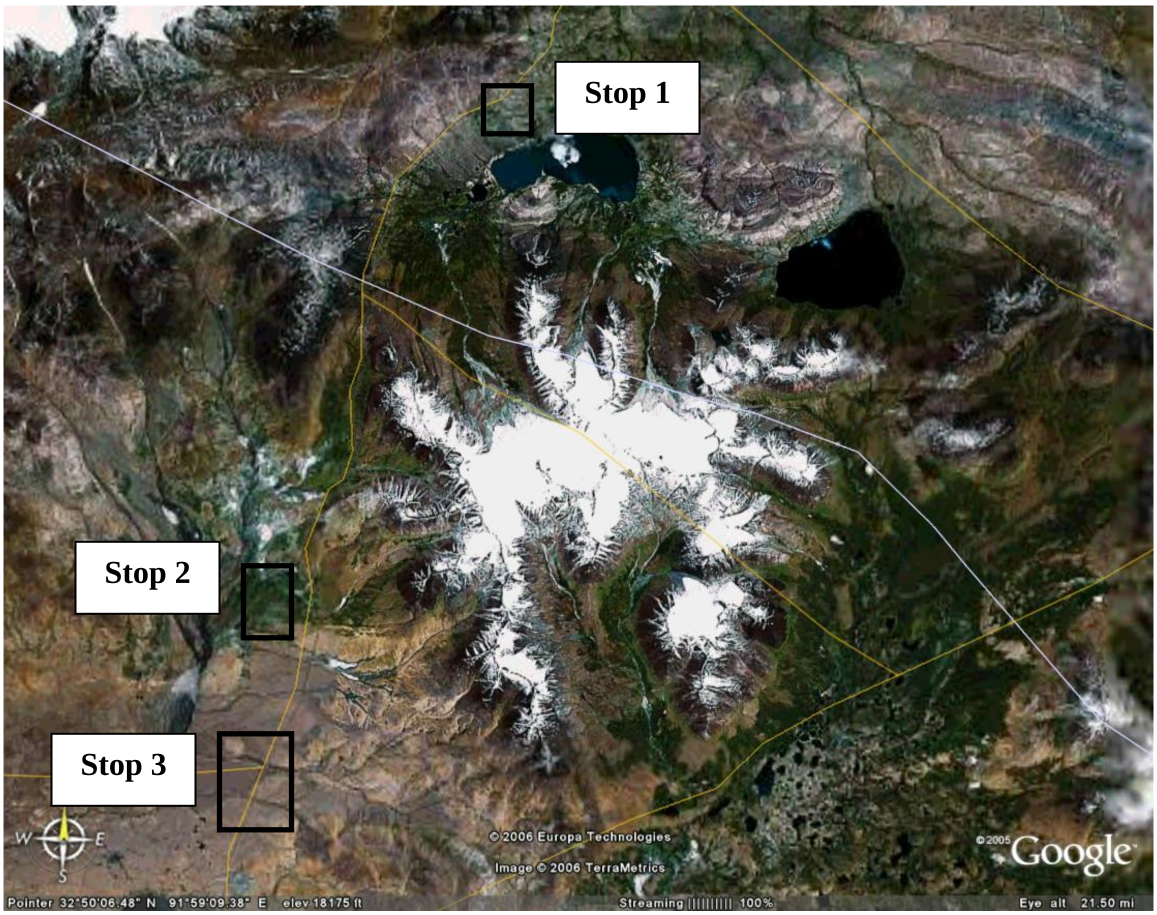

Figure 2.1: Close-up of the main areas to be examined during the field excursion.

Stop 3: South side of the Tanggula
The erratics of the Tanggula Glacial Stage will be examined at this stop (Fig. 2.1). These were dated by Schäfer et al. (2001) and Owen et al. (2005) using SED methods and were shown to be >100 ka (Figs 1.2 and 1.3).

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Schäfer, J.M., Tschudi, S., Zhao, Z., Wu, X., Ivy-Ochs, S., Wieler, R., Baur, H., Kubik, P.W. and Schluchter, 2001. The limited influence of glaciations in Tibet on global climate over the past 170000 yr. Earth and Planetary Science Letters, 6069, 1-11.

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Zheng, B. and Jiao, K., 1991. Quaternary glaciations and periglaciations in the Qinghai-Xizang (Tibetan) Plateau. Excursion Guidebook XI, INQUA 1991, XIII International Congress, Beijing, 54 pp.

DAY 4: QUATERNARY GEOLOGY OF NAM CO. AND THE WESTERN NYAINQENTANGUHLA

Lead by: Chaolu Yi, Frank Lehmkuhl and Benxing Zheng

Overview

The Nyainqentanglha Mountains are situated between 97 and 98°E and have a total length of about 740 km. This is a Tethyan fold belt formed during the Yenshan earth movement and is dominated by two major faults. The field trip will provide opportunities to examine the Quaternary glaciation in western Nyainqentanglha. The western part of the mountains is coincident with the Damxung Graben (from Yanbajain to Sangxung) and the Nyainqentanglha Horst (NE-SW). Four peaks rise to over 7000m asl in western Nyainqentanglha reaching 7163 m asl. To the west, the largest lake in Tibet, Nam Co, has an elevation of 4718 m asl and an area of 1920km^2. To the southeast lies the broad Yanbajain-Damxung valley at 4200-4500 m asl. The western Nyainqentanglha Mountains makes the divide between the drainage of Northern Tibet and the Lhasa River system, and a barrier to eastern monsoonal moisture. The annual precipitation is highest on the eastern slopes, with annual precipitation of ~ 490 mm in Damxung; while the climate is arid on the western side of the mountains, with annual precipitation of ~ 300 mm at Bangain. This precipitation contrast influenced the extent of the Quaternary glaciation, with more extensive glaciation on the eastern slopes compared with the western slopes.

Lehmkuhl et al. (2000) described different geomorphic zones in this area (Fig. 1): The highest peaks and mountain ranges are covered by glaciers with a snowline (ELA) at about 5,800 to 6,000 m asl. In the ice-free areas above 5,500 m the slopes are covered with frost-weathered debris and some nivation hollows occur. In the zone of about 4,000 to 4,500 m in the Yarlung Zangbo valley and up to about 4,800 m in the northern part, up to the uppermost boundary of alpine meadows and steppe vegetation at about 5,500 m asl the morphological processes are relatively weak and limited almost to frost shattering of bedrock and small gullies which cut into the bedrock and slope debris (zone of steppe gullies). On the middle parts of the slopes, aeolian mantels of loess and loess-like sediments of 0.5 to 1 m can be found (Lehmkuhl, 1997) above bedrock and slope debris. In the basins gravel gobi (Liu et al., 1996) and some sand dunes or sand sheets are distributed mainly on the surface of the widespread alluvial fans and fanglomerates. The lowermost semiarid areas below 4,000 m, e.g. in the deeply incised valleys of the Yarlung Zangbo and other tectonic basins, the vegetation cover is more spare. The fluvial incision on the slopes especially in Quaternary deposits is stronger, the main discharge is in summer time. The rivers are braided in box shaped valleys (zone of torrente valleys). Péwé et al. (1987) reported loess sections and re-transported loess in the Yarlung Zangbo valley close to Xigaze. This area below 4,000 m asl is one of the driest parts of the southern Xizang (Tibet) autonomous region with only sparse vegetation on the slopes and shifting sand and sand dunes. During the cold phases of the Pleistocene there was a lowering of the ELA of about 300 to 800 m and valley glaciers reached the basins in some regions

(Fig. 1). In the ice-free areas periglacial and nivation processes are dominating and produce debris. In the basins and at the foothills of the mountains large alluvial fans and fanglomerates (bajadas) were deposited. They extend several kilometres beyond the mountain front. These accumulation areas have produced send quite a lot of silt and sand during the Pleistocene (Lehmkuhl, 1997). Since the beginning of the Holocene there has been a reduction in sediment yield of the rivers due to the vegetation cover. In addition, there is fan trenching due to the reduction of precipitation with concentration on a few, but strong rainfall-events.

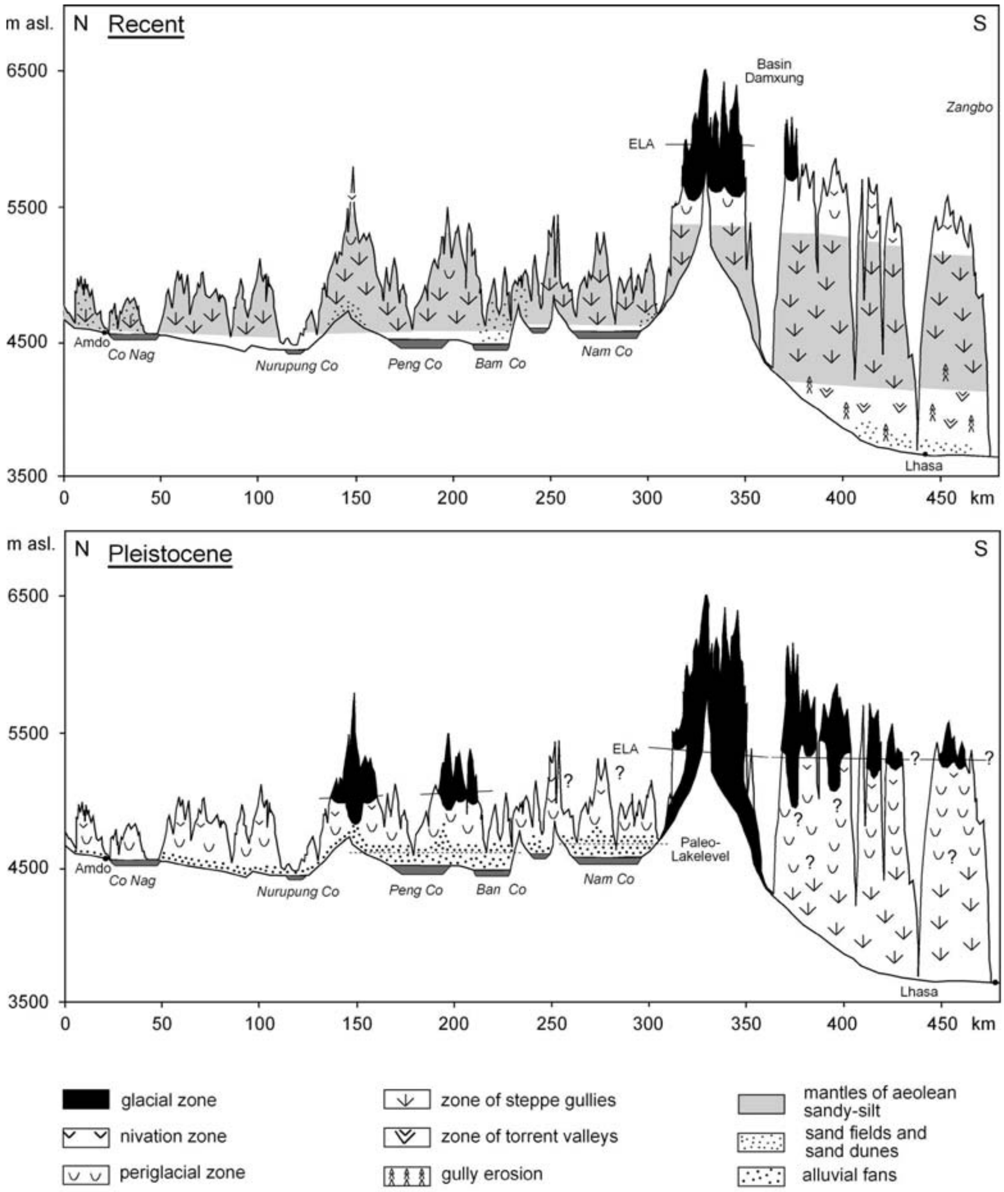

Fig. 1: Geomorphological zones in southern Tibet (Lehmkuhl et al. 2000). The cross-section is indicated in Fig. 1, day 5.

Quaternary glaciations in the western Nyainqentanghla has been studied by many researchers (Zheng et al, 1991; Lehmkuhl et al., 2000, 2002; Zhao et al; Zhu et al, 2002; Wu et al, 2003; Jiao et al, 2005; Owen et al, 2005; Na et al, 2006; Yi et al, 2006 and Fu et al, 2006, in prep). Four sets of moraines are present. Several fresh lateral moraines and terminal moraines are present several hundreds meters away from the front of the modern glaciers (Fig. 2). The highest lateral moraines are distributed on both sides of the valley and stretched beyond the tributary valleys into a series of terminal moraines in the front or the inside of the lateral moraines (Figs. 3 and 4). This suggests several glacial advances during the late Quaternary.

Lehmkuhl et al. (2000, 2002) distinguished two main glacial advances (M1, M2, Fig.5, 5, 6). The oldest terminal moraines (M2) show a slightly larger extension of the glaciated area comparing to the younger ones (M1) (Fig. 5). During glacial times, the glacier may have entered the Nam Co advancing from the main peaks (Fig. 6). Glaciofluvial fans are present beyond the terminal moraines. Ice wedge casts occur within the fans and aeolian sediments cover on the moraines at some locations (e.g. section 15, Fig. 7, 8). Fu et al (2006) measured the moraines using differential GPS and found that the landforms are related to slope gradient, rock properties of the moraines and glacial scale and timing. Using OSL methods, Lehmkuhl et al. (2000, 2002) dated the aeolian sediment that covers the terminal moraines between 10 and 89 ka. Older loess-like sediments have been preserved only at a few sites. They have been dated to 89 ±10.4 ka (M2, section 10) and 62 ±5 ka (M1b, section 12). Most other section showing a accumulation of silt showing a Holocene age (see day 5). Sand dunes also dated to early Holocene (section 2) and re-activated in Late Holocene (Lehmkuhl, unpublished data), sandy material accumulated in a particular ice-wedge (section 15, Fig. 7, 8). This one has developed in the fanglomerates in the east of the Nam Co and have a luminescence age of 4.8 ±1.0 ka. Later the ice melted and the wedge was filled with sand. In contrast, the later ice-wedge casts provide evidence for Mid-Holocene permafrost.

Using Be-10 and Al-26 SED dating methods, Na et al (2006) dated several glacial boulders on moraines, which represents the maximum extent of glaciation, in a valley near Qiongre peak and showed that they range in age from 22 ka to 44 ka. They suggest that the largest Quaternary glaciation occurred in the MIS-3.

Figure 2. Lateral and terminal moraines in front of the modern glacier in the Quga valley, on the western slopes of the western Nyainqentanghla.

Figure 3. Terminal moraine in front of lateral moraines, western slopes of western Nyainqentanghla.

Figure 4. Terminal moraine inside the lateral moraines on the western slopes of the western Nyainqentanghla

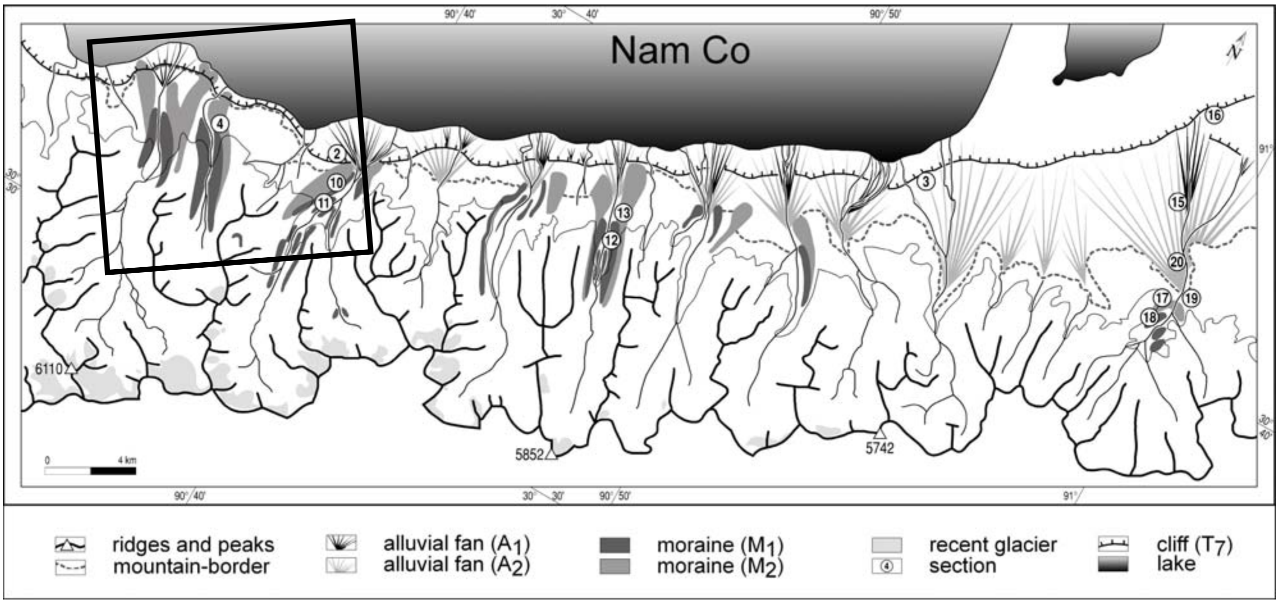

Figure 5: Geomorphological map from the study area at the southern bank of the Nam Co including the extent of modern glaciations, Pleistocene terminal moraines (M1, M2) and sample sites (modified from: Lehmkuhl et al. 2002, p199.) Box indicates Fig.6.

Figure 6. Google Earth image showing that three sets of moraines were present at the outlet of the valley in late Pleistocene

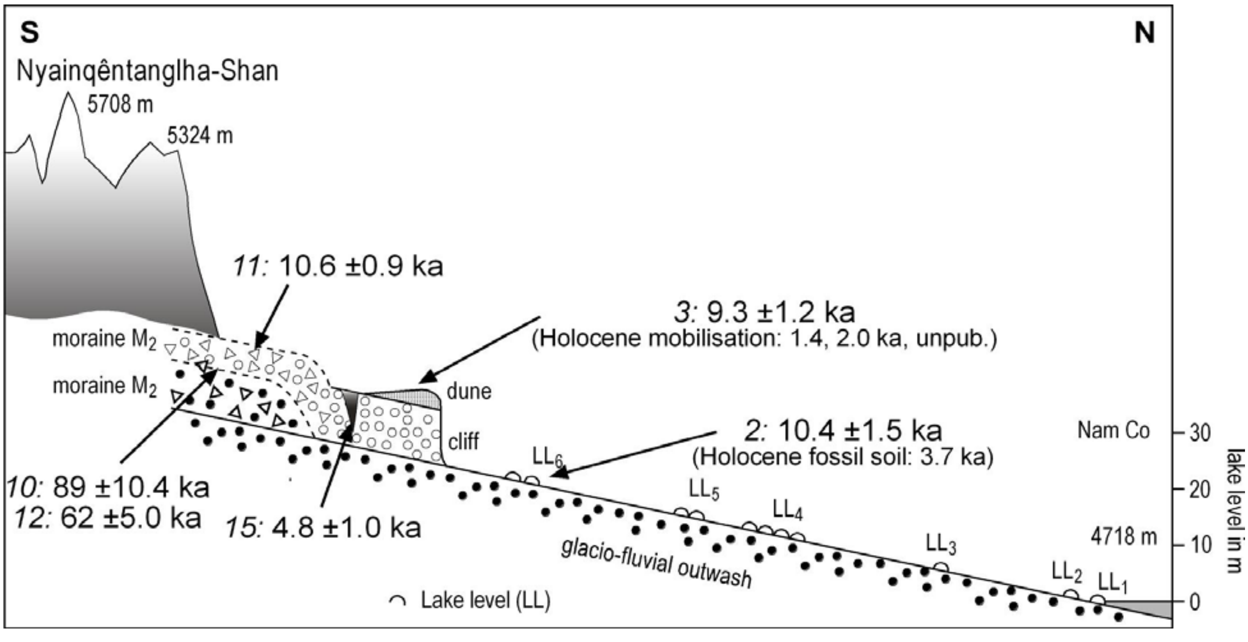

Figure 7. Sketch of the Pleistocene terminal moraines (M1, M2) from the northern slope of the Nyainqêntanglha Shan and lake terraces indicating different Late Quaternary lake levels (LL1 to LL 6) of the Nam Co. (modified from: Lehmkuhl et al. 2002, p 201.)

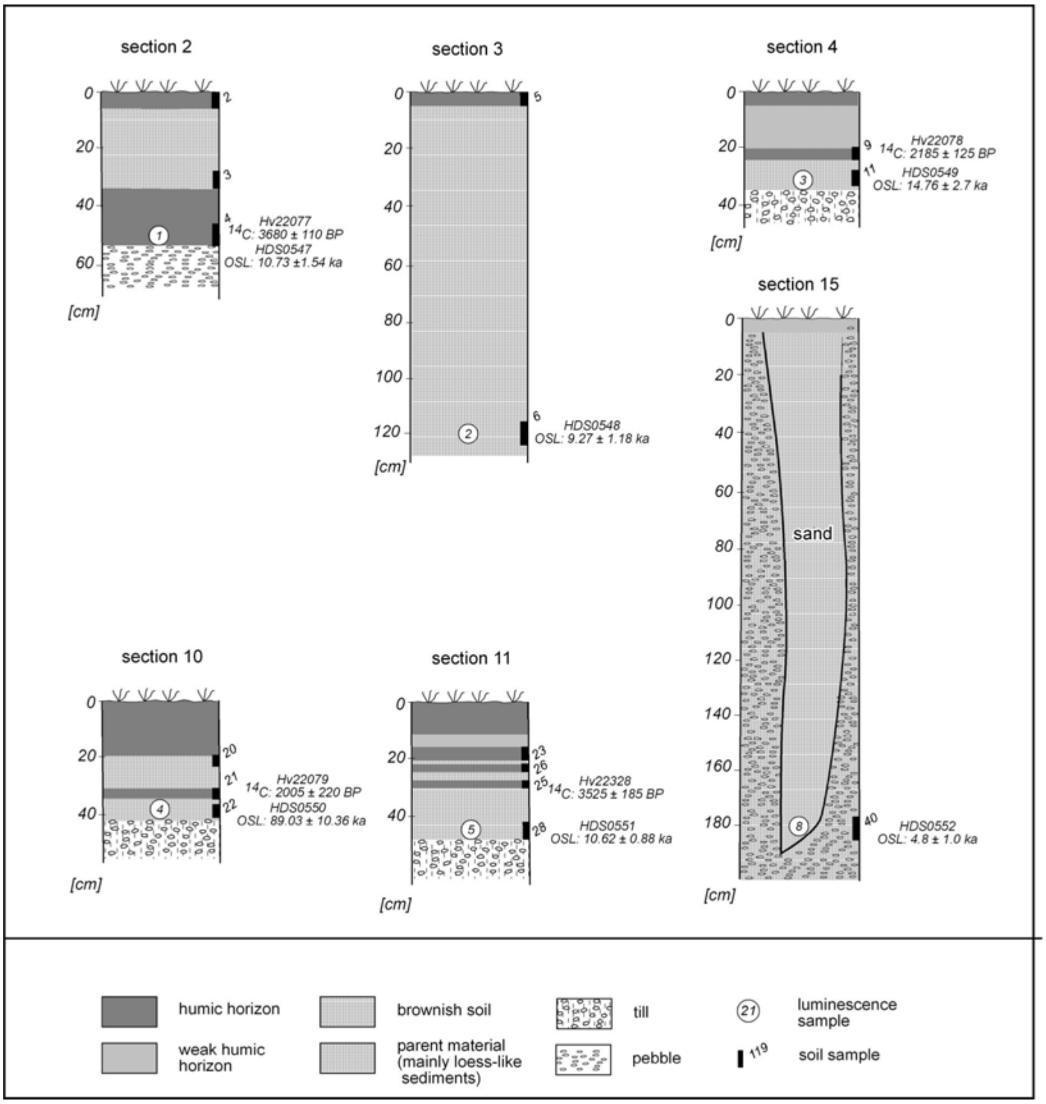

Figure 8. Selected sections from southern Tibet including the sample sites for luminescence and radiocarbon dating. (modified from: Lehmkuhl et al. 2002)

Figure 9. Ice wedge casts filled with the yellow sand in the fluvial fan, west slope of western Nyaiquentanghla

On the eastern slopes of western Nyainqentanghla, glaciers extended across the

Qinghai-Xizang High-Damxun to Namhu village at an altitude of 5500-5600 m asl. These probably reached <4400 m asl in some regions during the local last glacial maximum glaciation. Cirques and U-shaped valleys are common in the upper valleys. Zheng et al (1991) believed that these provided evidence for the largest Pleistocene glaciation in Tibet. Using electron spin resonance dating methods, Wu et al (2005), Zhao et al (2002) dated the calcite in till and related glaciofluvial deposit to 678±307 ka and 593±260 ka. They called this glacial advance the Ningzhong Glaciation. Calcite cement in the terraces ~40 to 60m above the Laergen river at Danxum, which they believed to be glaciofluvial in origin, was dated to be 205±54 ka and calcareous cements between the till clasts in a moraine 60-80m above the Laqu river, Ningzhong basin was dated, in U-series method, to 143±16.3 ka, 162.4±17.9 ka and 151.2±15.7 ka. OSL dating on terminal moraines yielded ages of 14.1±1.5 ka, 130±17 ka and 69.2±6.2 ka.

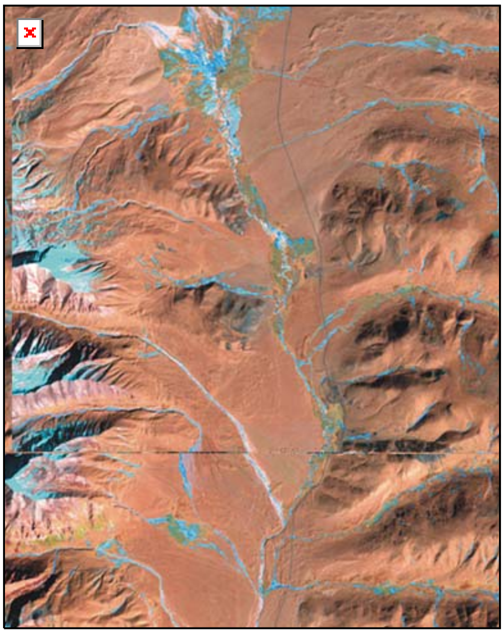

Figure 9: View of the eastern slopes of the western Nyainqentanghla.

Stop 1: Lateral and terminal moraines in La'ergen valley, glacial fluvial fan deposits
A series of lateral moraines and terminal moraines, and old moraine platform between Nam Co and Nagaqa will be examined. These were dated by Wu et al (2004) in ESR, OSL and U-series methods.

Stop 2: Alluvial fans and lake terraces related to lake level changes
Alluvial fans in the western slopes of the western Nyainqentanghla will be examined together with ice wedge casts in the distal reaches of the fans. The ice cast wedges are filled with yellow well sorted sand. On the edge of the fans, cliffs drop 21 to 25 m to Nam Co, and probably define a high lake level stand, helping to form a terrace at 18 to 21 m above lake level on the eastern shores. The ice cast wedge sands have an OSL date of 18 ka.

Stop 3: Quaternary glacial features in the valleys on the western slope of western Nyainqentanghla
There were many glaciers in the valleys. Most of them were small valleys glaciers. The largest Quaternary glaciers were near the main peak and reached lengths over 10 km. These advanced from valleys and reached and entered Nam Co. Cirques, lateral and terminal moraines will be examined. Some of these landforms were measured this summer by Chaolu Li and colleagues. They were mapped using differential GPS to study their forms to aid in examining the relationships between climate, bedrock properties and slope processes.

Stop 4: Golug village moraine
In the Nyainqentanglha Mountains near Golug, summits rise above 6000 m asl and contain numerous small cirque and hanging glaciers. Moraines of the last glacial are present at ~5000 m asl. Moraines, comprising granite, from large piedmont glaciers representing the maximum glaciation reached Golug.

Stop 5: Zhongri moraine
From here the present glaciers and U-shaped troughs on the eastern slopes of the Nyainqentanglha Mountains can be observed, as well as the moraines of the last glaciation. The Middle Pleistocene moraine platform are widely present here. There are many large boulders on both side of the highway, their lower limit being 1-2km east of the highway.

Stop 6: Quaternary glacial evidence on Sulfur Mountain in Yangbajain
Zheng et al (1975 and 1979) investigated the glacial geology in this region. A hummocky moraine at 5000 m asl is present at Hailong village and probably represents a 5 km long twin glacial system that advanced during the last glacial. Old glacial moraines and glaciofluvial fan deposit are also present in this area. The oldest moraine and their related glaciofluvial sediments were eroded and excavated by hot sulfurous springs, suggesting that the sulfur mine was formed in middle Pleistocene.

DAY 5: EASTERN NYAINGENTANGULHA SHAN

Chaolu Yi, Lewis Owen and Frank Lehmkuhl

Background

The Nyaingentangulha Shan forms an extensive east–west mountain range in southern Tibet to the north of the Tsangpo valley (Fig. 1.1A). This lies on the extreme margin of the present influence of the monsoon, receiving ~400mm precipitation per annum. The glaciers in this region are of cold continental type (Derbyshire, 1981; Su and Shi, 2002). Lehmkuhl et al. (2002) examined Late Quaternary glacier advances, lake level fluctuations and aeolian sedimentation on the northwestern side of the western Nyainqentanggulha Shan, and suggested evidence for multiple glaciations that spanned the last two glacial cycles. However, they were not able to date the moraines directly in this region. The glacial succession on the more accessible (eastern) side of the western Nyainqentanggulha was described by Owen et al. (2005). At least two major sets of incised latero-frontal moraines are present within the u-shaped valleys on the eastern side of the western Nyainqentanggulha Shan. Hummocky moraines are present in the forelands of the mountains as much as 5 km from the mountain front. These comprise diamictons containing meter-size boulders. Owen et al. (2005) chose a valley ~15km south of Samdainkangsang Peak (6532 m asl), that contained some of the best-preserved moraines, and associated hummocky moraine on the foreland to apply TCN surface exposure dating methods to date the moraines. Samples for surface exposure dating were collected and dated from the hummocky moraine and from two sets of moraines within the range (Fig 1A and B). Owen et al. (2005) showed that the three sets of moraines on the eastern slopes of the western Nyainqentanggulha Shan have ages that cluster around 70 ka (sample PR45 rejected), 20 ka (sample PR45 rejected) and 16 ka (Fig. 1.1B). Each successive glacial was progressively less extension. This supports the view that the local last glacial maximum in this region occurred early in the last glacial cycle (~ 70 ka).

Although the production of sand and silt in these semiarid and arid regions was maximised during glacial periods, most luminescence ages provide evidence for the development of aeolian mantles on top of cover bed and bedrock deposition in Late Glacial and Early Holocene times (Lehmkuhl et al. 2000, 2002). These loess-like sediments of 30 to 50 cm cover the slope debris, the fanglomerats and the Pleistocene moraines in the zone of alpine meadows and steppe vegetation below 5,500 m a.s.l., (Lehmkuhl 1997, Lehmkuhl et al. 2000, 2002). Everywhere in western Tibet a typical steppe brown soil profile (castanozem, chestnut soil) has been developed during the Holocene on top of these aeolian sediments. At depths between about 25 and 50cm, a buried fossil soil, rich in humic content, appears quite widespread. This dark soil looks similar to those found in eastern Tibet (mountain chernozem), and probably indicates more humid conditions than it is the case in the modern soils. The post-glacial sedimentation of wind-transported dust starts about 14 and 10 ka. The reason is the more humid and warmer climatic conditions as also indicated by higher lake levels (Fig. 2). The vegetation expanded so that the dust supply was minimised, but the vegetation cover as a main dust trap captured the loess-like sediments in this area (Nilson & Lehmkuhl 2001). During the cold-dry periods of the last glaciation, older aeolian sediments and soils were blown out, washed out by fluvial processes, or mixed within the periglacial debris. Therefore, older loess-like sediments, which date to the beginning of the Last Glacial period, may only be preserved at specific wind protected relief positions.

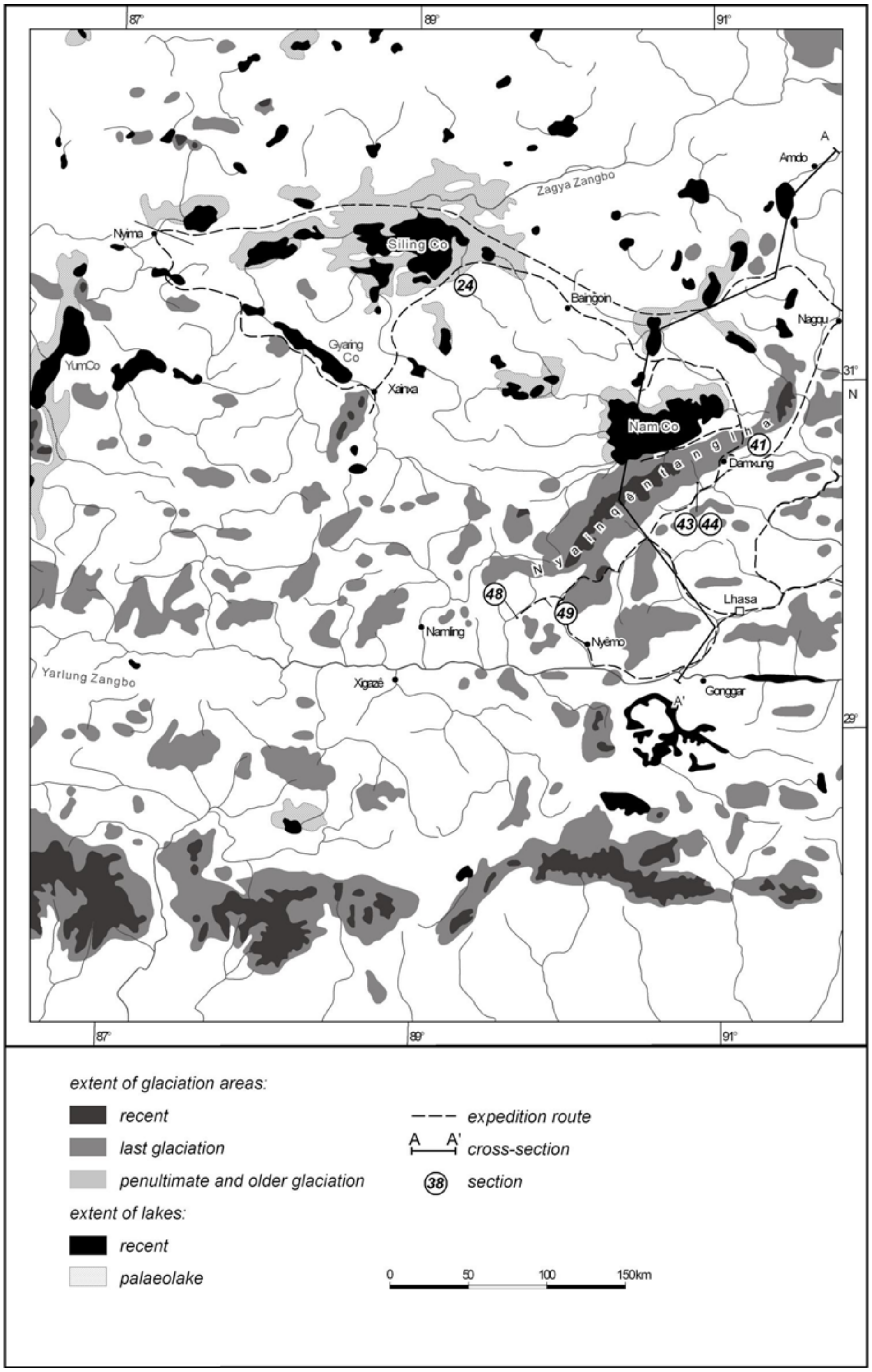

Fig. 1: Map of the investigation area of Lehmkuhl et al. (2000, 2002) including the extent of Pleistocene glaciation and palaeolakes according to Li et al. (1991). Selected sections and the cross-section (Fig 1, day 4) are indicated.

An example is given in Fig. 3 (Section 48) are located on the southwestern margin of the Nyainqêntanglha Shan. It is situated near the top of two lateral moraines close to the outer limit of valley glaciers. The section have a silty sediment cover of about 50-70 cm and the bases of these aeolian mantles are dated to 7.9 and 8.8 ka (Lehmkuhl et al. 2000). The aeolian mantles contain various palaeosols and radiocarbon dating of humic acid indicates, that two periods of soil formations have occurred at 4,370 ±125 BP, respectively. Fig. 3 (section 24) was situated at the Siling Co further west. Whereas the basis of the silt provide also an Early Holocene age and furthermore a Late-Holocene fossil soil can be found, there is only an initial modern soil developed on top of the section due to the enhanced aridity today.

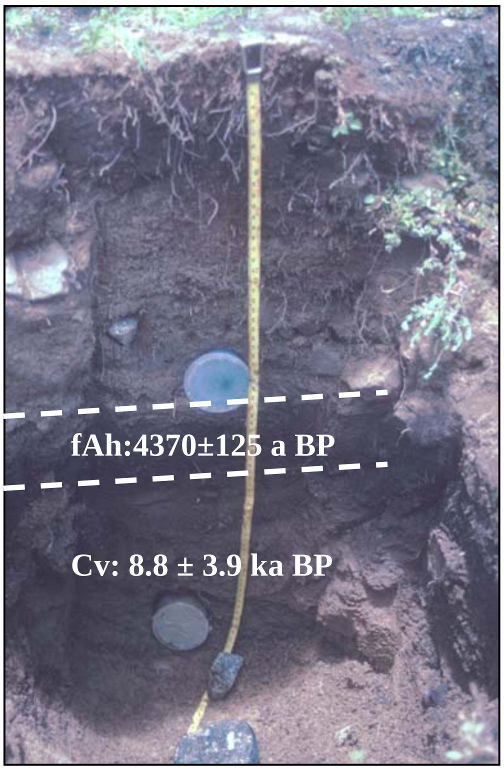

Fig. 2: Section 48: Western Nyainqêntanglha Shan, 4571 m, (29°44‘N, 89°48‘E). Brownish (chestnut) soil in silt above morainic material.

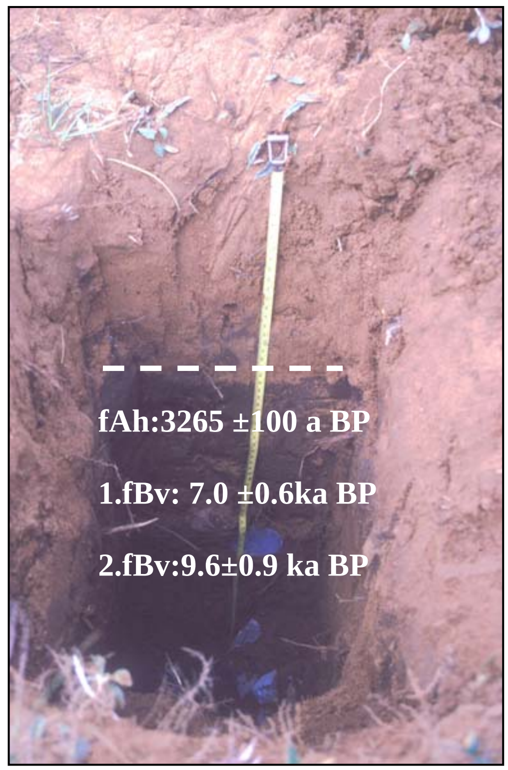

Fig. 3: Section 24: SE Siling Co, 4935 m, (31°29‘ N, 89°11‘ E). Initial soil on loess-like material and fossil chesnut soil in silt above periglacial debris

Stop 1: East side of Golmud-Lhaza Highway

At this stop we will examine a succession of moraines that Owen et al. (2005) dated to the early part of the last glacial cycle (Fig. 1.1).

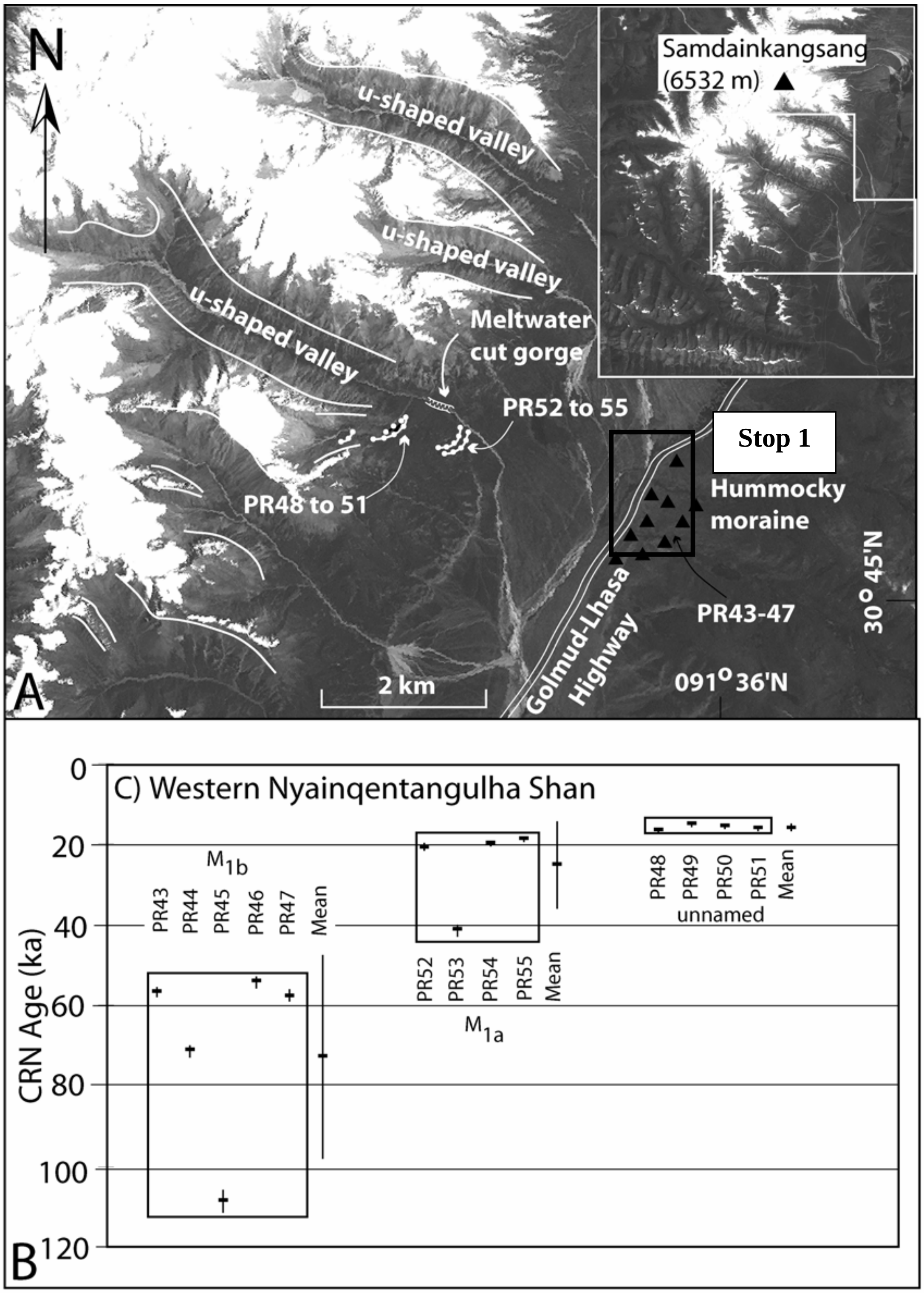

Fig. 1.1: Geomorphic map of the moraines and associated landforms south of Samdainkangsang Peak on the eastern slopes of the Nyainqentanggulha Shan. The moraines and sampling locations are mapped on a Landsat image.

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