Quaternary Science Reviews 25 (2006) 2162–2176

Landscape response to deglaciation in a high relief, monsoon-influenced alpine environment, Langtang Himal, Nepal

Patrick L. Barnard[a,*], Lewis A. Owen[b], Robert C. Finkel[c], Katsuhiko Asahi[d]

[a] United States Geological Survey, Pacific Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA
[b] Department of Geology, University of Cincinnati, P.O. Box 210013, Cincinnati, OH 45221, USA
[c] Lawrence Livermore National Laboratory, 7000 East Ave., MS L397, Livermore, CA 94550, USA
[d] Graduate School of Environmental Earth Science, Hokkaido University, Sapporo 060-0810, Japan

Received 4 September 2003; accepted 2 February 2006

Abstract

Significant glacial fluctuations and rapid paraglacial reworking of glacigenic sediments characterize the Middle and Late Holocene of the Langtang Khola Valley, Central Nepal Himalaya. Geomorphic mapping and beryllium-10 cosmogenic radionuclide (CRN) dating of moraines and paraglacial fans were undertaken to test the existing paraglacial fan, terrace and moraine chronologies. The new dating compares favorably with prior studies that utilized radiocarbon, adding additional support to the assumption that fan and terrace formation are strongly linked to deglaciation. Fan and terrace denudation rates are so rapid in this region, averaging ~33 mm/yr, that no depositional landforms older than 5 ka are preserved within 250 m of the valley floor. In this region, high rates of denudation during the Late Quaternary are driven by a combination of rapid tectonic uplift, numerous glacial fluctuations and intense weathering driven by an active monsoon climate. Extensive reworking of glacigenic sediments in Langtang during the latter half of the Holocene is consistent with studies completed in other areas of the Himalaya that are strongly influenced by the monsoon.

1. Introduction

The Langtang Himal, situated in the Central Nepal Himalaya, has received less attention than its more famous neighbors, Annapurna and Khumbu. This is despite the fact that it is easily accessible from Kathmandu and has one of the highest valley to peak gradients in the Nepal Himalaya, rising from 3850 m asl at Kyanjin Gompa to 7239 m asl at the peak of Langtang Lirung, over a distance of only 7 km. Furthermore, the Langtang Khola Valley has one of the best dated glacial and fan/terrace successions in the Himalaya (Shiraiwa et al., 1990; Watanabe et al., 1998). Numerous studies of glacial geology in the Langtang Himal have been completed (Franceschetti, 1968; Usselmann, 1980; Heuberger et al., 1984; Zheng et al., 1984; Ono, 1985, 1986; Zheng, 1988; Osmaston, 1989). This prior work makes the Langtang Himal an excellent region for testing the moraine and fan/terrace chronology using cosmogenic radionuclide (CRN) dating, and for studying the impact of climatic oscillations on the landscape evolution of the High Himalaya.

In this paper, the timing and relationship of glaciation and debris fan development are examined and rates of denudation are calculated to test the existing glacial and fan chronology and to examine the importance of paraglaciation in the landscape evolution of a Himalayan environment. To achieve this we use geomorphic mapping, sedimentologic and gemorphologic analysis, and ^{10}Be CRN surface exposure methods to date landforms in the Langtang Himal. These chronologies have been rarely tested in Himalayan environments and so this provides a unique opportunity to test the viability of CRN dating by sampling moraines and terraces previously dated using radiocarbon methods by Shiraiwa et al. (1990), Baumler et al. (1997) and Watanabe et al. (1998).

2. Prior work

Shiraiwa and Watanabe (1991) proposed the first glacial chronology for the Langtang Himal, based on radiocarbon

*Corresponding author. Tel.: +1 831 427 4756; fax: +1 831 427 4748.
E-mail address: pbarnard@usgs.gov (P.L. Barnard).

0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2006.02.002

and relative dating methods (Fig. 1, Table 1). They divided the glacial succession into six stages: Lama (oldest), Gora Tabela, Langtang, Lirung, and Yala I and II (youngest). The Lama stage is defined by the U-shaped valley extending down the Langtang Valley to ~2600 m asl. The Gora Tabela stage is defined by a weathered till that extends down to ~3200 m asl. Based on the timing of glacier advances of similar extent in other regions of the Himalaya, Shiraiwa (1993) speculated that the Lama Stage is equivalent to the early Last Glacial, and the Gora Tabela Stage is equivalent to the Last Glacial Maximum (LGM). The remaining stages are defined by morphostratigraphy, relative dating methods, and seven radiocarbon dates obtained by Shiraiwa et al. (1990) and five radiocarbon dates undertaken by Watanabe et al. (1998). The Holocene chronology is summarized in Watanabe (1998): Langtang Stage (3650–3310 ^{14}C yr BP), corresponding to the greatest advance during the Holocene, followed by three smaller advances, Lirung Stage (2800–2000 ^{14}C yr BP) and two recent advances, Yala I (<550 ^{14}C yr BP) and Yala II (1910 AD).

Shiraiwa (1993) used a steady-state glacier model of the Langtang Valley to reconstruct the climate for the Gora Tabela Stage (summer precipitation reduced to 200 mm, increased winter balance to 400 mm and reduced air temperature 6 °C) and for the Langtang Stage (contemporary summer precipitation of 400 mm, increased winter balance to 300 mm and decreased air temperature 4 °C). The model indicates that glaciers during the Gora Tabela Stage were supported by a non-monsoonal climate, demonstrating that Himalayan glaciers may advance during global cooling periods (cf. Sarkar et al., 1990; Owen et al., 1998). A more limited advance is described during this time period in the Khumbu Himal (Finkel et al., 2003).

Heuberger and Ibetsberger (1997) disputed the proposed Langtang Stage of Shiraiwa and Watanabe (1991), suggesting that such an extensive valley glaciation at this time was impossible based on the relatively limited extent of other Himalayan glaciers during this period. However, significant advances of glaciers during the Mid-Late Holocene have been defined in Garhwal (Sharma and Owen, 1996; Barnard et al., 2004b).

Based on prior studies, Fort (1996) estimated the equilibrium line altitude (ELA) depression during the Langtang Stage to be 600 m below the present ELA of 5320 m. Baumler et al. (1997) substantiated the dating of Shiraiwa et al. (1990) by producing equivalent dates for the

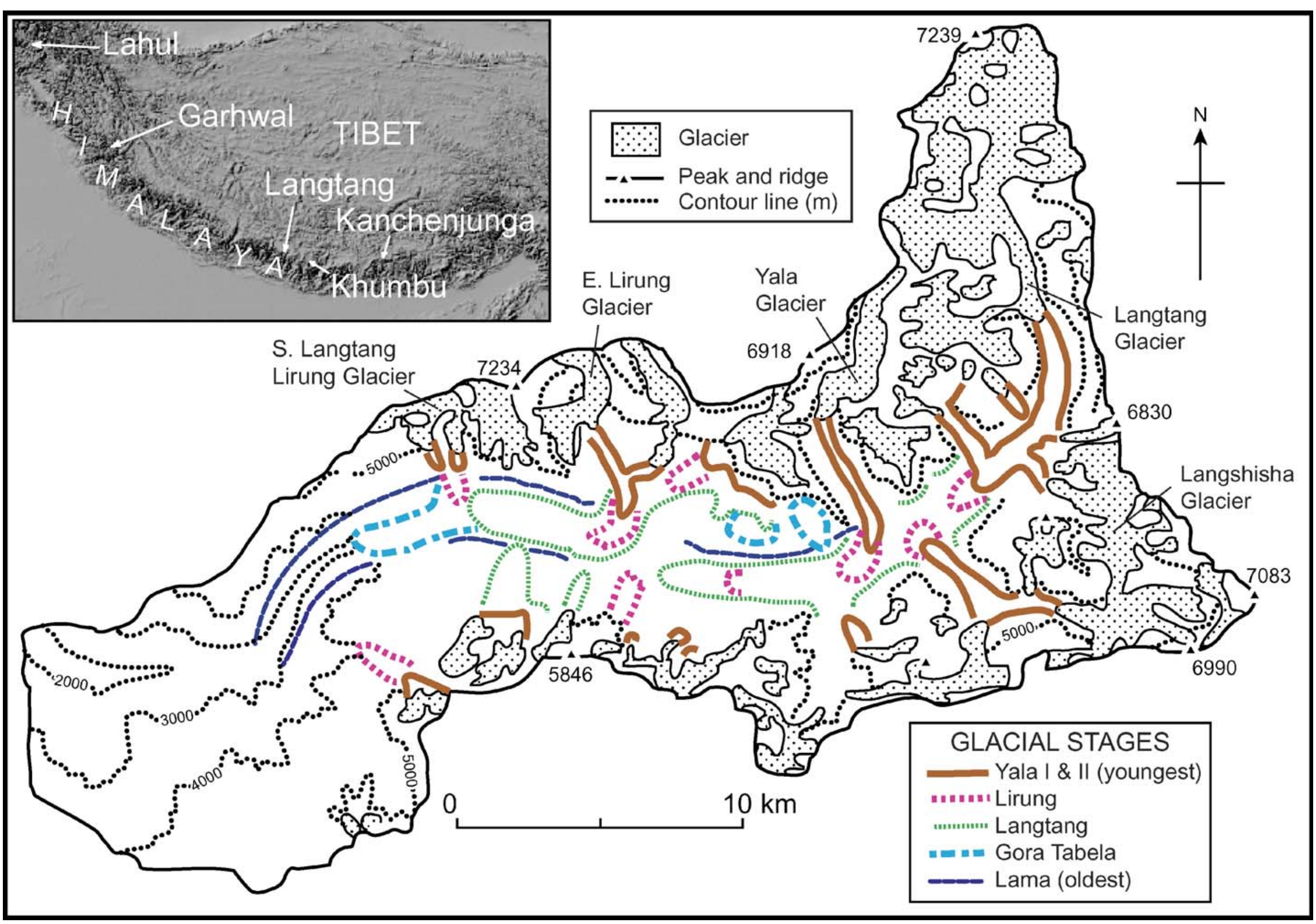

Fig. 1. Existing Langtang glacial chronology, modified from Shiraiwa and Watanabe (1991).

Table 1
The ^{14}C dating results and glacial chronology of Shiraiwa et al. (1990) = S, Baumler et al. (1997) = B, and Watanabe et al. (1998) = W

Glacial Stage	Time	Evidence	Sample no.	Location	Material	^{14}C date (yr BP)	Lab no.
YalaII	1910 A.D.	^{14}C dating	S1	Lirung Glacier, inner moraine	Organic layer	40±130	NUTA-740
Yala I	<550 yr BP	^{14}C dating	S2	Langshisha, valley train	Buried A-horizon	550±70	GaK-14029
			B1	Lirung moraine (precise location NA)	soil	1150±120	N/A
Lirung	2800-2000 ^{14}C yr BP	^{14}C dating	W1	Sindum	buried soil	1980±60	Beta-81006
			B2	Lirung moraine (precise location NA)	soil	2020±85	N/A
			B3	Lirung moraine (precise location NA)	soil	2500±111	N/A
			W2	Sindum	buried soil	2530±100	Gak-15792
			W3	Sindum	buried soil with charcoal	2800±90	Beta-94734
			S3	Tangdemo, slope deposit	Buried A-horizon	2800±110	GaK-10996
			S4	Mundro, till	Buried A-horizon	2850±140	NUTA-739
			S5	Lharung Chu, till	Superposed A-horizon	2980±110	GaK-14028
Langtang	3650-3310 ^{14}C yr BP	14C dating	B4	Sindum terrace	soil	3140±80	N/A
			W4	Sindum	layers of pure charcoal	3190±100	Gak-15793
			W5	Sindum	layers of pure charcoal	3310±80	Gak-15794
			S6	Mundro, till	Buried A-horizon	3650±320	GaK-10997
			S7	Mundro, till	Wood, not in situ	3860±110	GaK-14027
Gora Tabela	LGM	weathered till to ~3200 m asl	none	N/A	N/A	N/A	N/A
Lama	Last Glacial	U-shaped valley to ~2600 m asl	none	N/A	N/A	N/A	N/A

Langtang Stage by dating organic material that overlies till associated with the Langtang Stage within the Sindum terrace (3140±80 ^{14}C yr BP) and buried soils that overlie till linked to the Lirung Stage (2500±111 ^{14}C yr BP, 2020±85 ^{14}C yr BP, 1150±120 ^{14}C yr BP; Table 1).

Watanabe et al. (1998) used radiocarbon to date charcoal fragments and soils within debris cones in the Langtang Valley. They showed that major debris cone sedimentation was initiated immediately following the termination of the Langtang (3310 ^{14}C yr BP) and Lirung (2000 ^{14}C yr BP) Stages. Based on the incision of the debris cones, they were able to calculate Late Holocene sediment denudation rates in the Langtang Valley that ranged from 3.2 to 15.6 mm/a. These high rates of denudation are of similar magnitude to rates calculated throughout other monsoonaly influenced High Himalayan environments such as Nanda Devi (~19–57 mm/a; Barnard et al., 2004a). Debris flow was the dominant means of sediment transport onto the debris cones, but modification by debris avalanche, rockfall, glaciers and fluvial erosion was also common (Watanabe et al., 1998).

Shiraiwa and Watanabe (1991) logged 12 sections from fan/terrace surfaces and moraines throughout the Langtang Khola Valley, focusing on the broad, relatively flat surfaces on the north side of the valley between Thyangshap and Sindum. Their results show that the sections comprise primarily bouldery diamicts of glacial origin, commonly lodgement and ablation tills, that have been reworked by fluvial activity. This reworking is expressed in the bedded sand units that commonly cap these glacial diamicts, and the terrace expression of their surfaces.

These prior studies suggest that paraglacial processes are particularly prevalent and important in this high mountain environment. Many other workers have also recognized that the alluvial/debris flow fans within the Himalaya are the result of rapid sedimentation during periods of deglaciation (Derbyshire and Owen, 1990; Owen et al., 1995; Owen and Sharma, 1998; Barnard et al., 2004a, b, 2006). These findings are similar to studies completed in other glaciated environments that illustrated the significant role of paraglacial processes in landscape evolution (Ryder, 1971a, b; Church and Ryder, 1972; Ballantyne and Benn, 1994; Ballantyne, 1995, 2002, 2003).

3. Research area

The Langtang Himal is located in central Nepal, ~60 km north of Kathmandu (Fig. 2). The Langtang Khola Valley

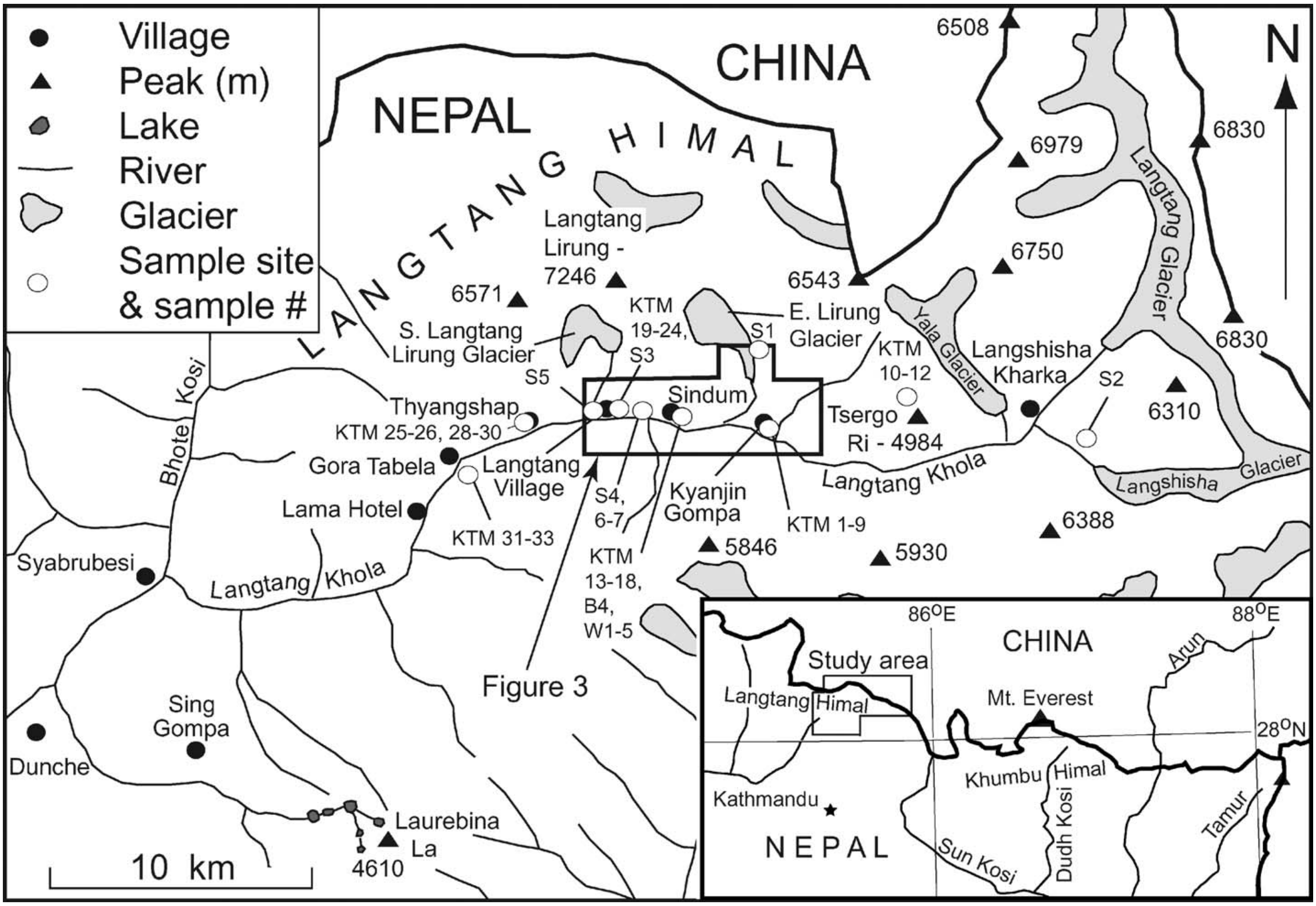

Fig. 2. Location map of the Langtang Valley showing the study areas and CRN sampling locations (prefix KTM) and the ^{14}C sampling sites of Shiraiwa et al. (1990: prefix S), Baumler et al. (1997: prefix B) and Watanabe et al. (1998: prefix W). The ^{14}C dates are listed in Table 1.

is an east–west trending valley situated 15 km south of the South Tibetan Detachment System (MacFarlane, 1993). Primarily gneiss, leucogranite, and migmatites are exposed within the region (Schramm et al., 1998). The study area stretches 25 km east (i.e. upvalley) from Gora Tabela (~3000 m asl) to the Tsergo Ri landslide (4848 m asl), high above Kyanjin Gompa (3924 m asl). The villages of Kyanjin Gompa (upvalley), Sindum, Langtang village, Thyangshap and Gora Tabela (downvalley) are all built on abandoned fans and/or terraces (Figs. 2 and 3). A major moraine field of the Eastern Lirung Glacier is located west of Kyanjin Gompa. Other prominent moraines are located at Langtang village and Thyangshap.

The climate of Langtang is dominated by the southwest Indian summer monsoon. The gauging station at Kyanjin Gompa shows that ~80% of the annual 622 mm of precipitation falls between May and September, with an average annual temperature of 2.0 °C (DHM, 1993, 1995, 1996, 1997). Monsoonal weather systems move from south to north into the Langtang Himal. This prevailing weather pattern has influenced geomorphic processes to produce an asymmetric valley profile, with the bulk of fan and glacial sedimentation originating on the south-facing slopes that capture the majority of the monsoonal precipitation. Therefore, glaciers are more prevalent and fans build out into the main valley from north to south, constricting the flow of the Langtang Khola against the steep north-facing slopes. Alternatively, glacial ice can more easily melt on the south-facing slopes due to the stronger insolation. In contrast, weaker ablation of glacial ice on the north-facing slopes can maintain glacial snouts because the mountain ridge gives day-long shade to these slopes. Therefore, fans and terraces, most of which originate from moraine material, are best developed at the foot of south-facing slopes (Seko and Takahashi, 1991; Shiraiwa et al., 1992).

4. Methods

4.1. Field methods

Sites for field research in the upper Langtang Khola Valley were selected where the landforms dated by Shiraiwa et al. (1990), Baumler et al. (1997) and Watanabe et al. (1998) could be sampled and where the geomorphic relationships of fans and moraines could be clearly examined (Fig. 2). A geomorphic map was constructed

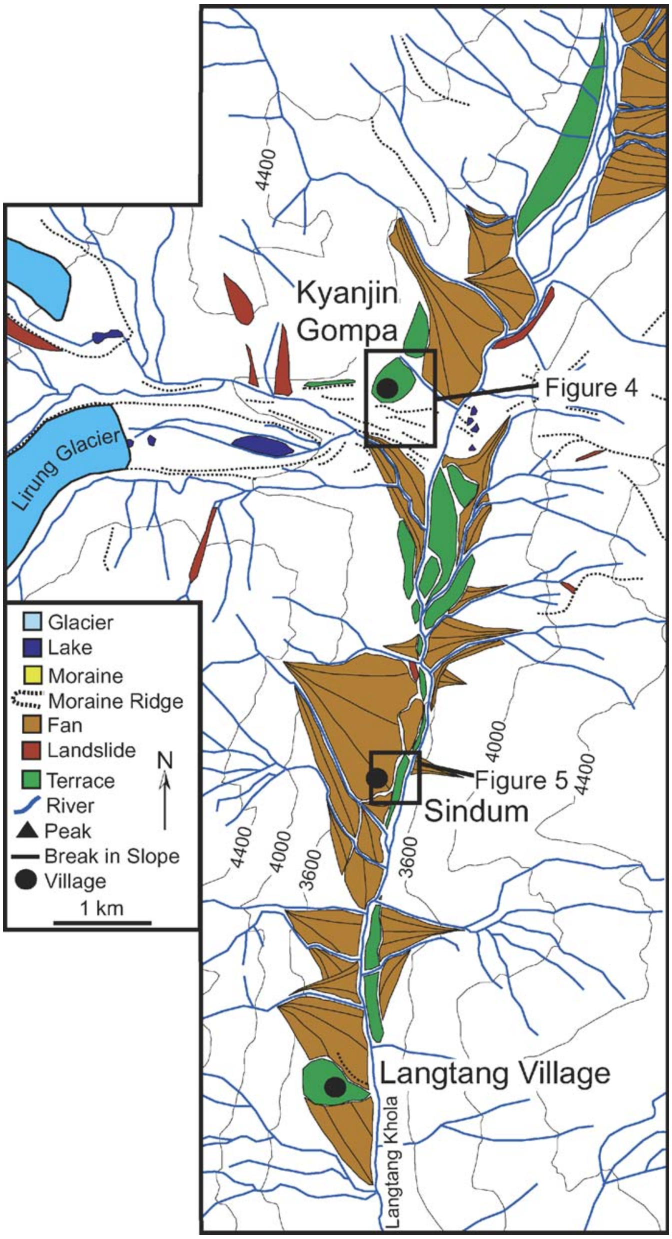

Fig. 3. Geomorphic map of the upper Langtang Valley. Mapped at 1:25 000.

for the lower reaches of the Langtang Valley between Langtang Village and Kyanjin Gompa at a scale of 1:25 000 (Fig. 3). This was composed using a basemap with a scale of 1:10 0000 (Finsterwalder et al., 1987). More detailed maps (1:5000) were made at Kyanjin Gompa and Sindum using chain surveys (Figs. 4 and 5).

Sampling sites for CRN dating of fans and terraces (Fig. 3) were selected that were located along the distal edges of the landforms where the chances of erosion and exhumation of surface boulders due to denudation or anthropogenic activity (e.g. agriculture) is low. Samples from moraines were taken from boulders on moraine crests. This minimizes the effects of overburden shielding and toppling that can produce erroneously young ages (cf. Barnard et al., 2004b). Prior exposure of CRN samples (i.e. derived boulders) is a common problem with the CRN surface exposure dating process (Anderson et al., 1996; Hancock et al., 1999). To test for derived boulders, multiple samples were collected from each fan/terrace and moraine. The age of each landform was estimated by calculating the weighted mean of the samples from each surface/landform.

Three CRN samples were collected from the Tsergo Ri landslide, located northeast of Kyanjin Gompa at 4840 m asl (Fig. 3). These samples served to test the reliability of CRN to date older deposits in the Langtang Valley. In such a dynamic environment, it is important to date landforms from a wide range of altitudes, ages and surfaces to ensure that erroneously young dates are not a result high rates of erosion and denudation on surfaces that may be more susceptible to erosion. Thus, the ancient Tsergo Ri landslide, high above the Langtang Valley, provides a stable surface for CRN dating comparisons with the less stable fans and moraines proximal to the valley floor. The full context of these samples is described in Asahi et al. (2006).

Cross-valley profiles were constructed across the fan and terrace surfaces, perpendicular to the valley axis (Figs. 4 and 5). This allows the relative relief to be measured. Fan incision rates were estimated from the relative relief and the CRN ages. A similar survey was also conducted across the moraine field west of Kyanjin Gompa to aid in moraine correlation (Fig. 4).

4.2. Laboratory/dating methods

Samples for CRN dating were processed at Lawrence Livermore National Laboratory (LLNL) and in situ ^{10}Be ($t_{1/2} = 1.5$ Myr) produced by cosmic rays in the quartz was measured. The samples were crushed and sieved to a uniform size of 250–500 μm. Approximately 100 g of this fraction was extracted and chemically leached in HCl and HF:HNO_3 to isolate the quartz using the methods of Kohl and Nishiizumi (1992). Beryllium carrier of 0.5 mg was added to the clean quartz separates and the sample was dissolved in 3:1 HF:HNO_3. Beryllium was separated in ion exchange columns. The processed samples were loaded into the LLNL accelerator mass spectrometer to determine the ratio of the CRN to the stable isotope (Davis et al., 1990). Age determinations were calculated with the high altitude production of $^{10}\text{Be} = 5.16$ atoms/gram/quartz using the scaling factors of Lal (1991) as modified by Stone (2000). Corrections were made for time varying geomagnetic field. Full details of the methodology used in the age determination are described in Owen et al. (2001, 2002b).

5. Geomorphology

In the Kyanjin Gompa area, a complex series of glacier moraines are situated in front of the Eastern Lirung Glacier. The Eastern Lirung Glacier is fed by avalanches

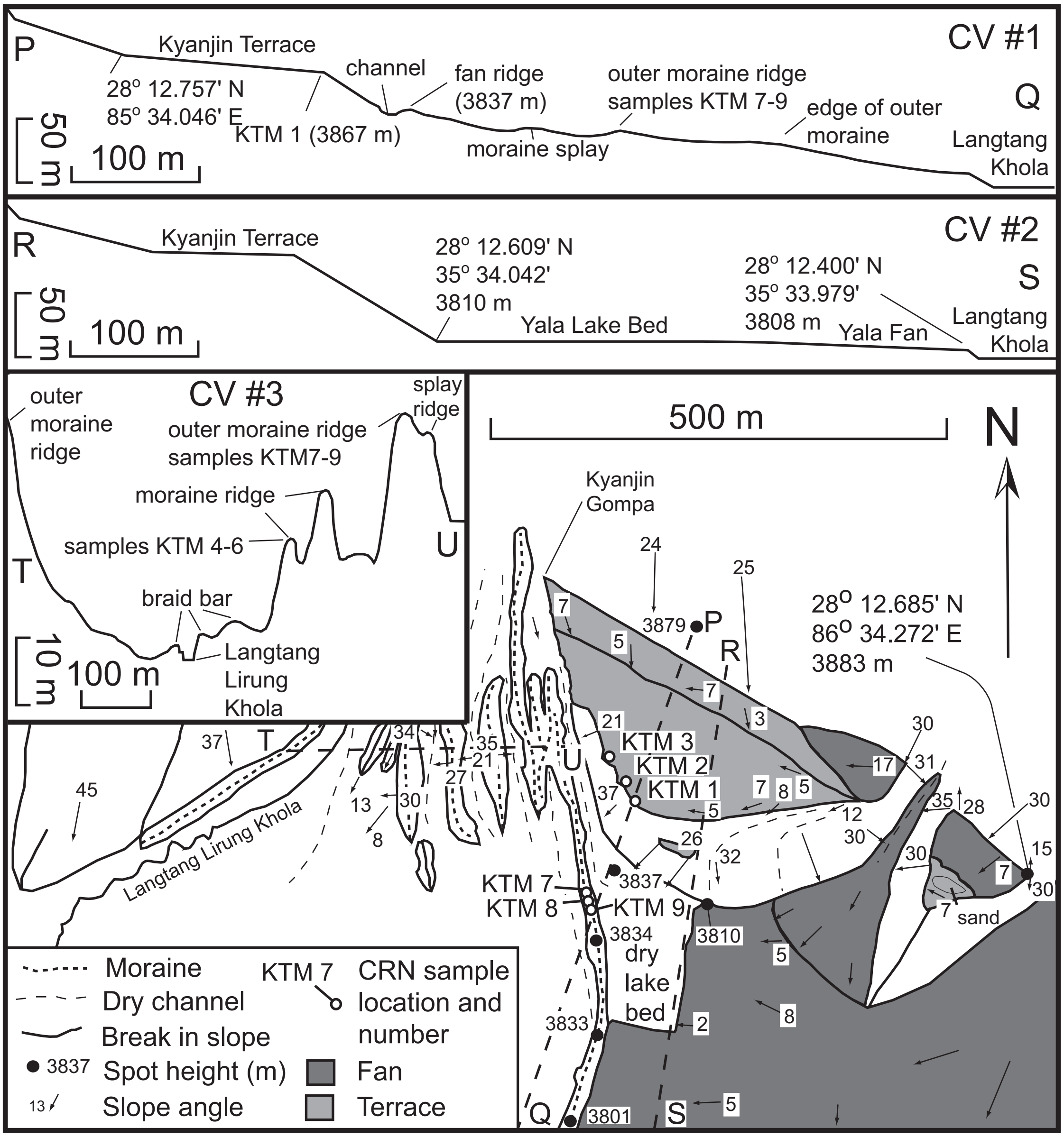

Fig. 4. Chain survey, cross-valley profiles (CVs) and a photo showing an overview of the geomorphic relationships in the Kyanjin Gompa area. The photo inset view is looking directly to the south down onto the village and terrace of Kyanjin Gompa and across the Langtang Valley.

from the eastern slope of Langtang Lirung (7239 m asl). These moraines are sharp-crested and contain boulders commonly measuring 4–5 m in diameter, with some in excess of 8 m (electronic archive Figs. 1A–C available at QSR website http://www.elsevier.nl/locate/quascirev). Many of the existing moraines are separated and truncated by glaciofluvial channels that contain sub-rounded to rounded boulders up to 1.5 m in diameter (electronic archive Fig. 1D). The outermost moraine extends down to the Langtang Khola and can also be traced on the opposite side of the valley (electronic archive Fig. 1E). A section cut by the Langtang Khola at this point exposes a sub-angular diamict supported by a matrix of gravely sand. Numerous fluvially polished boulders up to 10 m in diameter rest in the narrow neck (~10 m) of the Langtang Khola where this moraine was incised (electronic archive Fig. 2A). Upvalley from this point the river widens from ~10 to 100 m and numerous braid bars are present (electronic archive Figs. 2B–D). Downvalley the channel maintains its narrow width (~10 m) and contains other large boulders up to 8 m in diameter. These are lodged in the channel surface or rest along the narrow banks.

The village of Kyanjin Gompa sits on a gently sloping terrace (~5°) that is truncated to the west by Eastern Lirung Glacier moraines (Fig. 4). The terrace surface is vegetated with grasses and a few boulders up to 3 m in diameter are scattered across its surface. The terrace at Kyanjin Gompa is incised to the east (upvalley) 25 m by a

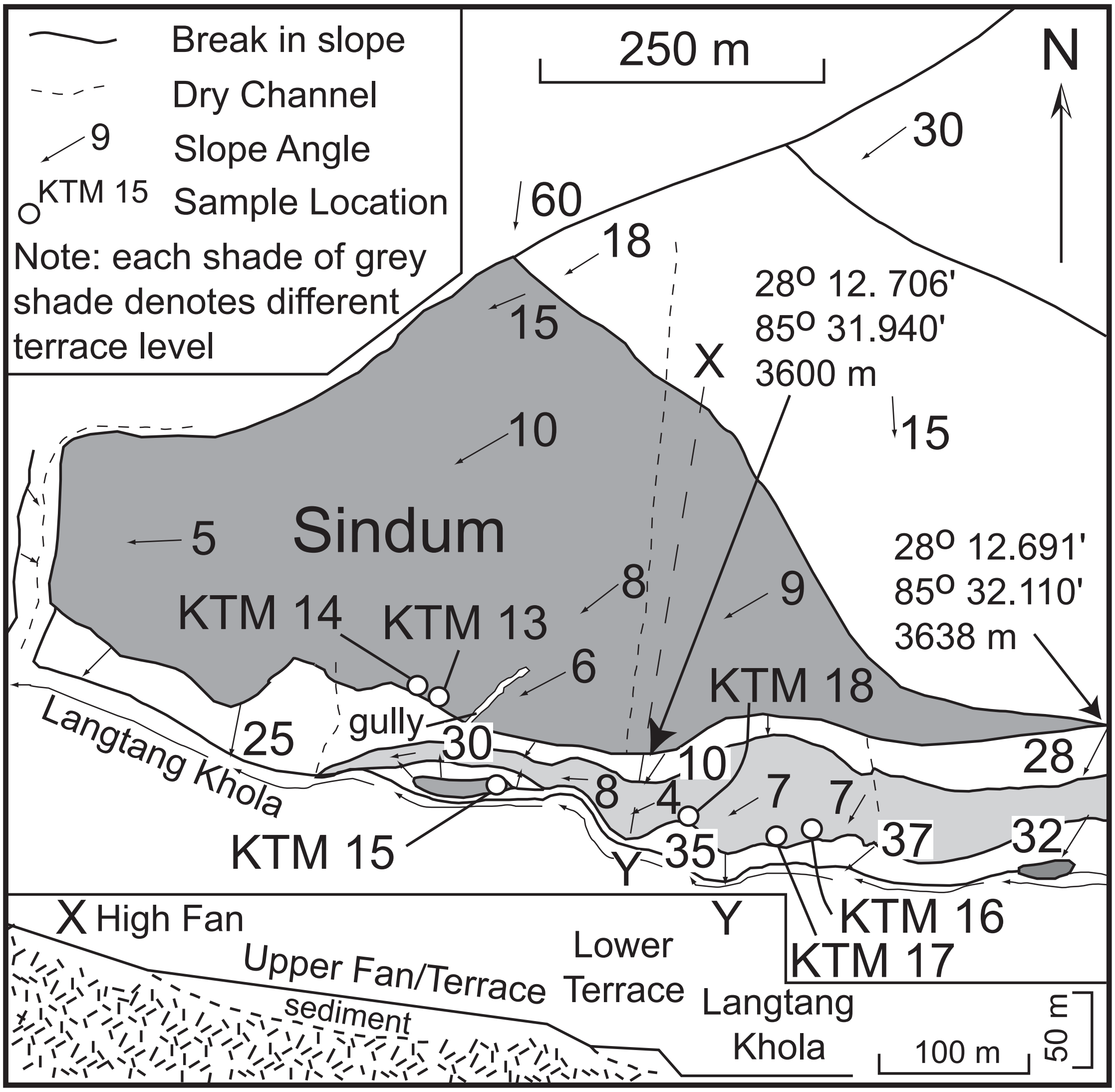

Fig. 5. Chain survey and cross-valley profile (CV) of the Sindum terraces.

tributary channel of the Yala Glacier. Ono (1986) believed this to be a glaciofluvial terrace.

A smaller but morphostratigraphically equivalent terrace to Kyanjin Gompa is located to the east (Fig. 4). The surface contains few boulders ($<1\%$ of surface area) and is covered with low shrubs. A cluster of small cobbles 12 cm in diameter is in the center of the undulating fan. Quartz rich clayey fine sand is exposed in a small portion of the terrace surface, covering 30 m^2 (electronic archive Fig. 1F). The sand unit is ~1 m thick and small surface ripples have formed along the southern edge of the exposure.

A dry lakebed is present directly to the south of the Kyanjin Gompa terrace (Fig. 4). This is nestled between the Kyanjin Gompa terrace, an inactive moraine of the Eastern Lirung Glacier and a large, low lying fan that is incised by the Langtang Khola (electronic archive Fig. 2E). Desiccation cracks are visible on the surface, a result of mud that was deposited when the Eastern Lirung Glacier advanced across the main valley and dammed the drainage of the Langtang Khola (electronic archive Fig. 1E). Upvalley from this point of blocked drainage, the Langtang Khola has a gentler gradient, delta-like stream pattern and a substantial increase in valley width (electronic archive Figs. 2B–D). Evidence of a major flood that followed the damming is suggested by sets of stratigraphically equivalent terraces downvalley and boulders up to 10 m in diameter resting in the deeply incised narrow channel neck of the Langtang Khola. This neck is at the position where the moraine would have extended across the valley bottom (electronic archive Fig. 2A). Heuberger et al. (1984) logged a 4.5 m thick unit of lacustrine sediments that they related to the damming of the Southern Langtang Lirung Glacier. Based on radiocarbon dating of organic material from a buried A-horizon within the lake sediments, Shiraiwa and Watanabe (1991) suggest that the damming occurred at ~2850 ^{14}C yr BP However, no mention of damming in the Kyanjin Gompa area has been mentioned in any prior studies.

Table 2
The ^{10}Be CRN dating results from the Langtang Khola Valley

Sample #	Location	Landform	Latitude (°±0.01°)	Longitude (°±0.01°)	Altitude (m)	Shielding factor[1]	Be-10[2] (10^6 atoms/g)	Exposure age (ka) Be-10[2]	Exposure age (ka) w/ geomag corr.[3](ka)
KTM1	Kyanjin Gompa	Terrace	28.21 N	85.57 E	3873	0.98	0.034±0.009	0.65±0.17	0.62±0.16
KTM2	Kyanjin Gompa	Terrace	28.21 N	85.57 E	3859	0.98	0.021±0.009	0.40±0.16	0.36±0.15
KTM3	Kyanjin Gompa	Terrace	28.21 N	85.57 E	3848	0.98	0.038±0.008	0.73±0.16	0.71±0.16
KTM4	Kyanjin Gompa	Moraine	28.21 N	85.56 E	3924	0.97	0.025±0.008	0.47±0.15	0.42±0.13
KTM5	Kyanjin Gompa	Moraine	28.21 N	85.56 E	3922	0.97	0.044±0.012	0.82±0.22	0.82±0.22
KTM6	Kyanjin Gompa	Moraine	28.21 N	85.56 E	3923	0.97	0.022±0.008	0.41±0.15	0.36±0.14
KTM7	Kyanjin Gompa	Moraine	28.21 N	85.57 E	3840	0.98	0.027±0.009	0.52±0.17	0.47±0.16
KTM8	Kyanjin Gompa	Moraine	28.21 N	85.57 E	3838	0.98	0.028±0.008	0.54±0.16	0.50±0.15
KTM9	Kyanjin Gompa	Moraine	28.21 N	85.57 E	3839	0.98	0.033±0.010	0.64±0.19	0.61±0.18
KTM10	Tsergo Ri	Landslide	28.21 N	85.61 E	4831	0.99	3.372±0.083	40.14±0.99	39.16±0.96
KTM11	Tsergo Ri	Landslide	28.21 N	85.61 E	4843	0.99	1.801±0.037	21.23±0.44	22.43±0.46
KTM12	Tsergo Ri	Landslide	28.21 N	85.61 E	4848	0.99	2.848±0.044	33.63±0.51	34.14±0.52
KTM13	Sindum	Fan/Terrace	28.21 N	85.53 E	3584	0.92	0.061±0.030	1.45±0.70	1.54±0.75
KTM14	Sindum	Fan/Terrace	28.21 N	85.53 E	3582	0.92	0.081±0.016	1.91±0.37	2.08±0.40
KTM15	Sindum	Fan/Terrace	28.21 N	85.53 E	3584	0.92	0.298±0.019	7.04±0.44	7.47±0.47
KTM16	Sindum	Terrace	28.21 N	85.53 E	3588	0.92	0.038±0.008	0.89±0.18	0.90±0.18
KTM17	Sindum	Terrace	28.21 N	85.53 E	3584	0.92	0.082±0.008	1.92±0.19	2.10±0.21
KTM18	Sindum	Terrace	28.21 N	85.53 E	3589	0.92	0.037±0.007	0.86±0.16	0.87±0.16
KTM19	Langtang Village	Moraine	28.21 N	85.51 E	3581	0.95	0.145±0.009	3.33±0.20	3.88±0.24
KTM20	Langtang Village	Moraine	28.21 N	85.51 E	3507	0.95	0.025±0.007	0.60±0.16	0.57±0.15
KTM21	Langtang Village	Moraine	28.21 N	85.51 E	3510	0.95	0.039±0.007	0.94±0.17	0.95±0.18
KTM22	Langtang Village	Terrace	28.21 N	85.51 E	3469	0.95	0.036±0.007	0.87±0.17	0.88±0.17
KTM23	Langtang Village	Terrace	28.21 N	85.51 E	3469	0.95	0.032±0.007	0.77±0.17	0.76±0.17
KTM24	Langtang Village	Terrace	28.21 N	85.51 E	3472	0.95	0.028±0.006	0.67±0.16	0.64±0.15
KTM25	Thyangshap	Moraine	28.21 N	85.47 E	3230	0.85	0.140±0.019	4.37±0.59	4.98±0.68
KTM26	Thyangshap	Moraine	28.21 N	85.47 E	3239	0.85	0.124±0.008	3.85±0.24	4.42±0.27
KTM28	Thyangshap	Fan/Terrace	28.21 N	85.48 E	3196	0.92	0.026±0.007	0.77±0.20	0.76±0.20
KTM29	Thyangshap	Fan/Terrace	28.21 N	85.48 E	3190	0.92	0.023±0.007	0.67±0.21	0.65±0.20
KTM30	Thyangshap	Fan/Terrace	28.21 N	85.48 E	3168	0.92	0.033±0.008	0.99±0.23	1.01±0.24
KTM31	Gora Tabela	Fan/Terrace	28.20 N	85.45 E	3012	0.90	0.022±0.007	0.72±0.22	0.70±0.22
KTM32	Gora Tabela	Fan/Terrace	28.20 N	85.45 E	3009	0.90	0.024±0.007	0.82±0.22	0.81±0.22
KTM33	Gora Tabela	Fan/Terrace	28.20 N	85.46 E	3011	0.90	0.021±0.007	0.70±0.24	0.68±0.23

Notes: [1]The topographic shielding factor was determined using the methods of Nishiizumi et al. (1989). [2]Uncertainty includes only uncertainty in AMS measurement.[3]Corrected for time varying geomagnetic field as described in text. The uncertainty is carried over from that in the exposure age. No additional uncertainty was assigned arising from correction for geomagnetic field change. These ages were calculated with a sea level high latitude production of ^{10}Be = 5.16 atoms/gram/quartz using the scaling factors of Lal (1991) as modified by Stone (2000).

A broad terrace at Sindum, comprising fluvially reworked till (Ono, 1986), is dissected by a much smaller, lower lying terrace (Fig. 5, electronic archive Fig. 3). A small island remnant of the upper terrace lies between the Langtang Khola bank and the lower terrace (electronic archive Fig. 3B). Both terraces are vegetated with low shrubs and grasses, and contain boulders up to 4 m in diameter (electronic archive Fig. 3C). The lowest terrace is 16 m below the upper terrace, and 18 m above the present level of the Imja Khola. The terraces slope ~7° downvalley.

Farther to the west (i.e. downvalley) and high above Langtang village, the Sindum terrace grades into a large end moraine complex (electronic archive Fig. 4). The irregular terrace surface, on which Langtang Village (3470 m asl) is situated, onlaps this moraine. Shiraiwa and Watanabe (1991) believe this to have been eroded by a tributary glacier. Two lateral moraines of the Southern Langtang Lirung Glacier are located just south of Langtang village. The moraines may have blocked the valley's drainage and formed a lake in which lacustrine sediments were deposited. A portion of Langtang village is now built on this lake deposit (Shiraiwa and Watanabe, 1991).

Farther downvalley, above the village of Thyangshap (3190 m asl) a linear ridge is present that trends parallel to the axis of the Langtang Khola Valley (electronic archive Fig. 5). This is the furthest downvalley moraine fragment that has been identified in the Langtang Khola Valley. The moraine ridge is heavily vegetated and only two boulders were exposed and embedded in the ancient moraine surface along the entire length of the ~50 m long ridge (electronic archive Fig. 5A). This ridge is at the same level stratigraphically as the Langtang Village moraine. Most of the ridge has been covered by talus supplied by a rock fall from the shear valley walls (electronic archive Fig. 5B). Thyangshap sits on a small terrace ~50 m beneath this ridge (electronic archive Fig. 5C), that is ~100 m above the present level of the Langtang Khola. This terrace originates from a side valley northeast of Thyangshap.

At the farthest downvalley extent of the U-shaped valley, fluvial terrace and fan deposits are located on both sides of the Langtang Khola at Gora Tabela (electronic archive Fig. 5). These surfaces are only 10 m above the present level of the Langtang Khola at 3010 m asl. The surface on the north side of the valley is distinctly planar, consistent with the terrace morphologies observed upvalley. The fan surface on the south side of the valley is much broader. The boulders scattered across the well-vegetated surface are heavily weathered, being derived and reworked from much older, collapsed moraine material (Shiraiwa and Watanabe, 1991). The existing ridge is vast and gentle, having clearly been reworked by fluvial activity and therefore takes on the appearance of a fan. No glacial material has been identified below this point, but the transition of the valley from V- to U-shaped morphology at ~2600 m asl suggests that the maximum extent of glaciation during the Quaternary was probably down to ~2600 m asl (Heuberger et al., 1984).

6. Fan sedimentology

Bouldery diamicts and pebbly sands dominate the fan/terrace sedimentology (electronic archive Figs. 7 and 8). Bouldery diamicts are exposed along the lower lying fans of the Langtang Khola Valley east of Kyanjin Gompa. The clasts are generally sub-rounded and measure up to 3 m in diameter. The deposits have an isotropic fabric with occasional imbrication and banding. Individual beds are up to 10 m thick, massive, with boulders and cobbles supported by a matrix of pebbly sand. These features are indicative of debris flows with the sediment originating from glacial deposits—there is no evidence of hyperconcentrated flows within these deposits (Beverage and Culbertson, 1964; Costa, 1988; Ballantyne, 1995, 2002, 2003; Coussat and Meunier, 1996; Zielinski and van Loon, 1996; Sohn et al., 1999; Barnard et al., 2004a, b, 2006). Zielinski and van Loon (1996) identified similar deposits in their study of fans derived from end moraines in Poland. They describe the sedimentology as a gravelly/clayey diamicton, in which boulders and pebbles predominate (40–60%), representing true mass flows: a coarse-grained debris flow.

Not all paraglacial sedimentation in Langtang is dominated by bouldery diamicts. A section in the Sindum upper terrace documents a ⩾2 m thick succession of thinly bedded (2–10 cm), moderately well-sorted pebbly sand and poorly sorted sandy pebble layers (electronic archive Fig. 8A). The clasts are sub-rounded and commonly imbricated. This represents low-energy fluvial sedimentation that reworked this former till surface (Ono, 1986). Fig. 13B in the online version of this article shows several exposures from a section ~1 km west of the previous section. In this exposure, Shiraiwa and Watanabe (1991) identified bouldery diamicts as lodgement and ablation tills. The diamicts are massive, matrix-dominated and matrix-supported, with an isotropic clast fabric. The diamicts are overlain by beds of gravel, sand and silt that total 2.5 m thick (Shiraiwa and Watanabe, 1991), similar to the low-energy fluvial units described in the section in the Sindum upper terrace.

7. Glacial and fan chronology

The chronologies most recently revised by Watanabe (1998) have been tested and modified using CRN dating (Tables 1 and 2, Fig. 6). The age of maximum Holocene glacial extent in the Langtang Khola Valley was determined to be ~4.5 ka by dating the moraine fragment at Thyangshap (KTM 25–26; Table 2). This possibly represents the maximum extent of the Langtang Stage. Subsequent glacial retreat resulted in the construction of the large end moraine complex above Langtang village. On the basis of CRN dating this end moraine formed at ~4 ka (KTM 19 = 3.88 ± 0.24 ka). Samples KTM 20–21 were rejected for yielding young ages (<1 ka) that were probably the consequence of weathering and/or exhumation. The age of the moraine is supported by the radiocarbon dating of organics from soils that formed within till sections linked to the Langtang Stage (B4 = 3140 ± 80 ^{14}C yr BP, S4 = 2850 ± 140 ^{14}C yr BP, S6 = 3650 ± 320 yr ^{14}C BP, W4 = 3190 ± 100 yr ^{14}C BP, W5 = 3310 ± 80 yr ^{14}C BP).

The range and extent of the Lirung Stage (2.0–2.8 ka) was established by Shiraiwa and Watanabe (1991). This was reinforced by Baumler et al. (1997), and modified by Watanabe (1998) who placed the lower limit of 2.0 ka on the Lirung Stage based on radiocarbon dates linked to the onset of paraglacial sedimentation. No CRN dating was undertaken on deposits attributed to the Lirung Stage.

The age of the Yala Stage I (<550 ^{14}C yrs BP; Shiraiwa and Watanabe, 1991) was substantiated by the CRN dating of moraines at Kyanjin Gompa. The CRN ages calculated from these moraines strongly correlate with the radiocarbon dating of Shiraiwa and Watanabe (1991) as modified by Watanabe (1998). The Lirung Stage inner moraine has an age of ~0.46 ka ($n = 3$, KTM 4–6) and the outer moraine was determined to be ~0.52 ka ($n = 3$, KTM 7–9). Therefore, the lower limit of the Yala I Stage is set at ~0.45 ka. This probably predates the Little Ice Age (LIA; Grove, 1988). However, the large uncertainty in the CRN dating of very young deposits precludes exact correlation. A smaller, younger advance (Yala II) was thought to have occurred in the last several hundred years, possibly coinciding with the end of the LIA (Ono, 1986).

The surface of the upper Sindum terrace is broadly defined by CRN dating (KTM 13 = 1.54 ± 0.75 ka, KTM 14 = 2.08 ± 0.40 ka, KTM 15 = 7.47 ± 0.47 ka). This surface was determined to be reworked glacial fluvial deposits related to the Lirung Stage (Ono, 1986) with the lower limit set at ~2 ka by Watanabe et al. (1998). Therefore, samples KTM 13 and KTM 14 mark the age of paraglacial

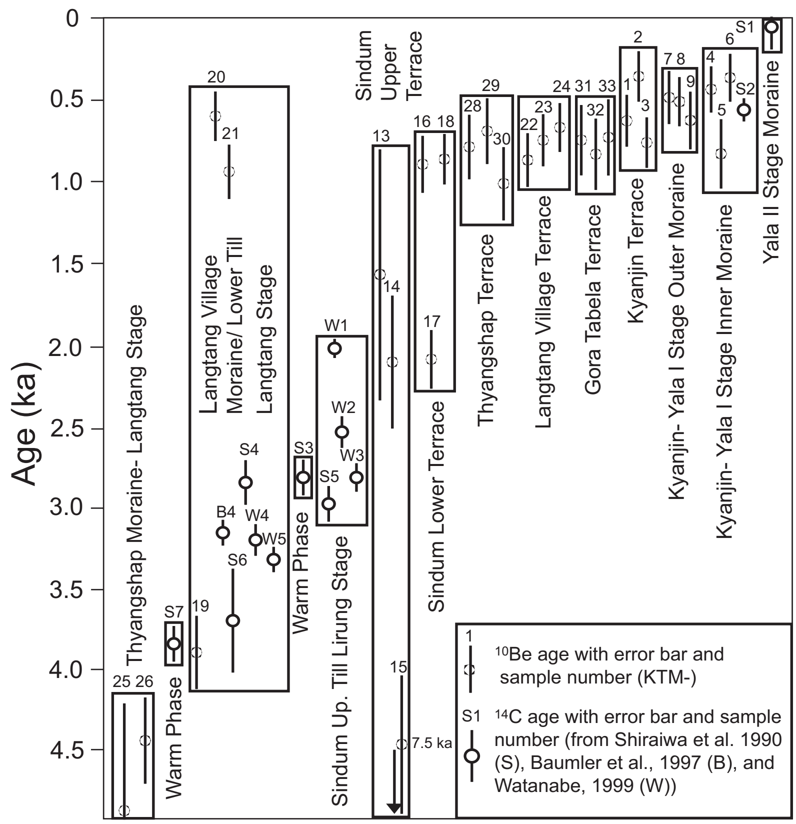

Fig. 6. Chronology of landforms in the Langtang Valley.

sedimentation on the terrace surface, and thus reinforce the lower limit of the Lirung Stage. The age of KTM 15 does not relate to the surface because the sample age predates every moraine and terrace dated in the Langtang Khola valley, and probably is the result of inherited CRNs within a derived boulder.

The terrace surfaces at Gora Tabela ($n = 3$, 0.73 ± 0.13 ka), Thyangshap ($n = 3$, 0.78 ± 0.12 ka), Langtang Village ($n = 3$, 0.75 ± 0.09 ka), Sindum lower ($n = 2$, 0.88 ± 0.12 ka, reject KTM 17), and Kyanjin Gompa ($n = 3$, 0.55 ± 0.09 ka) are broadly linked by CRN dating and morphostratigraphy, except for the Thyangshap terrace, which is higher stratigraphically. The Yala I moraine dated at Kyanjin Gompa (~0.52 ka) onlaps and postdates the Kyanjin terrace (0.55 ka).

8. Sediment incision rates

Fan incision rates were determined from the CRN dating of five terraces in the Langtang Khola Valley (Table 3). The rates range from 8 to 60 mm/yr and average ~33 mm/a throughout the Late Holocene (<2 ka). The results from Thyangshap are not included in the average because the rate appears erroneously high (~130 mm/a). This may be due to sampling derived boulders that fell from the cliff face along the northern valley wall. Rockfalls were responsible for covering most of the moraine fragment dated above the terrace (Fig. 10B in the online version of this article). No bedrock strath terraces were identified in the study area.

Table 3
Sediment incision rates calculated from the CRN dating of terraces in the Langtang Khola Valley

Terrace location	Altitude (m)	^{10}Be exposure age (ka)	Height (m)	Incision Rate (mm/za)
Kyanjin	3860	0.55	25	45.5
Sindum (upper)	3583	1.96	15	7.7
Sindum (lower)	3570	0.88	18	20.5
Langtang Village	3470	0.75	45	60.0
Thyangshap	3185	0.78	101	(129.5)*
Average				33.4

*Not included in the calculation of the average incision rate.

9. Discussion

The ^{10}Be CRN dating results (Tables 2, 4, Fig. 6) broadly agree with the radiocarbon dating undertaken by Shiraiwa and Watanabe (1991), Baumler et al. (1997), and Watanabe et al. (1998). Based on CRN dating, the Langtang Stage of Shiraiwa and Watanabe (1991) can be extended back to at least 4.5 ka (range 3.0–4.5 ka). The moraine fragment at

Table 4
Revised chronology of Watanabe (1998) using the CRN dates of this study

Glacial stage	Previous stage	Revised stage	Sample #	Location	CRN age	Landform
Yala II	1910 A.D.	not sampled				
Yala I	< 550 yr BP	450–550 yrs	KTM1	Kyanjin Gompa	0.62±0.16	Terrace
			KTM2	Kyanjin Gompa	0.36±0.15	Terrace
			KTM3	Kyanjin Gompa	0.71±0.16	Terrace
			KTM4	Kyanjin Gompa	0.42±0.13	Inner Moraine
			KTM5	Kyanjin Gompa	0.82±0.22	Inner Moraine
			KTM6	Kyanjin Gompa	0.36±0.14	Inner Moraine
			KTM7	Kyanjin Gompa	0.47±0.16	Outer Moraine
			KTM8	Kyanjin Gompa	0.50±0.15	Outer Moraine
			KTM9	Kyanjin Gompa	0.61±0.18	Outer Moraine
			KTM16	Sindum	0.90±0.18	Lower Terrace
			KTM18	Sindum	0.87±0.16	Lower Terrace
			KTM22	Langtang Village	0.88±0.17	Terrace
			KTM23	Langtang Village	0.76±0.17	Terrace
			KTM24	Langtang Village	0.64±0.15	Terrace
			KTM28	Thyangshap	0.76±0.20	Fan/Terrace
			KTM29	Thyangshap	0.65±0.20	Fan/Terrace
			KTM30	Thyangshap	1.01±0.24	Fan/Terrace
			KTM31	Gora Tabela	0.70±0.22	Fan/Terrace
			KTM32	Gora Tabela	0.81±0.22	Fan/Terrace
			KTM33	Gora Tabela	0.68±0.23	Fan/Terrace
Lirung	2000–2800 ^{14}C yr BP	minimum age reinforced	KTM13	Sindum	1.54±0.75	Paraglacial Fan/Terrace
Lirung	3310–3650 ^{14}C yr BP	3000–4500 yrs	KTM14	Sindum	2.08±0.40	Paraglacial Fan/Terrace
			KTM19	Langtang Village	3.88±0.24	Moraine
			KTM26	Thyangshap	4.42±0.27	Moraine
			KTM25	Thyangshap	4.98±6.68	Morain

Thyangshap (~4.5 ka) is morphostratigraphically equivalent to the end moraine at Langtang Village that dates to ~4 ka. The Thyangshap moraine represents an earlier advance during the Langtang Stage. Therefore, the Langtang Stage reached its peak in the Middle Holocene during a period of relatively high global warmth and precipitation. High glacial accumulation rates in upper altitudes of the glacial catchment must have offset the increased ablation rates. Evidence of a warmer climate during this period is documented by a humic layer dated to 3860 ± 110 ^{14}C yr BP (sample S7) by Shiraiwa et al. (1990). Warm phases during glacial periods show that despite a warm climate, increased snowfall at higher elevations drives glacial advances despite increased ablation rates. Glacier advances during the Middle Holocene have been documented in the Gangotri region of Garhwal at ~5 ka (Sharma and Owen, 1996, Barnard et al., 2006), in the adjacent Khumbu Himal at ~3.6 ka (Finkel et al., 2003), in Chitral (Owen et al., 2002c) and in Kachenjunga (Tsukamoto et al., 2002).

A warm climate was also identified by Shiraiwa et al. (1990) at the onset of the Lirung Stage (2800–2000 ^{14}C yr BP) by a radiocarbon date from a humic layer in a slope failure (sample S3 = 2800 ± 110 ^{14}C yr BP). This stage corresponds to the Neoglacial (3.5–2.0 ka; Grove, 1988). Therefore, limited glacier advances are also possible during warmer times, when, despite higher ablation rates, glaciers are able to advance because of extremely high accumulation rates and positive mass balances. Watanabe et al. (1998) showed that debris cones formed and sedimentation quickly abated following the end of the Lirung stage at ~2.0 ka. The CRN dates from this same surface suggest that reworking of Lirung Stage tills on the Sindum surface also ceased by ~2.0 ka.

A series of smaller glacier advances during the Late Holocene (Yala I Stage, ~0.55 ka) are defined by the radiocarbon and CRN dating of the complex moraine field near the Eastern Lirung Glacier, at Kyanjin Gompa. These may relate to the LIA (Grove, 1988). A moraine dated to ~0.52 ka (samples KTM 7–9) extended across the valley and temporarily blocked the drainage of the Langtang Khola. Massive boulders (~10 m in diameter) in the narrow channel neck at this point and a wide, braided stream morphology upvalley of this point indicate that this was the point of dam bursting of the Yala Flood, where maximum flood velocities were focused. The morphostratigraphic and chronologic correlation of several terraces downvalley of this point (Fig. 6), which are dated to this time, provide further evidence of a glacial lake outburst flood. However, the Langtang Village terrace would have been largely protected from the Yala Flood by the massive end moraine complex that is present immediately upvalley. Nevertheless, it is likely that the Southern Langtang Lirung glacier was behaving similarly at this time and thus flooding may have also occasionally occurred from the tributary valleys as well. Glacial lake outburst floods have been identified during historical times in the nearby Khumbu Himal region (Ives, 1986; Zimmermann et al., 1986). The major flood that occurred in Langtang at some point during the last 1 ka shows that even limited glacial fluctuations can have major effects on the geomorphology.

The Yala II glacier advance (1910 AD) identified by Shiraiwa et al. (1990) may be related to the end of the LIA. Historical glacier advances have been recognized in a number of Himalayan regions, including Garhwal Himalaya (Sharma and Owen, 1996) and Khumbu Himal (Benedict, 1976; Fushimi, 1978; Müller, 1980; Finkel et al., 2003).

The data of Owen et al. (2002a), Finkel et al. (2003) and Barnard et al. (2004a, b) show that major glacial advances appear to be synchronous with periods of increased insolation in the Himalaya. During periods of global cooling, the southwest Asian summer monsoon is significantly weakened (Sirocko et al., 1991) and there was not enough moisture reaching the High Himalaya to cause advances of similar relative magnitude to the northern hemisphere ice sheets. During the winter months, mid-latitude westerlies carry moisture from the Mediterranean, Black and Caspian Seas toward the Himalaya, but significant snowfall from this source is restricted to the western Himalaya (Benn and Owen, 1998).

Massive diamicts with isotropic clast fabrics and only minor banding and imbrication show that large-scale debris flow processes dominated sedimentation. Similar deposits have been described in fan and terrace sections from the Khumbu Himal (Barnard et al., 2006), where they were linked to rapid sedimentation related to the retreat of adjacent glaciers. Well-sorted sands on the top of the Kyanjin terraces indicate a period of aeolian deposition.

Farther downvalley on the upper Sindum terrace, several exposures indicate that not all paraglacial sedimentation occurred as debris flows. At Sindum, stacks of low energy fluvial units, primarily pebbly sands and sandy pebbles, dominate the terrace stratigraphy. These finer sediments may dominate this portion of the Langtang Valley because they are farther from the source region, and thus the potential for larger clast transport is lower than in the vicinity of the glacial front near Kyanjin Gompa. Conversely, this could indicate that glacial retreat following the Lirung Stage was gradual and thus the potential for high magnitude sedimentation events was reduced. This is unlikely based on the coarse debris flows described by Watanabe et al. (1998) attributed to the Lirung Stage in the vicinity of Yala Glacier (Fig. 2).

The timing of fan and terrace sedimentation coincides or quickly follows the periods of maximum glacial advance in Langtang. The CRN and radiocarbon dating show that reworking of the upper Sindum surface, which was initially formed by the Lirung Stage (2.08–2.8 ka), ceased between 1.5 and 2.0 ka. At least five major terraces (Fig. 6) formed contemporaneously with the Yala I advance (0.45–0.55 ka). Regardless of the precise chronology of events, it is clear that major phases of sedimentation in the Langtang Khola Valley are closely associated with glacial fluctuations.

Extremely high rates (averaging 33 mm/a) of fan/terrace denudation during the Late Holocene were determined by the fan incision. Watanabe et al. (1998) calculated denudation rates ranging from 3.2 to 15.6 mm/a on debris cones in the Langtang Valley during the Middle and Late Holocene. Shroder et al. (1999) estimated denudation rates of 7–25 mm/a for localized glacier and river basins in the Nanga Parbat Himalaya. However, Shroder et al. (1999) also noted rates as high as 120 mm/a that were associated with catastrophic floods resulting from the breaking of repetitive landslide dams.

The only terrace that is older than 1 ka is the upper Sindum terrace (~2 ka). Incision through this surface occurred at a rate of ~8 mm/a. It is likely that rapid glacial fluctuation during the last 1 ka (Yala I and II stages) and associated hydrological changes and events (i.e. Yala Flood, ~0.5 ka) resulted in extremely high rates of denudation, but when averaged over longer time periods the rates approach the average background Himalayan bedrock denudation rate of ~6 mm/a, as calculated using the following studies: Brunsden et al. (1981), Zeitler (1985), Valdiya and Bartarya (1989), Burbank and Beck (1991), Gardner and Jones (1993), Burbank et al. (1996), Leland et al. (1998), Shroder et al. (1999), Barnard et al. (2001, 2004a, b) and Vance et al. (2003). Conversely, Langtang may be very vulnerable to slight changes in monsoon intensity, and thus may have heightened denudation rates when compared to other regions of the Himalaya. However, the present annual average rainfall at Kyanjin Gompa (622 mm/a; DHM, 1993, 1995, 1996, 1997) is less than half of the Nanda Devi region of the Garhwal Himalaya (~1550 mm/a; Indian Meteorological Department, 1989) where denudation rates for sediment average ~37.9 mm/a (Barnard et al., 2004a). Therefore, it is likely that the long-term rates of denudation in the Langtang Himal are significantly lower than what was calculated for the Late Holocene terraces, and that the rate derived from the upper Sindum terrace may provide an adequate approximation (~8 mm/a) of average Holocene denudation rates. The study by Leland et al. (1998) in the Nanga Parbat region of the Northwest Himalaya documents an acceleration of average denudation rates during the last 15 ka in Nanga Parbat, and attributed this acceleration to an increase in discharge and/or sediment load related to deglaciation in the surrounding mountains following the major glacial advances of the Last Glacial. They also noted a substantial increase in bedrock incision rates during the last 7 ka, from 1–6 mm/a from 65–7 ka to 9–12 mm/a from 7 ka to the present. It must also be emphasized that the incision rates quoted in this study are for erosion through sediment that is clearly less resistant than bedrock. This may also explain the difference. Nevertheless, the high incision rates in Langtang record the rapid degradation of landforms in this active geomorphic environment. Despite the inherent uncertainty of obtaining extremely precise

CRN dates and therefore precise denudation rates in such a dynamic environment, it is clear from the CRN dating that the reworking of glacigenic deposits is extremely rapid during the Holocene in Langtang, and that erosion and denudation rates are exceptionally high.

All landforms in the lower elevations of the Langtang Valley (i.e. within ~250 m of the present valley bottom), both glacially and paraglacially generated, formed during the Middle and Late Holocene. The dating of the Tsergo Ri landslide to ~29 ka shows that older CRN ages can be achieved, and the favorable comparison of radiocarbon dating from prior studies with the CRN dating in this study proves that CRN can be broadly accurate even for young landforms (e.g. <1 ka). A common problem with CRN dating is the potential pre-exposure of a boulder before it reached the position at which it was sampled (i.e. derived boulders, Anderson et al., 1996; Hancock et al., 1999). However, if erosion rates are high, such as in Langtang, inheritance is only a minimal concern.

The impact of anthropogenic activity on denudation rates in the Langtang Khola has not been quantified. Starkel (1972) estimated a 10-fold increase in denudation rates (0.5–5.0 mm/a) in an area of Darjeeling in India after deforestation. Barnard et al. (2001) showed that anthropogenic influences accelerated landsliding and hence denudation in the Chamoli region of Garhwal Himalaya by as much as several mm per year. However, Ives and Messerli (1989) surveyed numerous Himalayan environments, and concluded that natural denudation far exceeds human-induced denudation by several orders of magnitude, on average, even in the Khumbu Himal, where the influx of Sherpas ~400 years ago has been well documented. Watanabe (1994) analyzed soil erosion on Yak-grazing steps in the Langtang Khola Valley. This study showed that grazing was an insignificant contributor to overall denudation rates at only 0.02–0.16 mm/yr when averaged over the last 50 years. Therefore, the high rates of denudation in the Langtang Khola valley observed during the Late Holocene can be largely attributed to rapid tectonic uplift and climate fluctuations.

10. Conclusions

CRN dating in the Langtang Khola Valley broadly agrees with previous radiocarbon studies, emphasizing that glacial advances occurred during the Middle Holocene, Neoglacial, and Little Ice Age. Perhaps more importantly, the ages and sedimentological relationships between moraines and correlative fans demonstrate the rapid reworking of glacigenic sediment during deglaciation phases. The CRN dating also shows that in areas with rapid erosion rates, inheritance is not significant and thus accurate age approximations can be achieved for extremely young deposits (<1 ka). Terrace morphology is dominated by the evidence of a glacial lake outburst flood that occurred at ~0.5 ka, and formed or reworked multiple terrace surfaces. Sedimentology of the fans is similar to other Himalayan regions. These are dominated by debris flows, but low energy fluvial deposits comprise the upper 2 m of the terraces farther from the present glacial margins. Fan incision rates were calculated to be ~33 mm/a during the Late Holocene. These high erosion rates during the Late Holocene are attributed to multiple glacial cycles that are driven by climatological variations, but the human-induced acceleration of erosion rates cannot be totally ignored. Rapid denudation has eliminated evidence of any low-lying fans, terraces and moraines that might have formed prior to the Middle Holocene. The high denudation rates that correlate with rapid glacial fluctuations clearly demonstrate the impact of paraglacial processes on the landscape evolution of high mountain environments.

Acknowledgments

Funding for the field component of this project was provided by a grant from the University Research Expeditions Program (UREP). Many thanks are due to the UREP volunteers for their financial and field support: Linda Dunaway, Susan Morton, Sheldon Gilchrist, Christopher Teng, and Anthony Barnard. Thanks are due to our wonderful Tamang guides: Pemba, Bila, Bijae, Mundu, Krishna and Kagi, for their help in the field. The cosmogenic radionuclide dating analysis was undertaken at the Lawrence Livermore National Laboratory (under DOE contract W-7405-ENG-48) as part of an IGPP/LLNL research grant and a Student Employee Graduate Research Fellowship. Helpful and constructive comments on this paper were provided by Quaternary Science Reviews reviewers.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2006.02.002.

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