Using Lichenometry to Assess Long Term GLOF and Landslide Frequency in the Nepal Himalaya

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ABSTRACT

Glacial lake outburst floods (GLOFs) and other debris flow and flood events are major hazards in and downstream from glaciated areas in the Nepal Himalaya and many other mountainous areas. Furthermore, global warming likely will increase GLOF frequency. However, in the Nepal Himalaya little is known of the frequency of GLOFs prior to 50 years ago making it difficult to assess the long term hazard they pose. In light of this, the objectives of our study were to develop the first lichen apparent growth curve for the Nepal Himalaya and use lichenometry to date pre-historic GLOF events and major landslides in the Nepal Himalaya.

The study's first stage was carried out near Kyanjin Gompa in Langtang Valley, Nepal, where data were collected to link rock surface exposure age to the maximum diameter of *Rhizocarpon geographicum* in order to produce an apparent growth curve. Diameters of *R. geographicum* were measured on boulders at two sites where local people recalled the position of ice blocks from Khyimjung Glacier at 1959 and 1982 AD. Lichen diameters were also measured on boulders downslope from Kyanjin Gompa on two debris flow deposits that had been previously dated at 1611 ± 95 and 1474 ± 94 AD using ^{10}Be. The apparent growth curve that best fits the data is $y = 51.11(1 - \exp(-0.0458x)) + 0.1620x$, where y is maximum lichen diameter (mm) and x is time (years). The apparent growth curve was combined with lichen diameter measurements to date a landslide that dammed the Langtang River above Kyanjin Gompa at 1683 AD, a landslide that occurred along the Langtang River above Langtang Village at 1904 AD, and the end moraine of Khyimjung Glacier that recorded its most recent advance at 1966 AD.

The second stage of the study will include expanding the project beyond Langtang Valley, and dating more pre-historic GLOF, glacial moraine and debris flow deposits.

INTRODUCTION

Glacial lake outburst flood (GLOF) and other flood events are major hazards in and downstream from glaciated areas in the Nepal Himalaya and many other mountainous areas around the world. Many workers consider it likely that the retreat of the Himalayan glaciers will result in an increase in the frequency of GLOF events (e.g., Yamada, 2000; Komori et al., 2004; Chalise et al., 2006). In response, international agencies and governmental bodies of the Himalayan countries are attempting to formulate policies for the mitigation of GLOF-related hazards (Reynolds, 1999; Chalise et al., 2005). A difficulty in the formulation of policy is that the history of GLOF events and glacier-related flood events is known almost exclusively from the historical record of the past few decades (Cenderelli and Wohl, 2001, 2003; Komori, 2006) and the almost complete absence of any history for GLOF-related events in the Himalaya prior to approximately 50 years ago. Only a small number of pre-historic mass wasting deposits in the India and Nepal Himalaya have been dated, and they were dated by the relatively expensive methods of ^{10}Be and ^{26}Al dating (Barnard et al., 2001, 2006a, 2006b; Abramowski, 2004; Mitchell et al., 2007). None of the dated deposits have been specifically related to GLOF events. There is preliminary evidence for numerous large depositional events from GLOF or debris flow events close in time to glacial advance maxima (Barnard et al., 2006b). However, with the current age data on flood events and glacial advances in the Nepal Himalaya, it is not possible to discern whether the flood events were most frequent just before, at the peak of, or soon after the peak of an advance when there is a large supply of meltwater to mobilize sediment in moraines.

Numerous landslides around the world have been dated using the relatively inexpensive method of lichenometry, which utilizes knowledge of lichen growth rate and the size of lichen on a rock surface to date the age of exposure of the rock surface. The size of lichen on gravestones is commonly used to determine apparent growth rates. There have been only a handful of lichenometric studies in the Himalaya, partly due to the lack of gravestones that can be used for calibration. Vohra (1981), Srivastava et al. (1995), Srivastava et al. (2004) and Awasthi et al. (2004) have reported on the used of lichenometry to date the moraines in the India Himalaya. Gupta (2005) carried out relative dating of portions of a major landslide in Himachal Pradesh (India Himalaya) using percent lichen cover without regard to lichen species. Chaujar (2006) and Chaujar (2009) used *Rhizocarpon geographicum* in the Himachal Pradesh and the Garhwal Himalaya to date the moraines of the Chorabari Glacier. Yang et al. (2008) has used the maximum diameter of *R. geographicum* growing on a fan formed by a GLOF of known age to date moraines on the Tibetan Plateau. We are not aware of any lichenometry that has been carried out anywhere in the Bhutan, Nepal or Pakistan Himalaya prior to this study.

This paper reports the development of an apparent growth curve for *R. geographicum* in Langtang Valley, Nepal Himalaya (Fig. 1), and the ages of two landslides and an end moraine. To our knowledge, this is the first apparent growth curve and use of lichenometry in the Nepal Himlaya. Because lichen growth rates are variable, it is necessary to calibrate lichen growth rate of a selected lichen species for each study locality by measuring the growth rates of individual lichens over a period of years (called the direct method) or by measuring the maximum lichen diameters on surfaces for which age is known from independent evidence (called the indirect method) (Innes, 1988). An apparent growth curve is a model curve fitted to data collected using the indirect method (e.g., Innes, 1998). An apparent growth curve does not directly reflect the actual biological growth rate of individual lichens. Rather, the largest measured lichen diameter reflects lichen growth and mortality rates, and the probability of finding and recognizing the oldest lichen on a set of rock surfaces formed in a single event (e.g., Loso and Doak, 2006). *R. geographicum* was chosen because it is the lichen variety most commonly used for lichenometry (Bradwell and Armstrong, 2007) and it was revealed to be very abundant upstream from Langtang Village during this study. This study's apparent growth curve was developed using the indirect method. The model curve was fitted to data collected in the vicinity of Kyanjin Gompa village (Figs. 1-2). Lichen diameters measured on boulders known by local residents to have been ice covered until specific times and two ridges of diamict sediment dated by Barnard et al. (2006a) using ^{10}Be were used to calibrate the curve (Fig. 2). The two ridges were interpreted by Barnard et al. (2006a) as lateral moraines; we suggest that they were deposited by hyperconcentrated stream flow or debris flows (following the flow terminology of Pierson and Costa (1987)), that possibly were the result of GLOF events.

The two landslides chosen for dating by lichenometry are called Landslide A (Fig. 3) and Landslide B. Landslide A was chosen because it is a very large landslide that dammed Langtang Khola (river). Landslide B was chosen because the front of its deposits are very near and parallel to a mani wall (Buddhist sacred wall) and an age younger than the time of human settlement of the area would be consistent with Weidinger's (2001, 2002) view that mani walls were constructed as warnings of landslides, which are a significant hazard in Langtang Valley (e.g., Weidinger, 1998). The youngest end moraine created by the retreat of the Khyimjung Glacier (Figs. 1, 4) was also dated.

MATERIALS AND METHODS

Site Selection

Four sites for calibration of the lichen apparent growth curve were selected based on the availability of reliable independent information on the age of surface exposure of rocks at the sites (Fig. 2). Two sites are known to have been exposed in 1982 and 1959 based on interviews with well respected local residents. The sites are along a creek and were permanently ice-covered, possibly as a result of over-flow or remnants of the retreat of the Khyimjung Glacier (Fig. 1), until their respective times of exposure. Lichen measurements were restricted to

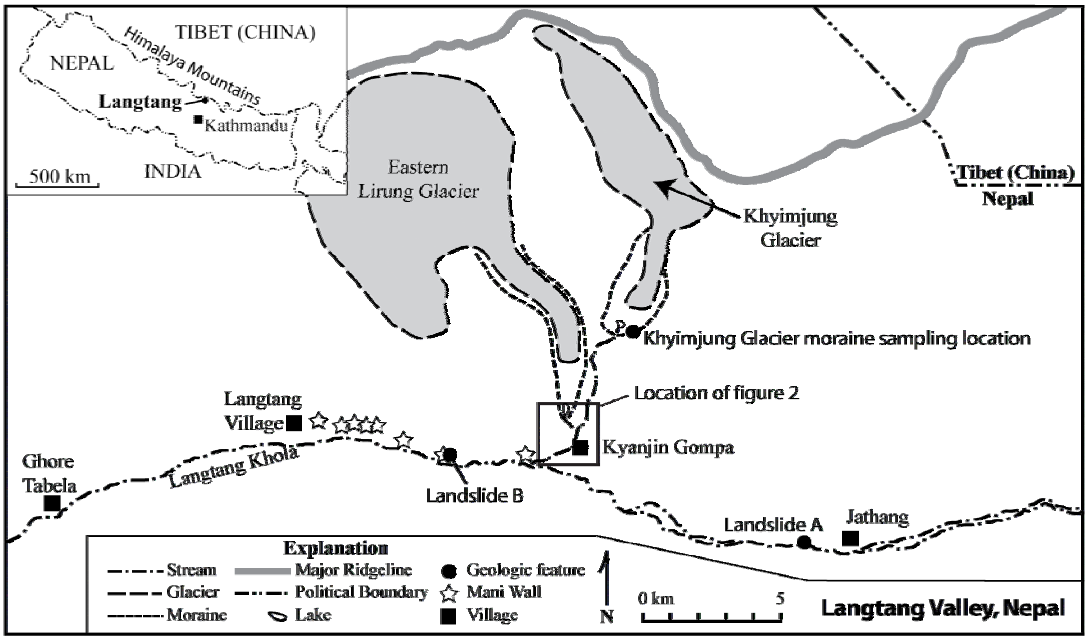

Figure 1. Map of Langtang Valley showing locations of Fig. 2, Landslides A and B, Khyimjung Glacier and its end moraine and other features discussed in the text.

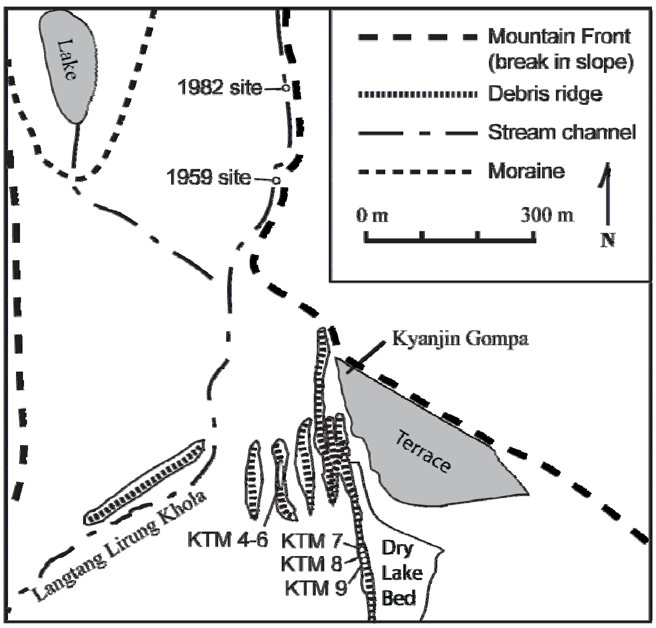

Figure 2. Map showing Kyanjin Gompa, locations of debris ridges, ^{10}Be samples dated by Barnard et al. (2006a) (KTM 4, 5, 6 and KTM 7, 8, 9), and locations of areas covered by ice until 1959 and 1982 and sampled for *R. Geographicum* to produce an apparent growth curve. Dry lake bed inferred by Barnard et al. (2006a) to have formed as a result of damming of Langtang Khola by the mapped debris ridges is also shown. Modified after Barnard et al. (2006a).

boulders within one vertical meter of the current creek bed to ensure that the sampled surfaces were not exposed prior to the indicated dates. Two other calibration sites of older known ages were chosen to extend the apparent growth curve further back in time. The sites were dated by Barnard et al. (2006a) using ^{10}Be and were selected because they were in the needed age range (200 to 600 years before present) and had relatively small ^{10}Be age errors. The sites are ridges of diamict, and are the locations of Barnard's (2006a) samples KTM 4-6 and samples KTM 7-9

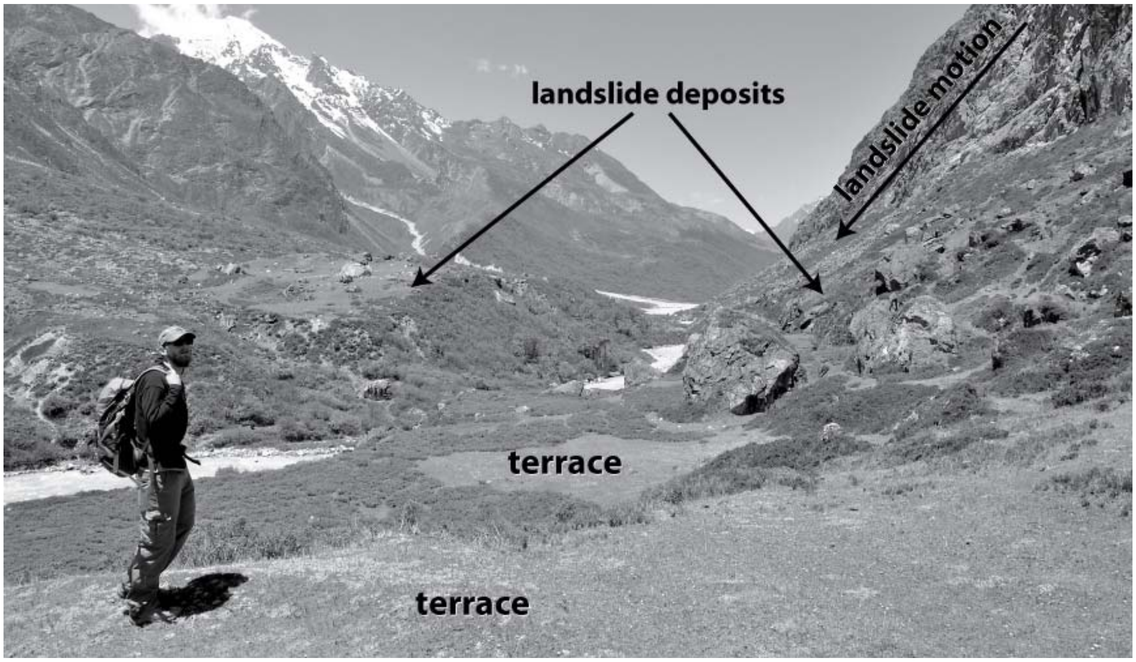

Figure 3. View of landslide A. The view is towards the west; the landslide moved from right to left and the deposit debris on both sides of the river. Marked terraces comprise sediments deposited in lake formed when the landslide deposits dammed the river.

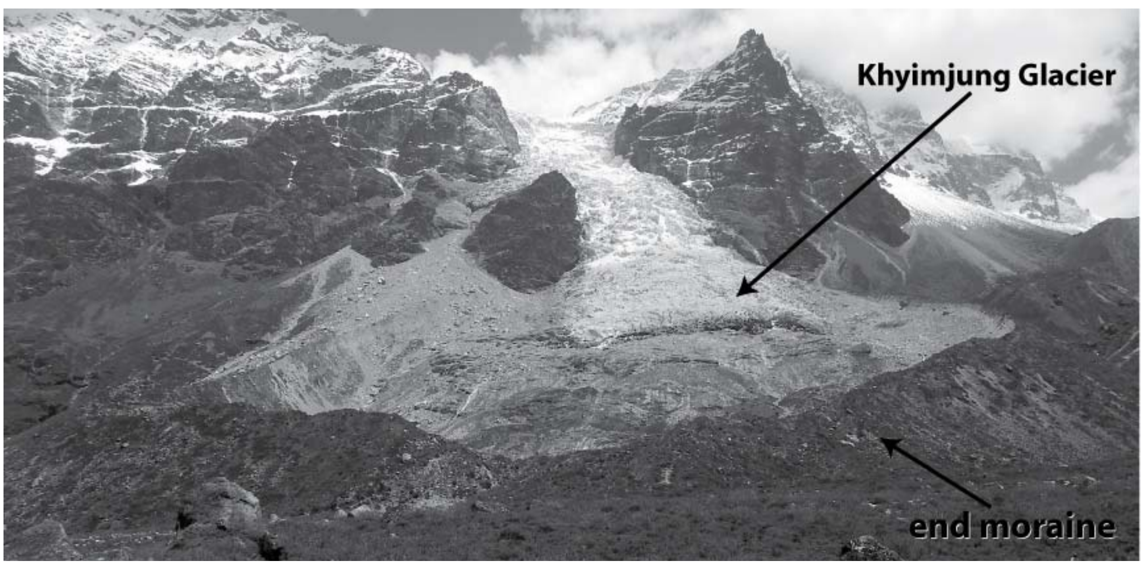

Figure 4. Khyimjung glacier and its end moraine; view is towards the north.

(Figs.2, 5). Barnard et al.'s (2006a) exact sampling sites were located, and lichen were measured on boulders on the same ridges they sampled and within 30 meters of their sample sites.

Lichen Measurements

Innes (1988) reviewed the range of procedures used in measuring lichen for a lichenometric age determination or creation of an apparent growth curve. There are three crucial aspects to measuring lichen diameters: 1) the lichen species must be correctly identified, 2) thalli of single individuals must be measured, as opposed to composites formed when two or more individuals grow together, and 3) lichen sizes must be measured from surfaces exposed during the event of interest, as opposed to an inherited surface that was exposed prior to the event of interest. We carefully searched each study site to find and measure the largest lichens present.

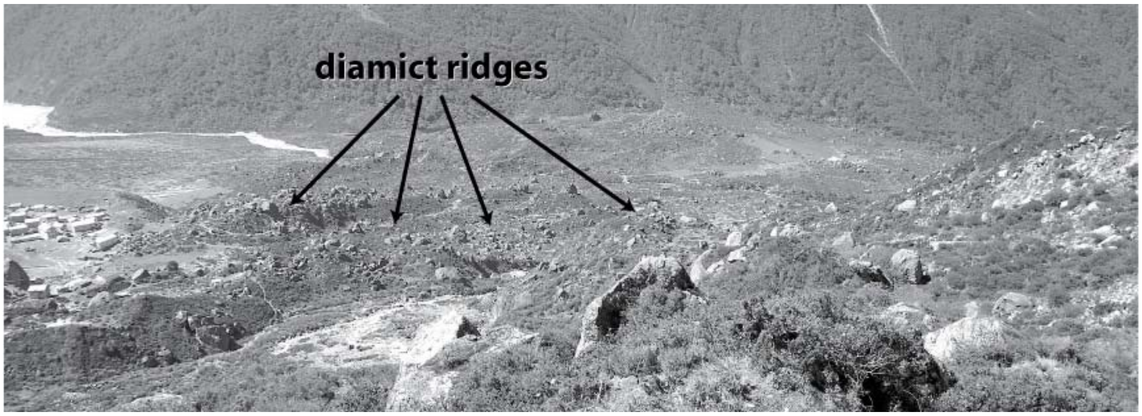

Figure 5. Bouldery diamict ridges dated by Barnard et al. (2006a); view is to the south.

R. geographicum was identified following the general criteria of Purvis et al. (1992) and St. Clair (1999). One of the several advantages of *R. geographicum* for lichenometry is that it has a very distinctive appearance and is not easily mistaken for other species in high elevation environments. In order to discriminate between individual and composite thalli, we used the following criteria: approximate circular to smoothly elliptical shape (Ellis et al. 1981; Proctor, 1983), sharp margins, well defined hypothallus, and homogeneity of color and texture within the thallus. To avoid inherited surfaces, lichen were measured on boulders in distal portions of deposits wherever possible. Boulders in distal areas were transported farther and it is more likely they had fresh surfaces exposed by either fracturing or abrasion during transport. At all sites except Landslide A, the single largest lichen that met our criteria was used for calibration of the apparent growth curve or lichenometric age determination (Calkin and Ellis, 1980; Innes, 1988). The largest lichen identified at Landslide A was excluded as an outlier because it was more than 20% larger than the next largest lichen measured at that site (Calkins and Ellis, 1980; Loso and Doak, 2006).

At each site where lichen were measured except for the Khyimjung Glacier end moraine, six to eight people carefully scrutinized the area and hundreds of *R. geographicum* thalli were identified, with the exception of the smaller 1959 calibration site where tens of thalli were identified. The largest three to eight lichen at each site that met our selection criteria were measured and photographed. The longest diametrical axis of each lichen, including the hypothallus, was measured to ± 0.01 mm using digital calipers; however reproducibility of lichen size is probably ± 0.05 mm due to error in positioning calipers at the hypothallus edge. The lichen were photographed using a digital SLR camera and 60-mm macro lens to minimize distortion. Photographs were taken to aid possible future repeat measurements of individual lichen to build a growth curve by the direct method. Lichen on the Khyimjung moraine were identified and measured by two people using a ruler with 1 mm markings and photographed using a digital pocket camera.

RESULTS

Best-fit Apparent Growth Curve

The best-fit lichen apparent growth curve was generated by fitting a curve to a plot of the size of the largest lichen at each calibration site against the time since surface exposure (Fig. 6, Table 1). Ages of the two diamict ridges were taken as averages of Barnard's (2006a) ^{10}Be dates of the ridges. Barnard et al. (2006a) collected and dated three samples from each ridge. Reported ages for the younger ridge are 1581 ± 130, 1181 ± 220, and 1641 ± 140 AD (Barnard 2006a; samples KTM 4, 5, 6; all dates are AD). Because the 1181 date is more than twice the mean of the other two dates, we excluded it on the presumption that an inherited surface was sampled. The mean of the other two dates and their standard error is 1611 ± 95 . Reported ages for the older ridge are 1531 ± 160, 1501 ± 150 and 1391 ± 180 (Barnard et al., 2006a). We took the mean of all

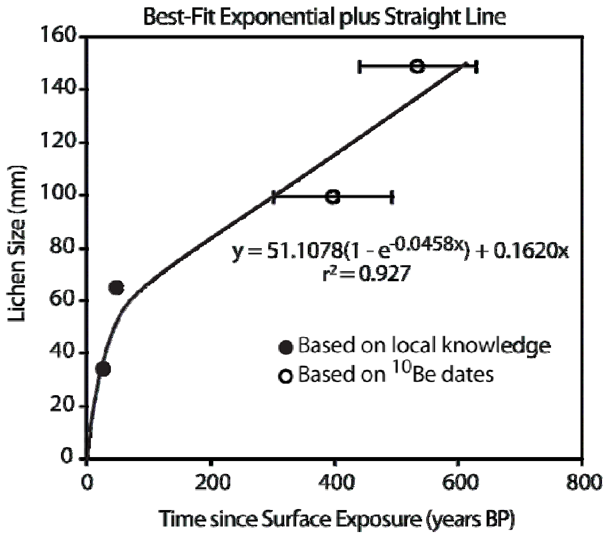

Figure 6. A best-fit exponential curve plus straight line is the best fit to the growth calibration data and is the preferred apparent growth curve. It adequately fits both the data based on local knowledge and the data based on ^{10}Be dates, and is a very good overall fit (r^2 = 0.927).

three ages and calculated the standard error of the three measurements taken together to obtain 1474 ± 94. We fit numerous model functions commonly used in lichenometry to the data, including power-law, linear, negative exponential, logistic, and Gompertz (Innes, 1988), and found the best fitting model to be an exponential plus straight line (Fig. 6):

$$y = 51.108(1 - e^{-0.0458x}) + 0.162x, \quad (1)$$

where y is lichen diameter in mm and x is time since rock surface exposure in years. It has a very good overall fit (r^2 = 0.927), a zero intercept, and is a good fit to both the younger and older dates. The data suggest no colonization delay.

Ascertaining errors in lichenometric ages is challenging. Contributions to error include errors in ^{10}Be ages of calibration sites and errors related to measured lichen sizes, such as variations in growth rate or failure to find the largest lichen on surfaces formed in a dated event. Because the apparent growth curve combines two ^{10}Be ages, their error contribution should be somewhat less than the standard error of the age of each site. The ages of the younger calibration sites are known precisely, so errors in younger ages determined lichenometrically should be substantially less than for older ages. We estimate that errors in older ages (i.e., > 100 years before present, ybp) may approach or exceed ± 100 years, errors in ages between 50 and 100 ybp are on the order of ± 50 years, and errors in ages less than 50 ybp are on the order of two decades.

Landslide and Moraine Ages

Two landslides (A and B) and a glacial moraine were selected for lichenometric age determinations (Fig. 1; Table 1). The landslides were selected for study because they were two of the largest landslides in the valley and they were considered good candidates for reliable age determinations because they met the following criteria: 1) morphology indicative of a single, large landslide, 2) presence of large boulders in the distal area of the slide deposit on which lichen could be measured, and 3) ease of access. Criterion (1) was evaluated based on the presence of a single lobe to the landslide deposit and one identifiable source area. The second criterion provided assurance that sampled boulders were deposited in a large event responsible for the bulk of the landslide deposit; in contrast, smaller boulders located higher on the deposit may have fallen subsequent to the primary landslide event.

The deposit from Landslide A (Fig. 3) is approximately 200 m wide, 125 m long and up to 20 m thick, and is lobate. It dammed the Langtang Khola, as evidenced by a large deposit of landslide debris on the far side of the river from the landslide source and the presence of terraces

Site Name	Site purpose	Latitude	Longitude	Elevation (m.a.e.)	Largest Lichen diameter (mm)	Age (AD)
1982 ice cover	calibration	28.2180 N	85.5662 E	3900	33.73	1982
1959 ice cover	calibration	28.2161 N	85.5657 E	3880	64.72	1959
Debris Ridge 1 (Barnard et al. 2006a samples KTM 4-6)	calibration	28.2123 N	85.5630 E	3806 - 3819	99.75	1611
Debris Ridge 2 (Barnard et al. 2006a samples KTM 7-9)	calibration	28.2093 N	85.5655 E	3791 - 3802	148.92	1474
Landslide A	age determination	28.1969 N	85.6074 E	3877 - 3919	103.89	1683
Landslide B	age determination	28.2109 N	85.5388 E	3617	67.74	1904
Khyimjung glacier terminal moraine	age determination	28.2308 N	85.5730 E	4217	51	1966

Table 1. Locations, maximum sizes and inferred or known ages of lichenometric sampling sites. Positions are WGS84, and elevations are meters above ellipsoid.

comprising sediments interpreted to have been deposited in a lake that formed behind the landslide deposit. The sediments consist of silt and sand deposited on landslide boulders in the upstream lateral edge of the lobate landslide deposit. Sampling of landslide A was done on large (up to ~ 4 m x 3 m x 3 m) boulders on the source side of the river because it was not possible to safely cross the river. The deposit from Landslide B is approximately 30 m wide, 150 m long and up to 8 m thick, lobate in shape and contains large (up to ~ 4 m x 3 m x 3 m) boulders in the distal areas of the deposit that were sampled for lichen. Lichen size measurements from Landslides A and B were converted to surface exposure ages using the exponential plus straight apparent growth curve (Fig. 6). Landslide A was dated to 1683 and Landslide B was dated to 1904 .

The moraine of the Khyimjung glacier (Fig. 4) was selected because it has a simple morphology indicative of its development in the most recent advance of the glacier. The morphology consists of lateral moraines spaced 700 to 800 m apart that extend downhill approximately 700 m from the present location of the glacier's terminus and connect to an approximately semi-circular end moraine that is breached by a single gully through which meltwater drains. There is no evidence for the existence of an end moraine younger than the one sampled. Lichen measurements were taken along the top of the moraine, where boulders presumably were deposited at the peak of the most recent glacial advance. The age of the moraine was found to be 1966 (Table 1).

DISCUSSION

The best-fit apparent growth curve (Fig. 6) indicates a 1.3 mm/yr diametric apparent growth rate for lichen < ~50 years old, and 0.15 mm/yr for older lichen. These rates are consistent with rates determined by the direct and indirect methods in other in other parts of the world (e.g., Armstrong (1983); Winchester and Chaujar (2002); Armstrong (2004); Bradwell and Armstrong (2007)). Previous studies of *R. geographicum* growth rates in the Himalaya are sparse but broadly consistent with our results. Chaujar (2006, 2009) reported growth rates for *R. geographicum* from two locations in the India Himalaya. Chaujar (2006) used measurements on monuments that date from 1863 – 1949 in four towns in Himachal Pradesh (India Himalaya) at elevations ranging from 1980 – 2360 m a.s.l. to find diametrical growth rates of 0.54 – 0.79 mm/yr and colonization delays of 24 – 86 years. Chaujar (2009) used the direct method in the Garhwal Himalaya (India) to find a growth rate of 1.0 mm/yr on moraine boulders at elevations ranging from 3160 – 3640 m a.s.l. Chaujar (2009) used the absence of any lichens on an 85-year-old bridge at Kedarnath Temple in the same region to argue that the colonization delay for *R. geographicum* is at least 85 years. While growth rates determined in this study are similar to those of Chaujar (2006, 2009), no evidence for a colonization delay was found. However, there are other lichenometric studies in which no colonization delay was assumed or inferred from data. For example, in a study on the Tibetan Plateau, Yang et al. (2008) assumed immediate colonization and determined a *R. geographicum* growth rate of 0.6 mm/yr based on the size of lichens found on a fan formed by a GLOF event in 1940. Sancho and Pintado (2004) reported on immediate colonization of *R. geographicum* in the maritime Antarctic.

It is unclear how this study's results could be extrapolated to other parts of the Himalaya. Chaujar's (2006, 2009) results are similar, but sufficiently different to suggest that a growth curve should be developed for each local study area. However, there is little knowledge as to the geographical area over which a growth curve can be applied, and Denton and Karlen (1973) and Bull at al. (1994) have argued that microclimatic factors, especially shelter from sun and wind, are the most important factors.

The diamict ridges (Figs. 2, 5) dated by Barnard et al. (2006a) (their samples KTM 4-9) and used to calibrate this study's lichen apparent growth curve were interpreted by Barnard et al. (2006a) to be inner and outer lateral moraines formed in an advance of the Eastern Lirung Glacier between 1451 and 1551. The advance was interpreted to be coincident with the Yala I Stage of Watanabe (1998). Barnard et al. (2006a) also noted evidence for damming of Langtang Khola by the deposits, the formation of a lake behind the deposits (Fig. 2) and breaching of the dam that resulted in a significant flood event. The evidence includes flat-lying deposits of sand overlain by desiccated mud just up valley from the ridges, the fact that the longer ridge extends to the southern side of Langtang Khola, a change in the morphology of the Langtang Khola from delta-like with a low gradient upstream from the ridges to narrow and higher–gradient below, incision of the Langtang Khola into the ridge, and the presence of large boulders downstream from the ridge (Barnard et al., 2006a). We propose that the diamict ridges were formed by large hyperconcentrated streamflow or debris flow events, possibly the result of GLOF events from the Eastern Lirung Glacier, Khyimjung Glacier (e.g., Mool et al., 2001), or another glacier north of Kyanjin Gompa. This interpretation is based on the following observations. The ridges are a series of complexly anastomosing ridges, rather than parallel ridges typical of lateral and medial moraines (Fig. 5). They do not have the morphology of paired lateral moraines connected by end moraines. The sedimentology of the deposits, a diamict of large angular to sub-angular boulders in a finer-grained matrix (Barnard et al., 2006a) is consistent with debris flow deposits. The large volume of these deposits and the large boulders in them suggest that they formed in large events, possibly GLOF – induced debris flows. The ridges likely were deposited during glacial retreat from the peak of the Yala I stage. The deposition of large volumes of bouldery diamicts in non-moraine deposits near in time to peak glacial advance (presumably shortly after the advance) has previously been described in the Khumbu Himal region (Barnard et al., 2006b).

The 1966 age for the Khyimjung Glacier end moraine is consistent with the ^{14}C date of 1910 ± 130 years for an organic layer in the end moraine of Eastern Lirung Glacier (Fig. 1) that Watanabe (1998) reported. He argued for a recent Yala II Glacial Stage based upon that date, and the lichenometric age for the Khyimjung Glacier end moraine is consistent with his assertion.

The apparent growth curve presented here for *R. geographicum* in the Langtang Himalaya may be useful for understanding the relationship of GLOF and other flood hazards such as debris flow events to glacial cycles in the Himalaya. It is now possible to identify deposits in Langtang Valley that record major flood events and date them using *R. geographicum* diameters. Therefore, it should be possible to add to the history of hazardous depositional events and begin to assess whether there have been any changes in the frequency of the events, perhaps as a result of global warming. Furthermore, it will be possible to investigate the temporal relationship between glacial advances and major flood events. A reasonable hypothesis is that GLOF and other flood events may be especially frequent soon after the peak of a glacial advance when end moraines have recently been deposited and there is a large supply of meltwater to mobilize the sediment in the moraines. However, with the current data it is not possible to distinguish whether flood events are most frequent during any time of glacial retreat, or whether they are particularly frequent just before, at the peak of, or only relatively soon after the peak of an advance. If major GLOF and other depositional events do occur frequently following glacial peaks, it is important to understand the duration of time over which they are particularly frequent following the glacial peak. Lichenometry can help answer these questions because it provides relatively quick and inexpensive age estimates, and large numbers of age determinations will allow the timing of the events in question to be gleaned from inherently imprecise surface exposure ages.

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REFERENCES

Abramowski, U., 2004: The use of ^{10}Be surface exposure of erratic boulders in the reconstruction of the late Pleistocene glaciation history of mountainous regions, with examples from Nepal and central Asia. Ph.D. Dissertation, Universität Bayreuth, 185 p.

Armstrong, R. A., 1983: Growth curve of the lichen *Rhizocarpon geographicum*. *New Phytologist*, 73: 913-918.

Armstrong, R. A., 2004: Lichens, lichenometry and global warming. *Microbiologist*, 5: 32-35.

Awasthi, D. D., Bali, R., and Tewari, N. K., 2004: Growth rate of lichen *Dimelaena oreina* in the Gangotri Glacier Valley, Uttarkashi District, Uttaranchal: Some significant observations. *Proceedings of Workshop on Gangotri Glacier, March 2003, Geological Survey of India Special Publication*, 80: 161-165.

Barnard, P. L, Owen, L. A., Sharma, M. C., and Finkel, R. C., 2001: Natural and human-induced landslides in the Garhwal Himalaya of northern India. *Geomorphology*, 40: 21-35.

Barnard, P. L., Owen, L. A., Finkel, R. C., and Asahi, K., 2006a: Landscape response to deglaciation in a high relief, monsoon-influenced alpine environment, Langtang Himal, Nepal. *Quaternary Science Reviews*, 25: 2162-2176.

Barnard, P. L., Owen, L. A., Finkel, R. C., 2006b: Quaternary fans and terraces in the Khumbu Himal south of Mount Everest: their characteristics, age and formation. *Journal of the Geological Society of London*, 163: 383-399.

Bradwell, T. and Armstrong, R. A., 2007: Growth rates of *Rhizocarpon geographicum* lichens: a review with new data from Iceland. *Journal of Quaternary Science*, 22: 311-320.

Bull, W. B., King, J., Kong, F., Montoux, T. M., and Phillips, W. M., 1994: Lichen dating of coseismic landslide hazards in alpine mountains. *Geomorphology*, 10: 253-264.

Calkin, P. E. and Ellis, J. M., 1980: A lichenometric dating curve and its application to Holocene glacier studies in the Central Brooks Range, Alaska, USA. *Arctic and Alpine Research*, 12: 254-264.

Cenderelli, D. A. and Wohl, E. E., 2001: Peak discharge estimates of glacial-lake outburst floods and 'normal' climatic floods in the Mount Everest region, Nepal. *Geomorphology*, 40: 57-90.

Cenderelli, D. A. and Wohl, E. E., 2003: Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. *Earth Surface Processes and Landforms*, 28: 385-407.

Chalise, S. R., Shrestha, M. L., Budhathoki, K. P., and Shrestha, M. S., 2005: Glacio-hydrological aspects of climate change in the Himalayas; mitigation of glacial lake outburst floods in Nepal. *IAHS-AISH Publication*, 295: 309-316.

Chalise, S. R., Shrestha, M. L., Bajracharya, O. R., and Shrestha, A. B., 2006: Climate change impacts on glacial lakes and glacierized basins in Nepal and implications for water resources. *IAHS-AISH Publication*, 308: 460-465.

Chaujar, R. K., 2006: Lichenometry of yellow *Rhizocarpon geographicum* as database for the recent geological activities in Himachal Pradesh. *Current Science*, 11: 1552-1555.

Chaujar, R. K., 2009: Climate change and its impact on the Himalayan glaciers – a case study on the Chorabari glacier, Garhwal Himalaya, India. *Current Science*, 96: 703-708.

Denton, G. H. and Karlen, W., 1973: Lichenometry, its application to Holocene moraine study in Southern Alaska and Swedish Lapland. *Arctic and Alpine Research*, 5: 347-372.

Ellis, J. M., Hamilton, T. D., and Calkin, P. E., 1981: Holocene glaciation of the Arrigetch Peaks, Brooks Range, Alaska. *Arctic*, 34: 158-168.

Gupta, V., 2005: Application of lichenometry to slided materials in the Higher Himalayan landslide zone. *Current Science*, 89: 1032-1036.

Innes, J. L., 1988: The use of lichens in dating. *In* Galun, M. (ed.), *CRC Handbook of Lichenology, Vol. III*. Boca Raton, FL: CRC Press, 75-92.

Komori, J., 2006: Glacial lake expansion and present situation in Himku and Hongu regions, eastern Nepal and Bhutan Himalaya. *Chigaku Zasshi (Journal of Geography)*, 115: 531-535.

Komori, J., Gurung, D. R., Iwata, S., and Yabuki, H., 2004: Variation and lake expansion of Chubda Glacier, Bhutan Himalayas, during the last 35 years. *Bulletin of Glaciological Research*, 21: 49-55.

Loso, M. G. and Doak, D. F., 2006: The biology behind lichenometric dating curves. *Oecologia*, 147: 223-229.

Mitchell, W. A., McSaveney, M. J., Zondervan, A., Kim, K., Dunning, S. A., and Taylor, P. J., 2007: The Keylong Serai rock avalanche, NW Indian Himalaya: Geomorphology and Palaeoseismic implications. *Landslides*, 4: 245-254.

Mool, P. K., Bajracharya, S. R., and Joshi, S. P., 2001, Inventory of glaciers, glacial Lakes and glacial lake outburst floods, Nepal: *International Center for Integrated Mountain Development, Nepal*, 191 pp.

Pierson, T. C., and Costa, J. E., 1987: A rheologic classification of subaerial sediment-water flows. *Geological Society of American Reviews in Engineering Geology*, 7: 1-12.

Proctor, M. C. F., 1983: Sizes and growth rates of thalli of the lichen *Rhizocarpon geographicum* on the moraines of the Glacier de Valsorey, Valais, Switzerland. *Lichenologist*, 15: 249-261.

Purvis, O. W., Coppins, B. J., Hawksworth, D. L., James, P. W., and Moore, D. M., 1992: The lichen flora of Great Britain and Ireland. *Natural History Museum Publications, London*.

Reynolds, J. M., 1999: Glacial hazard assessment at Tsho Rolpa, Rolwaling, central Nepal. *Quarterly Journal of Engineering Geology and Hydrogeology*, 32: 209-214.

Sancho, L. and Pintado, A., 2004: Evidence of high annual growth rates for lichens in the maritime Antarctic. *Polar Biology*, 27: 312-317.

Srivastava, D., Raina, V. K., and Kaul, M. K., 1995: Geomorphology around Gara Glacier, District Kinnaur, Himachal Pradesh. *Proceedings of Symposium on Northwest Himalaya and Foredeep, Geological Survey of India Special Publication*, 21: 327-331.

Srivastava, D., Shukla, S. P., and Bhattacharya, D. N., 2004: Lichens: A tool for dating the moraines of Gangotri Glacier area. *Proceedings of Workshop on Gangotri Glacier, March 2003, Geological Survey of India Special Publication*, 80: 155-160.

St. Clair, L. L., 1999, Common Rock Mountain Lichens. *M.L. Bean Life Science Museum of Brigham Young University*, 242 pp.

Vohra, C. P., 1981: Notes on recent glaciological expeditions in Himachal Pradesh. *Geological Survey of India Special Publication*, 6: 26-29.

Watanabe, T., 1998: Timing of Late Holocene debris supply and glacial fluctuations in Langtang Himal, central Nepal Himalaya. *Mitteilung der VAW-ETH Zurich*, 158: 207-216.

Weidinger, J. T., 1998: Progressive development and risk analysis of rock avalanches: Case study in the High Himalayan Crystalline of the Langtang National Park, central Nepal. *Journal of Nepal Geological Society*, 18: 319-328.

Weidinger, J. T., 2001: Torrent and avalanche control by sacred Buddhistic buildings in the Langtang Himalaya, Nepal. *Journal of Nepal Geological Society*, 24: 49.

Weidinger, J. T., 2002: Sacred Buddhistic monuments in the Himalaya: Indicators and protectors from mountain hazards. *Journal of Nepal Geological Society*, 26: 91-98.

Winchester, V. and Chaujar, R. K., 2002: Lichenometric dating of slope movements, Nant Ffrancon, North Wales. *Geomorphology*, 47: 61-74.

Yamada, T., 2000: Glacial lake outburst floods in Nepal. *Seppyo (Journal of the Japanese Society of Snow and Ice)*, 62: 137-147.

Yang, B., Bräuning, A., Dong, Z., Zhang, Z., and Keqing, J., 2008: Late Holocene monsoonal temperate glacier fluctuations on the Tibetan plateau. *Global and Planetary Change*, 60: 126-140.