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ORIGINAL PAPER

Dendrochronological reconstruction of snow avalanche activity in the Lahul Himalaya, Northern India

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Abstract Mass wasting and avalanche events substantially impact the landscape morphology and consequently human habitation throughout the Himalaya. There is, however, a paucity of snow avalanche documentation for the region. The application of dendrochronologic research methods introduces a sensitive approach to document the recurrence of snow avalanche events in a region where historical records are either non-existent or difficult to access. An exploratory dendrochronologic study was undertaken in the Lahul Himalaya of Northern India during the summer of 2006. Included within the fieldwork was an assessment of avalanche track morphology to enable identification of the slope characteristics that might be associated with an increase in avalanche activity. Thirty-six trees growing on the Ratoli avalanche track were sampled. The oldest tree was a *Cedrus deodara* with a pith date of 1950. A tree-ring-derived avalanche response curve highlights four avalanche events that occurred from 1972 to 2006. The successful scientific results based on the application of the method used provide the basis for local planners to quantify slope failure hazards in forested areas throughout the western Himalaya.

Keywords Dendrochronology · Snow avalanche · Lahul · Himalaya · India

1 Introduction

Snow avalanches represent a significant natural hazard to infrastructure and residents in high mountain regions of the world (Brundl et al. 2004). In many mountain landscapes, however, limited resources severely restrict the ability of local planners to assess the risk of

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snow avalanche activity in their regions. For instance, in the western Indian Himalaya, despite an average of 30–40 snow avalanche-related deaths per year, only a few researchers have attempted to develop a record of frequency and magnitude needed to properly mitigate the impact of snow avalanche activity (DeScally and Gardner 1994; Ganju and Dimri 2004; Gardner and Saczuk 2004; Sharma et al. 2004). The Indian Snow and Avalanche Study Establishment (SASE), based in Manali, is operated by a branch of the Indian army and has conducted extensive avalanche research throughout the region. However, the results and data from their investigations are difficult to access or not made available for public use.

In this article, the feasibility of reconstructing a history of snow avalanche occurrences in the western Indian Himalaya was examined by employing standardized dendrochronologic research techniques (Burrows and Burrows 1976; Shroder 1980; Wiles et al. 1996). Dendrochronology has been used to document snow avalanche behavior in forested high relief areas of North America, Japan, the Andes, and the European Alps (i.e., Casteller et al. 2007; Kajimoto et al. 2004; Rayback 1998; Shroder 1978; Shroder and Bishop 1995; Smith et al. 1994). However, this technique has only rarely been employed in the western Indian Himalaya (Bell et al. 1990).

It is anticipated that this exploratory use of dendrochronologic techniques to quantify snow avalanche frequency for this region will result in the creation of a model that can be used by local planners. This example has the potential to provide a simple way to assess and mitigate the future risk associated with snow avalanches and other mass wasting events in forested regions in the Himalaya.

1.1 Study site

The Lahul region of the western Indian Himalaya has a population density of approximately two people per square kilometer (Vijayanunni 1999). The majority of the population is concentrated along river corridors where the lower slopes have been terraced to provide suitable sites for agriculture (Owen et al. 1995). Much of the surrounding forested area on the upper slopes has been harvested and partially replanted allowing for regulated tree harvesting (Ministry of Forests and Environment, Government of India 2003).

The site chosen for this exploratory study was a well-demarcated avalanche track located west of the hamlet of Ratoli (3,016 m asl), ~3 km west of the village of Udaipur in the western region of Lahul, Indian Himalaya (32°43′ N Lat, 76°37′ E Long; Fig. 1). The climate of the area is related to its location in the transitional zone between the monsoonal climate south of the Pir Panjal range and the semi-arid Trans-Himalaya to the north. The mid-latitude westerlies and the southern Asian summer monsoon weather systems exert competing influences on the local climate (Benn and Owen 1998).

In the Lahul region, the permanent snowline is located above 4,260 m asl, while the lower limit of the snowline extends to 1,500 m asl (Owen et al. 1995). Mamgain (1975) suggests that the principal form of precipitation in Lahul is winter snow, as opposed to rain from the June–September monsoon. As indicated by distinct ecotone boundaries, precipitation in the area is strongly influenced by local terrain and elevation.

The geology of the Chandra/Chab River corridor in the Lahul region is dominated by a lithology comprised primarily of leucogranite and metasiltstone (Steck et al. 1993). Three major phases of Quaternary glaciation have been identified in the region, and subsequent fluvial erosion has resulted in the oversteepening of adjacent valley walls (Owen et al. 1995). The oversteepening of the valley walls makes them more prone to failure from mass wasting, as their competency is reduced from the retreat of the glacier which once supported them (Evans and Clague 1994).

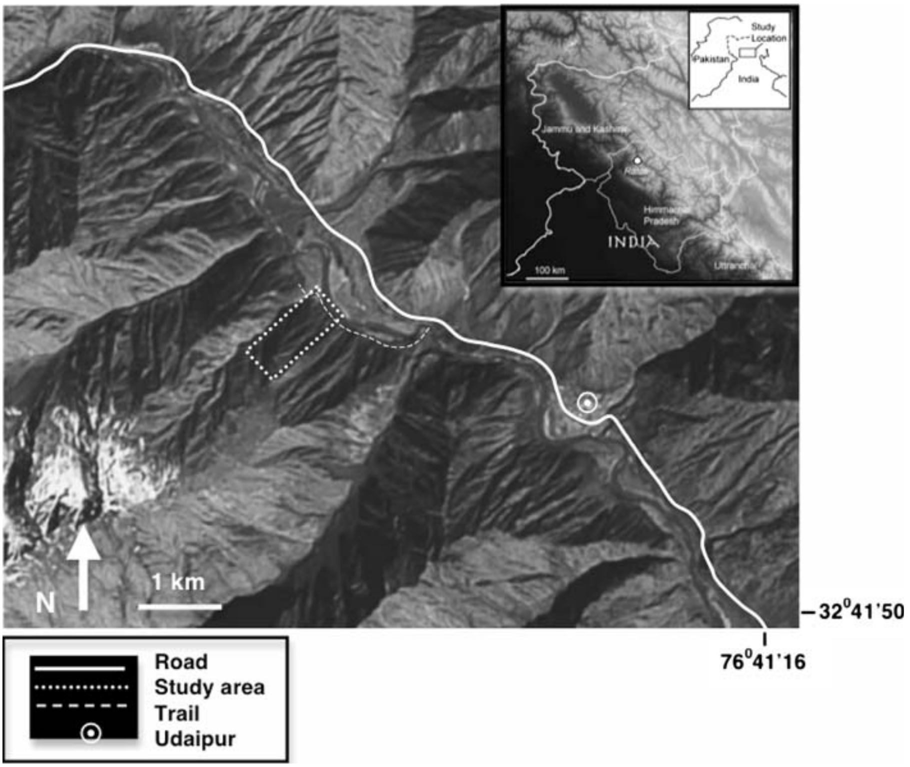


Fig. 1 Location of Ratoli avalanche track

1.2 Path description

The Ratoli avalanche path is situated on the southwest side of the Chenab River, ~5 km west of the village of Udaipur. The path is located on a steep (30–45°) easterly facing (70°) slope that extends over a length of ~199 m and averages 40 m in width (Fig. 2). The path terminates in the Chenab River; consequently, most of the woody debris and detrital material from previous avalanches have been swept away by the river. One narrow, infrequently used, footpath runs across the upper section of the track.

The dominant tree species found on this slope include Deodar cedar (*Cedrus deodara*), Himalayan pine (*Pinus wallichiana*), Himalayan fir (*Abies pindrow*), Himalayan birch (*Betula utilis*), and Himalayan spruce (*Picea smithiana*). Grasses and small herbaceous plants are the dominant groundcover. The upper tree line is located 300–400 m above the avalanche-track starting zone. All the evidence of selective tree harvesting is located at least 20 m from the avalanche track borders.

The sensitivity of the tree species growing on the avalanche track to non-biologic factors has been demonstrated by previous dendrochronologic studies in the Himalaya. Early identification of tree species in India that display climatic sensitivity was conducted by Pant (1979) where the ring structure of *Pinus* family displayed response to temperature and snowfall. The climatic response of *C. deodara* and its usefulness for climatic reconstruction in the Indian Himalaya has also been analyzed in depth (Pant et al. 2000; Yadav and Bhattacharyya 1992; Yadav and Park 2000; Yadav and Singh 2002; Yadav et al.

Fig. 2 Ratoli avalanche path

1999). Yadav et al. (1997) have also conducted dendroclimatic investigations using *Pinus wallichiana* and *Picea smithiana* in the western Himalaya, indicating that these species display the same sensitivity characteristics displayed by *C. deodara*.

The avalanche path appears to be only frequently used by people and animals. A few animal trails cross the path at various locations, and a narrow footpath crosses the uppermost section of the track. The paths and trails do not seem to have caused any slope instability or precipitated any slope failure. Although no evidence of grazing on the avalanche path was detected, it seems likely that domestic sheep and goats have nibbled tree seedlings, reducing the number of trees colonizing the track after an avalanche event.

Mature conifer trees found growing at various locations inside the avalanche path display morphology consistent with impact from snow avalanches and resulting snow press. The lower sections of most tree trunks have cambial scars and a lack of branches on their uphill-facing sides and many trees display a distinct J-growth morphology indicative of a post-avalanche growth response.

2 Research methods

In order to document the frequency and magnitude of snow avalanche activity at the study site, tree-ring samples were collected along five transects spaced 50 m apart along the long axis of the avalanche path in June 2006 (Fig. 3). A basic survey of the track topography was conducted using a tape measure and clinometer for the construction of a 3D slope

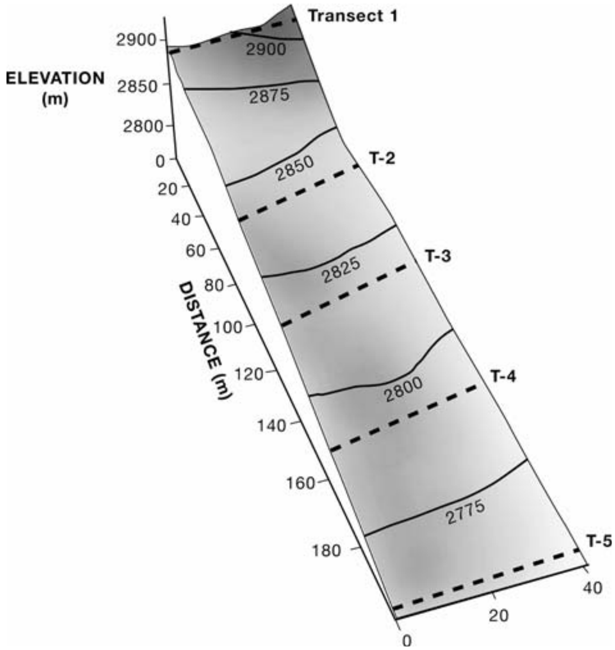


Fig. 3 Slope model of avalanche path, dashed black lines indicate transect locations

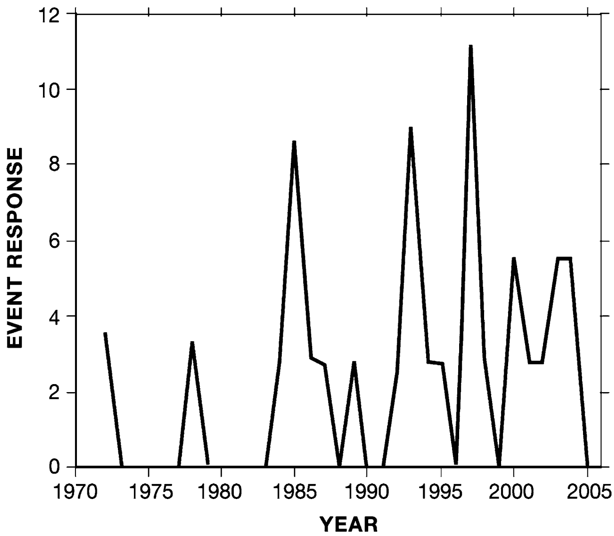
morphology diagram. Photographs were taken at the start of each transect with a view across the track toward the northwest side. The photographs recorded the tree morphology and changes in vegetation and slope properties along the length of the track. The survey data was plotted using Surfer (version 8) software to create a 3D slope model and used to identify whether the morphology of the track had any influence on the distribution of trees affected by avalanche events.

All tree seedlings and saplings found growing within a 2-m swath of each transect were cut down near their bases, and radial cross sections were taken. A handheld GPS was used to identify the location of the samples. Orientation of the cross section, species, and general morphology of the trees were also noted. Mature trees found growing adjacent to the track were sampled to estimate the minimum age of the most recent large magnitude snow avalanche event. Due to the large girth of these trees, two cores to pith were collected using an 18″ increment borer positioned 1.35 m above the ground surface.

The wood samples were returned to the University of Victoria Tree-Ring Laboratory and allowed to air-dry. The increment cores were dried and glued with water-soluble wood glue to slotted mounting boards. Once the radial cross sections and the increment cores were dry, they were sanded with progressively finer sandpaper to 600 grit, and the total ring widths measured using WinDENDRO™ (Version 6.1D, 1998) an image processing system (Guay et al. 1992). Tree-ring widths on the radial cross sections were measured along a minimum of three radial axes to the nearest 0.01 mm. Where the ring boundaries were difficult to identify, a 40× microscope and Velmex-type stage measurement system were used to verify the ring boundary positions.

Morphologic evidence of avalanche impact preserved in the anatomical structure of the samples was noted, and the year in which it occurred recorded to create an event chronology (Shroder 1978; Rayback 1998) (Fig. 4). Event years were only recognized if

Fig. 4 Avalanche event response curve for Ratoli avalanche path



anatomical features were apparent on all three of the sample radii analyzed. Following the methods presented by Shroder (1978), an event response curve for the avalanche path was created by calculating an index number for the years: 1972–2006. The index number, the sum of event responses expressed in the wood, is weighted according to the number of living trees growing in that year.

3 Research results

Thirty-six trees growing on the Ratoli avalanche track were sampled. The oldest tree was a *C. deodara* located on transect 3 with a pith date of 1950. As shown in Fig. 3, steeper areas on the track were less vegetated than the areas with smaller slope angles.

Four more extensive snow avalanche events that impacted trees on more than one transect in 1985, 1997, 2000, and 2004 were identified from the analysis of 36 samples collected from the avalanche track. Four trees had scars dating to snow avalanches in 1985 and 1997, five trees displaying evidence of a 2001 event, and three trees displayed evidence of an event in 2004 (Table 1; Fig. 5). As the Ratoli avalanche path run-out terminates above the near vertical bank of the Chenab River, woody debris from avalanches prior to 1985 has been washed away by the river. This made it impossible to date events older than 1985 due to a lack of woody debris on the slope.

3.1 Future implementation by local researchers

The successful implementation of dendrochronologic methods to identify the frequency/magnitude history of the Ratoli track demonstrates its usefulness as a technique for use by local environmental agencies. Compared with other methods for avalanche study, the cost of designing and implementing a dendrochronologic case study is relatively cheap. The equipment required is low tech and fairly easy to obtain. For example, the minimum amount of equipment required for reconstructions consists of sandpaper for preparing the surface for visual identification of event years, graphing paper to record the event years

Table 1 Dendrochronologic evidence of avalanche events

Event year	Transect	Evidence	Index number
1972	1	Resin ducts	3.57
1973–1977			0
1978	2	Resin ducts	3.33
1979–1983			0
1984	4	Scar	3.03
1985	3/3/3	Scar/scar/scar	8.57
1986	3	Scar	2.857
1987	3	Scar	2.77
1988			0
1989	1	Scar	2.77
1990–1991			0
1992	3	Scar	2.77
1993			0
1994	3	Scar	2.77
1995	2	Scar	2.77
1996			0
1997	3/4/3/5	Resin duct/scar/scar/scar	11.11
1998	3	Scar	2.77
1999			0
2000	5/3	Scar/scar	5.55
2001	2	Scar	2.77
2002	4	Resin duct	2.77
2003	4/5	Scar/scar	5.55
2004	3/3	Scar/scar	5.55
2005/2006			0

following the skeleton plot method described by Stokes and Smiley (1996), and a microscope or hand lens to observe damaged rings at the cellular level. While more sophisticated equipment was used in this study, the same results can be obtained by using the simpler equipment outlined above. This method is especially useful in regions where there is little in the way of scientific infrastructure or funding. For example, the cost of collecting and preparing the samples is low, and only basic training is required to count rings and identify anatomic anomalies in the wood indicative of avalanche events. Short courses covering the basic application of dendrochronologic techniques for avalanche reconstruction could be held for regional forestry and environmental hazard technicians. Once there is sufficient understanding of the method and its application, it can then be applied to numerous projects relating to hazard assessment and mitigation in forested regions of the Himalaya.

4 Summary and conclusions

Preliminary dendrochronologic investigations at a well-vegetated avalanche track near the village of Udaipur on the western boarder of Lahul provide a record of recent avalanche activity for the area. The coniferous tree species in the western Lahul region of the Indian

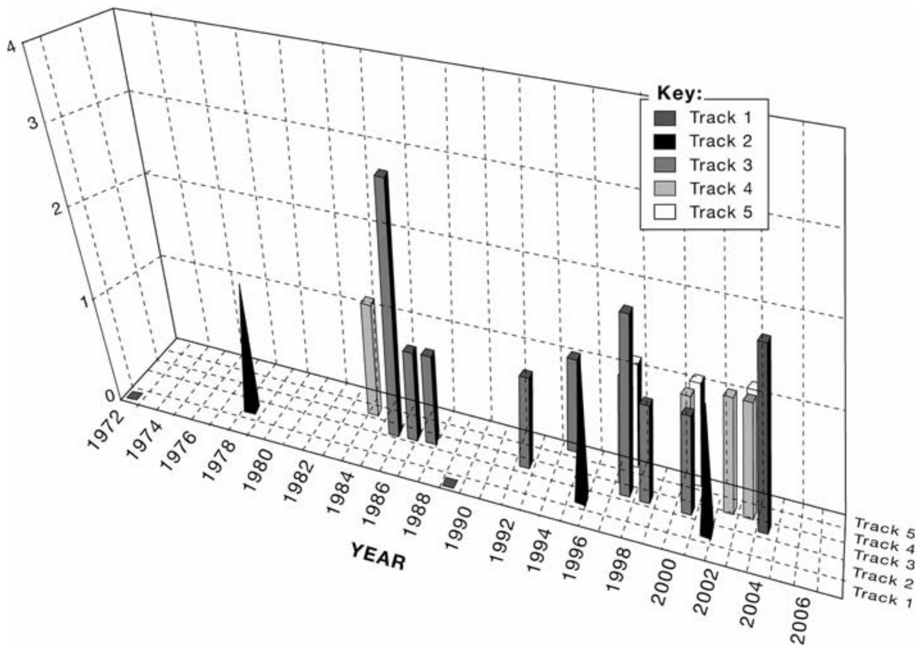


Fig. 5 Frequency of avalanche events on the Ratoli avalanche path

Himalaya display numerous anatomical indicators of historic snow avalanche activity including such features as reaction wood, cambial scars, and foliage destruction.

The creation of an avalanche-based chronology using these anatomical indicators demonstrates that the application of dendrochronologic methods clearly provides a cost-effective means for reconstructing local snow avalanche activity. Dendrochronologic methods provide a low cost option for local agencies, facilitating the employment of appropriate avalanche hazard mitigation measures specific to the region. Ultimately and wherever possible, the appropriate regional authorities ought to be able to monitor the antecedent conditions leading to these potentially catastrophic events.

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