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Snow avalanches in the Pyrenees: Dendrochronological dating, dendrogeomorphological mapping and detection of past snow-avalanche seasons at a regional scale

Allaus de neu al Pirineu : datació dendrocronològica, cartografia dendrogeomorfològica i detecció d'allaus del passat a escala regional

Elena Muntán Bordas

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DATACIÓ DENDROCRONOLÒGICA, CARTOGRAFIA DENDROGEOMORFOLÒGICA I DETECCIÓ D'ALLAUS DEL PASSAT A ESCALA REGIONAL

Memòria presentada per Elena Muntán Bordas per a optar al títol de Doctora per la Universitat de Barcelona

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A mi madre, de quien aprendí una parte de su ciencia y su paciencia.

Y a mi padre, que me ha transmitido la pasión y la necesidad de estar en contacto con la naturaleza.

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Els projectes ALUDEX - Caracterización de aludes catastróficos a través del estudio dendrocronológico y nivoclimático (REN2002-02768/RIES) i AVDENPYR - Reconstrucción de episodios de aludes de nieve a partir del análisis dendrocronológico en los Pirineos (CGL2007-62614/BTE) han finançat aquesta investigació.

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Ha estat un any sense estiu per a mi, però ha fet calor, no com l'estiu de fa 200 anys, segons expliquen els arbres...

Abstract

In recent decades, information about past snow avalanches in the Pyrenees is being acquired by searching in different sources. One of these sources are tree rings. In this Ph.D. thesis, dendrogeomorphological techniques are used to study the snow avalanche process in the Pyrenees.

The methodology to date snow avalanches using wood samples from trees of the genus *Pinus* L. is developed, and external signs of snow-avalanche effects and reactions on these trees are identified. Dendrogeomorphology is applied to date snow avalanche events, to reconstruct local event chronologies, and to map major avalanches. All these findings are subsequently used to estimate process frequency at specific avalanche paths. At a regional scale, by studying the snow avalanche events in several avalanche paths along the territory, dendrogeomorphology contributes to determine major avalanche winters.

Calibration and validation of the methodology was done in Roc Roig avalanche path (Núria, Catalonia). Evidence recorded in trees from the well-documented 1995-1996 avalanche season was used to establish fieldwork strategy and dendrochronological analyses to date past snow avalanches. Once the connection between external evidence and tree-ring reactions to the known avalanche events in 1995-1996 winters was understood, previous avalanche events were found out in the same avalanche path. In this site two extreme avalanches took place in 1996. *Pinus uncinata* trees disturbed during this avalanche season allowed to assess the associated tree-ring signals. Trees displayed a variety of responses to these events. The methodology was proved successful in detecting the 1996, 1986 and 1972 documented avalanche events, and provided evidence of undocumented past events such as the one in 1929-1930, which was a major avalanche as in 1996.

To obtain high-quality evidence it is necessary to correctly recognize external signs from snow avalanches on trees, to know the corresponding tree reactions and to distinguish associated tree-ring signals. The characterization of snow-avalanche effects and reactions in *Pinus uncinata* trees was carried out with a recent avalanche event in Barranco de las Fajas avalanche path (Sallent de Gállego, Aragon). Data was systematically gathered from all trees in selected transects across the avalanche path and tree structure was described. In the 2007-2008 avalanche clearing, shapes from trees affected by the event are compared to shapes from trees affected by earlier events. The distribution of tree morphologies along the path is discussed. Describing and quantifing disturbed tree morphologies should contribute to discriminate among different geomorphological hillslope processes.

By applying these findings to a set of six avalanche paths distributed throughout the territory, evidence for three regional-scale major avalanche years was identified in the SE Pyrenees from 1971 to 2004: 1971-72, 1995-96 and 2002-03. In the total count, dendrochronological analyses yielded the dates of nine winters when major avalanches occurred in the recent past in the six avalanche paths. Some of these avalanches were already known, but others had not been documented. Also in this chapter, an example on how dendrochronological evidence of a past major event on trees was used to map an extreme runout. This was done in an avalanche path descending from Pui de Linya (Espot, Catalonia). In this case a major avalanche occurred in 1971-1972 which had not been previously documented. Thus, the map done according to conventional techniques was improved by using dendrogeomorphological evidence.

The combination of information yielded by dendrogeomorphology together with data from the other sources is the best way to improve our knowledge on the snow avalanche process. In the Pyrenees, though still very scarcely applied, dendrogeomorphological analyses play an important part in the zonification of selected snow avalanche paths to prevent avalanche hazard where forest or trees are present.

Resumen

En las últimas décadas, se está recopilando información sobre aludes de nieve del pasado en los Pirineos a través de la investigación en diferentes fuentes. Una de estas fuentes son los anillos de crecimiento de los árboles. En esta tesis doctoral, se utilizan técnicas dendrogeomorfológicas para estudiar el proceso de los aludes de nieve en los Pirineos.

Se desarrolla la metodología para la datación de aludes de nieve utilizando muestras de madera de árboles del género *Pinus* L. y se identifican los signos externos de los efectos y las reacciones a los aludes de nieve en estos árboles. Se aplica la dendrogeomorfología para datar acontecimientos de aludes de nieve, para reconstruir cronologías de eventos locales y para cartografiar aludes mayores. Todos estos hallazgos se utilizan a continuación para estimar frecuencias del proceso en zonas concretas de avalanchas. A escala regional, estudiando los acontecimientos de aludes en varias zonas repartidas por el territorio, la dendrogeomorfología contribuye a determinar los inviernos de aludes mayores.

El calibrado y la validación de la metodología se llevó a cabo en el Canal del Roc Roig (Núria, Cataluña). Los indicios registrados en los árboles de la temporada de aludes documentada de 1995-1996 se utilizaron para establecer la estrategia de trabajo de campo y los análisis dendrocronológicos para datar aludes de nieve del pasado. Una vez comprendida la conexión entre las evidencias externas y las reacciones en los anillos de crecimiento a las avalanchas del invierno de 1995-1996, se dataron aludes de nieve anteriores en la misma zona. Los árboles *Pinus uncinata* afectados durante esta temporada de avalanchas permitieron verificar las señales asociadas en los anillos de crecimiento. Los árboles mostraron una variedad de respuestas a estos acontecimientos. La metodología fue efectiva en la detección de los aludes documentados en 1996, 1986 y 1972, y aportó evidencias de un acontecimiento no

documentado anteriormente en 1929-1930, que resultó haber sido un alud mayor como en 1996.

Para obtener muestras de calidad es necesario reconocer correctamente los signos externos de los aludes en los árboles, conocer las correspondientes reacciones de los árboles y saber distinguir las señales asociadas en los anillos de crecimiento. La caracterización de los efectos y las reacciones de los aludes de nieve en árboles Pinus *uncinata* se realizó con un alud reciente en la zona de aludes del Barranco de las Fajas (Sallent de Gállego, Aragón). Se recogieron sistemáticamente los datos de todos los árboles en transectos seleccionados y se describió su estructura. En el claro del alud de 2007-2008, se compararon las formas de los árboles afectados por el alud y con las formas de los árboles afectados por aludes anteriores. La descripción y cuantificación de las morfologías de los árboles debería de servir para discriminar entre los diferentes procesos geomorfológicos de ladera.

Al aplicar los resultados de esta investigación a un conjunto de seis zonas de aludes distribuídas a lo largo del territorio, se identificaron tres temporadas de aludes a escala regional en el SE de los Pirineos entre 1971 y 2004: 1971-1972, 1995-1996 y 2002-2003. En total, los análisis dendrocronológicos proporcionaron la datación de nueve inviernos en los que tuvieron lugar aludes mayores en el pasado reciente en las seis zonas de aludes. Algunos de estos aludes ya se conocían, pero otros no habían estado documentados anteriormente. También se muestra un ejemplo de cómo las señales dendrocronológicas de un alud mayor en los árboles se utilizaron para cartografiar la zona de llegada extrema en una zona de aludes que desciende del Pui de Linya (Espot, Cataluña). En este caso un alud mayor que no había sido documentado anteriormente tuvo lugar en 1971-1972. De esta manera, el mapa hecho con técnicas convencionales se pudo mejorar utilizando las señales dendrogeomorfológicas.

La combinación de información obtenida por medio de dendrogeomorfología con datos procedentes de otras fuentes es la mejor forma de completar nuestros conocimientos sobre el proceso de los aludes de nieve. En los Pirineos, a pesar de que se aplican de forma esporádica, los análisis dendrogeomorfológicos tienen un papel importante en la zonificación de zonas de aludes seleccionadas para prevenir el riesgo de aludes donde existe bosque o árboles.

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1 GENERAL INTRODUCTION

1.1 GENERAL CONSIDERATIONS

Dendrochronology is a useful tool to provide data related to snow avalanche dynamics (Potter, 1969; Carrara, 1979; Butler, 1979; Stoffel & Bollschweiler, 2008). In the Pyrenees, the use of dendrogeomorphological techniques to estimate snow avalanche process frequency and dimensions of extraordinary events was first put into practice by Muntan et al., (2004).

The use of dendrochronology applied to the study of snow avalanche dynamics in Catalonia stems from the avalanche crisis of winter season 1995-1996. This season an extraordinary number of avalanche events took place all over the Pyrenean range, and this triggered the necessity to study avalanche dynamics in the Pyrenees.

Snow avalanches are natural processes which have only been studied in the Pyrenees starting some twenty five years ago (Muñoz, 1988; Furdada, 1996), in contrast to other countries. As natural hazards it is important to know their frequency-magnitude as they interfere with people and goods. As natural disturbances it is interesting to know how they affect tree growth and the ecosystem (Butler, 2001).

Information on past snow avalanche events is usually obtained from different sources, i.e. historical documents, interviews to people, winter surveys, nivometeorology, aerial photographs and dendrochronology. Among them, dendrochronology has the advantage to provide quite complete event chronologies, although the length of the record is limited by the age of the trees (Reardon et al., 2008).

The geographical scope of this research along the Pyrenees unearthed the occurrence of regional-scale episodes by dating past events in different avalanche paths (Birkeland & Mock, 2001; Hebertson & Jenkins, 2003).

Hazard maps, in which dendrochronology can have a key role in forested avalanche paths, as it is demonstrated in this thesis, are necessary documents for land use planning in mountain terrain. Consequently this research is of use to snow avalanche risk zoning in the Pyrenees.

1.2 DENDROCHRONOLOGY AND WOODY SPECIES

Dendrochronology is the study of tree rings and can be applied to all kind of woody species as long as they can be dated. In mountain regions of temperate climate, trees ordinarily produce a ring per year. Classical dendrochronological techniques are used to date tree samples (Stokes and Smiley, 1968).

All tree species growing in the subalpine forest of the Pyrenean range are susceptible to be used to date avalanche events. In this thesis most of the work has been carried out on *Pinus uncinata* Ramond ex DC in Lam et DC. (*Pinus mugo* Turra subsp. *uncinata*) which is the highest reaching tree species in the Pyrenees. Pine trees are conifers, and the species of this division offer particular advantages to dendrochronological dating of growth disturbances. Conifer tree-ring reactions to disturbance can be abrupt growth changes, compression wood, growth cessation, and callous tissue. The production of compression wood to regain the vertical position when the tree is tilted is one of the most interesting dendrochronological evidence of growth disturbance in *Pinus*, because it is easy to detect. Conversely, *Pinus uncinata* has abundant resin ducts, and displays traumatic resin ducts very seldom. Therefore this feature is not very useful in this case. Tree-ring signals in *Pinus uncinata* are explained in detail in Chapter 1.

1.3 SNOW AVALANCHES

Snow avalanches occur in alpine and subalpine mountain domains in temperate- and cold-climate regions. In countries such as Switzerland, Canada, U.S.A, New Zealand, Russia, where a significant proportion of the territory is encumbered by this natural hazard, management of snow avalanches has been going on for a long time. In the Iberian Peninsula snow avalanches take place in several mountain ranges regularly (Pyrenees, Sierra Nevada, Sistema Central and Picos de Europa), but active management has only been applied in the past in very specific sites.

In the last decades, due to the increase of winter recreational activities and to the drift of mountain rural areas to the tourist trade, exposition of goods and people to this hazard is increasing. As a consequence, the different administrations are progressively more aware and local and more general plans are being implemented.

A snow avalanche is a rapid downslope movement of a mass of snow, and it is started when the forces that unite the snow layers due to meteorological cause or other reasons fail. In avalanche prone areas, snow avalanches flow along preferential zones, or avalanche paths. In the same avalanche path, avalanches of different size can flow. Avalanches that happen every 5 to 20 years, which exceed the ordinary dimensions, and can cause damage to forest and infrastructures are called major avalanches (McClung & Schaerer, 2006).

Most first works on dendrogeomorphology dealt with snow avalanches in the United States (Potter, 1969; Burrows & Burrows, 1976; Carrara, 1979; Butler, 1979). These were motivated by the need to manage hazard, because the people were emigrating to mountain areas in the West.

As in other geomorphic processes, from snow avalanches, knowledge is needed about extreme dimensions, frequency of events, and triggering conditions.

From a landscape-ecology point of view snow avalanches act as geomorphic process corridors (disturbance corridors) (Butler, 2001). Together with other mass movements such as debris flows, snow avalanches break the subalpine treeline and act as biological corridors between alpine and subalpine environments which host diverse communities, favor the exchange of flora and fauna elements from different altitudes and extend the boundary between forest and alpine meadows.

2 OBJECTIVES

2.1 GENERAL OBJECTIVE

The main objective of this Ph.D. thesis is to illustrate how dendrochronology contributes to the reconstruction of the snow avalanche process in the Pyrenees using specific dendrogeomorphological techniques.

2.2 PARTIAL TARGETS

- **Development of the methodology to date snow avalanches using wood samples from the genus *Pinus L.*** These are the most extended conifer trees in the subalpine forest in the Pyrenees. Obtaining quality samples and learning how to identify disturbance signals on tree rings is the first step to achieve good results.

- **Identification of external signs of snow-avalanche effects and reactions on *Pinus* L. trees.** Recent avalanche events are easily recognizable on affected trees. Traces from older events are not so straightforwardly perceivable.

- **Use of dendrogeomorphology to map snow avalanches.** Snow-avalanche events can be mapped using dendrochronological evidence if trees have recorded the process. Thus, the map done according to conventional techniques can be improved.

- **Reconstruction of local-event chronologies for specific avalanche paths.** By applying the dendrogeomorphological method to single avalanche paths the events that have occurred can be dated and a chronology of the process can be elaborated for this particular site.

- **Estimate avalanche process frequency for specific avalanche paths.** After building the event chronolgy for a particular site the minimum frequency of occurrences is approximated. Very often, the frequency of events differing in size can also be roughly calculated if several iterations have taken place.

- **Determination of avalanche seasons at regional scale.** By applying these findings to a set of avalanche paths distributed along the territory, the avalanche seasons which affected a great part of a region can be detected. This will be done for the Pyrenees of Catalonia by studying six avalanche paths located in different sectors.

- **Guidelines to use dendrochronology with the aim of avalanche hazard zoning.** The different researchers have used a variety of experimental designs to apply dendrochronological techniques in geomorphological processes. In the final part of this thesis, their recommendations will be discussed.

Currently, these findings are applied to the reconstruction of snow avalanche events in the alpine mountain ranges throughout the world. The combination of information yielded by dendrogeomorphological techniques together with the data from the other sources is the best way to improve our knowledge on the snow avalanche process. In the Pyrenees, though still very scarcely applied, dendrogeomorphological analyses play an important part in the zonification of selected snow avalanche paths to prevent avalanche hazard.

2.3 OUTLINE

The main body of this Ph.D. thesis is organised in three chapters as follows:

- **Chapter 1 Dating of snow avalanche events using dendrochronology.**

  Calibration and validation of the methodology was done in Roc Roig avalanche path (Núria, Catalonia). Evidence recorded in trees from the well-documented 1995-1996 avalanche season was used to establish fieldwork strategy and dendro-chronological analyses to date past snow avalanches. Once the connection between external evidence and tree-ring reactions to the known avalanche events in 1995-1996 winters was understood, previous avalanche events were found out in the same avalanche path.

- **Chapter 2 Characterization of snow-avalanche effects and reactions in Pinus uncinata trees.**

To obtain high-quality evidence it is necessary to correctly recognize external signs from snow avalanches on trees, to know the corresponding tree reactions and to distinguish associated tree-ring signals. This objective was carried out with an avalanche event of late in Barranco de las Fajas avalanche path (Sallent de Gállego, Aragon). Data was systematically gathered from all trees in selected transects across the avalanche path and tree structure was described. In the 2007-2008 avalanche clearing, shapes from trees affected by the event are compared to shapes from trees affected by earlier events. The distribution of tree morpholgies along the path is discussed.

- **Chapter 3 Determination of avalanche seasons at regional scale.** [1]

By applying these findings to a set of avalanche paths distributed throughout the territory the avalanche seasons which affected a great part of a region were detected. This was done for the Pyrenees of Catalonia by studying six avalanche paths located in different sectors. Also in this chapter, an example on how dendrochronological evidence of a past major event on trees was used to map an extreme runout. This was done for an event in an avalanche path descending from Pui de Linya (Vall d'Espot, Catalonia). In this case a major avalanche event occurred in 1971-

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[1] Published at the peer-reviewed journal *Natural Hazards and Earth System Science*. Impact factor:1,357 (Muntan et al., 2009) (see Appendix at the end of the document).

1972 which had not been previously documented. Thus, the map done according to conventional techniques was improved.

3 CHAPTERS

3.1 CHAPTER 1: DATING OF SNOW AVALANCHE EVENTS USING DENDROCHRONOLOGY

3.1.1 ABSTRACT

Information about past snow avalanches is scarce in the Pyrenees. By dendrochronological techniques data from past avalanches can be obtained. In this chapter, the methodology is put into practice in Canal del Roc Roig avalanche path. In this site two extreme avalanches took place in 1996. *Pinus uncinata* trees disturbed during this avalanche season allowed to assess the associated tree-ring signals. Trees presented a variety of responses to the 1996 avalanche events. The methodology was proved successful in detecting the 1996, 1986 and 1972 documented avalanche events, and provided evidence of undocumented past events such as the one in 1930, which was a major avalanche as in 1996.

3.1.2 INTRODUCTION

Twenty years ago, winter 1995-1996 was an unprecedented avalanche season in the Pyrenees (García et al., 2000). In particular, February 1996 registered intense avalanche activity on the south face of this mountain range. Extreme avalanches reached and destroyed wide stretches of subalpine forest. Several buildings and transportation routes were affected, as well.

Snow avalanche data recording in the Catalan Pyrenees began in the 1980s, and information before this date is scarce and inaccurate. At present, several approaches are regularly used to collect information from past avalanche events, i.e. historical documents, enquiries to locals, winter surveillance, nivometeorological records and dendrochronology. The combination of these allows reconstruction of past avalanche events and, bit by bit, avalanche dynamics in the Pyrenees is understood.

In 2001 dendrochronology was applied on in Roc Roig avalanche path where two avalanche events were registered during the same winter 1995-1996 in Vall de Núria. No previous experience had been carried out in this field in Europe. The aim was to identify tree-ring reactions from trees disturbed by 1996 snow avalanches in order to validate a method which would enable us to detect previous avalanche events using dendrochronology.

3.1.2.1 Study site

Vall de Núria is an historic tourist location with a small ski resort located at 1970 ma.s.l., in the south-eastern Pyrenees. Access is by means of a rack railway, which climbs 1000 m over 12.5 km through a narrow valley (Figure 1). Twenty-six spots along the railway line can be reached by avalanches (ICC, 2000). Between 6 and 9 February 1996, two great mixed (powder and dense-flow) avalanches and other smaller ones reached the railway. One of these occurred at Canal del Roc Roig.

Canal del Roc Roig avalanche-path starting zone is located at 2300 m a.s.l. on an open east-facing slope; the track zone is channelled from 2150 to 1850 m a.s.l.; at the run-out zone it becomes a dejection cone, and reaches Núria river at 1770 m a.s.l., climbing to the opposite slope.

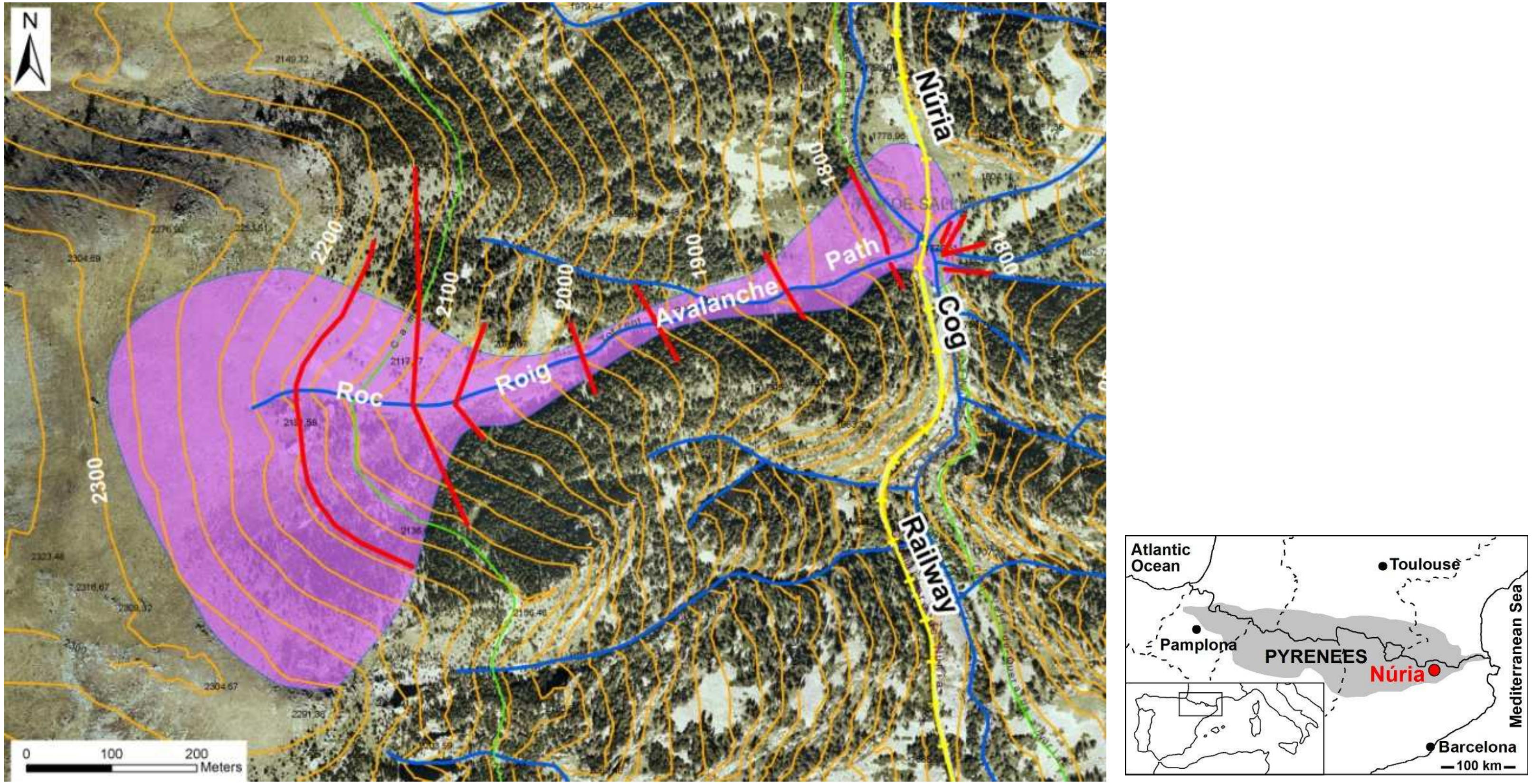


Figure 1: Roc Roig avalanche path in Núria. Red lines indicate the sectors where six transversal transects were placed along the avalanche track and close to the starting zone, and four parallel transects to the avalanche trajectory at the runout.(Avalanche path map in pink colour) (Orthophoto 2000, ICC).

Four avalanches reaching the railway line have been recorded on the Canal del Roc Roig avalanche path since the line was inaugurated in 1931 (ICC, 2002). The first was in January 1972, the other in 1986, and the other two were observed in February and March 1996. We know that the 1972 avalanche reached the railway and caused some damage, but the size and type of avalanche are unknown. The 1996 events are well documented and mapped. The first, a mixed avalanche on 7 February, reached the rack railway and Núria river and ran up the opposite slope to 1790 m a.s.l. The second, a wet-slab avalanche on 22 March, ran up the opposite slope to 1780 m a.s.l.

3.1.3 MATERIALS AND METHODS

3.1.3.1 Field procedures

A total of 265 mountain pines (*Pinus uncinata* Ramond ex DC. in Lam et DC) were sampled at selected locations at Canal del Roc Roig. Fieldwork was carried out between 2002 and 2004. Detailed scale orthophoto maps (Institut Cartogràfic de Catalunya, 1:5000) to locate sampled sites and trees were used. These maps allowed good visualization of the zones and a better understanding of the processes by an exact localization of individuals in the area.

A three-step sampling strategy was put into practice as follows:

1) Trees were sampled along transects crossing the avalanche path at different altitudinal heights. Transects were placed covering most of the avalanche path from the extreme runout zone up to the treeline. Each transect was 2 m wide. Length of transects varied depending

on local width of the avalanche path. Transects penetrated some meters into the surrounding forest. Inside the transect area, data from all trees was systematically gathered.

2) Selected old pines growing inside the surrounding forest were sampled to document the occurrence of ancient avalanches (Pelfini et al., 2001).

3) After inspecting the area, several zones where trees were more exposed to avalanche effects were sampled: at the runout zone, at the end of the track where most trees were dead (some of them, transported), and in the centre of the gully path, above and below the upper transect where density of trees was low.

In total, six transversal transects from the runout zone at 1785 m a.s.l. to the upper part of the track at 2075 m a.s.l., and four longitudinal transects, parallel to avalanche trajectory, at the extreme runout were sampled (Figure 1).

Wood samples were obtained from 265 mountain pines. From trees that were dead or wounded, trunk cross-sections or wedges, respectively, were sampled. From living trees cores were preferred to cross-sections. Cores were sampled at various heights on the tree trunk. Wedges taken from scarred trees proved to be dangerous for tree survival (trees were found broken during the field campaign of the following year), so to reduce tree damage, an attempt was made to sample scars with increment borers (two to three cores per scarred tree) and this proved useful. From each tree the following data were recorded: diameter at breast height (dbh), height, tree morphology.

To use as a reference chronology to date the avalanche samples, a selection of old trees out of the avalanche zone that were apparently not affected by avalanches were sampled.

3.1.3.2 Laboratory procedures

Cores, wedges and cross-sections from the sampled trees were prepared (mounted and sanded), visually dated, and cross-dated according to standard dendrochronological methods (Stokes & Smiley, 1968).

Tree-rings were measured and the cross-dating was verified using the computer program COFECHA (Holmes, 1983). Most trees from the reference chronology were less than 200 years old. The reliable period was 125 years according to an expressed population signal (EPS) value of 0.85 (Wigley et al., 1984) (Cook & Kairiukstis, 1990). This chronology was used to compare with the series from trees that had been damaged by snow avalanches, to date the year of death of dead trees, and to verify the dates of tree-ring signals.

Of the samples from trees affected by avalanches, some could only be dated visually due to the anomalous tree-ring growth of disturbed trees. All samples were carefully checked under a microscope, and details of single tree-ring characteristics were recorded to build the time-frequency distribution of tree-ring signals related to avalanches (modified skeleton plot by Shroder, 1978).

From the avalanche samples, tree-ring growth signals revealed a variety of responses to disturbances (Figure 2), which could be due to avalanche events:

- Eccentricity
- Compression wood
- Abrupt growth changes (release and suppression)

- Scars
- Tree death

Eccentricity is a response to trunk tilting, although trees can also show eccentric tree-rings for other reasons. When conifers are forced to incline or bend, rings develop special characteristics: in the upper side of the trunk, rings become narrower, and in the downslope side rings grow wider. The latter can also form compression wood, which is darker than in normal rings (Timell, 1986).

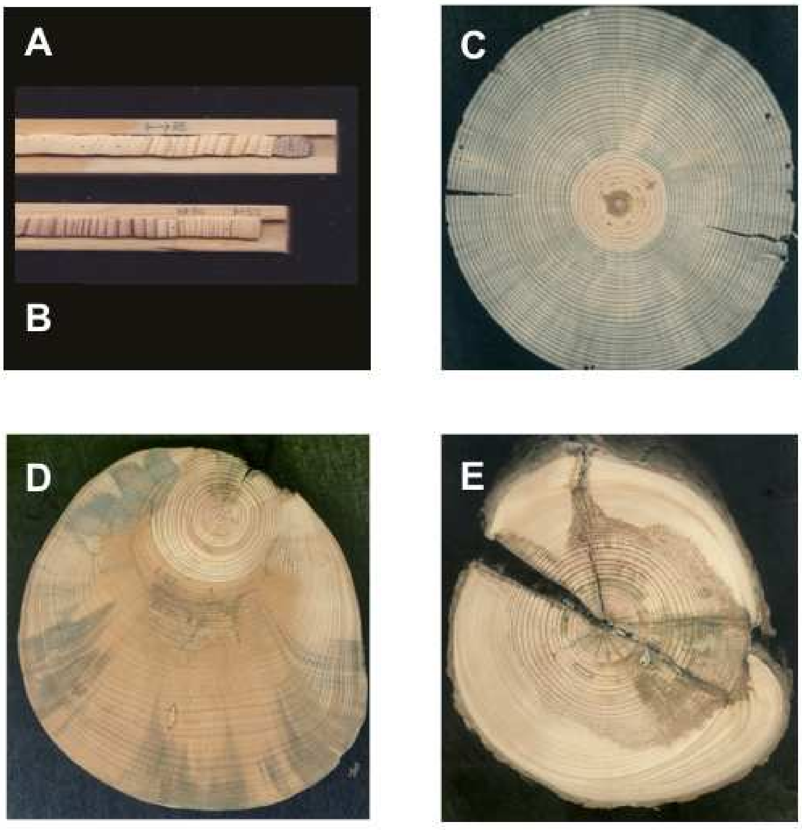


Figure 2: Samples showing different growth disturbances: A growth suppression, B growth release, C sudden tree death, D eccentricity and compression wood, and E scar.

Eccentricity may be detected by statistical analysis of the variation in ring width (Braam et al., 1987), but the simultaneous observation of narrow and wide rings, together with compression wood, is a better technique for obtaining exact dates of avalanches. However, when working with cores it is difficult to assess eccentricity. For this reason, in this study we consider suppression in the upslope samples, release in the downslope ones, and compression wood separately.

Abrupt growth changes, release and suppression periods, are sequences of wider and narrower rings, respectively, than the previous ones. A release is usually caused by elimination of competition, while suppression can be due to (i) partial loss of tree crown (breakage of branches or tree trunk), and/or (ii) partial uprooting.

Scars are produced by trees as a reaction to wounds from the impact of stones, flowing snow, and branches and trunks of dragged trees carried by the avalanche. Scars were only sampled in young trees.

Tree death was dated by crossdating of tree-ring series of dead trees with the reference chronology. We have considered sudden tree death when the last rings did not present a reduction in growth rate.

As resin ducts are ordinarily abundant in this species, only very few unmistakable tangential rows of traumatic resin ducts were quantified.

For the total count, the different tree-ring responses had identical weight, and disturbed trees were considered equal regardless of the number of responses per tree.

To sum up, dating of past snow avalanches was done in accordance with the following criteria:

- High proportion of trees showing synchronic growth disturbances.
- No similar growth disturbances in the reference chronology.

- Coexistence of a variety of tree-ring responses.
- Spatial concordance between in situ affected trees and avalanche trajectory.
- Growth disturbances starting in the early earlywood.

3.1.4 RESULTS

3.1.4.1 Validation of tree-ring signals from 1996 known avalanche season

A total count of 87 trees showed growth disturbances in the 1996 tree ring corresponding most likely to the avalanche events in winter 1995-1996. This means a 36% of the total number of analysed trees for year 1996. The encountered tree-ring signals in *Pinus uncinata* trees to date snow avalanche events are discussed below (Figure 3).

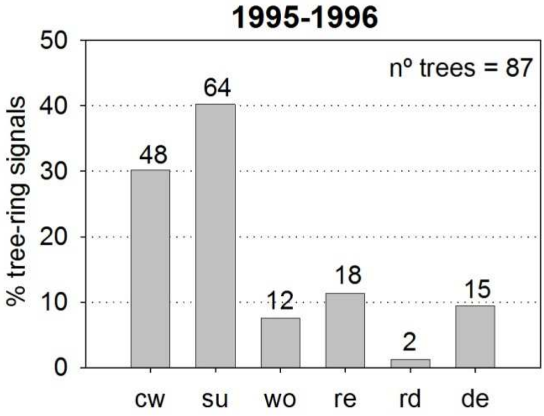


Figure 3: Percentage of disturbance tree-ring signals in year 1996. Numbers on top of bars indicate the absolute number of signals. (cw-compression wood; su-growth supression; wo-wounds; re-release; rd-traumatic resin ducts; de-death)

Growth suppression was the most frequent signal in 1996. In some samples, the narrowest ring was found to be not in 1996, the immediate growing season after the events, but in 1997. Some of the trees still presented a suppressed growth rate in 2002. However, loss of branches by snow accumulation on the tree crown (Schweingruber, 1996) and other disturbances can also cause suppression. This can magnify the amount of signals during avalanche seasons.

Compression wood was also very frequent in tree rings after 1995 and lasted from 1 to several years. This reaction wood is visually easy to identify in conifers for its darker colour.

Scars appeared mainly on the upper side of the trunk, but we only sampled a few scarred trees.

Near the run-out zone, the series of trunk cross-sections from dead trees showed a sudden tree death after the growing period of 1995. In the upper part of the track, however, the final year of growth (1996) of two dead trees was very narrow. In the case of one tree in the central part of the track, this growth behaviour was due to incomplete uprooting, and the tree survived another year. Even though data are scarce, it can be deduced that the impact of the snow was less severe in the upper part of the track, near the starting zone, than at the end of the track where most of the trees were completely uprooted or broken and sometimes transported.

Tree-age distribution differences exist between trees with and without 1996 signals. The proportion of trees older than 100 years that do not have signals is higher than those with signals. The fact that the avalanche did not affect old trees can be explained by (i) their larger dimensions, and (ii) the fact that they do not grow near the path, where snow-avalanche effects are more severe. Only 3 out of 22 trees older than 100 years recorded a response in the 1996 ring and it was suppression.

Suppression was present in all age classes. Compression wood was more abundant in young individuals (age below 50 years), but was also present in a few trees 50-100 years old, though not in trees older than 100 years.

The age of dead trees ranged from 50 to 100 years, but this could be due to biased sampling; we specifically sampled dead trees near the end of the track, near the run-out zone.

3.1.4.2 Past avalanche events at Canal del Roc Roig

At present, when snow avalanches reach the railway of Núria tourist resort and damage the line, the train crew report the avalanche events. On account of the damage to the railway, three snow avalanche seasons were reported (1971–1972, 1985–1986, and 1995–1996) which showed respectively 26.3%, 16.9%, and 35.7% of trees with dendrochronological evidence (Figure 4).

In line with Butler & Sawyer (2008), who recommend tempering an index value with historical records for specific sites, after the documented 1985–1986 snow avalanche, 16% was used as the threshold to consider the occurrence of events. As a result, other most likely avalanche seasons were identified: 1915–1916, 1929–1930, 1973–1974, 1981–1982, and 1990–1991. However, trees are scarce and younger than 75 years at the runout, and this hampered the interpretation of extent for events prior to 1925.

Winters 1995–1996 and 1929–1930 held the highest proportion of growth disturbed trees (35.7% and 42.6% respectively) corresponding to high-magnitude snow avalanches, and coming close to 40%, which was the index value first used by Butler & Malanson (1985).

Based on the spatial distribution of trees, the extent of these major avalanches showed that the starting zone was broader than the ones mapped shortly after the avalanches released (Figure 5). Tree-ring data determined that the 1929–1930 event was a first magnitude snow avalanche, even wider than 1995–1996. In situ affected trees at the starting zone comprised the whole catchment (Muntan et al., 2010).

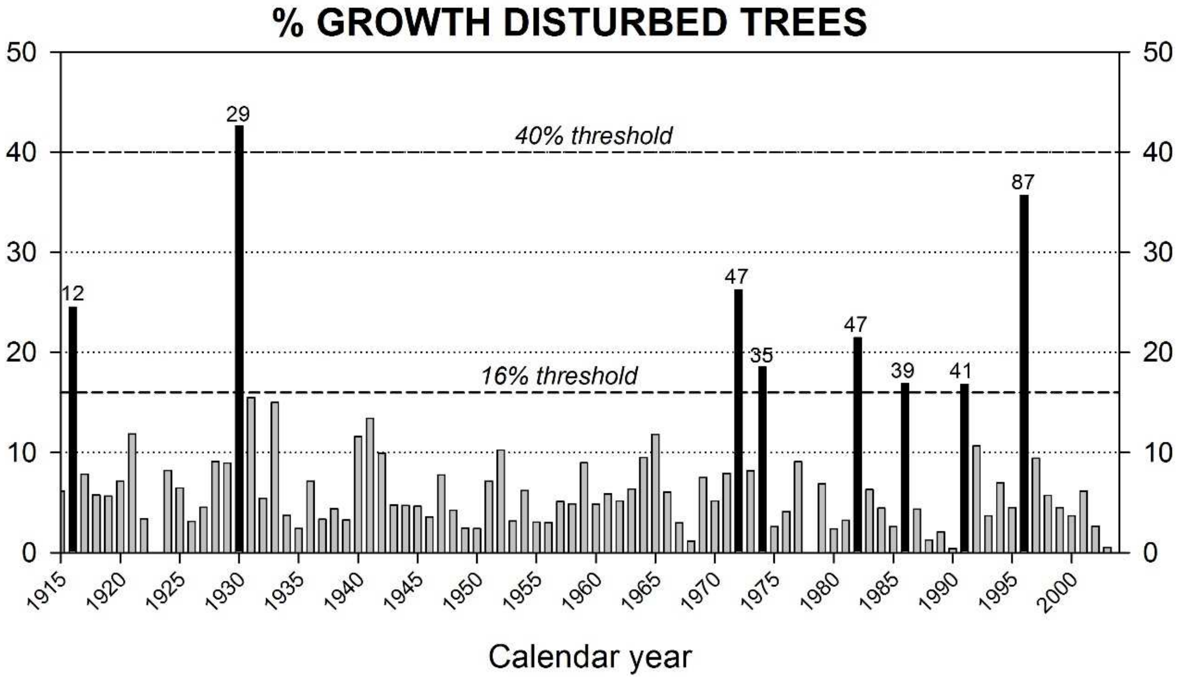


Figure 4: Histogram showing percentage of growth disturbed trees in Roc Roig avalanche path. Eight event-years were dendrochronologically dated for the period 1915-2004.

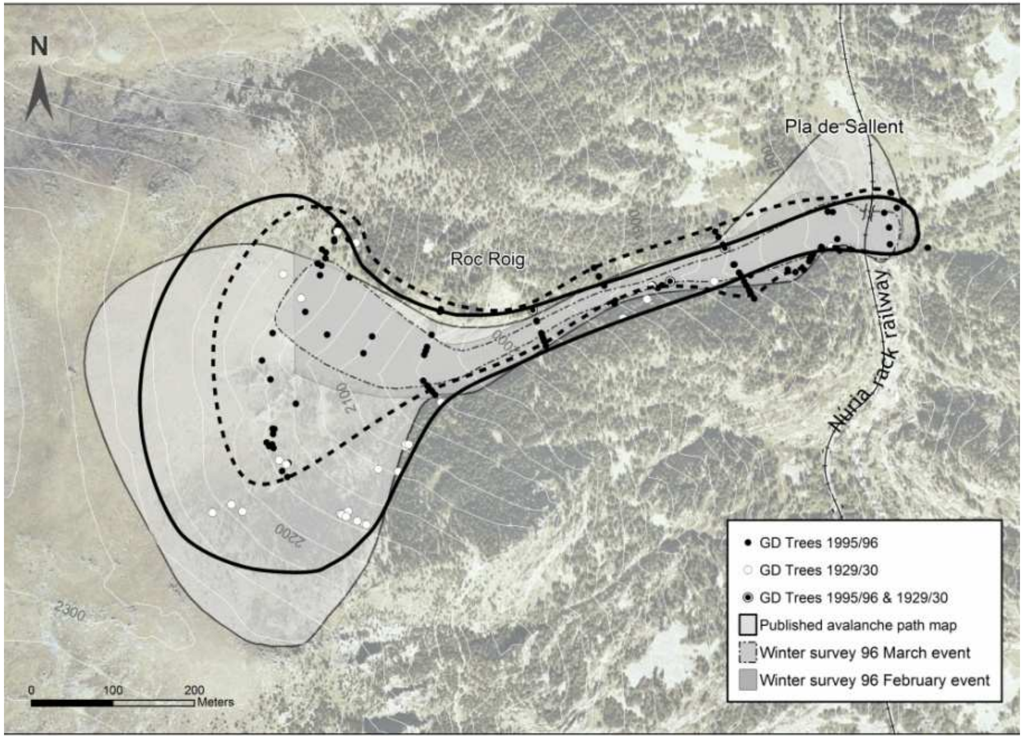


Figure 5: Map of the events in 1995-1996 and 1929-1930. The snow avalanches in 1996 were mapped shortly after the events in February and March. Black dots show trees with tree-ring signals in 1996. Dashed line indicates the improved map of the 1996 events. White dots correspond to trees with tree-ring signals in 1930. Black line indicates the map of the 1929-1930 event, the starting zone was even wider than in 1996.

3.1.5 DISCUSSION

Tree growth responses can show a delay, and tree-ring features may not appear until one or more years later (Johnson, 1987). The problem of dating the 1996 avalanche was solved because most of the signals were detected during the immediate growing period of 1996. Only a small proportion of trees showed a reaction during subsequent years. We found that scars provide a decisive criterion for establishing the exact year, because they are produced by an immediate tree reaction to wounds.

One of the clearest signals in tree-rings is sudden tree death, but wood goes rotten and tree-rings become decayed after 50-70 years (Bosch and Gutiérrez, 2001). Near the run-out zone, it was observed that the sapwood of some of the dead trees from 1996 was already rotting in 2003 (7,5 years later), so this source of information about the date and age of dead trees may disappear fast.

As explained above, two snow avalanches were documented in 1996. However, it is not possible to distinguish them in tree-ring signals. Avalanche events take place during the vegetation dormant season so tree signals are not different for the two events. Avalanche events can be seasonally dated, but we can not distinguish whether there has been one or more events.

It is important to point out the significance of finding all these signals together because tree-rings can show similar responses to different environmental disturbances. Consequently, only the combination (redundancy) and a high number of these responses reliably confirms past events. For instance, tilting of tree trunks causes eccentricity and provides redundant signals: abrupt growth changes (suppression and release), compression wood or all together. Therefore, the exact year of tilting can be dated, providing reliable information on past events.

These results demonstrate that dendrogeomorphology can be used to improve maps performed by conventional techniques. Furthermore, these results highlight the potential of dendrogeomorphology to yield information on avalanche occurrences, provided that a high sample density fieldwork is performed.

3.2 CHAPTER 2: CHARACTERIZATION OF SNOW AVALANCHE EFFECTS AND REACTIONS IN PINUS UNCINATA TREES

3.2.1 ABSTRACT

In this work the results of the effects of a recent avalanche are presented with the aim to describe morphological changes in trees and to quantify them. The shapes and their proportion have allowed us to characterize the effects of avalanches on trees of the genus *Pinus* and to distinguish between the effects of a recent avalanche and past events.

3.2.2 INTRODUCTION

In tree rings, reactions to different causes (snow avalanches, rockfalls, debris flows, etc.) are similar and thus, in principle, it is not possible to distinguish the type of process only from dendrochronological signals. However, the set of morphological changes in trees is characteristic of every process. Moreover, it could be possible that there were alteration shapes exclusive to each particular process. These could give us the clues to identify the process and to date it. Frequently, several hillslope processes come together; knowing the type of effects on trees from each process should help us to distinguish between one or another.

In forest zones affected by geomorphological processes, the appearance of trees is one of the first signs of the activity. As stated by Shroder (1978, 1980), a process produces a number of events affecting trees which result in different responses. The shape of the trees becomes modified by episodes or reactivations of processes. The density of morphological changes depends on factors inherent in the geomorphological process, such as the age of the last event, and the frequency or intensity of the episodes.

The identification of modified shapes serves several purposes. For the experienced geomorphologist, they are used to map the process and to distinguish affected sectors in a higher or lower degree or more or less old. For the dendrochronologist who must date the events, they are useful for obtaining high quality samples.

Trees that grow in snow avalanche paths are periodically affected by this process. In the subalpine mountain of the Pyrenees the most abundant conifer is mountain pine (*Pinus uncinata* Ramond ex DC. in Lam et DC.). As most conifers, this species shows disturbance signals on tree rings which are quite easily identified and which, at present, are well described in the dendrogeomorphological literature (Stoffel & Bollschweiler, 2008). However, to optimize the job of dendrochronological dating it is necessary to know how to identify particular shapes of trees hit by the particular process. The aim of this work is to present the typology of shapes of trees affected by snow avalanches.

3.2.2.1 STUDY SITE

The avalanche path of this study is located in Barranco de las Fajas in Sallent de Gállego (Valle de Tena, Aragon). This avalanche path starts in the southwestern slope of Pico de Musales at 2653 m altitude. Approximately at 1950 m a.s.l. it channels along Barranco de las Fajas torrent and after turning to the northwest below 1650 m a.s.l. ends in the river Aguas Limpias at 1445 m a.s.l. (Figure 6).

During 2007-2008 winter season an avalanche destroyed a tract of forest close to Barranco de las Fajas. Avalanches descending Barranco de las Fajas can follow two trajectories. The most frequent trajectory follows the torrent path, at 1650 m a.s.l. it fits in the torrent canal and turns to the northwest reaching the river Aguas Limpias at the end. In less frequent cases, more or less at the same altitude, a branch of the avalanche can deviate from the watercourse and continue straight to the west overflowing into the pine forest, as it was observed on 23 April 2008 (Cuchí et al, 2008). On this occasion the avalanche started at 2550 m a.s.l. as a slab avalanche and it moved downwards as a dense snow avalanche. The high inertia of this type of avalanche and the main trajectory being clogged by snow could have been the reasons for the snow to overflow into the forest. Characteristics of the occurred avalanche, the map of the event and meteorological triggering conditions are explained in Chueca et al, 2009.

Frequency of avalanches along the main trajectory at 1650 m a.s.l. is of one event every twelve years, approximately, from dendrochronological dating of samples. Also from dendrochronology, two most likely events were dated which followed the less frequent trajectory in 1970-1971 and 1960-1961, one event every 25 years (38 and 48 years before the 2007-2008 avalanche) (Muntán, unpublished data).

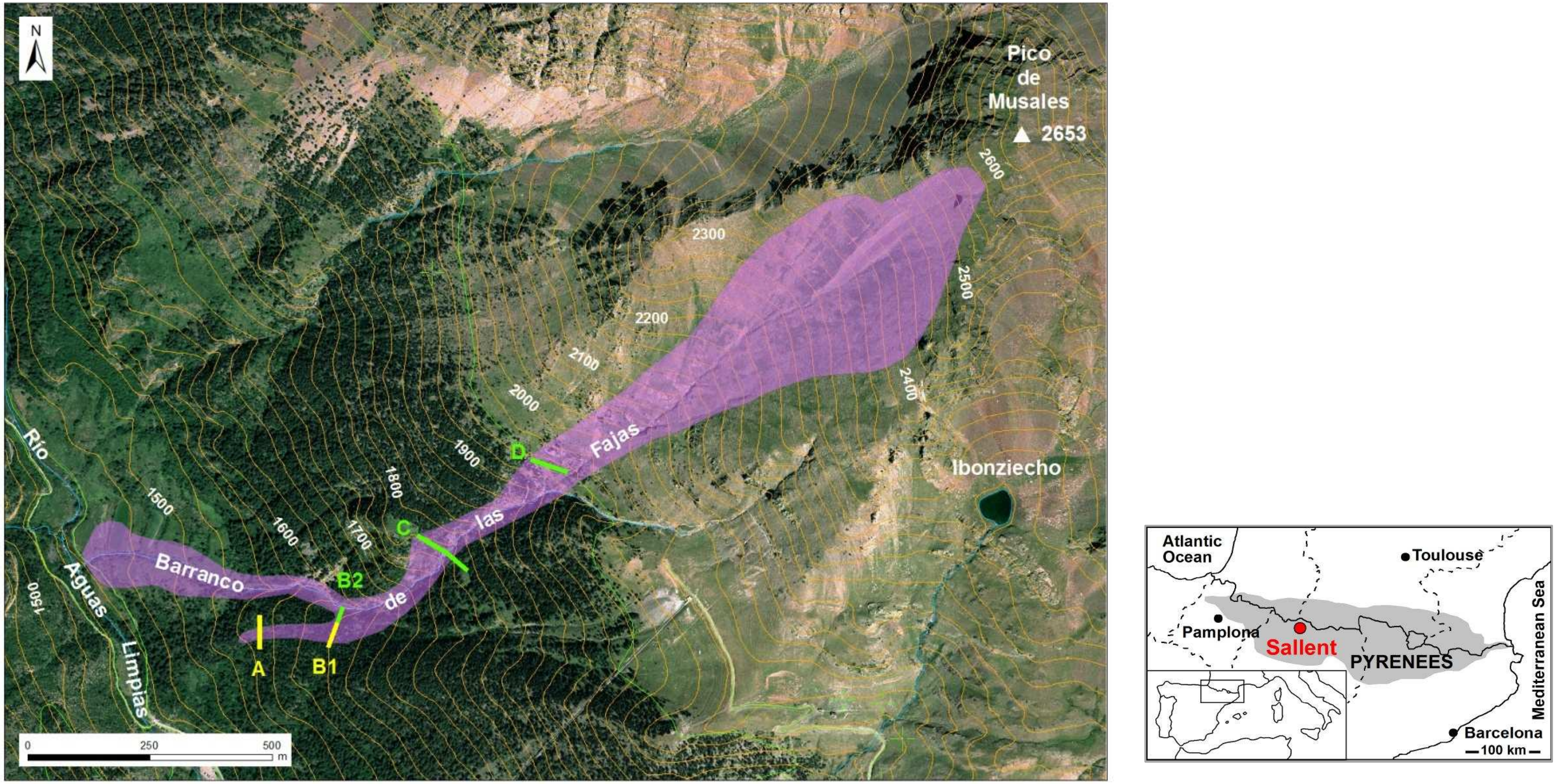


Figure 6: Location map of Barranco de las Fajas avalanche path. In purple, map of 2008 avalanche. The five transects of the study are shown (green and yellow lines).(Orthophotomap, 2007 SITAR)

Subalpine forest in this zone is of *Pinus uncinata* in its upper limit and of hibrid pines *Pinus uncinata x sylvestris* as we descend towards Aguas Limpias river, and it is not easy to distinguish individuals from one species or the other due to intermediate characters. Dendrochronologically these species, which belong to the same taxonomical subgroup of *Pinus*, are difficult to tell from one another. The dominant species in this forest is pine, although other species are present very sporadically: birch (*Betula* L. sp.), beech (Fagus *sylvatica* L.), whitebeam (*Sorbus aria* (L.) Crantz), rowan (*Sorbus aucuparia* L.), aspen (*Populus tremula* L.), and hazelnut (*Corylus avellana* L.).

3.2.3 MATERIALS AND METHODS

With the objective to evaluate the effects of avalanches along both trajectories in the avalanche path, five sectors were selected to gather data from trees (Figure 6). In each sector transects of variable length and a fixed width of 2 m were established. Length of transects covered the local width of the avalanche path in each sector. Fieldwork included a systematic sampling of trees which allowed us to quantitatively analyse morphologies. For the present work data from all the pine trees growing inside the 2008-avalanche clearing were analysed. In Table 1 details from the transects are indicated. Transects B2 and D did not cover the whole clearing of the avalanche path because the slope was too steep to work on. In these transects the parts left out had very few trees.

Table 1:Characteristics of study transects in Barranco de las Fajas avalanche path. The vertical distance to the starting point from the 2007-2008 avalanche event is indicated.

Transects characteristics	A	B1	B2	C	D
altitude (m a.s.l.)	1565	1627	1627	1765	1940
vertical distance to starting altitude (at 2550 m a.s.l.) (m)	985	923	923	785	610
length x width (m x m)	36 x 2	46 x 2	26 x 2	80 x 2	78 x2
aspect (º)	0-180	20-200	200-20	130-300	110-290

Transect D was set at the upper forest limit nearly 600 m below the scar of the starting zone of the 2008 avalanche, clearly in the track of the avalanche which would have acquired considerable energy already. The ecotone of the mountain pine forest is located around 1950 m alt. on this mountain slope.

The next C transect was drawn around 175 m alt. below in the channeled zone of the avalanche track.

Approximately 135 m alt. below, at the divergence point between the gully and the lateral branch destroyed in 2008, two transects were located, each one in each trajectory with the same starting point. Transect B1 crossed the devastated forest to the hydrographic left, and B2 was perpendicular to the gully canal to the right where the most frequent avalanches descend. Although the avalanche reached the river Aguas Limpias, below this transect B2 no other transect was installed because forest is scarce owing to some cultivation patches. Transect A was set some 65 m below in the lateral branch close to the 2008 final runout zone.

Thus, transects D, C, and B2 were placed in avalanches most frequent trajectory, and transects B1 and A, in the less frequent branch.

Fieldword was carried out during 2008, a few months after the avalanche descent, and was continued in 2009, a year after. Avalanche effects were very recent and clearly perceivable from the effects of preceding disturbances. For this reason in most cases evidence from 2007-2008 avalanche could be distinguished from previous events.

Distribution of trees per transects is shown in Table 2. The total number of trees in the transects was 168, from which 133 were mountain pines.

Table 2: Distribution and details from trees of the five sampled transects. Trees includes pines, other trees and craters from uprooted trees.(average and standard deviation)*

Trees from transects	**A**	**B1**	**B2**	**C**	**D**	**TOTAL**
trees	32	43	34	36	23	168
living trees	14	15	23	25	19	96
dead trees	18	28	11	11	4	72
mountain pines	19	33	30	28	23	133
other trees	12	2	3	8	0	25
density (trees/m2)	0.44	0.47	0.65	0.22	0.15	0.4±0.2*
basal area /transect area	61.0	64.1	88.1	18.8	29.0	52.2±28.1*

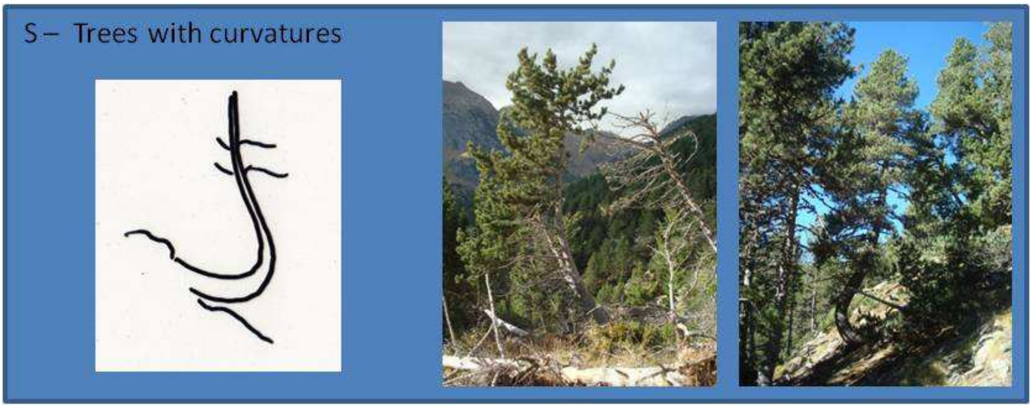
Altogether, the effects on 133 pines have been studied. From all trees, data of their structure was collected, and shapes were visually classified in cathegories which are explained in the results section. Shapes are described as they affect the main axis or trunk of the tree.

3.2.4 RESULTS

In Figure 7 the typology of shapes and the number of pine trees which presented these shapes in the five studied transects is shown. To a great extent, the names of shapes have been taken from the literature (e. g. Schweingruber 1996) (I - inclined, H - horizontal, S - (S from sabre) with curvatures, E - decapited, R - bowing, P - multistem with several main stems, B - forked, C - candelabra, Fe - with impact scars, FeA - with corrassion scars, FeFi - with longitudinal cracks/fissures, PD - partially uprooted, TD - completely uprooted, M - dead). In the next pages some drawings and pictures of these shapes are displayed.


I – Inclined, tilted trees


H – Horizontal trees


S – Trees with curvatures

E – Decapìted trees

R – Bowing trees

Fe – Wounded trees

FeA –
corrassion scars

FeFi –
longitudinal cracks

PD – Partially uprooted trees

TD – Completely uprooted trees

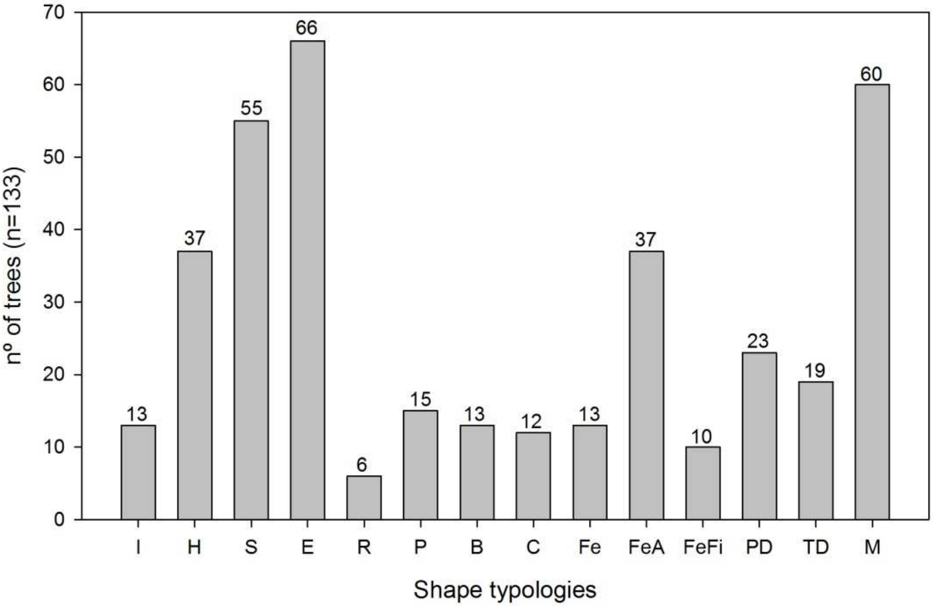


Figure 7: Types of shapes of pine trees in Barranco de las Fajas avalanche path.

In this classification there are primary shapes, direct effect from avalanches, and secondary shapes, reactions coming from the primary shapes after some years. Thus, inclined trees (I) are commonly primary shapes that become curved shapes (S) afterwards, clearly secondary. Other secondary forms, in principle, are multistem (P), forked (B) and candelabra (C). These shapes come from decapitated trees (E) (which can also be primary and secondary) at different heights. The rest of the names are ambiguous. That is, horizontal (H) are primary shapes if the avalanche effect has just happened or secondary if some time has passed and the tree has not been able to straighten. The bowing (R) are trees leaning down from a point where the trunk is not completely broken, and are primary shapes if the fracture has just happened, or secondary if years have passed and the tree has developed a scar margin in this place. The same for the three types of wounds (Fe, FeA, FeFi) which are primary if they have just happened, and secondary if they have already developed a scar margin.

A tree can display several of the proposed shapes and some typologies go together often. Like that, horizontal trees usually exhibit corrassion scars (FeA) too. Inclined or horizontal trees can show longitudinal fissure/crack scars. Of course, trees completely uprooted are dead.

As displayed in Figure 7, the two most abundant classes are decapited trees (E), nearly half of all the individuals, and dead trees (M), also almost half. The 2008 avalanche produced a great devastation of mountain pines. To these destroyed pines a great proportion of the horizontal ones will have to be added, because these usually sprout the year after, but few survive more than that.

In Figure 8 avalanche effects have been separated by transects. For every shape typology, bars indicate from left to right: pines affected by the 2007-2008 avalanche, pines affected by previous events, and the total number of disturbed pines. Values stand for the percentage of trees per transect. For different reasons -among which, the difficulty to assign an age to an effect- from a great proportion of trees we did not write down whether they had been struck by 2008 avalanche or by previous avalanches, and for that reason these values are explorative. The total bar for every signal is a systematic measure and accurately reflects the percentage of trees with a particular shape.

The proportion of dead trees increases from the upper transect D to the lowest A. This is owing to the mass of snow transporting the trees. A high percentage of dead trees is caused by 2008 avalanche. In the lower transects, A and B1, a remarkable portion of these pines have been transported with roots (TD class).

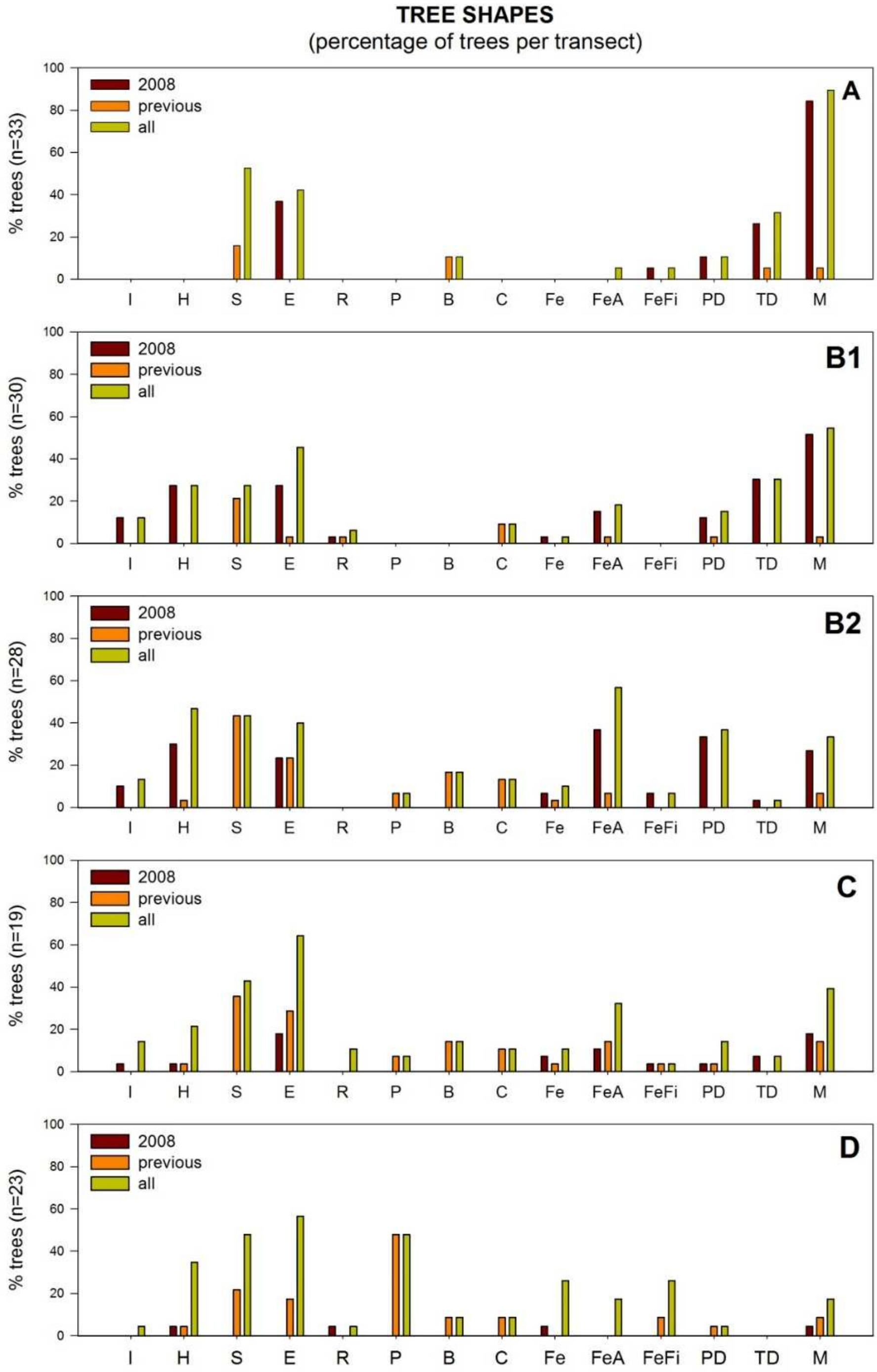


Figure 8: Percentage of shapes per transects, and effects separated owing to age: 2008 avalanche, previous avalanches or all effects together (some shapes could not be dated, therefore the third bar in all shapes can be longer than the sum of the other two). Trees can display more than one shape.

The decapited pine category, class E, is present in all transects patently. Percentage of decapited trees is higher than 40% of all pine trees of the transects, and even higher in the upper transects C and D.

Curved shapes, class S, are clearly present in all transects, surpassing 40% in transects A, B1, C and D, and 30% in B2. In spite of this being a secondary morphology, because it is a reaction of the tree to tilting, during the fieldwork, not all of these curved shapes have been identified as reactions to previous avalanches and they have been left in this way in the results.

On the contrary, most leaning trees of the H class are as a consequence to 2008 avalanche and they are very abundant in transects B2 and B1 which are found at a similar distance to the avalanche origin. In A they are also present, but they affect mostly the other species and not pine trees. Trees that remained inclined -class I- after the 2008 avalanche were very scarce in all transects, most of them were knocked down (class H).

In the scars cathegory, the three formulated classes are abundant among trees at transect D and trees affected were more than 20% of the total in the transect (all trees in the transect are pines). Despite this, in transects C, B1 and B2 only corrassion scars outstand, FeA class, with a maximun in B2 about 60% of trees.

Among classes P, B and C with trees bearing more than one axis, it is worth highlighting the great abundance of multistem trees, class P, only at transect D.

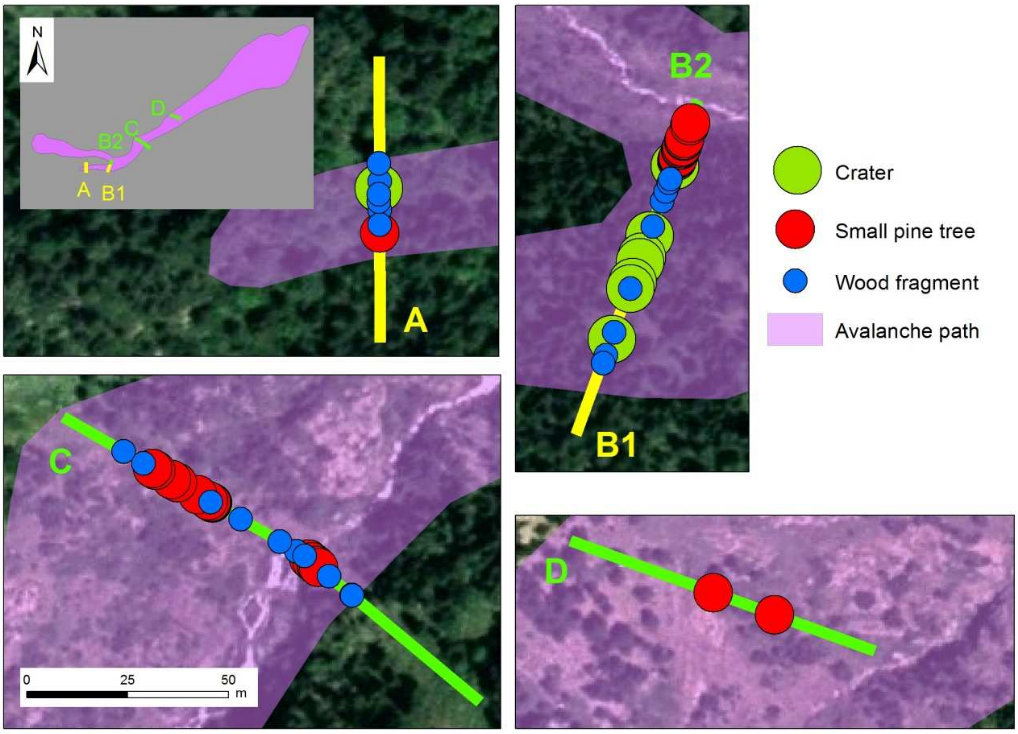


Figure 9: Location of craters of uprooted trees (n=8), small mountain pines of the regeneration class (less than 150 cm tall) (n=35) and tree fragments (n=27) in the five transects.

In Figure 9 three elements are displayed which are also consequence of avalanche descent in this zone. These are: the regeneration class, pine trees less than 150 cm tall which already existed before the 2008 avalanche; craters left by uprooted trees by 2008 avalanche; and the resulting fragments from decapitations and broken branches transported by the same avalanche. We found out that young pine trees grow specifically in transects C and B2.

3.2.5 DISCUSSION

The great proportion of decapited, horizontal and dead trees (E, H, and M) indicates the high magnitude of the 2008 event. It is expected that in lower magnitude avalanches the proportion of these classes would be lower.

Trees which don't break get knocked down on account of the avalanche energy. Many of these H trees remain partially uprooted and depending on the intensity of damage to roots and to the aerial part, will also die after sprouting during the first or second year after the avalanche. Another observed effect in many trees is the loss of needles which gives them a plucked appearance.

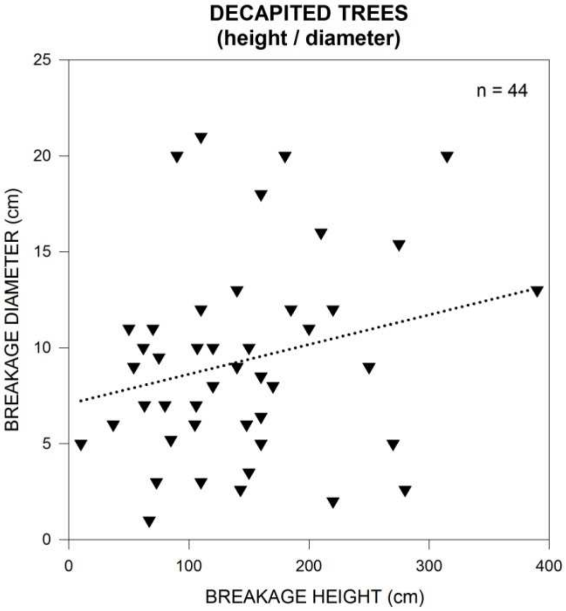


*Figure 10: Decapited trees, relationship between breakage/fracture diameter and height. (Regression; the power of the performed test 0,0347 is below the desired power of 0,8; DE = 7,069 + (0,0155 * HE); R = 0,239 R^2 = 0,0572)*

From the total number of decapited trees in the five transects (n=66), discarding those which were transported downslope, 44 remained *in situ*. The ones which were displaced would have probably undergone subsequent breakage in the transportation and for this reason they have not been considered when analysing the relationship between diameter and height of decapitation. Johnson (1987) states that the breakage threshold depends on tree size. However, our results are not definitive, although some tendency is observed (Figure 10). More than 80% of trees were broken at a height where diameter was smaller than 15 cm. The other 16% had a stem-fracture diameter between 15 and 21. The height at which tree trunk has broken was quite variable, most of them below 2.5 m, although some have exceeded this value.

From the set of injuries that can be fountd on trees striked by snow avalanches, the most profuse are corrassion scars (FeA) associated with quite tilted trees. These are the result of compact/dense snow friction or by dragged objects on the bark of the side of the trunk facing upslope. Corrassion scars are tipically long and their angular mesure ordinarily does not exceed a quarter of the trunk perimeter. Quite often, it can be observed that they have registered several avalanche episodes because they display a number of scar margins. This type of wound morphology is very typical from trees that grow in avalanche paths. The type of corrassion scars in debris flows are wider and they affect the laterals of the trunk. Yet, corrassion scars, due to the way they are produced, will hardly appear in slope processes such as landslides or rockfalls. However, they could be mistaken for corrassion scars from floods.

Regarding trees with more than one main axis, the forked class -which, in principle, would seem that they originate in a similar way to multistem trees- is found in relatively low and similar proportions in all transects (except for A, where it is missing). It could be that it has a genetic origin in part, as it happens to some tree species. It would be necessary to see if the proportion of forked trees inside the forest is similar to this. Concerning multistem trees, which are so abundant in the upper transect D, their origin could have different explanations. In line with the genetic origin could be the fact that *Pinus mugo* subsp. *mugo*, closely related to *P. uncinata,* but which does not grow in the Pyrenees, is a shrub-like species with several stems. It could be that at the highest altitudes a multistem form of *P. uncinata* is more likely to grow. At the same time, the exposition of these individuals to high mountain conditions, having to endure winds carrying ice particles that can damage and erode plant shoots, could be another cause for these shapes to be more abundant at the forest limit. However, an explanation linked to the effect of avalanches is that these trees are covered by snow during winter, often with protruding stems which would be decapited by the fall of avalanches, more frequent at these higher altitudes.

With respect to regeneration, from the differences in the location of the youngest pine trees some hypothesis can be formulated. While estimating the age by whorl counting, it was found out that ages differed depending on the transects. In C young pines were between 5 and 20 years old, and in B2, between 20 and 40. It is logical to think that events in transect C are more frequent, because it is placed higher on the avalanche path and for this reason the regeneration class is younger. Whereas, in B2 which is located lower, avalanches reach this sector less frequently and allow trees to grow older. In contrast, in the lateral branch, in transects B1 and A there are hardly any pines of the regeneration class, fact that seems to corroborate that no clearing has been produced in this forest for a long time, and that could coincide with the event in 1970-1971.

In parallel with the lack of regeneration in transect B1 it was observed that the 2008 avalanche dragged a high proportion of trees, leaving the craters which will serve as the niche for the forest regeneration in the years to come. *Pinus uncinata* is a heliophyte species. Having become so devastated and favored by the existence of these craters, one would expect a monocohort forest to develop in the following years, very similar to the one that existed before the 2008 avalanche in this sector.

3.3 CHAPTER 3: RECONSTRUCTING SNOW AVALANCHES IN THE SOUTHEASTERN PYRENEES[2]

3.3.1 ABSTRACT

A regional study of snow avalanche processes was undertaken in the SE Pyrenees. Dendrogeomorphology was used to date and reconstruct large-scale snow avalanche events that occurred in the last four decades. Dendrochronological analyses yielded the dates of nine winters when major avalanches occurred in the recent past in six studied avalanche paths. Some of these avalanches were already known, but others had not been documented. In one case, the existing avalanche path map was improved with the dendrogeomorphological information of a larger past event. As a result of the dendrogeomorphological analyses, evidence for three regional-scale major avalanche years was identified in the SE Pyrenees from 1971 to 2004: 1971-72, 1995-96 and 2002-03. The specific synoptic atmospheric situations and the most likely nivometeorological and snowpack conditions that released these major avalanches were determined using weather data for the seasons of major avalanche releases. In 1971-72 the snow avalanche episode was characterized by a deep trough crossing the Pyrenees. In 1995-96 a variety of meteorological situations produced several episodes of major avalanches. In 2002-03 the more significant of two episodes was attributed to a north advection pumping an arctic air mass over the Pyrenees. The 1995-96 avalanche season proved to be the most notable in the four past decades in the Pyrenees.

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[2] Elena Muntán did all the tasks related to dendrogeomorphology in this work, which was published at the peer-reviewed journal *Natural Hazards and Earth System Science* (Muntan et al., 2009) (see Appendix at the end of the document).

3.3.2 INTRODUCTION

In recent times, the southern Pyrenees have undergone a profound land-use and economic transformation. Traditional rural society has given way to a growing leisure industry related to winter sports and mountain recreation in general. Rapid urbanisation and the resulting population densities have increased the number of people at risk in these areas. In 1995-96 a large number of avalanches occurred in the Pyrenees. An avalanche warning system (avalanche forecast) prevented human casualties, however there was considerable damage to forests and infrastructure.

For hazard analysis and risk prevention in alpine and subalpine mountain areas, knowledge of snow avalanche characteristics is of paramount importance. To this end, present and past events must be researched in order to obtain information on avalanche extent, frequency and intensity. In every avalanche path, snow avalanches can attain different extents depending on interactions between terrain, weather conditions and existing snowpack structure. Small avalanches take place regularly, but large avalanches occur less frequently. Study of historical documents, interviews with local people, winter monitoring, meteorological data, field survey and avalanche path mapping are some of the conventional means to characterize snow avalanches. Dendrogeomorphological analysis of trees at avalanche sites is helpful in providing information about the return period and extent of avalanche events where these data are lacking.

Temporal and spatial characteristics of snow avalanches can be reconstructed by dating tree-ring responses caused by past events. Trees growing in mountain environments can be affected by a variety of natural disturbances (biological and non-biological). Different kinds of damage produce similar responses and thus similar tree-ring evidence. After a thorough dendrochronological dating process, those tree-ring features not caused by snow avalanches are discarded and thus clues to the occurrence of past events may be obtained from evidence of disturbances and spatial distribution of trees at avalanche sites.

The usefulness of dendrochronological techniques in snow avalanche research has been demonstrated since the beginnings of dendrogeomorphology (e.g: Potter, 1969; Burrows & Burrows, 1976; Butler, 1979; Carrara, 1979). The most common features used by these researchers were scars on trees, changes in growth patterns from concentric to eccentric, appearance of reaction wood, abrupt growth disturbances (increase or decrease in growth rate), age of trees in naturally reforested paths, year of death of trees in debris, and breakage of stems or branches. Recent dendrogeomorphological works on snow avalanches continue to use these features to date events (e. g. Hebertson & Jenkins, 2003; Dubé et al., 2004; Germain et al., 2005; Stoffel et al., 2006; Casteller et al., 2007; Mundo et al., 2007; Reardon et al., 2008).

Snow avalanches have been poorly documented in the Pyrenees. Despite some pioneering mitigation work in the central Pyrenees in the early twentieth century, the study and management of snow avalanches was not undertaken until the 1980s (Muñoz, 1988; Furdada, 1996). The significant avalanche season 1995-96 raises two main questions: Was 1995-96 such an extraordinary avalanche season? Had there been any similar avalanche seasons in the recent past? The present work seeks to answer these questions. Specifically our objectives were to: 1) date and reconstruct the spatial extent of recent past avalanches using dendrogeomorphological methods in a set of six selected avalanche paths; and 2) determine the synoptic atmospheric patterns releasing major avalanches and their regional extent.

Our findings will be helpful to land-use planners who can utilize the information to develop more rational avalanche protection strategies and implement measures to mitigate snow avalanche risk. With respect to this, details on the dendrogeomorphological methodology, its strengths and weaknesses, are also discussed.

3.3.2.1 Study region

The Pyrenees mountain range extends over 450 km from the Mediterranean Sea to the Atlantic Ocean and forms the isthmus that links the Iberian Peninsula to the rest of the Eurasian continent. The high Pyrenees range between 2000 and 3000 m in altitude reaching a maximum of 3404 m and they are about 120 km wide in the middle of the chain. The amplitude and the altitude of the Pyrenees diminish dramatically when the mountains approach either the Atlantic Ocean or the Mediterranean Sea. Two main kinds of relief can be broadly differentiated: elevated areas with abrupt peaks but having vertical drops not exceeding 700 m, and valley areas having a flatter relief but with altitude variations higher than 1500 m in some cases.

Our study area was specifically located on the southeastern part of the range (Pyrenees of Catalonia), an area of about 150 km in length, 52 km wide in the western part and 19 km wide in the eastern part (Figure 11). In this region, the highest mountain villages are situated at an altitude of 1500 m. The highest roads that are open in winter are located at an altitude of 2300 m and nine alpine ski resorts are distributed at altitudes exceeding 1500 m. The “Pica d’Estats” at an altitude 3143 m is the highest peak in the area.

The peculiar geographical features that shape the Pyrenees play a major role in the climatic conditions affecting the whole chain. The zonal disposition of the axial range retains polar and arctic maritime air masses from north advections, and tropical maritime air masses from the south and southwest.

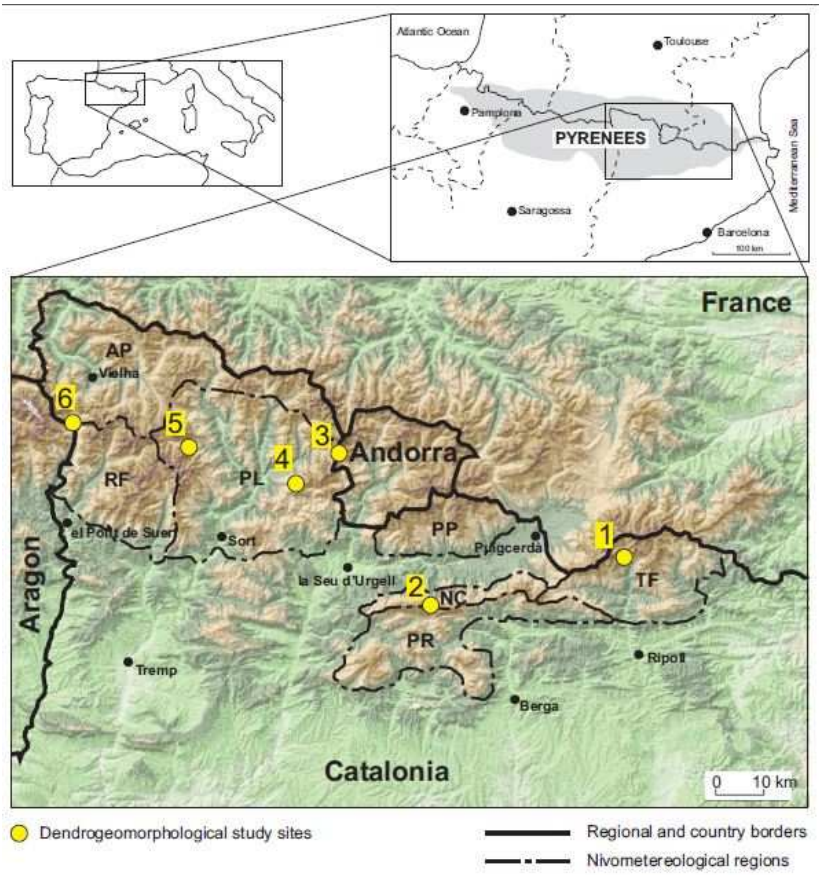


Figure 11: Shadow relief image (ICC) of the study region, Pyrenees of Catalonia, showing nivometeorological regions used in avalanche forecasting (AP: Aran-N border of Pallaresa, RF: Ribagorc¸ana-Vall Fosca, PL: Pallaresa, PP: Perafita-Puigpedrós, NC: N slopes of Cadí Moixeró, PR: Prepirineu, and TF: Ter-Freser) and the location of dendrogeomorphological study sites (numbered from E to W).

The meridian valley configuration favours the penetration and the placement of unstable air masses, i. e. the forced lifts caused by the relief may sometimes result in heavy and persistent snowfalls. Because of the proximity of the Pyrenees to the Mediterranean Sea and the Atlantic Ocean, temperatures are less extreme than in inland ranges. Interestingly, there are extensive rain shadows close to the Mediterranean. Finally, the massif is a boundary between the humid oceanic climate and the subtropical dry climate due to its relatively low latitude.

Despite the small size of the study area, three different climatic conditions are found: Oceanic, Continental and Mediterranean. The northwestern part of the study area is characterized by a humid oceanic climate. Precipitations are abundant and show a regular interannual distribution. The total amount of fresh snow at 2200 m altitude is about 500-600 cm per year. The oceanic influence crosses the main divide and extends few km to the south. However, the climate becomes more continental south of the main divide. Winter is the driest season and snow precipitation increases in the equinoctial periods, while interannual variability of precipitation increases. The total amount of fresh snow at 2200 m altitude slightly exceeds 250 cm per year. Predominant winds come from the north and northwest often with gusts over 100 $km \cdot h^{-1}$. The Mediterranean Sea plays a crucial role in the climate in the eastern part of the Pyrenees. Thus heavy snowfalls can occur because of humid air masses from the Mediterranean Sea. Interannual variability of snowfalls is high. The total amount of fresh snow at 2200 m altitude is about 350-450 $cm \cdot yr^{-1}$. The formation of persistent lows over the lee-side of the Alps and the Gulf of Lions gives rise to prevailing winds from the north. Maximum wind gusts may occasionally exceed 200 $km \cdot h^{-1}$ at 2200 m altitude.

According to weather and snow conditions the study area has been divided into 7 nivometeorological regions (Figure 11). Given the absence of long meteorological records for the area, these regions do not constitute a strict climatic classification, but are the result of 15 years of avalanche forecasting in the Catalan Pyrenees. They fall into regions of different climatic influence. Oceanic: Aran-Northern border of Pallaresa (AP). Continental: Ribagorçana-Vall Fosca (RF), Pallaresa (PL), Perafita-

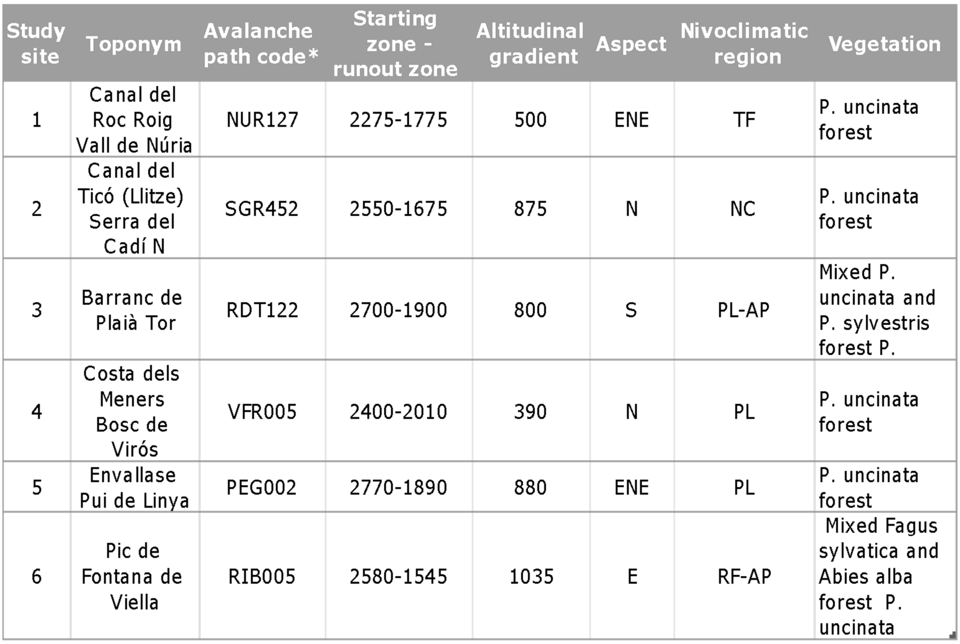
Puigpedrós (PP) and V. N. Cadí Moixeró (NC). Mediterranean: Prepirineu (PR) and Ter-Freser (TF).

3.3.2.2 Dendrogeomorphological study sites

Six snow avalanche paths were selected to conduct a dendrogeomorphological study. These were distributed over the area to provide information for the whole territory (Figure 11). Some characteristics of the study sites appear in Table 3. For the purpose of this research, the sites were chosen in forested paths. Potential treeline altitude has been fixed at ~ 2200-2450 m altitude in the Pyrenees (Carreras et al., 1996). The most widely distributed tree species growing at the highest altitudes (from 1600-2300/2500 m) is *Pinus uncinata* Ramond ex DC. in Lam et DC. (mountain pine). At lower elevations, other conifers as *Pinus sylvestris* L. (Scots pine) and *Abies alba* Mill. (silver fir) can also be found. All the dated avalanches in this study were naturally released.

Avalanche Path 1 (AP 1, Núria) is located near the eastern end of the high Pyrenees, in the Núria valley. This path has a broad, concave starting zone, a narrow track and an unconfined runout. A mountain pine forest begins some meters below the starting zone, at 2200 m altitude. In the runout major avalanches affect the rack railway that connects the valley villages to the tourist resort of Vall de Núria. The first dendrogeomorphological study on snow avalanches in the Pyrenees was performed in this avalanche path (Muntán et al., 2004).

Table 3: Study site characteristics.[3]



Study site	Toponym	Avalanche path code*	Starting zone - runout zone	Altitudinal gradient	Aspect	Nivoclimatic region	Vegetation
1	Canal del Roc Roig Vall de Núria	NUR127	2275-1775	500	ENE	TF	P. uncinata forest
2	Canal del Ticó (Llitze) Serra del Cadí N	SGR452	2550-1675	875	N	NC	P. uncinata forest
3	Barranc de Plaià Tor	RDT122	2700-1900	800	S	PL-AP	Mixed P. uncinata and P. sylvestris forest P.
4	Costa dels Meners Bosc de Virós	VFR005	2400-2010	390	N	PL	P. uncinata forest
5	Envallase Pui de Linya	PEG002	2770-1890	880	ENE	PL	P. uncinata forest
6	Pic de Fontana de Viella	RIB005	2580-1545	1035	E	RF-AP	Mixed Fagus sylvatica and Abies alba forest P. uncinata

Avalanche Path 2 (AP 2, Ticó) starts at the top of a north facing, rocky wall with a snow corridor that is adjacent to a steep scree slope. The mountain pine forest in this path starts a few meters below the base of the rocky wall where the scree slope recedes (at 2200 m asl). Beneath the middle track, the avalanche path becomes more confined ending up in a narrow runout. This avalanche path does not affect human dwellings.

Avalanche Path 3 (AP 3, Tor) is located in a remote area near the border of Andorra. This path has a concave starting zone adjacent to a narrow track. Avalanches in this path can take different trajectories in the final stretch.

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[3] AP – six-digit code corresponding to specific avalanche path identification in the Avalanche Paths Map of Catalonia (ICC 1996–2006); SZ – Starting zone; RZ – Runout zone; NM – Nivometeorological region.

Either they are hedged in the mountain torrent which bends abruptly to the west, or overshoot the torrent talveg and invade a flat pasture surface straight ahead. The forest is mainly composed of mountain pine, but some Scots pine appear below 2150 m altitude.

In Avalanche Path 4 (AP 4, Virós) iron mining which started about 1500 years BP (High-Mountain Archaeology Group, Department of Prehistory, Autonomous University of Barcelona, pers. comm. , 2004) inhibited the growth of forests until the XIX century, sometime between 1850 and 1880 (Albert Pèlachs, pers. comm, 2004). Nowadays, the dominant species of this forest is also mountain pine (that grows up to treeline at 2250 m). The topography of this avalanche path is uneven, i. e. there are a number of mining deposits in the middle track. It is reasonable to assume that the majority of avalanches stop above this zone because of the existence of a clear concavity on the topography. Occasionally, snow avalanches can cross a dirt road in the runout.

Avalanche Path 5 (AP 5, Pui de Linya) is in the National Park of Aigüestortes and Estany (lake) de Sant Maurici in the central Pyrenees. It has a long, wide starting zone. The track and the runout have a width ranging between 50 and 75 m. The slopes of this mountain are covered with mountain pine forest reaching 2400 m altitude interspersed with silver fir patches (northern slopes) and Scots pine (southeastern slopes) at lower elevations.

In Avalanche Path 6 (AP 6, Fontana) the catchment occupies a stony, glacial cirque. The track begins at the neck of the cirque and is 100-150 m wide. A mountain pine forest mixed with silver fir flanks the avalanche track up to 2000 m altitude. The runout is on top of a debris cone ending up in a main road that runs along the valley. However, most snow avalanches stop short of overrunning the road. There is a parking lot in the wide runout zone, obviously exposed to avalanche hazard. Only a few woody plants are available in the runout for the dendrogeomorphological study.

3.3.3 MATERIALS AND METHODS

To achieve our objectives, the methods used in our study were as follows: 1) dendrogeomorphology to date and reconstruct past avalanches in six avalanche paths, and 2) analysis of meteorological and nivometeorological records to determine the weather conditions that could have triggered individual avalanches and widespread avalanche events.

3.3.3.1 Dendrogeomorphological procedures

Samples from *Pinus uncinata* trees were collected by utilizing dendrogeomorphological methods described by Burrows & Burrows (1976) and Shroder (1978). Care was taken to employ non-destructive methods for environmental reasons and thus, increment borers were used to extract cores (5 mm in diameter) from living trees. Cross-sections were obtained from dead trees, but these have not been used for the present work. A reference chronology with samples from old trees apparently not affected by avalanches was built at each study site. Reference chronologies were used to confirm correct datings and to exclude any atypical growth responses that could be attributed to climate or other growth disturbances. The field sampling campaigns were performed during the summers of 2003 and 2004.

Figure 12 illustrates the sampling method in AP 1, 4 and 5. Here the dendrogeomorphological study was performed by running a number of 1 to 2-m wide transects across the avalanche track and runout at different elevations. Whenever possible, the transects were set at a distance of 50 m uphill, to cover the whole avalanche trajectory from the runout up to the treeline. Scattered trees with particular external features possibly caused by snow avalanches were also sampled.

In AP 2, 3 and 6 the sampling work was less exhaustive (Figure 12). In AP 2, only one transect across the middle track and ten selected trees in the runout zone were sampled. In AP 3, trees were sampled systematically along five 30m-transects in the runout-zone forest. In AP 6, selected trees were sampled at different elevations along the track. Standard dendrochronological procedures were used to prepare and analyse the wood samples (Fritts, 1976; Stokes & Smiley, 1968). All samples were visually cross-dated.

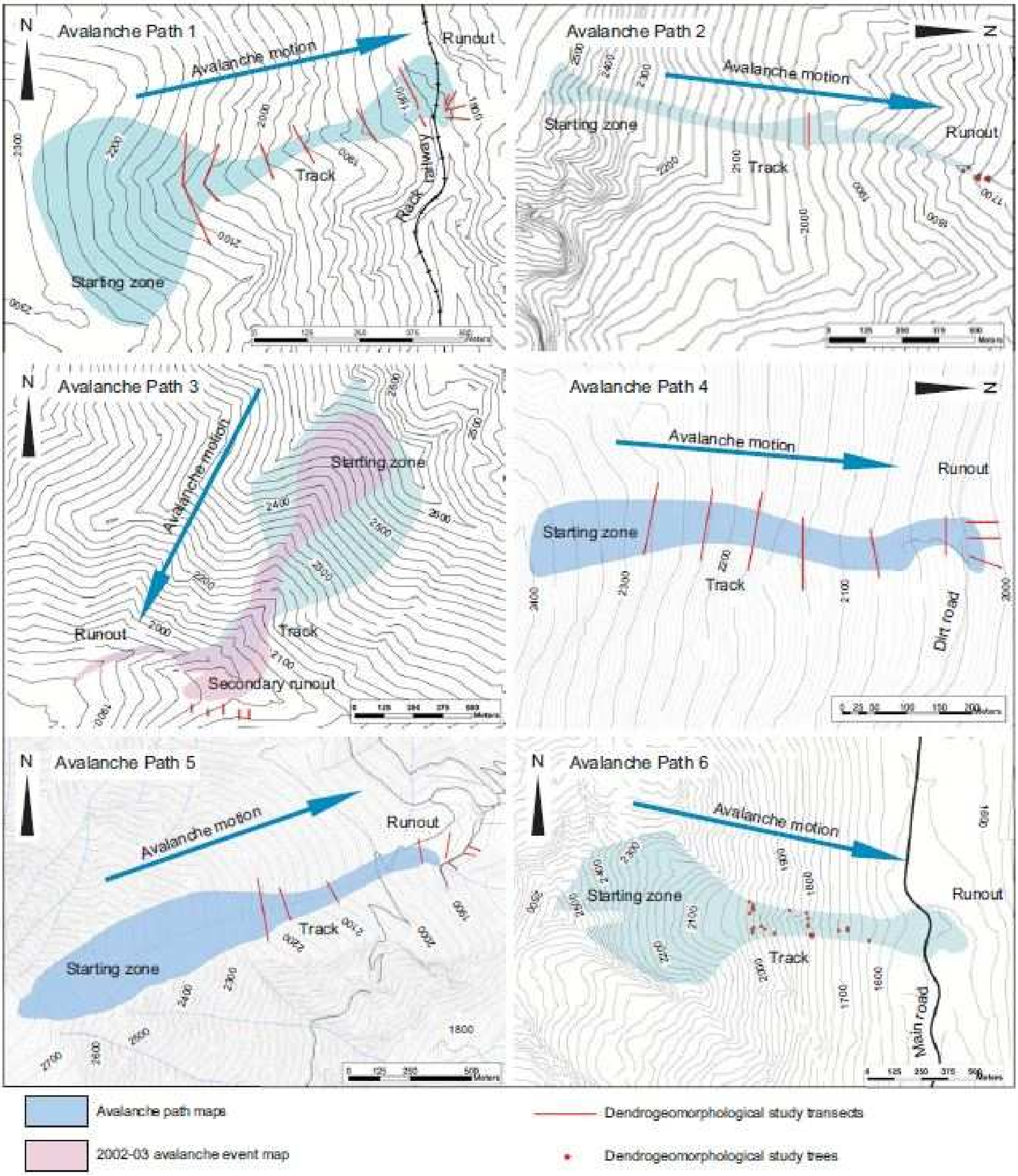

Figure 12: Avalanche path maps (ICC) showing the sampling strategies used in each of the study sites.

Statistical verification was done using the computer programm COFECHA (Holmes, 1983), but visual description of ring characteristics was crucial because statistical dating tests were not successful in a large number of the avalanche path samples owing to extreme ring-width alterations.

Abrupt growth changes in ring width (release and suppression sequences that are not present in the reference chronology), reaction wood (which is ordinarily related to tree tilting) and growth cessation (due to local death of cambial cells in the case of scars) were used to date avalanche events. Regeneration as evidence of past disturbances was not employed given discrepancies in tree establishment dates. Resin ducts as indicators were also avoided because of the number of resin ducts ordinarily displayed by *Pinus uncinata*. Root samples were not used owing to the difficulty for cross-dating them. Dead trees supply complete tree sections where ring features are more easily observed. However, as tree debris get rotten and disappear, part of the evidence is lost making comparisons between percentages of recent and past events tricky. Moreover, given that most dead trees are transported, they do not provide reliable information about event extent. For this reason, only living trees were used to infer avalanche occurrences and size on this occasion. In our research, the different tree-ring signals had equal weight in the event-response sum. Although a tree could present several tree-ring signals, it was counted only once. Finally, no attempt was done to rate avalanche intensity using the duration of tree-ring responses.

The following criteria were used to confirm the occurrence of snow avalanches by means of dendrogeomorphological analyses: 1) the absence of similar growth reactions in the reference chronology, 2) the concurrence within the same tree or among trees of a variety of tree-ring responses, 3) the spatial distribution of growth-disturbed trees in the track and in the runout, and 4) the proportion of trees with ring evidence similar to or higher than the results from documented avalanches.

Avalanches can attain different sizes in the same avalanche path. For the purpose of this research, we have considered events reaching the runout as an indicator of most likely major avalanches. According to Schaerer (1986), avalanches that occur once in every 5 to 20 years affecting transport infrastructure and causing damage to property are typically much larger than annually observed avalanches. Therefore, in addition to the total count of trees with growth disturbances along the avalanche path, we paid particular attention to growth disturbed trees (GD trees) located in the lower track and in the runout zone. The time period considered was directly related to a lower limit of twenty trees sampled in the whole avalanche path, or ten trees sampled at the lower tract (track/runout), and in this way, it varied from one site to another (see section 3.3.4.1). In addition to this spatial consideration, to set a rough threshold for the percentage of trees needed (Index Number by Shroder, 1978) to accept the occurrence of a snow avalanche, we used the minimum value corresponding to a documented event in AP 1 (where several events had been reported) which was 16%. This cut-off number was used in the densely sampled AP 1, 4 and 5. In less-exhaustively sampled paths AP 2, 3 and 6, we used a higher index of 40% after Butler et al., (1987).

3.3.3.2 Archival data from past avalanches

Information about past avalanche events was obtained from the Avalanche Database of Catalonia (Base de Dades d'Allaus de Catalunya, Institut Geològic de Catalunya: http://siurana.icgc.cat/visorIGC/allaus.jsp), which gathers data from various sources: winter monitoring, field survey, historical documentation, interviews with local people and eyewitness accounts. This was used to corroborate some of the dates yielded by our dendrogeomorphological study.

3.3.3.3 Weather and snow conditions

Major snow avalanches occur when critical combinations of weather and snowpack conditions arise. Once avalanche event years were determined by the dendrogeomorphological study, daily weather records were examined to find reasonable avalanche-release conditions. Owing to data availability, the analysed period was from 1971-72 to 2003-04. Data were obtained from manual and automatic meteorological stations of the National Meteorological Institute of Spain (INM), the Meteorological Survey of Catalonia (SMC), and the Nivometeorological Observers Network (NIVOBS) of the Cartographic Institute of Catalonia (ICC). The NIVOBS has carried out winter surveys to report snowpack conditions and avalanche events since 1986. These observations became daily after 1996.

Attention was focused on the meteorological conditions responsible for unstable structures of the snowpack (Armstrong, 1976). The nivometeorological parameters and conditions that play a role in critical avalanche situations in the SE Pyrenees (García et al., 2006) are as follows: fresh snow accumulation in 72 hours, rain precipitation over 2200 m altitude, wind speed exceeding 15 $m \cdot s^{-1}$ and sequences of days with isozero above 3000 m. In addition, conditions that generate weak layers in the snowpack (faceted grains, depth hoar and surface hoar) were also detected, since not all major avalanches are linked to intense precipitation. Weak layers overloaded by thick wind slabs and by wet slabs in melting situations generate major avalanches, as well. Thus, we looked for weather conditions such as sequences of days of high snow irradiation and sequences of days with daily maximum temperature below 0ºC. When the most predictable meteorological and nivometeorological avalanche-release conditions were identified, synoptic atmospheric situations were selected from the NCEP-

NCAR[4] reanalysis data (Kalnay et al., 1996) by using maps at sea level pressure, at 850 hPa, and at 500 hPa.

3.3.4 RESULTS

3.3.4.1 Past snow avalanches

Results refer to *Pinus uncinata* exclusively, the most abundant tree species in all the study sites. The length of the study period varied within each site, but as a rule, the youngest tree samples covered the last 10 years and the oldest, from 180 to 250 years (Table 4). No attempt was done to date the age of the trees. Roughly, half of the trees were older than 40 years at all sites, and older than 90 years in AP 3 and 4. As has been pointed out in section 4.1, the sample methodology in AP 1, 4 and 5 was more intensive than in AP 2, 3 and 6.

3.3.4.1.1Avalanche paths 1, 4 and 5

The occurrence of large-scale snow avalanches was widespread in the Pyrenean range during the winter of 1995-96. Many of these events were regarded as major avalanches damaging vast tracts of forest. Because major avalanches in paths 1, 4, and 5 were documented during this winter they were chosen to find out whether similar events took place in the past. The event-response histograms for AP 1, 4 and 5 are shown in Figure 13. The bar corresponding to the 1995-96 events clearly stands out in these sites. The proportion of trees showing tree-ring signals was 32% at AP 1, 53% at AP 4, and 57% at AP 5 of the total number of sampled trees (131, 92, and 129, respectively).

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[4] National Centers for Environmental Prediction and National Center for Atmospheric Research, USA

Table 4: Trees used for dendrochronological analyses.

Study site	No. of trees for dendrochronology	Sample age range	Age median	Age x ± 1SD
1	131	10-219	40	49,7 ± 35,1
2	36	18-188	47	53 ± 31,7
3	34	10-181	89	81,7 ± 37,2
4	92	14-196	95	95,7 ± 43,3
5	129	10-250	38	43,7 ± 30,5
6	26	14-185	45	57,3 ± 38,6

In AP 1 major avalanches damaged the rack railway in the winters of 1971-72, 1985-86 and 1995-96. These seasons hold the highest proportion of GD trees along the track and some trees show evidence at the runout as well (see corresponding histogram in Figure 13). Although evidence for events is also high in 1973-74, 1981-82 and 1990-91, it is likely that snow avalanches in these seasons did not reach the runout, but stopped some way up the track.

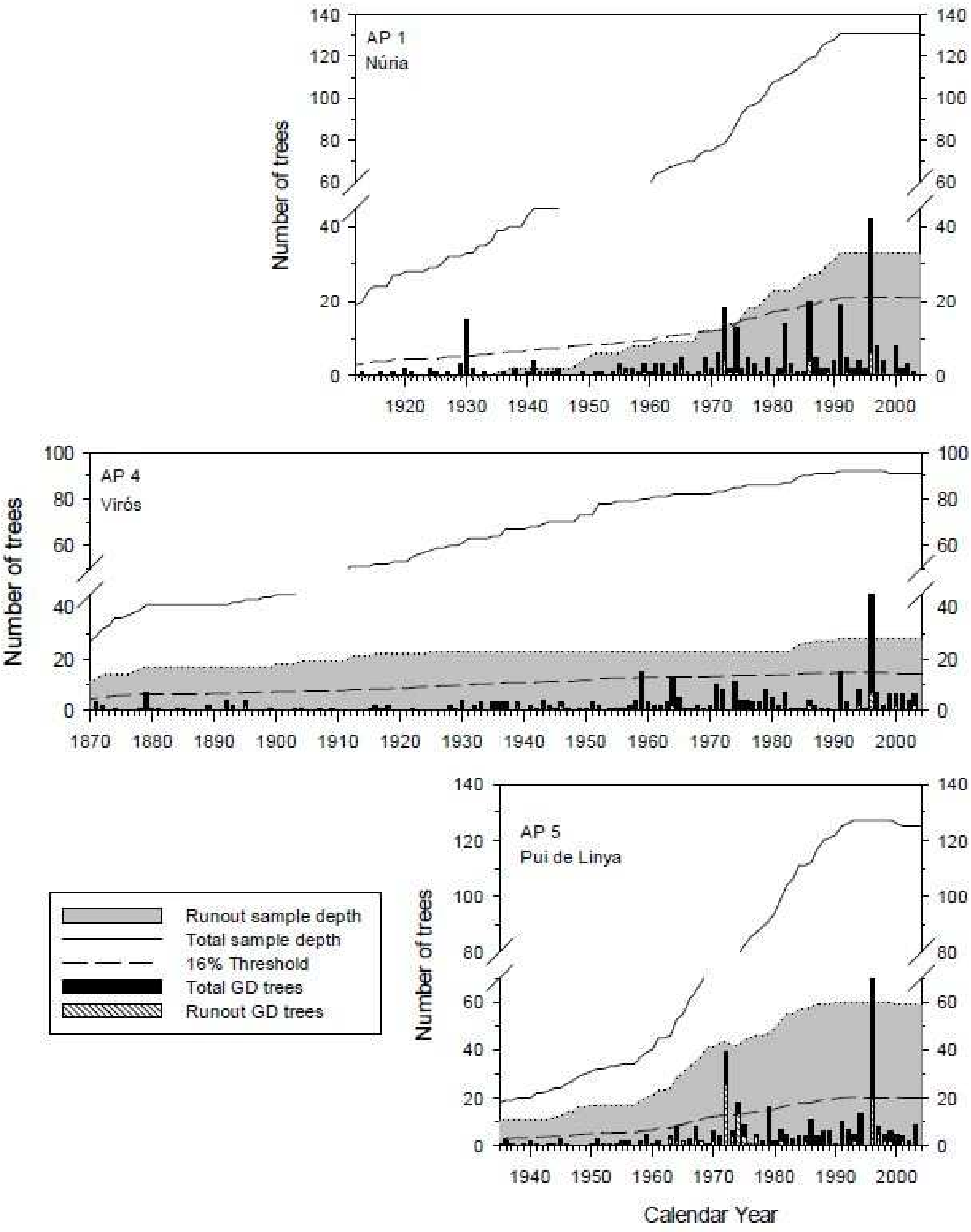


Figure 13: Event response histograms for paths AP 1, AP 4 and AP 5. The length of the time spanned coincides with a minimum sample size of 20 trees.

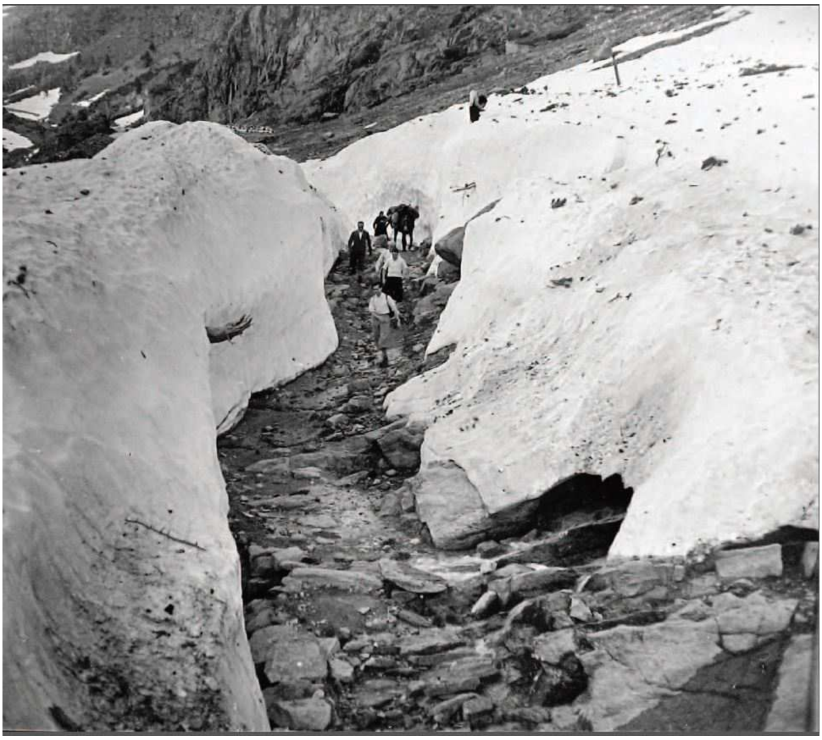


Figure 14: Old photograph showing an avalanche event in AP 1 that occurred in 1929–1930. The people are walking through the snow deposition in the runout zone. Note the broken trees protruding from the snow. From the picture, the deposition was more or less four meters high (in 1995–1996, the deposition was two meters) (with permission of Centre Excursionista de Catalunya archive; author, Albert Oliveras).

In this avalanche path, we were able to enlarge the span period owing to the unexpected finding of a picture taken in 1930 portraying an avalanche deposit at the runout, which corroborated the tree-ring evidence of a high magnitude avalanche in 1929-30 (Figure 14).

In AP 4 an avalanche in 1996 swept through a stretch of mature forest. As shown in Figure 13 a high proportion of GD trees in 1995-96 was detected in the upper portions of the path. Seven trees in the runout zone of AP 4 provided evidence of this same avalanche event as well. Dendrogeomorphological results showed no similar event for more than a century. A high proportion of GD trees in 1878-79, 1958-59, 1963-64 and

1990-91 may correspond to avalanche events that reached the middle track.

In AP 5, many trees were destroyed in the 1995-96 season. The dendrogeomorphological analysis corroborated this event and revealed another major avalanche that took place in 1971-72. A high amount of evidence was found for 1973-74 at the runout as well (13 trees), but although the 16% threshold was surpassed, there was little evidence in the track (5 trees). A smaller event was dated in 1978-79.

3.3.4.1.2Avalanche paths 2, 3 and 6

The event response histograms of the less exhaustively sampled avalanche paths are presented in Figure 15. In AP 2, according to an eyewitness, an avalanche released in 2003 and brought down numerous trees. Only samples from ten trees were collected in the narrow runout and from 26 along a transect at the middle track.

Here five events reaching the runout were dated by dendrochronology: 1968-69, 1971-72, 1981-82, 1995-96 and 2002-03. There was no evidence of the avalanche in 1995-96 at this site previous to the analysis. In AP 3, winter surveys reported two major avalanches in 1996 and in 2003. The 1995-96 event followed the mountain torrent, but the event in 2002-03 ran into the secondary runout (Figure 12) breaking and uprooting a few large trees (> 70 cm diameter at breast height). The sampling design was focused on this secondary runout area linked to rare high magnitude events. Here 39 trees were sampled in the runout. Dendrogeomorphology confirmed the event in 2002-03. It also confirmed that the event in 1995-96 had not reached this secondary runout. Tree-ring evidence found in 1909, 1927 and 1935 (three, four and three trees, respectively) could not be evaluated, since no samples were collected in the avalanche track. In AP 6, dendrogeomorphological evidence for events in 1985-86, 1993-94, 1995-

96 and 2002-03 was obtained, but no living trees were sampled in the runout.

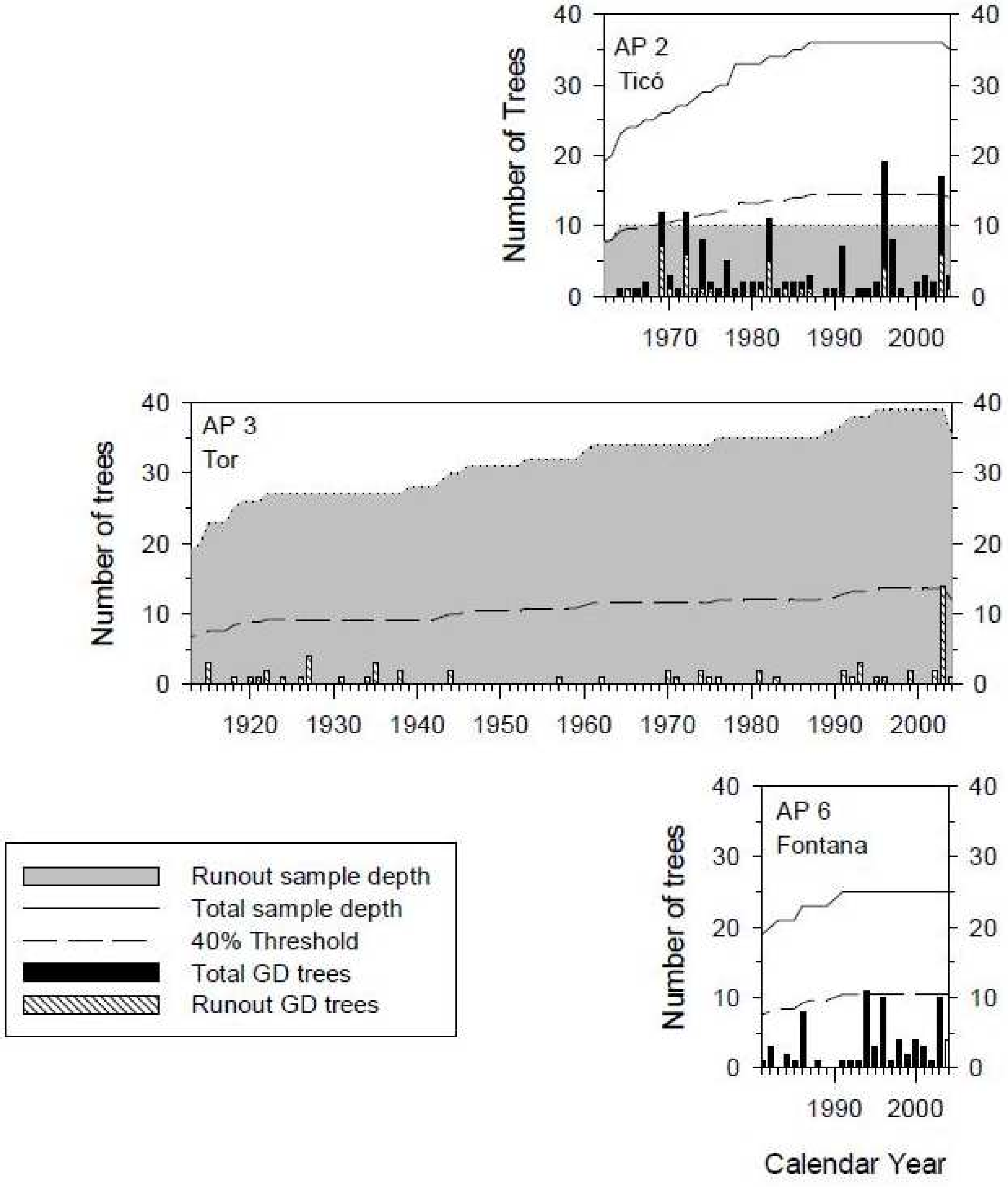


Figure 15: Event response histograms for avalanche paths AP 2, AP 3, and AP 6.

For this reason we could not verify the extent of these avalanches. Interestingly, a reported avalanche in 2003-04, which engulfed a car driving along the road in the runout, was not detected. In this study site, the dendrogeomorphological analyses were limited by the scarcity of trees and woody plants in the runout. *Figure* 16 summarizes all the dated snow-avalanche events in the six avalanche paths of the study.

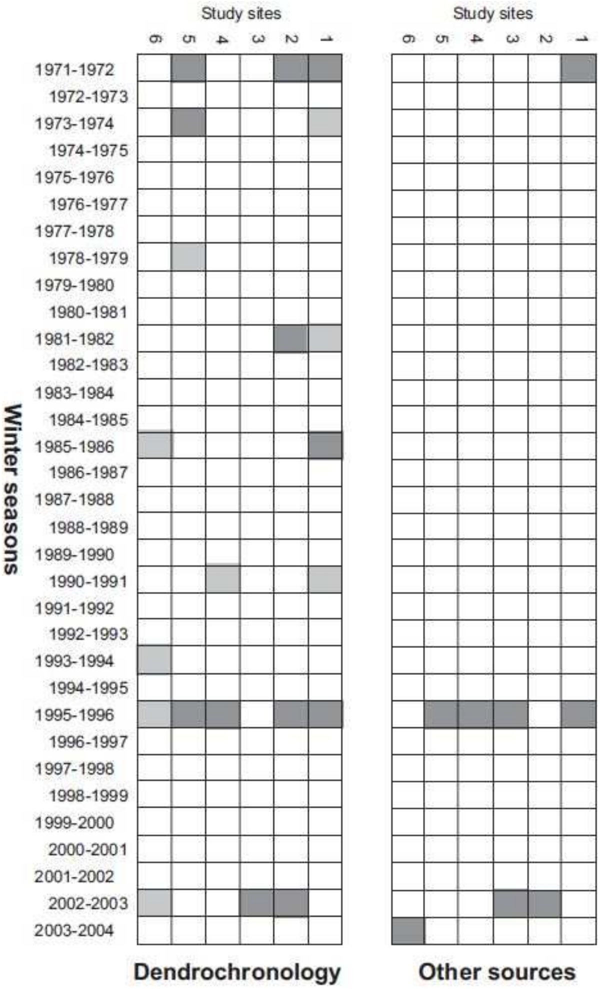
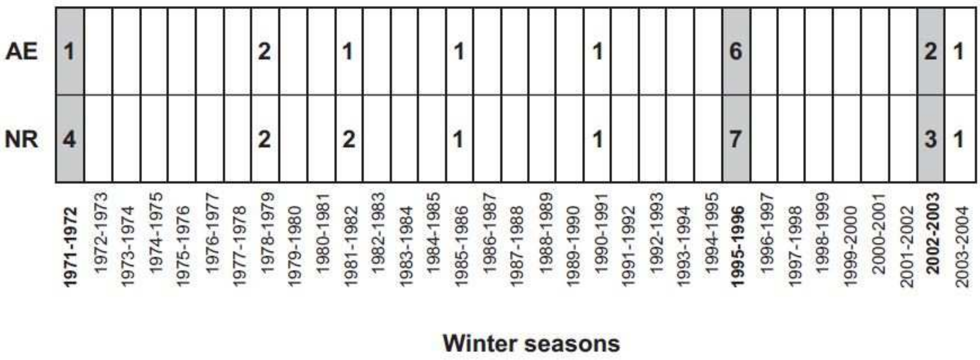


Figure 16: Dates of snow-avalanche events from 1971–1972 to 2003– 2004 in the studied avalanche paths. The left chart shows the dates obtained from the Avalanche Database of Catalonia. The right chart depicts the dates obtained by dendrochronology. Dark grey squares correspond to major avalanches and light grey to smaller avalanche events where there is no tree-ring evidence at the runout.

3.3.4.2 Meteorological and nivometeorological factors associated with major avalanche winters

The results of the research in meteorological and nivometeorological records for the period between 1971-72 and 2002-03 are shown in Figure 17. Compared with the other avalanche seasons, in 1971-72, 1995-96 and 2002-03 winters, a higher number of nivoclimatic regions were affected by avalanches (four, seven and three, respectively).



	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976	1976-1977	1977-1978	1978-1979	1979-1980	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989	1989-1990	1990-1991	1991-1992	1992-1993	1993-1994	1994-1995	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2003	2003-2004
AE	1							2			1				1					1					6							2	1
NR	4							2			2				1					1					7							3	1

Figure 17: Potential avalanche episodes and nivometeorological regions affected from 1971–1972 to 2003–2004. Avalanche activity was particularly high in winters 1971–1972, 1995–1996, and 2002– 2003 (AE-number of avalanche episodes, NR-affected nivometeorological regions).

3.3.4.2.1Major avalanche season 1971-72

In 1971-72 an extensive avalanche episode took place affecting a large area that comprised four nivometeorological regions. On 16-17 January, extensive but moderate snowfalls were recorded across the Pyrenees (40-60 $l{\cdot}m^{-2}$ of snow-water equivalent above 2000 m, but less in the valley bottoms). The synoptic atmospheric situation consisted in a deep trough crossing the range from west to east. Southern winds in cyclonic circulation blew over the Pyrenees, which favoured the precipitation by uplift effect due to the configuration of the main valleys. Taking into account the distribution of the thermal isolines at 850 hPa topography, the snow level was assumed to be above 1600-1700 m above sea level (asl) in the beginning, but descending as time passed. Under these conditions, fresh snow might have been wet and dense. The weather of the days preceding the snowfall was characterized by the passing of warm and cold frontal systems from the Atlantic Ocean. In these circumstances precipitations are usually scarce, but in the Pyrenees between 1500 and 2000 m, rain and snow alternate. These conditions favour the formation of weak faceted grains above thin crusts and as it is observed in a variety of snow climates avalanches may release as a result of that unstable snowpack structure. In addition on 18 January a cut-off low was identifiable both in the sea level surface map and in the 500 hPa map over the Mediterranean Sea. This situation generally generates strong northern winds over the TF region, resulting in the formation of thick wind slabs on south-oriented slopes. On 18 January, a large avalanche released from the south-oriented slope that damaged the rack railway in Nuria Valley at AP 1 (TF region).

3.3.4.2.2Major avalanche season 2002-03

During the winter 2002-03, two avalanche episodes that affected three nivometeorological regions were reported (AN, PL and RV). In the first episode, from 26-30 January 2003, a north advection produced heavy snowfalls during 96 hours accounting for more than two meters of new fallen snow at 2200 m asl. Much of the snow accumulation was due in part to wind drifting. Data was difficult to measure because of the strong winds (around 90 $km \cdot h^{-1}$) at high-altitude weather stations. However, the total amount of fresh snow that accumulated in the valley floors, which were sheltered from the strong winds corresponds to a return period of 30 years and draws attention to the severity of the event (Esteban et al., 2005). Following this storm, a total of 39 major avalanches released in three regions (AN, PL and RV). Snow profiles done close to the fracture line showed the formation of thick wind slabs on lee slopes with densities ranging from 140-180 kg·m^{-3}. Ram profiles indicated that below these wind slabs were thin crusts alternating with weak interfaces. A strong thermal gradient in the contact between the crust and the new fallen snow likely favoured the formation of a weak interface propitious to avalanche release.

The second episode took place from 26-28 February. As in the 1971-72 episode, a deep trough crossed the Pyrenees from west to east, but on this occasion, a small vortex with a humid, strong south-eastern flow coming from the Mediterranean Sea towards the southern side of the Pyrenees was generated. Winds blew from the south at 40-90 km·h^{-1}. The total fresh snow accumulation ranged between 40-100 cm at 2200 m in 72 hours. The new snow was very wet and dense and largely comprised of rimed crystals. Large avalanches released from 27-28 February mainly on north-oriented slopes.

3.3.4.2.3Major avalanche season 1995-1996

The 1995-96 winter was unusual because of the large number and regional extent of avalanche episodes (six in total). In addition, these episodes were triggered by different meteorological conditions (García et al., 2006). All the seven nivometeorological regions were affected by major avalanches in the winter of 1995-96. Indeed, some regions such as the western RF and the eastern TF were affected by major avalanches several times in the same winter (three times each). Figure 17 provides a schematic overview of the nivometeorological regions affected by the diverse atmospheric conditions.

The episode of December, 1995 corresponded to an east advection. It was explained by a blocking high pressures situation at 500 hPa over Central Europe and a cut-off low centred over the southwest of the Iberian Peninsula. A warm and very humid Mediterranean flow on surface penetrated from the east affecting the regions closest to the Mediterranean Sea, and also distant regions such as south-facing RF.

The most intense major avalanche episode took place at the end of January, 1996 as a result of a southwestern synoptic situation. A number of large, powder snow avalanches over four nivometeorological regions were triggered shortly after snowfall (Figure 18). A deep low pressure was located over the northwestern coast of the Iberian Peninsula. From surface to upper atmospheric levels south and southwesterly winds prevailedbringing warm and humid air from the Atlantic and the Mediterranean to the lower levels in the Pyrenees. High instability was attributed to a deep cold core at 500 hPa level. In the PR region, a precipitation gauge at the Port del Comte nivometeorological station recorded a maximum of 220 $l{\cdot}m^{-2}$ of snow water equivalent in 24 hours, and snowfall exceeding 150 $l{\cdot}m^{-2}$ was recorded in several other nivometeorological regions. These extreme values were largely atributted to convective cell growth. This means a Gümbel return period (Gumbel, 1958) for a snowfall slightly exceeding 100 years in the PR region. A return period is the average interval of time which the runout distance is reached or exceeded at a given location (McClung and Schaerer, 2006); note that it means that an event will not happen regularly in the given interval of time, but it has been observed to ocur in this interval. As shown by Esteban et al., (2005), heavy snowfall including torrential rains affect the southern side of the Pyrenees in such a synoptic circulation pattern. Shortly afterwards the following avalanche episode began to form.

From 6 through 9 February, 1996 another large avalanche episode occurred. The storm was a result of typical northwestern advection characterized by both warm and cold fronts passing over the Pyrenees and giving rise to high and low snow levels and intermittent precipitation. Intense drifting that occurred during the storm made it difficult to determine the amount of precipitation. However, the maximum amount of new snow above 2000 m asl reached 100 to 140 cm after 72 h of snowfall in the AP region.

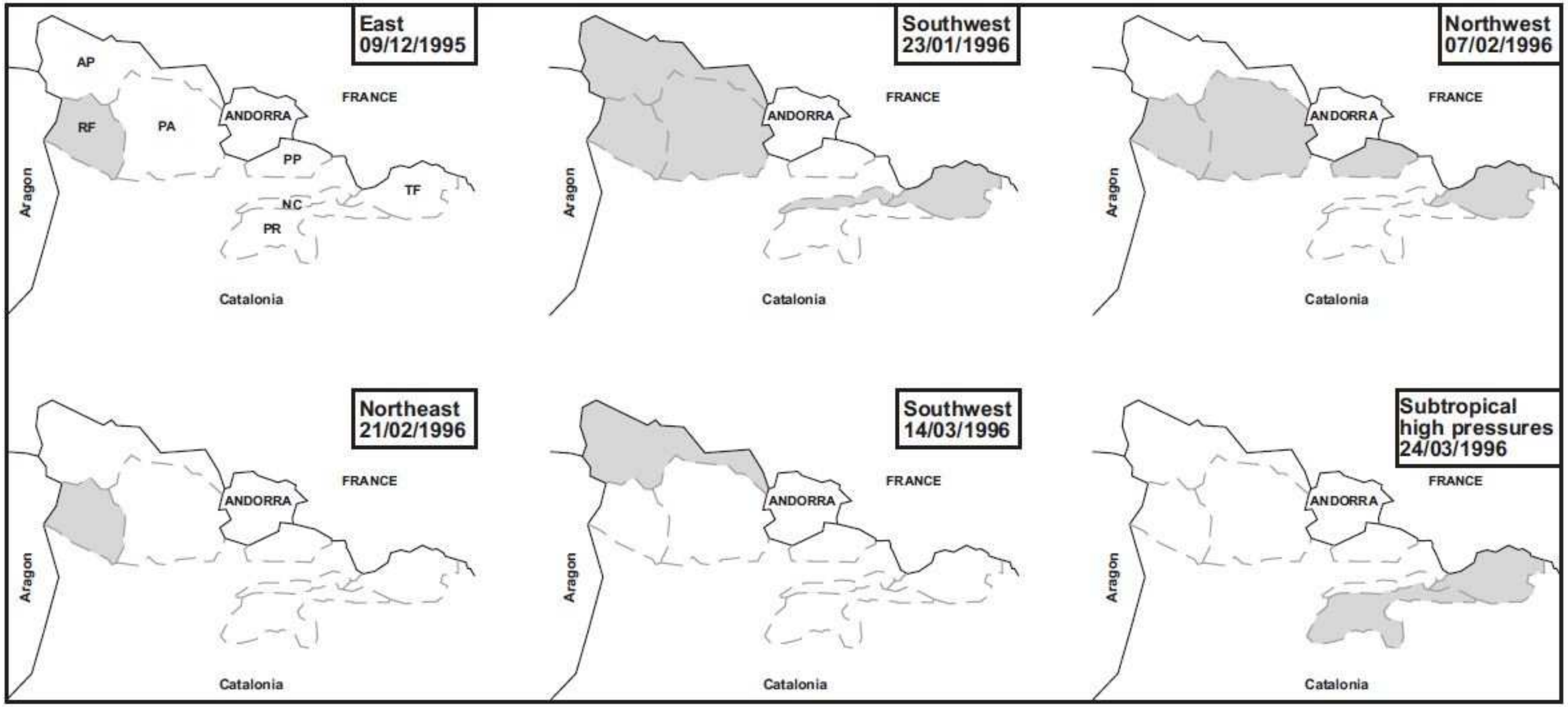


Figure 18: Atmospheric conditions of potential avalanche episodes and affected nivoclimatic regions in 1995–1996 winter in the SE Pyrenees.

Although some regions uncommonly experience snowfall in the northwestern advection regime, extreme avalanches do occur under this synoptic pattern where snowfall is abundant.

It may also be suggested that extreme avalanches took place in regions where new snowfall amounts were moderate owing to snow accumulated/transported by the wind from the preceding episode (21-24 January). Large amounts of drifted snow exceeding four to five meters in depth were measured in the avalanche starting zones on lee slopes. The new snow was mainly comprised of small, low density fragments that drift easily. Fresh wind slabs overloaded southern lee slopes and eventually released.

The fourth episode was caused by a storm with strong winds from the north on 22 February. The Azores high pressures were extended in a north-south axis over the Atlantic Ocean, while a deep low pressure was located on the Baltic Sea-Italian Peninsula axis in a typical configuration. This pattern pumps either an arctic or a maritime polar air mass over the Pyrenees, and generates very low temperatures (-15 to -20º C at 2200 m asl), intense snowfalls, strong winds and very active snow drift processes which can result in avalanche releases.

The fifth episode occurred on 14 March and it corresponded to a trough passing. In this pattern, atmospheric circulation is characterized by a long trough at 500 hPa exhibiting an oblique NW-SE axis, caused by the Siberian high pressure over Europe which diverts troughs to the Mediterranean basin. Normally, this yields a small low at surface atmospheric level over the Mediterranean Sea. A humid, maritime flow on surface produces heavy precipitation in the regions closest to the Mediterranean Sea. Instability is high due to the contrast between cold air at 500 hPa and a relatively warm air mass at low atmospheric levels. The snowpack usually contains weak layers with depth hoar and faceted grains before fresh snow arrives, since low temperatures and strong irradiation prevail below the Siberian high pressures influence.

The last episode took place from 22 through 24 March and it was associated to melting processes. A ridge from the subtropical anticyclonic belt spread to the north over the Western Mediterranean Sea. Usually, when this occurs, a warm advection at low atmospheric levels (850, 700 hPa) reaches the Pyrenees. The snow cover suffered sudden melting processes and major avalanches descended while the inner layers still contained cold, persistent grains.

3.3.5 DISCUSSION

3.3.5.1 Dendrogeomorphology

Our dendrochronological analyses corroborated most of the documented dates and yielded other avalanche dates that had not been recorded hitherto in the six avalanche paths we sampled (Figure 19). By examining the spatial distribution of GD trees within each path, we verified whether avalanches had reached the runout or had most likely stopped higher in the track. The number of detected major avalanche events increased from 1971-72 to 2003-04 from 8 to 14. These occurred in a total of nine winter seasons. Twelve minor events were also detected. As indicated by Hebertson and Jenkins (2003), major avalanche episodes are expected to affect a large number of paths. In our study, regional-scale weather patterns during the winters of 1971-72, 1995-96, and 2002-03 resulted in avalanches affecting at least three paths each. Snow avalanches occurred in all six paths in 1995-96 suggesting the severity of this winter.

The sampling design in AP 1, 4 and 5, provided the most reliable results on avalanche dating, and allowed the extent of successive events to be more accurately mapped, or existing maps expanded. This is an improvement over conventional avalanche mapping techniques, particularly in paths where visual indications of forest damage are no longer apparent. For example, in AP 5, dendrogeomorphology revealed that a high-magnitude avalanche in 1971-72 exceeded the runout by a considerable distance (Figure 19). Consequently, the runout map was increased by 200 m.

The less exhaustive sampling carried out in paths AP 2, 3, and 6 did not provide interesting results in terms of time period and extent of avalanche events, but rather illustrated the limitations of different sampling strategies. As long as these limitations are realized however, results can still be robust. For example, in the narrow AP 2 path we discovered that avalanches are very frequent, but we conjecture that event size or severity could vary according to avalanche width and not to length. This could not be evaluated by sampling trees only in the middle track and in the runout. Further research to settle this presumption should include sampling along transects at intermediate elevations. In AP 3, where sampling was done in the runout, the evidence detected for 1909, 1927 and 1935 could not be validated with samples from the track.

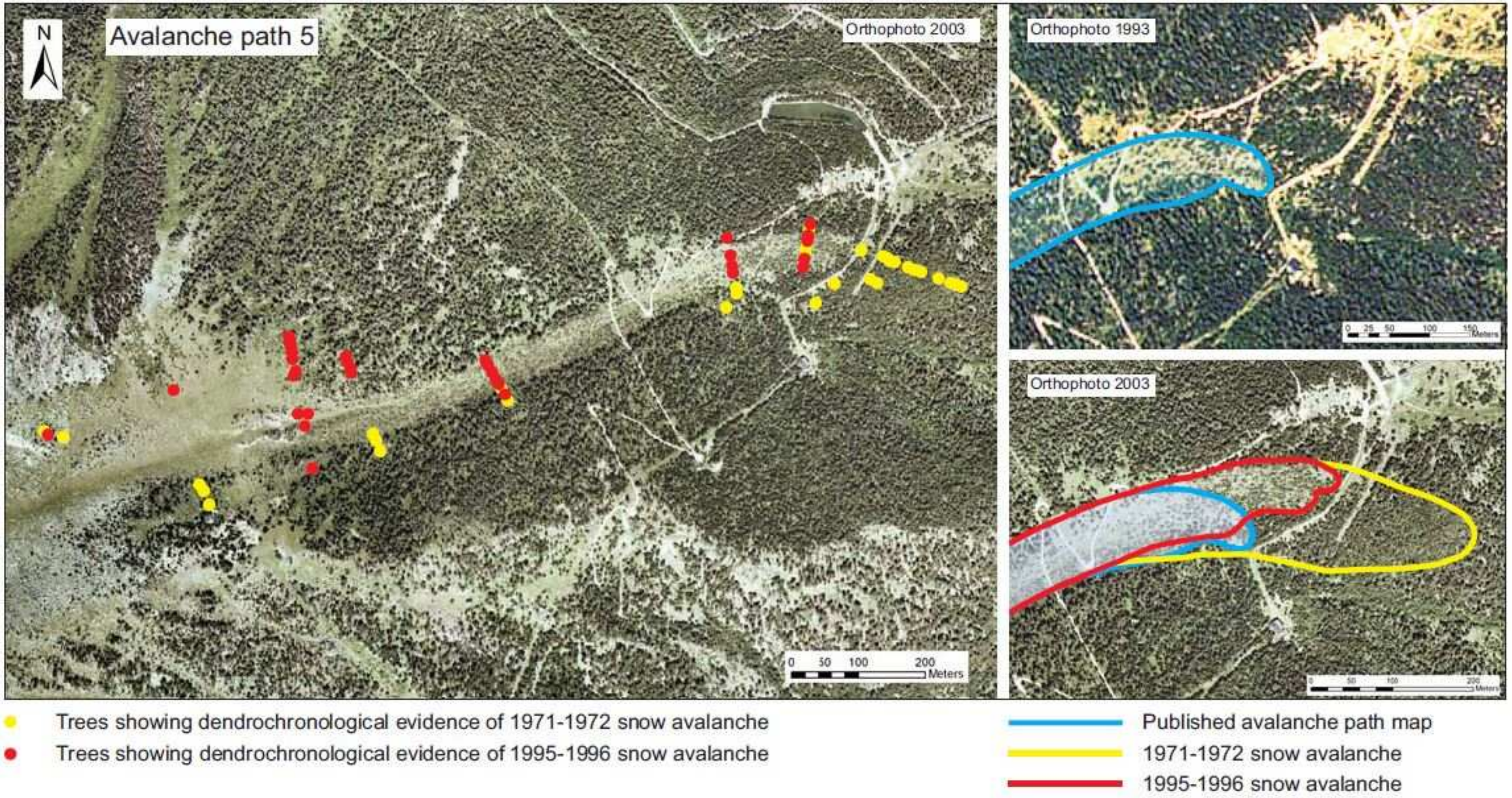


Figure 19: Dendrogeomorphological mapping. The avalanche path map in AP 5 was improved using dendrogeomorphology. The 1971–1972 major event (not detected by conventional field surveys) allowed us to extend 200m the vulnerable area in the runout.

This hampered the interpretation of potential events of similar magnitude such as the exceptional avalanche occurred in 2002-03.

In AP 6, an avalanche documented in 2003-04 was not detected by dendrogeomorphological means. This could be due to the natural scarcity of trees in the runout, or perhaps to previous avalanches that occurred in 1995-96 and 2002-03 and destroyed the trees along the track.

A similar circumstance could have happened in AP 5 for the 1973-74 event. A major event in 1971-72 could have removed the majority of trees in the avalanche path reducing the possibility of recording a subsequent event. This previous large event could also have facilitated the release of a later event a short time after. The removal of a large number of trees that typically serve as snowpack anchors results in a smoother path. This can contribute to greater avalanche frequency even in regions where nivometeorological conditions are not especially propitious. Further support for this idea was found at AP 1, where two major avalanches were registered in the same winter, 1995-96 (see Molina et al., 2004). In this same way, Germain et al., (2005) reported evidence of increased avalanche activity in paths denuded by forest fires and logging.

Events that had been documented in 1995-96 showed high index numbers (from 32 to 57% of GD trees), but these were extreme events. The documented event in 1985-86 at AP 1 displayed a lower 16%. This percentage was used in the present work as a rough threshold to decide avalanche occurrences. In our opinion, low indexes should be used only in the case of densely sampled avalanche paths (such as AP 1, 4 and 5). The prevailing rule in this present research was not only to consider the spatial distribution of evidence, stressing the importance of the runout GD trees, but also the importance of track sample replicates. In the case of poorly sampled avalanche paths (AP 2, 3 and 6) deciding thresholds were more restrictive and, apart from the runout consideration, more than 40% GD trees were required to assess avalanche occurrence. The question is how to develop complete tree-ring chronologies in the event an avalanche destroys all the trees in a path and consequently most evidence. Carrara (1979) first posed this question suggesting that avalanches which were not powerful enough to destroy trees, but instead only damage them, record their occurrence in the sequence of annual rings. Evidence of more destructive events can be lost because dead trees disappear. On the other hand, avalanche events do not always result in tree ring responses in trees as was observed in 2003-04 documented event in AP 6. For all the above reasons, expert criteria is still compulsory to obtain reliable results, particularly in the case of sparsely forested paths, or when attempting to date old events. Experienced dendrogeomorphologists sometimes need only one tree to assess the occurrence of an avalanche (Furdada, pers. comm. 2002). Nevertheless, information provided by means of dendrogeomorphological methods is the most reliable compared to other approaches such as vegetation evidence or enqueries to old people. The dates yielded by trees have annual resolution, are absolutety dated and have spatial positioniong. Thus, by means of an appropriate sampling, dendrogeomorphology can provide information about the extent and occurrence of past avalanche events.

3.3.5.2 Nivometeorology

From a nivometeorological point of view, it should be noted that the three major avalanche seasons (1971-72, 1995-96 and 2002-03) were characterised by a wide variety of atmospheric situations that released major avalanches. Nine avalanche release episodes corresponded to six different synoptic patterns. The major avalanche episodes were correlated with synoptic patterns in the Eastern Pyrenees from 1985-86 to 2005-06. Synoptic patterns leading to major avalanches were found out. They were northwestern advection, trough passing pattern, eastern advection, southwestern advection, low centered pattern and subtropical ridge pattern, Compared with nearby mountain ranges like the French Alps, the Eastern Pyrenees exhibit a wider variety of synoptic patterns releasing major snow avalanches. Accordingly, weather patterns resulting in some avalanche episodes were more localized, i.e one nivometeorological region affected during the second episode of 2002-03, and others resulted in a wide spatial extent of releases, i.e. four regions affected during the episode of 1971-72. In this study, the southwestern synoptic pattern was most common during the three winters with major avalanche occurrence and was the synoptic pattern that affected most nivometeorological regions (three in average).

As shown by Beniston et al., (1996), the evolution of the main meteorological parameters such as temperature, precipitation and winds is conditioned by the North Atlantic Oscillation index (NAOi) in mountain ranges such as the Alps. The correlation between winter precipitation and NAOi has been investigated in the Pyrenees by Martín-Vide et al., (1999) and Esteban et al., (2001). Both their results show a negative correlation. Accordingly, in this study the three major avalanche winters of 1971-72, 1995-96 and 2002-03 were correlated with the variation of NAO (Climatic Research Unit, University of East Anglia: http://www.cru.uea.ac.uk). These three winters had negative NAOi anomalies (standardized NAOi values for the reference period series 1961-1990 as follows: -0.13 for 1971-72, -2.23 for 1995-96 and -0.09 for 2002-03). Hence, more major avalanche episodes should be investigated in order to verify the correlation between major avalanches and NAOi.

In view of these results, the winter of 1995-96 was most extraordinary with respect to the occurrence of major avalanche events in recent decades in the SE Pyrenees. The combination of a regional dendrogeomorphological study and meteorological and nivometeorological analyses of weather records allowed us to determine whether avalanches had been the result of a generalised nivometeorological situation or whether weather conditions for avalanche release were more localized.

4 GENERAL DISCUSSION

Several issues are still in debate among the dendrogeomorphological community working on snow avalanche reconstructions. These include the question of sample size, the decision making index number and the possibility of weighing signals to quantify avalanche severity. Other questions are already quite settled although some may need further research. I will start with the latter.

4.1 EXACT DATE OF AVALANCHE SEASON

Dendrochronological analyses of samples from trees growing in snow avalanche paths allow to date past events with an annual resolution. In the beginnings, researchers (Burrows & Burrows, 1976; Carrara, 1979) dated events by simply counting tree rings. Sometimes an approximation of decades was enough. Nowadays this is still the habit when using roots and short-lived woody species because a proper dating is not easy in these cases. However, dendrochronological techniques permit an exact dating of the avalanche season in a great proportion of samples. Dating to the year is necessary to estimate process frequency and also, to reconstruct the most likely episode if nivometeorological records are available.

In the case of *Pinus uncinata* from the Pyrenees, samples from disturbed trees have proved to be easier to date, and longer-lived trees than other available species from the angiosperm division growing in the same region. These include *Fagus sylvatica* L., *Betula* L. sp. (*B. pendula* Roth, *B. pubescens* Ehrh.), *Corylus avellana* L., *Sorbus aucuparia* L., *S. aria* (L.) Crantz, *Salix* sp. (*Salix caprea* L.), *Acer* L. sp. (*Acer opalus* Mill.), *Tilia* L. sp.

(*T. platyphyllos* Scop., *T. cordata* Mill.), *Populus* L. sp. (*P. nigra* L., *P. tremula* L.), *Fraxinus* L. sp. (*F. excelsior* L., *F. angustifolia* Vahl), *Quercus* L. sp. (*Quercus petraea* (Matt.) Liebl.) *Alnus glutinosa* (L.) Gaertn.

When working with snow avalanche samples from trees, dendrochronological signals of disturbance appear already in the first rows of cells in the tree ring. Therefore there is ordinarily no doubt about the season when the event took place, which is the inactive growth period of the tree, i. e. winter. Despite this, it is not possible to disentangle in which moment of the winter season did the snow avalanche descend. This would be useful in the cases when more than one avalanche occurred during the same year as it happened in Canal del Roc Roig (see section 3.1) in 1995-1996, and for instance, this would help to corroborate whether the occurrence of one major avalanche facilitates the occurrence of a second one as is suspected.

4.2 LIMITATION TO 150 YEARS AVALANCHE DENDROCHRONOLOGIES

Initially, there were high hopes of dendrochronology expanding snow avalanche chronologies in the Pyrenees. To accurately calculate event frequency a high number of events is needed. This means having a long record. Tree age is a first order limiting factor. After working on several avalanche paths, my experience is that it will be difficult to exceed 150 years in the Pyrenees as a rule. Tree longevity in avalanche paths is not the reason. Trees, *Pinus* sp. in particular, can reach 200, 500, even 800 years in the Pyrenees. The main reason is likely the long history of high-mountain land uses, for cattle and forest exploitaition. Therefore in practice, the length of the dendrochronological record seemingly will not surpass the length of the archival record. Nevertheless, dendrochronological records have some advantages over historical documents. Usually, described facts explain circumstances which have happened to people or goods, and generally neglect punctual or far-away events. Conversely, dendrogeomorphology is faithful to the facts, on condition that sample gathering is profuse, well distributed throughout the avalanche path and the dendrochronological analyses reach high standards.

4.3 SAMPLING DESIGN IN TRANSECTS

In my opinion, the clues to a successful dendrogeomorphological job lie in two main activities: fieldwork and dendrochronological analysis. Although this assertion may seem obvious, emphasis must be placed on these tasks.

Fieldwork entails sampling design. The sampling strategy is of crucial interest. Researchers tend to concentrate efforts in avalanche runout sectors. Detecting and dating major-avalanche events is behind their plan. Major avalanches are destructive events which can cause fatalities, loss and notable expenses. Therefore finding out extent of extreme runouts should always be bore in mind. If no such recent event is recorded, dendrochronologists will have to sharpen their skills to unleash hidden evidence from trees. Nevertheless, I avow for a sampling campaign at different heights reaching the highest altitudes where forest is available up to the treeline. In the studies presented in this thesis the sampling was designed in transects across the avalanche paths at several heights. These transects covered the avalanche paths clearing transversally, but penetrated also in the forest some meters to look for exceptionally wide events. In the runout, if forest is available, past major events which remain hidden can be searched for. Gathering samples from a variable number of trees growing along the transects rendered dendrochronological evidence of a variety of growth disturbances. Redundancy along and among transects was the hint to decide whether we had to consider the particular year as an avalanche year. Transect distribution along the avalanche path was previously determined by observing the avalanche path poligon on the Avalanche Paths Map, and this simple decision can ban out other ecological disturbances coming from processes different from snow avalanches. For instance, forest fires can cause scars which can be misinterpreted, particularly if they are old, also they can provoke tree fall and tilting of neighbours which will produce reaction wood, but the shape of this event will probably be different from the avalanche trajectory and there will be clues to interpret that it is a different process. By embodying most of the avalanche path shape, processes which could have a different shape can be discriminated. Similar conclusions are stated by Martin & Germain (2016).

Furthermore, this approach of transversal-transects at several heights allows to follow avalanche events downslope and discern the approximate lowest level which they reached. The underlying purpose to follow avalanche events downslope is to assess whether a disturbance detected at the lowest levels is also detected at higher levels and thus decide if it was an avalanche or not. The likelihood of a disturbance being a snow avalanche when the only evidence is detected at the runout is not well supported.

Another benefit of the multi-transect approach at different heights is the reconstruction of the various sizes that avalanches can attain in an avalanche path and also their particular approximate frequency (Figure 20).

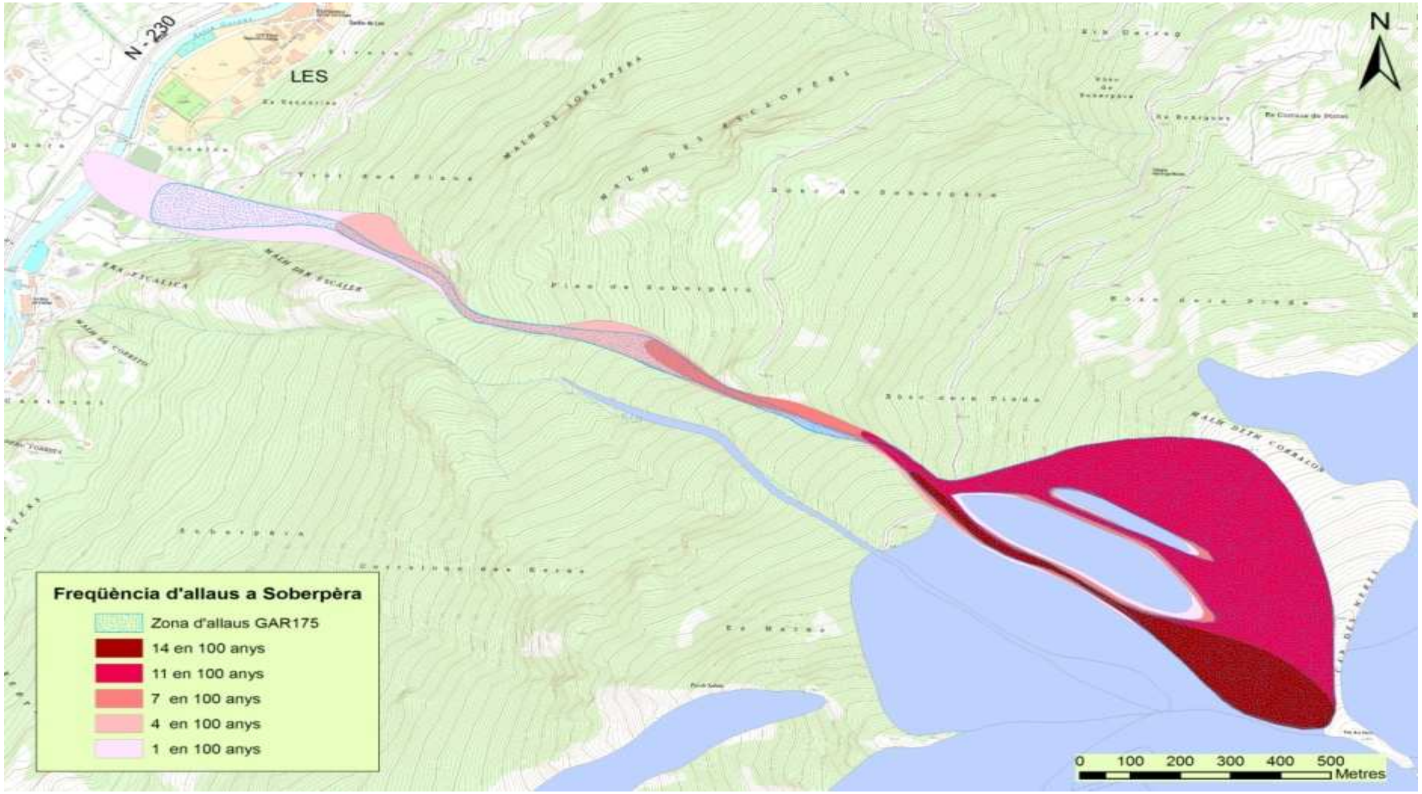


Figure 20: Snow avalanche frequency map developed from analysis of samples from growth disturbed trees at different heights (Barranc de Soberpèra, Val d'Aran). Estimation of the number of events per altitudinal sectors, from 1 every 100 years at the extreme runout at 640 m a.s.l. (information from interviews to locals) to 14 or more events every 100 years above 1575 m a.s.l. (data from dendrochronological analysis) (from Muntan, 2012)

4.4 BUDGET CONSTRICTIONS FOR AVALANCHE PATHS SURVEYS

All this said, time constraints, field logistics, and safety and monetary considerations are among the items that must be balanced when deciding upon a sample size as stated by Butler & Sawyer (2008). For that reason, when a survey is needed, a three-step previous preparation should be done. First, a search in all possible sources (historical documentation, interviews to people preferably local elders, avalanche data bases, etc) should be carried out. Secondly, a careful contrast of all available aerial photographs to find out previous events and depict the critical areas in the avalanche path. Finally, a thorough field inspection before deciding the sectors where the dendrochronological sampling should be done. Usually this previous field inspection of the avalanche path discloses details and reveals target areas where sampling is most decisive and which can save time and money.

4.5 DECIDING ON THE INDEX NUMBER AND NUMBER OF TREES TO SAMPLE

The index number as defined by Shroder (1978) was used in this Ph.D. thesis to build the event-response curve at every avalanche path. There has been a long discussion about the proportion of growth disturbed samples needed to decide whether the cause was an avalanche or not. Butler & Malanson (1985) propose a 40% for a major event, and in accordance with them the amount of trees with growth disturbances for the major events in 1996 in Roc Roig avalanche path was very close to this number. More recently, Butler & Sawyer (2008), in the case of smaller events, advocate for a 20%, and they suggest to temper the number with a known event. Also in Roc Roig avalanche path the threshold to accept avalanche years was decided in view of the results from 1986 avalanche event (see section 3.1.4.2.). My opinion is that a lower number could be too low to accept a number of tree disturbances as an avalanche event, because there is ordinarily a varying number of undetermined disturbances going on in tree stands. Only when an avalanche event is very recent and unmistakable one could accept such low index number as 10%.

As for the number of trees to sample, Corona et al., (2012) calculate a rough estimate of 100 trees, which is in agreement with the number of trees sampled in most of the study sites in this thesis.

4.6 AGAINST WEIGHTED SIGNALS

Some geomorphologists starting with Frazer (1985) working on the snow avalanche process devised a damage classification. Butler & Sawyer, 2008 summarize the tree-ring damage rating in five cathegories, at the same time as they state that there is no agreement among dendrogeomorphologists as whether this is necessary. Some researchers even develop specific weighting factors for the growth disturbances of their species, e.g. Kogelnig-Mayer (2011) working with *Picea abies* which displays traumatic resin ducts. Many factors influence the response of trees to snow avalanches which are still not well understood, meaning that the same process can produce very different effects on trees which are living close to one another. These factors include tree size, tree shape, tree age, growth rate and tree species. Position in the avalanche path, reactions to previous events and time passed since the preceding events are also factors which influence the response and filter the tree-ring reactions which will remain or disappear. Personally I don't rely on the rating criteria and prefer to weight all reactions equally. Intensity of reaction of a tree to a particular event can depend on factors as described above. Furthermore, evidence from old events is often kept in trees not too much affected, or well out of the reach of unusual high magnitude events, for trees which are more exposed are more likely to disappear. In these cases, more feeble tree-ring signals can signify a higher magnitude event.

5 CONCLUSIONS

5.1 GENERAL CONCLUSIONS

Dendrochronology proved to be a good tool to date past avalanche events using wood samples from *Pinus uncinata* trees growing in avalanche paths in the Pyrenees. The combination of data obtained by dendrochronological techniques and information gathered from other sources (historical archives, enquires to local people, winter surveys, nivometeorological records) is the best way to acquire data about past avalanche events.

Dendrogeomorphological techniques provide us with information on date and extent of past events and thus, the frequency of events in an avalanche path can be estimated and the map of the most extraordinary events can be drawn. Like that our knowledge on avalanche dynamics in the Pyrenees is improved.

5.2 CHAPTER 1: DATING OF SNOW AVALANCHE EVENTS USING DENDROCHRONOLOGY

- The 1996 avalanche season was clearly detected in *Pinus uncinata* tree rings. Thus dendrochronology proved to be a good tool to date past avalanche events, and other documented and undocumented events were also dated.

- From a total number of eight avalanche events, five could only be dated by dendrogeomorphological means, revealing the potential of this tool to increase the knowledge on avalanche frequency in the Pyrenees.

- In Roc Roig avalanche path (Vall de Núria, Catalonia) the documented extreme event in winter 1995-1996, and the previously unknown 1929-1930 event, also extreme, showed growth disturbances in a high proportion of trees close to 40% of all sampled trees (87 out of 244 trees in 1996, and 29 out of 68 in 1930).

- *Pinus uncinata* tree rings showed a variety of signals in response to avalanche effects. The combination of different signals is important to ascertain the occurrence of avalanche events.

5.3 CHAPTER 2: CHARACTERIZATION OF SNOW AVALANCHE EFFECTS AND REACTIONS IN PINUS UNCINATA TREES

- In Barranco de las Fajas avalanche path (Sallent de Gállego, Aragon) the effects of a recent major avalanche event in 2007-2008 on *Pinus uncinata* showed the diversity of tree morphologies in an avalanche site. A great proportion of trees were killed and transported, decapited or thrown over to the horizontal position. A typical traumatism caused by snow avalanches, displayed by many trees, were elongated corrassion scars on the upper-slope face of the trunks.

- Describing and quantifing disturbed tree morphologies should contribute to discriminate among the different geomorphological hillslope processes, at the same time that it can help us to select trees most interesting for dendrochronological dating purposes.

5.4 CHAPTER 3: RECONSTRUCTING SNOW AVALANCHES IN THE SOUTHEASTERN PYRENEES

- The 1995-1996 winter was the most extraordinary avalanche season in the last decades in the SE Pyrenees. The combination of a regional-scope dendrochronological study together with meteorological and nivometeorological analyses of weather records, allowed us to determine whether avalanches had been the result of a generalised nivometeorological situation or otherwise, conditions for avalanche release had been more local. In this manner, three regional-scale avalanche seasons were detected by dendrochronology and their synoptic atmospheric patterns described in 1971-72, 1995-96, and 2002-03.

- The present study contributed to reassert that where snow avalanche records are scarce, the number of detected past avalanche events increases susbstantially by dendrochronology. In the present study, the total number of dated avalanche events doubled, reaffirming the usefulness of this tool in avalanche research.

- A high number of sampling transects and sampled trees, as was carried out in several avalanche paths, constitute the most desirable sampling method to accurately date the highest number of past avalanche events per site, and to allow avalanche size comparisons as well.

- As was demonstrated by the dendrochronological analyses in an avalanche path, extreme runout distances can exceed regular distances by a long tract. For land-use planning, the identification of the area in danger is of paramount importance. In hazard zoning, dendrogeomorphological mapping should be used where woody plants are available. Dendrogeomorphology is the only tool which can render evidence of the extent of past events when other sources are missing.

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7 APPENDIX

7.1 RECONSTRUCTING SNOW AVALANCHES IN THE SOUTHEASTERN PYRENEES

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Reconstructing snow avalanches in the Southeastern Pyrenees

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Abstract. A regional study of snow avalanche processes was undertaken in the SE Pyrenees. Dendrogeomorphology was used to date and reconstruct large-scale snow avalanche events that occurred in the last four decades. Dendrochronological analyses yielded the dates of nine winters when avalanches occurred in the recent past in six studied avalanche paths. Some of these avalanches were already known, but others had not been documented. In one case, the existing avalanche path map was improved with the dendrogeomorphological information of a larger past event. As a result of the dendrogeomorphological analyses, evidence for three regional-scale major avalanche years was identified in the SE Pyrenees from 1971 to 2004: 1971–1972, 1995–1996 and 2002–2003. The specific synoptic atmospheric situations and the most likely nivometeorological and snowpack conditions that released these major avalanches were determined using weather data for the seasons of major avalanche releases. In 1971–1972 the snow avalanche episode was characterized by a deep trough crossing the Pyrenees. In 1995–1996 a variety of meteorological situations produced several episodes of major avalanches. In 2002–2003 the more significant of two episodes was attributed to a north advection pumping an arctic air mass over the Pyrenees. The 1995–1996 avalanche season proved to be the most notable in the four past decades in the Pyrenees.

1 Introduction

In recent times, the southern Pyrenees have undergone a profound land-use and economic transformation. Traditional rural society has given way to a growing leisure industry related to winter sports and mountain recreation in general. Rapid urbanisation and the resulting population densities have increased the number of people at risk in these areas. In 1995–1996 a large number of avalanches occurred in the Pyrenees. An avalanche warning system (avalanche forecast) prevented human casualties, however there was considerable damage to forests and infrastructure.

For hazard analysis and risk prevention in alpine and subalpine mountain areas, knowledge of snow avalanche characteristics is of paramount importance. To this end, present and past events must be researched in order to obtain information on avalanche extent, frequency and intensity. In every avalanche path, snow avalanches can attain different extents depending on interactions between terrain, weather conditions and existing snowpack structure. Small avalanches take place regularly, but large avalanches occur less frequently. Study of historical documents, interviews with local people, winter monitoring, meteorological data, field survey and avalanche path mapping are some of the conventional means to characterize snow avalanches. Dendrogeomorphological analysis of trees at avalanche sites is helpful in providing information about the return period and extent of avalanche events where these data are lacking.

Temporal and spatial characteristics of snow avalanches can be reconstructed by dating tree-ring responses caused by past events. Trees growing in mountain environments can be affected by a variety of natural disturbances (biological and non-biological). Different kinds of damage produce similar responses and thus similar tree-ring evidence. After a thorough dendrochronological dating process, those tree-ring features not caused by snow avalanches are discarded and thus clues to the occurrence of past events may be obtained from evidence of disturbances and spatial distribution of trees at avalanche sites.

The usefulness of dendrochronological techniques in snow avalanche research has been demonstrated since the

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beginnings of dendrogeomorphology (e.g.: Potter, 1969; Burrows and Burrows, 1976; Butler, 1979; Carrara, 1979). The most common features used by these researchers were scars on trees, changes in growth patterns from concentric to eccentric, appearance of reaction wood, abrupt growth disturbances (increase or decrease in growth rate), age of trees in naturally reforested paths, year of death of trees in debris, and breakage of stems or branches. Recent dendrogeomorphological works on snow avalanches continue to use these features to date events (e.g. Jenkins and Hebertson, 2003; Dubé et al., 2004; Germain et al., 2005; Stoffel et al., 2006; Casteller et al., 2007; Mundo et al., 2007; Reardon et al., 2008).

Snow avalanches have been poorly documented in the Pyrenees. Despite some pioneering mitigation work in the central Pyrenees in the early twentieth century, the study and management of snow avalanches was not undertaken until the 1980s (Muñoz, 1980; Furdada, 1996). The significant avalanche season 1995–1996 raises two main questions: was 1995–1996 such an extraordinary avalanche season? Had there been any similar avalanche seasons in the recent past? The present work seeks to answer these questions. Specifically our objectives were to: 1) date and reconstruct the spatial extent of recent past avalanches using dendrogeomorphological methods in a set of six selected avalanche paths; and 2) determine the synoptic atmospheric patterns releasing major avalanches and their regional extent.

Our findings will be helpful to land-use planners who can utilize the information to develop more rational avalanche protection strategies and implement measures to mitigate snow avalanche risk. With respect to this, details on the dendrogeomorphological methodology, its strengths and weaknesses, are also discussed.

2 Study region

The Pyrenees mountain range extends over 450 km from the Mediterranean Sea to the Atlantic Ocean and forms the isthmus that links the Iberian Peninsula to the rest of the Eurasian continent. The high Pyrenees range between 2000 and 3000 m in altitude reaching a maximum of 3404 m and they are about 120 km wide in the middle of the chain. The amplitude and the altitude of the Pyrenees diminish dramatically when the mountains approach either the Atlantic Ocean or the Mediterranean Sea. Two main kinds of relief can be broadly differentiated: elevated areas with abrupt peaks but having vertical drops not exceeding 700 m, and valley areas having a flatter relief but with altitude variations higher than 1500 m in some cases.

Our study area was specifically located on the southeastern part of the range (Pyrenees of Catalonia), an area of about 150 km in length, 52 km wide in the western part and 19 km wide in the eastern part (Fig. 1). In this region, the highest mountain villages are situated at an altitude of 1500 m. The highest roads that are open in winter are located at an altitude of 2300 m and nine alpine ski resorts are distributed at altitudes exceeding 1500 m. The “Pica d’Estats” at an altitude 3143 m is the highest peak in the area.

The peculiar geographical features that shape the Pyrenees play a major role in the climatic conditions affecting the whole chain. The zonal disposition of the axial range retains polar and arctic maritime air masses from north advections, and tropical maritime air masses from the south and southwest. The meridian valley configuration favours the penetration and the placement of unstable air masses, i.e. the forced lifts caused by the relief may sometimes result in heavy and persistent snowfalls. Because of the proximity of the Pyrenees to the Mediterranean Sea and the Atlantic Ocean, temperatures are less extreme than in inland ranges. Interestingly, there are extensive rain shadows close to the Mediterranean. Finally, the massif is a boundary between the humid oceanic climate and the subtropical dry climate due to its relatively low latitude.

Despite the small size of the study area, three different climatic conditions are found: Oceanic, Continental and Mediterranean. The northwestern part of the study area is characterized by a humid oceanic climate. Precipitations are abundant and show a regular interannual distribution. The total amount of fresh snow at 2200 m altitude is about 500–600 cm per year. The oceanic influence crosses the main divide and extends few km to the south. However, the climate becomes more continental south of the main divide. Winter is the driest season and snow precipitation increases in the equinoctial periods, while interannual variability of precipitation increases. The total amount of fresh snow at 2200 m altitude slightly exceeds 250 cm per year. Predominant winds come from the north and northwest often with gusts over 100 km h^{-1}. The Mediterranean Sea plays a crucial role in the climate in the eastern part of the Pyrenees. Thus heavy snowfalls can occur because of humid air masses from the Mediterranean Sea. Interannual variability of snowfalls is high. The total amount of fresh snow at 2200 m altitude is about 350–450 cm yr^{-1}. The formation of persistent lows over the lee-side of the Alps and the Gulf of Lions gives rise to prevailing winds from the north. Maximum wind gusts may occasionally exceed 200 km h^{-1} at 2200 m altitude.

According to weather and snow conditions the study area has been divided into 7 nivometeorological regions (Fig. 1). Given the absence of long meteorological records for the area, these regions do not constitute a strict climatic classification, but are the result of 15 years of avalanche forecasting in the Catalan Pyrenees. They fall into regions of different climatic influence. Oceanic: Aran-Northern border of Pallaresa (AP). Continental: Ribagorçana-Vall Fosca (RF), Pallaresa (PL), Perafita-Puigpedrós (PP) and V. N. Cadí Moixeró (NC). Mediterranean: Prepirineu (PR) and Ter-Freser (TF).

3 Dendrogeomorphological study sites

Six snow avalanche paths were selected to conduct a dendrogeomorphological study. These were distributed over the area to provide information for the whole territory (Fig. 1). Some characteristics of the study sites appear in Table 1. For the purpose of this research, the sites were chosen in forested paths. Potential treeline altitude has been fixed at ∼2200–2450 m altitude in the Pyrenees (Carreras et al., 1996). The most widely distributed tree species growing at the highest altitudes (from 1600–2300/2500 m) is *Pinus uncinata* Ramond ex DC. in Lam et DC. (mountain pine). At lower elevations, other conifers as *Pinus sylvestris* L. (Scots pine) and *Abies alba* Mill. (silver fir) can also be found. All the dated avalanches in this study were naturally released.

Avalanche Path 1 (AP 1, Núria) is located near the eastern end of the high Pyrenees, in the Núria valley. This path has a broad, concave starting zone, a narrow track and an unconfined runout. A mountain pine forest begins some meters below the starting zone, at 2200 m altitude. In the runout major avalanches affect the rack railway that connects the valley villages to the tourist resort of Vall de Núria. The first dendrogeomorphological study on snow avalanches in the Pyrenees was performed in this avalanche path (Muntán et al., 2004).

Avalanche Path 2 (AP 2, Ticó) starts at the top of a north facing, rocky wall with a snow corridor that is adjacent to a steep scree slope. The mountain pine forest in this path starts a few meters below the base of the rocky wall where the scree slope recedes (at 2200 m). Beneath the middle track, the avalanche path becomes more confined ending up in a narrow runout. This avalanche path does not affect human dwellings.

Avalanche Path 3 (AP 3, Tor) is located in a remote area near the border of Andorra. This path has a concave starting zone adjacent to a narrow track. Avalanches in this path can take different trajectories in the final stretch. Either they are hedged in the mountain torrent which bends abruptly to the west, or overshoot the torrent talveg and invade a flat pasture surface straight ahead. The forest is mainly composed of mountain pine, but some Scots pine appear below 2150 m altitude.

In Avalanche Path 4 (AP 4, Virós) iron mining which started about 1500 years BP (High-Mountain Archaeology Group, Department of Prehistory, Autonomous University of Barcelona, personal communication, 2004) inhibited the growth of forests until the XIX century, sometime between 1850 and 1880 (A. Pèlachs, personal communication, 2004). Nowadays, the dominant species of this forest is also mountain pine (that grows up to treeline at 2250 m). The topography of this avalanche path is uneven, i.e. there are a number of mining deposits in the middle track. It is reasonable to assume that the majority of avalanches stop above this zone because of the existence of a clear concavity on the topography. Occasionally, snow avalanches can cross a dirt road in the runout.

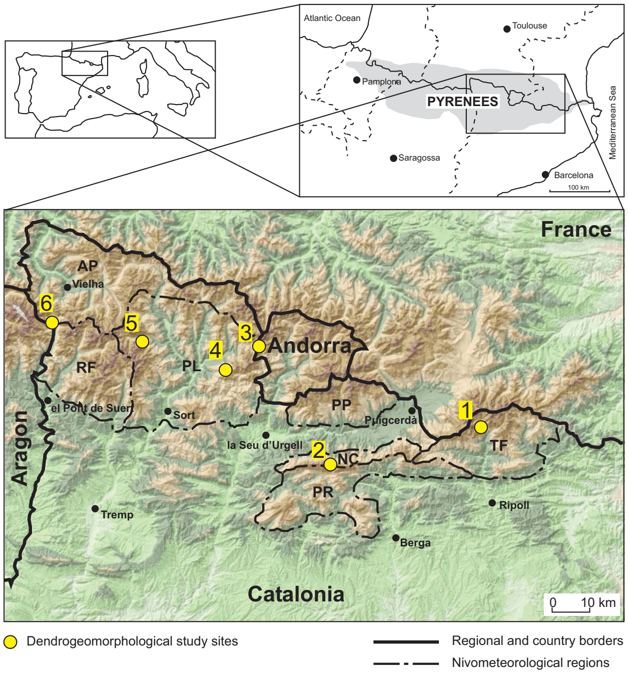

Fig. 1. Shadow relief image (ICC) of the study region, Pyrenees of Catalonia, showing nivometeorological regions used in avalanche forecasting (AP: Aran-N border of Pallaresa, RF: Ribagorçana-Vall Fosca, PL: Pallaresa, PP: Perafita-Puigpedrós, NC: N slopes of Cadí Moixeró, PR: Prepirineu, and TF: Ter-Freser) and the location of dendrogeomorphological study sites (numbered from E to W).

Avalanche Path 5 (AP 5, Pui de Linya) is in the National Park of Aigüestortes and Estany (lake) de Sant Maurici in the central Pyrenees. It has a long, wide starting zone. The track and the runout have a width ranging between 50 and 75 m. The slopes of this mountain are covered with mountain pine forest reaching 2400 m altitude interspersed with silver fir patches (northern slopes) and Scots pine (southeastern slopes) at lower elevations.

In Avalanche Path 6 (AP 6, Fontana) the catchment occupies a stony, glacial cirque. The track begins at the neck of the cirque and is 100–150 m wide. A mountain pine forest mixed with silver fir flanks the avalanche track up to 2000 m altitude. The runout is on top of a debris cone ending up in a main road that runs along the valley. However, most snow avalanches stop short of overrunning the road. There is a parking lot in the wide runout zone, obviously exposed to avalanche hazard. Only a few woody plants are available in the runout for the dendrogeomorphological study.

Table 1. Study site characteristics[a].

Study site	Toponym	AP	SZ-RZ elevation (m a.s.l.)	Altitudinal gradient (m)	Aspect	NM	Vegetation
1	Canal del Roc Roig Vall de Núria	NUR127	2275-1775	500	ENE	TF	*Pinus uncinata* forest
2	Canal del Ticó (Llitze) Serra del Cadí N	SGR452	2550-1675	875	N	NC	*P. uncinata* forest
3	Barranc de Tor Plaià	RDT122	2700-1900	800	S	PL-AP	Mixed *P. uncinata* and *P. sylvestris* forest, *P. uncinata* (above 2150 m a.s.l.)
4	Costa dels Meners Bosc de Virós	VFR005	2400-2010	390	N	PL	*P. uncinata* forest
5	Envallase Pui de Linya	PEG002	2770-1890	880	ENE	PL	*P. uncinata* forest
6	Pic de Fontana de Viella	RIB005	2580-1545	1035	E	RF-AP	Mixed *Fagus sylvatica* and *Abies alba* forest, *P. uncinata* (above 1800 m a.s.l.)

[a] AP – six-digit code corresponding to specific avalanche path identification in the Avalanche Paths Map of Catalonia (ICC 1996–2006); SZ – Starting zone; RZ – Runout zone; NM – Nivometeorological region.

4 Materials and Methods

To achieve our objectives, the methods used in our study were as follows: 1) dendrogeomorphology to date and reconstruct past avalanches in six avalanche paths, and 2) analysis of meteorological and nivometeorological records to determine the weather conditions that could have triggered individual avalanches and widespread avalanche events.

4.1 Dendrogeomorphological procedures

Samples from *Pinus uncinata* trees were collected by utilizing dendrogeomorphological methods described by Burrows and Burrows (1976) and Shroder (1978). Care was taken to employ non-destructive methods for environmental reasons and thus, increment borers were used to extract cores (5 mm in diameter) from living trees. Cross-sections were obtained from dead trees, but these have not been used for the present work. A reference chronology with samples from old trees apparently not affected by avalanches was built at each study site. Reference chronologies were used to confirm correct datings and to exclude any atypical growth responses that could be attributed to climate or other growth disturbances. The field sampling campaigns were performed during the summers of 2003 and 2004.

Figure 2 illustrates the sampling method in AP 1, 4 and 5. Here the dendrogeomorphological study was performed by running a number of 1 to 2-m wide transects across the avalanche track and runout at different elevations. Whenever possible, the transects were set at a distance of 50 m uphill, to cover the whole avalanche trajectory from the runout up to the treeline. Scattered trees with particular external features possibly caused by snow avalanches were also sampled.

In AP 2, 3 and 6 the sampling work was less exhaustive (Fig. 2). In AP 2, only one transect across the middle track and ten selected trees in the runout zone were sampled. In AP 3, trees were sampled systematically along five 30 m-transects in the runout-zone forest. In AP 6, selected trees were sampled at different elevations along the track.

Standard dendrochronological procedures were used to prepare and analyse the wood samples (Fritts, 1976; Stokes and Smiley, 1968). All samples were visually cross-dated.

Statistical verification was done using the computer programm COFECHA (Holmes, 1983), but visual description of ring characteristics was crucial because statistical dating tests were not successful in a large number of the avalanche path samples owing to extreme ring-width alterations.

Abrupt growth changes in ring width (release and suppression sequences that are not present in the reference chronology), reaction wood (which is ordinarily related to tree tilting) and growth cessation (due to local death of cambial cells in the case of scars) were used to date avalanche events. Regeneration as evidence of past disturbances was not employed given discrepancies in tree establishment dates. Resin ducts as indicators were also avoided because of the number of resin ducts ordinarily displayed by *Pinus uncinata*. Root samples were not used owing to the difficulty for cross-dating them. Dead trees supply complete tree sections where

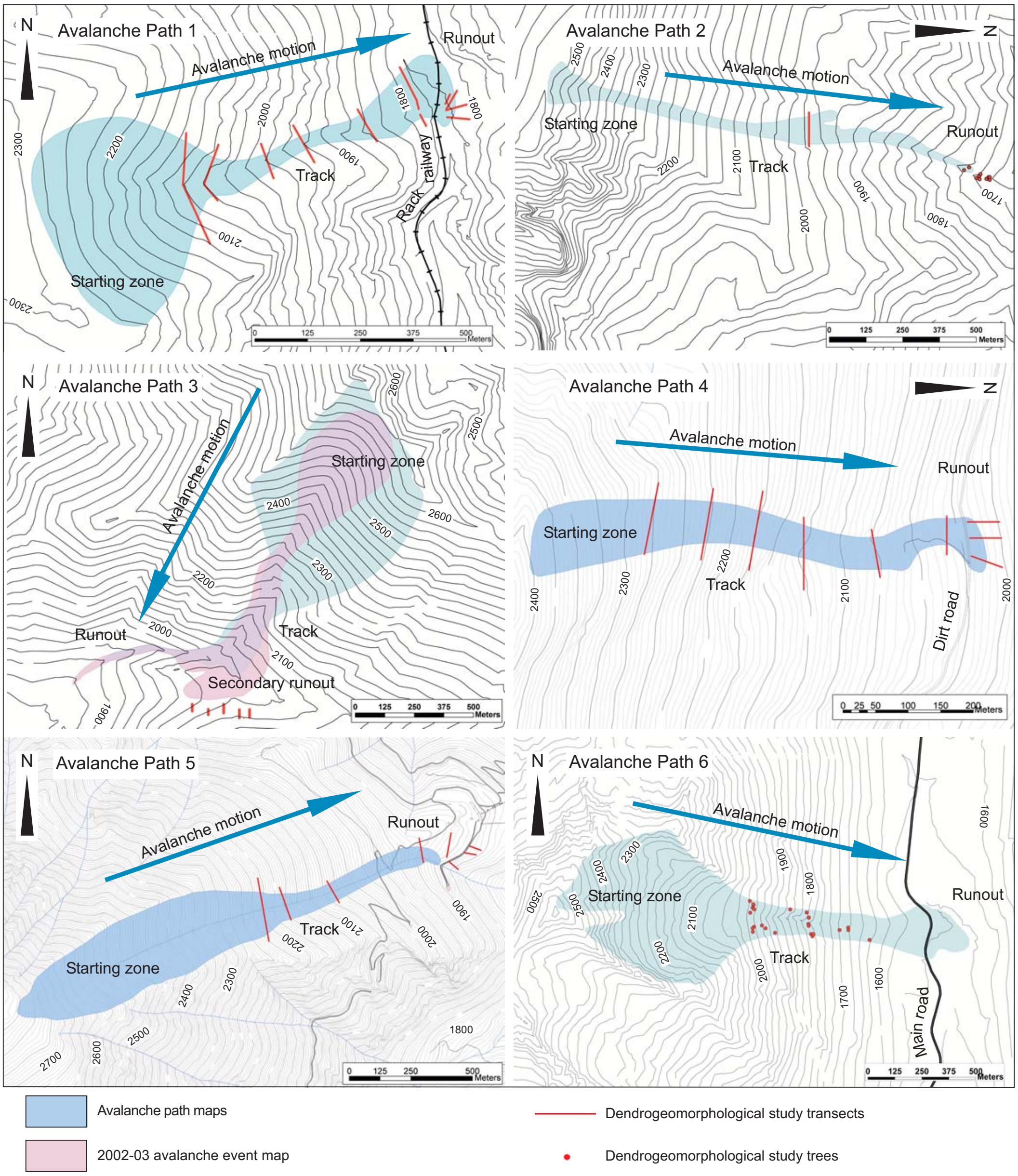

Fig. 2. Avalanche path maps (ICC) showing the sampling strategies used in each of the study sites.

ring features are more easily observed. However, as tree debris get rotten and disappear, part of the evidence is lost making comparisons between percentages of recent and past events tricky. Moreover, given that most dead trees are transported, they do not provide reliable information about event extent. For this reason, only living trees were used to infer avalanche occurrences and size on this occasion. In our research, the different tree-ring signals had equal weight in the event-response sum. Although a tree could present several tree-ring signals, it was counted only once. Finally, no attempt was done to rate avalanche intensity using the duration of tree-ring responses.

The following criteria were used to confirm the occurrence of snow avalanches by means of dendrogeomorphological analyses: 1) the absence of similar growth reactions in the reference chronology, 2) the concurrence within the same tree or among trees of a variety of tree-ring responses, 3) the spatial distribution of growth-disturbed trees in the track and in the runout, and 4) the proportion of trees with ring evidence similar to or higher than the results from documented avalanches.

Avalanches can attain different sizes in the same avalanche path. For the purpose of this research, we have considered events reaching the runout as an indicator of most likely major avalanches. According to Schaerer (1986), avalanches that occur once in every 5 to 20 years affecting transport infrastructure and causing damage to property are typically much larger than annually observed avalanches. Therefore, in addition to the total count of trees with growth disturbances along the avalanche path, we paid particular attention to growth disturbed trees (GD trees) located in the lower track and in the runout zone. The time period considered was directly related to a lower limit of twenty trees sampled in the whole avalanche path, or ten trees sampled at the lower tract (track/runout), and in this way, it varied from one site to another (see Sect. 5.1.). In addition to this spatial consideration, to set a rough threshold for the percentage of trees needed (Index Number by Shroder, 1978) to accept the occurrence of a snow avalanche, we used the minimum value corresponding to a documented event in AP 1 (where several events had been reported) which was 16%. This cut-off number was used in the densely sampled AP 1, 4 and 5. In less-exhaustively sampled paths AP 2, 3 and 6, we used a higher index of 40% after Butler et al. (1987).

4.2 Archival data from past avalanches

Information about past avalanche events was obtained from the Avalanche Database of Catalonia (Base de Dades d'Allaus de Catalunya, Institut Geològic de Catalunya: http://galileo.icc.es/website/cartoallaus_icc/viewer.htm?ActiveLayer=foto&Usuari=consulta&), which gathers data from various sources: winter monitoring, field survey, historical documentation, interviews with local people and eyewitness accounts. This was used to corroborate some of the dates yielded by our dendrogeomorphological study.

4.3 Weather and snow conditions

Major snow avalanches occur when critical combinations of weather and snowpack conditions arise. Once avalanche event years were determined by the dendrogeomorphological study, daily weather records were examined to find reasonable avalanche-release conditions. Owing to data availability, the analysed period was from 1971–1972 to 2003–2004. Data were obtained from manual and automatic meteorological stations of the National Meteorological Institute of Spain (INM), the Meteorological Survey of Catalonia (SMC), and the Nivometeorological Observers Network (NIVOBS) of the Cartographic Institute of Catalonia (ICC). The NIVOBS has carried out winter surveys to report snowpack conditions and avalanche events since 1986. These observations became daily after 1996.

Attention was focused on the meteorological conditions responsible for unstable structures of the snowpack (Armstrong, 1976). The nivometeorological parameters and conditions that play a role in critical avalanche situations in the SE Pyrenees (García et al., 2006) are as follows: fresh snow accumulation in 72 h, rain precipitation over 2200 m altitude, wind speed exceeding 15 $\mathrm{m\,s^{-1}}$ and sequences of days with isozero above 3000 m. In addition, conditions that generate weak layers in the snowpack (faceted grains, depth hoar and surface hoar) were also detected, since not all major avalanches are linked to intense precipitation. Weak layers overloaded by thick wind slabs and by wet slabs in melting situations generate major avalanches, as well. Thus, we looked for weather conditions such as sequences of days of high snow irradiation and sequences of days with daily maximum temperature below 0°C. When the most predictable meteorological and nivometeorological avalanche-release conditions were identified, synoptic atmospheric situations were selected from the NCEP-NCAR[1] reanalysis data (Kalnay et al., 1996) by using maps at sea level pressure, at 850 hPa, and at 500 hPa.

5 Results

5.1 Past snow avalanches

Results refer to *Pinus uncinata* exclusively, the most abundant tree species in all the study sites. The length of the study period varied within each site, but as a rule, the youngest tree samples covered the last 10 years and the oldest, from 180 to 250 years (Table 2). No attempt was done to date the age of the trees. Roughly, half of the trees were older than 40 years at all sites, and older than 90 years in AP 3 and 4. As has been pointed out in Sect. 4.1, the sample methodology in AP 1, 4 and 5 was more intensive than in AP 2, 3 and 6.

5.1.1 Avalanche paths 1, 4 and 5

The occurrence of large-scale snow avalanches was widespread in the Pyrenean range during the winter of 1995–1996. Many of these events were regarded as major avalanches damaging vast tracts of forest. Because major avalanches in paths 1, 4, and 5 were documented during this winter they were chosen to find out whether similar events took place in the past. The event-response histograms for AP 1, 4 and 5 are shown in Fig. 3. The bar corresponding to the 1995–1996 events clearly stands out in these sites. The proportion of trees showing tree-ring signals was 32% at AP 1, 53% at AP 4, and 57% at AP 5 of the total number of sampled trees (131, 92, and 129, respectively).

In AP 1 major avalanches damaged the rack railway in the winters of 1971–1972, 1985–1986 and 1995–1996. These seasons hold the highest proportion of GD trees along the track and some trees show evidence at the runout as well (see corresponding histogram in Fig. 3). Although evidence

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[1] National Centers for Environmental Prediction and National Center for Atmospheric Research, USA

Table 2. Trees used for dendrochronological analyses.

Study site	Sampled trees	Age range	Age $\overline{X} \pm 1\,SD$
1	131	10–219	49.7±35.1
2	36	18–188	53.0±31.7
3	34	10–181	81.7±37.2
4	92	14–196	95.7±43.3
5	129	10–250	43.7±30.5
6	26	14–185	57.3±38.6

for events is also high in 1973–1974, 1981–1982 and 1990–1991, it is likely that snow avalanches in these seasons did not reach the runout, but stopped some way up the track. In this avalanche path, we were able to enlarge the span period owing to the unexpected finding of a picture taken in 1930 portraying an avalanche deposit at the runout, which corroborated the tree-ring evidence of a high magnitude avalanche in 1929–1930 (Fig. 4).

In AP 4 an avalanche in 1996 swept through a stretch of mature forest. As shown in Fig. 3 a high proportion of GD trees in 1995–1996 was detected in the upper portions of the path. Seven trees in the runout zone of AP 4 provided evidence of this same avalanche event as well. Dendrogeomorphological results showed no similar event for more than a century. A high proportion of GD trees in 1878–1979, 1958–1959, 1963–1964 and 1990–1991 may correspond to avalanche events that reached the middle track.

In AP 5, many trees were destroyed in the 1995–1996 season. The dendrogeomorphological analysis corroborated this event and revealed another major avalanche that took place in 1971–1972. A high amount of evidence was found for 1973–1974 at the runout as well (13 trees), but although the 16% threshold was surpassed, there was little evidence in the track (5 trees) (see Sect. 6.1). A smaller event was dated in 1978–1979.

5.1.2 Avalanche paths 2, 3 and 6

The event response histograms of the less exhaustively sampled avalanche paths are presented in Fig. 5. In AP 2, according to an eyewitness, an avalanche released in 2003 and brought down numerous trees. Only samples from ten trees were collected in the narrow runout and from 26 along a transect at the middle track. Here five events reaching the runout were dated by dendrochronology: 1968–1969, 1971–1972, 1981–1982, 1995–1996 and 2002–2003. There was no evidence of the avalanche in 1995—1996 at this site previous to the analysis.

In AP 3, winter surveys reported two major avalanches in 1996 and in 2003. The 1995–1996 event followed the mountain torrent, but the event in 2002–2003 ran into the secondary runout (Fig. 2) breaking and uprooting a few large trees (>70 cm diameter at breast height). The sampling design was focused on this secondary runout area linked to rare high magnitude events. Here 39 trees were sampled in the runout. Dendrogeomorphology confirmed the event in 2002–2003. It also confirmed that the event in 1995–1996 had not reached this secondary runout. Tree-ring evidence found in 1909, 1927 and 1935 (three, four and three trees, respectively) could not be evaluated, since no samples were collected in the avalanche track.

In AP 6, dendrogeomorphological evidence for events in 1985–1986, 1993–1994, 1995–1996 and 2002–2003 was obtained, but no living trees were sampled in the runout. For this reason we could not verify the extent of these avalanches. Interestingly, a reported avalanche in 2003–2004, which engulfed a car driving along the road in the runout, was not detected. In this study site, the dendrogeomorphological analyses were limited by the scarcity of trees and woody plants in the runout.

Figure 6 summarizes all the dated snow-avalanche events in the six avalanche paths of the study.

5.2 Meteorological and nivometeorological factors associated with major avalanche winters

The results of the research in meteorological and nivometeorological records for the period between 1971–1972 and 2003–2004 are shown in Fig. 7. Compared with the other avalanche seasons, in 1971–1972, 1995–1996 and 2002–2003 winters, a higher number of nivometeorological regions were affected by avalanches (four, seven and three, respectively).

5.2.1 Major avalanche season 1971–1972

In 1971–1972 an extensive avalanche episode took place affecting a large area that comprised four nivometeorological regions. On 16–17 January, extensive but moderate snowfalls were recorded across the Pyrenees (40–60 $\mathrm{l\,m^{-2}}$ of snow-water equivalent above 2000 m, but less in the valley bottoms). The synoptic atmospheric situation consisted in a deep trough crossing the range from west to east. Southern winds in cyclonic circulation blew over the Pyrenees, which favoured the precipitation by uplift effect due to the configuration of the main valleys. Taking into account the distribution of the thermal isolines at 850 hPa topography, the snow level was assumed to be above 1600–1700 m above sea level (a.s.l.) in the beginning, but descending as time passed. Under these conditions, fresh snow might have been wet and dense. The weather of the days preceding the snowfall was characterized by the passing of warm and cold frontal systems from the Atlantic Ocean. In these circumstances precipitations are usually scarce, but in the Pyrenees between 1500 and 2000 m, rain and snow alternate. These conditions favour the formation of weak faceted grains above thin crusts and as it is observed in a variety of snow climates avalanches

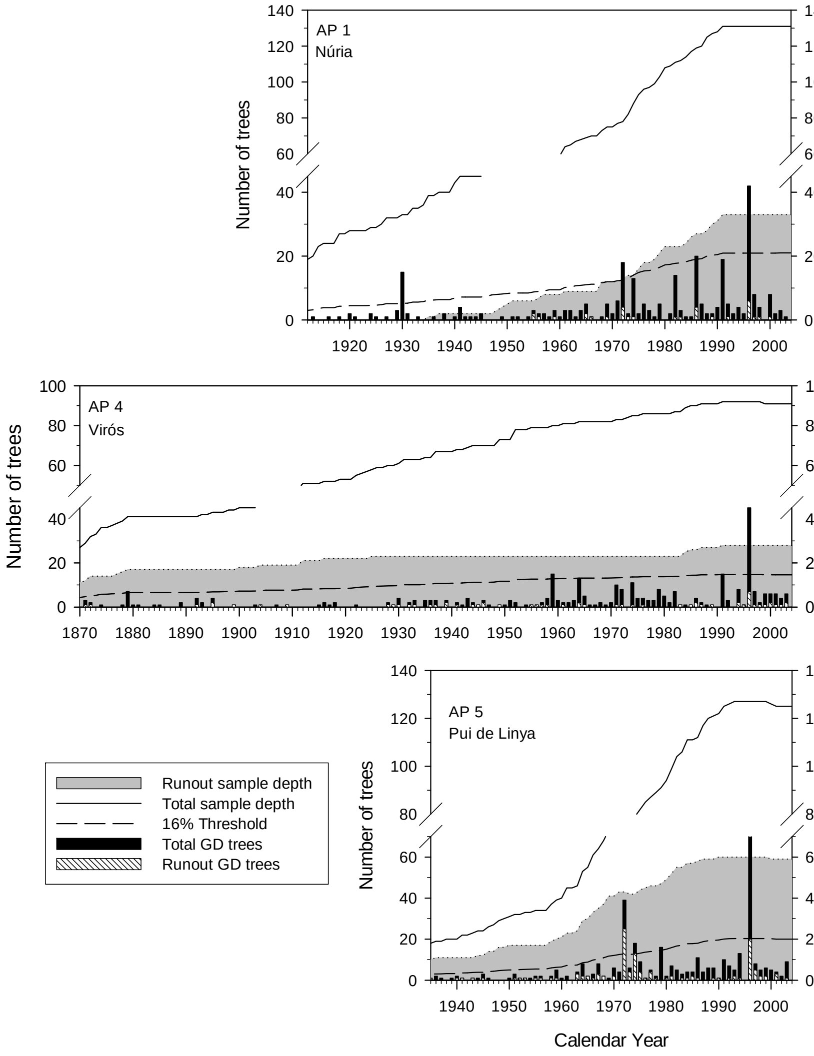


Fig. 3. Event response histograms for paths AP 1, AP 4 and AP 5. The length of the time spanned coincides with a minimum sample size of 20 trees.

may release as a result of that unstable snowpack structure (Jamieson, 2006). In addition on 18 January a cut-off low was identifiable both in the sea level surface map and in the 500 hPa map over the Mediterranean Sea. This situation generally generates strong northern winds over the TF region, resulting in the formation of thick wind slabs on south-oriented slopes. On 18 January, a large avalanche released from the south-oriented slope that damaged the rack railway in Nuria Valley at AP 1 (TF region).

5.2.2 Major avalanche season 2002–2003

During the winter 2002–2003, two avalanche episodes that affected three nivometeorological regions were reported (AN, PL and RV). In the first episode, from 26–30 January 2003, a north advection produced heavy snowfalls during 96 h accounting for more than two meters of new fallen snow at 2200 m a.s.l. Much of the snow accumulation was due in part to wind drifting. Data was difficult to measure because of the strong winds (around 90 km h^{-1}) at high-altitude weather stations. However, the total amount of fresh snow that accumulated in the valley floors, which were sheltered from the strong winds corresponds to a return period of 30 years and draws attention to the severity of the event (Esteban et al., 2005). Following this storm, a total of 39 major avalanches released in three regions (AN, PL and RV). Snow profiles done close to the fracture line showed the formation of thick wind slabs on lee slopes with densities ranging from 140–180 kg m^{-3}. Ram profiles indicated that below these wind slabs were thin crusts alternating with weak interfaces. A strong thermal gradient in the contact between the crust and the new fallen snow likely favoured the formation of a weak interface propitious to avalanche release.

Fig. 4. Old photograph showing an avalanche event in AP 1 that occurred in 1929–1930. The people are walking through the snow deposition in the runout zone. Note the broken trees protruding from the snow. From the picture, the deposition was more or less four meters high (in 1995–1996, the deposition was two meters) (with permission of Centre Excursionista de Catalunya archive; author, Albert Oliveras).

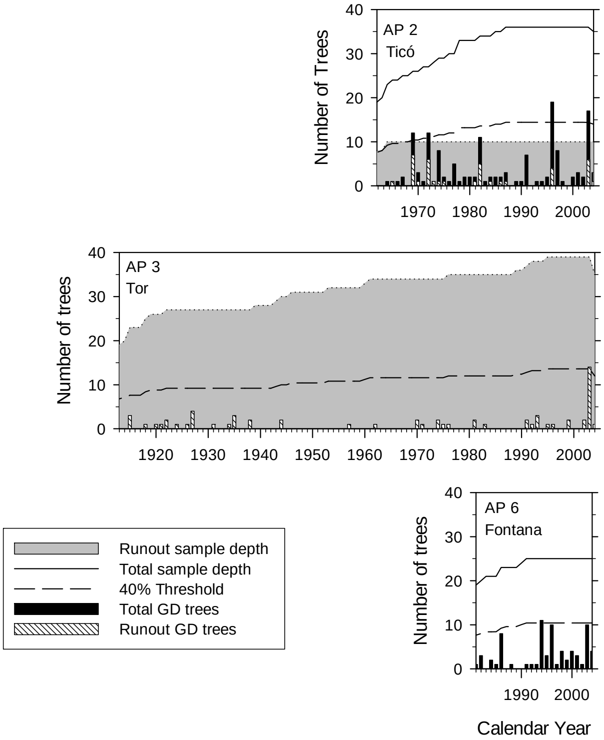


Fig. 5. Event response histograms for avalanche paths AP 2, AP 3, and AP 6.

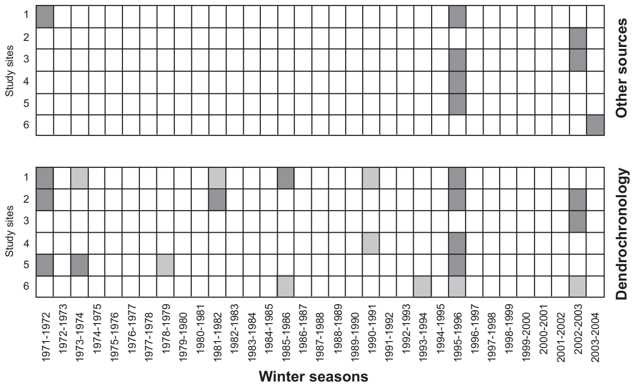
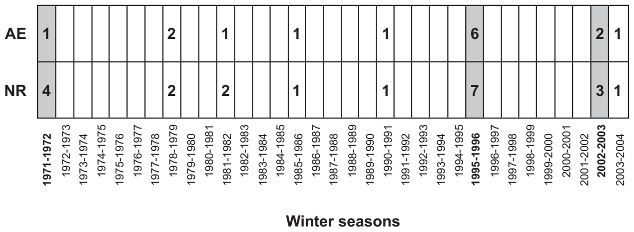


Fig. 6. Dates of snow-avalanche events from 1971–1972 to 2003–2004 in the studied avalanche paths. The upper chart shows the dates obtained from the Avalanche Database of Catalonia. The lower chart depicts the dates obtained by dendrochronology. Dark grey squares correspond to major avalanches and light grey to smaller avalanche events where there is no tree-ring evidence at the runout.



	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976	1976-1977	1977-1978	1978-1979	1979-1980	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989	1989-1990	1990-1991	1991-1992	1992-1993	1993-1994	1994-1995	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2003	2003-2004
AE	1							2			1				1					1					6							2	1
NR	4							2			2				1					1					7							3	1

Winter seasons

Fig. 7. Potential avalanche episodes and nivometeorological regions affected from 1971–1972 to 2003–2004. Avalanche activity was particularly high in winters 1971–1972, 1995–1996, and 2002–2003 (AE-number of avalanche episodes, NR-affected nivometeorological regions).

The second episode took place from 26–28 February. As in the 1971–1972 episode, a deep trough crossed the Pyrenees from west to east, but on this occasion, a small vortex with a humid, strong south-eastern flow coming from the Mediterranean Sea towards the southern side of the Pyrenees was generated. Winds blew from the south at 40–90 $\mathrm{km\,h^{-1}}$. The total fresh snow accumulation ranged between 40–100 cm at 2200 m in 72 h. The new snow was very wet and dense and largely comprised of rimed crystals. Large avalanches released from 27–28 February mainly on north-oriented slopes.

5.2.3 Major avalanche season 1995–1996

The 1995–1996 winter was unusual because of the large number and regional extent of avalanche episodes (six in total). In addition, these episodes were triggered by different meteorological conditions (García et al., 2006). All the seven nivometeorological regions were affected by major avalanches in the winter of 1995–1996. Indeed, some regions such as the western RF and the eastern TF were affected by major avalanches several times in the same winter (three times each). Figure 8 provides a schematic overview of the nivometeorological regions affected by the diverse atmospheric conditions.

The episode of December 1995 corresponded to an east advection. It was explained by a blocking high pressures situation at 500 hPa over Central Europe and a cut-off low centred over the southwest of the Iberian Peninsula. A warm and very humid Mediterranean flow on surface penetrated from the east affecting the regions closest to the Mediterranean Sea, and also distant regions such as south-facing RF.

The most intense major avalanche episode took place at the end of January 1996 as a result of a southwestern synoptic situation. A number of large, powder snow avalanches over four nivometeorological regions were triggered shortly after snowfall (Fig. 8). A deep low pressure was located over the northwestern coast of the Iberian Peninsula. From surface to upper atmospheric levels south and southwesterly winds prevailed bringing warm and humid air from the Atlantic and the Mediterranean to the lower levels in the Pyrenees. High instability was attributed to a deep cold core at 500 hPa level. In the PR region, a precipitation gauge at the Port del Comte nivometeorological station recorded a maximum of $220\,\mathrm{l\,m^{-2}}$ of snow water equivalent in 24 h, and snowfall exceeding $150\,\mathrm{l\,m^{-2}}$ was recorded in several other nivometeorological regions. These extreme values were largely atributted to convective cell growth. This means a Gümbel return period (Gumbel, 1958) for a snowfall slightly exceeding 100 years in the PR region. A return period is an estimate of the expected interval of time between events; note that it means that an event will not happen regularly in the given interval of time, but it has been observed to occur in this interval. As shown by Esteban et al. (2005), heavy snowfall including torrential rains affect the southern side of the Pyrenees in such a synoptic circulation pattern.

From 6 through 9 February 1996 another large avalanche episode occurred. The storm was a result of typical northwestern advection characterized by both warm and cold fronts passing over the Pyrenees and giving rise to high and low snow levels and intermittent precipitation. Intense drifting that occurred during the storm made it difficult to determine the amount of precipitation. However, the maximum amount of new snow above 2000 m a.s.l. reached 100 to 140 cm after 72 h of snowfall in the AP region. Although some regions uncommonly experience snowfall in the northwestern advection regime, extreme avalanches do occur under this synoptic pattern where snowfall is abundant. It may also be suggested that extreme avalanches took place in regions where new snowfall amounts were moderate owing to snow accumulated/transported by the wind from the preceding episode (21–24 January). Large amounts of drifted snow exceeding four to five meters in depth were measured in the avalanche starting zones on lee slopes. The new snow was mainly comprised of small, low density fragments that drift easily. Fresh wind slabs overloaded southern lee slopes and eventually released.

The fourth episode was caused by a storm with strong winds from the north on 22 February. The Azores high pressures were extended in a north-south axis over the Atlantic Ocean, while a deep low pressure was located on the Baltic Sea-Italian Peninsula axis in a typical configuration. This pattern pumps either an arctic or a maritime polar air mass over the Pyrenees, and generates very low temperatures (-15 to -20°C at 2200 m a.s.l.), intense snowfalls, strong winds and very active snow drift processes which can result in avalanche releases.

The fifth episode occurred on 14 March and it corresponded to a trough passing. In this pattern, atmospheric circulation is characterized by a long trough at 500 hPa exhibiting an oblique NW-SE axis, caused by the Siberian high pressure over Europe which diverts troughs to the Mediterranean basin. Normally, this yields a small low at surface atmospheric level over the Mediterranean Sea. A humid, maritime flow on surface produces heavy precipitation in the regions closest to the Mediterranean Sea. Instability is high due to the contrast between cold air at 500 hPa and a relatively warm air mass at low atmospheric levels. The snowpack usually contains weak layers with depth hoar and faceted grains before fresh snow arrives, since low temperatures and strong irradiation prevail below the Siberian high pressures influence.

The last episode took place from 22 through 24 March and it was associated to melting processes. A ridge from the subtropical anticyclonic belt spread to the north over the Western Mediterranean Sea. Usually, when this occurs, a warm advection at low atmospheric levels (850, 700 hPa) reaches the Pyrenees. The snow cover suffered sudden melting processes and major avalanches descended while the inner layers still contained cold, persistent grains.

6 Discussion

6.1 Dendrogeomorphology

Our dendrochronological analyses corroborated most of the documented dates and yielded other avalanche dates that had not been recorded hitherto in the six avalanche paths we sampled (Fig. 6). By examining the spatial distribution of GD trees within each path, we verified whether avalanches had reached the runout or had most likely stopped higher in the track. The number of detected major avalanche events increased from 1971–1972 to 2003–2004 from 8 to 14. These occurred in a total of nine winter seasons. Twelve minor events were also detected. As indicated by Hebertson and Jenkins (2003), major avalanche episodes are expected to affect a large number of paths. In our study, regional-scale weather patterns during the winters of 1971–1972, 1995–1996, and 2002–2003 resulted in avalanches affecting at least

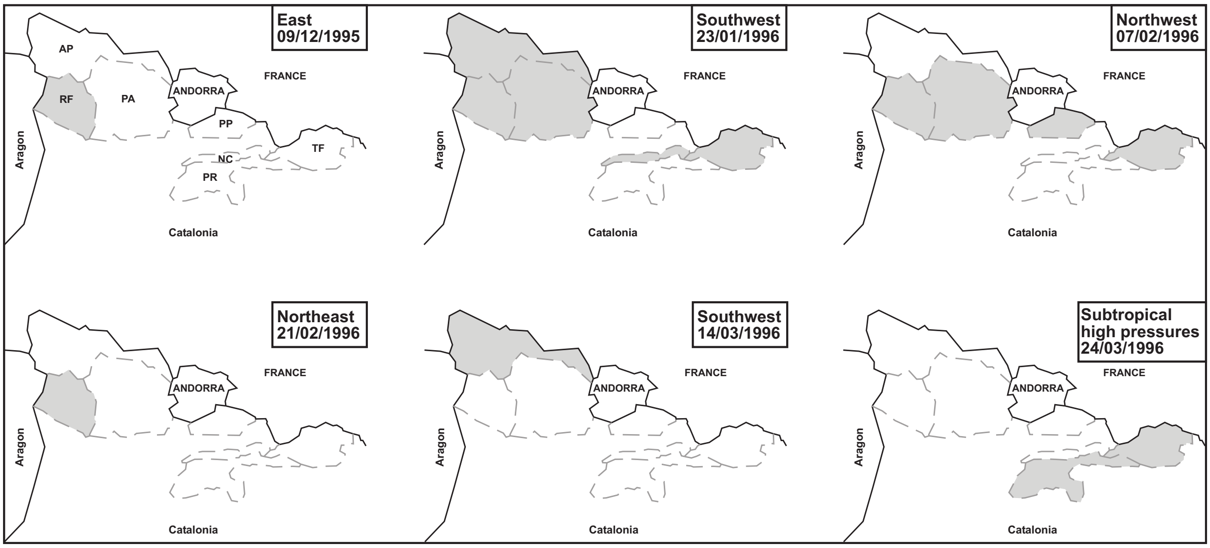


Fig. 8. Atmospheric conditions of potential avalanche episodes and affected nivoclimatic regions in 1995–1996 winter in the SE Pyrenees.

three paths each. Snow avalanches occurred in all six paths in 1995–1996 suggesting the severity of this winter.

The sampling design in AP 1, 4 and 5, provided the most reliable results on avalanche dating, and allowed the extent of successive events to be more accurately mapped, or existing maps expanded. This is an improvement over conventional avalanche mapping techniques, particularly in paths where visual indications of forest damage are no longer apparent. For example, in AP 5, dendrogeomorphology revealed that a high-magnitude avalanche in 1971–1972 exceeded the runout by a considerable distance (Fig. 9). Consequently, the runout map was increased by 200 m.

The less exhaustive sampling carried out in paths AP 2, 3, and 6 did not provide interesting results in terms of time period and extent of avalanche events, but rather illustrated the limitations of different sampling strategies. As long as these limitations are realized however, results can still be robust. For example, in the narrow AP 2 path we discovered that avalanches are very frequent, but we conjecture that event size or severity could vary according to avalanche width and not to length. This could not be evaluated by sampling trees only in the middle track and in the runout. Further research to settle this presumption should include sampling along transects at intermediate elevations. In AP 3, where sampling was done in the runout, the evidence detected for 1909, 1927 and 1935 could not be validated with samples from the track. This hampered the interpretation of potential events of similar magnitude such as the exceptional avalanche occurred in 2002–2003.

In AP 6, an avalanche documented in 2003–2004 was not detected by dendrogeomorphological means. This could be due to the natural scarcity of trees in the runout, or perhaps to previous avalanches that occurred in 1995–1996 and 2002–2003 and destroyed the trees along the track.

A similar circumstance could have happened in AP 5 for the 1973–1974 event. A major event in 1971–1972 could have removed the majority of trees in the avalanche path reducing the possibility of recording a subsequent event. This previous large event could also have facilitated the release of a later event a short time after. The removal of a large number of trees that typically serve as snowpack anchors results in a smoother path. This can contribute to greater avalanche frequency even in regions where nivometeorological conditions are not especially propitious. Further support for this idea was found at AP 1, where two major avalanches were registered in the same winter, 1995–1996 (see Molina et al., 2004). In this same way, Germain et al. (2005) reported evidence of increased avalanche activity in paths denuded by forest fires and logging.

Events that had been documented in 1995–1996 showed high index numbers (from 32 to 57% of GD trees), but these were extreme events. The documented event in 1985–1986 at AP 1 displayed a lower 16%. This percentage was used in the present work as a rough threshold to decide avalanche occurrences. In our opinion, low indexes should be used only in the case of densely sampled avalanche paths (such as AP 1, 4 and 5). The prevailing rule in this present research was not only to consider the spatial distribution of evidence, stressing the importance of the runout GD trees, but also the importance of track sample replicates. In the case of poorly sampled avalanche paths (AP 2, 3 and 6) deciding thresholds were more restrictive and, apart from the runout consideration, more than 40% GD trees were required to assess avalanche occurrence. The question is how to develop complete tree-ring chronologies in the event an avalanche destroys all the trees in a path and consequently most evidence. Carrara (1979) first posed this question suggesting that avalanches which were not powerful enough to

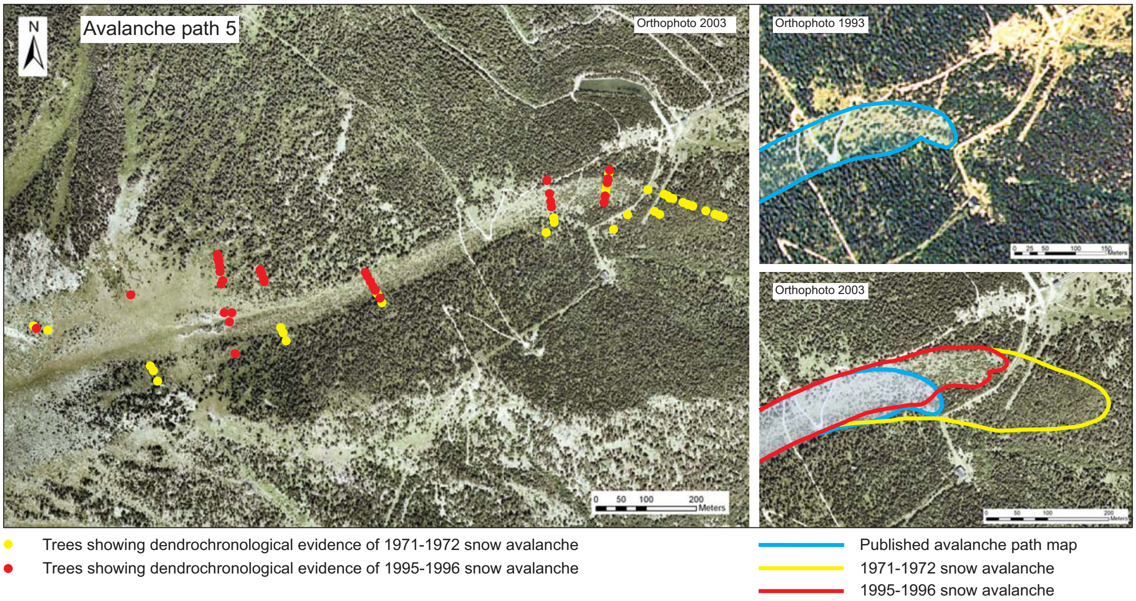


Fig. 9. Dendrogeomorphological mapping. The avalanche path map in AP 5 was improved using dendrogeomorphology. The 1971–1972 major event (not detected by conventional field surveys) allowed us to extend 200 m the vulnerable area in the runout.

destroy trees, but instead only damage them, record their occurrence in the sequence of annual rings. Evidence of more destructive events can be lost because dead trees disappear. On the other hand, avalanche events do not always result in tree ring responses in trees as was observed in 2003–2004 documented event in AP 6. For all the above reasons, expert criteria is still compulsory to obtain reliable results, particularly in the case of sparsely forested paths, or when attempting to date old events. Experienced dendrogeomorphologists sometimes need only one tree to assess the occurrence of an avalanche (G. Furdada, personal communication, 2002). Nevertheless, information provided by means of dendrogeomorphological methods is the most reliable compared to other approaches such as vegetation evidence or enquiries to old people. The dates yielded by trees have annual resolution, are absolutety dated and have spatial positioning. Thus, by means of an appropriate sampling, dendrogeomorphology can provide information about the extent and occurrence of past avalanche events.

6.2 Nivometeorology

From a nivometeorological point of view, it should be noted that the three major avalanche seasons (1971–1972, 1995–1996 and 2002–2003) were characterised by a wide variety of atmospheric situations that released major avalanches. Nine avalanche release episodes corresponded to six different synoptic patterns. The major avalanche episodes were correlated with synoptic patterns in the Eastern Pyrenees from 1985–1986 to 2005–2006. Synoptic patterns leading to major avalanches were found out. They were northwestern advection, trough passing pattern, eastern advection, southwestern advection, low centered pattern and subtropical ridge pattern. Compared with nearby mountain ranges like the French Alps, the Eastern Pyrenees exhibit a wider variety of synoptic patterns releasing major snow avalanches. Accordingly, weather patterns resulting in some avalanche episodes were more localized, i.e. one nivometeorological region affected during the second episode of 2002–2003, and others resulted in a wide spatial extent of releases, i.e. four regions affected during the episode of 1971–1972. In this study, the southwestern synoptic pattern was most common during the three winters with major avalanche occurrence and was the synoptic pattern that affected most nivometeorological regions (three in average).

As shown by Beniston et al. (1996), the evolution of the main meteorological parameters such as temperature, precipitation and winds is conditioned by the North Atlantic Oscillation index (NAOi) in mountain ranges such as the Alps. The correlation between winter precipitation and NAOi has been investigated in the Pyrenees by Martín-Vide et al. (1999) and Esteban et al. (2001). Both their results show a negative correlation. Accordingly, in this study the three major avalanche winters of 1971–1972, 1995–1996 and 2002–2003 were correlated with the variation of NAO (Climatic Research Unit, University of East Anglia: http://www.cru.uea.ac.uk). These three winters had negative NAOi anomalies (standardized NAOi values for the reference period series 1961–1990 as follows: -0.13 for 1971–1972, -2.23 for 1995–1996 and -0.09 for 2002–2003). Hence, more major avalanche episodes should be investigated in order to verify the correlation between major avalanches and NAOi.

7 Conclusions

In view of these results, the winter of 1995–1996 was most extraordinary with respect to the occurrence of major avalanche events in recent decades in the SE Pyrenees. The combination of a regional dendrogeomorphological study and meteorological and nivometeorological analyses of weather records allowed us to determine whether avalanches had been the result of a generalised nivometeorological situation or whether weather conditions for avalanche release were more localized.

This study supports the assertion that where historic snow avalanche records are scarce, dendrogeomorphological methods can be used to detect past avalanche events improving the reliability of data used to determine critical parameters such as avalanche frequency and extent. This study also tested several sampling designs. From this information it was determined that sampling a high number of trees along numerous transects provides the most reliable methods to accurately date the highest number of past avalanche events per site, and to allow avalanche size comparisons as well.

As was demonstrated by the dendrogeomorphological analyses at AP 5, extreme runout distances can greatly exceed mapped distances. For land-use planning, the identification of the area in danger is of paramount importance. In hazard zoning, dendrogeomorphological mapping should be used where woody plants are available. Dendrogeomorphology is the only tool which can render evidence of the extent of past events when other sources are missing.

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