# Dendrogeomorphology as a tool to unravel snow-avalanche activity: Preliminary results from the Fnjóskadalur test site, Northern Iceland

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Decaulne A. & Sæmundsson Þ. 2008. Dendrogeomorphology as a tool to unravel snow-avalanche activity: Preliminary results from the Fnjóskadalur test site, Northern Iceland. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography* Vol. 62, 55-65. Oslo. ISSN 0029-1951.

Snow avalanches are a major hazard for many settlements and transportation corridors in northern Iceland. At many sites the occurrence of snow avalanches during the past century has not been recorded. Visible damage, such as tilting, scars and decapitation of trees and shrubs (*Betula pubescens*) growing on colluvial cones in a remote area in Central North Iceland clearly identifies snowavalanche paths of a given magnitude and frequency. An analysis of tree-ring data was made using the chronology of ring sizes and wood reaction in snow-avalanche tracks subject to frequent avalanches. Abnormal growth, correlated with abrupt increases or decreases in growth rates, is related to snow-avalanche impact. The preliminary results provide reliable dendrogeomorphological data that show the spatial extent and frequency of snow avalanches in the study area. Further investigation that includes a broader sampling strategy and dendrochronological laboratory analysis is required.

Keywords: dendrochronology, dendromorphology, Iceland, snow avalanches

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## Introduction

The annual increment rings in tree growth reflect and record local environmental conditions (Wiles et al. 1996). Therefore, all changes in climate, weather and other external factors are manifested in the wood reaction occurring in the trunk morphologies and tree-ring sequences (Schroder 1980; Schroder & Butler 1987; Schweingruber 1996; Strunk 1997; Stoffel 2005). Dendrogeomorphology has been used effectively in snow-avalanche research (Ives et al. 1976; Carrara 1979; D.P. Butler & Malanson 1985a; 1985b; Jenkins & Hebertson 1994; Patten & Knight 1994; Rayback 1998; Larocque et al. 2001; Hebertson & Jenkins 2003; Dubé et al. 2004), although mostly using softwood from diverse conifer species.

This paper examines the potential of dendromorphology and dendrochronology for research into mass movement in Iceland by using the available hardwood stand, i.e. *Betula pubescens*. The research focuses especially on the lateral and vertical spreading of snow avalanches on colluvial cones dominated by snow-avalanche activity. The analysis of the longitudinal component is based on the position of large boulders deposited by extreme snow avalanches (Decaulne & Sæmundsson 2006; in press). Such an analysis is of interest for natural hazard research since the results can be transferred from remote uninhabited areas to inhabited areas where the geomorphological evidence from the runout and deposition zones affected by snow avalanches activity has disappeared because of changes in land use (Decaulne & Sæmundsson 2006; 2007). Knowledge of avalanche recurrence is essential in areas into which settlements are expanding and for which there are few complete records.

## The study area

The study area is located in the south-eastern part of the Fnjóskadalur glacial U-shaped valley, in Central North Iceland (65°35' N and 17°44' W) (Fig. 1A). The topography is characterized by steep concave slopes ranging from 200 m a.s.l. to 820 m a.s.l. on the eastern side of the valley. An arctic heath grows in the valley bottom and a mixed stand of heath and birch (*Betula pubescens*) cover is present on the slopes. *Salicacaea* are also sparsely represented. There are numerous indications of snow-avalanche activity on the lower slopes, especially large accumulations of snow-avalanche boulders far from the toe of the slope (Decaulne & Sæmundsson 2005). The three selected colluvial cones (Fig. 1B & 1C) are among the most active in the valley. Broken trunks and branches are strewn across the avalanche paths as far as the distal area of the cones.

## Methods

### Dendromorphology

Dendromorphology uses the shape of tree trunks to infer the amount of external disturbance to tree growth, such as that caused by repetitive pressure by various types of mass movements, snow pressure and snow depth, and by scars from impacts (Alestalo 1971; Schroder 1978; D.R. Butler 1987). On the three investigated colluvial cones, repetitive snow avalanches together with other mass movements such as debris flows and rockfall have left numerous impacts on many of the trees. There has also been strong tilting of the trunks, scar formation and decapitation of the upper parts of the trunks. A total of 1884 trees on the colluvial cones was observed and mapped with a GPS to produce an inventory of size and of visible damage (Fig. 2A). In addition, the vertical distribution of damage (scars and decapitation) was measured on trunks from the ground surface upwards. The radial distribution of 462 scars on 57 trunks is shown in Fig. 2A and 4C. The measurements indicate (1) the preferred snow-avalanche paths, (2) the height above ground of transported rock debris that might impinge on the tree growth, and (3) the lateral spread of damage. Sectors with sapling trees and bushes are areas in which there has already been major tree elimination and the present growth is a sign of tree recolonization after winters with intense avalanching.

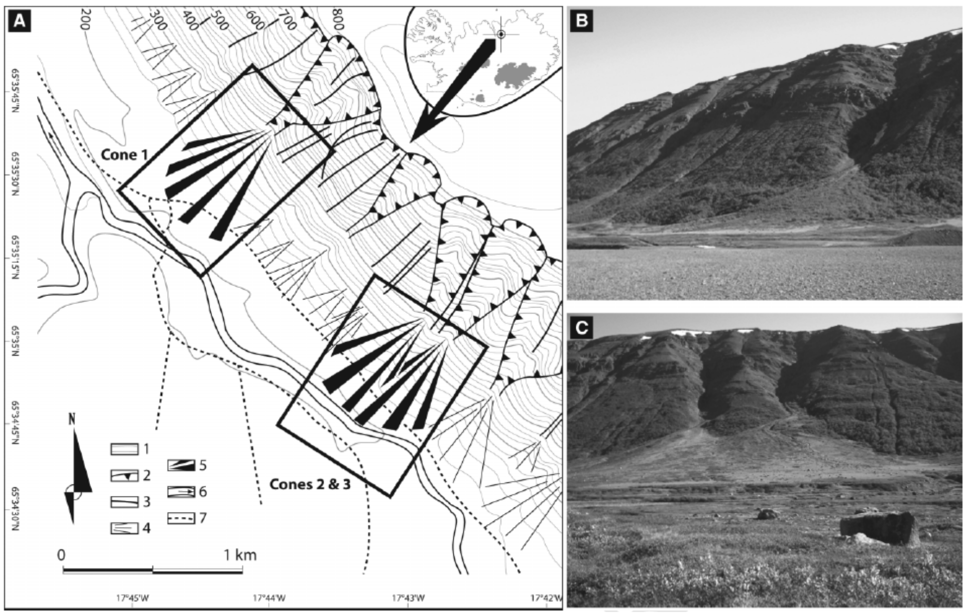


*Fig. 1.* Location of the study area, in the Fnjóskadalur valley, Central North Iceland. A. Simplified geomorphological map; 1 - contour lines (20 m); 2 - cliff edges; 3 - secondary rocky edges; 4 - colluvial cones; 5 - studied colluvial cones; 6 - river; 7 - trails. B. Cones 1. C. Cones 2 and 3. (Photos: A. Decaulne, 2006).

### *Dendrochronology*

Dendrochronology examines the annual increment in tree rings (Schweingruber 1987) to determine the occurrence and duration of growth disturbance. On the colluvial cones in the Fnjóskadalur valley, trees were sampled within the main flux lines of the cones and on the peripheries. Four increment cores were extracted following Stoffel (2005). Cores c (upslope) and d (downslope) were taken along the main line of the slope and provide a good indication of the geomorphic processes impacting tree growth. Cores a and b were taken laterally, at right angles to the line of c and d, to record any lateral impact from snow avalanches that occurred as the avalanche progressed downslope (Fig. 2B). Samples of trees were randomly selected at various locations (Fig. 2C) to examine the birch growth in the proximal, central and distal parts of the cones. On deciduous trees, reaction wood forms on the upward side of the trunk (Scurfield 1973), hence it was recorded by core c. Cores were extracted with a 20 cm Mattson increment borer (from Binétruy Sarl, Forestry Supplier1) following Grissino-Mayer (2003). The cores showed the very disturbed morphology of the trees and their low elevation. The GPS position of samples was noted and the boreholes refilled with wood filler to prevent further damage or insect attacks. The cores were later prepared to enable further analysis of individual tree rings. The prepared samples were scanned at a high resolution (1600 dpi) and the rings then counted from the outermost ring inwards towards the pith. Annual increment rings were measured visually with Adobe Illustrator CS2, allowing a 0.1 mm precision. Ring-width graphs and statistical analyses were performed with Microsoft Excel.

## Results

### *Dendrogeomorphology*

Fig. 3 shows the distribution of trees on the selected cones related to trunk diameter. On cone 1, the distribution of small trees clearly represents the main snow-avalanche paths, which largely follow a track south of the creek. On cone 2, which has far fewer trees, the path located south of the creek seems to be more active than the one following the creek itself because the proximal part of the cone is less wooded south of the creek. On cone 3 the avalanche path appears to follow the main line of the cone. Predictably, the larger trunks are found on the periphery of the cones, either on the lateral boundaries (cones 2 and 3), or the downslope boundary (cone 1).

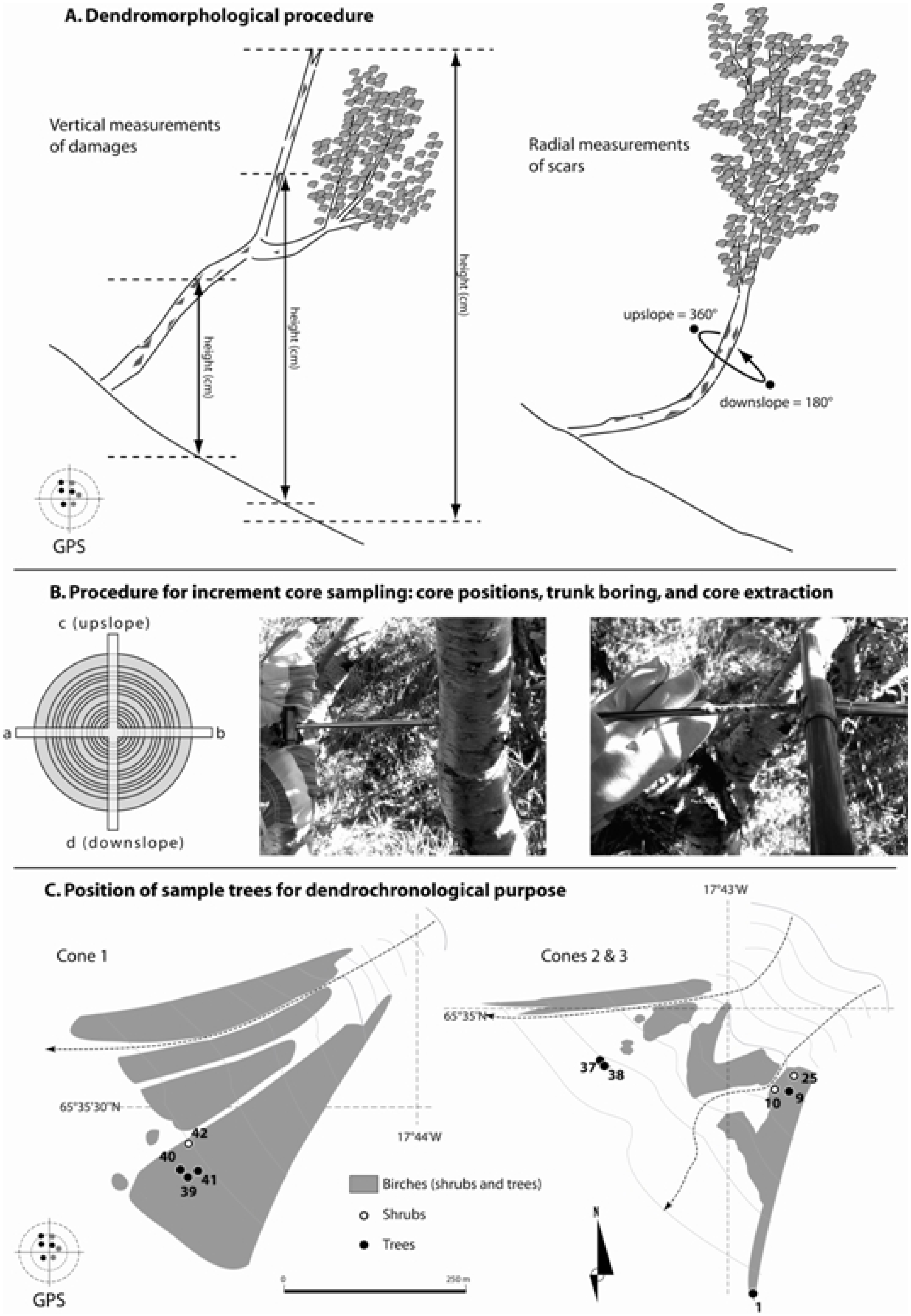


*Fig. 2.* Methodological procedure for dendromorphological investigation (A), and dendrochronological investigation (B). C. Shows the location of the trees and shrubs sampled for dendrochronological purpose. (Photos: A. Decaulne, 2006).

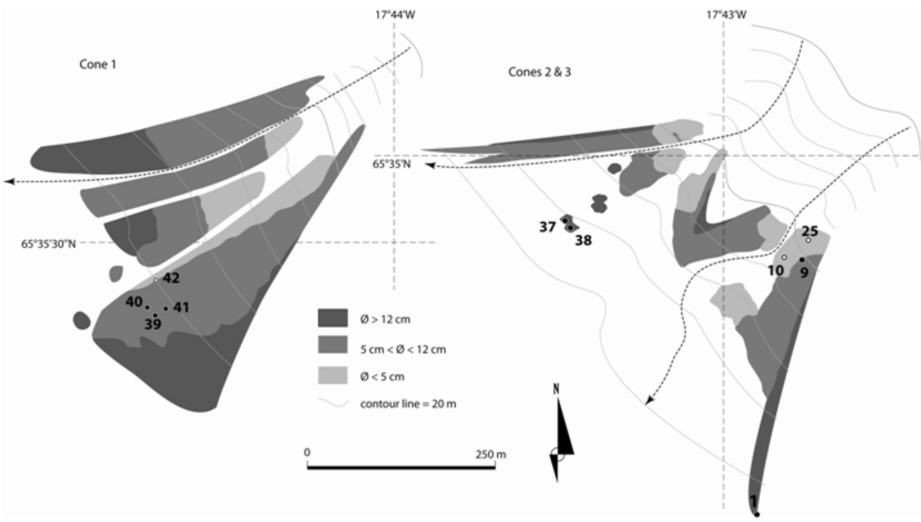


*Fig. 3.* Spatial distribution of trees on the three cones related to the diameter of the main trunks.

Table 1 shows the amount of damage to the sampled trees. Tilted trees with scars are most frequent. The spatial distribution of damage (Fig. 4) does not show a clear pattern (Fig. 4B) and reflects the selective impact of snow avalanches along their tracks. On cone 2 the greatest damage is on trees near the apex of the cone because normally the velocity of the snow flux and its rock debris yield is at a maximum on reaching the top of the cone. On cones 1 the greatest damage was observed further down within the path, almost at the lower boundary of the track and the beginning of the deposition zone. Shrubs are common in the proximal parts of cones 1 and 3 but are less affected by snow avalanches as they are prone to bend rather than break (Johnson 1987). The topography of these two cones is also a factor in damage distribution (Decaulne & Sæmundsson 2005). Both cones 1 and 3 are convex in the upper areas, more pronounced in cone 3, which affects the velocity of the snow avalanches fluxes and leads to a more destructive impact on the trees and shrubs. The uneven topography of the cone, with recurrent areas of low convexity, also increases the impact of avalanches downslope of such terrain unevenness (McClung & Schaerer 1993). The vertical distribution of scars on trunks shows impacts from 10 cm to 220 cm in height above the ground level (Fig. 4C). The maximum height of impacts from snow-avalanche transported rock debris is visible within the centre area of the cones but reaches c.100 cm towards the end of the track. In the proximal part of the cone, the shrubs are not tall enough for the maximum impact elevation of this type of debris to be recorded. The radial distribution of scars on the upslope side of trunks, opposite the tilting direction, indicates that the impacts are almost exclusively from rocks originating from the cone catchments, as they are predominantly in the main lines of flux. If the majority of scars (51%) is located within 40° segment around the snow-avalanche line (340-20°), all impacts occur between 270° to 90° on the upslope surfaces of the trunk. These data show that there has been conspicuous lateral spreading of snow avalanches because scars are also visible out of the direct line of snow-avalanche fluxes. The potential for lateral spreading is increased by the uneven topography of the cone surface, the deviation induced by impacts on the ground, and the shape of the rock fragments (Stoffel 2005).

### *Dendrochronology*

The ring-width measurements shown in Fig. 5 indicate the uneven growth of all trees and shrubs. Both cores c and d and cores a and b have successions of narrow and large rings. The cores c and d (sampled parallel to the slope) and cores a and b (at right angle to the slope) show clear asymmetric growth, indicated by the limited match of the curves and the high variations in ring development from one area to another. The mean annual tree-ring growth varies from 0.3 to 1.5 mm (Fig. 6). Cores within the same tree and between trees are highly variable, reflecting the eccentric growth trend of all the sampled trees that results from strong trunk tilting.

*Table 1.* Visible defects of sampled trees on cones 1, 2 & 3.

| | cone 1 | | cone 2 | | cone 3 | |
|---|---|---|---|---|---|---|
| trunk characteristics | # of trunks | % | # of trunks | % | # of trunks | % |
| slightly tilted trunks | 54 | 12 | 0 | 0 | 0 | 0 |
| tilted trunks | 116 | 25 | 211 | 33 | 191 | 25 |
| tilted trunks with scars | 216 | 46 | 187 | 29 | 503 | 65 |
| tilted trunks with scars and decapitation | 79 | 17 | 246 | 38 | 81 | 10 |
| total | 465 | 100 | 644 | 100 | 775 | 100 |

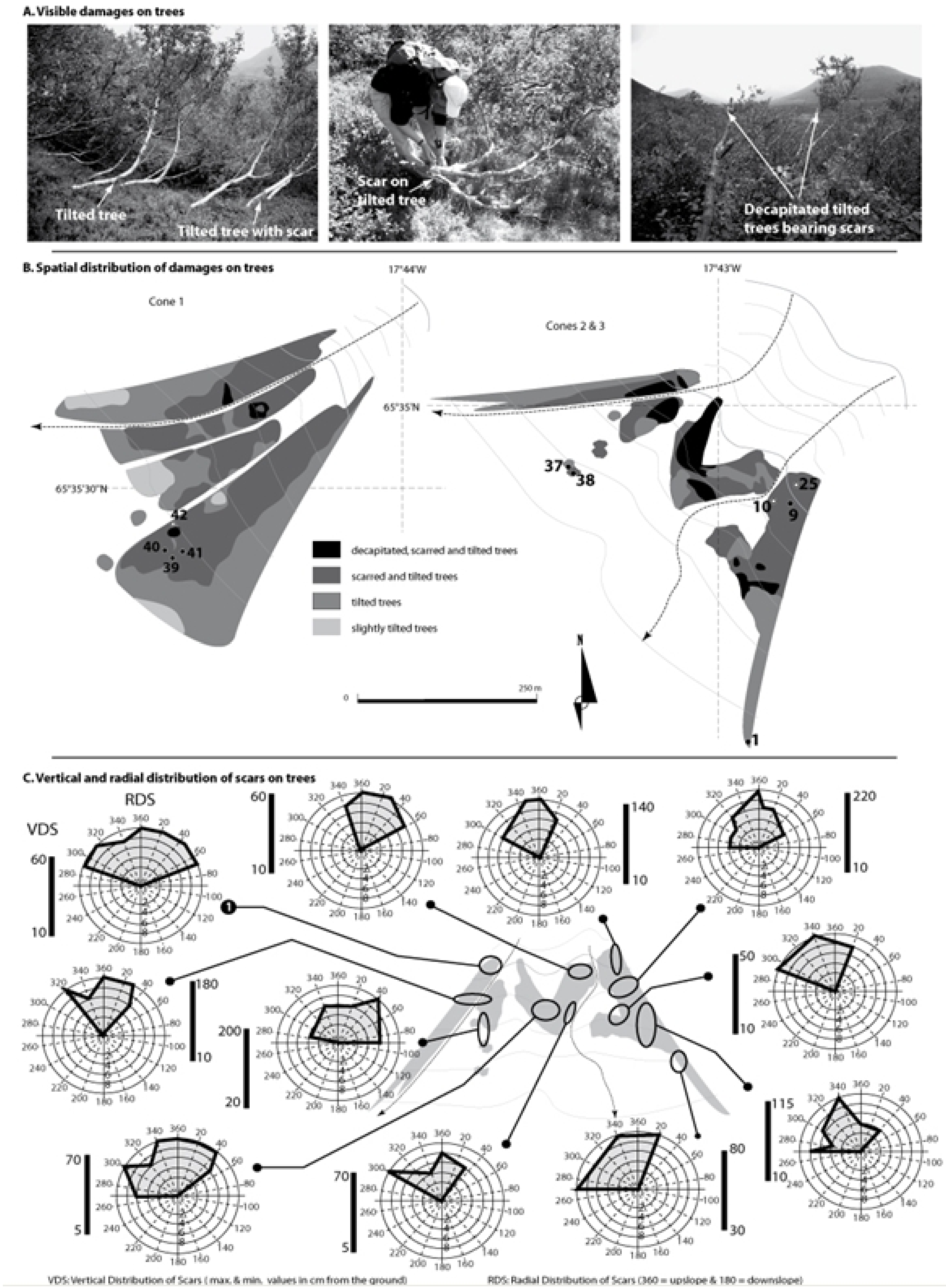


*Fig. 4.* Visible damage on trees considered for dendromorphological purposes (A), spatial distribution of damage on the three cones (B), and vertical and radial distribution of scars on trees (C). (Photos: A. Decaulne, 2005, and 2006 (middle)).

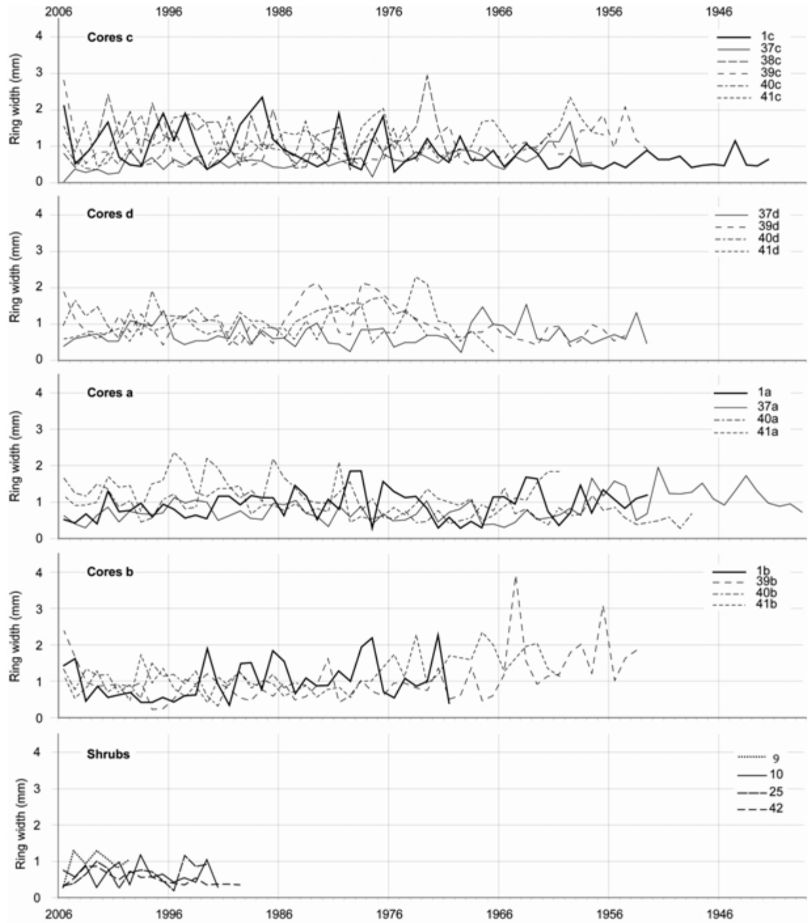


*Fig. 5.* Plots of ring widths on sample trees showing the disturbed development of trees and shrubs between 1946 and 2006.

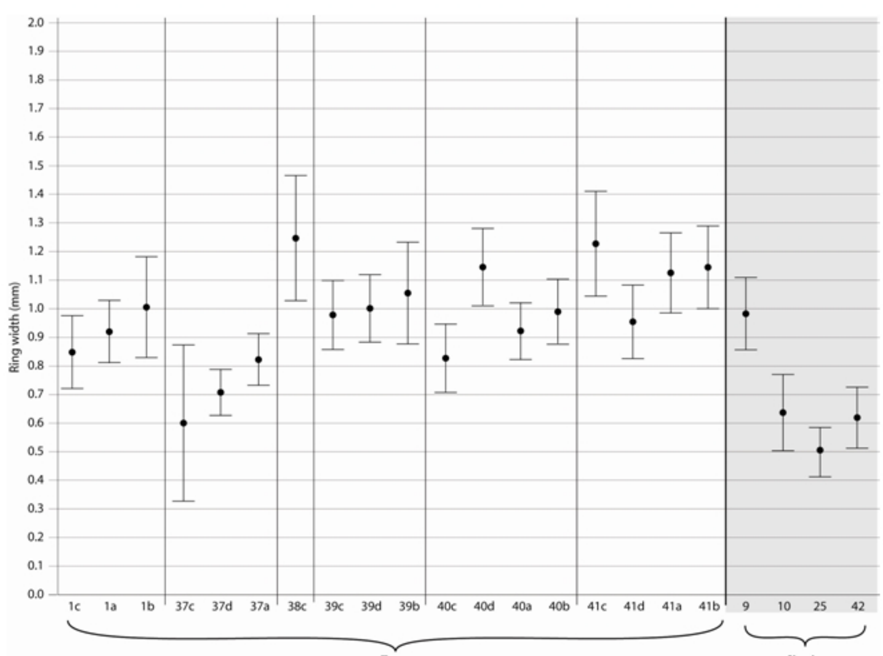


*Fig. 6.* Summary plot of mean ring widths with a 95% confidence interval, showing a clear dissymmetry of trees, and a large variation in ring width.

The development of the wood shows a zigzag pattern, a measure of the recurrent reductions in both tree and shrub growth. This appears to be evidence of repetitive damaging events through time, which hamper the 'normal' growth of woods (Bryant et al. 1989). The upslope growth is often greater than the downslope growth. This is interpreted as reaction wood formation on the upslope side of the deciduous trees (cores c) after debris impacts (Fig. 7). Fig. 8 shows the timing of the main growth disturbances, emphasizing the periods during which the greatest damage occurs; these occur at different periods on each investigated cone and are assumed to be specifically associated with avalanching. Generally, the incidence of single avalanches during one specific year is apparent but there are also avalanche cycles occurring during several years which clearly underline a pattern of recurrent snow avalanche events in the area. On cone 1 there is a pronounced dissymmetry in tree growths from 1960 to 1965 and from 1968 to 1975, evidence of periods of recurring avalanche activity. On cone 2, there appears to have been recurrent avalanching from 1973 to 1985, and from 2000 to 2005 reaction wood growth has been observed. The timing of long-term snow avalanching is difficult to reconstruct on cone 3 because of the high proportion of shrub samples but tree development has been strongly affected. The number of shrubs and small trees in the main snow-avalanche path reflects the difficult conditions for tree development on the cone.

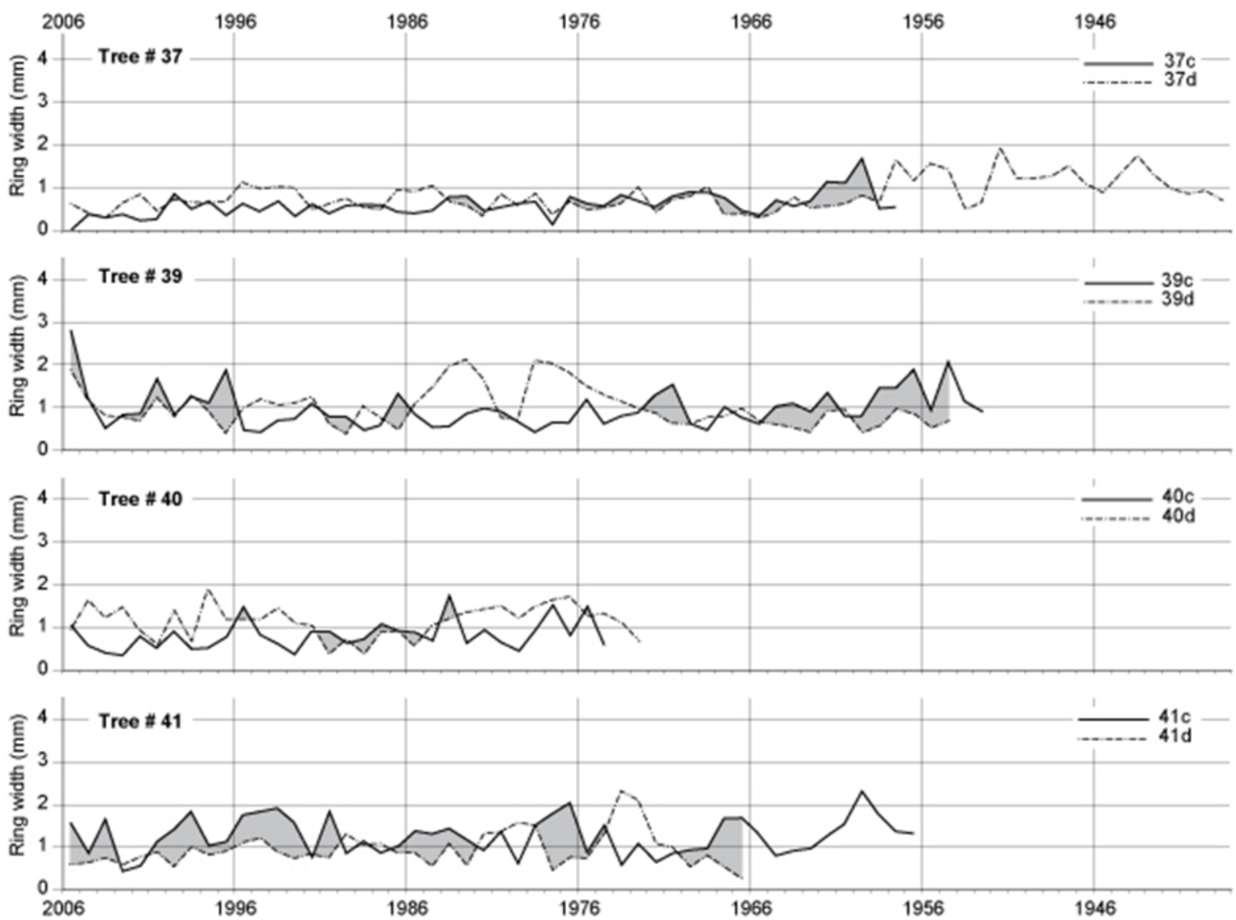


*Fig. 7.* Growth curves of selected trees highlighting the growth disturbance of the trunks. Grey shading indicates the periods when upslope increment (core c) is larger than the downslope one (core d), and probably corresponds to reaction wood initiation on the upslope face of the trunks after pronounced tilting of the main trunks.

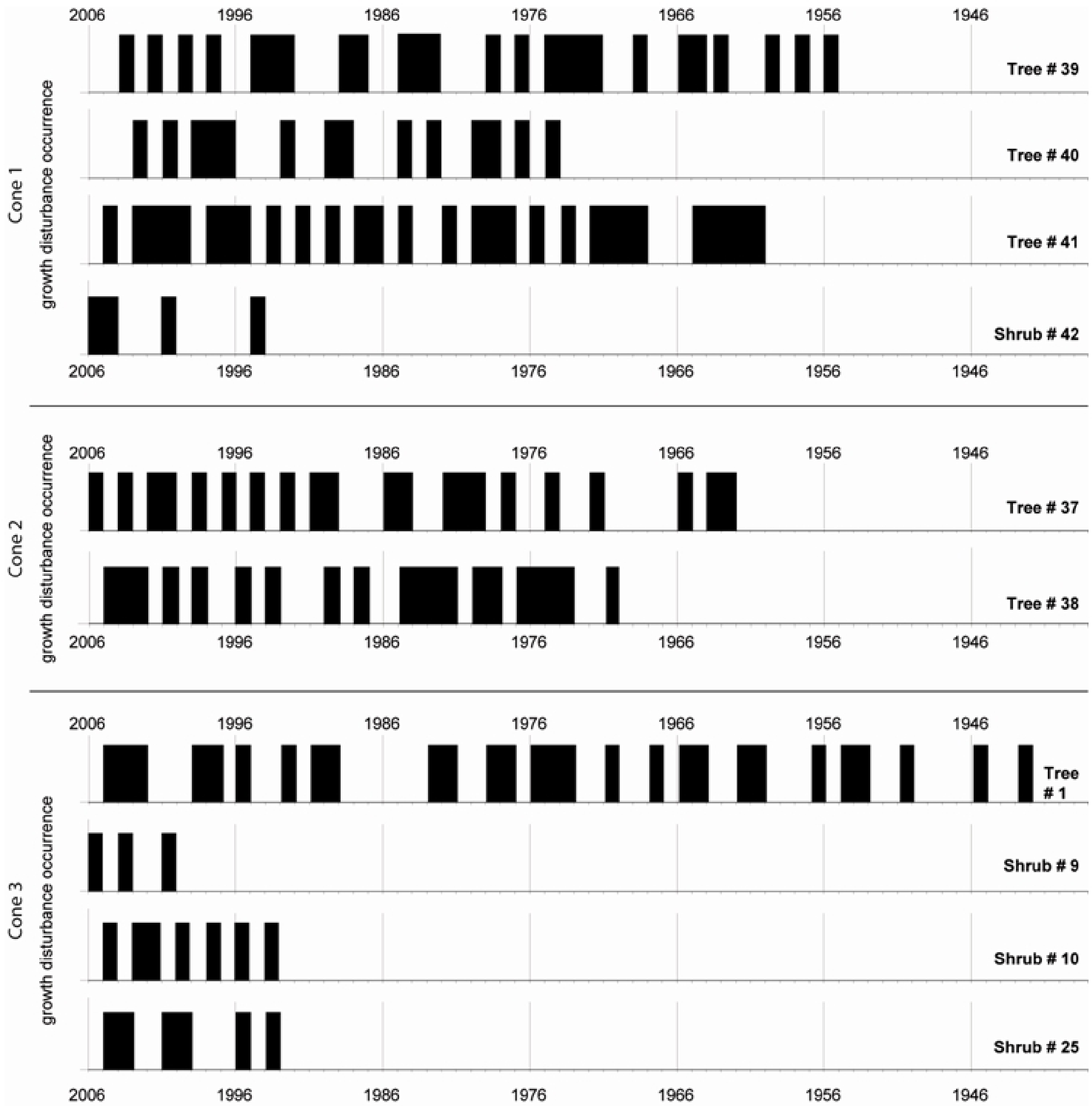


*Fig. 8.* Annual occurrence of growth disturbances for selected years, highlighting spatio-temporal anomalies on the three cones, based on the growth of tree rings on the upslope side of the trees (cores c).

## Discussion and conclusions

This study presents data on the height and nature of damage to trees on avalanche paths for an area in Northern Iceland. The data show spatial indicators of recurrent past unobserved snow avalanches. The widespread patterns of damage are shown by tree morphology and size.

The data also identify three main snow-avalanche regimes:

- Snow avalanches cover the apex and central parts of the cones with a high frequency and low magnitude. The avalanches impinge on shrub growth in these areas, demonstrated by the tree diameter distribution.
- Low frequency, high magnitude snow avalanches reach the end of the runout of the paths, approaching and sometimes crossing the Fnjóská River (Fig. 1). They have a larger lateral spread and transport boulders up to 2 m in height, toppling and damaging larger trees far downslope within the avalanche path. A deposit of boulders indicates the furthest extent of the avalanche activity in the distal part.
- Snow avalanches of intermediate frequency and magnitude impede the normal development of wood within the central and distal parts of the cones. This is manifested by the numerous scars and tilting of most trees in the stand located within the path. The dense tree and shrub cover on cone 1 appears as evidence of a lower occurrence of severe snow avalanches, in contrast to the patterns of occurrence on cones 2 and 3.

Dendromorphological evidence can be used to estimate the distribution of snow avalanches of different frequencies and magnitudes. The lateral spread of the snow fluxes originating from single source areas on a cone can also be observed. Damage to trees, even at high elevation, illustrates the potential destructive effects of snow avalanches along much of the extent of the path. The dendromorphological information, combined with evidence of the timing of damage-producing snow avalanches derived from tree-ring analyses, provides an indication of the spatial and temporal distribution of snow avalanches in the study area. In a case study undertaken in Colorado, Bryant et al. (1989) validate the relevance of dendrogeomorphological analyses for such purposes, with reaction wood being a useful time marker to date the occurrence of snow avalanches. In the literature, although most of the existing studies are based on conifer stands, areas covered by deciduous trees have also been studied. For instance, Owen et al. (2006) report similar damage to birches and rowans impacted by snow avalanches on a colluvial cone from southern Norway.

The tree samples have a highly variable pattern of ring growth. Abrupt changes in growth rates illustrate the disturbed environment in which the trees and shrubs develop. These are thought to reflect an active and recurrent influence from processes acting on the slopes, with snow avalanches appearing to be the most important at the cone scale. The small number of tree samples analysed does not allow the development of a reliable chronology of avalanche occurrence as recorded in tree rings for the entire cone surfaces. Several tree-ring measurements are not significant statistically, as shown in Fig. 9. The box plot distribution of ring widths highlights the abnormal results (indicated by circles on Fig. 9). These higher than mean growths probably reflect errors in ring counting, perhaps due to the difficulty of recognizing the position of probable missing rings, frequently the case in species of birch. Use of a LINTAB measuring table, or of other dendrochronological software, up to 0.001 mm precision should enable more accurate visual recognition of seasonal tree rings, so that missing and narrow rings can also be counted.

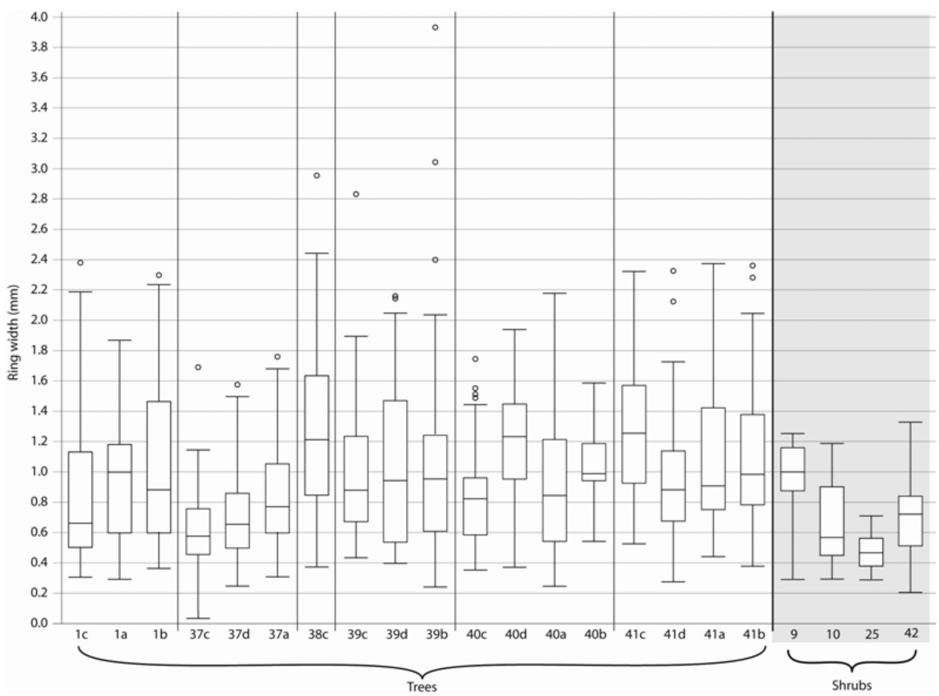


*Fig. 9.* Box plot distribution of tree-ring widths, showing recurrent overgrowth, as in the case of trees nos. 39 and 41. Circles show the abnormal results.

In areas of substantial disturbance, the recurrence of damaging events has a strong effect on reaction wood formation, release, and sprouting, all of which can be delayed. The twisted and deformed nature of some trunks made the sampling of four cores in a trunk as far as the pith difficult. Higher resolution of data for analysis is therefore essential. If a wider sampling strategy is carried out on the cone surfaces the observations of tree behaviour at various locations could be greatly increased and reflect more detailed patterns of the effects of snow-avalanche activity and the associated trunk damage (D.R. Butler et al. 1987). A reference chronology is also required in the vicinity of the study area located off snow-avalanche paths. This would help in the assessment of the relative importance of the snow avalanches and climatic events in abrupt changes in tree-ring width.

In conclusion, the preliminary research has produced significant dendromorphological data that show the main sectors of tree growth that are hampered by snow-avalanche activity. The approach also locates the areas reached by less frequent but more destructive snow-avalanche events. There is clearly potential for dendrochronology to reveal annual fluctuations and spatial distribution of snow-avalanche activity in areas where records are lacking. Further research is required in order to produce an accurate chronology of damage recorded in birch stands.

## Note

1 http://www.binetruy-sarl.com/catalogue/p30.pdf (accessed February 2007)


## Acknowledgements

Financial support was received from the Natural Research Centre of Northwest Iceland, Sauðárkrókur, Iceland, from the Geolab CNRS-UMR6042 Laboratory of Physical and Environmental Geography, Clermont-Ferrand, France, and from the Arctic Research Network, Besançon, France. The authors thank Erik Grüneberg, Elisabeth Janssen, Helgi Páll Jónsson, and Olga Sandberg for the helpful assistance they provided during the fieldwork. The authors are grateful to the reviewers for their constructive comments on the manuscript.


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