58

Dendroecology A Guide for Using Trees to Date Geomorphic and Hydrologic Events

2005

British Columbia

Ministry of Forests Forest Science Program

Dendroecology A Guide for Using Trees to Date Geomorphic and Hydrologic Events

David Wilford, Paolo Cherubini, and Matt Sakals

British Columbia

Ministry of Forests Forest Science Program

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the Government of British Columbia of any product or service to the exclusion of any others that may also be suitable. Contents of this report are presented for discussion purposes only. Funding assistance does not imply endorsement of any statements or information contained herein by the Government of British Columbia.

Library and Archives Canada Cataloguing in Publication Data
Wilford, D. J. (David J.), 1950-

Dendroecology : a guide for using trees to date geomorphic and hydrological events
(Land management handbook, ISSN 0229-1622 ; 58)

Includes bibliographical references: p.
ISBN 0-7726-5347-X

1. Dendrochronology. 2. Dendroclimatology. 3. Trees - Ecology. 4. Tree-rings. I. Cherubini, Paolo. II. Sakals, M. E. III. British Columbia. Forest Science Program. IV. Title. VI. Series.

QK477.2.A6W54 2005 582.16 C2005-960095-0

Citation
Wilford, D.J., P. Cherubini, and M.E. Sakals. 2005. Dendroecology: a guide for using trees to date geomorphic and hydrologic events. B.C. Min. For., Res. Br., Victoria, B.C. Land Manage. Handb. No. 58. <http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh58.htm>

Prepared by
David Wilford
B.C. Ministry of Forests
Smithers, B.C.
and
Paolo Cherubini,
Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)
Birmensdorf, Switzerland
and
Matt Sakals
Bulkley Valley Centre for Natural Resources Research and Management
Smithers, B.C.

© 2005 Province of British Columbia

Copies of this report may be obtained, depending upon supply, from:
Crown Publications
521 Fort Street
Victoria, BC V8W 1E7
(250) 386-4636
www.crownpub.bc.ca

For more information on Forest Science Program publications, visit our Web site at: http://www.for.gov.bc.ca/hfd/pubs/index.htm.

ABSTRACT

The study of tree response to environmental conditions is called dendroecology. This discipline can offer key advice to forest practitioners regarding when landslides or flooding have occurred in the past. When trees are tilted, buried, or scarred by events, or established on sediment following an event, a record is left in the tree rings. This guidebook provides forest practitioners with information and straightforward techniques for interpreting those records. The additional time and expense incurred is of minor importance compared to the information generated and the degree of confidence that can be placed in the identification of geomorphic and hydrologic hazards influencing a site.

ACKNOWLEDGEMENTS

We appreciate the thorough and constructive reviews by Roberta Parish, Bill Grainger, Steve Doyle, and David Coates. This project was financially supported by the B.C. Ministry of Forests, Forest Renewal BC, Forest Investment Account, and the University of British Columbia Faculty of Forestry.

TABLE OF CONTENTS

1 INTRODUCTION

Trees are exposed to a wide range of environmental conditions, from extreme climatic events such as drought or frost, to fire, fungal, insect, or other ecological disturbances, to burial by flood water and sediment. Trees may respond quickly by changing their radial growth, developing wood anatomical features, or dying if conditions are too severe. The study of tree response to environmental conditions is called dendroecology (Fritts and Swetnam 1986; Schweingruber 1996). Environmental conditions may be classified as widespread when entire stands are influenced, or localized when only groups of trees are influenced. Weather has a widespread influence on forest stands, and is an example of an exogenous influence (Cook and Kairiukstis 1990). Burial of a group of trees by sediment is a localized influence and is an example of an endogenous influence (Cook and Kairiukstis 1990). A key in dating hydrologic and geomorphic events is to distinguish widespread and localized influences.

Trees are commonly found in the runout zones of debris flows, and are frequently influenced by floods, debris floods, and rock falls (processes defined by Hungr et al. 2001). These are collectively referred to as hydrogeomorphic events. Trees can be buried by sediment, tilted, or scarred, and their water supply can be radically changed. Trees can also be removed by an event, and a new group of trees (referred to as a cohort) can be established on the fresh sediment (Oliver and Larson 1996). The application of dendroecology to the dating of hydrogeomorphic events is relatively recent (Alestalo 1971; Strunk 1997). It is becoming a common investigative tool because it is fairly easy and accurate, and allows for detailed geomorphological mapping (Jakob 1996; Yoshida et al. 1997; Gärtner et al. 2003). The techniques are particularly useful for forest practitioners (including seasoned forest technicians, foresters, geoscientists, and engineers) to identify hydrogeomorphic hazards while developing harvesting prescriptions and designing roads and drainage structures.

In this guide, field and laboratory methods are presented for the application of dendroecology techniques to determine dates, or approximate years, of hydrogeomorphic events. Specific topics include: identification of areas on fans that are influenced by hydrogeomorphic events; sampling techniques; sample preparation; and analysis using a simple and straightforward dendroecological method (skeleton plot analysis). Illustrations and a case study are presented from an investigation of forested fans in west-central British Columbia (Wilford et al. 2002).

2.1 Office Work

The first step in the dating of geomorphic or hydrologic events is to identify the areas that are being influenced by hydrogeomorphic processes. Aerial photographs can be used to identify clearings or cohorts (forest stands or groups of trees of approximately the same age) that are linked to the stream channel or steep slopes (Figure 1). These forest cover features are potential evidence of powerful hydrogeomorphic events that have cleared the original forest. Cohorts can also be established from other natural causes such as forest fires or windthrow, or be associated with logging. A key feature of cohorts derived from hydrogeomorphic events is a connection to a stream channel or the apex (top) of the fan. Aerial photographs will also provide evidence of other features that can indicate hydrogeomorphic activity: multiple stream channels and abrupt angles in stream channels (Wilford et al. 2005).

FIGURE 1 *An aerial photograph with a cohort (outlined in white) that is connected to the stream channel. The direction of streamflow is from the lower left to the upper right. This is a 100-year-old cohort following a major flood event. Scale 1:11 000 (approx.).*

2.2 Fieldwork

2.2.1 Where to sample

In the field it is necessary to delineate forested areas that are being influenced by hydrogeomorphic activity. This zone is referred to as the hydrogeomorphic riparian zone and has a series of diagnostic features that include: buried trees, cohorts (in areas cleared by high-power events, or established under a forest canopy on sediment deposited by low-power events), scarred trees, recent sediment splays, log steps (sediment accumulated on the upslope side of downed logs), scattered boulders, and elevated sediment and debris (Figures 2, 3, 4, and 5) (Wilford et al. 2005). Sampling should also be undertaken on other areas of a fan, as control sites, to ensure that growth responses are the result of hydrogeomorphic events (endogenous influences) as opposed to other influences (e.g., exogenous influences such as insects or weather).

FIGURE 2 *A young cohort of spruce and hemlock growing on the sediment of a high-power debris flood.*

FIGURE 3 *A 35-year-old cohort of hemlock growing on sediment deposited by a low-power debris flood.*

FIGURE 4 *Erosion of sediment deposited around this tree has exposed adventitious roots that were formed following a previous burial.*

FIGURE 5 *An example of a buried tree. Note the lack of butt flare.*

2.2.2 Sampling intensity

Sampling intensity is related to the objectives of the project. For example, developing relationships between landslides and weather records requires high sampling intensity (Schwab 1996). Conversely, if the number of debris flow events over the past 50 or 100 years is required for the design of a drainage structure, then a lower intensity of sampling is appropriate because exact dates (or years) is not required. In order to date events influencing a forest stand, it is common to collect samples from 12–15 trees, because it has been demonstrated that the variability of sample data remains approximately the same when more than 12 trees are sampled (Schweingruber 1996). Depending on the objectives, each tree may be sampled once or several times.

2.2.3 Labelling and storing samples

All samples should be labelled with a waterproof pen or pencil. This can be done directly on the wedge or disk samples, or on masking tape attached to the samples. Increment cores should be stored in large-diameter drinking straws and labelled on the masking tape used to seal the ends. Long cores should be stored in two or more straws rather than wrapping tape around the extended portion of a core (the extended portion is subject to breaking either during transport or when the tape is removed).

If samples will not be prepared for analysis immediately it is necessary to store them in a freezer to avoid decay. Decay can proceed quickly in some tree species and the deterioration can limit the ability to detect tree-ring patterns and wood anatomical features (discussed below). Storing samples in a freezer for at least 48 hours will also kill insects that may be on a sample. This may be a requirement if the samples are to be subsequently analyzed in a multi-use laboratory or transported across an international border.

2.2.4 Field notes

Field notes about the samples should include:

- date sampled,
- location,
- tree species,
- sample height,
- tree condition,
- reason for sampling, and
- comments regarding the relation of a tree to its neighbours (e.g., indications of blowdown or other factors that would have resulted in a growth response) (see Appendix 1).

Sampling date is essential with regards to radial growth development. In northern latitudes, radial growth may not be evident until mid summer (because radial growth is secondary until apical growth has ended). Radial growth can continue until mid to late September. Noting tree species is important because growth factors may influence some species in an area (e.g., periodic defoliation of western hemlock, *Tsuga heterophylla* (Raf.) Sarg., by the western hemlock looper, *Lambdina fiscellaria lugubrosa*, or of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, by the western spruce budworm, *Choristoneura occidentalis* Freeman [Alfaro et al. 1982]). If a tree is sampled to determine age, it is necessary to record sampling height to adjust for the number of years to reach that height. Tree condition includes features that influence growth, such as broken tops, pathology indicators, and position in canopy (e.g., suppressed). Reasons for sampling include: to determine a date of burial, to represent a cohort of a given dimension, or to date a scar. Details regarding scars should include: the orientation of the scar relative to slope or stream location, height and dimensions of the scar, and comments regarding the exposed wood surface (e.g., smooth versus gouged). Notes should also be made on the quality of a core (e.g., good, scar noted, or rotten beyond 20 cm).

2.2.5 Selection of sample trees

Care must be used in selecting sample trees. Heart or butt rot can limit the quality and length of the sample. Indicators of rot are external fungi ("conks") or a "ringing sound" when the tree is struck with a shovel. Broken tops may produce a growth response that is not related to a hydrogeomorphic event. Understory trees may have growth so suppressed that the signal from an event cannot be determined. When sampling a young cohort in an opening, ensure that sample trees are rooted in sediment rather than in woody material (i.e., the tree may have been there before the event). Most tree species provide good-quality material for dating events; however, cottonwood, *Populus trichocarpa* Torr. and Gray ex Hook., which is frequently found on areas disturbed by hydrogeomorphic events, can be very difficult to date because of indistinct growth rings in all or a portion of a core.

2.2.6 Sampling equipment and sampling details

Increment borers are specialized tools used to extract 5 to 12 mm diameter cores from trees. Collecting high-quality cores is important and requires appropriate coring techniques and maintenance of borers (Jozsa 1988). When using an increment borer to sample trees in the hydrogeomorphic riparian zone it is important to sample the downslope side of a tree. This reduces the potential of encountering overgrown scars and thus missing a series of growth rings. Increment cores should be taken as low as possible on a tree because growth responses from burial decline with distance up a tree stem (Strunk 1997). A core sample that extends well beyond the centre of tree can be useful for identifying or confirming certain features. For example, when a conifer is pushed from the uphill side by sediment or debris from a hydrogeomorphic event, the tree responds by producing compression wood on the lower or downhill side of the stem. Usually, concurrent with these denser, darker (because of higher lignin content), and frequently wider growth rings is a reduction in ring width on the uphill side of the stem. Deciduous trees have an opposite growth response when pressure is applied. They establish tension wood (wider tree rings characterized by higher cellulose content) on the side that is receiving the pressure. Compression and tension wood is collectively referred to as reaction wood.

If cores are being taken to establish tree age it is essential that the core includes the pith. Estimation errors can be made when the pith is not sampled. When increment cores are taken it is necessary to note the height of the sample on a tree. This will allow for an age correction to be estimated. Trees that have been buried will require excavation to the original root collar if age of establishment is required. Notes should also be made on the overall condition of a tree.

Disks, cut with handsaws, can be taken from small trees to determine age and observe growth and wood anatomical features. Disks also allow for a complete view of a cross-section of a tree. This can be very helpful if a tree has been suppressed, because very narrow growth rings may "disappear" in a portion of the cross-section (so-called "missing rings" or "locally absent rings"). If disks are taken at two heights (the germination point and the height where most cores are taken) it is possible to establish height-growth relationships to correct for ages determined from cores (although recognition must be given to the level of competition during early growth, as this can significantly influence the height-growth relationship).

Prior to sampling a scar on a tree stem, it is necessary to determine possible causes of the injury. If a scar faces upslope or toward a stream, it may be related to a hydrogeomorphic event. Scars should not be sampled if observations indicate that the cause was wildlife, windthrow, or some other damaging agent. Scars can be sampled by cutting a wedge out of a larger tree or by cutting a small tree down (through the scar). Use of a power saw may be required in areas where a handsaw limits the size of tree that can be sampled or limits the age of scar that can be sampled (i.e., because the callous or growth tissue around the scar may be too thick to cut a wedge with a handsaw). Increment bores can be taken through the callous growth around a scar; however, it is often difficult to locate the exact edge of a scar accurately (see Barrett and Arno 1988 for coring techniques).

A key aspect of fieldwork is to establish and estimate the time period between an event and the establishment of tree seedlings on the exposed sediment in the study area. This estimate is necessary to link cohorts to hydrogeomorphic events. If dates of recent events are not known, it is necessary to determine the establishment delay by sampling scars and cohorts (preferably young cohorts sampled with disks at the point of germination).

The time required to collect dendroecology samples and make field notes is approximately 5 minutes per sample. On a site where 15 samples are collected this would represent approximately 75 minutes.

2.3 Field Analysis

Field analysis is useful to direct further sampling because there may be indications of more activity than is apparent from observing a stand. In some situations, field analysis may be adequate to date hydrogeomorphic events. For example, a series of cohorts may be present and the cores or wedges may provide clear identification of growth rings. However, it is likely that narrow growth rings and wood anatomical features may be visible only in prepared samples using a laboratory stereo microscope. To improve the accuracy of field analysis a 10-power hand lens is recommended. There are several techniques to improve the visibility of growth rings. A sharp knife can be used to shave a core. The shaving should be done at right angles to the fibres (visible at the end of the core with a hand lens). Soft chalk can be used to accentuate growth rings: chalk is rubbed onto the core and then wiped off, forcing the chalk into the wider, early-wood pores.

Field analysis can be conducted relatively quickly—approximately 2 minutes per sample. On a site where 15 samples are analyzed this would represent approximately 30 minutes.

2.4 Preparation for Analysis

It is generally necessary to prepare samples for laboratory analysis in order to observe narrow growth rings and wood anatomical features, and to ensure accurate analysis. Increment cores are glued to slotted wooden mounts, with the fibres oriented vertically (check with a hand lens) (Figure 6). Mounts can be made from 9.5-mm (3/8-inch) plywood (Figure 7). Having a range of mount lengths (e.g., 20, 30, and 40 cm) economizes on materials. Multiple cores can be glued to a single mount, but attention must be paid to labelling each core (Figure 8). Water-based wood glue is recommended, as this

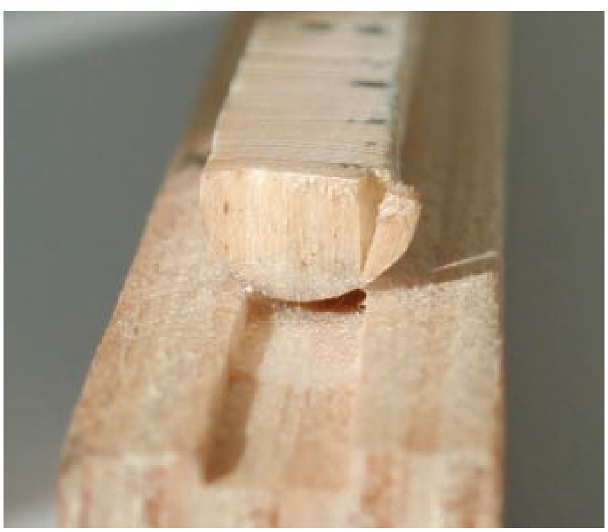


FIGURE 6 *An end-view of a sanded core showing vertical orientation of wood fibres.*

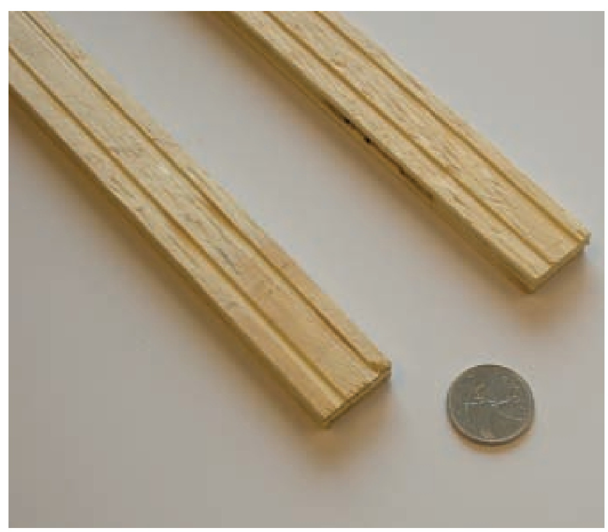


FIGURE 7 *A view of two slotted wooden mounts. The mounts are made from 9.5-mm plywood and are 2.4 cm wide. The slots are 3 mm wide and 1 mm deep (a single saw blade cut). The spacing between the slots is 8 mm, which allows for labelling.*

FIGURE 8 *A wooden mount with two sanded cores.*

allows for removal of a sample from a mount if a problem is observed (particularly useful with cores in multiple pieces). When a core is broken, care must be exercised in removing the pieces from the drinking straws and ensuring that the pieces are re-connected in the appropriate order. Transparent tape is used to hold the cores in place until the glue dries. The amount of tape used is dependent upon a specific core, but the core should be held securely on the mount. The mounted cores (with the tape removed), wedges, and disks are sanded with a bench belt sander (beginning with 100- or 150-grit paper and finishing with 300- or 400-grit paper). Sanding reduces the diameter of cores by 50%. Attention should be paid to how quickly a core is being reduced because different tree species have different sanding rates. Prior to sanding wedges and disks, it is important to ensure that labels will not be removed. Sanding produces a smooth finish on wedges and disks that allows for accurate identification of growth rings and wood anatomical features. The amount of sanding required on wedges and disks is related to the roughness produced by a saw and how flat the samples are cut.

Preparation of samples requires approximately 6 minutes per sample. For a site where 15 samples are collected this would represent approximately 90 minutes.

2.5 Analyzing Samples

2.5.1 Dating samples

Samples are analyzed using a stereo microscope. For the most comprehensive and efficient analysis, a 30-power zoom microscope is preferable, but analysis can be completed with a hand lens. The first task is to date samples by counting growth rings. Growth rings on most tree species are usually apparent; however, with cottonwood samples it may be necessary to apply dyes (Maeglin 1979; Blais 1995), highlighter ink, tea, or cola to improve ring identification. Dating starts at the most recent growth ring, counting backwards to the pith or end of the core/sample. Care should be taken in dating the outside ring, because lateral growth may or may not have occurred for the present calendar year. In west-central British Columbia, lateral growth characteristically begins in June and ceases in September. For ease of dating, a simple notation system is used: one dot is used for every decade (e.g., 1980, 1990), two dots are used for every 50 years (e.g., 1850, 1950), and three dots are used for every century (e.g., 1900, 2000) (see Figure 10). To ensure accuracy it is wise to count down a decade of rings, place a dot and count back up the decade of rings.

Once samples are dated, the task is to date scars, determining the year of establishment, and identify growth and wood anatomical features. Scars can occur during the dormant season or during the growing season. Abrasion generally removes the bark and may result in gouging into the wood of a tree. The objective in analysis is to determine the outermost ring layer of a scar for dating purposes. If late wood (the denser, darker wood that generally begins to be formed in August) is present, then the scarring event occurred during the dormant season (late September through May). This allows for a time bracketing of the event that will include 2 years (e.g., the fall of 2004 through the spring of 2005). If only early wood is present on the scar, then a narrower time bracket is possible (e.g., the mid summer of 2004). Local information or climatic records may provide better direction as to the actual date of the event. Samples should be examined with a microscope to ensure that multiple scars are not present (Figure 9).

Dating a hydrogeomorphic event using tree establishment involves two estimates. The first is to determine an age correction for the height of the sample. This estimate can be avoided if the sample is a disk taken at the germination point of a small tree. Applying the age correction to cores requires either direct knowledge of seedling growth in the area (including consideration for canopy closure) or it may be estimated for open-grown trees using site index curves for the sampling area (e.g., Thrower et al. 1994; Nussbaum 1996). The second estimate is the

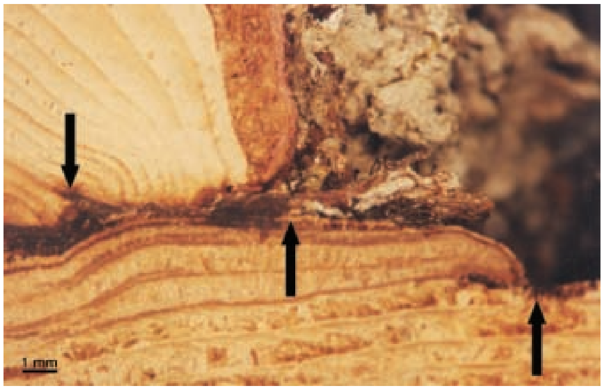


FIGURE 9 *A close-up of a wedge through a scar, with arrows indicating multiple scars.*

time delay between an event and seedling establishment. Observations in west-central British Columbia indicate that this time period ranges between 0 and 5 years. Notes taken on field observations or correlating scars and regeneration establishment (e.g., disks taken at the germination point for seedlings or small trees) in a specific area should be used to determine this estimate.

Abrupt tree growth changes can be associated with hydrogeomorphic events. Abrupt negative growth that continues for 5 to more than 20 years may be associated with tree burial (Figure 10) (Strunk 1997). The period of this negative growth is an indicator that the cause is not poor weather in a growing season, but that other factors (such as insect defoliation) should be explored through sampling of the same tree species in areas outside the hydrogeomorphic riparian zone. Growth can return to, or exceed, pre-event levels as adventitious roots become established

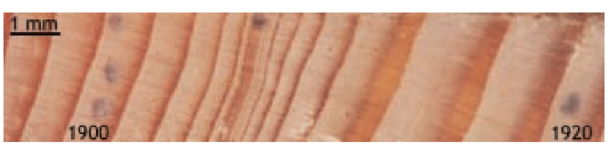


FIGURE 10 *A close-up of an increment core from a spruce (*Picea glauca*), showing abrupt reduced growth and the system of noting years. Abrupt negative growth changes began in 1903 and continued until 1915. Growth was normal in 1916, then increased. These growth responses were due to deep burial by flood sediments, subsequent establishment of adventitious roots, and reduced competition (the event resulted in a 200 m wide swath cleared adjacent to the tree).*

just below the new soil surface (Figure 4). Abrupt positive growth is generally associated with the removal of adjacent competing vegetation (Strunk 1997) but can also be associated with the decreased distance to newly formed stream channels. There are many agents that can remove adjacent vegetation, including a hydrogeomorphic event, windthrow, forest harvesting, and fire. Information on adjacent openings should be included in field notes to enable appropriate conclusions to be drawn during sample analysis.

Wood anatomical features caused by physiological stress included scars, traumatic resin canals, and compression wood (Figures 11 and 12). It is common to observe traumatic resin canals in the growth rings of a callous around a scar, but they can also be found throughout a cross-section or core. Compression wood and tension wood formation is a reaction to a pressure being applied to conifer and deciduous trees, respectively.

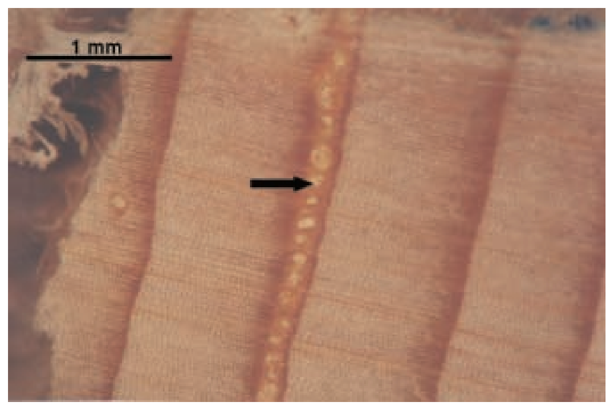


FIGURE 11 *Traumatic resin canals formed in late wood of a growth ring.*

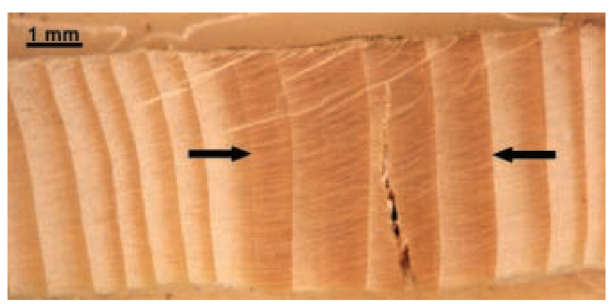


FIGURE 12 *Dark, lignin-enriched cells and wider growth rings are characteristic of compression wood that is formed when conifers are tilted.*

2.5.2 Skeleton plots

Information derived from tree-ring width, tree scars, wood anatomical features, and dates of establishment can be portrayed in skeleton plots (Schweingruber et al. 1990) (Appendix 1). These plots include time (in years) on the x-axis and abrupt growth response on the y-axis represented by three increments (slight, moderate, or strong) to represent positive or negative abrupt growth response. Each sample has a separate horizontal line, beginning with either the date of establishment or the date of the end of a sample. Growth response, scars, and wood anatomical features are noted for the year they occur. In addition to the date of a growth response it is necessary to identify the degree of change and its duration. Three classes of change for positive and negative growth are used, and the change is measured relative to an average ring width, which is determined following examination of a sample (Appendix 1).

It is important to plot the control samples on the skeleton plot to identify non-hydrogeomorphic factors that may be influencing tree growth. This is where tree species become important, particularly if some have been influenced by factors such as insects. If most (i.e., 90%) of the samples have individual years with conspicuously wide or narrow growth rings they are referred to as "pointer years" (Schweingruber 1996). Pointer years are generally related to good or poor growing conditions and are used to reconstruct skeleton plots for dead trees and to cross-date living trees to ensure that missing rings are identified.

Once the skeleton plot is completed for a fan it is examined for evidence of hydrogeomorphic events. "Certain" events are indicated where cohorts are established or where scars are present together with abrupt growth changes and wood anatomical features in other samples. "Probable" events are indicated where only growth and wood anatomical features are noted. A summary of events is then prepared for the fan. The case study presented in Appendix 1 was undertaken to provide information regarding the number of past debris floods for the installation of a bridge, a structure that was intended to be serviceable for 25 years. From the dendroecology investigation we determined that three events had occurred in the past 50 years and eight in the past 122 years. Furthermore, adding "probable" events, there have been 13 events in the past 143 years. With this information, the bridge, which was designed to pass a 50-year flood, was raised 1 m, and the approaches were heavily armoured. Had the information been available prior to the initial installation, a longer bridge would have been installed that would not have required the armouring, and the total cost would have been lower.

While dendroecology samples can provide information going back three centuries on some sites, the most complete coverage and reliable data are usually for the past 50 years. The key data relate to the dating of scars and cohorts, both of which can present challenges beyond 50 years, due to decreasing evidence and declining data quality. Generally, scars older than 50 years have significant callous tissue that may make identifying and sampling the scar difficult. If more complete dendroecology coverage is needed, it is necessary to consider sampling with a power saw or perfecting the use of increment cores for sampling scars (Barrett and Arno 1988). Dating events using cohorts can be challenging because of the increased probability that cohorts are removed by a subsequent high-power event (Luckman 1992). For this reason, a 50-year time frame is considered to limit but not eliminate the error associated with absent cohorts.

Where possible, it is instructive to determine the history of observed events in a study area. Climatic or water flow records can also be instructive; however, debris flows and debris floods may not occur in conjunction with these events (Bovis and Jakob 1999).

2.5.3 Time required for dendroecology investigations

Analysis of dendroecology samples to construct skeleton plots requires approximately 15 minutes per sample. For a site where 15 samples are collected this would represent approximately 3.75 hours. Following the analysis, the summary of hydrogeomorphic events requires approximately 30 minutes. In addition to normal fieldwork that would be conducted on a site, the total time required to undertake dendroecology investigations that conclude with a summary, for a site based on 15 samples is approximately 7.5 hours. On some sites it is possible to gain valuable information from field analysis only, reducing the time to approximately 1.75 hours plus additional time for including the information in a report.

3 CONCLUSIONS

Dendroecology is a very useful means of determining the dates of hydrogeomorphic events influencing a site. Equipment to undertake the work is available in most situations, and the techniques outlined here are reasonably simple to master. The time required to undertake the work on a site where 15 samples are collected is less than 8 hours. This is of minor importance compared to the information generated and the degree of confidence that can be placed in the identification of hydrogeomorphic hazards influencing a site.

The case study is a project that used dendroecology to provide guidance for the installation of bridge. The original bridge design was based on a 50-year flood event and was intended to be serviceable for 25 years. As a result of the evidence provided by the dendroecology work, the structure was raised 1 m, and the approaches were heavily armoured, to accommodate frequent debris flood events. Had the information been available prior to the initial installation, a longer bridge would have been installed that would not have required the armouring, and the total cost would have been lower.

Field Notes – 39 k Upper Kitimat

Type of sample: C = core
D = disk
W = wedge

Species: B = *Abies amabilis*
H = *Tsuga heterophylla*
S = *Picea* spp.
Ac = *Populus trichocarpa*

Aspect of sample: D = downstream
U = upstream
XS = across slope facing stream
XN = across slope away from stream

Sampling Dates: April 19, 2001 (1–8)
May 15, 2001 (9–33)
June 13, 2001 (34)

TABLE A1.1

Tree no.	Sample type	Species	Sample ht. (cm)	Aspect	Tree dia./ht. (cm/m)	Field notes
1	C	B	130	D	50.5/26	On left bank of contemporary channel. GPS #1
2	D	H	0		/1	On recent sediments on left bank, near toe of fan. GPS #1
3	D	S	0		/1	On recent sediments on left bank, near toe of fan. GPS #1
4	D	Ac	0		/1	On recent sediments on left bank, near toe of fan. GPS #1
5	C	S	130	U	58.5/16	On left bank, broken top, appears buried. GPS #1
6	W	B	80	XS		Scar 1.0 × 0.10 m on upstream side of tree, on right bank. GPS #2
7	C	S	10	XS	6.5/4	Just upstream of Tree 6, on right bank, in cohort of 12 trees. GPS #2
8	D	S	0		/1	Just on downstream side of proposed cribbing, 9 m downstream of centre line. GPS #3
9	C	S	130	U		On upstream side of proposed cribbing on levee, has adven titious roots, beside creek. GPS #17
10	C	S	130	XS		2 m further from right bank, otherwise as Tree 9 without adventitious roots. GPS #17
11	C	S	130	U		Repeat of Tree 10. GPS #17
12	C	S	20	U	/6	Cohort of 3 trees, behind lobe just above proposed cribbing. GPS #17
13	D	S	0			7.5 m below the 2 big spruce on the lobe, 1 m from channel right bank. GPS #17
14	C	B	80	XS		10 m N of big spruces, up on fan surface, dug around bole - buried. GPS #18

Appendix 1 continued

TABLE A1.1 *continued*

Tree no.	Sample type	Species	Sample ht. (cm)	Aspect	Tree dia./ht. (cm/m)	Field notes
15	D	H	0			Event marker, on top of log that fell before event and forms log step, just upstream of Tree 14. GPS #18
16	C	S	130	XN		Beside Trees 14 and 15, dug around bole - buried. GPS #18
17	W	H	110	U		2 m further from stream than Tree 16, scar 1 m above ground, 0.3 m high and 0.15 m wide. GPS #18
18	C	B	130	D		Has scar on upstream side, 6 m upstream from Tree 17, 1.5 m to creek, near edge of deposit area. GPS #18
19	C	S	130	D	36.5	Does not appear buried, 15 m from right wet bank. GPS #19
20	C	S	130	U	21	Does not appear buried, 20 m from right bank. GPS #19
21	C	S	130	U	10	Does not appear buried, 20 m from right bank. GPS #19
22	D	H	0		/3	Potentially knocked over, looking for onset of compression of compression wood, on right side of fan, in younger channel-bottom cohort. GPS #20
23	C	S	30	XN	16	In younger channel-bottom cohort, just upstream of Tree 24, stem rotation could be from germinating on log. GPS #21
24	C	H	130	D		Veteran in younger cohort (Tree 23), has scar 1.5 m high × 0.5 m wide, one of few older trees in vicinity. GPS #21
25	D	S	0			Broken top, on channel side of right bank deposit lobe/lateral channel bar, 2 m from right bank. GPS #22
26	C	B	130	D		At tail end of levee, appears buried, just right of more active deposit and 5 m from right bank, may have been scarred. GPS #23
27	C	S	130	U		Upstream 1 m from Tree 26, also buried. GPS #23
28	D	S	0		/4	In right bank cohort (3 × 25 m) with an older cohort further from the channel, 5 m from right bank. GPS #24
29	C	B	60	XS	14/10	In the older cohort described above. GPS #24
30	C	S	60	XN	/14	Same as above, scar of questionable origin. GPS #24
31	C	S	40	D	24.4	2.5 m from left bank, buried, must have survived event as it is among a younger cohort (3.5 × 25 m). GPS #25
32	C	S	0		/3	Just 10 m below Tree 31 in the younger cohort. GPS #25
33	C	S	0		/1	30 m below road centre line, 5 m from right bank on sediment lobe. GPS #26
34	C	Sx	10	U/Xs	6.5/4	Repeat of Tree 7. Cohort of 12 trees. GPS #2

Legend for Skeleton Plot

Abbreviations

S = scar
A = abrupt growth change (+ or -)
F = frost ring
R = radial crack
C = compression wood
T = traumatic resin canal (resin duct)
E = early wood
L = late wood
( ) = other side of pith

Notation

✻ = an event
○ = date of establishment – a dashed circle indicates an estimate due to stem burial
↔ = over the circle indicates an estimate
● = date of pith – actual if skeleton plot line solid, estimated if line dashed
□ = date of end of core or wedge
←□ = core or wedge continues, establishment date not estimated

Visual Growth Analysis

Growth reductions (shown below the tree plot line with a "–A"):

- slight = 40–55%
- moderate = 56–70%
- strong = >71%

Growth increase (shown above the tree plot line with a "+A"):

- slight = 50–100%
- moderate = 101–200%
- strong = > 201%

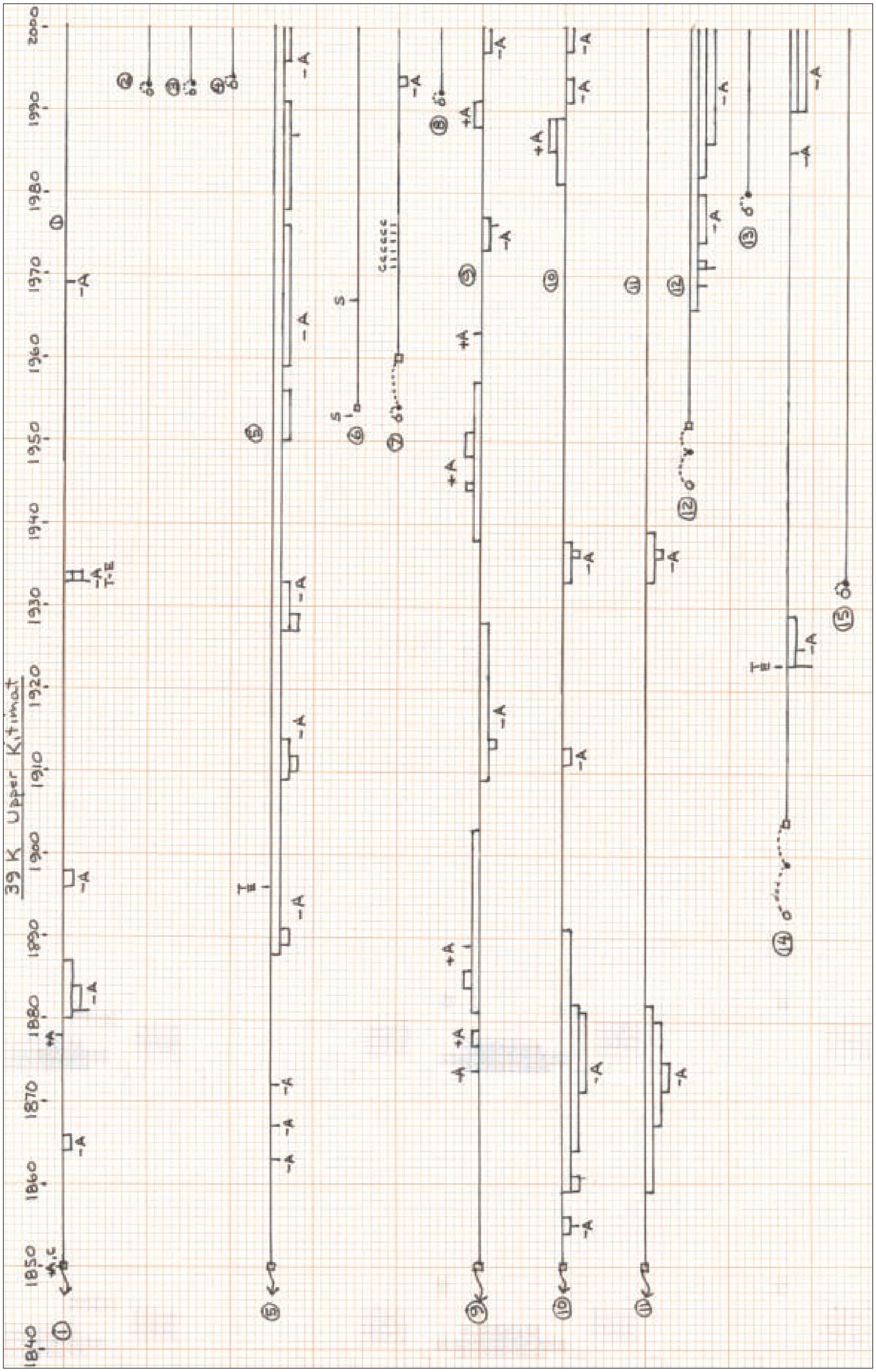
In cases where growth changes are gradual, two approaches are used in the skeleton plots:

↦ "release" / "suppression" indicates a gradual change starting at that point. This is used in cases where the growth is in long-term change due most likely to a change in stand conditions.

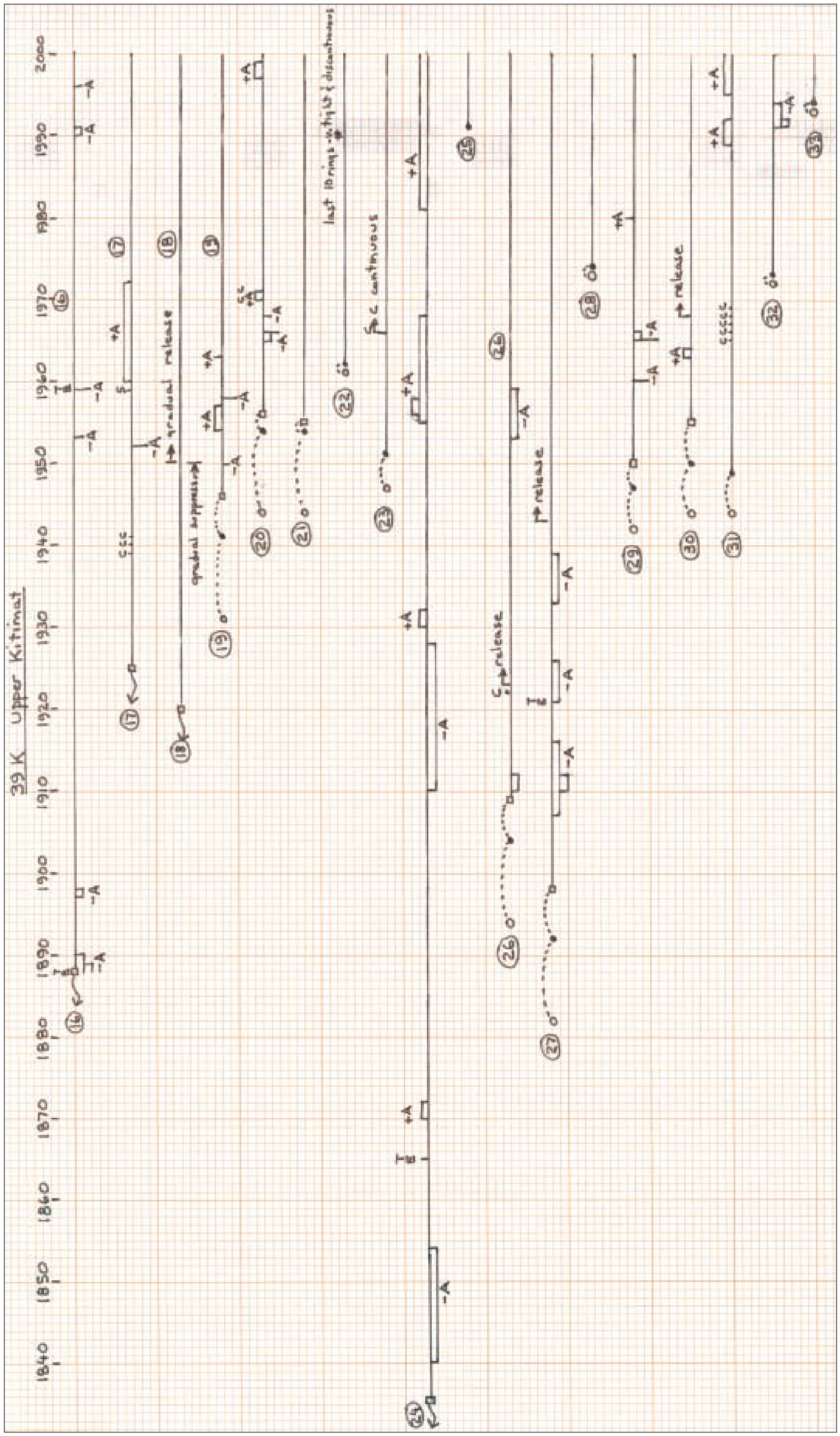
a dashed diagonal line from the start of change to the point where growth has changed enough to achieve the required ring width. This is used in cases where growth change is gradual, but most likely due to a hydrogeomorphic event—the tree generally returns to normal growth after a period of time.

Appendix 1 continued

Skeleton Plot



Skeleton Plot



Summary of Events – June 20, 2001

39 k Upper Kitimat Dendrochronology Summary
Sampling was undertaken on April 19, May 15, and June 13, 2001 with 34 cores, disks, and wedges collected. This fan is subject to debris flood events. Years in bold font indicate "certain" events, while years in normal font indicate "probable" events.

An event in **1990** could have caused the following growth changes and tree establishments. Tree 32 had moderate, negative abrupt growth change (AGC) in 1991 that persisted for 2 years, dropping to slight for another 2 years. Tree 10 had slight –AGC in 1991 that persisted for 4 years. Cohorts established on the sediments from this event are found from the upper to the lower fan. Samples representing these cohorts are 2 (1992), 3 (1992), 4 (1993), 8 (1991), and 25 (1991).

An event in **1970** could have caused the following growth changes and tree establishments. Tree 7 experienced 6 years of compression wood beginning in 1971. Tree 12 had strong –AGC in 1971 that lasted 1 year, dropping to slight –AGC that continues to the present. Tree 28 was established in 1973 and represents a cohort on the upper fan. Tree 32 was established in 1972 and represents a cohort on the upper middle fan.

A scar in **1953** on Tree 6 could have been caused by an event that also led to the establishment of a cohort represented by Tree 7.

An event in **1938** could have caused the following growth changes and tree establishments. Tree 17 had compression wood in 1939 that persisted for 3 years. Tree 27 was released in 1943. Tree 11 ended a period of suppression in 1940. Trees 29 and 30 were established in 1942 and 1944, respectively, and represent a cohort on the upper fan. Tree 31 was established in 1944 and represents a cohort on the upper middle fan. Trees 20 and 21 were established in 1944 and represent a cohort on the middle fan.

An event in **1932** could have caused the following growth changes and tree establishments. Tree 1 had strong –AGC in 1933 that became moderate for 1 year. Tree 10 had slight –AGC in 1933 that persisted for 6 years. Tree 11 had slight –AGC in 1933 that persisted for 7 years. Tree 27 had traumatic resin canals in 1933 and began a 7-year period of slight –AGC. Tree 24 ended a 3-year period of slight +AGC in 1933. Tree 5 dropped from moderate to slight –AGC in 1934. Tree 19 was established in 1933 and represents a cohort on the mid fan. Tree 32 was established in 1933 and represents a cohort on the upper fan.

An event in 1926 could have caused the following growth changes. Tree 5 went from slight to strong –AGC in 1927 that persisted for 3 years and continued for another 4 years as moderate –AGC. Tree 27 ended a 6-year period of slight –AGC in 1927. Tree 9 ended a 20-year period of slight –AGC in 1929.

An event in 1909 could have caused the following growth changes. Tree 5 went from moderate –AGC to strong –AGC in 1910 that persisted for 3 years. Tree 26 had slight –AGC in 1910 that persisted for 3 years. Tree 27 had moderate –AGC in 1910 that persisted for 3 years. Tree 24 had slight –AGC in 1910 that persisted for 19 years.

An event in **1895** could have caused the following growth changes and tree establishment. Tree 1 had slight –AGC in 1896 that persisted for 3 years. Tree 5 had traumatic resin canals in 1896. Tree 9 ended a 4-year period of moderate +AGC, dropping to slight +AGC in 1897. Tree 26 established in approximately 1896, potentially on sediments from this event.

An event in **1887** could have caused the following growth changes and establishments. Tree 1 ended an 8-year period of slight to strong –AGC in 1888. Tree 5 had slight –AGC in 1888 that became moderate in 1889 and persisted at that level for 2 more years. The –AGC in Tree 5 continues until the present, with several periods of moderate and strong –AGC. Trees 14 and 26 were established in 1893 and 1894, respectively, potentially on sediments from this event.

An event in **1879** could have caused the following growth changes and tree establishment. Tree 1 had slight –AGC in 1880 that became strong in 1881, moderate for the following 3 years, and then slight for the next 3 years (8 years total –AGC). Tree 9 had slight +AGC in 1881 that continued for 24 years, with several 1- to 4-year periods of moderate +AGC. Tree 27 was established in 1882, potentially on sediments from this event.

An event in 1873 could have caused the following growth changes. Tree 1 had slight –AGC in 1874 that persisted for 3 years. Tree 9 had slight +AGC in 1874 that lasted 1 year.

An event in 1870 could have caused the following growth changes. Tree 10 went from moderate to strong –AGC in 1871 that persisted for 11 years. Tree 11 also went from moderate to strong –AGC in 1871 and persisted for 3 years.

An event in 1858 could have caused the following growth changes. Tree 10 had moderate –AGC in 1859 that persisted for 33 years. Tree 11 had slight –AGC in 1859 that persisted for 24 years.

Summary Abrupt growth changes, scars, and tree establishments provide evidence of eight "certain" events in the past 122 years, with three events in the past 50 years. In addition, it is possible that five more "probable" events occurred over the past 143 years, based on abrupt growth changes in at least two trees per event.

Alestalo, J. 1971. Dendrochronological interpretation of geomorphic processes. Soc. Geographica Fenniae. 105: 1–140.

Alfaro, R.I., G.A. Van Sickle, A.J. Thomson, and E. Wegwitz. 1982. Tree mortaility and radial growth losses caused by western spruce budworm in a Douglas-fir stand in British Columbia. Can. J. For. Res., 12: 780–787.

Barrett, S.W. and S.F. Arno. 1988. Increment-borer methods for determining fire history in coniferous forests. USDA For. Serv., Intermountain Res. Sta. Gen. Tech. Rep. INT-244.

Blais, R. 1995. Improvements in growth ring analysis of hardwoods using dye and esciter filters. For. Chron. 71(2): 211–212.

Bovis, M.J. and M. Jakob. 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surf. Process. Landforms 24: 1039–1054.

Cook, E.R. and L.A. Kairiukstis. 1990. Methods of dendrochronology. Applications in the environmental sciences. International Institute for Applied Systems Analysis. Kluwer Academic Publications., Dordrecht, Netherlands.

Fritts, H.C. and T.W. Swetnam. 1986. Dendroecology: a tool for evaluating variations in past and present forest environments. Hunton and Williams Printers, Washington, D.C.

Gärtner, H., M. Stoffel, I. Lièvre, and M. Monbaron. 2003. Tree ring analyses and detailed geomorphological mapping on a forested debris flow cone in Switzerland. In Debris flow hazards mitigation: mechanics, prediction, and assessment. D. Rickenmann, and C. Chen. (editors). Vol. 1, pp. 207–217.

Hungr, O., S.G. Evans, M.J. Bovis, and J.N. Hutchinson. 2001. A review of the classification of landslides of the flow type. Environ. and Eng. Geosci. 7(3): 221–238.

Jakob, M. 1996. Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia. PhD thesis. Dept. Geog. Univ. British Columbia, B.C.

Joza, L. 1988. Increment core sampling techniques for high quality cores. Forintek Canada Corp., Vancouver, B.C. Special Publication SP-30.

Luckman, B.H. 1992. Debris flows and snow avalanche landforms in the Lairig Ghru, Criangorm Mountains, Scotland. Geogr. Ann. 74A: 109–121.

Maeglin, R.R. 1979. Increment cores: how to collect, handle and use them. USDA For. Serv. Forest Products Laboratory. Gen. Tech. Rep. FLP 25.

Nussbaum, A.F. 1996. Site index curves and tables for British Columbia: coastal species. 2 edition. B.C. Min. For. Res. Br., Victoria, B.C. Land Manage. Handb. Field Guide Insert 3.

Oliver, C.D. and B.C. Larson. 1996. Forest stand dynamics. John Wiley and Sons, Inc. New York, N.Y.

Schwab, J.W. 1996. Landslides on the British Columbia north coast, processes, rates, and climatic events. In Proc. Carnation Creek and Queen Charlotte Islands fish/forestry workshop: applying 20 years of coastal research to management solutions. D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (editors). Queen Charlotte City, B.C. May 1994. B.C. Min. For. Land Manage. Handb. 41, pp. 41–47.

Schweingruber, F.H. 1996. Tree rings and environment dendroecology. Paul Haupt Publishers. Berne, Switzerland.

Schweingruber, F.H., D. Eckstein, F. Serre-Bachet, and O.U. Braker. 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia 8: 9–37.

Strunk, H. 1997. Dating of geomorphological processes using dendro-geomorphological methods. Catena 31: 137–151.

Thrower, J.S., A.F. Nussbaum, and C.M. Di Lucca. 1994. Site index curves and tables for British Columbia: interior species. 2 edition. B.C. Min. For. Res. Br., Victoria, B.C. Land Manage. Handb. Field Guide Insert 6.

Yoshida, K., S. Kikuchi, F. Nakamura, and M. Noda. 1997. Dendrochronological analysis of debris flow disturbance on Rishiri Island. Geomorphology 20: 135–145.

Wilford, D.J., M.E. Sakals, and J.L. Innes. 2002. Forestry on fans: identifying hydrogeomorphic hazards. *In* Terrain stability and forest management in the interior of British Columbia. P. Jordan and J. Orba (editors). B.C. Min. For. Res. Program, Victoria, B.C. Tech. Rep. 3.

_____. 2005. Forest management on fans: recognition of hydrogeomorphic hazards and general prescriptions. B.C. Ministry of Forests. Land Manage. Handb. 57.

Other information sources:

http://web.utk.edu/~grissino/dense.htm - the Ultimate Tree-Ring Web Pages

http://www01.wsl.ch/dendrobiblio/ - Bibliography of Dendrochronology

http://www.treeringsociety.org/ - Tree Ring Society

http://www.tree-ring.org/ - Association for Tree Ring Research

http://www.elsevier-deutschland.de/artikel/647563 - Dendrochronologia -an international journal of tree-ring research