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REPORT

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EARTHQUAKE TREE-RING IMPACTS IN THE MIDDLE AND UPPER BULLER RIVER CATCHMENT

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Report prepared for:

EARTHQUAKE COMMISSION RESEARCH FOUNDATION

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EARTHQUAKE TREE-RING IMPACTS IN THE MIDDLE AND UPPER BULLER RIVER CATCHMENT

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Geotech Consulting Ltd

LAYPERSONS SUMMARY AND ABSTRACT

Earthquakes produce strong ground shaking and numerous secondary effects such as landslides, rockfalls and liquefaction. In steep mountainous terrain the abrupt increase in debris following the earthquake also leads to major sediment build up in the valley and river systems (aggradation). Where earthquakes occur in densely forested regions the trees can suffer severe damage. Some of the damage occurs simply from the earthquake shaking, in which the tree acts as a relatively top heavy inverted "pendulum", and can suffer breakage of the main trunk, side branches or root system.

A lot of damage also arises from secondary damage to the ground on which the trees grow by landslides or liquefaction and the impact of debris at rock fall margins and on alluvial fans. Finally aggradation can bury the trunks of trees in alluvium sufficient to cause their decay and eventual death. While all these factors cause damage, an earthquake is also beneficial for some of the surviving trees. Frequently there is an increase in the available light and sometimes the less severe incursions of debris and alluvium bring new beneficial nutrients.

In all these ways earthquakes impact on tree growth and the impacts are ultimately recorded in the tree ring widths of those trees that survive. Potentially tree rings provide a reliable dating method and where trees are old enough they may provide an important tool to help date pre-historic large earthquakes in forested areas. The Buller region of the West Coast of the South Island is a forested area that has experienced two large earthquakes in the 20th Century, the 1929 Buller earthquake and the 1968 Inangahua earthquake. A study of growth rings of trees in this area provides an excellent opportunity to better understand the way New Zealand trees react and record the effects of a strong earthquake. The extraction of a thin core of wood with an appropriate boring implement does not harm the tree but provides a record of the growth rings over the life of the tree. By counting the rings, and measuring the relative width of the rings, the rate of tree growth before and after the earthquakes can be determined.

We have found that both the 1929 and 1968 earthquakes have left a clear impact in the tree growth patterns. There are some trees in which the negative impacts of damage have dominated but most of these trees regain their former growth patterns as they "heal" following the earthquake. Those that do not recover, or progressively decline, tend to die and so now there are not many living examples of the most severely affected trees remaining for us to sample. However, in many cases we have sampled trees that have experienced the benefits of extra light and nutrients so that they have accelerated their growth and never slowed back down. By adjusting our method of analysis to focus

[1] Refer end of report for contact details

on those trees that have undergone life long changes in growth, we have been able to make a very clear distinction between the earthquake impacts and other normal growth fluctuations caused by climatic factors such as drought, severe frost and wind.

We have also sampled a range of tree species, and the landforms on which they grow, so that we can determine the species and landform that most clearly and consistently record the earthquake signal. Knowing this will enable future studies in forested areas to better target the most useful trees and the areas in which they grow. We have found that swampy hollows and pakihis (swamps on slightly elevated older terraces with relatively impermeable iron pans) are generally the best sites. They appear to provide the most consistent earthquake record and are also often the areas that are least affected by drought and strong wind.

Our study has included a total of 12 long-lived indigenous tree species commonly found growing on the landforms, but in particular has focussed on the three most common beech species (red beech, silver beech, mountain beech) along with mountain cedar, pink pine and rimu. The results show that while virtually all species have the potential to record growth changes from earthquakes, silver beech is the best. Fortuitously silver beech is one of the most widely distributed indigenous tree species in New Zealand, and can be found growing in a wide range of elevations and settings.

The study areas that have been selected include areas that have experienced a reasonably range in the degree of strong earthquake shaking in the two historical earthquakes. The degree of earthquake shaking is measured in units of an intensity scale (Modified Mercalli Intensity ranging from 1 to 10). We have found that the earthquake record starts to clearly stand out amongst the normal growth fluctuations of the trees once the earthquake shaking approaches Modified Mercalli Intensity 8. Recognition of this threshold level provides a possible way to delineate the main epicentral areas of pre-historic earthquake shaking.

We conclude that tree ring analysis provides a very good tool in helping to better understand the timing and extent of prehistoric earthquakes in New Zealand, particularly where there is reliable collaborating evidence from geological investigations of the faults which have been responsible. Two important faults that have forests in close proximity, and which would repay further study, is the Alpine Fault of the South Island, and the Wellington Fault in the lower North Island.

TECHNICAL ABSTRACT

Earthquakes can be a major disturbance agent in forests because strong earthquake shaking breaks branches and tree crowns, damages root systems, and causes trees to fall amongst closely growing neighbours. Earthquakes also affect trees by secondary effects such as the generation of landslides and debris movement on slopes and fans, as well as aggradation and liquefaction in valley and swamp areas. Forests not only preserve an earthquake signal in their forest age structure (reflecting tree mortality and subsequent regeneration) but also in the tree ring patterns of the trees that survive the event. Potentially the analysis of tree ring patterns provides a possible method to narrow down the dates of inferred prehistoric earthquake events where paleoseismic trenching and related geological investigations demonstrate earthquake occurrence.

The Buller area of the West Coast of the South Island is a densely forested region that has experienced two large earthquakes in the twentieth century. The largest was the 1929 M 7.8 Buller earthquake, followed almost 40 years later by the 1968 M 7.4 Inangahua earthquake. Potentially the area offers an opportunity to carefully assess the nature and variability of tree ring impacts from large earthquakes in New Zealand terrain. We have selected two forested areas in the Buller River catchment within the epicentral area of each of these earthquake events. At each location we have systematically sampled tree rings from a representative variety of indigenous New Zealand tree species, and across a range of landforms, so that we can determine both the most useful tree species, and the landform that best records the earthquake signal.

At both the study sites the earthquakes of 1929 and 1968 resulted in clearly, relatively easily distinguishable pulses of impact on tree growth that stand out amongst the normal fluctuations from climatic factors. We have also developed an improved analysis method to better distinguish between tree ring impacts caused by earthquakes, and more normal fluctuations from wind and drought. It appears that by focussing on the subset of trees that record extremely severe and long-lasting growth changes it is possible to most clearly distinguish earthquakes from other factors. For some trees earthquakes are life changing events from which they either never recover their former growth rate, or else are able to exploit new nutrient and gaps in the forest canopy to abruptly accelerate and maintain their growth. Using this long-lasting analysis method we are able to clearly distinguish the two historical twentieth century earthquakes from background fluctuations.

We conclude that swamps and pakihis record earthquake events most clearly and consistently because tree response is not dependant on spatially variable secondary processes such as debris movement and rockfall, and the potential complications in tree ring patterns from severe climatic events (wind and drought) are generally minimised. The most extreme tree ring response is recorded in some alluvial fan and rockfall margins, but the record at such sites is much less consistent, and is frequently spatially restricted within each landform.

Our results show that while virtually all tree species have the potential to record growth changes resulting from earthquake impacts, some species record the impacts much more frequently and consistently than others, and in this sense can be considered “sensitive” to earthquake impacts. The most promising species are silver beech and mountain beech. Silver beech has the added advantage of being one of the most widely distributed indigenous tree species in New Zealand, and can be found growing in most areas from valley floors to sub-alpine timberlines, and on well drained sites through to wet infertile bogs.

The two study areas included a range in Modified Mercalli shaking intensity from MM 7 to MM10 and thus provide an opportunity to investigate whether tree ring patterns vary in a systematic way with shaking intensity. We conclude that is possible to at least map the outer limits of MM 8 shaking, on the basis that MM 7 does not always show up significantly above background levels of

normal growth variation. This has important potential in allowing an assessment of the spatial distribution of prehistoric earthquake shaking.

The results of the study will allow future research to target the most suitable tree species and landforms and will provide a foundation for better interpretation of the paleoseismic record in forested areas over the last approximately 800 years (the typical maximum age of the key tree species).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1) INTRODUCTION

In densely forested tectonically active regions such as New Zealand, earthquakes can be a major disturbance agent in forests (Veblen & Ashton 1978; Garwood et al. 1979; Stewart & Veblen 1982); these landscapes therefore offer great potential for old-forest growth patterns to provide information about prehistoric earthquake events (paleoseismology). Forests can preserve an earthquake signal in the forest age structure (i.e. forest disturbance events marked by simultaneous regeneration of an even aged cohort of trees) and also in the pattern of tree rings preserved in individual trees that survive the event (tree ring analysis). This study focuses on the tree ring patterns that have resulted from strong historical earthquake shaking in the early and mid twentieth century within the forest environment of the Buller area located on the western coast of the South Island. Tree-ring analyses can greatly complement geological efforts to date and delineate large earthquakes, and have the potential to give very precise information on not only the timing of prehistoric earthquakes but also on their rupture lengths, intensities and epicentres.

Earthquake damage to trees is caused directly by strong shaking as well as indirectly by debris movement from earthquake-induced landsliding and sedimentation. This damage may result from the shaking or shearing of tree roots and branches (e.g. LaMarche & Wallace 1972; Jacoby et al. 1988; Allen et al. 1999), the uplift of the ground surface or changes in the water table (Jacoby & Ulan 1983; Allen et al. 1999), or by debris movement around trees (Vittoz et al. 2001). Although the damage may kill trees, it is common for trees to survive and retain permanent signs of the disturbance in the stem and tree growth. These include production of reaction wood after tilting (Page 1970; LaMarche & Wallace 1972; Berryman 1980; Jacoby et al. 1997), fractures in the wood (Van Arsdale et al. 1998), growth suppression in the years following disturbance (Jacoby et al. 1988; Kitzberger et al. 1995), or growth releases after the death of neighbouring trees (Kitzberger et al. 1995; Vittoz et al. 2001). Earthquake impacts on forest age-class distributions have also been identified (Kitzberger et al. 1995; Wells et al.1999; 2001; Vittoz et al. 2001), reflecting colonisation after widespread tree mortality. Furthermore, the intensity of damage to forests varies strongly with distance from the earthquake's epicentre (Veblen & Ashton 1978), and also according to geomorphology and the climatic conditions at the time of the earthquake (Kitzberger et al. 1995; Van Arsdale et al. 1998).

Tree ring analysis has been used outside New Zealand in combination with geological evidence to precisely date the timing of past earthquakes overseas (e.g. Jacoby et al. 1988; 1997; Sheppard & Jacoby 1989; Wiles et al. 1996), and the rationale for this approach is well established. However, these studies have virtually all focused on identifying the dates of ruptures on a fault using trees that were obviously severely impacted by shaking, and there has been very little work on the wider application of tree-ring methods to other aspects of earthquakes such as the delineation of epicentre, shaking intensities and variation in impacts between landforms and tree species. Furthermore, application of these tools to paleoseismology within New Zealand has been limited (Berryman 1980; Allen et al. 1999; Wells et al. 1999; 2001; Cullen et al. 2001; Vittoz et al. 2001). The previous New Zealand studies have demonstrated the potential of tree-rings to be used in earthquake studies, but to date there has been no foundation of background knowledge that systematically catalogues the impact of New Zealand historical earthquake events across a typical range of tree species that are growing on a variety of landforms. By collecting and carefully analysing tree ring data from well defined historical earthquake events there can be much greater confidence in the application of the tree ring analysis method to the study of prehistoric earthquake events in New Zealand.

In this study, we reconstruct the nature and variability of tree-ring responses to the historic 1929 Buller and 1968 Inangahua earthquakes in two study sites located close to the epicentral areas of the earthquakes. The primary objective of our study is **to determine the nature and variability of**

tree-ring responses to strong earthquake shaking within a typical diverse forested South Island catchment. There are several secondary objectives that are aimed at more detailed analysis of the earthquake effect:

(1) comparison of the nature and clarity of tree-ring responses across a full range of dominant landforms

(2) comparison of tree-ring responses to earthquakes in at least 5 key long-lived canopy tree species

(3) analysis of the variation in earthquake effects with distance from epicentre

(4) determination of the combination of landform, species and proximity to epicentre that best records earthquake impacts

(5) examination of the oldest trees for growth anomalies that might have been caused by the most recent northern Alpine fault earthquake in the 1600's.

2) STUDY AREA

We chose the Buller Gorge/Murchison area for our research because it is heavily forested, is situated close to the epicentre of two large 20th century earthquakes, and the forest is known to have suffered severe impacts from both the earthquakes. The Buller earthquake occurred on June 17 1929 with a magnitude of 7.8, and was the largest 20th century earthquake in the South Island (Pearce & O'Loughlin 1985). Shaking intensities reached or exceeded 10 (Modified Mercalli Intensities, Eiby 1966) over 3900 km^2, and triggered hundreds of landslides within an area of 5000 km^2 (Adams 1981; Pearce & O'Loughlin 1985; Hancox et al. 1997). The Inangahua earthquake occurred on May 24 1968, with a magnitude of 7.4 (Adams et al. 1968), and triggered landslides in a 16 km radius of the epicentre. No other major historical earthquake is known in the region. However, the most recent northern Alpine fault earthquake (c. 1620 AD) probably resulted in shaking intensities of MM7 in the area, while the inferred 1717 AD event on the central Alpine fault probably resulted in shaking intensities of MM6 in the area (Yetton et al. 1998; Yetton 2002). Adams (1981) also suggested that Lake Matiri and seven other nearby prehistoric landslide-dammed lakes were formed simultaneously during a major earthquake about three centuries ago, and this may correspond to the 16th century northern Alpine fault event.

Other historic disturbances are known to have affected the region, the most notable being windstorms in 1898 (Foster 1931) and 1905 (Benn 1990), and periods of drought in the early 1930s (New Zealand Meteorological Service unpublished data) and in 1974-78 (Hosking & Kershaw 1985). Other unrecorded, more localised disturbances could also have affected parts of the area.

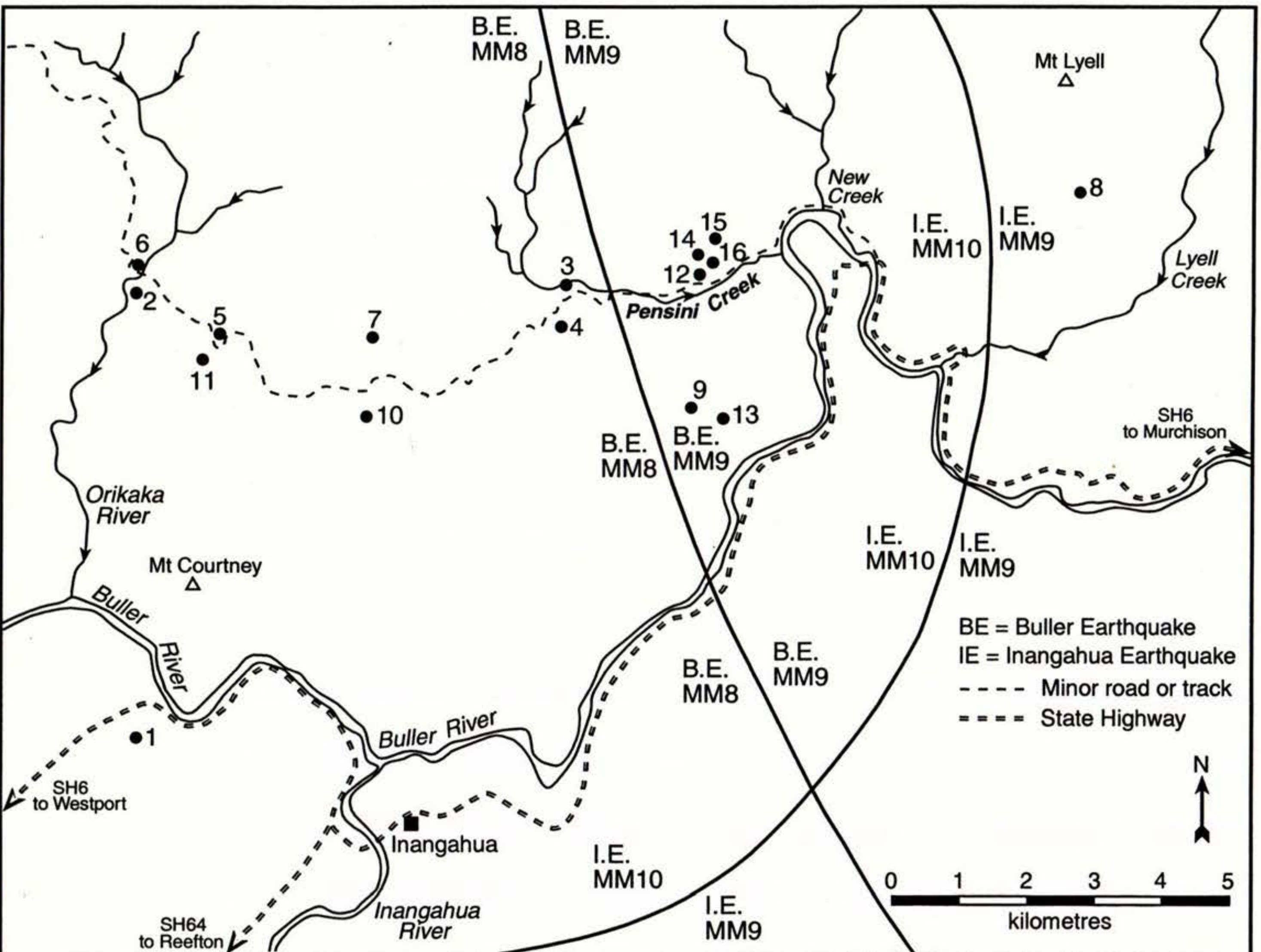
The two historical earthquakes caused severe damage to forests in the region, as indicated by aerial photography surveys and eye-witnesses. Direct observations of the 1929 Buller earthquake provide interesting anecdotes of some of the damage to vegetation that accompanied this earthquake. S.M. Badcock describes a scene in the Buller Gorge as follows: "In one place there was about an acre of trees on a hilltop. They looked as if they had been climbed with a jigger-board and cut off three-parts of the way up. You could see all the white marks where they were severed. It must have been a terrific jolt to break them off like that. Sights like that one could never forget." (Murchison District Historical and Museum Society 1979, page 10). Similar dramatic shaking impacts were observed in the Matiri Valley, where "trees were being snapped off like carrots" (Nell Sagar, op. cit. page 41). Violent shaking was also observed to bash trees around but not snap or kill them. In the Mangles Valley Ken Rouse commented that, "bush and trees were shaking as if on a turbulent sea and I was amazed that they did not topple over" (op. cit. page 50), and Malcom Brown saw "a large white pine tree near us (that was) shaking violently and branches were breaking off and falling to the ground, also the tree was lifting a bit at its roots." (op. cit. page 22). In other places slips had taken out forest or there were abundant treefalls caused by earthquake shaking alone, as described by Bernard Teague (op. cit. page 1) on the Maruia Saddle: "I pushed my cycle to the top of the Saddle, lifting it over fallen trees and dragging it over small slips."

Study Sites

Two study sites were chosen for detailed sampling. Sites were selected primarily to include a range of landforms that experienced MM10 shaking associated with either the Inangahua or Buller earthquake.

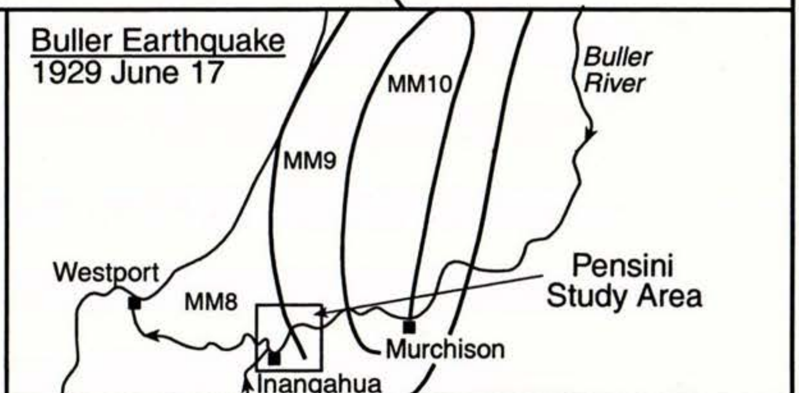
The first site, referred to as the Pensini site, was centred on the north bank of the Buller River between Lyell Creek and the Orikaka River, but also including the White Cliffs area on the south bank of the Buller River. This area experienced MM10 shaking during the Inangahua earthquake, and MM8 or 9 shaking during the Buller earthquake (Figure 1).

The second site, referred to as the Matiri site, was centred on the area just upstream of Lake Matiri in the Matiri Valley, including the Thousand Acre Plateau. This area experienced MM10 shaking during the Buller earthquake, and MM7 shaking during the Inangahua earthquake (Figure 2).



Key to sampled localities

1. Whitecliffs Hill
2. Orikaka Hill
3. Pensini Hill
4. Coal Yard Slope
5. Tertiary Slope
6. Orikaka Terrace
7. Coal Flat Ridge
8. Mt Lyell Ridge
9. Welshman's Pakihi
10. Coal Flat Swamp
11. Frosty Swamp
12. Pensini Fan
13. Buller View Slide
14. Tilted Rimu Patch
15. Fissure Zone
16. Pensini Toeslope



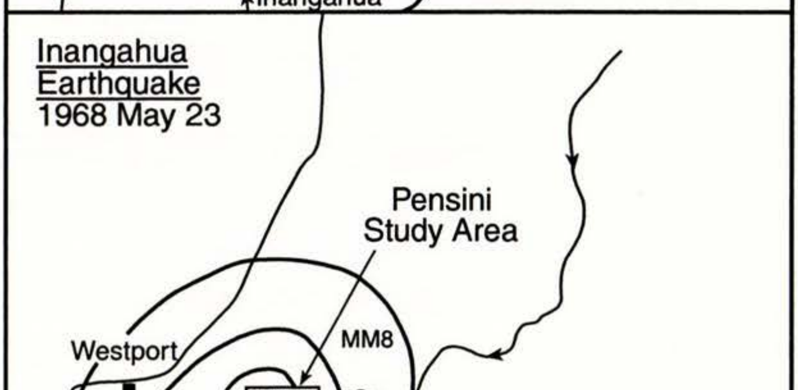
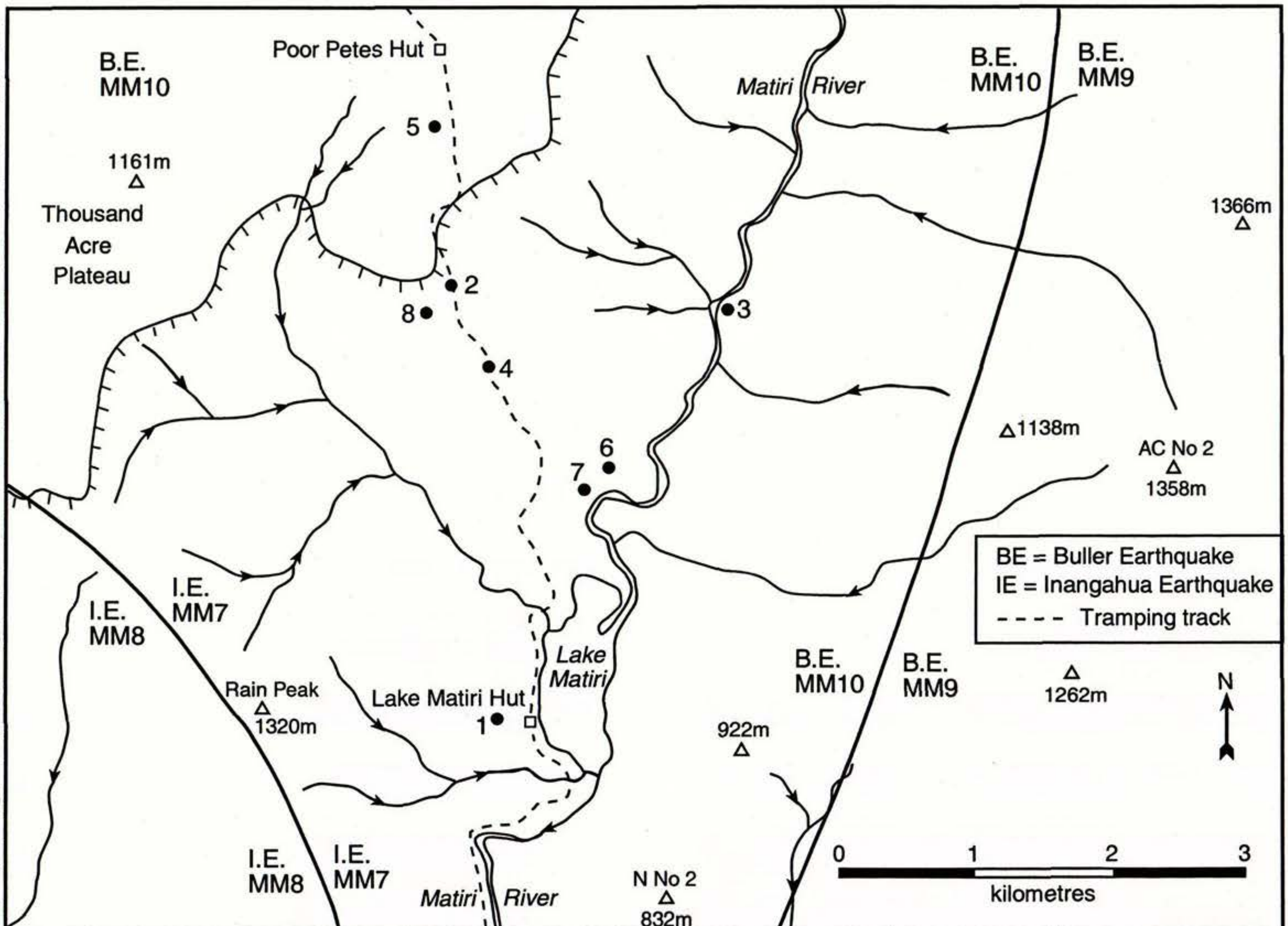
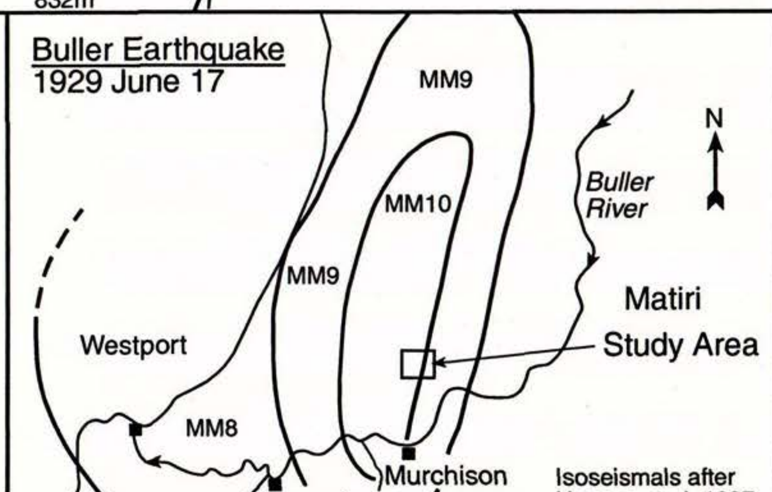


Figure 1: Pensini study area sample localities and isoseismals



Key to sampled localities

1. Matiri Hill
2. Plateau Hill
3. Matiri Terrace
4. Matiri Ridge
5. Poor Petes Plateau
6. Matiri Fan 1
7. Matiri Fan 2
8. Plateau Rockfall



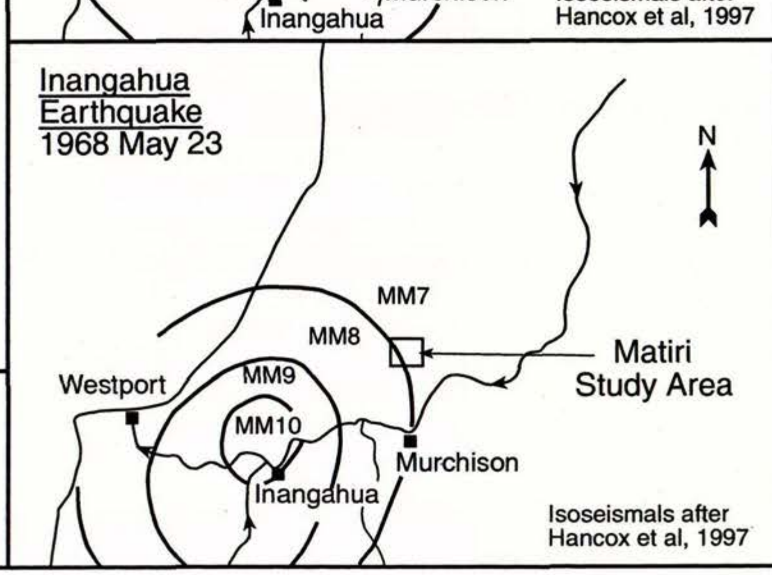


Figure 2: Matiri study area sample localities and isoseismals

3) METHODS

Forest selection and sampling

The twelve tree species sampled are listed in Appendix 1. In particular the study has focussed on the most commonly distributed beech species (red beech, silver beech and mountain beech), mountain cedar, pink pine, and various podocarps (of which rimu was the most abundant).

Major landforms within each study site formed the basic units for detailed tree sampling (Tables 1 and 2. See Appendix 2 for fuller descriptions of sampled localities). The key landforms identified in both study sites were ridges, steep side slopes, gentle side slopes, alluvial terraces, alluvial fans, and rockfall margins. A few other key landforms were found at only one of the study sites – pakihi and swamps (Pensini site), and elevated mountain plateau (Matiri site). At Pensini an area of obvious old landslide deformation was also sampled that was essentially a subset of the sloping ground classes. In some instances more than one site was sampled for a given landform, in order to increase sample sizes, or to obtain information from areas of different shaking intensities.

Table 1. Summary of the landforms and locations selected for detailed sampling in the Pensini study site. MM intensity for the 1968 earthquake was 10 for all locations sampled. For full details, see Appendix 2.

Landform	Site Name	Location (grid ref.)	1929 MM intensity
Steep side slope	White Cliffs hill	L29 285188	8
	Orikaka hill	L29 349187	8
	Pensini hill	L29 349253	9
Gentle side slope	Coal Yard slope	L29 344249	8
	Tertiary slope	L29 345200	8
Landslide deformation	Tilted rimu patch	L29 354270	9
	Fissure zone	L29 357272	9
Alluvial terrace	Orikaka terrace	L29 352188	8
Ridge	Coal Flat ridge	L29 343222	8
	Mt Lyell ridge	L29 366327	9
Pakihi swamp	Welshman pakihi	L29 327264	8
Swamps (depressions)	Coal Flat swamp	L29 333223	8
	Frosty swamp	L29 342198	8
Alluvial fan	Pensini fan	L29 352271	9
Rockfall margins	Buller View slide	L29 328267	8
Old landslide toe	Pensini toeslope	L29 353272	9

Table 2. Summary of the landforms and locations selected for detailed sampling in the Matiri study site. MM intensity for all sites was 10 for the 1929 earthquake and 7 for the 1968 earthquake. For full details, see Appendix 2.

Landform	Site Name	Location (grid ref.)
Steep side slope	Matiri hill	M29 537497
	Plateau hill	M28 536528
Alluvial terrace	Matiri terrace	M28 557527
Ridge	Matiri ridge	M28 538524
Elevated plateau	Poor Pete's plateau	M28 535541
Alluvial fan	Matiri fan 1	M28 547515
	Matiri fan 2	M28 546514
Rockfall margins	Plateau rockfall	M28 534525

On each landform, at least 25 trees were cored using hand corers at a height of about 1 metre above ground level. Species were sampled approximately in proportion to their abundance on each landform. Although trees of all sizes were sampled, trees of moderate size were chosen where present in preference to very small or very large trees – this was because our research was most interested in growth over the last 100 years. Where trees were bent or leaning, cores were extracted along a radius in the direction to which the trunk was inclined wherever possible.

Only one core sample was taken per tree. This enabled us to cover the full range of landforms and species in each study site in good detail. The trade-off in not taking two cores is the inability to investigate eccentric growth patterns that may be attributable to earthquake shaking. However, previous studies strongly suggest that growth releases and suppressions are far more promising criteria than tension wood recognition or eccentricity (e.g. Vittoz et al. 2001; Fenwick 2004), so this sampling approach is preferable.

For each sampled tree, diameter was measured at a height of 1.3 metres and notes were recorded on site position, slope angle, distinctive or unusual features of the tree, and descriptions of the surrounding vegetation and landform, including any evidence of debris movement or deposition.

Tree cores were mounted on blocks of grooved wood, and sanded using successively finer grades of sandpaper until rings were clearly visible. Individual tree-ring widths were measured to the nearest 0.01 mm for each core using a computerised tree-ring measurement system.

Crossmatching of tree-ring series was attempted, using visual methods and skeleton plots. However, this proved to be very difficult for the majority of the trees. Growth patterns were usually very variable between trees at a site, even for individuals of the same species. For this reason, crossmatching was generally not achieved in this study. Consequently raw tree-ring series were used for dating growth changes. Similar difficulties have been encountered in New Zealand at favourable lowland sites and sites where there are frequent small-scale disturbances such as wind and storm-induced debris movement, and these difficulties have been found even in species that are usually easily crossmatched such as mountain cedar (Jonathan Palmer, pers. comm.; Bill Bull, pers. comm.).

The approach we took was to crossmatch trees wherever this was possible, and where not possible to simply use the raw ring width series. However, trees with periods of difficult and unclear rings were removed from the final data set. We would expect possible errors in dating to result from this in some of the uncrossmatched trees, but these would be unlikely to be greater than five years over the last 100 years for the lowland trees we sampled (Wardle 1967; Dunwiddie 1979; Norton 1983a; 1983b; Xiong 1996; Xiong & Palmer 2000; Vittoz et al. 2001).

Analysis of ring width series for growth changes

Dates of growth releases and suppressions were recorded for all cores using the measured ring width series. The same thresholds in recognising growth changes were used for all species. We analysed ring width series for two types of growth change: short (5 years) or long (10 years). For each core, we compared sequential 5-year and 10-year ring width means, and calculated the percentage growth change using the formula proposed by Nowacki and Abrams (1997):

$\%GC = [(M2 / M1) / M1] * 100$ for growth releases, and
$\%GC = [(M2 / M1) / M2] * 100$ for growth suppressions.

where %GC = percentage growth change between preceding and subsequent 5-year or 10-year means, M1 = preceding 5-year or 10-year mean, and M2 = subsequent 5-year or 10-year mean. The growth change is affixed to the last year of the preceding period (M1). When growth changes were present for two or more consecutive years, only the first year was identified as a release or suppression.

The 5-year span we selected has been previously used in forest disturbance studies in South America (Veblen et al. 1992) and New Zealand (Vittoz et al 2001; Wells et al. 2001; Fenwick 2004). Anything shorter than this is probably too short to eliminate short-term growth responses related to climate (in dendroecological research, only sequences of more than three marker years are considered abrupt growth changes (Schweingruber 1996), while longer periods may obscure the detection of shorter growth responses. At the other end of this time-span spectrum is the 10-year period used in some studies (e.g. Nowacki & Abrams 1997; Vittoz et al. 2001). This may help eliminate relatively short term fluctuations caused by severe droughts or several unusually warm or cold years.

We defined two 'levels' of severity of growth releases and suppressions: >100% or >250% changes in mean ring width between consecutive periods. Selection of these two thresholds was subjective, although in other studies the values have ranged from 25% to 250% depending on the purpose of research, species investigated and site conditions. Previous studies in the region have used values of 100, 150 and 250% (Vittoz et al 2001; Wells et al. 2001; Fenwick 2004), and these have shown potential to effectively differentiate storm and earthquake events. 100% represents a moderate value which could be expected to capture all major disturbance events as well as some smaller-scale events, while 250% represents a high value that is unlikely to capture smaller-scale events.

Earthquakes have the greatest potential to be the most severe disturbance events at a regional scale, and could be expected to be most unambiguously and clearly recorded at the more severe end of the spectrum of growth change. We therefore investigated a third 'level' of growth changes which we term 'extremely severe and long-lasting growth changes'. These are defined as growth changes in which there was a >250% increase or decrease in mean ring width between consecutive 5-yearly means, and for which these changed levels of growth were sustained for at least 25 years. This measure incorporates very abrupt and large-magnitude growth change as well as very long-lasting change.

For each site, we combined the dates of growth changes for all trees and grouped them into 5 year classes. This grouping more readily allows visual presentation of the results, and is also justified because crossmatching was not complete and trees often show a delay of several years in responding to a disturbance event (Veblen et al. 1992; Kitzberger et al. 1995; Wells et al. 1999)

Earthquakes are also likely to destabilise and tilt trees (LaMarche & Wallace 1972), which then respond by producing tension wood and showing eccentric growth. Cores were therefore also examined under a microscope for rings of tension wood. Tension wood can be recognised by its darker colour and fewer and narrower vessels (Schweingruber 1996). Eccentricity was not investigated in this study, because this requires comparing the relationship between annual growth along two radii.

4) RESULTS

4.1 Nature and variability of tree-ring response to earthquake shaking

General patterns of releases and suppressions

(i) 'Moderate' growth changes

At both the Pensini and Matiri study sites, the two earthquakes resulted in clear, easily distinguishable pulses of impact on tree growth patterns as measured by moderate, short-lived releases and suppressions (i.e. >100% changes in growth over 5-year periods)(Figure 3). Both growth releases and suppressions were associated with each earthquake, and these formed obvious peaks in comparison to other growth changes over the last several centuries.

At Pensini, background levels of releases and suppressions are relatively high and consistent, with generally about 2-10% of trees showing a growth change within any given 5 year period (Figure 3ic). However, the 1929 and 1968 earthquakes stand out as the two periods with the greatest levels of growth impacts since 1585 AD, in terms of releases, suppressions and combined impacts. Levels of growth changes are at least double the background levels, and are sustained above background levels for at least the 10 years immediately following the earthquakes. About 43% of trees show either a release or suppression in the ten years following the 1929 earthquake, and about 38% of trees following the 1968 earthquake. This compares with background levels of growth changes over any ten-year period of 4-20%. The only other period that approaches these unusually high levels of growth impacts is 1610-1620, in which 30% of trees show a growth change. All other ten year periods are within the expected 20% background levels, although there are four periods which slightly exceed this by a few percent (21-23% of trees affected) – these are 1655-1665, 1710-1720, 1795-1805 and 1865-1875. However, these periods do not stand out in the combined graph (Figure 3ic) as periods of unusually high growth change.

At Matiri, there were fewer old trees that can be used to extend the record back before 1700. The background levels of releases and suppressions are similar to Pensini, with about 2-10% of trees showing some form of growth change within any given 5 year period (Figure 3iic). The 1929 earthquake stands out as the only period since 1710 with marked unusually high levels of releases and suppressions to trees – i.e. about 51% of trees show either a release or suppression in the ten years following the 1929 earthquake. No other period approaches these levels of growth impact. Four other periods do, however, reach levels above the expected 20% background - 1725-35 (31%), 1760-70 (25%), 1895-1905 (25%) and 1970-80 (29%). These periods differ from the 1929 period in that only suppressions exceed normal background levels, and in that they generally do not stand out noticeably in the combined graph. The exception to this is the 1970-80 period, in which levels of suppressions are sufficiently high to make an impression on the combined graph (Figure 3iic).

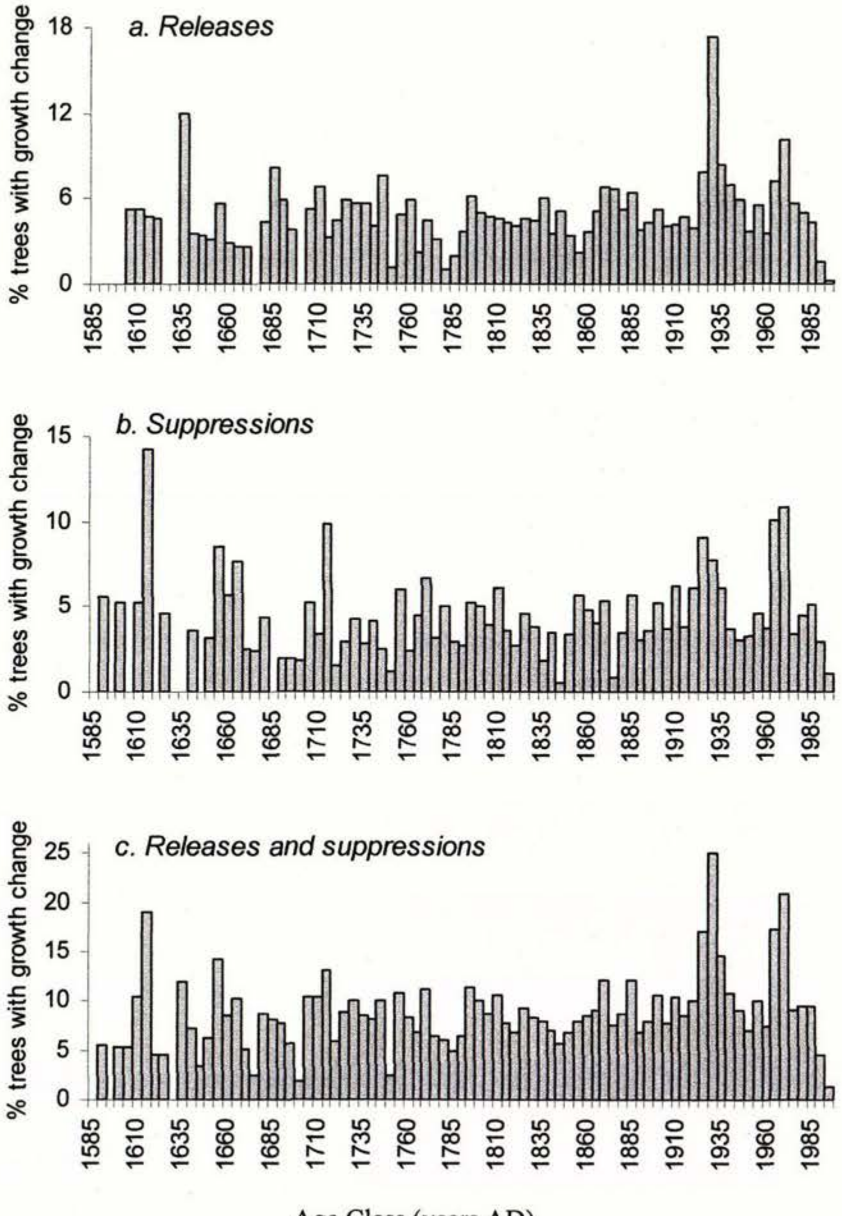
(ii) More severe and longer-lasting growth changes

Assuming that earthquakes are the most severe natural disturbance events that trees can experience at a regional level, it follows that earthquake events should become more and more pronounced in regional tree growth change records (and other disturbance events less and less pronounced) as criteria for measuring growth change become more and more 'severe' (i.e. greater-magnitude increase/decrease in growth, and longer duration of increased/decreased growth).

The results so far have only considered changes of >100% between consecutive 5 year periods – i.e. moderate short-lived releases and suppressions. To examine variability in response, we investigated

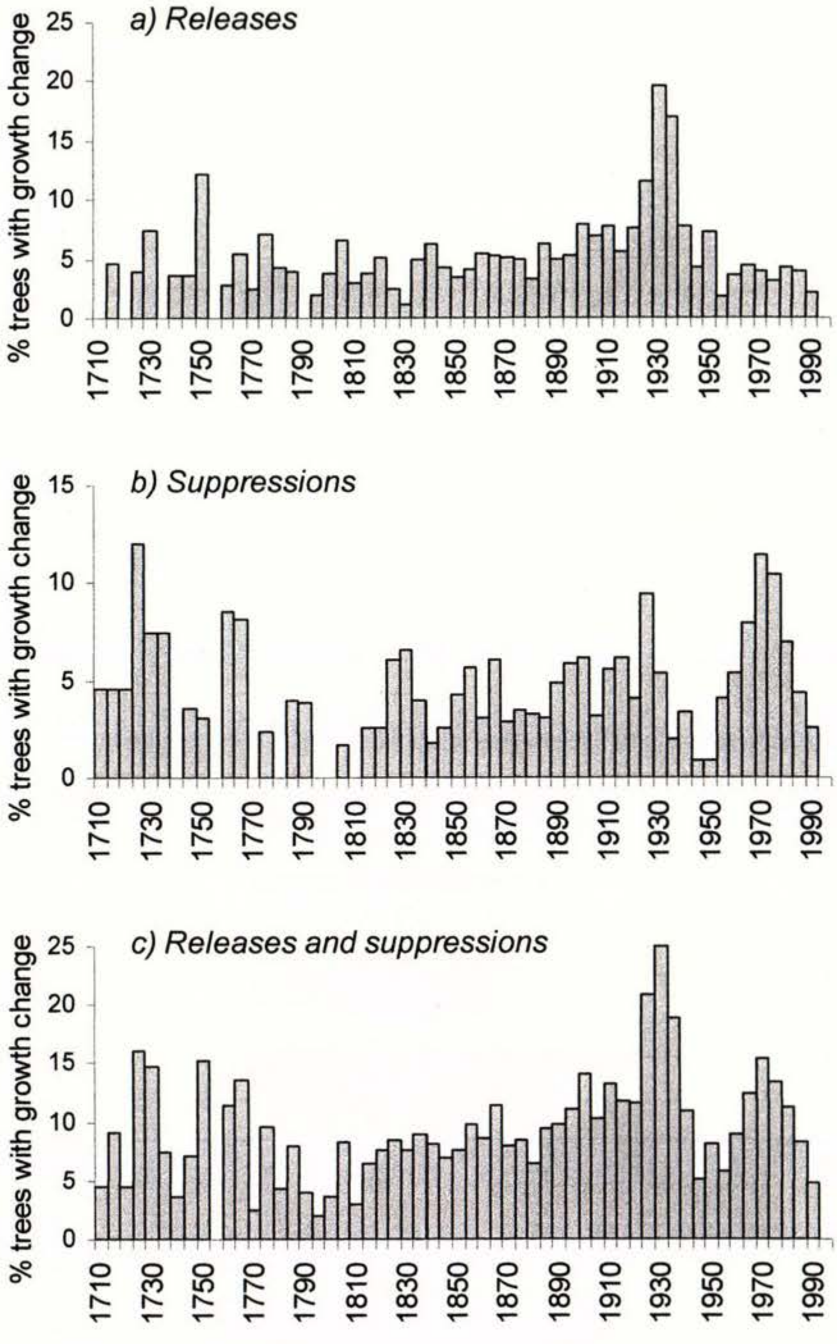
FIGURE 3. Proportions of 'moderate' growth releases and suppressions recorded in trees at i) Pensini study site and ii) Matiri study site. A release or suppression is defined as a >100% difference between consecutive five-year means of growth. a) growth releases, b) growth suppressions and c) releases and suppressions combined. The numbers at the bottom record the sample size (number of trees) for a given age class.

i) Pensini Study Site



Sample Size: 15-----20-----------50------------100----150-------200----300---400--444

ii) Matiri Study Site



Age Class (years AD)

Sample Size: 15----20-------------50---------100---------150------200---------231----

growth changes using three other criteria of greater magnitude and/or duration (representing an increasing level of severity):

1) Moderate, long-lasting releases and suppressions. Criteria: changes of >100% between 10–year means of growth (i.e. sustained for at least 10 years)
2) Severe, long lasting releases and suppressions. Criteria: changes of >250% between 10-year means of growth (i.e., higher magnitude, and sustained for at least 10 years)
3) Extremely severe and long lasting releases and suppressions. Criteria: changes of >250% between 5-year means, and with these new levels of growth sustained for at least 25 years (i.e. abrupt high-magnitude, and sustained for at least 25 years). Examples of tree-ring width series that fulfilled this criterion are given in Figure 4.

Growth changes for >100% differences between consecutive 10-year means were very similar to those in Figure 3 (for 5-year means), with the only difference being slightly lower percentages of trees with growth changes in each age class. However patterns of growth changes were considerably different for analyses based on the more severe criteria (2 and 3 above). The results of these analyses are presented in Figures 5 and 6. As expected there are progressively lower proportions of trees showing growth changes as the severity of criteria increases, reflecting the removal of the more common moderate growth changes.

There is also change in the relative abundance of releases and suppressions - the proportion of suppressions is progressively reduced compared with releases as criteria for defining growth changes become increasingly severe (Table 3). For the two most severe criteria (Figures 5 and 6), releases were at least twice as frequent as suppressions at both sites and for both earthquakes, and usually far more frequent than this. In some cases suppressions were almost non-existent in the record. This is in contrast to the two 'moderate' criteria, in which suppressions always formed an important component of total growth changes and were sometimes dominant over releases.

Table 3. Summary of the variation in type of tree-ring response following the 1929 and 1968 earthquakes, for three different severities of criteria for defining growth change. Proportion of trees with a growth change was calculated using the ten year period immediately following the earthquake. Criteria for defining growth changes are moderate (>100% change sustained for 5 years), severe (>250% change, sustained for 10 years), and extremely severe (>250% change, sustained for at least 25 years).

		Proportion of trees with response to earthquake					
		Moderate (%)		Severe (%)		Extremely severe (no.)	
Study Site	**Response**	**1929**	**1968**	**1929**	**1968**	**1929**	**1968**
Matiri	Release	37	7	9	0	17	1
Matiri	Suppression	14	22	1	1	1	0
Pensini	Release	26	16	4	4	12	12
Pensini	Suppression	17	22	2	2	3	7

This difference makes sense based on the expected reaction of negatively-impacted trees (i.e. those showing a suppression) to disturbance severity. In general moderate growth suppressions will reflect a moderate disturbance severity to those trees, and consequently the majority of trees that suffer this level of disturbance impact will live through it. However, very severe growth change criteria deliberately target those trees that record very severe disturbance impacts. Trees that were severely negatively impacted (i.e. those that will show suppressions) are increasingly likely to be so adversely impacted that they die (immediately or in the following few decades) and in so doing are removed from the pool of potential trees available for later sampling. Furthermore, this gives other relatively non-impacted trees greater potential to rapidly gain great advantage from the large increases in light and nutrients, and thus to respond with vigorous, long-lasting releases. Therefore

Figure 4. Examples of tree ring-width series for trees showing extremely severe and long-lasting growth changes, Matiri and Pensini study sites. The y axis gives ring width in millimetres. Arrows mark the onset of the growth changes.

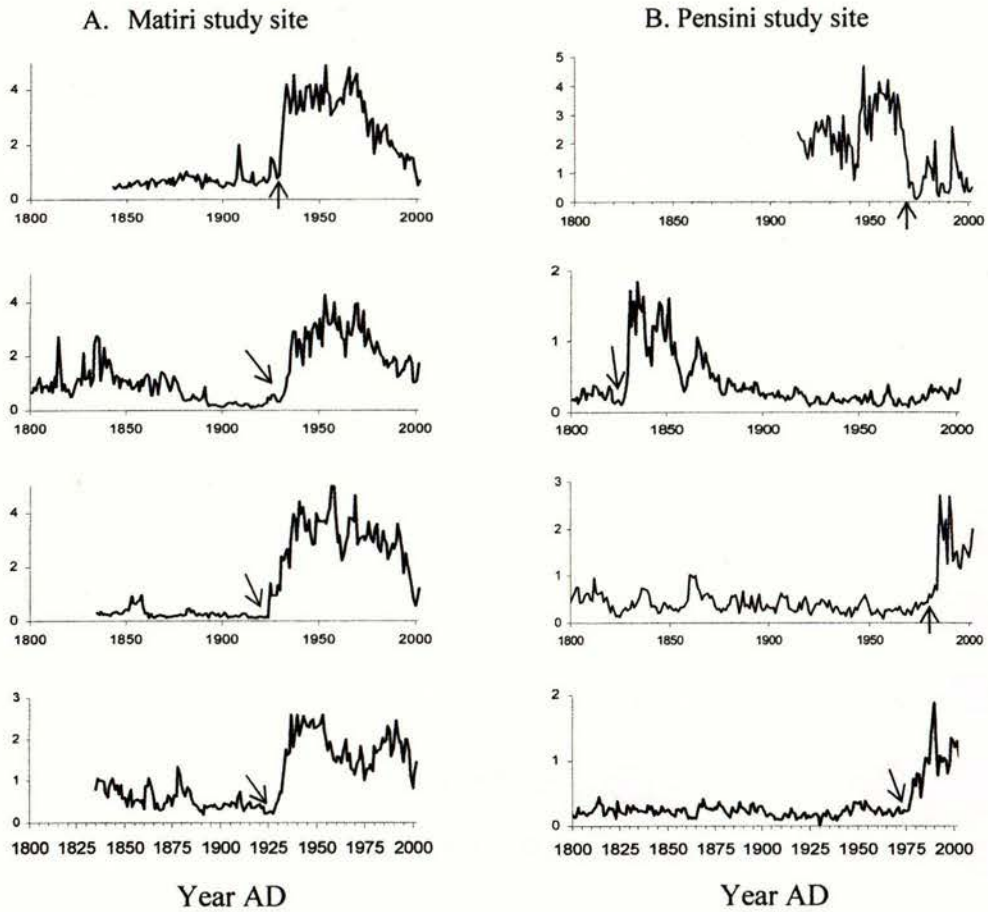
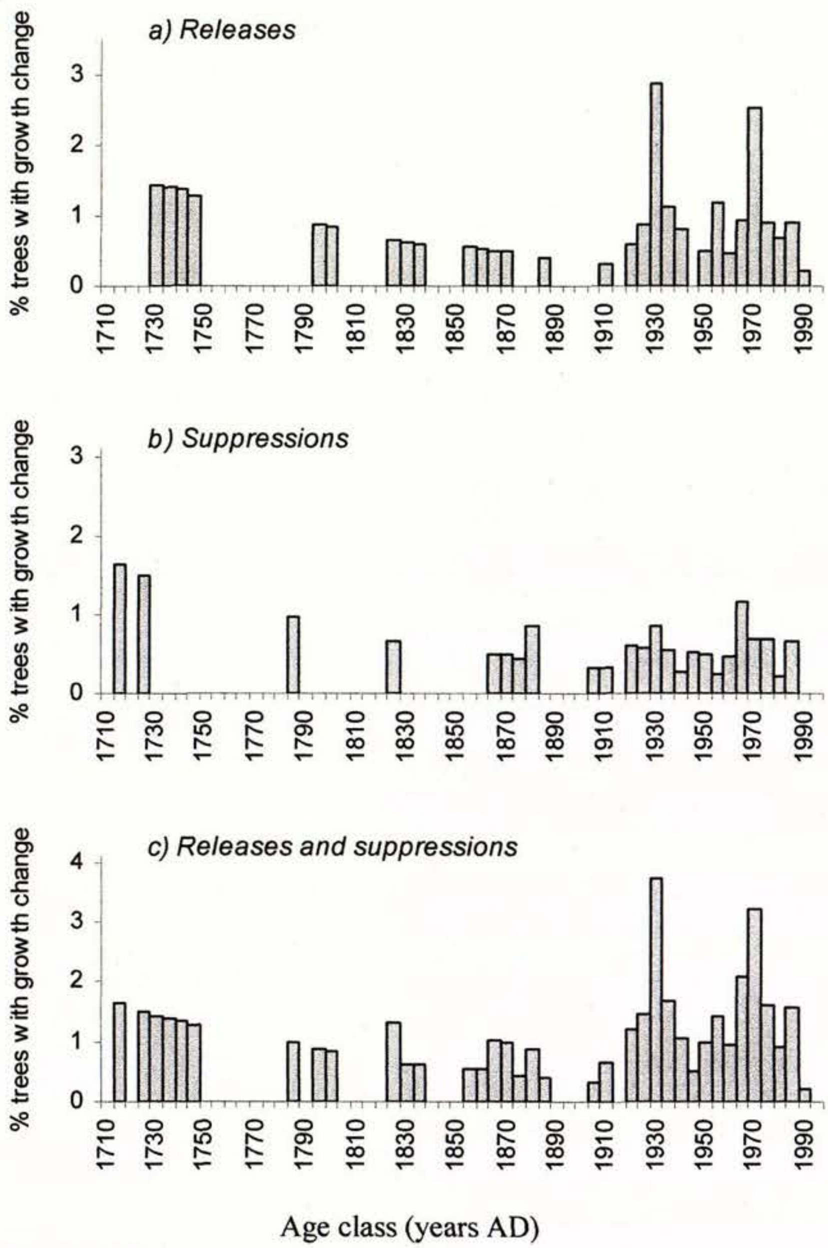


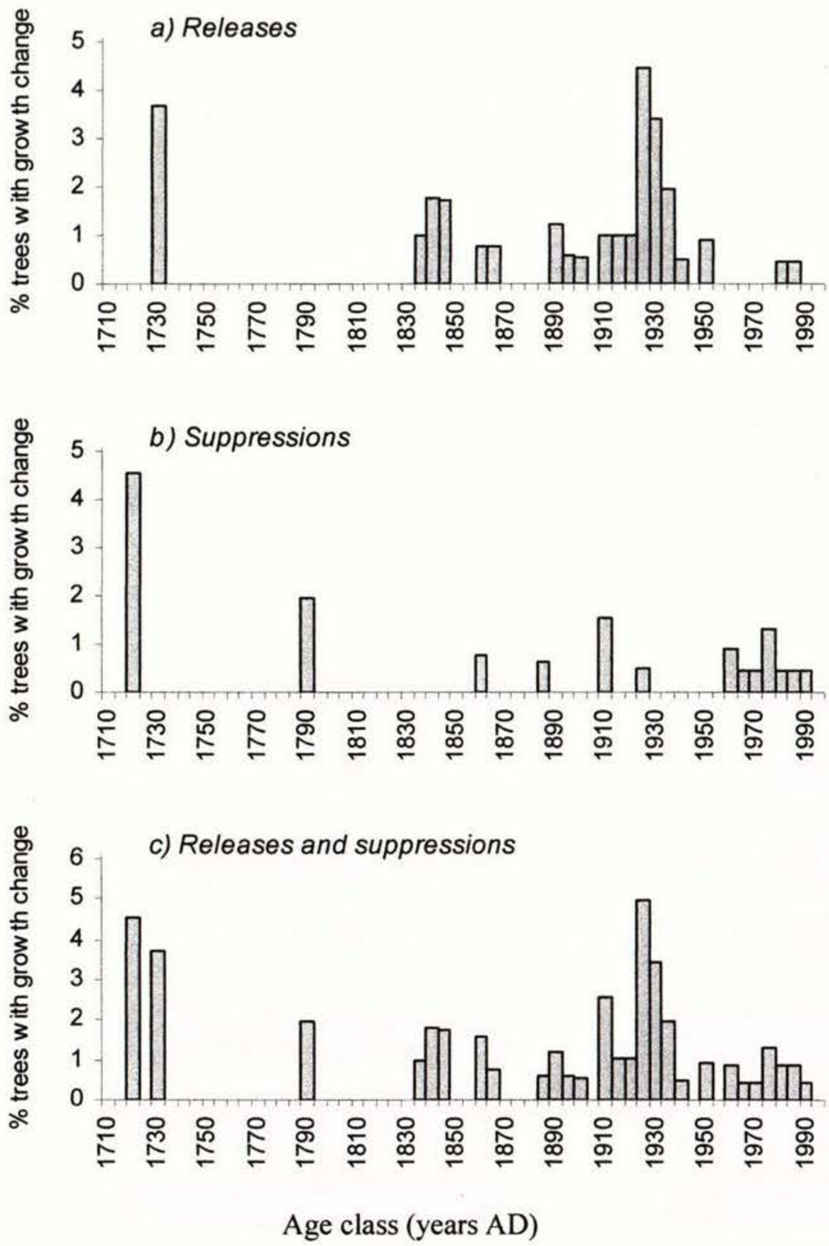
Figure 5. Proportions of trees with severe, long-lasting releases and suppressions (>250% growth change, sustained for 10 years), for i) Pensini study site and ii) Matiri study site. Data prior to 1710 AD are not shown, as no age classes showed more than 1% of trees with a growth change.

i) Pensini study site



Sample Size: 60----------------100------150-------------200----300--------400--444--

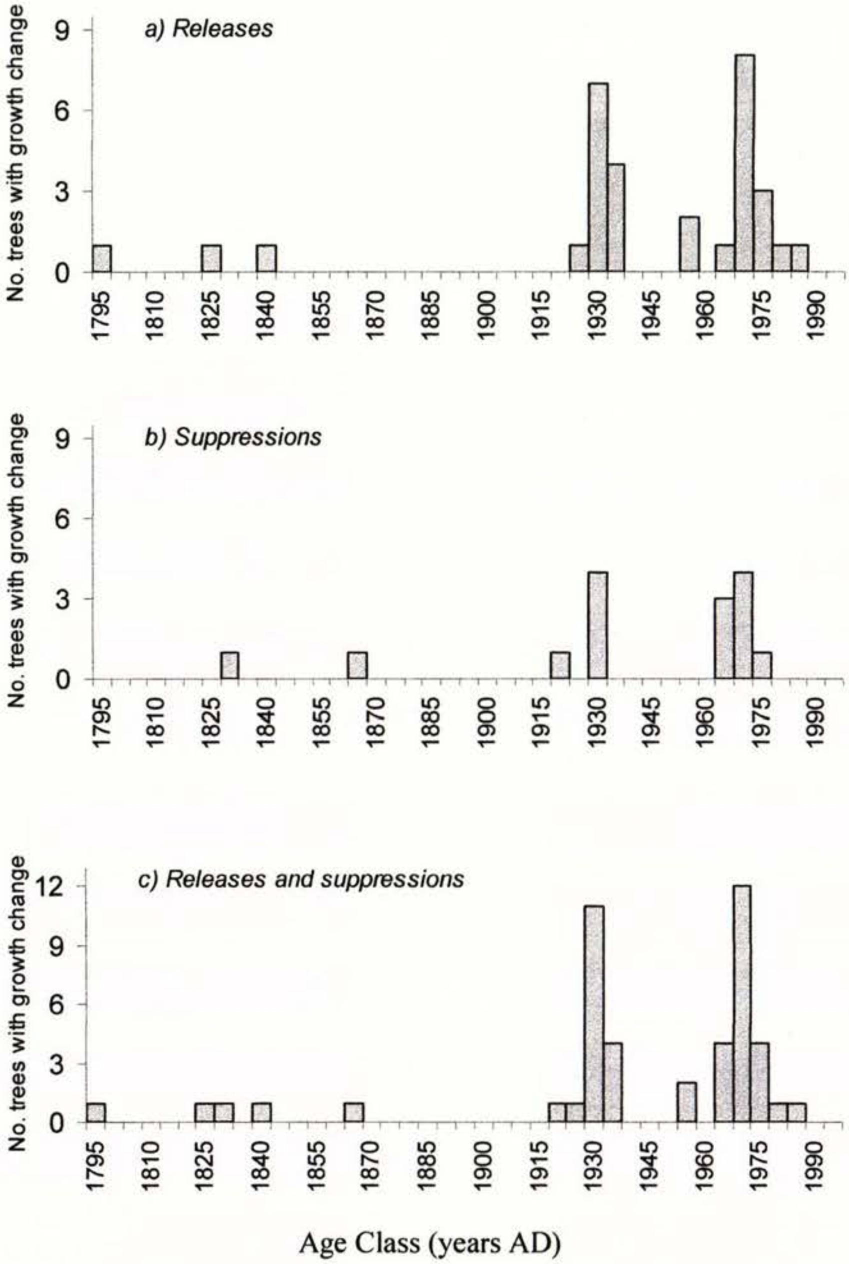
ii) Matiri study site



Sample Size: 15----20-----------50---------100---------150-----200---------231-----

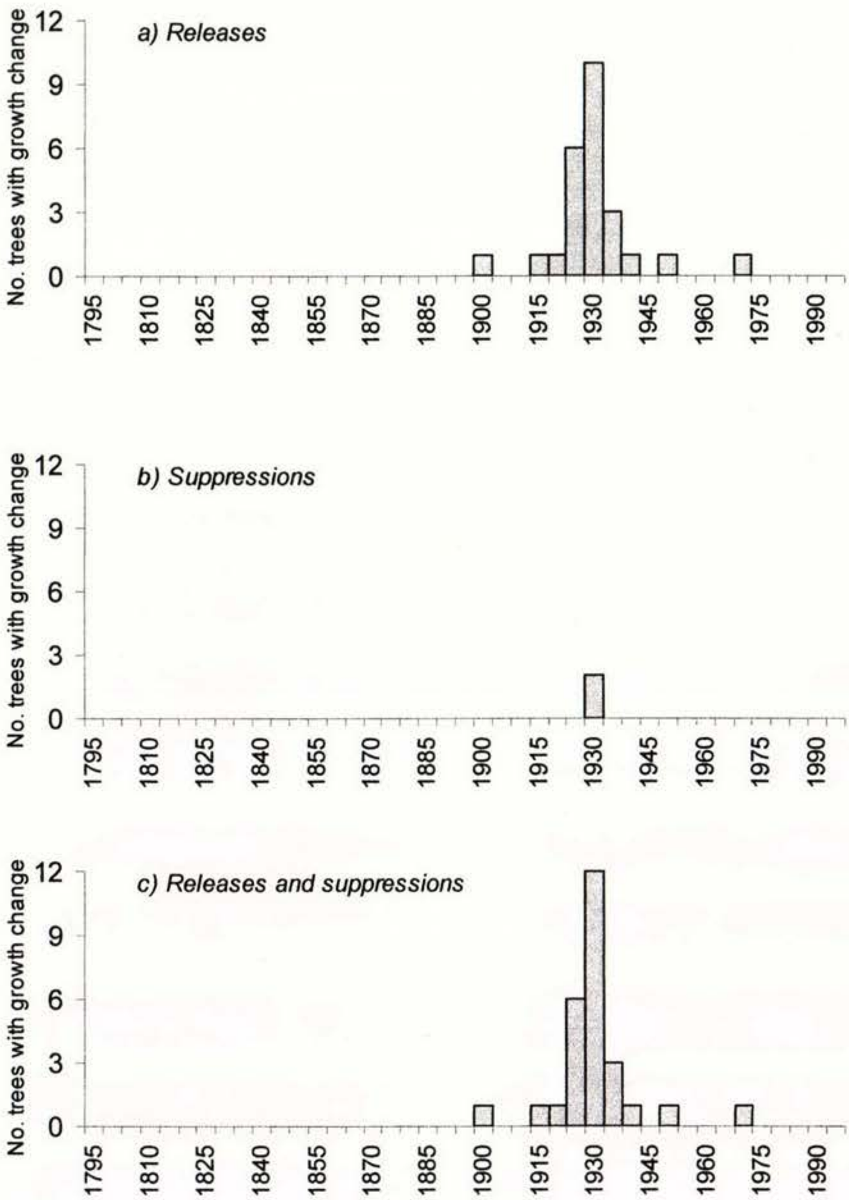
Figure 6. Numbers of extremely severe and long-lasting releases and suppressions (changes of >250% and sustained for at least 25 years), at i) Pensini study site and ii) Matiri study site. Releases, suppressions and combined releases and suppressions are shown for both sites. Data prior to 1795 are not shown, as there were very few growth changes. The y axis records the number of trees with a growth change, and not the percentage of trees as for Figures 3-5.

i) Pensini study site



Sample size 110-----150------------------200---------300----------400------444--

ii) Matiri study site



Age Class (years AD)

Sample size 51----------100-------------150------------200-------------231-------

severe growth changes across a landscape will tend to be dominated by releases with fewer suppressions. At the other end of the scale, moderate growth changes across a landscape will show releases and suppressions, with variation in proportions reflecting variation in the nature of the actual disturbance event leading to the growth changes.

Another important change is that the earthquake events stand out more and more clearly as criteria for recognising growth changes become increasingly severe. Thus for moderate growth changes (Figure 3), several other periods of higher than usual growth change are apparent in the last few centuries. For the more severe growth changes in Figure 5, only one other period (1715-1730) is present other than the two earthquakes (1929 and 1968), while for the most severe growth change criteria (Figure 6) the two earthquakes are unique events and no other periods even register as unusual. At Pensini both the 1929 and 1968 earthquakes are the only periods of major growth change in the last two centuries, and at Matiri the 1929 earthquake is the only period of major growth change over this time (the 1968 event is not recorded at all). The use of these criteria in the separation of earthquake impacts from the more typical variations in a tree's growth pattern has very important potential application in paleoseismology, and will greatly increase the level of confidence that the event being defined is actually an earthquake.

Can we recognise criteria that allow recognition of earthquake impacts as opposed to other disturbance impacts?

Based only on the generalised analysis of growth releases and suppressions, in which all growth changes that are at least moderate are identified (Figure 3), it is not possible to solely distinguish earthquakes from other factors, except an inference on the basis of the percentage of trees showing a growth change. At both study areas, earthquakes with MM intensities of 8 or greater can be distinguished on the basis of obvious peaks in combined releases and suppressions. Over the last 400 years, these earthquakes do stand out as the only times when combined growth changes have exceeded 20% of trees sampled in any 10-year period. Importantly, the 1968 earthquake at Matiri does not stand out as one of these clear events (although there are higher than usual levels of growth changes), reflecting its lower shaking intensity (MM7).

However, by undertaking more specialised investigations of severely impacted trees it is possible to improve the recognition of earthquake events. Based on a criteria of trees with major impacts defined as greater than 250 % changes in growth that last over 25 years, the strong earthquakes at each area entirely dominate the record (Figure 6). The growth changes are also overwhelmingly dominated by releases, which would be expected for severe events as discussed.

Other tree ring growth anomalies

Only two trees contained evidence of tension wood formation, suggesting that this is not a useful technique for identifying earthquakes in these forest types. However, the onset of tension wood dated to 1930 in both these trees. No other unusual features were identified in the cores or growth series.

Variation in the type of growth change – releases versus suppressions

The nature of 'moderate' tree ring responses following each earthquake was different in the 1929 and 1968 earthquake events (Figure 3). Although both releases and suppressions were generally associated with each event, their relative proportions varied (Table 3). Following the 1929 earthquake, releases were far more common than suppressions for moderate changes at both Pensini and Matiri - over twice as abundant at Matiri, and one and a half times at Pensini. In contrast, suppressions dominated slightly over releases at Pensini following the 1968 earthquake, and were totally dominant at Matiri (releases were at background levels only).

Several factors may be involved, singly or in combination, in controlling tree response to each earthquake. The most likely factors are intensity of earthquake shaking, duration of strong earthquake shaking, differences in rainfall patterns immediately preceding and following the earthquake, and time of the year that the earthquakes occurred (Table 4).

Intensity of shaking alone does not appear to be a key factor, based on the differing responses of trees to MM10 shaking for the two earthquakes. MM10 shaking from the 1929 earthquake (Matiri site) resulted in more than twice as many releases as suppressions, while MM10 shaking from the 1968 earthquake (Pensini site) resulted in one and a half times more suppressions than releases. Furthermore, the same trend was consistent in each earthquake at lower shaking intensities of MM8-9 (1929, Pensini site) and MM7 (1968, Matiri site).

Table 4. Summary of earthquake shaking intensity, relative durations of intense shaking, earthquake timing and climatic factors for the 1929 and 1968 earthquakes at Pensini and Matiri sites.

Earthquake	Earthquake Shaking Intensity	Duration of intense shaking	Timing of earthquake	Preceding rainfall	Following rainfall
1929	MM10 (Matiri) MM8-9 (Pensini)	Relatively long	17 June – winter	Very wet	Very dry
1968	MM7 (Matiri) MM10 (Pensini)	Relatively short	24 May – late autumn	Slightly dry	Slightly dry

A possible explanation may be the varied duration of intense shaking experienced by the forest in each earthquake event. MM shaking intensity, and the various criteria used to define it, is mainly controlled by the peak ground acceleration, and provides a less accurate measure of the duration of any particular ground acceleration. The 1929 Buller earthquake was of higher magnitude (Ms 7.8) than the Inangahua event (Ms 7.4), and thus characterised by more prolonged intense shaking for any given ground acceleration and MM class (particularly in the epicentral MM 10 area), and with more intense aftershocks. This same pattern of greater impact associated with the 1929 Buller event, for any given MM class, has been recently noted in relation to the reported historical incidence of liquefaction in these events (Carr, 2004). Liquefaction is another earthquake related phenomena that is sensitive to the duration of earthquake shaking as much as the peak acceleration.

As already discussed, it can be expected that the more severe a disturbance event is, the higher the proportion of growth releases to suppressions that is likely to result across a landscape (due to the removal by death of severely-injured trees from the pool available for future sampling). Therefore, earthquakes with longer durations of strong shaking may result in tree-ring records dominated by releases with few suppressions, while earthquakes with shorter durations of strong shaking may result in more suppressions. The data collected in this study fit this concept quite well (Table 5), although defining relative severity of earthquakes is subjective. But if we assume that the duration of strong shaking is as important as the actual intensity, then observed growth impacts are what would be expected.

The timing of an earthquake in relation to the growing season may also have an impact on the subsequent response of trees. The most obvious potential mechanism is that trees disturbed during times of vigorous growth and high metabolic activity are much more likely to suffer setbacks than trees disturbed during times of dormancy or very slow growth. For example, trees transplanted or pruned in spring/summer are far more likely to suffer ill effects than trees transplanted or pruned in late autumn/winter. Consequently, it is reasonable to assume that trees damaged by severe shaking during the growing season will be more likely to show abrupt suppressions in growth, but trees unaffected by the shaking will be able to respond to the increased resources with releases. This would lead to growth changes showing both releases and suppressions. Equally, it is reasonable to assume that trees damaged by severe shaking during winter dormancy may not exhibit abrupt suppressions to the same degree because the trees have time to deal with the injury before the onset of spring growth, while undamaged trees would still be able to respond abruptly to increased resources in the spring. This would lead to growth changes being dominated by releases.

Table 5. Summary of tree growth responses to varying levels of estimated severity of earthquake shaking (measured by intensity and duration).

Site	Earthquake Event	Intensity	Relative Duration	Relative 'Severity' Ranking	Nature of 'Moderate' Growth Impacts
Matiri	1929	MM10	Long	Extremely high	3 times as many releases as suppressions
Pensini	1929	MM8-9	Long	High	1.5 times as many releases as suppressions
Pensini	1968	MM10	Short	Moderately high	Suppressions marginally more abundant than releases
Matiri	1968	MM7	Short	Low	Suppressions totally dominant; releases not above background levels

However, the two earthquakes in this study occurred just three weeks apart, and both at times when growth could be expected to have ceased for the season or at least slowed to very low rates. This makes it very unlikely that the differences in growth responses are due to earthquake timing. Nevertheless it is possible that the increased occurrence of suppressions following the 1968 earthquake is partly attributable to its earlier timing in the autumn, perhaps before the onset of the first very cold snap of winter.

A further possible factor is the patterns of rainfall immediately before the earthquake and in the few seasons after the earthquake. The month of May 1968 was slightly drier than average in the region, while June 1929 was markedly wetter than average (Figure 7). Earthquake impacts may potentially be more severe during a very wet period, due to a greater likelihood of slope instability, mass movement and small-scale soil collapse in saturated soils.

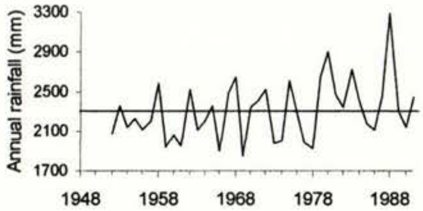
Rainfall in the year following the 1968 earthquake was slightly drier than average, but for 1970-1973 was about average. In contrast, 1930 was an extremely dry year in the region (the lowest rainfall recorded at Reefton over an 80 year record), and was followed by a further five much drier than average years. 1931-1935 were years of low spring rainfall also, and represent the driest series of springs on record at Reefton (Figure 7).

Periods of several dry years (and especially dry springs) are known to stress beech trees in the region, and often result in outbreaks of the defoliating scale insect *Inglisia fagi* (Hosking & Kershaw 1985). This can lead to significant tree mortality at times – for example, widespread mortality of red beech forest in the Maruia Valley followed the dry years of 1974-78. The effects of the 1929 earthquake may therefore have been compounded by the very dry years following the event acting to further stress trees and increase the likelihood of mortality of earthquake-damaged

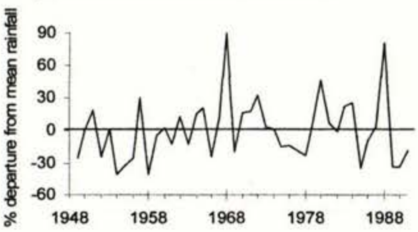
Figure 7. Rainfall statistics measured at i) Inangahua Station (F11891) and ii) Reefton Mine Station (F21181). A. Annual rainfall (horizontal bars mark long-term mean annual rainfall). B. Rainfall for September-November (% departure from the long-term mean rainfall for these months). C. Rainfall for May (Inangahua Station) and June (Reefton Mine Station) (horizontal bar marks long-term mean May or June rainfall).

i) Inangahua Station

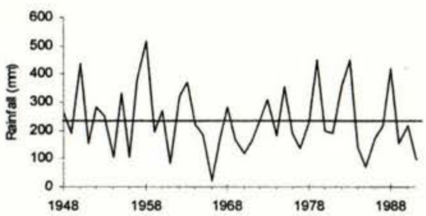
A. Annual rainfall



B. September-November rainfall

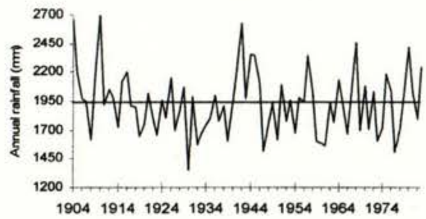


C. May rainfall

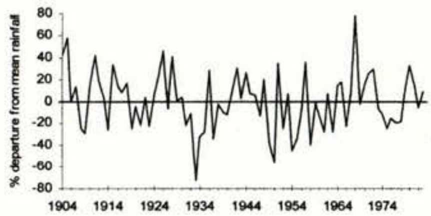


ii) Reefton Mine Station

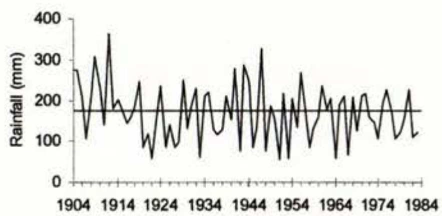
A. Annual rainfall



B. September-November rainfall



C. June rainfall



trees. This may partially account for the greater impacts recorded after this event, and also for the greater incidence of releases over suppressions.

In conclusion, it is difficult to assign specific casual agents to the variability observed in tree-ring responses to the two earthquakes. The variation appears to reflect the combined effect of differences in the duration of intense earthquake shaking and differences in climatic conditions following the earthquakes. This highlights the complexity of tree-ring responses to disturbance events, and the consequent caution that is required in making inferences regarding earthquake parameters from generalised tree-ring information.

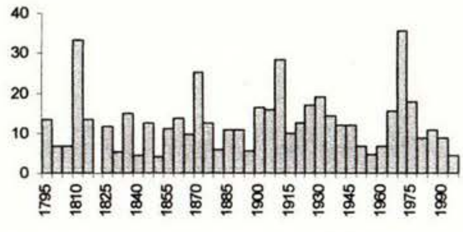
Delays in growth changes following earthquake events

Previous studies of tree-ring growth responses have noted that the onset of growth change following a severe disturbance event is sometimes several years after the event itself (e.g. Fritz & Swetnam 1989; Veblen et al. 1992; Kitzberger et al. 1995). To investigate this, we examined all trees showing a release or suppression in the ten years following the 1929 and 1968 earthquakes and obtained the year in which the growth release or suppression commenced. This information is summarised in Table 6.

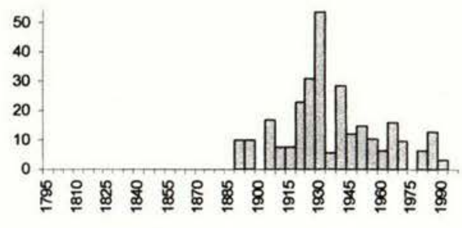
Table 6. The timing of the onset of 'moderate' growth changes around the time of the Inangahua and Buller earthquakes, for the Matiri and Pensini sites. Numbers refer to the number of trees that record a growth change beginning in a given year. Highlighted years represent the 10-year periods immediately following each earthquake.

1929 Buller Earthquake					1968 Inangahua Earthquake				
	Matiri Site		Pensini Site			Matiri Site		Pensini Site	
YEAR	Rel.	Supp.	Rel.	Supp.	YEAR	Rel.	Supp.	Rel.	Supp.
1920	2	1	1	3	1960	1	2	2	4
1921	0	4	4	5	1961	2	3	1	5
1922	4	1	1	3	1962	0	1	4	2
1923	4	0	3	7	1963	3	4	6	4
1924	4	1	3	1	1964	2	1	2	3
1925	3	2	2	2	1965	1	3	1	2
1926	2	1	3	0	1966	4	3	3	1
1927	2	1	4	2	1967	1	0	1	2
1928	3	4	6	3	1968	0	2	5	5
1929	1	4	3	4	**1969**	1	4	12	15
1930	15	9	10	22	**1970**	4	9	9	18
1931	11	4	11	3	**1971**	2	5	11	10
1932	10	0	17	7	**1972**	0	10	4	12
1933	8	4	9	7	**1973**	3	4	11	11
1934	7	3	13	2	**1974**	1	2	8	3
1935	4	0	6	7	**1975**	3	5	6	8
1936	12	1	9	4	**1976**	2	3	2	3
1937	6	0	9	4	**1977**	2	7	6	2
1938	7	0	7	4	**1978**	0	5	5	1
1939	7	0	2	4	1979	2	6	8	4
1940	3	3	2	4	1980	0	3	3	4
1941	3	1	5	6	1981	2	6	6	4
1942	4	2	2	3	1982	1	1	6	2
1943	3	1	6	1	1983	1	3	2	5
1944	2	1	5	2	1984	4	4	6	4
1945	4	2	6	1	1985	1	1	1	5

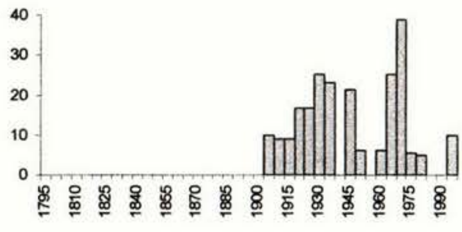
There is an abrupt onset of high levels of growth changes after the Buller earthquake beginning in 1930 at both study sites, the year immediately after the earthquake. Unusually high levels of growth *xi. Coal Flat Swamp* (n = 46)



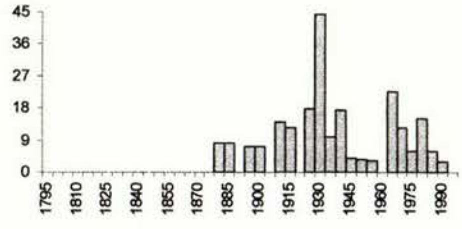
xii. Pensini Fan (n = 31)



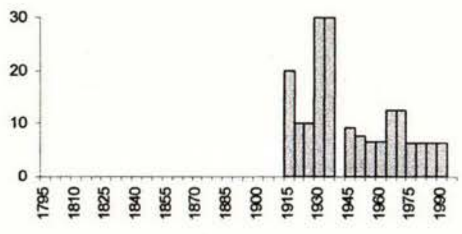
xiii. Buller View Landslides (n = 20)



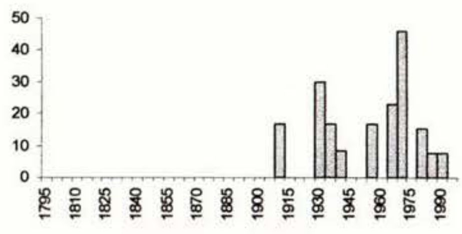
xiv. ***Fissure Zone*** (n = 33)



xv. Tilted Rimu Patch (n = 16)

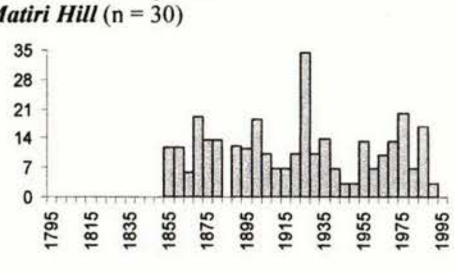


xvi. ***Pensini toeslope*** (n = 13)

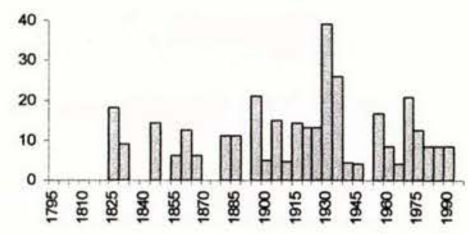


B) Matiri Study Site

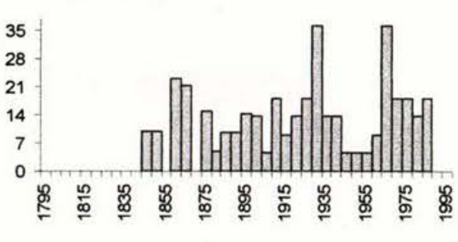
i. Matiri Hill (n = 30)



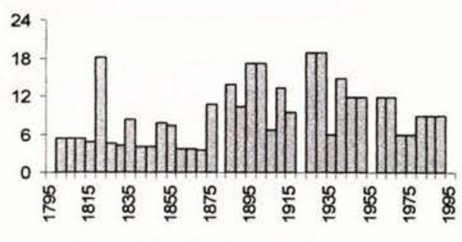
ii. ***Plateau Hill*** (n = 24)



iii. Matiri Terrace (n = 22)



iv. Matiri Ridge (n = 34)



changes are sustained at both sites through until 1936 or 1937, 7 to 8 years after the earthquake event. After that, growth changes return to within the bounds of usual background levels. It is interesting to note that even though there were far fewer suppressions than releases following this earthquake, the initiation of the majority of suppressions occurred within one to two years following the earthquake (whereas high levels of releases spanned the longer period). This is consistent with expectations, whereby the impact of increased light and nutrients is virtually indefinite, as neighbouring trees can never "catch up".

Following the 1968 earthquake, unusually high levels of growth changes at the Pensini site commenced the very next year and were sustained at high levels for 7 years before returning to normal. This event was not as clear at Matiri, with growth changes not apparent until 1970 and then only obvious for one or two years. There are also reasonably high occurrences of growth changes at both sites from 1977 to about 1981, and this may be a response to the known severe droughts in the region during the mid to late 1970's (Hosking & Kershaw 1985).

Similar results are recorded by the subset of trees that experienced extremely severe and long-lasting growth changes (Table 7). The onset of severe changes was one to two years following the earthquake, and continued for up to 8 years following the events. The three severe growth changes recorded at Pensini in 1980 are unlikely to be the result of the earthquake, given the length of time after it, and are most probably related to the droughts mentioned above.

Table 7. The timing of the onset of extremely severe and long lasting growth changes around the time of the 1968 Inangahua and 1929 Buller earthquakes, in the Matiri (MAT) and Pensini (PEN) sites. Numbers refer to the number of individual trees that record a growth change beginning in a given year.

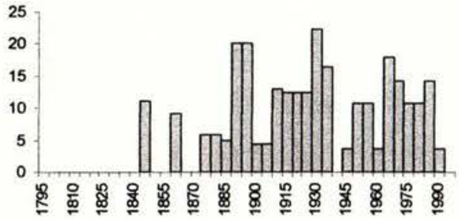
1929 Earthquake				**1968 Earthquake**		
YEAR	**MAT**	**PEN**		**YEAR**	**MAT**	**PEN**
1925	1			1965		
1926				1966		
1927				1967		
1928		1		1968		1
1929				**1969**		
1930	6			**1970**		3
1931	5	2		**1971**		5
1932	2	2		**1972**		2
1933	2	2		**1973**		4
1934	2			**1974**	1	
1935	1	5		**1975**		
1936	2	1		**1976**		
1937	1	3		**1977**		2
1938				**1978**		
1939				1979		
1940				1980		3

The fact that many trees were not able to be crossmatched may also have contributed to the wide spread of times of growth change found in this study. However, this is unlikely to have exceeded one to three years in almost all cases, given that the analysis is based on just the last 40-90 years, and that trees with unclear sections of rings were removed. The results are therefore likely to be a true representation of typical delays in growth responses.

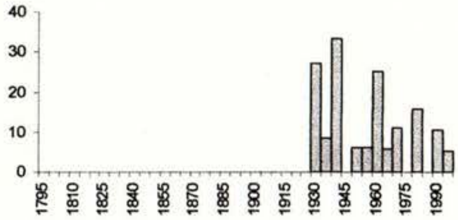
Figure 8. Percentages of 'moderate' growth changes (releases and suppressions combined) for individual sampled localities at (a) Pensini study site and (b) Matiri study site. Growth changes are shown only for age classes in which there were at least 10 sampled trees, and only for age classes younger than 1795 AD. Y axis on all graphs is % trees showing growth change, and x axis is age class in years AD.

A) Pensini Study Site

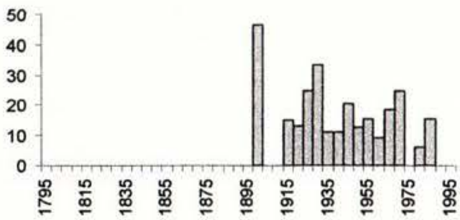
i. Orikaka Hill (n = 28)



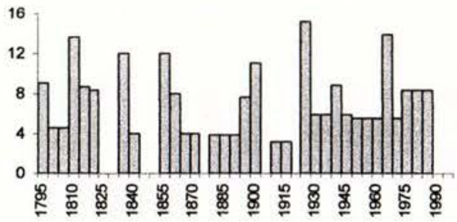
ii. *WhiteCliffs Hill* (n = 19)



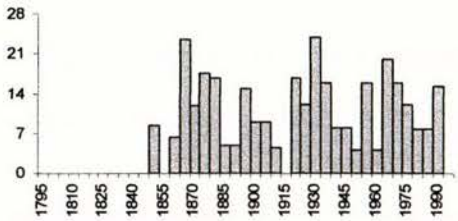
iii. Pensini Hill (n = 32)



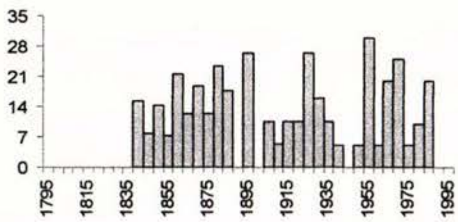
iv. Tertiary Slope (n = 36)



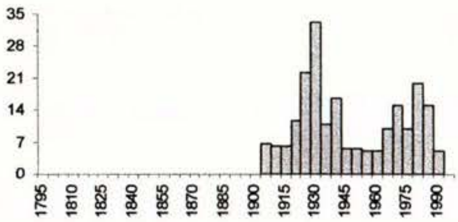
v. Coal Yard Slope (n = 27)



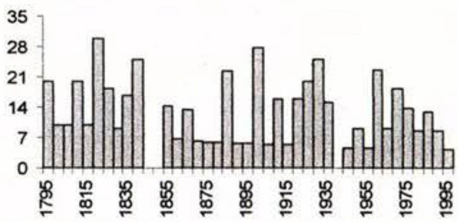
vi. Orikaka Terrace (n = 20)



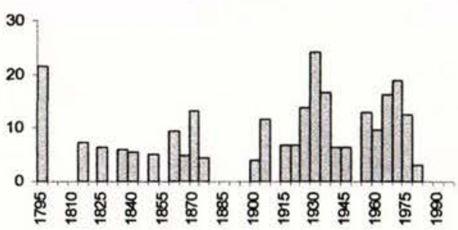
vii. Coal Flat Ridge (n = 20)



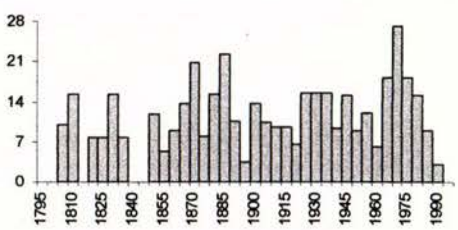
viii. *Lyell Ridge* (n = 23)



ix. Welshman's Pakihi (n = 32)



x. *Frosty Swamp* (n = 33)



4.2 Variations in landform sensitivity to earthquake impacts and the role of debris movement

Growth changes associated with the earthquakes were found in trees on all landforms and localities sampled, but to varying degrees (Table 8 and Figure 8. See also Appendix 2 for fuller details on each landform). In particular, extremely severe growth changes tended to be clustered on certain landforms and were absent from others. Consequently, at some sampled localities the earthquake impacts were clearly evident in growth changes, while on many the earthquake impacts were not clearly distinguishable above other impacts over the last two or three centuries. We infer this to reflect real differences in the susceptibility of trees on various landforms, although it may also in part be a reflection of a low sample size at some sites (c. 20 trees), that is too small to clearly discern events and trends. Based on these patterns, it is possible to examine which landforms consistently show effects most clearly and which sites are least useful.

Before considering individual landforms, it is important to distinguish two main types of earthquake impacts that landforms can experience: impacts caused purely by earthquake shaking, and impacts caused by earthquake-induced debris movement or deposition as well as earthquake shaking. We term these 'shaking' and 'debris' landforms respectively. Because this distinction is likely to have implications for types of tree ring responses, we separated 'shaking' landforms from 'debris' landforms and examined growth responses for sampled landforms within each grouping. Figure 9 presents the results of this for moderate growth changes, and Table 9 for extremely severe and long-lasting growth changes – these will be referred to in the following comparisons.

i. Landforms with debris movement combined with earthquake shaking
Alluvial fans, rockfall margins, landslide deformation –

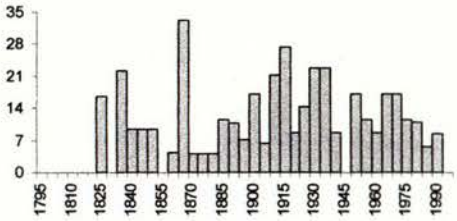
These landforms comprised three sampled localities at Matiri (Alluvial Fans 1 and 2, and Plateau rockfall) and four at Pensini (Pensini Fan, Buller View Slide, Fissure Zone and Tilted Rimu Patch). The nature of growth changes at all these landforms was very similar, and so we consider them together here.

All seven localities recorded clearly just one of the earthquakes in frequencies of moderate growth changes, but with extremely high clarity. These patterns were also reflected in frequency of extremely severe growth changes – 23 of the 29 recorded on these landforms dated from an earthquake, and these growth changes were found across all but two of the localities (Table 8). Where an earthquake is recorded, these landforms gave the clearest record of the events. Thus, these landforms can be exceptionally sensitive recorders of earthquake events.

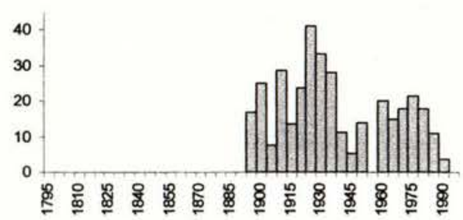
This is a reflection of the fact that the recorded events were all associated with significant debris movement at the sampling locality (and not just the effects of earthquake shaking). Debris movement often leads to the death or severe damaging of many trees, leading to large gaps in the forest and associated growth changes in surviving trees (e.g. Vittoz et al. 2001). We identified young cohorts of trees that had colonised new debris after the earthquake events at all these landforms, providing evidence of debris movement and widespread tree death coinciding with the periods of growth change.

An implication of this, however, is that these landforms were inconsistent in recording earthquakes and did not reliably record earthquake history at a locality. While these landforms record most unequivocally earthquake events when there is associated debris movement, only events that result in significant debris movement are well recorded. Consequently large events which caused little associated debris movement at a locality went totally unrecorded. For example the Pensini Fan

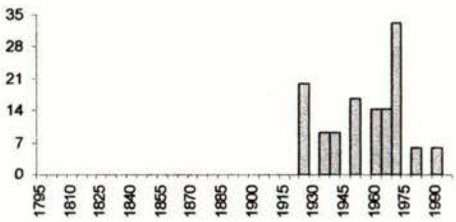
v. Poor Pete's Plateau (n = 36)



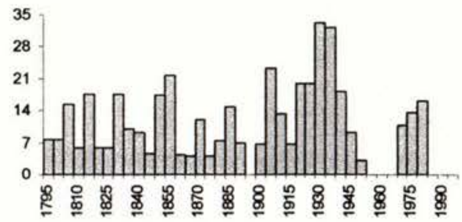
vi. Alluvial Fan 1 (n = 29)



vii. Alluvial Fan 2 (n = 17)



viii. *Plateau Rockfall* (n = 37)



(Figure 8axii) records the 1929 earthquake (MM9) very clearly indeed, but there is almost no evidence of the 1968 event (MM10). Similarly, Fan1 at Matiri (Figure 8bvi) strongly records the

Table 8. Overview of tree-ring growth changes recorded in trees on different landforms at the Pensini and Matiri study sites. Summaries of growth responses are presented for the two earthquakes, the storms of 1895-1905 and the 1974-78 drought. Responses are summarised for (a) moderate growth changes (i.e. >100% changes between consecutive 5-year means), and (b) extremely severe and long-lasting growth changes (i.e. >250 % changes, sustained for at least 25 years). Responses for (a) are recorded only when there were clear pulses of growth changes for an event, in which >25% of trees showed a growth change in the 10-year period immediately following the event. Bracketed dates indicate that the responses did not stand out clearly above other pulses of growth changes.

Landforms/ specific localities	**Summary of growth responses** (moderate growth changes and extremely severe long-lasting growth changes)		
1) 'Debris' Landforms	**1929/1968 earthquakes**	**1895-1905 storms**	**1974-78 drought**
Alluvial Fans *Alluvial Fan1*	a. 1929 and (1968) b. 4/4 trees	a. (1895-1905) b. 0/4 trees	a. (1980-85) b. 0/4 trees
Alluvial Fan2	a. 1968 b. 0/0 trees		
Pensini Fan	a. 1929 b. 7/7 trees		
Rockfall Margins *Plateau rockfall*	a. 1929 b. 7/11 trees	a. (1900-1910) b. 0/11 trees	a. (1975-1985) b. 0/11 trees
Buller View Slide	a. (1929) and 1968 b. 0/0 trees		
Substrate Deformation *Fissure Zone*	a. 1929 and (1968) b. 3/4 trees		
Tilted Rimu Patch	a. 1929 b. 2/3 trees		a. b. 1/3
2) 'Shaking' Landforms			
Steep Side Slopes *Plateau hill*	a. 1929 and (1968) b. 6/9 trees	a. (1895-1905) b. 0/9 trees	
Matiri hill	a. 1929 and (1968) b. 3/3 trees		a. (1975-1985) b. 0/3 trees
Orikaka hill	a. 1929 and (1968) b. 2/2 trees	a. 1895-1905 b. 0/2 trees	a. (1980-1990) b. 0/2 trees
Pensini hill	a. 1929 and (1968) b. 5/7 trees	a. 1900-1905 b. 0/7 trees	
WhiteCliffs hill	a. 1929 b. 0/0 trees		
Gentle Side Slopes *Tertiary slope*	a. b. 2/3 tree		
Coal Yard slope	a. 1929 and 1968 b. 0/3 trees		a. b. 2/3
Terraces *Matiri terrace*	a. 1929 and 1968 b. 0/0 trees		
Orikaka terrace	a. 1929 and 1968 b. 0/1 tree	a. 1895-1900 b. 0/1 tree	
Ridges *Matiri ridge*	a. 1929 b. 0/0 trees	a. 1895-1905 b. 0/0 trees	
Coal Flat ridge	a. 1929 b. 0/0 trees		a. 1980-1990 b. 0/0 trees
Lyell ridge	a. (1929) b. 3/5 trees	a. (1900-1905) b. 0/5 trees	
Swamps/Pakihis			

Frosty swamp	a. (1929) and 1968 b. 3/3 trees		
Coal Flat swamp	a. (1929) and 1968 b. 3/4 trees	(Pulse in 1915, but unlikely to be storms)	
Welshman pakihi	a. 1929 and 1968 b. 3/4 trees		
Elevated Mountain Plateau *Poor Pete's plateau*	a. (1929) b. 2/3 trees		a. b. 1/3 trees
Old Landslide Toe *Pensini toeslope*	a. 1929 and 1968 b. 0/1 trees		

1929 event, while the adjacent Fan2 (Figure 8bviii) has no evidence of this event but clear recording of the MM7 1968 event in moderate growth changes. The two localities with landslide deformation (Figure 8axiv and 8axv) recorded the 1929 event very clearly but the 1968 event was barely discernable.

This weakness is highlighted in the combined growth change data for all 'debris' landforms in the Pensini study site (Figure 9bii, and Table 9). The 1929 event is recorded exceptionally clearly, while the MM10 1968 event barely stands out above a number of other periods of high levels of growth change over the last two centuries. The fact that many of these landforms do not appear to have substrates sensitive to earthquake shaking impacts (e.g. coarse-textured, well-drained and relatively strong) no doubt further contributes to this pattern. These landforms are also likely to be the most sensitive to local sedimentation and landslipping accompanying storm events, which may confound the earthquake record. This may account for the several periods of relatively high disturbance recorded in moderate growth changes at Pensini over the last two centuries (Figure 9bii).

Table 9. The occurrence of sampled trees showing extremely severe and long-lasting growth changes following the 1929 and 1968 earthquakes, on 'shaking' and 'debris' landforms in the two study sits.

Site and Landform	No. trees with severe growth change following EQ	
	1929 event	**1968 event**
Pensini:		
'Debris' landforms (5)	8	4
'Shaking' landforms (9)	7	13#
Matiri		
'Debris landforms (3)	10	1
'Shaking' landforms (5)	11*	0

8 of these trees were from swamps/pakihis, and 5 from steep slopes.

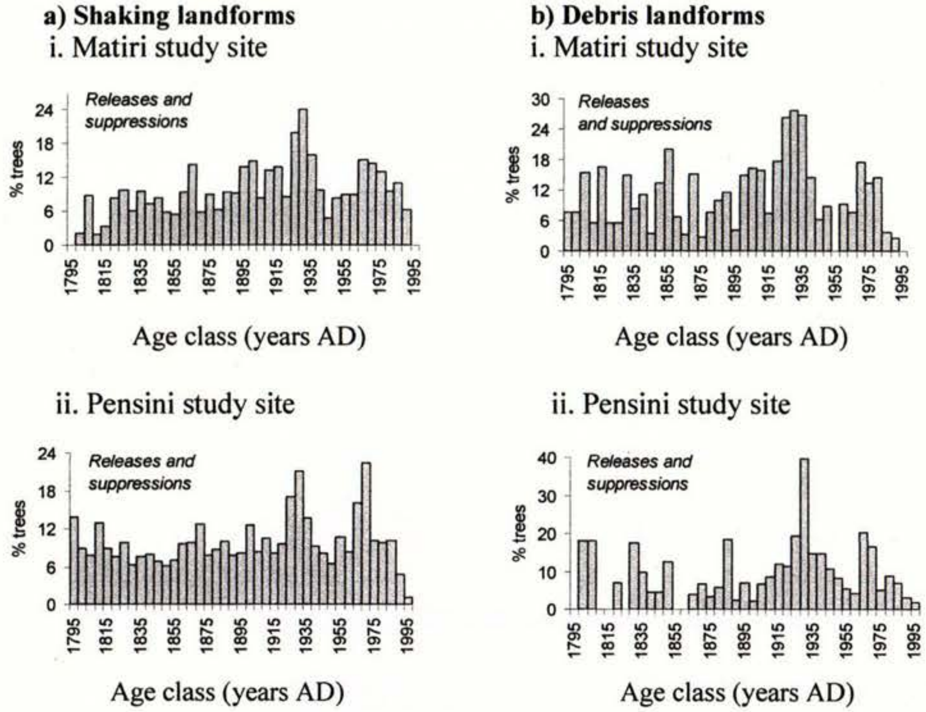
* 9 of these trees were from steep slopes

However, despite these limitations it is clear that where debris movement does occur during an earthquake, then this will be recorded most unequivocally in the tree rings of surviving trees. These landforms may also provide the best realistic comparison of the overall geomorphic impact of an earthquake, which in research may be an important secondary objective in addition to the determination of earthquake timing.

ii. Landforms with earthquake shaking only (i.e. no debris movement)

This grouping of landforms included 17 sampled localities. Due to major differences in the nature of growth changes recorded between localities, we consider landform types separately here.

Figure 9. A comparison of 'moderate' growth changes at the Matiri and Pensini study sites for (a) all landforms affected by shaking alone ('shaking landforms'), and (b) all landforms also affected by debris movement or deposition ('debris landforms').



Swamps and Pakihis

Swamps and pakihis recorded events the most clearly and consistently of all the 'shaking' landforms. All three sampled localities at Pensini recorded very clearly the MM10 1968 earthquake in moderate growth changes, and one also recorded the MM8 1929 event clearly (Welshman Pakihi, Figure 8aix). Significantly too, 8 of the 20 extremely severe growth changes from 'shaking' landforms at Pensini were from these landforms (Table 9).

Other periods of moderate growth changes are present at some localities at times other than the earthquakes, but these do not show as clearly as the earthquakes and are not consistent between localities. Furthermore, they do not correspond with times of known droughts or windstorms. This highlights an advantage of these wet, flat and usually low-lying sites - they are unlikely to be as susceptible to drought or wind damage as other landforms such as ridges, fans or steep slopes which are usually free draining and more exposed to wind.

Steep Slopes

Steep slopes at Matiri recorded the 1929 earthquake exceptionally clearly, and 9 of the 11 extreme growth changes on 'shaking' landforms at Matiri were from steep slopes. This demonstrates the ability of this landform to clearly record strong shaking.

At Pensini, however, recording of earthquakes was inconsistent in moderate growth changes. One locality recorded both earthquakes clearly, while two showed the 1929 event but not the 1968 event. However, 5 of the 13 extreme growth changes following the 1968 event were on steep slopes, while just 1 of the 7 following the 1929 event were. This indicates that severe impacts can be common and well recorded, even if more moderate impacts are not. Steep slopes are thus an important landform.

A limitation of steep slopes is that they also record droughts and wind storms better than most other landforms. For example, at the Orikaka and Pensini Hills (Figures 8ai and 8aiii), growth changes associated with the storms of 1895-1905 show as the most prominent periods of moderate growth changes at these localities. Likewise, there are high levels of growth changes at some localities following the 1974-78 drought. Importantly though, despite this there were no extreme growth changes at these times.

Ridges

Ridges were generally not as good recorders of earthquakes as swamps or steep slopes, with much fewer extreme growth changes and more confounding from other disturbance events. For example, the 1895-1905 storms and late-1970s drought caused marked growth changes at ridge localities. However, the Coal Flat Ridge (Figure 8avii) was an exception, with the 1929 event standing out clearly in moderate growth changes. The three extreme growth changes at Lyell Ridge (Table 8) also demonstrate the ability of ridges to record severe impacts.

Terraces and Gentle Slopes

These landforms recorded earthquake events in moderate growth changes, but generally they were unclear above background levels of disturbance. Further, just two trees on the four localities sampled showed extreme growth changes corresponding with an earthquake. Despite this, two localities did record earthquakes relatively clearly in moderate growth changes (i.e. Pensini Toeslope (Figure 8axiv) and Matiri Terrace (Figure 8biii)). Nevertheless, these landforms appear to be the least promising overall for recording earthquakes.

Geographical distribution of impacts as a method for differentiating earthquake-caused tree ring growth changes

The geographical distribution of growth changes offers potential to also be used to distinguish earthquake-caused periods of growth changes from other causes such as drought and storms. We could expect earthquake impacts to be the most widespread across an entire landscape, reflecting the fact that earthquakes can cause severe damage on all landforms. In contrast, we could expect impacts from droughts and storms to be much more restricted geographically, with marked concentration of impacts on landforms most vulnerable to the disturbance and near absence of impacts on less vulnerable sites.

Table 8 provides a summary of locations in our study that clearly record the key disturbance events of the last century - the earthquakes, the 1895-1905 storms, and the late 1970s drought. These results allow for a clear differentiation of earthquake-caused impacts from other periods of impacts, on the basis of geographical distribution of growth changes. The earthquakes were recorded clearly on the majority of landforms, and there were very few exceptions. Even the 'least sensitive' landforms generally recorded the earthquakes in moderate growth changes. However, the storm events were recorded clearly only on steep slopes and ridges – i.e. the locations most exposed to wind. The only exceptions were the Orikaka terrace and Tertiary slope. (The Plateau rockfall locality is on a steep slope). Similarly, the late 1970s drought was recorded clearly at one ridge and three steep slopes – i.e. locations on well-drained sloping ground prone to drying out. On this basis, in this study earthquake impacts can be distinguished from drought and storm impacts on the basis of widespread distribution of impacts across many landforms including those not particularly sensitive to drought, wind storms or storm-induced debris movement.

A further point to note is that that it is important to investigate the full 'spectrum' of growth changes at each landform – i.e. both 'moderate' and 'severe' growth changes. A focus on just one criterion may omit important information on disturbances, because localities may sometimes record only one type of growth change clearly for a particular event. For example, Pensini Hill recorded 5 extremely severe growth changes following the 1968 earthquake, but 'moderate' growth changes do not even stand out clearly for this event. Similarly at Lyell Ridge 3 extremely severe growth changes followed the 1929 event, while 'moderate' growth changes are not unusually high. Thus, an analysis of the combined growth change data will allow the best record of disturbance history to be obtained from tree ring analysis.

Overall conclusion on landform sensitivity

In summary, most landforms have both positive and negative aspects in terms of ability to consistently and clearly record earthquake events (Table 10). 'Debris' landforms have the potential to record earthquake events most unequivocally (in terms of proportions of moderately and severely impacted trees) when there is associated debris movement at the site, but they may totally miss recording other equally severe events. The best sampling position is likely to be at the distal end of the deposition area, where trees will have survived through events but will have had many neighbouring trees die. Thus some discretion is involved in choosing sample sites.

However, our results suggest that 'shaking' landforms are more likely to reliably record overall earthquake history than 'debris' landforms, particularly where debris movement is more limited (Figure 9). For example, 'shaking' landforms at Pensini recorded both the 1929 and 1968 earthquakes very clearly, with both events recording similar high proportions of both moderate and extreme growth changes. In contrast the 'debris' landforms showed the 1929 earthquake as by far the dominant event of the last 200 years with the 1968 event being clear only in extreme growth changes. (At Matiri, both 'debris' and 'shaking' landforms show very similar patterns of growth changes with the 1929 earthquake standing out obviously, reflecting the fact that this event was extremely severe in the area and resulted in much landsliding and sedimentation as well as severe shaking).

Table 10. Positive and negative aspects of landforms in the Buller catchment for recording tree-ring growth changes caused by earthquakes.

Landform	Positive Features	Potential Limitations
Alluvial Fans	· Extremely sensitive at recording EQ when there is associated debris movement at the site. -Catastrophic nature of impacts means that extremely severe and long-lasting growth changes are common.	-Inconsistent recording of EQ – unlikely to record EQ that do not cause debris movement at the site. -Sensitive to recording climatic disturbances such as rain storms, which may confound EQ record. -Poor ability to distinguish shaking intensities.
Rockfall Margins	· Extremely sensitive at recording EQ when there is associated rockfall at the site. -Climatically-induced rockfall events are unlikely, so confounding is less of a problem. -Catastrophic nature of impacts means that extremely severe and long-lasting growth changes are common.	-Inconsistent recording of EQ – unlikely to record EQ that do not cause rockfall at the site. -Poor ability to distinguish shaking intensities.
Substrate deformation	· Extremely sensitive at recording EQ when there is associated substrate deformation at the site. -Catastrophic nature of impacts means that extremely severe and long-lasting growth changes are likely.	-Inconsistent recording of EQ – unlikely to record EQ that do not cause rockfall at the site. -Poor ability to distinguish shaking intensities.
Swamps/ Pakihis	-Very sensitive at recording earthquakes from shaking alone. -Extremely severe and long-lasting growth changes are common, reflecting relatively high sensitivity to strong shaking. -Best potential for distinguishing shaking intensities. -Potential for high consistency, as response not dependent on secondary processes such as debris movement or rockfall. -Climatic events (wind and drought) likely to have a minimal effect on trees compared with other landforms, minimising possible confounding factors.	-Lower intensity shaking (MM8) may not be reliably recorded.
Steep side slopes	-Able to record EQ with high consistency in areas of strong shaking. -Extremely severe and long-lasting growth changes are common, reflecting relatively high sensitivity to strong shaking.	-Unreliable recording of earthquakes at shaking intensities of less than MM10. Droughts and wind storms are often well recorded by trees, confounding the EQ record.
Gentle side slopes	-Have the ability to record EQ events clearly in some cases.	-Poor consistency in recording EQ, even for MM10 shaking. -droughts and wind storms are often well recorded by trees, confounding the EQ record. -Extremely severe and long-lasting growth changes are uncommon, reflecting low sensitivity to strong shaking.
Ridges	-Can record EQ events clearly in some cases.	-Poor consistency in recording EQ, even for MM10 shaking. -droughts and wind storms are often well recorded by trees, confounding the EQ record. -Extremely severe and long-lasting growth changes are uncommon, reflecting low sensitivity to strong shaking.
Alluvial terraces	-Can record EQ events clearly in some cases.	-Poor consistency in recording EQ, even for MM10 shaking. -Extremely severe and long-lasting growth changes are uncommon, reflecting low sensitivity to strong shaking.

These differences reflect the fact that shaking affects all of the landscape during each event, whereas debris deposition will not affect all possible debris-sensitive sites during any single earthquake. This highlights an important potential advantage of 'shaking' landforms. Also, the impact of the predominant mode of disturbance other than earthquake shaking on 'shaking' landforms (i.e. wind storms) is more dependant on forest age structure than the impact of debris movement from intense rainstorms. For example young forests are unlikely to be impacted by wind damage during a severe storm, but similar young forest may well be impacted by debris deposition during the same event. These landforms have the added advantage of requiring less sampling discretion because their effectiveness as recording sites does not require the coincidence of earthquake shaking and debris movement.

Of the 'shaking' landforms, the best localities are clearly swamps/pakihis or similar areas of wet, difficult and insecure growing conditions. Steep slopes are also very promising landforms, but appear to be more inconsistent, with some sites showing effects well while others do not. Swamps and steep slopes combined accounted for the vast majority of extreme growth changes on 'shaking' landforms, and also for the clearest recording of earthquakes in moderate growth changes. All other landforms (ridges, terraces and gentle slopes) have the potential to record earthquake events, but generally are the most inconsistent and have the fewest extreme growth changes.

Although this is the relative order of landform reliability in recording earthquake generated tree ring signatures, it is obvious that even on the best landforms there is still not a 100% consistency (e.g. Alluvial Fan2 (Matiri) and Coal Flat Swamp (Pensini) do not record the 1929 earthquake). We recommend that in undertaking future paleoseismic studies the most effort go into tree ring analysis on the most promising group of landforms, because this combination is most likely to detect all large regional events. Specifically, this should include the landforms most sensitive to shaking alone (i.e. swamps, pakihis and steep slopes) as well as landforms prone to debris movement (i.e. rockfall margins, alluvial fans and areas of substrate deformation). A wide geographic sampling of landforms is also important as it best enables differentiation of earthquake events from climatic impacts, as discussed above. The combined regional picture of growth changes across landforms best highlights earthquake impacts, and minimises the influence of more localised climatic events that may appear important at just a few localities.

4.3 Variation between tree species in growth responses to earthquakes

A total of twelve tree species were sampled during this study, providing an opportunity to investigate the relative sensitivity of species to recording earthquake impacts through growth changes. The species sampled comprise four angiosperms/hardwoods (red beech, silver beech, mountain beech and kamahi) and eight conifers/softwoods (pink pine, mountain cedar, rimu, miro, kahikatea, totara, matai and mountain toatoa). All but four of these species (kamahi, totara, matai and mountain toatoa) have sufficient individuals sampled to make meaningful comparisons between species.

There are clear differences in the effectiveness of species in recording earthquakes, as measured by differences in the proportion of trees showing growth changes following each earthquake event at the two study sites. These are summarised in Table 11.

For the angiosperms, silver beech has a consistently high proportion of trees showing a growth change – over 50% in all cases. Mountain beech also shows consistently high levels that are very similar to silver beech. In comparison, red beech is consistently lower than the other two beech species, although at least a quarter of trees still record a growth change in all cases.

For the conifers, mountain cedar has a consistently high proportion of trees showing a growth change – at least a third of trees and up to three quarters of trees. These levels are similar to silver and mountain beech, except for the Matiri site. In contrast, pink pine and rimu show consistently significantly lower proportions of affected trees. Kahikatea and miro appear to have the ability to record impacts in a high proportion of trees, but lack consistency.

Table 11. The proportion of trees of eight species showing a moderate growth change in the 10 years following the 1968 and 1929 earthquakes. A moderate growth change is defined as a >100% increase or decrease in mean ring width between consecutive 5 year means. Numbers in brackets are sample sizes (i.e. number of individuals at the site that were alive at the time of the earthquake). Data are shown only for species for which there are more than 5 sampled individuals at a site. No data are shown for the 1968 earthquake at Matiri, because the earthquake impacts were relatively insignificant at this site. Landscape distribution gives the proportion of landforms in each study site where the species was found growing.

	% trees showing a growth change, by species							
	Silver Beech	Red Beech	Mtn Beech	Mtn Cedar	Pink Pine	Rimu	Kahik-atea	Miro
PENSINI SITE								
1929 earthquake	69	40	46	65	27	28	17	65
	(89)	(60)	(13)	(31)	(30)	(50)	(18)	(20)
1968 earthquake	51	25	60	74	13	17	60	29
	(99)	(108)	(15)	(31)	(31)	(52)	(20)	(21)
Landscape distribution	11/15	10/15	2/15	2/15	3/15	9/15	4/15	5/15
MATIRI SITE								
1929 earthquake	66	36	68	35	0	-	0	-
	(119)	(36)	(19)	(17)	(3)		(2)	
Landscape distribution	7/7	4/7	3/7	2/7	1/7	0/7	1/7	0/7

The four other species sampled (mountain toatoa (1 tree), totara (5 trees), matai (1 tree) and kamahi (2 trees)) also all recorded at least one growth change coinciding with an earthquake event, which suggests that these species are also capable of recording such changes.

Based on this analysis, while virtually all species have the potential to record growth changes resulting from earthquake impacts, some species record the impacts far more frequently and consistently than others, and in this sense can be considered to be 'sensitive' to earthquake impacts. The most promising species in this respect are silver beech and mountain beech – these recorded proportions of trees of about 50% or more in all cases. Mountain cedar is also promising, with generally high to moderate proportions of growth changes. Red beech shows consistently moderate proportions of growth changes, and although not approaching the levels of the other two beeches or cedar it is a valuable species for identifying earthquakes. Both kahikatea and miro show impacts clearly on some occasions, but their lack of consistency makes them less desirable species. Pink pine and rimu are overall the poorest species at recording impacts.

Similar conclusions are reached by considering the frequency of 'extremely severe and long-lasting growth changes' for different species (Table 12). Silver beech had the highest proportion of trees showing these severe growth changes, followed by mountain beech. Mountain cedar showed high levels also. Rimu and miro had significant proportions too, which was surprising - however, virtually all the rimu with changes were from one severely-affected locality (Tilted Rimu patch). Red beech had a very low proportion of affected trees, consistent with the previous findings suggesting a lower sensitivity.

The fact that some species were not found growing on the most 'sensitive' landforms (e.g. swamps and scarps) is unlikely to have biased these results significantly. As an example, consider red and silver beech. Red beech was not found in either of the swamps at Pensini nor on the pakihi, three of the most 'sensitive' landforms in the study site. However, on landforms where the two species were both present, silver beech recorded far greater proportions of impacted trees than red beech in almost all cases (Table 13). There were just two exceptions to this, both on ridges (Coal Flat ridge, 1968 event, and Matiri ridge, 1929 event). Other than these, proportions of silver beech with growth changes were more often than not at least double those of red beech. Furthermore, on the most 'sensitive' landforms, proportions of silver beech impacted were not dissimilar to those on the other landforms where red beech was also present (consistently between about 65 and 80%).

Table 12. Proportions of key tree species showing extremely severe and long-lasting growth changes. Data are for both study sites combined. Numbers in brackets give total sample size for each species.

Species	% trees showing growth change
Silver beech	18 (245)
Red beech	1 (161)
Mountain beech	14 (36)
Mountain cedar	10 (50)
Miro	8 (23)
Rimu	12 (50)
Kahikatea	0 (24)
Pink pine	3 (37)

In addition to relative sensitivity to earthquake impacts another important aspect of any desirable tree species is a wide distribution across the landscape. In both sites, silver beech is the most widely distributed species, followed by red beech and rimu (Table 11). Silver beech was found abundantly from the valley floors to the subalpine timberlines, and on well drained sites through to very wet infertile bogs. This contrasts with most other species, including red beech (tends to favour more fertile sites at low to moderate elevations) and rimu (usually more scattered individuals, and absent where beech is prolific). Other species also tend to be more localised in their habitat, often only appearing at higher elevations or in specialised conditions such as swamps (mountain beech, cedar, kahikatea) or older stable surfaces (e.g. miro). These generalisations apply throughout much of New Zealand, with the main exception of the beech gap in central Westland, and we conclude that (rather fortuitously) the best recorder of earthquake related tree ring impacts is also one of New Zealand's most widely distributed tree species.

Table 13. A comparison of the proportions of red and silver beech showing 'moderate' growth changes in the ten years following the 1968 and 1929 earthquakes, for landforms on which both species were present.

Landform	Proportion of trees with a growth change			
	1929 event (%)		1968 event (%)	
	S. beech	R. beech	S. beech	R. beech
Matiri Site				
Ridge	38	63	N/A	N/A
Terrace	65	29		
Matiri Hill	54	11		
Fan	80	41		
Pensini Site				
Orikaka Hill	88	20	55	17
Pensini Hill	63	38	63	0
Coal Flat Slope	55	25	67	25
Coal Flat Ridge	82	50	27	38
Mt Lyell Ridge	62	25	44	0
Fissure Zone	100	45	40	30
Pensini Fan	100	50	51	16

A further aspect of any species suitability as a potential earthquake recorder is the actual characteristics of the tree rings including their clarity and consistency as annual indicators. Many species in New Zealand are known to have the potential for relatively high frequencies of missing and/or false rings, and for poor circuit uniformity (i.e. poor consistency between growth patterns on different radii of the tree) due to wedging and lobate growth. These problems can be minimised by using species with relatively reliable annual growth and circuit uniformity, and species that can be routinely crossmatched in most cases. Silver beech, mountain beech, mountain cedar and pink pine all fulfil these criteria, and crossdated chronologies have been produced from sites throughout the country (Norton 1983a & b; Xiong & Palmer 1996; Vittoz et al. 2001; Fenwick 2004). However the other species are generally impossible or very difficult to crossmatch and are known to have problems with lobate growth and missing/false rings to varying degrees. Chronologies have yet to be successfully developed from these species, despite attempts. Therefore their reliability will be lower, and errors will increase the further back in time that tree ring records are extended.

In conclusion, silver beech consistently stands out as the most promising species overall, showing both high sensitivity to earthquake impacts, a wide distribution across the landscape, and good tree-ring characteristics including the ability to crossmatch if desired. Other beech species also show these qualities to varying degrees, as does mountain cedar. Other conifers and angiosperms have more potential difficulties associated with them, but still have the ability to record earthquake impacts albeit with reduced reliability and sensitivity.

4.4 Growth changes in relation to MM intensity/isoseismals

The sites sampled in this study span isoseismals ranging from MM7 to MM10, providing an opportunity to investigate whether tree growth patterns vary in a systematic fashion with earthquake shaking intensity. Table 14 summarises the variation in tree growth changes found across the isoseismals within the study sites.

The first point to note is that for MM10 shaking, earthquake impacts are clearly recorded for both earthquake events. This includes 'moderate' growth changes as well as extremely severe and long lasting growth changes. Impacts on tree growth are also found over a wide range of landforms in the sites, and this is particularly true for the 1929 earthquake where virtually all landforms record the event. The fact that the 1929 earthquake is recorded more widely and dramatically in the MM10 areas than the 1968 earthquake probably reflects the fact that the 1929 earthquake was a more severe event (see previous discussion). This is also clearly identified in records of trees showing 'extreme changes' – both earthquakes are clearly recorded at Pensini (MM8-10), but the 1968 event (MM7) is not recorded at Matiri.

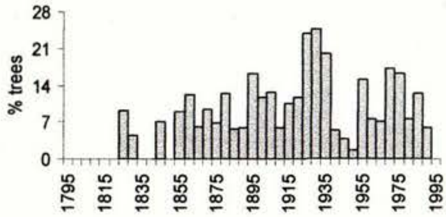
The second point to note is that as MM intensity lessens, so does the magnitude of impacts and the extent of impacts across landforms. This is particularly striking for extremely severe and long lasting growth changes – these are very abundant for MM10 shaking, and steadily become less abundant for MM9, 8 and 7 shaking. Nevertheless, the impacts are still significant enough for the 1929 earthquake to be recorded as a major event for intensities of 8 and 9, both for combined sites and for many individual sites. However, impacts from the MM7 intensity for the 1968 earthquake were not sufficient to be recorded above background levels of disturbance across the landscape, with the only evidence for the event coming from suppressions at two sites.

It is also interesting to note the changes in the nature of the type of dominant growth change with MM intensity as discussed in section 1 (i.e. the relative proportions of releases verse suppressions). Although there is insufficient replication in this study to determine whether this is due to MM intensity or a combination of other factors, this possibility should be kept in mind for future studies.

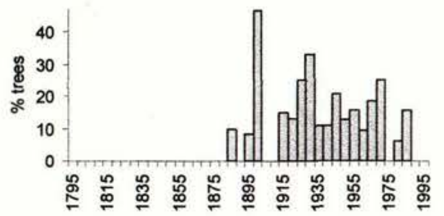
Figure 10. 'Moderate' growth changes (combined releases and suppressions) on stable landforms that experienced different shaking intensities in the 1929 and 1968 earthquakes. The x axis on all graphs is age class in years AD.

A. Steep side slopes, 1929 earthquake

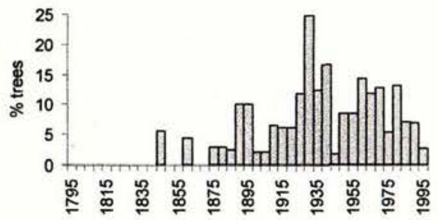
i. MM10 (Matiri & Plateau Hills)



ii. MM9 (Pensini Hill)

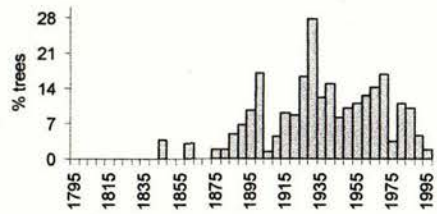


iii. MM8 (Orikaka & WhiteCliffs Hills)

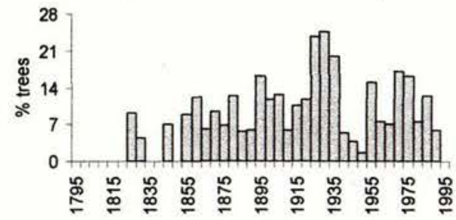


B. Steep side slopes, 1968 earthquake

i. MM10 (WhiteCliffs, Orikaka & Pensini Hills)

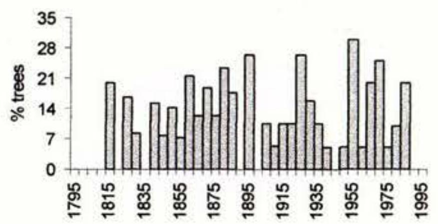


ii. MM7 (Matiri & Plateau Hills)



C. Terraces, both earthquakes

i. Orikaka (1929 = MM8; 1968 = MM10)



ii. Matiri (1929 = MM10; 1968 = MM7)

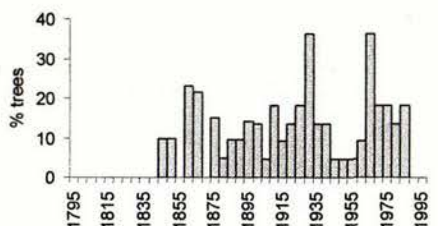


Table 14. Descriptions of growth changes for sites within isoseismal bands for the 1929 and 1968 earthquakes.

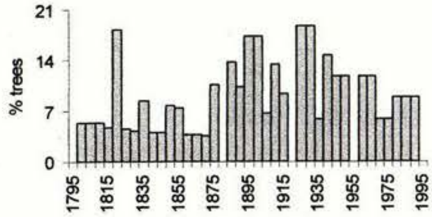
Earthquake	Intensity	Tree growth responses
1929	MM10 – Matiri	Major event of last 200 years Releases very dominant Impacts clear on almost all landforms 21 extremely severe and long lasting growth changes
	MM9 - Pensini	One of two major events in the last 200 years Releases and suppressions present Impacts clear on some landforms but not on others 12 extremely severe and long lasting growth changes
	MM8 - Pensini	One of two major events in the last 200 years Releases and suppressions present Impacts clear on a few landforms, and unclear on others 4 extremely severe and long lasting growth changes
	MM7 - N/A	
1968	MM10 - Pensini	One of two major events in the last 200 years Releases and suppressions, suppressions dominant Impacts clear on many landforms 17 extremely severe and long lasting growth changes
	MM9 - N/A	
	MM8 - N/A	
	MM7 - Matiri	Not recorded as a major event, but is present Suppressions very dominant Impacts clear on two landforms only 1 extremely severe and long lasting growth change

Although the tree-ring record clearly gives a good indication of shaking intensities of MM8 and above, it is not possible to consistently distinguish actual shaking intensities from 'moderate' growth changes. Shaking intensities of 8, 9 and 10 can all result in similar patterns of 'moderate' growth changes (in terms of nature and magnitude), and variability in growth changes shows no clear pattern with shaking intensity between sites. This is illustrated by patterns of growth changes on landforms that experienced shaking at a range of intensities (Figure 10). On steep side slopes, there is a general trend of decreasing growth impacts with decreasing MM intensity for the 1929 earthquake – percentages of trees with a growth change in the 10 years after the event drop from about 70% to about 55% and finally to about 35% (Figure 10a). However, on virtually all other landforms and for both earthquakes there is no such pattern, and proportions of growth changes with MM intensity are variable and inconsistent (Figure 10b-e). There is a general trend for greater MM intensities to result in slightly greater proportions of impacted trees, but this relationship is too weak to be of any practical use and there appear to be many exceptions. For example, impacts on ridges following the 1929 earthquake were about the same for MM10 and MM8 intensities, but were lower for MM9 intensity.

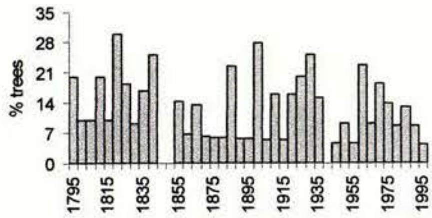
Extremely severe and long lasting growth changes show more potential to distinguish shaking intensities. MM10 shaking is consistently characterised by the highest frequencies of growth changes at a landscape level, with systematic reductions as MM intensity drops to 7. Nevertheless, this pattern still does not hold true at all individual localities. For example the Pensini Fan recorded 5 trees with extremely severe and long lasting growth changes following the MM9 1929 earthquake, but just 2 for the MM10 1968 earthquake.

D. Ridges, 1929 earthquake

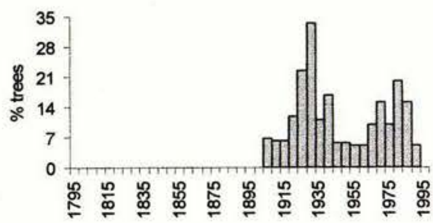
i. MM10 (Matiri Ridge)



ii. MM9 (Mt Lyell Ridge)

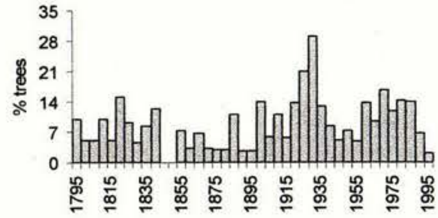


iii. MM8 (Coal Flat Ridge)

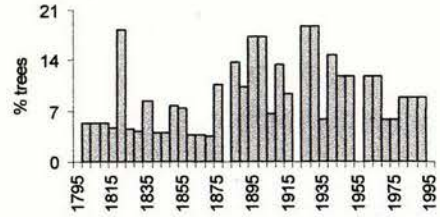


E. Ridges, 1968 earthquake

i. MM10 (Coal Flat & Mt Lyell Ridges)



ii. MM7 (Matiri Ridge)



What we do conclude from this study is that it is theoretically possible to at least map the outer limits of MM8 shaking, on the basis that MM7 does not show up significantly above background levels of normal growth variations. It would then be possible to use the shape of the MM7/8 isoseismal to estimate the approximate epicentral area, and the area of the MM7/8 isoseismal can also be related to the earthquake magnitude. Thus potentially the tree ring analysis method offers a unique insight into prehistoric earthquake events within the lifespan of most forest tree species (the last c. 800 years).

4.5 Sampling strategies that are likely to best record tree ring earthquake impacts

The results of this study indicate several important considerations in undertaking forest sampling so as to best allow recognition of earthquake events from tree growth changes. Firstly, both 'moderate' and 'severe' criteria for defining growth changes are of value, and the combination of these criteria is likely to give the most information on disturbance history. Moderate criteria give the best general overview of disturbance events, while severe criteria allow major earthquake events to be more conclusively identified and distinguished from climatic events. Secondly, sampling should be undertaken over a wide range of landforms that includes those most sensitive to shaking alone (e.g. swamps and steep hills) as well as those prone to debris movement (e.g. rockfall margins and fans). This wide coverage best ensures all large regional events are detected, as well as assisting in differentiating earthquake events from climatic events. Thirdly, tree species with the greatest sensitivity at recording earthquake impacts and with reliable annual ring formation should be preferentially sampled wherever possible. The most promising species in this respect are silver beech, mountain beech, mountain cedar and red beech.

It should also be kept in mind that earthquake events can still be distinguished from tree ring analysis using less desirable tree species on the least sensitive landform positions. The key is to make the best use of whatever is available within the landscape.

4.6 Possible evidence of the c. 1717 AD and c. 1620-30 AD Alpine fault earthquakes

The most recent two earthquakes along the Alpine fault most probably produced significant shaking in the Pensini and Matiri sites, and it is possible that these events are recorded in growth changes. Modelling of these earthquake events suggests that shaking intensities for the c. 1717 event were around MM6 at both sites, and for the c. 1625 event MM7-8 (Yetton 1998; 2002). Based on the results from this present study, we could therefore expect to find a record of the c. 1625 event in growth releases and suppressions, and probably little hint of the c. 1717 event.

Just 20 trees at Pensini were old enough to allow investigation of the 16th century event. Nevertheless, the period around 1616-1620 does stand out clearly as a period of major growth change (Figure 3i). As already stated, this period has the third highest frequency of growth changes over the last 450 years, and is the only other period that stands out clearly along with growth changes following the 1929 and 1968 earthquake events. Releases and suppressions are present at this time, but suppressions are very dominant. These results are all consistent with the impacts expected from an earthquake with shaking intensities of around MM8, based on the impacts following MM7-9 shaking for the 1968 earthquake. Although there are also many releases recorded around 1635 at Pensini no suppressions were recorded at this time, and this period does not show unusually high growth changes in the combined analysis.

At Pensini, growth changes around 1717 AD do stand out slightly above the normal background levels in the 60 trees that were old enough (Figure 3i). As already mentioned, 1710-1720 is one of just four periods over the last 450 years that has growth changes above background levels. Also, the majority of these changes are growth suppressions. Thus 1717 can be identified as a period of moderately high growth changes, although not to the extent that would suggest a severe disturbance event was experienced at the site. These results are all consistent with the impacts expected from an earthquake with shaking intensities of around MM6, based on the impacts following MM7 shaking for the 1968 earthquake.

The trends around 1717 are similar at Matiri, with suppressions once again being particularly prominent around 1720 and this period also showing slightly higher than normal combined levels of growth changes (Figure 3ii). Unfortunately too few sampled trees extended back to the early 16th century to allow investigation of patterns for the earlier Alpine fault earthquake.

None of the 'extremely severe and long-lasting growth changes' identified in this study dated from times coinciding with the last two Alpine fault earthquakes. While this may at first appear surprising, especially for the more severe 16th century event, it is not unexpected given that older trees were not the focus of this study and our sampling did not attempt to gain a representative or systematic sample of old trees (which are more time consuming both to bore and analyse). Consequently on landforms with many younger trees, we deliberately tended to avoid sampling the older trees, and as a result many of the older trees are from the more stable landforms that were relatively less affected by the historical earthquakes and presumably also by the earlier earthquakes. In addition the majority of the old trees sampled were from species with low sensitivity to recording earthquakes – i.e. rimu and pink pine.

5 DISCUSSION

This study shows that there is great potential for using tree rings to investigate prehistoric earthquakes over the last c. 800 years in forested regions of New Zealand. Although generalised analyses of moderate growth changes may not always clearly record earthquakes over and above other disturbances, focussing on the subset of trees that show extremely severe and long-lasting growth changes is likely to clearly reveal the occurrence and timing of severe earthquake events. Both the 1929 and 1968 earthquakes resulted in dramatic periods of severe growth changes, and these periods began in the year immediately after the earthquakes (i.e. 1930 and 1969) and peaked in the following five years. Thus, these severe impacts provide a strong method for identifying and dating prehistoric earthquake events in forested regions.

Furthermore, strong earthquake shaking was easily distinguished from moderate and weak shaking in this study. Specifically, widespread growth impacts were evident when shaking intensity was MM8 or greater, but with shaking intensity of MM7 growth impacts were barely distinguishable above background levels. It was not possible to differentiate amongst strong shaking intensities (i.e. MM8-10) based on the tree-ring responses to the earthquakes. Nevertheless, it is useful to be able to identify areas where earthquake shaking intensity is MM8 or greater, because this is the magnitude at which implications for human wellbeing and infrastructure, as well as for landscape and ecosystem processes, are likely to become critical.

The variability in the nature of tree-ring growth changes following the earthquakes in this study indicates the complexity of factors leading to tree growth responses to disturbances. This variability has been observed overseas in previous studies. For example, tree-ring responses to earthquakes in the beech forests of the southern Andes have been shown to vary with climatic conditions at the time of the earthquake, and the effects of climate have in turn varied with the landform/substrate on which trees are growing (Kitzberger et al. 1995). Our study concurs with these results, and further highlights the complex nature of tree-ring growth changes following a particular disturbance event. For prehistoric events it may be virtually impossible to untangle the intricate interaction of factors leading to the particular combination of growth responses following the event. While this limits the extent to which tree-ring data can make detailed inferences regarding earthquake intensity and magnitude, it does not detract from the usefulness of the method in identifying and dating major earthquake events and in differentiating areas of strong shaking from areas of more moderate shaking.

In agreement with previous studies, we found nothing in the actual nature of the tree-ring earthquake signal that is unique to earthquakes, other than the greater frequency and duration of releases and suppressions. We could find no evidence of growth responses to earthquakes that were not also found after storm-induced or other disturbance agents. This reinforces that caution is required in attributing growth changes in only one or a few trees to earthquakes. For example, just because a few trees on or near a fault scarp show releases or suppressions does not necessarily mean they are recording an earthquake event, even if they do occur within the radiocarbon error bands for a fault rupture. Rather, it is important to base inferences from tree-ring studies on a thorough dataset that incorporates many trees, the most sensitive species, and the most reliable landforms.

Nevertheless, in this study it was possible to identify the two earthquake events based solely on tree ring impacts, and we were able to distinguish the tree ring effects of earthquakes from those of storms and droughts. The 1929 and 1968 earthquakes were the only times in which many trees showed extremely severe and long-lasting growth changes, and even for moderate releases and suppressions the earthquake events resulted in distinctly higher levels of growth changes than any of the other regional disturbances of the past century. The 1974-78 drought did have an effect on trees, as indicated by higher than normal levels of releases and suppressions around 1978-81 and a few extremely severe and long-lasting growth changes around 1980; however, levels of growth changes were much lower than those following the earthquakes, and did not form obvious peaks in frequency distributions. This is in agreement with the findings of Vittoz et al. (2001) in their study of earthquake impacts on forest structure and composition in the Matiri Valley. Vittoz et al. (2001) also noted that droughts resulted in short-lived and sharp pulses of growth changes, whereas the 1929 earthquake resulted in a protracted period of high levels of growth changes. We found this same distinction in our study, and this may reflect the rapid recovery of drought-stressed trees as soon as adequate rainfall is restored. Furthermore, earthquake impacts were clearly recorded over the full range of landforms sampled, while the storm and drought impacts had a much more limited geographic distribution with obvious impacts on the most vulnerable landforms only.

Unfortunately both the 1929 and 1968 earthquakes were followed by drier than average years, which means that at least some of the effects we attribute to the earthquakes may have in part been emphasised by subsequent drought. But, based on the relatively low levels of growth impacts in our study areas in response to the severe 1974-1978 drought (as described by Hosking & Kershaw 1985), we consider this is most unlikely to have been a significant factor in the patterns we have observed. This is especially so given that most localities sampled showed insignificant growth impacts from this drought.

The clarity and distinctiveness of the earthquake tree-ring record described here suggest that (theoretically at least) tree-ring studies could be used on their own to identify earthquake events in forested regions. However, as with all indirect methods of identifying and dating earthquakes, in general reliance on a single method is undesirable, and could lead to the misinterpretation of earthquake history. In our opinion other collaborating evidence for an earthquake is still required to have complete confidence in the tree-ring signal, even for times with very profound growth changes. It is always possible that climatic or biotic disturbance events could result in periods of abundant extremely severe and long-lasting growth changes.

In this respect, there is great potential to also use forest age structures as a second line of evidence in support of earthquake origins for observed patterns of tree-ring growth changes. Forest disturbance events are recorded by the simultaneous regeneration of even-aged cohorts of trees in areas where trees were killed. At a landscape level, the mosaic of forest age structures thus provides a record of disturbance history. Previous studies have shown that severe earthquakes in mountainous terrain are frequently the dominant forest disturbance agent and result in forest death and regeneration through shaking alone and debris movement (e.g. Allen et al. 1999; Veblen & Ashton 1978; Garwood et al. 1985; Vittoz et al. 2001; Yetton et al. 1998; Wells et al. 2001). Thus, the coincidence of major periods of tree-ring growth changes across many landforms and major periods of forest regeneration following disturbance provides very strong evidence for earthquakes.

We were unable to crossmatch many trees in this study. As a consequence, many of the dates of releases and suppressions may potentially be in error by a few years (due to missing or false rings), and these errors are likely to increase the further back in time the growth change is. This is unlikely to be a serious issue, however, because trees will still record the actual patterns of major growth change accurately – an occasional missing or false ring will have little effect in detecting periods of major release or suppression. Thus, a lack of crossmatching will not affect the recognition of growth changes, but may potentially affect their dating. In this study, even this was not an issue, and the onset of growth changes was clearly dated to the years immediately following the earthquakes in both crossmatched and uncrossmatched trees.

Ideally, all trees would be crossmatched to remove possible errors. However, this is unrealistic for the majority of New Zealand tree species, and may be difficult for almost all species in the typical lowland forest environments that are most useful for earthquake studies. Most studies of forest disturbance history in New Zealand are based on ring counts without crossmatching, and these have reliably reported impacts following historic storms, droughts and earthquakes (e.g. Hosking & Kershaw 1985; Stewart et al. 1991; Runkle et al. 1995; Wells et al. 2001). Crossmatched chronologies in New Zealand have generally been constructed only for the use of detailed climate reconstructions, and these are almost all from high-altitude sites where trees are near their climatic limits and consequently growth is controlled largely by climatic variation. This allows for easy crossmatching. But such sites are generally poorly suited to studies of disturbance history. The best sites for earthquake studies are generally in lowland areas near faults and where trees grow vigorously and respond dramatically to disturbances but only subtly to climate. At such sites crossmatching (which relies on consistent responses to climatic variation) will always be relatively difficult. Consequently, poor success in crossmatching is likely to be a reality for many areas of New Zealand suited to earthquake tree ring studies.

Lack of cross matching should not have a major impact on the usefulness and applicability of earthquake tree-ring studies (as demonstrated by this study). Growth changes are still reliably recorded, and actual dates of events can be obtained with certainly and yearly accuracy by using impacted trees that can be crossmatched. Also, by focussing sampling on sensitive species with good tree-ring characteristics (such as silver beech, mountain cedar and mountain beech), many of these problems will be avoided or minimised.

6 CONCLUSIONS

1. At both of the study sites the earthquakes of 1929 and 1968 resulted in clear, easily distinguishable pulses of impact on tree growth patterns as measured by moderate, relatively short-lived releases (growth accelerations) and suppressions (i.e. >100% changes in growth over 5-year periods). Both growth releases and suppressions were associated with each earthquake as some trees took advantage of new gaps in the canopy and locally increased nutrient levels (from debris) while other trees suffered damage from some combination of earthquake shaking and falling neighbouring trees.

2. The Pensini Creek site provides the oldest tree ring record which extends back to approximately 1585 AD. The 1968 and 1929 earthquakes stand out as the two periods with the greatest levels of growth impact which affected approximately 40% of the trees sampled for at least the 10 years following the earthquakes. Notably the only other period that approaches the unusually high levels associated with the historical earthquakes is the period 1610 – 1620, in which 30% of trees show a growth change. This is the inferred timing for the most recent Alpine Fault earthquake on the north section of the Alpine Fault, and this section of the Alpine Fault is close enough to the Pensini area to have resulted Modified Mercalli Intensities in the range MM 7 – 8.

3. The results suggest that for some trees the earthquake events are effectively life changing experiences. However, because our sampling can only represent currently living trees, our record in this respect is dominated by trees that have abruptly accelerated in growth following the earthquake in response to either better light or nutrients, and have never slowed back to pre-earthquake growth rates. The most severely damaged trees will always tend to die relatively quickly following the earthquake and will not be available for subsequent analysis. Those trees that are moderately damaged generally recover reasonably well, and with time most can regain their former growth rates.

4. Recognition of the importance of severely earthquake impacted trees has led to an improved analysis method to aid the recognition of the earthquake events. Based on a criteria of trees with major impacts defined as greater than 250% changes in growth that last over 25 years, the strong historical earthquakes at both the sites entirely dominate the record.

5. We have sampled tree species over several landform classes to determine the most suitable landform to record earthquake impacts. Although the most profound growth changes are generally apparent amongst particular trees growing on landslide or alluvial fan margins, such sites do not necessarily provide a reliable record. Generally the impacts are related to spatially limited and specific incursions of debris, and such events do not necessarily repeat in exactly the same locations in successive earthquakes. Our results suggest that the sites that record earthquake shaking the most clearly and consistently are swamps and pakihis. Not only are such sites generally removed from debris movement and rockfall, but they have the added advantage of the being the least sensitive to drought effects, and often relatively sheltered from wind damage.

6. Our results show that while virtually all tree species have the potential to record growth changes resulting from earthquake impacts, some species record the impacts much more frequently and consistently than others, and in this sense can be considered "sensitive" to earthquake impacts. The most promising species are silver beech and mountain beech. Silver beech has the added advantage of being one of the most widely distributed indigenous tree

species in New Zealand, and can be found growing in most areas from valley floors to subalpine timberlines, and on well drained sites through to wet infertile bogs.

7. The two study areas included a range in Modified Mercalli shaking intensity from MM 7 to MM10 and thus provide an opportunity to investigate whether tree ring patterns vary in a systematic way with shaking intensity. We conclude that is possible to at least map the outer limits of MM 8 shaking, on the basis that MM 7 does not show up significantly above background levels of normal growth variation. This has important potential in allowing an assessment of the spatial distribution of prehistoric earthquake shaking.

8. We conclude that there is great potential for the application of tree rings to the investigation of earthquake history in New Zealand over the life span of long-lived forest trees (the last c. 800 years). While the clarity and distinctiveness of the earthquake tree-ring record that we describe suggests that, in theory at least, tree ring studies could be used on their own to identify earthquake events, in our opinion other collaborating direct evidence from paleoseismic trenching etc remains a vital component. However, this study provides an important foundation upon which future earthquake tree ring investigations can now be designed and applied.

7 FUTURE WORK

There is great potential for the application of tree rings to investigate earthquake histories in New Zealand over the lifespan of long-lived forest trees (the last c. 800 years). We see potential application of this approach to enhance paleoseismic investigations throughout much of New Zealand. In particular, we see immediate application to determining the limits of strong shaking and/or rupturing for the most recent three Alpine fault earthquake events (in c. 1460, 1620 and 1717), and in determining the prehistoric rupture history of the Wellington fault using forests in the Rimutaka Ranges.

Clarification of the role of an earthquake's timing in the tree's growing cycle in determining the nature of tree-ring growth responses would be beneficial. This could be achieved by examining the growth responses of trees to historical earthquakes that occurred at different times of the spring-summer period. Obvious examples include the 10 February 1990 Lake Tennyson earthquake and the 10 August 2003 Fiordland earthquake. These recent earthquakes (and particularly the Fiordland event) also offer the opportunity to observe and describe patterns of damage and resulting tree-ring responses based on trees still standing (both dead and alive). An additional advantage of the Fiordland area is its proximity to the southern Alpine fault, and the potential to obtain further background information on trees which may be of value to Alpine fault studies.

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APPENDIX ONE.

Scientific Names of Tree Species Referred to in This Study

Common Name	Scientific Name
Silver Beech	*Nothofagus menziesii*
Red Beech	*Nothofagus fusca*
Mountain Beech	*Nothofagus solandri*
Kamahi	*Weinmannia racemosa*
Mountain Cedar	*Libocedrus bidwillii*
Pink Pine	*Halocarpus biformis*
Rimu	*Dacrydium cupressinum*
Miro	*Prumnopitys ferruginea*
Kahikatea	*Dacrycarpus dacrydioides*
Totara	*Podocarpus totara*
Mountain Toatoa	*Phyllocladus alpinus*
Matai	*Prumnopitys taxifolia*

APPENDIX TWO

Details of Individual Sampled Localities and Landforms.

(A) PENSINI STUDY SITE

1) Steep Side Slopes

WhiteCliffs Hill -

Steep slope at the north-eastern end of WhiteCliffs just below the escarpment. No evidence of recent debris deposition. A diverse forest that included red and silver beech, rimu, miro, totara, matai and kahikatea. 21 trees sampled.

Orikaka Hill

Steep slope on the north bank of the Orikaka River. No evidence of recent slope failure or significant debris deposition. Forest dominated by red and silver beech and miro, with occasional rimu also. 22 trees sampled.

Pensini Hill

Steep slope on the south bank of Pensini Creek. Forest dominated by red and silver beech, totara and miro. 31 trees sampled.

2) Gentle Side Slopes

Coal Yard Slope

Slopes behind logged area near Coal Flat. Well drained soils. Forest comprised of red beech, silver beech and rimu, with occasional miro. 27 trees sampled.

Tertiary Slope

Gently sloping hill side, substrate Tertiary coal measures. Forest dominated by pink pine and silver beech, with occasional mountain cedar and rimu. 37 trees sampled.

3) Alluvial Terrace

Orikaka Terrace

Terrace of the Orikaka River, true right bank. Forest composed of silver beech and kahikatea, with occasional miro. 20 trees sampled.

4) Ridges

Coal Flat Ridge

Sharp ridge crest at about 420 m altitude above Coal Flat. Some large, old blocks with trees growing on top of them. Near to landslide scars from the 1929 earthquake. Forest composed of red and silver beech. 21 trees sampled.

Mt Lyell Ridge

Broad, gently sloping ridge crest at about 900 m altitude Crack and slumps occasionally present. Forest composed of silver and red beech. 23 trees sampled.

5) Pakihi Swamp

Welshman Pakihi

Very poorly drained old terrace high above the Buller River. Forest composed of mountain beech, pink pine and rimu, and the occasional mountain toatoa and kamahi. 21 trees sampled.

6) Swamps (depressions)

Coal Flat Swamp

Large basin, very poorly drained. Diverse forest dominated by mountain cedar, kahikatea and silver beech, but also with occasional mountain beech. 42 trees sampled.

Frosty Swamp
Small, poorly drained depression. Forest dominated by mountain cedar, pink pine and silver beech, with rimu, kahikatea and totara also present. 35 trees sampled.

7) Alluvial Fan
Pensini Fan
Young, coarse-textured fan at the base of old landslide. Evidence of recent debris deposition, with young trees established on top of debris. Forest dominated by silver and red beech, with occasional miro and kahikatea. 23 trees sampled.

8) Rockfall Margins
Buller View Slide
Landslide deposits from slips off the side of Welshman Pakihi. Steep slopes of up to 55 degrees. Forest composed of red beech and rimu. Trees were sampled on the peripheries of old landslide scars and deposits. 23 trees sampled.

9) Landslide Deformation
Tilted rimu patch
An area of deep tension cracking adjacent to a stream gully on an old landslide. Slope about 15 degrees. Many tilted trees of rimu and red beech, and occasional silver beech. 19 trees sampled.

Fissure zone
An area of ground deformation and fissuring, presumably resulting from earthquake shaking, on an old landslide. Several old, heavily tilted trees and smaller, straight trees. Forest comprised of red beech, silver beech, rimu and kamahi. 37 trees sampled.

10) Old Landslide Toe
Pensini toeslope
Lobe of debris at base old landslide deposit, where it joins with the Pensini Fan. Well-drained, gently sloping. Forest composed of red and silver beech and miro. 8 trees sampled.

(B) MATIRI STUDY SITE
1) Steep Side Slopes
Matiri Hill
Steep slopes above the south bank of Lake Matiri. Gradient > 40°. Forest composed of red and silver beech. 28 trees sampled.

Plateau Hill
Steep slopes at about 900m altitude on the eastern side of Thousand Acre Plateau. Coarse limestone blocks on shallow soils dominate the substrate, but no evidence of debris deposition in the recent past. Forest almost entirely silver beech, but with an occasional mountain beech also. 23 trees sampled.

2) Alluvial Terrace
Matiri Terrace
An old terrace of the Matiri River, situated on the true left bank upstream of Lake Matiri. No evidence of debris deposition in the recent past. Forest dominated by red and silver beech, with occasional kahikatea. 23 trees sampled.

3) Ridge

Matiri Ridge

Stable ridge crest midway between valley floor and the Thousand Acre Plateau. Diverse forest, with a mixture of mountain cedar, totara, and silver, red and mountain beech. 33 trees sampled.

4) Elevated Plateau

Poor Pete's Plateau

Rolling surfaces on the top of Thousand Acre Plateau (c. 1100m altitude). Poorly drained shallow soils over limestone bedrock. Low forest comprising mountain beech, silver beech, pink pine and mountain cedar. 32 trees sampled.

5) Alluvial Fans

Matiri Fan 1

Small fan on the true right of the Matiri River just upstream of Lake Matiri. Sampling undertaken at the distal end where the fan grades into the floodplain of the Matiri River, up to the mid fan. Evidence of debris deposition in the recent past. Forest dominated by silver beech, with red beech also present. 29 trees sampled.

Matiri Fan 2

Position as for Fan 1, but narrower and steeper. Evidence of debris deposition in the recent past. Sampling was concentrated in the mid fan, but extended to the distal end. Forest dominated by red beech, with silver beech also present. 15 trees sampled.

6) Rockfall Margins

Plateau Rockfall

Steep slopes at about 900m altitude on the eastern side of Thousand Acre Plateau, which had been impacted by rockfall activity in the recent past. Coarse blocks and thin soils dominate the substrate, with areas of forest partially destroyed by the most recent rockfalls. Forest entirely silver beech. 38 trees sampled.

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