

DATING OF PAST ALPINE FAULT RUPTURE IN SOUTH WESTLAND

RESEARCH UNDERTAKEN BY:

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Mr Trevor Wright

(Geology Department, Otago University)

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Funded by EQC, PGSF and Otago University

EQC RESEARCH REPORT 99/341

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EXECUTIVE SUMMARY

We present the results of a detailed investigation of the Alpine Fault in the area between the Haast and Okuru Rivers, South Westland. This study builds upon previous investigations in order to develop a better chronology of large earthquakes generated by ruptures on the Alpine Fault. Work during the 1990s has established that the Alpine Fault is a major source of potential seismic hazard and incorporation of data from the fault into seismic hazard maps has greatly changed the perception of earthquake hazard in the South Island. A number of outstanding problems remain in regard to the Alpine Fault, two of which are:

- How does the chronology of fault ruptures compare for different sections of the fault, particularly the northern and southern sections? Is there evidence for the whole fault rupturing in a single magnitude 8 event or may it break in two or more closely spaced smaller events affecting different sections of the fault?
- What is the long-term (i.e. several thousand years) chronology of fault ruptures? Is the behaviour of the fault relatively constant through time and can we use this information to derive better estimates of future probability of ruptures and the accompanying level of hazard?

The project involved four principal avenues of investigation:

- Detailed mapping of the fault trace to determine the nature of the fault at the surface, the number of traces (if more than one), offset features such as channels, river terraces, etc. and amount of offset where determinable, and the location of suitable sites for detailed paleoseismic investigations.
- Excavation of a trench at the Turnbull River, a site identified during the fault mapping, in order to expose the fault and the sediments accumulated on the downthrown side of the fault. From these, it was hoped to identify past rupture events and constrain their age using radiocarbon dating.
- Collection of rounds from stumps of trees along the fault scarp felled during the 1960s and 70s and, using ring-counting techniques, to establish the approximate ages of forest disturbances possibly associated with ground rupture events.
- A further investigation was carried out on a rapidly subsiding swamp situated between two strands of the Alpine Fault on the south bank of the Turnbull River. The intention was to see whether the swamp stratigraphy could be linked to fault displacements and hence be used as a record of ground ruptures in the area.

All four investigations were successfully carried out and a wealth of detailed information obtained. Unfortunately, unforeseen problems with obtaining meaningful radiocarbon ages on some of the trench material and intense weathering of the tree stumps prevented us obtaining the tight age constraints we had hoped for. Nevertheless, the data obtained substantially improved knowledge of rupture history of the fault in the south and opened up further possibilities for addressing the questions raised above.

Results from the four approaches may be summarised as:

• Detailed mapping of the fault trace shows that the fault is essentially a single straight trace between the Haast and Turnbull Rivers. Slight changes in orientation are associated with *en*

echelon traces that overlap each other and are offset from a few to a few tens of metres. Offset channels show displacements that cluster crudely around 8 and 15 m, possibly reflecting the amount of the last, and combined penultimate and last, ruptures respectively. South of the Turnbull River, the surface faulting is more complex with multiple parallel traces in places.

- The site selected for the trench at the Turnbull River was the only suitable site identified. A 22 m long and 2-3 m deep trench was excavated across the fault. There was clear evidence for three fault displacements within the last 1000 years and radiocarbon dating of the lowest horizon placed a maximum age on the earliest event of 1105 ± 85 AD. Unfortunately natural contamination of organic material faulted by the penultimate event resulted in widely variable and inconsistent radiocarbon ages and prevented better age constraints being established. Deposits related to the last event had been highly disturbed during forest clearance and road construction.
- Although over 20 samples of trees (Rimu) were collected and prepared for tree-ring counting, loss of the sapwood on most of these, due to the long period of exposure in an inclement climate, prevented their use in establishing well-constrained times of forest disturbance related to possible fault rupture.
- Detailed investigation of the South Turnbull Swamp established a rapid rate of subsidence over the past 1200 years commensurate with that expected from models of fault controlled subsidence. Inundations of river-derived silt possibly reflect fault ruptures. A major inundation shortly before 1260 ± 55 AD is almost certainly due to fault displacement. Three others since then may relate to earthquakes but it is possible to generate additional bands through other processes. Nevertheless, swamps such as this potentially contain valuable long records of sedimentation related to fault displacement.

By reviewing our new data in conjunction with existing data, we can conclude:

- Three major ground rupturing events have occurred on the Alpine Fault in South Westland over the last 1000 years. All three had dextral offsets of approximately 8 metres. The first occurred between 1105 and 1220 AD and may correlate with a similar event in central and north Westland. The second occurred between 1400 and 1600 AD, but it's correlation with northern events, if any, is not established. The last event occurred after 1665 AD and before 1826 AD and may correlate with a fault-wide rupture at 1717 AD.
- An earlier event occurred around 880 ± 110 AD and may correlate with a widespread event to the north at around 900 AD.
- A major earthquake recorded by sailors in 1826 appears to have no direct fault break in the present area. The break may have extended onto land or was confined to offshore segments of the fault. The best approach for dating this and the post 1665 AD event may be dendrochronological studies on silver beech trees along the fault scarp.

The Alpine Fault is a major potential seismic hazard throughout the South Island. Although this work has advanced our knowledge of the fault history, the questions raised at the start still require further research.

TECHNICAL ABSTRACT

Investigation of the Alpine Fault south of Haast was undertaken to extend and improve the prehistoric record of ground rupture events. Detailed mapping of the fault trace between the Haast and Arawhata Rivers was completed (partly funded by PGSF). Excavation of a trench across the trace at the Turnbull River was undertaken to expose the fault and the related sediments in order to identify rupture events and constrain their timing by radiocarbon dating. A collection was made of rounds from stumps of podocarps from along the fault trace which were felled during the 1960s and 70s. It was hoped that ring-counting of these would enable periods of growth suppression to be identified and dated. Finally, a small deep swamp situated in a rapidly subsiding pull-apart between two strands of the fault was investigated to evaluate its use as a record of fault displacement.

The fault has a relatively straight and single trace from the Haast to Turnbull Rivers but multiple traces occur to the south. Horizontal offsets of features are consistent with an average slip of c. 8 m for each of the last two events. The trench provides evidence for three ground ruptures in the last 1000 years. The first is constrained between 1105 ± 85 AD and 1220 ± 50 AD. This is also supported by an event shortly before 1260 ± 55 AD recorded in the South Turnbull Swamp. The swamp also provides evidence for an earlier event at c. 880 ± 110 AD. The penultimate event is bracketed between 1400 and 1600 AD and the last event occurred after 1665 AD. Most of these ages may be correlated with ground ruptures recorded from the northern section of the Alpine Fault although the age constraints are insufficiently precise to conclude that they represent single breaks. An earthquake recorded by sailors in 1826 off the Fiordland coast does not appear to have broken the fault in the present area and appears to be of lower magnitude than the last rupture recognised in this study. Unknown natural contamination of radiocarbon samples from one horizon in the trench prevented better age constraints being obtained on the penultimate earthquake. Excessive degradation of the collected tree rounds since felling prevented determination of useful tree-ring ages.

The Alpine Fault in the south appears to have broken on average every 250–300 years. This is consistent with a slip rate of 27 mm/yr and an average slip per event of 8 m. Comparison with the rupture chronology established on more northern sections of the Alpine Fault strongly suggests that the fault breaks along its whole length at these times. Whether this occurs in a single M 8 event or whether by two or more smaller events over a short time period cannot be determined within the time constraints available. Nevertheless, the northern and southern records differ in the number of events recognised suggesting that, at least on occasions, the two fault sections behave independently.

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- Appendix 2: Turnbull Trench log and photo-mosaic.
- Appendix 3: South Turnbull Swamp stratigraphy.

1 INTRODUCTION

1.1 Background

The earliest work on active deformation of the Alpine Fault was carried out by Harold Wellman over 50 years ago (e.g. Wellman, 1955). This work clearly identified the Alpine Fault as a major active structure and produced estimates of the rate of slip. The lack of evidence for fault creep indicated that large earthquakes accompanying ground rupture were likely along the fault. A small amount of intermittent work followed (e.g. Suggate, 1963) but little on the fault as a seismic hazard. The development of the theory of plate tectonics resulted in the recognition of the Alpine Fault as a major component of the Australian/Pacific plate boundary (e.g. Le Pichon, 1968). The lack of major earthquakes on the fault during the period of instrumental records produced a gap in seismicity along this part of the plate boundary in the central South Island. The use of seismicity data for estimates of probabilistic seismic hazard (e.g. Smith & Berryman, 1986) leads to low values of hazard in the central South Island.

Resurgence of interest in the Alpine Fault was sparked by the publication in 1979 of Royal Society of New Zealand Bulletin 18 "Origin of the Southern Alps" edited by R. I. Walcott and M. M. Cresswell. This followed a highly successful workshop which drew together the majority of New Zealand researchers with an interest in current tectonics. Detailed fieldwork on the Alpine Fault during the 1980s and 90s (e.g. Hull & Berryman, 1986; Cooper & Norris, 1990; Norris et al., 1990; Berryman et al., 1992; Cooper & Norris, 1994; Sutherland & Norris, 1995) began to establish the structure of the fault zone and produce evidence for high slip rates on the fault of between 20 and 30 mm/yr. Geodetic measurements (Walcott, 1978) also demonstrated high rates of current surface strain accumulation in the vicinity of the fault. The lack of historical seismicity coupled with the high rates of slip on the fault, high rates of strain accumulation, and lack of evidence for fault creep, lead logically to the conclusion that strain must be released in large fault rupture events at infrequent intervals of at least 100 years or more.

With no historical earthquake record for the Alpine Fault, paleoseismology is the only approach that can yield directly a chronology of fault rupture events. The first to attempt to date large prehistoric earthquakes on the fault was Adams (1980) who argued that major aggradation upstream of the fault would occur following an earthquake and used clustering of ages from aggradation surfaces to suggest past events at approximately 500 year intervals. Wardle (1980) pointed out that large areas of West Coast forest had been established at about the same time in the early 18th Century and argued that this followed widespread forest destruction during a major Alpine Fault earthquake at this time. Cooper & Norris (1990) used ages from small sagponds along the fault trace at Milford and estimates of age of tree damage along the fault scarp to suggest that the last major ground rupture occurred between 1650 and 1720 AD. This conclusion was supported by the work of Sutherland & Norris (1995) at L. McKerrow who also confirmed the suggestion of Hull & Berryman (1986) that the last two events here were both of about 8 m horizontal displacement.



Fig. 1.1 Map of South Island showing Alpine Fault, some localities referred to and area of current investigation.

During the mid 1990s, two major projects were initiated on the paleoseismology of the Alpine Fault. Mark Yetton, funded by EQC, undertook trenching and other investigations north of Hokitika (Yetton et al., 1998) while our group (Wright, 1998; Wright et al., 1997, and in preparation; Berryman et al., 1998), funded by PGSF, carried out detailed investigations including trenching at Waitaha River and at Haast and Okuru (Fig. 1.1). A fruitful collaboration between Mark Yetton and Andrew Wells, a forest ecologist from Lincoln, led to the realisation that periods of extensive forest disturbance and re-

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establishment in Westland corresponded to suggested times of ground rupture on the Alpine Fault (as foreshadowed by Wardle, 1980). Tree-ring counting enabled these times to be established much more precisely than could be done using radiocarbon dating alone (Wells et al, 1999). Craig Wright (Wright, 1998), as part of his MSc thesis, studied the fault in detail at a location in the Waitaha Valley where a series of sag-ponds and blocked swamps enabled a chronology of events at a single site to be established. He also used tree-ring counting on recently felled Rimu and Matai trees along the fault trace to determine times of major trauma effecting these trees. A combined Otago University/IGNS team excavated four trenches across the fault trace at the Haast and Okuru rivers (Berryman et al., 1998) and were able to identify three ground ruptures in the last 1000 years, each with c. 8m horizontal displacement. Independently, Bill Bull (Bull, 1996) was using lichen growth rates to determine the ages of rock falls east of the Main Divide. He argued that regional rockfall events may be related to major earthquakes along the Alpine Fault.

By 1998, a substantial body of evidence had been accumulated to support the claim that the Alpine Fault ruptures in infrequent but very large earthquakes every 2-300 years. A meeting of interested parties in Lower Hutt in 1998 drew up a provisional chronology of ground ruptures on the Alpine Fault for the past 1000 years (Fig. 1.2). The data suggest that the seismic history of the northern part of the fault may differ from the southern. A question arises as to whether any of the events recognised broke the whole length of the fault (some 350-400 km, resulting in a c. M8 event) at one go or whether the data actually represent clusters of smaller events fairly closely spaced in time. The whole question of the behaviour of different parts of the fault is critical to assessing its potential hazard.

Another aspect needing attention is the length of paleoseismic record. One thousand years and three events is not a long chronology on which to base assessments of rupture probability. It is difficult to obtain a good chronology of earlier events, in part because evidence is less likely to be preserved and partly because radiocarbon dating uncertainties make correlation of events problematical. Nevertheless, collection of sufficient data from a number of localities may allow a pattern to emerge that would enable a much longer chronology of Alpine Fault events to be developed.

SUMMARY OF CONCLUSIONS ON PAST EVENTS AND RATES ON ALPINE FAULT

(Based on discussions at workshop on the paleo-seismology of the Alpine Fault held at IGNS , Gracefield, 1998).

PAST MAJOR RUPTURES



Fig. 1.2 Summary of rupture chronology for the Alpine Fault over the last 1000 years as established at the Alpine fault Workshop held at IGNS Gracefield, Lower Hutt, in 1998. Data are mainly from work of Berryman, Bull, Cooper, Norris, Wells, Wright, Yetton)

1.2 Project objectives

The original aims of this project were to improve the chronology of fault ruptures in South Westland by

(i) excavating another trench across the fault trace south of Haast River with the hope of obtaining a rupture chronology with better radiocarbon age constraints, particularly on the penultimate event;

(ii) examining rounds cut from trees along the fault felled during the 1960s and 70s with the aim of using a ring-counting approach to identify times of widespread growth attenuation possibly related to ground rupturing, particularly associated with the last event. This followed a similar successful approach at the Waitaha River locality (Wright, 1998) A grant from the EQC Research Foundation supported an MSc student (Trevor Wright; note that he is no relation of Craig Wright, an MSc student who worked at the Waitaha River – see above) to carry out a study of the fault south of Haast River and participate in trenching and tree-ring studies. This report is partly based on his thesis (Wright, 2000, which at time of writing, is still undergoing examination) although with considerable rewriting and editing in order to fulfil the needs of the EQC.

The authors are also involved in a PGSF-funded programme to produce a map of the fault and some of the work reported in here (particularly Chapter 2) is funded under that programme. The participation of Norris and Cooper is also partly funded from this source.

The objectives were carried out successfully in terms of obtaining the field data and materials. Unfortunately, as detailed later, unforeseen problems occurred both with radiocarbon dating and with the tree rounds. As a result, the improvement obtained in detailed rupture chronology was less than hoped for. Such is the nature of research! Nevertheless, further support for the existing chronology was obtained and some extra time constraints were able to be placed on events.

A detailed study was made of a swamp situated in a pull-apart zone between two fault strands south of the Turnbull River. This was discovered during fault mapping and the investigation concentrated on establishing a model for the swamp evolution linked to fault displacement. Such sediment repositories (over 7 m of sediment in the swamp) adjacent to active faults have the potential to record long histories of fault movement. The difficulty is that the earthquake signal is indirect and hence may contain noise and ambiguities. The study reported here aims to evaluate the possible use of such sediment records for paleoseismic purposes.

1.3 Location and logistics

The area under investigation is the section of the Alpine Fault between Haast and Arawhata Rivers in South Westland (Fig. 1.1 and Appendix 1). The main area of detailed study was from the Okuru River to a few kilometres south of the Turnbull River (Appendix 1). The area is bounded on the west by the Jackson Bay Highway. Private gravel roads extend up either bank of the Turnbull River with a branch over to the Okuru River. Most of the area is covered in thick bush except for areas of cleared pasture along the river banks and large areas of impenetrable swamp between the Okuru and Haast Rivers. Rainfall is high and fieldwork is often disrupted by the weather. Excavation of trenches invariably penetrates the water table so that an efficient pumping system is required to prevent the trench from becoming a swimming pool!

Accommodation in the field was provided by the Haast Beach Holiday Park (Motor Camp) at Okuru. Travel in the field area was by vehicle along roads and by foot elsewhere. Field locations were established from published maps and air photographs using standard techniques. Attempts to use GPS methods were unsuccessful due to the bush cover and the height of the Southern Alps blocking sight lines to low elevation satellites to the east. Subsurface investigation was carried out using a Russian D-Corer, capable of penetrating soft mud and peat to about 6 m and retrieving a half core of

CHAPTER ONE: INTRODUCTION

material, and a soil auger able to penetrate and sample coarser material to 7 m. Radiocarbon dating was carried out on a commercial basis by the Radiocarbon Laboratory at the University of Waikato for specimens large enough for standard counting techniques, and at the Rafter Laboratory at IGNS by Accelerator Mass Spectrometry when only small amounts of material were available. A total of twelve radiocarbon ages were obtained from material collected.

CHAPTER TWO: STRUCTURE OF THE ALPINE FAULT

2 STRUCTURE OF THE ALPINE FAULT

2.1 Introduction

The Alpine Fault trace can be divided into three sections between Haast River and Arawhata River (Fig. 2.1). Section 1, from Haast River to Turnbull River was mapped in detail. In section two, the lengths between South Turnbull Swamp and Debris Creek and between Drizzle Creek and Macpherson Gully, were mapped in detail. The remainder of section two and all of section three are based on aerial photograph interpretation (SN C5386 D6-D22, E1-E8 and 3976/7 – 3976/9).

From Haast River to Arawhata River, a fault trace overlay was produced using aerial photographs. The overlay was then assigned topographic co-ordinates using Mapinfo, a GIS system, and incorporated into a 1:25000 scale map (see appendix 1). The registration of topographic maps to ground features in the Mapinfo package has an accuracy of better than 50 m. An estimated error of up to 100 m may occur when relating the fault trace to topographic features. The fault trace as mapped could therefore have a cumulative positional error of up to 150m, although generally it will be much less than this.

2.2 Methods

Five types of measurements were made along the fault trace. These include scarp orientation, scarp height, stream offsets, lengths of individual fault trace segments and east or west offsets between segments. Ground mapping of the fault trace in the bush was carried out on foot using tape and compass. Having no landmarks with which to accurately verify locations made this procedure necessary. GPS measurements to give exact locations were attempted over a number of days but proved unsuccessful due to a dense forest canopy and the height of the adjacent Southern Alps restricting the sky spectrum for receiving satellite signals. Calibration of tape and compass distance measurements have been made by comparison with known points on the map.

Many problems were encountered while undertaking this work, leading to lengthy delays. By far the greatest problem faced was the actual travelling through bush and subsequently getting lost. Another difficulty was the vast amount of swamp mostly on the down-thrown side of the fault trace, but sometimes overlying and therefore obscuring the trace. Travelling through these swamps was nearly impossible.

CHAPTER TWO: STRUCTURE OF THE ALPINE FAULT



Figure 2.1: Location map of the Alpine Fault divided into three distinct sections from Haast River to Arawhata River. This map is shown in detail at 1:25000 scale in the back cover pocket.



Figure 2.2: Detailed mapping of the Alpine Fault trace between Haast and Turnbull Rivers was conducted in five parts based on known starting points.



Figure 2.3: Non-spatial graph detailing the relationship between fault traces and offsets in sequential order from Turnbull River (left) to Haast River (right). Individual fault segment lengths are shown in black and relate to the scale on the left of the graph. Step offsets relating to each trace are in grey and are associated with the scale on the right. East stepping offsets are below and west stepping offsets above zero on the Y - axis.

2.3 Section 1: Alpine Fault trace between Turnbull River and Haast River

The active fault trace, down-thrown to the west, forms a near linear feature oriented between 052° and 057° through low-lying swamp and forest. The fault trace lies 1.5-2.0 km west of the range front between Haast and Okuru Rivers. From the Okuru River to the Turnbull River, the trace occurs 0.5 km west from, and trends parallel to, the range front.

Mapping of the Alpine Fault trace from Turnbull River to Haast River was conducted in five parts (Fig 2.2), with the starting points of each part based on the identification of the fault trace at a particular location from aerial photographs. Mapping of part 1 north of Turnbull River follows the trace north-east for 350 m until it enters a swamp and disappears. Parts 2 and 3 together form a continuous section of the fault trace heading southwest from Okuru River until it too disappears into the same swamp as part 1. North of Okuru River, part 4 of the fault trace is often ill-defined and disappears completely for hundreds of metres in places, before finally disappearing altogether approximately 3 km north of Okuru. From here northwards, it runs through a large pond then swamp and regenerating bush with no trace observable until the southern side of Haast River, where a scarp trends southwest through a paddock for 300 m (part 5).

2.3.1 Alpine Fault trace location and orientation

Between Turnbull and Haast Rivers, the Alpine Fault forms a single trace, downthrown to the west, locally discontinuous and with scarp heights ranging form 0.5 - 16 m. On the north bank of Turnbull River, the fault trace trends north-east for 200 m striking 055° before disappearing in swamp. 300 m further north-east the fault trace was relocated and mapped to Red Hut Road. Here the fault trace is parallel with and northwest of the road, trending 055° with a scarp up to 16 m in height. Immediately south of Okuru River, the fault trace is located 40 m west of Red Hut, trending at 054° with an average height of 2 m. Between Okuru River and Swampy Creek, the fault trace forms a well-defined scarp trending 052° and averaging 3 - 4 m and up to 6 m in height. Two kilometres north-east of Swampy Creek the fault trace is a poorly defined linear scarp trending 057° and between 2 - 3 m in height before disappearing for a further 3 km along strike. The fault trace is relocated on the south bank of Haast River, forming a 2 m scarp oriented at 054°.

2.3.2 Relationship of fault traces and stepovers

Examination of the fault trace between Turnbull River and Haast River by aerial photographs indicates that it forms a single linear feature. The detailed ground survey of the fault trace reveals it is split into twenty-three individual traces (A-W, Table 2.1), varying in length from 9 m to 2539 m. Except at Okuru River and south of Haast River, where the fault trace is not located for >3 km, sections where the fault trace disappears and reappears are assumed continuous, thus giving maximum possible trace lengths. The two longest traces are A and B totalling c.3800 m from South Turnbull Swamp to just north of the Red Hut Road gate. Northward from Red Hut gate toward Okuru River, eleven individual segments occur (C – L, Table 2.1), generally decreasing in length to the north-east. North of Okuru River, trace lengths vary but are on average between 100 m and 300 m long. Traces R – S, from 1.5 km north of the Okuru River are greater than 600 m in length.

CHAPTER TWO: STRUCTURE OF THE ALPINE FAULT

Fault trace	Distance fro Turnbull Ri	om north bank of ver	Trace length (m)	Trace stepover (m)
	From (m)	To (m)		
A	-800	597	1397	12 West
В	597	3136	2539	11 East
С	3140	3375	235	14 East
D	3379	3609	444	8 West
E	3625	3856	230	8 West
F	3875	4026	151	5 West
G	4026	4116	90	3 East
Н	4116	4342	226	5 West
I	4342	4369	26	5 West
J	4369	4377	9	4 West
K	4377	4432	55	3 East
L	4432	4500	68	4 East
1000		Okuru Rive	r	
М	4850	4972	122	10 West
N	4955	5433	478	6 West
0	5392	5515	122	9 East
P	5516	5606	90	11 West
Q	5591	5639	48	6 West
R '	5639	6260	621	20 West
S	6260	6880	620	23 West
Т	6880	7159	279	8 East
U	7159	7417	258	9 West
v	7414	7591	173	
W	7804	7906	102	

Table 2.1: Trace lengths and stepover distances between Haast and Turnbull Rivers. Note a negative value is given for the start of trace A as it is interpreted to extend to South Turnbull Swamp, south of the Turnbull River.

Stepovers between two traces are less than 25 m and are present in three types (Fig. 2.4). These are under-lapping, perpendicular and overlapping. Of the twenty-one stepovers, fifteen step to the left (i.e. west relative to the southern trace) and seven to the right (east relative to the southern trace).



A non-spatial graph (Fig. 2.3) details the relationship between fault traces and stepovers in sequential order from Turnbull River (left) to Haast River (right). The graph indicates that for approximately 2 km either side of Okuru River, there is a positive relationship between the length of a trace and the size of a stepover. It is possible that subtle changes in the trend of the fault trace

account for the observed fault trace segment lengths and stepovers in this area. (i.e. from 055° along Red Hut Road to 052° north-east of Red Hut Gate, to 054° on either side of Okuru River, to 052° immediately north of Okuru River, to 057° 3 km north of Okuru River (Fig. 2.5)).

Small changes in fault orientation within a couple of kilometres of Okuru River are compensated for by either left or right steps and shorter segment lengths. Right-stepping segments relate to a more northerly strike of the fault trace; for example right-stepping segments C and D coincide with a rotation of the fault trend from 055° to 052°. Similarly, north of Okuru River, segments N and O exhibit a right-step where a change of orientation from 054° to 052° occurs. Left-stepping accommodates an eastward rotation in the trend of the fault trace, as shown for segments E - M, where a change from 052° - 055° occurs and also P - T which changes from 052° to 057°. Fig. 2.5, therefore illustrates that segment lengths, and the size of both right and left steps, can be correlated to small orientation changes along the Alpine Fault trace in the vicinity of Okuru River. Here the fault trace is at least 2 km away from the Southern Alps range front and strikes through relatively flat alluvial outwash plain composed of unconsolidated sediment. An exception to this relationship are the two segments A and B, which show no change in the fault trace orientation between Turnbull River and Red Hut gate. Due to a lack of data immediately south of Haast (including segments V and U), no relationship in this vicinity has been determined.





2.3.3 Channel offsets

Offset channels have been used extensively to determine individual horizontal displacements on faults in many parts of the world. This technique is most successful in arid climates where channels are easily identifiable due to a lack of vegetation on the surface and are not so

susceptible to morphological change compared to channels in a perhumid and mesothermal climate such as is found on the West Coast.

Nineteen apparent offset channels were measured along the trace of the Alpine Fault by determining the location and orientation of related channels above and below the fault scarp and then measuring the horizontal offset. Although many more channels cut through the fault trace than are documented here, channels evanescing in swamp on the downthrown side hampered determination of channel offsets. In these cases, swamp effectively obscures offsets and accurate measurements could not be made. Four channel offsets from the south terrace of Okuru River are taken from data collected by Berryman et al. (1986), as this portion of the fault trace has been destroyed and the data are no longer obtainable in the field.

Lengths and direction of channel offsets are plotted on a histogram (Fig. 2.6) to determine any groupings that may indicate the amount of displacement along the Alpine Fault trace for an earthquake event. Of the twenty-three offset channels, sixteen are dextral and seven sinistral. The fact that over 25% of offsets determined were sinistral indicates that many apparent offsets are not due to direct fault displacement. In many cases, apparent sinistral offsets on a dextral fault can occur when a creek switches to an approaching channel on the downthrown side.



Figure 2.6: Histogram for lengths and direction of channel offsets. Three concentrations are indicated at 4-5 m, 7-11 m and 15-18 m.

If we ignore the sinistral offsets as clearly being due to processes other than direct fault displacement, the dextral offsets range from 4 to 60 m with the bulk of measurements being in the range 7–22 m. We cannot assume that the dextral offsets are purely the result of fault displacement either, as these could also be due to channel switching along the fault trace. In addition, offset values may be modified by subsequent lateral erosion by the creek. If we assume that offsets can be measured in the field to ± 1.5 m (allowing for taping errors, uncertainty in determination of equivalent points on offset features, etc.), then the data for dextral displacements may be plotted as a running mean with a 3 m window. Two maxima appear, one at 8m and one at 15 m (Fig.2.7). These maxima could be interpreted to represent

one and two offsets, respectively, with the spread being due to variation in actual surface displacement and/or channel modification. The values are consistent with similar, better quality data from Haast (Berryman et al, 1998) and Lake McKerrow (Sutherland and Norris, 1995). However, the data are insufficient to draw firm conclusions.





2.3.4 Scarp heights

Scarp height is variable along the length of the section. Between Haast and Okuru Rivers, the scarp is between 1 - 6 m high and is generally poorly defined or covered by recent accumulation of sediment.

The fault scarp between Okuru and Turnbull Rivers is 2 - 4 m high, except for where Red Hut Road runs parallel with the fault scarp. Along this portion of the fault, scarp heights are on average 15 - 16 m high. It is also interesting to note that here the scarp-face dips around $60 - 80^{\circ}$ W, whereas the remainder of the fault trace had scarp faces usually dipping ~45°W.

Based on the relationship of scarp heights to their position on topographic maps (Fig. 2.8), it appears scarp heights from Turnbull River to Haast River are directly related to local morphological features extending out from the Southern Alps range front. A large area of alluvial outwash is situated over the 4 km missing section of the fault south of Haast River, obliterating any scarp that may have formed. Along Red Hut Road, the high scarp heights and steep scarp angle occur directly below a large promontory of the Southern Alps range front, and represent a greater amount of preserved cumulative offset unaffected by the Okuru and Turnbull River systems.

CHAPTER TWO: STRUCTURE OF THE ALPINE FAULT



Figure 2.8: Scarp height along the Alpine Fault trace between Haast and Turnbull Rivers is directly related to morphology as seen in the relating topographic maps.



Figure 2.9: Main features of section 2 Alpine Fault trace. Features include South Turnbull Swamp fault splay, 1.2 km dilational jog and a Shutter ridge named Drizzle Creek Spur. Continual lines indicate ground mapping, dashed lines indicate aerial photograph interpretation.

2.4 Section 2: Turnbull River – Compass Creek.

South of Turnbull River, the Alpine Fault trace strikes through the foot-hills of the Southern Alps (Fig. 2.9). Immediately south of Turnbull River, a 047°-linear feature interpreted to be a trace of the Alpine Fault, intersects the 054°-striking trace. The fault splay produced forms a tectonically controlled swamp described in detail in Chapter 4. Further south, a dilational jog trending 075° is interpreted before the fault becomes a single trace striking 043° on the south side of Murdoch Stream. On this part of the fault, between Drizzle Creek and Macpherson Gully, a shutter ridge is identified.

The fault trace was not identified on the ground between Debris Creek and Macpherson Gully. Aerial photographs, however, indicate that the 047° fault trace disappears at Debris Creek. Two lineaments, 250 m apart, trend west 255° from Debris Creek for 1.2 km, where they intersect the interpreted north-eastern extent of the 043° striking trace at Murdoch Stream. The set of lineaments described is interpreted as a dilational jog (Fig. 2.9).



Figure 2.10: Drizzle Creek Spur has a likely offset of 415 m, initiated between 12500-20000 B.P based on displacement rates by 1) Sutherland and Norris, (1995), and 2) Cooper and Norris, (1995).

At GR F37/812838, between McPherson Gully and Drizzle Creek, the Alpine Fault is mapped in detail and is defined by a 5 - 10 m wide, 043° trending gully, bound to the east by the Southern Alps. On the west side of the gully, a 2 - 5 m high scarp is present, defining the edge of the 400 m Drizzle Creek Spur. Aerial photograph interpretation indicates Drizzle Creek Spur is an offset shutter ridge. Dextral movement of the Alpine Fault would require the shutter ridge to be displaced to the north-east and the most likely place for its original position is approximately 415 m southwest along fault strike (Fig. 2.10). Horizontal displacement rates have been calculated for the Alpine Fault at Lake McKerrow of 27 ± 6 mm/yr (Sutherland and Norris, 1995) to the south of Drizzle Creek Spur and a minimum rate of 23.5mm/yr (Cooper and Norris, 1995), immediately north of Haast River to the north. Using these displacement rates, the likely age of the onset of

movement of Drizzle Creek Spur is 12500 – 19800 B.P (according to the calculation of Sutherland and Norris, 1995) and a maximum age of 17500 B.P (based on Cooper and Norris, 1995). These age estimates are consistent with topography being essentially post-glacial.

Section 3: Compass Creek – Arawhata River

At Compass Creek, the lineament interpreted to be the Alpine Fault splits into two traces. Heading south, the traces move away from the Southern Alps foot-hills forming two sub-parallel features through the Waiatoto River and at least as far south as the south side of Arawhata River. Between these two rivers, the eastern trace trends at 060° and the western trace 064°. Field evidence from Berryman et al. (1986), in an unpublished reconnaissance report and current work by Heather Campbell (Geology Department, University of Otago, pers. comm) on the Alpine Fault south of Arawhata River support the aerial photograph interpretation. The eastern trace is verified at two locations. On the north bank of Waiatoto River (GR F38/792774), Berryman et al. (1986), describe the occurrence of 300m of the fault trace, as a series of right stepping en-echelon scarps. The fault trace varies in strike from 047° to 066° and is upthrown on the southeastern side. On the eastern side of Jackson River at the confluence with Arawhata River (GR E38/682742), both Berryman et al (1986) and Heather Campbell found the fault trace consists of a 1.5 m high scarp upthrown on the southeast side and striking at approximately 070°. Heather Campbell has found a zone of deformed fault rocks on the southwest side of Jackson River (GR E38/753683) in agreement with the strike of the interpreted western trace.

2.5 Conclusions

- 1. Between Haast and Turnbull Rivers:
 - A positive relationship exists between fault trace segment lengths and size of stepovers in the vicinity of Okuru River as a reflection of small changes in strike of the Alpine Fault.
 - Channel offsets are variable and processes other than fault displacement must contribute to their development. Assuming dextrally displaced channels are due to fault movement, peaks at 8 and 15 m, with considerable variation, may represent one and two displacements respectively on the Alpine Fault.
 - Preservation of scarp heights along the fault trace are controlled by local geomorphological processes.
- 2. Likely age of initial offset of a shutter ridge (Drizzle Creek Spur) is 12000 17500 B.P. consistent with it being post-glacial.
- 3. Aerial photo interpretation between Compass Creek and Arawhata River, combined with field observations, suggests the fault splits into two traces.

3 TURNBULL TRENCH

3.1 Introduction

Suitable sites for trenching across the recent trace of the Alpine Fault are difficult to find in Westland. Sites need to be on young surfaces, where the scarp is the result of only two or three events, and where sediment accumulation has occurred, for instance in a swamp on the downthrown side. Most importantly, access for a mechanical digger is required that does not result in wholesale destruction of Westcoast forest. Such sites are largely restricted to terraces on either side of major rivers (see Chapter 2). Previously, we had dug trenches across the fault trace at Haast and Okuru Rivers, with some degree of success, and we hoped that a further trench would provide better datable material with which to determine the age particularly of the penultimate event. From the detailed mapping of the fault trace reported in Chapter 2, the only site that fulfilled all the criteria listed above was along the access road to the Powerhouse up the north bank of the Turnbull River.

Turnbull River is a major river system draining out of the Southern Alps. The Alpine Fault intersects Turnbull Road 1.5 km northwest of the powerhouse (GR F37:8428578) marking the change in the Turnbull River from a steeply confined, to a single braid river system. Trenching across the Alpine Fault was undertaken 100 m north-east of the current Turnbull River channel, adjacent to Turnbull Road (Fig. 3.1).

The Alpine Fault scarp here is defined by a 1.5 m high linear scarp trending 055° with a 30° slope angle. The scarp defines a boundary between a mature podocarp stand above the scarp and grassed flood plain below. Above the scarp, the surface is underlain by well-rounded boulders, while below, it is boggy silty/sand.

Building of the Turnbull Road to the powerhouse involved bulldozing a 25 m wide strip across the Alpine Fault scarp. Material from the up-thrown side was pushed onto the down-thrown portion. Nevertheless, this site provided the only practical location for trenching, as it was clear of forest, accessible and far enough away from Turnbull River for the down-thrown side not to be influenced by periodic flooding episodes.

Trenching occupied two days and one night of fieldwork. A Komatsu excavator with a 2 m wide bucket was employed to dig a 22 m long trench up to 3 m deep, 13 m southwest of Turnbull Road, perpendicular to the fault trace (Fig. 3.2A). At the fault scarp a permeable zone of gravel on the up-thrown side was breached, allowing water to pool in the trench. A suction pump was utilised for the duration of trenching to remove water. Minor problems with wall stability occurred at the lower end of the trench, particularly in sand layers where water had access to erode the trench wall base. On completion of excavation a 1m grid was installed along the southern wall and datable material collected and catalogued. On day 2, a combined effort of IGNS and Otago University personnel logged the trench (Fig. 3.2B), surveyed the fault surface and cored a 106 m transect from the fault scarp perpendicular to the fault trace on the down thrown side to establish total down-throw accommodation (Fig. 3.3). On completion of this work, the trench was filled in.

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Figure 3.2: A) Excavation of a 22 m long and up to 3 m deep trench on the down thrown side of the Alpine Fault. B) Logging of the southwest wall. The Fault trace intersects at the top of the photo.

3.2

3.2 Stratigraphy and interpretation of units

The trench log is presented in appendix 2. Ten stratigraphic units are recognised and interpreted as three periods of soil development, two of which (units 2 and 5) are overlain by alluvial sand deposition (units 4 and 6), and a modern soil (unit 8) partially disturbed by road excavation, all of which overlie a terrace surface (unit 1).

A basal unit of coarse sand/pebble-supported coarse boulder alluvium (unit 1) identified as an old river terrace, is overlain by a non-bedded, medium to dark yellow/brown sandy silt (unit 2). In grid squares 0,4-3,4, unit 2 is a mottled grey /blue clay containing abundant detrital wood. Unit 2 is interpreted as a paleosol that developed on the terrace surface, part of which was a swampy channel of impermeable clay under reducing conditions and thus able to preserve wood samples. In grid squares 2,4, a small packet of brown clay (unit 3) overlies stratigraphic unit 2. Unit 3 is most probably the remnants of a slack-water flood deposit or an oxidized equivalent of unit 2. Unit 4 is a weakly bedded, medium to coarse sand with clayey lenses at the base, interpreted as an alluvial sand deposit. Initial stages of unit 4, alluvial sand deposition, probably eroded most of the original unit 3 slack-water deposit. Unit 5 is a medium to dark tan, sandy silt with a gradational lower contact, interpreted as a paleosol that developed at the top of unit 4. Unit 6 is a channelised, moderately well-bedded, medium to coarse sand. Coarser components are greybrown, whilst yellow-brown when finer. A number of lenses of coarse to pebbly sand occur. Unit 6 is interpreted as an alluvial sand deposit and channels indicate scarp-parallel flow. A sharp lower contact defines the base of unit 7, identified as a rich organic brown, coarse sand with clay lenses. This unit may be the modern topsoil or alternatively, and more likely, it represents a backwater flood deposit. Unlike most of the other units on the down-thrown side of the fault that terminate at the fault trace, the eastern margin of unit 7 terminates at the 11 m vertical marker. Deposition of unit 7 possibly occurred in a depression at a lower level than the base of the fault scarp. Near the fault scarp, unit 8 is an organic grey silty sand with abundant carbonaceous horizons of roots and woody material. Also included are rare clasts up to 3cm. Away from the fault scarp and above the interpreted back-water deposit of unit 7, unit 8 is the uppermost unit before the surface and is composed of mottled grey/brown, unbedded clay and reworked sand. Unit 8 is interpreted as a modern soil. Unit 9 is a mixed, structureless, matrix-supported, gravelly sand with abundant roots and broken woody material. Clasts are subrounded, with an average size of 6cm and consist of 10 % of unit 9 composition. Unit 9 is interpreted as fill from bulldozing of the scarp during the formation of Powerhouse Road. Unit 10 rests on unit 1 on the up-thrown side of the fault scarp and is a grey-brown to yellow-brown matrix supported, cobbly sand with fine roots. Clasts comprise 30% of the rock type and are on average 4 cm in size, with a maximum of 10 cm. Like unit 9, unit 10 is interpreted as bulldozed material.

By combining trench stratigraphy (appendix 2) and core logs from holes at 20 m intervals away from the fault scarp, the extent of individual units above the terrace surface and perpendicular to the fault trace may be reconstructed (Fig. 3.3). The cross section in Figure 3.3 clearly defines the terrace surface (unit1) underlying modern soil 100 m from the fault trace. It appears that within this 100 m section, accommodation has been created by faulting and subsequent infilling by alluvial sand, presumably from the Turnbull River, resulting in the covering and preservation of soil profiles (for example units 2 and 5). Soil horizons are established over time on a base of alluvial sand. Subsequent accommodation space, created by faulting, allows the process of alluvial sand influx, followed by soil development, to be repeated. Although the upper level of

the interpreted cross-section in Fig. 3.3 is consistent with the upper level of stratigraphy in the trench, some offsets related to the most recent rupture on the fault scarp may be missing through truncation of the faulted section by the bulldozed deposit unit 9.

3.3 Number of events identified in stratigraphy

Three events are recognised based on four fault planes either cross-cutting or offsetting stratigraphy at the fault trace (black lines in Fig. 3.4A) and a sediment injection (Fig. 3.5). Event 1 is identified by 2 east-dipping planes, offsetting unit 2 paleosol and the overlying alluvial sand (unit 4) (Fig. 3.4B). Event 2 is indicated by an east-dipping plane displacing unit 5, the next paleosol above unit 2 (Fig. 3.4B). Alluvial sand of unit 6 that overlies the unit 5 paleosol, is not offset at the fault trace, and therefore post-dates the second event. In grid 0,3, a sediment column from unit 5 has injected into unit 6 alluvial sand (Fig. 3.5). The most likely cause of the injection is from liquefaction, a phenomenon commonly associated with earthquakes (e.g. North Ridge earthquake of January 1 1994 (Hithcock et al, 1999)). As unit 6 was deposited post-event 2, intrusion of the underlying unit 5 into unit 6 is interpreted as representing a third event.





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Figure 3.4: A) Events 1 and 2 are recognized from offsets at the fault trace, B) based on offsets of units 2,4 and 5. Key as for Fig. 5.3.



Figure 3.5: A sediment plume injection of unit 5 into post-event 2 alluvial sand of unit 6. This phenomenon is commonly associated with earthquakes and is evidence for a third event. Key as for Fig. 5.3.



Figure 3.6: Age constraints for the 3 trench sites show 3 event s over the last 1000 years. Event 1 was between 1155±35 A.D, event 2 has a maximum age of 1540±105 A.D and event 3 is post 1655±20 A.D.

3.4 Radiocarbon dating of events

Radiocarbon ages for Turnbull Trench were obtained from 8 samples collected from the two paleosols, units 2 and 5 (Table 3.1). Ages of wood fragments were measured using conventional radiocarbon analysis whereas AMS dating was used for carbonaceous clay samples. Four samples each were dated from the lower (unit 2) and upper (unit 5) paleosols.

Of the samples dated, only Wk8122, Wk8123, and Wk8301 are considered valid. These are all from the blue/grey clay of unit 2 and give an age range between $1000\pm50 - 1410\pm50$ B.P. The modern age for Wk8302 in unit 2 is inconsistent with other samples from the same unit suggesting probable contamination. Although found at the base of the trench in mud, it is possible Wk8302 fell into the trench and was embedded into the side-wall before being retrieved. Whether Wk8121 from unit 5 was a relict wood fragment or a tree root was questioned when collected in the field. The modern age given suggests it is a tree root.

The results of the three AMS ages from carbonaceous clay samples in unit 5 give grossly inconsistent ages ranging from 1083 – 12982 B.P. Not only are they inconsistent with each other, but also inconsistent with the dated wood samples from unit 2 below. Whereas contamination by modern material is a common problem in radiocarbon dating, this is not the case here. The ages are all too high, and in the case of AMS 1 and AMS 3, impossibly high. This inconsistency of ages from carbonaceous clay displays similarities with the study by Shore et al. (1995), who found from a study of four columns of peat using 127 radiocarbon samples, that the results were

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highly variable and mutually inconsistent. All three AMS ages for carbonaceous clay samples are therefore considered invalid. The cause of the excess ages is difficult to understand, since the amount of old carbon required to contaminate AMS 1 is very large. A source of such carbon is unknown, as organic material does not survive very long on the West Coast unless it is enclosed in a relatively impermeable material such as clay. No independent evidence for recycling of older organic deposits during formation of unit 5 is apparent.

Sample	Unit	Material dated	Location	Age
Wk8302	2	Wood (contaminated)	Grid 13,2	Modern
Wk8123	2	Wood	Grid 3,4	1000 ± 50 B.P
Wk8122	2	Wood	Grid 1,4	1410 ± 50 B.P
Wk8301	2	Wood	Grid 1,4	1390 ± 60 B.P
AMS 1	5	Carbonaceous clay	Grid 8,2	12982 B.P
AMS 2	5	Ponga bark	Grid 9,3	1083 B.P
Wk8121	5	Wood (tree root)	Grid 9,3	Modern
AMS 3	5	Carbonaceous clay	Grid 3,3	4725 B.P

Table 3.1: Radiocarbon ages for material collected in Turnbull Trench. Only Wk8122, Wk8123 and Wk8301 from unit 2 are considered valid.

Because of these problems in radiocarbon dating, the only data that can be used to constrain the age of the sequence are the ages on the wood samples from the blue/grey clay-filled channel at the top of the gravels (unit 2). This channel could have been in existence for a period of time so the range in ages obtained (1410-1000 BP) is understandable. The large sample sizes and well-preserved wood lends confidence to the results. The youngest sample at 1000 ± 50 BP represents a maximum age for cessation of accumulation of material in the channel and coeval soil formation on the old terrace surface, prior to burial by the sands of unit 4. This is the only age constraint that can be obtained as all datable material has been processed. Unfortunately, the younger part of the sequence remains a problem.

3.5 Interpretation of trench sequence

Uplift and stabilisation of the gravel terrace surface occurred sometime prior to 1400 BP, possibly in response to a rupture event on the fault. A soil developed on the terrace although small channels remained and were filled with swampy clay deposits and wood fragments. At sometime after 1000 BP, the terrace surface was inundated with sand and silt from the river, burying the soil and channel deposit. The sand is not present on the upthrown side of the fault, suggesting that a scarp existed at this time. Faults visible in the trench wall cut unit 2 but not unit 5. We interpret the sands of unit 4 to have been deposited in the accommodation space formed on the downthrown side of the fault immediately following a surface rupture. A soil horizon (unit 5) subsequently developed above unit 4 as the terrace once again stabilised. The sequence of events was then repeated following a further surface rupture on the fault, with unit 6 sands being deposited. A further surface rupture is interpreted to have occurred, based on the thickness of the overlying deposits and the occurrence of an injection structure of unit 5 material into the overlying unit 6, but most of the evidence has been destroyed during bulldozing of the road. The

ratio of vertical to horizontal displacement here is quite low (<0.1) so that the amount of accommodation space created during a rupture is small. The fact that a visible scarp is clearly evident indicates that infilling on the downthrown side is not complete following the last rupture. Most of the last colluvial wedge along the fault scarp is highly disrupted by forest clearance and so the relationships are obscured. Nevertheless, we consider that clear evidence exists for at least three surface rupture events subsequent to accumulation of wood in the clay-filled channel at 1000 BP.

3.6 Comparison of Turnbull trench with Okuru and Haast trenches

Within the field area, four trenches, two on the south bank of Okuru River and two at Snapshot Creek south of Haast River, have previously been excavated (Berryman et al., 1998).

At the Okuru River site, three events are recognised. The first event occurred immediately prior to accumulation of fine grained deposits above a gravel terrace surface with an average age of 850 ± 50 B.P. Two later events are recognised from liquefaction and stratigraphy, although ages obtained from seeds in accumulated sediments show evidence of recycling. The possible mixing of older and younger seeds places an uncertainty on radiocarbon ages for these samples, so that ages must be considered a maximum. Radiocarbon data constraining the age of the penultimate event (event 2) are an age of 520 ± 160 B.P, from the associated colluvial wedge and an age of 400 ± 120 B.P, in slackwater sediments preceding and associated with event 2. Seeds in the last colluvial wedge have a radiocarbon age of 262 ± 56 B.P. which is likely to represent a maximum for event 3.

At Haast River site, a total of 25 ± 1 m of dextral offset has occurred in three events, the first of which was immediately prior to 850 ± 50 B.P (average age of ages for Haast event 1). Seeds from colluvial wedges attributed to the two subsequent events give radiocarbon ages similar to the first event, suggesting the seeds were reworked during the last two events (as would be expected in a colluvial wedge).

Comparing these results with the Turnbull trench, it is likely that the first event recognised at all three sites is the same one. It post-dates a channel with a maximum age of 1000 ± 50 BP at Turnbull and predates sediments with an average age of 850 ± 50 BP at Haast and Okuru. Converting the ages to calendric ages (Stuiver and Reimer 1993), the event occurred between 1105 ± 85 AD and 1220 ± 50 AD, i.e. sometime in the late 12^{th} century. All sites have evidence for a further two events, but the dating is poor. From Okuru, the penultimate event probably occurred sometime between 1400 and 1600 AD and the last event after 1650 AD. The other two sites unfortunately provide no further constraints.

3.7 Conclusions

- Excavations of a 22 m long trench across the recent trace of the Alpine Fault at Turnbull River successfully exposed the fault zone and a sequence of buried soil horizons on the downthrown side.
- On the basis of fault traces and stratigraphy, a total of three rupture events are inferred. Unfortunately, most of the record of the most recent event has been destroyed by forest clearance activities.
- Radiocarbon ages on wood samples from a silt-filled channel at the base of trench provide a
 maximum age of 1105±85 AD for the earliest event recognised. Combined with data from
 trenches at Haast and Okuru, this brackets the event to between 1105±85 AD and 1220±50
 AD.
- Due to major natural contamination of samples from the younger buried soil, radiocarbon ages are inconsistent, impossibly old and cannot be used.
- The trench data add further support to the rupture chronology of the Alpine Fault for the last 1000 years and place constraints on the earliest event.

4 SOUTH TURNBULL SWAMP – Development of a tectonically controlled swamp and implications for Alpine Fault events.

4.1 Introduction

South Turnbull Swamp (herein called 'the swamp') is situated south of the Turnbull River. The swamp is approximately 150m in length and has a maximum width of 60 m in the northeast tapering at the southwest to a small gully. Bounded by the foothills of the Southern Alps to the southeast and to the northwest by a low ridge (Fig. 4.1), this swamp is hemmed in on three sides opening northeast toward the Turnbull River. A fluvial sediment buttress c.50 m wide and 3 m vertical height, relative to the normal level of an adjacent channel of the Turnbull River, has been deposited across the northeastern margin of the swamp. The swamp surface is therefore, above the normal river level and is controlled by the height of the sediment barrier. The elevated swamp surface and its distance (50 m) from the nearest Turnbull River channel provides partial protection from minor flooding.



Figure 4.1: Location of South Turnbull Swamp.

The sediment buttress provides a mechanism for filtering of sediment, as any sands and gravel entrained in floodwater are deposited onto the buttress due to a decrease in flow velocity, allowing fine-grained suspended sediment to pass into the swamp. Except for young tree stands at the swamp margins and the southwest where a gully enters the swamp, the majority of the swamp is covered with a raft of flax and cyrix growing in 0.5 - 1.5 m of water (Fig. 4.3). Typical of many organic-rich swamps, most plant material regenerates on the fringes, building out stable organic mat platforms toward the centre.

4.2 Structural Setting at South Turnbull Swamp

The swamp is situated in an area defined by the intersection of two fault traces with a 7° difference in trend. Aerial photographs and ground mapping indicate a 054° trending linear scarp along the eastern boundary of the swamp, interpreted to be a trace of the Alpine Fault and co-linear with the trace on the north side of the river. The trace is cut off in the gully at the southern end of the swamp by a linear feature defining the boundary between the western side of the swamp and the low ridge, also interpreted as an Alpine Fault trace, trending at 047° (Fig. 4.1). South of Haast, the Alpine Fault has predominantly dextral displacement. Assuming both traces here are dominantly dextral, displacement will increase the distance between them at any one point, producing a truncated pull-apart basin. The resulting subsidence creates the area now occupied by the swamp and the offset forms a shutter ridge defined by the present low ridge on the west (Fig. 4.1). Long term (c.1000 years) accumulation rates in the basin should equal subsidence rates.

4.3 South Turnbull Swamp as a record of seismic events

The history of swamp formation is linked to the inferred development of a pull-apart structure on the Alpine Fault (Fig. 4.1). A number of mechanisms may contribute to the formation of a swamp stratigraphy containing several swamp-wide sediment accumulations overlying organic layers. One possibility is catastrophic flooding of the Turnbull River resulting from the formation and breaching of natural dams from landslides. A major discharge of water could erode the north-east sand barrier, thus exposing the swamp and allowing inundation of fluvial sediment. Although individual landslides are commonly associated with large earthquake events (Keefer, 1984), it is difficult to associate one landslide to a specific earthquake. Another possibility is sudden subsidence of the swamp accompanying displacement on the Alpine Fault. Both the river and swamp subside, but rapid aggradation of the river to a pre-displacement level exposes the subsided sediment buttress making it more prone to breaching and sediment influx into the swamp (see Fig. 4.15). A feedback cycle follows in which the sediment buttress filters out all but fine silt and clay sediment, building up the buttress over time to a pre-displacement level and preventing further fluvially derived sediment accumulating in the swamp. Fine silt and clay suspended sediment would infiltrate the vegetation on the swamp surface. As the vegetative swamp mat becomes denser due to an increased weight of infiltrating sediment, the vegetative swamp mat will ultimately sink, killing much of the vegetative cover and forming a layer of organic material underlying fine clay at the base of the swamp.

During investigation and interpretation of swamp stratigraphy, the following principles for the evolution of a periodically subsiding swamp on the Alpine Fault were developed.

1) Although catastrophic flooding unrelated to fault movement may produce sediment pulses, significant accumulation of clastic sediment requires subsidence of the swamp to provide accommodation space. This is most likely to accompany displacement on the boundary faults.

2) Due to faulting, average rates of accumulation in the swamp equal average rates of subsidence produced through volume change in the pull apart.

4.4 Core Recovery and Logistics

Access and core recovery from the swamp proved difficult (Fig. 4.4A). Initially three traverses of the swamp were made with a tape and compass to determine 10 m intervals for coring sites (Fig. 4.2). A custom-made plywood platform was constructed to use as a drilling base and decrease the chance of sinking into the swamp. Two tools were used for coring, a 50mm diameter Russian D-corer (Fig.4.4B) allowing for recovery of 50 cm long cores and a soil auger able to retrieve 40 cm barrels. For the D-corer, after initial logging, samples were placed in PVC half tubes and covered in plastic wrap to preserve them for detailed logging in the laboratory. Logging of the auger barrels necessarily occurred on site (Fig. 4.4C). Twelve holes were cored along traverses X, Z and hole Y1, totaling 62 meters (Fig. 4.2) Additionally, a longitudinal traverse with no core recovery along traverse Y was undertaken to determine the depth to a thick swamp-wide layer of sand. For initial core recovery and depths to sand along traverse Y, the Russian D-corer was utilised with success. The D-corer was unable to penetrate the sand layer and augering was employed to reach maximum depth. Problems were encountered with augering (eg. losing hole entrances towards the centre of the swamp, and only having enough rods to auger for 7 m and for later holes only 6 m, due to rod breakage).



Figure 4.2: X,Y and Z core traverses for South Turnbull Swamp. Crosses indicate cored holes and dots are sites where depth to sand layer was determined.
I



Figure 4.3: Looking Southeast over South Turnbull Swamp. Note the linear eastern margin of the swamp, defining the Alpine Fault trace.



Figure 4.4: A: Core recovery. B: Retrieving the Russian D-corer from a hole. C: On site logging of auger cores.

4.5 Stratigraphy

The main purpose of examining the swamp was to determine rates of sedimentation and identify periods of swamp-wide rapid accumulation possibly related to seismic events. This has dictated the style of logging which entails the documentation of periods of clastic sedimentation relative to organic accumulation within the swamp. Details of logged profiles of the swamp are presented in appendix 3 (A & B), with the main features of the interpreted stratigraphy presented in Fig. 4.14.

4.5.1 Clastic Sediment

Micaceous clay: Clay is either intermingled with vegetation or occurs as distinct 1–15cm bands of very well sorted, grey to light brown, micaceous clay. These clay layers form swamp-wide homogeneous layers, commonly overlying preserved vegetation (Fig. 4.5) and are the basis for correlation between sections of logged cores above and below the thick fine sandy silt unit.

Micaceous fine sandy silt: Micaceous fine sandy silt occurs as a clearly defined stratigraphic horizon within the swamp (Fig. 4.6). Although a number of irregular layers of wood fragments, organic pulp and preserved vegetation are present within the unit, sandy silt dominates as a laterally persistent horizon. Some cores indicate a minor decrease in particle size in the upper portion of the unit. Thickness of the unit ranges from >3m in the centre of the swamp to tens of centimetres at the edges. Traverse Y running parallel with the swamp (Fig. 4.12) indicates this sediment is deposited as a packet shallowing to the north-east. Together with the similar sediment characteristics of homogeneous micaceous fine sandy silt of the sediment buttress, the shape and distribution of the packet suggests the sandy silt within the swamp is the same unit as that which forms the sediment buttress.

Poorly sorted coarse gravelly sand: Consisting predominantly of coarse sand with between 10 and 30% angular schist gravels, these highly irregular units are deposited within 10 m of the edge of the swamp (Appendix 3) and sourced from small channels running across the fringe of the swamp from the adjacent hillsides.

Coarse sandy gravel: Penetration of the swamp was halted at many hole sites when a layer of coarse angular sandy gravel was hit seen in (Appendix 3A). This layer marks a change in sediment type not apparently related to the swamp sequence. It has therefore been inferred to represent the base of the swamp.

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 Distinctive 8 cm thick, well sorted micaceous clay band overlying nondecomposed organic matter in X3, 2.3m depth

Figure 4.5: Clay banding overlying preserved organic matter.



Characteristic thick unit of fine sandy silt at 4-4.5m depth on core X4

Figure 4.6: Core of thick fine sandy silt.



Diatom-rich 'green pulp'

Intermixed bands of clay and decomposed vegetation-derived 'brown pulp'.

Figure 4.7: Core showing decomposed matter of brown and green 'pulp'.



Defined band of grey micaceous clay

Over lying

Preserved organic matter

Grading to

Decomposed brown pulp organic matter

Figure 4.8: Preserved organic matter under a clay layer.

4.5.2 Sources for clastic sediment

Distal Sources: Minerals forming the well-sorted micaceous silt/sand and clay are dominated by biotite, muscovite, chlorite and quartz, with minor albite and epidote, strongly suggesting a Haast Schist origin from uplifted Southern Alps, east of the Alpine Fault. Abundant micas within very well sorted sand and clay are consistent with fluvial deposition suggesting sediment transport occurred via the adjacent Turnbull River.

Proximal Sources: Poorly sorted angular gravelly sands commonly found within cores at the edge of the swamp (for example X0.4 and X6 in Appendix 3A) are most likely derived from the adjacent slopes and deposited by small stream channels close to the edge of the swamp.

A major alluvial fan abutting the shutter ridge southwest of the swamp, is currently accumulating sediment (Fig. 4.1). There was no evidence in the swamp from cores recovered (e.g. in hole Y1, appendix 3B) for deposition of large quantities of alluvial fan-derived sediment via flow down the gully at the southern end, although the base was not reached.

4.5.3 Organic Components

Dr Kath Dickinson (University of Otago, Department of Botany) was unable to identify individual plant species within cores and therefore organic components have been divided into two categories based on the degree of decomposition.

Decomposed Organic Matter: Physically, decomposed organic matter within the swamp has the consistency of fine pulp (Fig. 4.7). It constitutes the largest component of accumulation within the swamp and overwhelmingly dominates accumulation above the micaceous fine sandy silt layer. This component can be divided into two types, 'green-pulp' and 'brownpulp'. Dr Marc Schallenberg (University of Otago, Department of Zoology) examined a sample of 'green-pulp' and concluded that it was composed of nearly 100% skeletal fragments of fresh-water diatoms common in many New Zealand open fresh water systems. Significant deposition of diatomaceous layers in the swamp stratigraphy suggests that at the time of deposition, the swamp surface was devoid of a swamp mat. A detailed analysis of species was not carried out for this study as it gives little indication of accumulation rates. Accumulation of 'brown pulp' is from a uniform supply of dead vegetative particles of the overlying swamp mat falling out as part of normal swamp vegetation growth cycles.

Deposition and compaction of accumulated swamp sediment is slow (see Table 4.2) and individual particles may remain in suspension until further deposition occurs, as seen in the upper sections of logged holes X2 and X3 (Appendix 3A).

Preserved Organic Matter: Solid wood fragments, preserved root structures and flax layers comprise this group. Wood fragments are common in the sandy silt unit and more rarely in clay layers. Distinguishing between flax and root mesh in cores was very difficult so they were grouped together. Individual layers are usually preserved below a clay band and above brown pulp or intermixed in clay.

4.6 Types of accumulation at South Turnbull Swamp.

South Turnbull swamp exhibits two very different types of accumulation. One type is predominantly fine sandy silt, the other is cyclic deposition of decomposed organic matter and clay lenses, although these two end members are commonly discontinuously interbedded.

4.6.1 Fluvial sand inundation

The fine sandy silt is interpreted to result from fluvial sand inundation of the swamp area from the adjacent river channel of the Turnbull River. Initial deposition was probably rapid but slowed during the later part of deposition. This reduction in accumulation rate is indicated by an increase in organic components present, requiring time for colonisation of the sediment surface by plants.

4.6.2 Closed swamp accumulation

Stratigraphically above and below the thick unit of sandy silt lies sediment dominated by the accumulation of organic matter. Accumulation of major amounts of 'pulp' (Fig. 4.7) comprising skeletal diatoms and decomposed vegetative matter requires a quiet freshwater body with or without a vegetative cover, suggesting a closed swamp environment. Homogeneous swamp-wide layers of micaceous clay generally overlie preserved organic matter (Fig. 4.5), which itself overlies decomposed organic matter. These micaceous clay layers within the closed swamp are interpreted as deposition from the suspended load of a current overtopping the sediment buttress at the northern end of the swamp. When the swamp is covered by a vegetative mat, micaceous clay sediment infiltrates the mat causing it to sink to the bottom, thus preserving the killed off portion as organic matter.

4.7 Ash analysis

Ash provides a quantitative estimate of the proportion of accumulated sediment in the swamp that is organic or clastic.

4.7.1 Sampling method

Five cores (X1 - X5) were sampled for ash analysis. As samples were collected using the D-corer, very few samples are from below the micaceous sandy silt horizon as the corer was unable to penetrate it. In addition, the upper 1.5 meters of core for X1, X2 and X3 were not sampled due to missing or poor sample recovery.

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Figure 4.9: Clastic sediment percentage of selected cores of X-profile. Three anomalous sediment layers exist within stage 3.

Samples were collected adjacent to stratigraphic boundaries within cores or at regular intervals where little visible change was apparent. After heating samples overnight at 105°C to release free water, samples were weighed, placed in air at 1100°C for one hour, cooled and weighed again to determine volatile loss on ignition (LOI). The Turnbull catchment lies within Haast Schist and LOIs for clastic sediment from the Turnbull River are expected to be similar to nearby hard rock. To account for loss of bound water in micas, a 1.6% correction was made by averaging LOI values for samples from Big Bluff along the Haast valley (Roser and Cooper, 1990) and Debris Creek (Wright, 2000). A 1.6% difference assumes all sediment core is schist-derived. If there is a significant organic content, the mica content will be lower and presumably LOI contribution would be less than 1.6%. In determining sediment-dominated or organic-dominated accumulation, a 1.6% LOI does not greatly affect the outcome of results. Results were plotted and graphed (Fig. 4.9) to identify dominant sediment types during swamp accumulation.

4.7.2 Results

Ash analysis highlights the deposition of silty sediment above the sandy silt unit contemporaneously with organic swamp vegetation. Sediment rates in the centre of the swamp are much greater than at the fringes. Three anomalous increases in amount of clastic sediment occur above the sand unit corresponding to swamp-wide clay bands in Appendix 3, (A & B).

4.8 Environmental Reconstruction of South Turnbull Swamp

Determination of clastic and organic sediment components, their source and percentages, accumulation processes and logged core stratigraphy enable a broad environmental reconstruction to be made (Figs 4.10, 4.11 and 4.13). Three major stages of sediment accumulation are interpreted within the swamp history.

4.8.1 Stage 1: Closed swamp accumulation

The base of logged cores X0.6, X1, X5, Z3 and Z4 (Appendix 3, A&B) indicate cycles of micaceous clay overlying decomposed and preserved organic matter. At hole site Y1, clay layers are intermixed with organic components. The base of core X5 is rich in diatoms. These observations are consistent with closed swamp sedimentation over the entire swamp (Fig. 4.10). This would require the emplacement of a protective barrier (similar to present), to prohibit fluvial sand from entering. Layers of silty clay suggest the swamp was disturbed periodically by deposition of suspended sediment. Onset of organic accumulation was before 880 ± 110 A.D as constrained by ¹⁴C ages from a layer of organic matter immediately overlying the coarse gravelly sand at the inferred swamp base in hole X1. A major packet of fluvial sand dominates in stratigraphic mid-swamp as indicated by the basal material of cores X2, X3 and X4 (Appendix 3A).

4.8.2 Stage 2: Fluvial Sand Inundation

A major change marking the onset of stage 2 deposition is a swamp-wide fluvial sand wedge dipping to the south (Fig. 4.12) and at least 3.5 m thick in mid swamp (Appendix 3A).

Deposition of the sandy-silt had commenced by 1261±55 A.D as indicated by ¹⁴C ages on wood fragments at the base of the unit in core X1. It is likely that much of the Stage 1 closed swamp sequence was eroded away prior to, or more probably during, deposition of the fluvial sand (Fig. 4.11). Exposure of the swamp to inundation by a large volume of fluvial sand requires the removal of the protective sand buttress at the northern end. Two possibly linked mechanisms to account for this include coseismic subsidence of the swamp basin relative to the river channel and catastrophic flooding of the Turnbull River, eroding away the barrier and thus exposing the swamp to the nearby river channel. After replacement of the eroded Stage 1 swamp accumulation by fluvial sediment, continued net aggradation of fluvial sediment, concentrated at the north end reformed the barrier, restricting further encroachment of the river into the swamp basin.

4.8.3 Stage 3: Closed Swamp

Accumulation of fluvial sand at the north end of the swamp developed a stable sediment buttress. Following this, the only mechanism for clastic sedimentation was fallout from suspension after overtopping of the sediment buttress. Larger clasts would therefore fall out of entrainment first, being deposited on the sediment buttress due to a decrease in velocity as the sediment-carrying flow enters the swamp basin. Subsidence of the basin countered by periodic deposition onto the sediment buttress from the river channel meant a protected closed swamp developed (Fig. 4.13). Ash percentages for stage three deposition decrease with height in analysed cores (Fig. 4.9). A vegetation mat has formed a swamp cover since the onset of Stage 3, suggesting a decrease in influx of clastic sediment through time.







Figure 4.11: Stage 2 fluvial inundation.







Figure 4.13: Stage 3 closed swamp.

4.9 Sediment pulses

A sediment pulse is defined here as a swamp-wide, clastic sediment depositional event recorded in stratigraphic traverses X and Z (appendix 3, A & B) and where possible, identified by anomalously high values in the ash analysis.

Two types of sediment pulse are recognised in the swamp. In Stages 1 and 3, sediment pulses are identified by swamp-wide clay bands with associated underlying preserved organic matter, interpreted as suspended sediment encroaching onto the swamp from flooding of the Turnbull River.

The second type of sediment pulse recognised is at the boundary of Stage 1 and 2 deposition, marking a major change in depositional character from closed swamp environment to fluvial inundation. Onset of this major swamp-wide change is interpreted as a sediment pulse.

Radiocarbon ages were obtained for the base of core X1 in preserved organic matter under clay at 4.9 m depth, the oldest stratigraphic layer recognised in the swamp (Wk8176, 880±110 A.D). Wood fragments in core X1 at the base of depositional Stage 2 from 3.95 m depth gave 1261±55 A.D (Wk8175). Wood fragments within a clay band at the base of Stage 3 deposition in core X1, 2.75 m depth, give an age of 1350 ± 50 A.D (Wk8624) and at 2.45 m depth, carbonaceous mud has an age of 1325 ± 60 A.D (Wk8623). Below the upper-most clay layer in Stage 3 from core X4 at 0.95 cm depth, a modern age was obtained.

Six sediment pulses are identified in the swamp since 880±110 A.D (summarised in Table 4.1 and illustrated in Fig. 4.14). Pulses A, B, D, E and F all exhibit similar depositional characteristics of clay layers in a closed swamp. Pulse C is at the base of Stage 2 defining a major change of depositional character in the swamp. Pulse A is the oldest pulse recognized, resting on the inferred base with a minimum age of deposition at 880±110 A.D. Cores from the centre of the swamp (holes X2, X3 and X4) did not reach sandy gravel at the inferred base of the swamp and therefore it is not known if there are any pulses preceding pulse A in this deep part of the swamp. A poorly constrained age for pulse B is between a maximum of 880±110 A.D and a minimum of 1261±55 A.D. Maximum age of onset and minimum age of cessation for deposition of pulse C was between 1261±55 A.D and 1350±50 A.D. Age constraints for pulse D, 1350±50A.D and pulse E, 1325±60 A.D although indistinguishable from each other, are consistent relative to other ages in the swamp. A modern result for pulse F could still indicate an age as old as 1690 A.D as all ages less than 200 years B.P are returned as modern. Ages relating to the last displacement on the Alpine Fault at 1717 A.D. are commonly returned as modern (Yetton et al., 1998; pers. comm., Cooper and Norris, unpublished data).





NOTE: Horizontal distances are not to scale

Figure 4.14: Interpretation of the main swamp stratigraphy features in X and Z profiles showing three depositional stages and 6 sediment pulses.

DEPOSITIONAL SEDIMENT STAGE PULSE		DESCRIPTION	CALIBRATED RADIOCARBON AGES FOR TIMING OF PULSES	
Stage 3	F	Upper pulse - Within stage 3 stratigraphy Middle pulse - Within stage 3	- Modern Radiocarbon age	
	Е	stratigraphy Lower pulse –Immediately above the boundary of	- 1325±60 A.D	
	D	stage 2 and 3 deposition	- Immediately post 1350±50 A.D	
Stage 2	С	Boundary of stage 1 and 2	- Immediately prior to 1261±55 A.D	
Stage 1	В	Upper pulse -Within stage 1 stratigraphy Lower pulse - Immediately above	- Between 880±110 A.D and 1261±55 A.D - Immediately post 880±110 A.D	
	A	inferred swamp base		

Table 4.1: Summary and timing of sediment pulses within depositional stages.

4.10 Relationship of swamp stratigraphy to ruptures on the Alpine Fault.

Wright (1998), has produced an up-to-date revised provisional chronology consisting of 6 Alpine Fault rupture events since 940 ± 50 AD. There is agreement between this chronology and both the number and time constraints of sediment pulses identified in the swamp. This is consistent with an interpretation of sediment pulses caused by overtopping of a subsided sediment barrier following rupture on the Alpine Fault. A model is presented in Fig. 4.15 to demonstrate a cycle of swamp deposition for a post rupture sediment pulse, followed by organic sediment accumulation. Initially, subsidence of the riverbed, sediment buttress and swamp occurs following an Alpine Fault rupture (2). Relatively rapid aggradation of the riverbed to a pre-earthquake steady-state level occurs (3). The swamp and sediment buttress remain subsided and, therefore, vulnerable to overtopping from normal flooding of the river. Sediment particles larger than fine silt are filtered out of floodwater overtopping the sediment buttress, thus aggrading the buttress (4).





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The remaining sediment is deposited as clay bands in the swamp. As the sediment buttress builds up towards a pre-earthquake level, it is more difficult for floodwater to overtop the sediment buttress (5). This in turn has the effect of protecting the swamp from clastic sediment input and enables organic sediment to dominate accumulation (1). However, it remains uncertain if all sediment pulses are coseismic even though their number and ages are consistent with the inferred paleoseismic record further north.

For pulse C, the only process that could comprehensively remove the barrier protecting stage 1 closed swamp, is catastrophic flooding. The timing of this event, shortly before 1261 ± 55 AD, is within error of dates suggested for a major rupture of the Alpine Fault based on trenching and forest disturbances (Wright, 1998; Berryman et al., 1998; Yetton et al., 1998; this report, Chapter 3).

4.11 Determination of accumulation rates

Minimum average accumulation rates are determined by the maximum depth of the two oldest radiocarbon ages obtained. Discrimination between types of sediment deposition within the swamp is not considered when calculating overall accumulation rates. Extrapolation to the centre of the swamp, where subsidence is greatest, of radiocarbon ages Wk8175 at the base of Stage 1 deposition and Wk8176 at the base of Stage 2 deposition, suggest very fast rates of accumulation. Minimum subsidence rates of 5.9mm/yr occurred over the past c.1200 years and 6.3 mm/yr in the last c.750 years (Table 4.2).

Sample	Minimum Rate	Maximum Rate
Sponge Swamp (Wk7407)	0.6mm/yr	0.9mm/yr
Sth Turnbull Swamp (Wk8175)	6.3mm/yr	7.3mm/yr
Sth Turnbull Swamp (Wk8176)	5.9mm/yr	6.9mm/yr

Table 4.2: Comparison of maximum and minimum time averaged accumulation rates at Sponge Swamp and South Turnbull Swamp based on radiocarbon ages.

An unpublished report (Tim Moore, Coal Research Ltd, pers. comm.), describes accumulation at Sponge Swamp, a large closed swamp west of the Alpine Fault north of Arawhata River. The swamp is unaffected by the present river, as it is located well above the present channel and drains away to the north-east. Aerial photo interpretation suggests the swamp is located in a tectonic depression. Radiocarbon dates at 2.6 m depth give an age of 3340 ± 550 B.P (Wk7407, Tim Moore pers. comm.). Therefore, even though the swamp is susceptible to tectonic subsidence, maximum rates of accumulation are on the order of 0.9mm/yr (Table 4.2). Since Sponge Swamp is a relatively closed system for accumulation and is close to the South Turnbull Swamp, it is used as a control on likely rates of swamp accumulation away from the fault trace. The difference in accumulation rates between the two swamps is significant, with those at South Turnbull swamp nearly an order of magnitude higher than Sponge Swamp.



Horizontal Constraints

A simple block model of faulting around the swamp is developed to examine subsidence at South Turnbull Swamp (Figs 4.16 and 4.17). The aim is to see if predicted subsidence of the swamp during fault displacement is of the right order to explain rates of swamp accumulation.



Figure 4.16: Horizontal constraints of the simple block model. $\alpha = 7^{\circ}$, Δv is displacement during a single event.

Individual horizontal displacements on the southern section of the Alpine Fault are on the order of 8 m as derived from trenching at Haast (Berryman et al., 1998), and displaced river channels at Hokuri Creek (Sutherland and Norris, 1995). If the displacement during a single event (Δv) is assumed to be 8 m, the displacement of the junction of the two faults would also be c. 8 m in a dextral sense (Fig 4.16). Let the angle between the two fault traces be 7° (based on aerial photo interpretation). The difference (Δn) between swamp width before displacement (n_0) and after displacement (n_1), can be calculated from

Equation 1: $\Delta n = \Delta v \sin \alpha$.

For $\Delta v = 8$ m, $\Delta n = 0.975$ m.

The dips of the two fault planes are represented by $(90 - \beta)$ and $(90 - \gamma)$ (Fig. 4.19). Vertical subsidence Δs accompanying a single event is given by:

Equation 2:
$$\Delta s = \underline{\Delta n}$$
.
 $(\tan\beta + \tan\gamma)$

A major drawback is that Δs is dependent on β and γ , which we don't know. The model becomes unrealistic if β and γ both approach zero (as $\Delta s \gamma \rightarrow 0$).

Vertical Constraints





The fault trace defining the eastern boundary of the swamp (dip $90 - \beta$) is characterised by a linear trace, with small en-echelon steps, extending from South Turnbull Swamp to at least Haast River in the North. Recent seismic monitoring of the Alpine Fault at Okuru suggests the fault is near vertical (Bradley Eales, University of Otago, pers. comm.) and paleoseismic evidence from Haast and Okuru suggests a predominantly strike-slip sense of movement. These observations are consistent with a near vertical fault plane. Reasonable dips are between 70° - 90° , converting to β values of 0° - 20° .

The southern trace defining the western boundary of the swamp, dip $(90 - \gamma)$, runs oblique to the northern trace, suggesting an increased reverse-slip component. Reasonable dips are assigned to be 50° - 70°, corresponding to γ values of 20°- 40° for this transpressional fault plane.

Subsidence from an Alpine Fault displacement for end members of the spectrum of reasonable dip values are calculated from Equation 2 (Table 4.3).

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This simple block model suggests South Turnbull swamp subsidence (Δs) is on the order of 0.69 to 2.68 m per displacement on the Alpine Fault for a range of fault plane dips. From a probable chronology of 6 Alpine Fault events over the past c.1200 years, total time average subsidence rates are calculated in Table 4.4.

βγ	20° Y	40° Υ
0 °β	8.45 mm/yr	3.4 mm/yr
20 °β	5.2 mm/yr	3.1 mm/yr
Table 4.4: Total avera	ge subsidence rates	over the past c.1200 yr.

Time averaged rates of accumulation, determined from stratigraphy, are between 5.9 - 7.3 mm/yr. Long term rates of subsidence, based on modelling, give numbers from 3.1 - 8.45 mm/yr. Predicted subsidence and measured accumulation rates are of the same order of magnitude in South Turnbull Swamp and are consistent with a fault-controlled subsidence model for the swamp.

4.13 Summary of South Turnbull Swamp

	Stage 1 and 3		Stage 2	
Type of accumulation	Closed swamp		Fluvial sand inundation	
Stratigraphy	Micaceous clay Preserved organic matter Decomposed organic matter		Micaceous fine sandy silt	
Clastic sediment source	Haast Schist - distal		Haast Schist - distal	
Identification of sediment pulses	Swamp-wide clay bands overlying preserved organic matter		Thick swamp-wide unit of fluvial fine sand	
Pulse numbers	ABDEF		С	
Range for accumulation rates		5.9 mm/yr – 7.3 mm/yr		
Range for subsidence rates		3.1 mm/yr - 8.45 mm/yr		

Table 4.5: Summary of South Turnbull Swamp.

4.14 Conclusions

- There is some evidence for up to six subsidence events, possibly related to Alpine Fault ruptures, since 880 AD based on sediment pulses at South Turnbull Swamp.
- Pulse C is the strongest candidate for an earthquake-related sediment pulse. The age of deposition is consistent with ages suggested for a major rupture inferred at several localities along the whole fault (the Muriel Creek event of Yetton et al., 1998) at around 1200±50 A.D.
- Fast accumulation rates within South Turnbull Swamp are consistent with calculated subsidence rates resulting from six Alpine Fault displacements over the past 1200 years.

5 TREE RING ANALYSIS

Large earthquakes often cause severe physical damage to trees growing near the fault trace (Page, 1970; Meisling & Sieh, 1980). If the surface is ruptured, displacement and accelerations of substrate can physically affect trees by crushing or ripping apart root systems, snapping off major limbs or tops of trees, causing internal stress. Older trees may be toppled over. These effects can disrupt growing sites and induce a change in the normal growth ring patterns (Table 5.1). While mature trees may show a drastic reduction in tree ring growth, due to a greater inertia, younger trees that are more resilient may not show any sign of damage. In the years immediately following an earthquake, these young trees can experience tree ring growth acceleration due to a loss of competitors (e.g. Van Arsdale et al., 1998). An example of this is older trees falling over and opening the canopy, allowing younger trees to become established. Major earthquakeinduced changes in land surfaces can disturb tree growth sites by causing tilting, burial, damming of rivers to flood forests, uplift to create, improve, or damage growth environments, subsidence to cause drowning or deterioration of growth environments, scarring of trees by rockfall or landslide debris and other physical damage by earthquake-activated geological materials (Jacoby, 1997). These changes essentially affect hydrological and nutrient supply conditions that have marked effects on tree-ring pattern growth.

Change in trees	Physical change	Possible cause	
Physical change (Unusually narrow or missing rings, abnormal cells)	Top, major limb, or root system broken off Scaring	Violent shaking and/or local earth movement Seismically activated material impacting tree (e.g., landslide, seiche, tsunami)	
Growth rate change Increase (wider rings)	Improved growth environment, nutrient supply, or site hydrology	Change of site into more favourable conditions, loss of competitors	
Decrease (narrower rings)	Poorer growth environment, nutrient supply, or site hydrology	Change of site into less favourable conditions	
Variation increase (ring widths change inconsistently)	Some damage, some competitors felled, surface disrupted	Disturbance overrides normal growth	
Reaction wood	Ground surface tilted or tree pushed over	Surface rupture, landslide, tilting minor subsidence	
Traumatic resin canals	Partial flooding	Minor subsidence	
Tree growth initiated (date of first tree ring)	Barren surface stabilized or newly available	Uplift change in base level, landslide or other catastrophic event	
Tree growth terminated (date of terminal ring)	Surface covered, burying trees	Rapid sedimentation, landslide, or other catastrophic event	
	Surface inundated	Subsidence	

Table 5.1: Trees as indicators of seismic disturbance. From Jacoby (1997).

5.1 Requirements for tree ring analysis

For tree ring analysis in relation to paleoseismicity, three fundamental requirements need to be met (Jacoby, 1997).

1) Identification of the exact year in which each ring was formed.

Simple counting of rings is not a reliable method of determining the true date of a tree, due to the fact that in some tree species, there can be false, missing or locally absent rings due to unusual growth conditions or trauma. Determining a climatic signal expressed in tree ring patterns by

cross-matching is, therefore, essential if precise dating is to be achieved. It can be a difficult task, especially on the West Coast, due to the types of, and competition among, trees, changes in stand dynamics, disease, fire or storm damage and seismic disturbance itself making cross-dating more difficult. The major podocarp species that grow along the fault zone, in particular Rimu (*Dacrydium cupressinum*), are highly unsuitable for producing accurate, cross-matched chronologies and, to date, all attempts have failed (W. B. Bull, pers. comm.; C. Wright, pers. comm.).

2) Dating is absolute.

A sample is dated only when the date can be given with certainty.

3) Establishment of a control tree ring growth population.

After a climatic signal has been established, a control population is then identified far enough from an inferred rupture zone, so as not to be seismically affected. This population is then compared to samples immediately adjacent to the rupture zone that are considered within range to be damaged by an earthquake. Non-seismic noise can then be eliminated, allowing for the identification of a seismic disturbance in tree ring patterns.

5.2 Recent Alpine Fault tree-ring analysis

Tree-ring analysis has been applied on the West Coast of the South Island for determining prehistoric earthquakes on the Alpine Fault by Wells et al. (1999) and Wright (1998). Wells et al., (1999) examined cedars from the western side of the Southern Alps using a control from east of the main divide. They concluded an Alpine Fault event occurred at 1717 A.D and another event at 1620±10 A.D. Wright (1998) examined 25 podocarp slabs immediately adjacent to the Alpine Fault at Waitaha River. Wright (1998) was restricted to using a ring counting approach for podocarps adjacent to the Alpine Fault, due to the problems of cross-matching mentioned above. The results of this study, however, were in agreement with Yetton et al. (1998).

5.3 Disturbances along the Alpine Fault south of Haast

5.3.1 Podocarp evidence

Fifteen Rimu (*Dacrydium cupressinum*) specimens were collected at three locations adjacent to the Alpine Fault. At Drizzle Creek, living tree specimens OU67707-OU67712, had two cores extracted at breast height from prominent tree buttresses. Along Red Hut Road, between Okuru and Turnbull Rivers, Rimu trees were selectively felled between 1964 and 1970. The tree stumps remaining are in an advanced state of decay. 5 slabs (OU67713 – OU67717) were sawn off what remained of these stumps and removed from the bush. Slabs from specimens OU67718 and OU67719 were from trees felled around 1995 ± 1 yr. It was later learned that that these two trees could have been dead for up to 30 years before this. Specimens OU67720 and OU67721 are from stumps located 400 m northwest of the Alpine Fault, from trees felled in 1998. Slabs were dried for three months, and sanded to a polished finish. Tree cores were sanded along a side where the rings were perpendicular to the core surface.

Rimu growth: Growth rings in conifers consist of layers of early wood and late wood. Early wood is formed in the early part of the growing season. In temperate regions, such as the West Coast, one growth ring is formed corresponding to one growing season a year. Franklin (1969) found that for Rimu trees, there is only circumstantial evidence that growth rings are consistently formed annually. It is also possible for two rings to occur in one year as well as an abundance of discontinuous rings in mature or slowly grown trees. Mature Rimu grow by buttressing, causing growth to be confined to one sector for a number of decades and then growth will stop and move to another sector (Fig. 5.1). These factors make cross-matching of trees very difficult and, for slowly grown trees with extremely fine ring-widths (Fig. 5.2), accurate counting is impossible. The very best that can be achieved by ring counting alone is an age estimate within a decade.

Specimen number	Samples taken	Eligibility of samples for analysis
OU67707	2 Cores	1 core rotten, 1 core useable
OU67708	2 Cores	1 core rotten, 1 core useable
OU67709	2 Cores	1 core with no visible rings, 1 core useable
OU67710	2 Cores	2 cores useable
OU67711	2 Cores	2 cores rotten
OU67712	2 Cores	2 cores useable
OU67713 - OU67717	5 Slabs	Last growth rings cannot be determined in most cases, due to complete decay of sapwood. Accurate ring counts are not possible
OU67718 OU67719	2 Slabs	Buttressing is severe in places. Already dead when felled. Cannot determine the youngest rings. Accurate ring counts are not possible
OU67720 OU67721	2 Slabs	Slowly grown, therefore large errors occurred in ring counting. Slab not suitable for analysis.

Table 5.2: 12 cores from 6 trees and 9 slabs were extracted and polished. None of the slabs and only 7 cores from 5 of the trees were useable.

5.3.2 Ring-width analysis

The inherent problems with ring growth in Rimu means that cross matching is nearly impossible. Wright's (1998) method of tree-ring counting was used for the study of these Rimu samples. Slabs and cores were studied with a Zeiss binocular microscope, using between 40x and 250x magnification. Each growth ring was counted and assigned one of six semi-quantitative width classifications: 1: very wide (c. 3 - 8 mm), 2: wide (c. 1.5 - 3 mm), 3: medium (c. 0.8 - 1.5 mm), 4: fine (c. 0.4 - 0.8 mm), 5: very fine (c. 0.2 - 0.4 mm), 6: extremely fine (c. 1 mm) (the quantitative values are only approximate; where a marked change in growth rate occurs, a change in width classification was always recorded). A greater margin of error in counting is expected for smaller ring growths.

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Figure 5.1: One of the inherent problems of Rimu for dendrochronology is buttressing, as seen here, making it difficult to determine the number of individual rings.



Figure 5.2: Specimen OU67720; closely spaced growth rings and buttressing has resulted in a 12 growth ring relative error between 2 transects.

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Figure 5.3: A typical edge representative of samples OU67713 - OU67717. In all cases the last grown ring cannot be determined.



Figure 5.4: Specimen OU67714; 30 years of exposure to the West Coast climate has resulted in most of the sapwood having rotted away.

Seven cores have been analysed from 5 of the trees, from a total data set of 12 cores from OU67707 – OU67712 (Fig. 5.5), for reasons summarised in Table 5.2. Tree specimens OU67710 and OU67712 each had 2 cores analysed. Trees OU67707, OU67708 and OU67709 had only one core analysed and for tree OU67711, no cores were analysed. The age of the oldest tree-ring is known and it is possible for tree-ring data from cores to be plotted and directly compared (Fig. 5.5). Tree-rings show little consistency between cores, even from cores within the same tree, and there is no evidence of a major disturbance for this set of data.

5.3.4 Slabs

Advanced decay of sapwood on slabs OU67713 – OU67717 (as seen in Figures 5.3 and 5.4) and partial decay of sapwood, with uncertain dates of death for trees pertaining to slabs OU67718 and OU67719, meant the last years of growth could not be determined. Although the last year of growth in slabs OU67720 and OU67721 could be determined, the rate of growth was very slow, indicated by small ring widths (Fig. 5.2). For these samples, an inaccurate ring count is likely (error may be as high as 10%) due to false or missing rings, buttressing and counting errors. Slab OU67720 highlights this problem (Fig. 5.2), where 2 transects from the same slab would be expected to have the same number of growth rings. After careful analysis, there was still a 12 ring difference. Even if this discrepancy in the two transects could be resolved, a significant error is probable due to highly concentrated ring spacing from slow growth. It is concluded that none of the slabs are of a quality fit for tree ring analysis. The uncertainties are simply too great to make any conclusions possible.



Fig 5.5: Plot of analysed ring growth from cores of 5 tree specimens at Drizzle Creek Spur. No tree disturbances have been identified in this set of data.

5.3.5 Evidence from silver beech (Nothofagus menziesii) and red beech (Nothofagus

solandri)

Cross-matched chronologies have been developed by Norton (1983a, 1983b) for silver and red beech. This set of data is useful in terms of Alpine Fault paleoseismicity, as it meets the requirements outlined in section 5.1, enabling the identification of the exact year in which each growth-ring was formed, absolute dating and the establishment of a control growth-ring population back to 1750 A.D. The control group is located east of the main divide along the Craigieburn Range. Yetton (1998) used these data sets and another control chronology as a major component in a broader tree-ring chronology study for inferring an Alpine Fault earthquake at 1717 A.D. A major earthquake was observed in Fiordland in 1826, accompanied by abundant landsliding north of the coast from Cascade Point (Taylor, 1855). There is also evidence for this from Drizzle Creek Slip. Norton's tree-ring chronologies for six Fiordland sites (Kea Flat, Upper Hollyford Valley, and West of Lake Te Anau (Takahe Valley, Upper Takahe Valley, Lake Orbell and Lake Eyles) and near the present field area are displayed in Fig. 5.6 to see if any anomalous tree-ring growth occurred in the third or fourth decades of the 19th century in relation to the 1826 earthquake. Sites were all on stable slopes of <20° between 950 and 1100 m and located 25 to 75 km from the Alpine Fault.

A marked decrease in tree-ring growth occurs in 1832 A.D in all but the Upper Hollyford Valley tree-ring chronologies. The five other chronologies match well with the control chronologies for Craigieburn. If the 1832 A.D decrease in growth was caused by an Alpine Fault event, a greater growth suppression would be expected from the Upper Hollyford Valley site that is geographically closer to the Alpine Fault. As this hasn't been observed and the data set matches up with the control, tree disturbance from an Alpine Fault event is unlikely as a possibility for the decrease in growth. Therefore, there is no evidence in these data showing a signal for the 1826 A.D earthquake in the western Fiordland area. It is interesting to note that Yetton et al (1998) infer a seismic cause (1717 A.D Alpine Fault earthquake) for a major growth suppression in this same set of data. If their inference is accepted, then another growth suppression should occur around 1826 A.D. A number of possibilities arise as to why this is not the case. Either the 1826 earthquake was a large event around west Fiordland, but of a lesser magnitude relative to the inferred 1717 A.D event, thus not recorded at these distant sites, or alternatively and probably less likely, the growth suppression inferred for the 1717 A.D earthquake was not seismically related.

Taylor's (1855) written account of an 1826 A.D event strongly suggests disturbance and uplift, geographically consistent with the Alpine Fault. Wells et al. (1999) have consistent suppressions at 1717 A.D, with a control chronology that suggests these suppressions were from a widespread major disturbance. Modified Mercalli intensity levels for tree disturbances from earthquakes are as follows; trees are shaken lightly at intensity V, moderately at VI and strongly at VII. Branches and trunks may be broken off during intensity VIII+ earthquakes (Wood and Neumann, 1931).

Wells et al., (1999) use MM VIII at the tree sites in their calculation of a provisional Modified Mercalli isoseismal map for the 1717 earthquake. The lack of evidence for a seismic event at 1826 from these tree-ring chronologies at these sites at least 25 km from the Alpine Fault, is interpreted to be consistent with a localized West Fiordland earthquake. It is inferred that these tree sites experienced Modified Mercalli intensity levels ≤ 7 ; insufficient to traumatise trees.

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Figure 5.6: Available cross-matched tree chronologies along the strike of the Alpine Fault from Lake Te Anau to Kea Flat. There is no evidence for a major earthquake at 1826 A.D, in Western Fiordland. The Y-axis on all the graphs is the ring-width index. After Yetton et al. 1998 and Norton 1983a,b.

5.4 Conclusions

• Tree-ring chronologies were not established for Rimu adjacent to the Alpine Fault. Despite the expenditure of a large amount of time and effort, attempts to use felled Rimu trees to determine times of forest disturbance were unsuccessful. Wright (1998) achieved some success using a similar approach at Waitaha River, but those trees had been felled only a year or two prior to sampling. The widespread decay of the sapwood, as seen in the Okuru trees, had not yet occurred at Waitaha River. Also, the time of death was known to a single year, whereas at Okuru, this uncertainty in itself may introduce a 10 year error or more. A round from a recently felled Matai tree at Okuru was collected by the authors in 1998 and proved a potentially valuable source of data, with a major growth suppression between 1710 and 1720

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• Tree ring chronologies for silver and red beech, from selected sites in the Fiordland and South Westland area showed no evidence of disturbance from a possible Alpine Fault earthquake around 1826 A.D. The lack of evidence, however, does not mean no earthquake occurred, but rather that the 1826 event was of lower magnitude than the 1717A.D event, did not rupture on a regional scale and did not traumatise trees in the East Fiordland and South Westland areas.

6 DISCUSSION

The work reported in this volume had the initial aims of providing better constraints on the timing of the last few ruptures on the Alpine Fault in the Haast-Okuru area. The approach was initially two-fold: (i) excavating a trench across the fault trace in order to find datable material to supplement the results from previous trenching; (ii) collecting sawn rounds off stumps of trees close to the fault trace that were felled during the 1960s and 1970s in order to measure variations in growth rate and, by ring-counting back from the sapwood, estimate the age of any major disturbances.

Both these approaches were carried out, but due to unforeseen problems discussed earlier, the results were not as useful as hoped for. Nevertheless, significant conclusions can be drawn from the data. Placed in a context of the paleoseismic history of the whole Alpine Fault, these add further evidence for repeated major ruptures along the southern section of the fault.

6.1 Paleoseismology

The Turnbull trench provides evidence for three rupture events in the last 1000 years. This is consistent with data from the trenches previously excavated at Haast and Okuru (Berryman et al., 1998). Age constraints, unfortunately, can only be placed on the earliest of the three, which is post 1105 ± 85 AD. This event is undoubtedly the same as the first of the three events recorded in the Haast and Okuru trenches as occurring shortly before 1220 ± 50 AD (Berryman et al., 1998). It also corresponds to a major influx of silty sand to the South Turnbull Swamp that occurred shortly before 1260 ± 55 AD. South of the Haast River, the fault slip in this event reached 8 m dextral (Sutherland and Norris, 1995; Berryman et al., 1998). Yetton et al. (1998) provide evidence for a major Alpine Fault rupture on the northern section of the Alpine Fault (Fig. 6.1) at around 1220 AD (the "Muriel Creek Event" of their chronology), and evidence for a rupture at this time was also found at Waitaha River in central Westland by Wright (1998). The data are insufficiently precise to conclude that these observations all refer to a single rupture along the length of the Alpine Fault, but this remains a clear possibility. In any case, it appears that the whole length of the Alpine Fault ruptured in either a single event or a series of events in the late 12^{th} or early 13^{th} centuries.

While the Turnbull trench provides evidence for two further events after 1200 AD, it unfortunately failed to add to the age constraints for these events. The best estimates are still those from the trenches at Okuru (Berryman et al., 1998) which place the penultimate event between 1400 and 1600 AD and the last event after 1665 AD. The last silty clay influx to the South Turnbull Swamp is also consistent with the latter date. Data from further south (Cooper and Norris, 1990; Sutherland and Norris, 1995) also place the last event after 1650 AD. These data are consistent with a date of 1717 AD suggested by Wells et al. (1999), based on dendrochronology, for a surface rupture on the Alpine Fault over much of Westland. A closely similar age was determined by tree-ring counting and radiocarbon dating by Wright (1998) at Waitaha River. Once again, however, the dating constraints are insufficient to conclude that a single fault length rupture is responsible, rather than a series of two or more ruptures over a short time period. A consistent displacement of 8 m dextral for the last event from Haast River to Lake McKerrow (Berryman et al., 1998; Sutherland and Norris, 1995; Chapter 2) is strong evidence that a single rupture is represented south of Haast River. Disturbance in growth of trees at 1717 A.D. in northern Fiordland near Te Anau is reported by Wells et al. (1999) as evidence for a single fault-length rupture and a single Matai tree growing on the fault trace at Okuru showed strong growth suppression for 5 years following an event between 1710 and 1720 (Berryman et al., 1998). Unfortunately, all trees sampled in

this study had lost their outer rims from post-felling weathering and could not be used with any confidence to support these observations. We feel the best approach in future would be to core large silver beech trees close to the fault, as a cross-matched chronology of silver beech in this region is available. A major problem here is likely to be the scarcity of sufficiently old beech trees along the fault trace.

A major earthquake occurred somewhere off the Fiordland coast in 1826 (Taylor, 1855) and the effects were reported by sailors in the area at the time. Extensive landsliding was noted extending north from Milford Sound as far as the Cascade River. We do not know of any evidence of Alpine Fault rupture onland in this event although an offshore rupture of the fault is quite possible. It is even possible that a small amount of slip occurred onland and is amalgamated with the early 18th Century event. Dating movement of this age would be impossible by radiocarbon methods as it is too young, and dendrochronology on beech trees is probably the only way to pick up traces of this event. From the contemporary reports, the 1826 event was of a sizeable magnitude – rough estimates based on the area of effects noted would give it a magnitude of c. 7–7.5. Beech trees away from the fault, studied by Norton (1983a, b), show no evidence of growth suppression at this time, consistent with a magnitude no larger than this.

6.2 Radiocarbon dating

Attempts to date material from the upper soil horizon in the Turnbull trench proved to be a problem. Ages obtained from carbonaceous clays were grossly inconsistent with each other and up to an order of magnitude older than ages obtained on the lower horizon. Clearly they have been contaminated with an unknown source of old carbon. In general, we have had few problems with radiocarbon ages on the West Coast. Most are consistent both with other ages from the same horizon and with their position in the local sequence. Where problems have arisen, they are usually for readily determinable reasons. For instance, ages on small seeds from colluvial wedges in the trenches at Haast are much older than they should be, due to recycling of readily transportable carbonaceous material the earliest deposits into later colluvial wedges. The ages of the younger wedges are similar to the ages from the oldest deposit, which displays a highly consistent set of dates. Given that colluvial wedges, by their very nature, are formed by recycling of older sediment from the fault scarp, such "contaminated" ages are both logical and to be expected.

In the case of the ages from the upper soil horizon in the Turnbull trench, however, the origin of the contamination is both unknown and perplexing. The oldest "age" obtained, c. 12000 yr BP, is an order of magnitude older than the ages obtained from wood samples just above the basal gravel terrace, and much older than the terrace itself (based on regional correlation). In order for the spurious age to be caused by contamination, around 75% of total carbon in the sample would need to be ancient carbon (i.e. free of any ¹⁴C). Where this came from is unclear. It is possible that erosion of older deposits upstream released wood fragments which floated down and were deposited during a flood which covered the terrace. The fragments subsequently decayed and formed the basis for the carbonaceous clay lenses. This is the only feasible possibility we can conceive of, although of course the truth may be quite different!

It may be significant that all three spurious ages from the upper horizon were measured on very small samples using Accelerator Mass Spectrometry (AMS) at GNS whereas the ages on the lower horizon were obtained from large wood samples using conventional counting techniques at the University of Waikato. Small samples are more likely to be susceptible to contamination since only a small total amount of contaminant is required. The large differences between the three ages suggest highly variable amounts of older carbon

contaminant. One approach might be to analyse a large number of small samples or splits from the clay lenses. The pattern of ages obtained may give some idea of the degree of contamination and provide a better estimate of the maximum age of the deposit. An alternative, and scientifically sounder, approach would be to separate out all the various organic components of the clay and analyse these separately using AMS methods. Similar studies on New Zealand carbonaceous soils have shown that the different components may indeed have slightly different ages, although not normally of the degree required here (Prior, 2000 and pers. comm.). Unfortunately, for the present study, time and financial constraints ruled out either of these detailed investigations.

6.3 South Turnbull Swamp

Although not part of the original proposal, the detailed study of the South Turnbull swamp was carried out to see whether a record of fault rupture events was decipherable from the swamp infill sequence. The setting of the swamp is clearly controlled by subsidence induced by fault displacement and the calculated rate of subsidence is an order of magnitude faster than would be expected for a similar swamp that was not directly fault-controlled. Swampwide incursions of river sediment occur which may readily be incorporated into a model linking fault displacement and subsidence. Unfortunately, these indirect signals of fault rupture are always subject to a degree of ambiguity as causes other than faulting may also be responsible. The major incursion of silty sand prior to 1260 AD observed in the swamp infill is the most compelling signal of fault rupturing. The catastrophic nature of the event and the large amount of subsidence required make such an interpretation robust. The five other swamp-wide layers of silty clay recorded since 880 AD may also reflect ground ruptures. However, a major flood event some time after an earthquake could conceivably create an extra layer in addition to those forming in response to the displacement-induced subsidence. It is also possible that a ground rupture may not be large enough to generate an observable signal by not creating sufficient subsidence to cause flooding.

In the model, the deposition of swamp-wide silty-clay layers is be related to the increased vulnerability of the swamp to overbank flooding by the Turnbull River during floods following fault rupture. This vulnerability to inundation decreases with time as the sand barrier is built up at the swamp margin. Since the barrier to flooding, the sand bar, is itself built up by flooding, it follows that rare large flood events may still inundate the swamp long after a fault rupture has occurred. Hence it is likely that some of the sediment layers may result from events other than fault displacement. Only by careful documentation and age bracketing of different sites may a chronology of fault movement be built up. Thus all five layers may record ground ruptures but the actual number could be less than this. Since the trenches only record two events after c.1200 AD whereas the swamp has three silty-clay layers, it is likely that at least one silt inundation has been generated other than by ground rupture.

Although the South Turnbull swamp does not therefore provide an unambiguous record of all fault rupture events since its inception, it does provide valuable data which may be used in conjunction with trench-based data. Its great advantage is that it provides a long and continuous record. Its disadvantage is the indirect nature of the signal with the resulting uncertainty. Nevertheless, we consider that investigation of similar swamps elsewhere is well worthwhile.



Fig. 6.1 Map of South Island showing locations of direct paleoseismological data reported by Cooper & Norris (Milford, 1990), Sutherland & Norris (L. McKerrow, 1995), Yetton et al. (Crane Ck., Haupiri, Toaroha, 1998), Wright (Waitaha, 1998), Berryman et al. (Haast, Okuru, 1998) and this report.

6.4 Regional correlation of rupture events on the Alpine Fault.

Yetton et al. (1998) have combined data from their own and other research to produce a composite chronology of Alpine Fault ruptures, to which they have given names (Table 6.1). Wright (1998) and Wright et al. (in preparation) have completed a detailed study at a single site at the Waitaha River (Fig. 6.1) where they have established an event chronology largely

CHAPTER SIX: DISCUSSION

consistent with that of Yetton et al. (1998) (Table 6.1). A major question is whether these "events" are ruptures extending the whole length of the fault or represent breaks on only a limited section of the fault. Thus the fault may rupture its whole length in a series of, say, magnitude 7.5 events within a limited time period rather than in a single magnitude 8 event. Radiocarbon ages are generally too imprecise to distinguish these possibilities. Tree-ring ages, and in particular dendrochronology, have the potential to narrow down the time-slot to a few years but, with the possible exception of the last event, have not yet achieved this.

Earthquake Chronology Comparison				
Event Name	Age (Yetton et al, 1998)	Age – Waitaha (Wright 1998)	Age (Bull, revised)§	Ages, south of Haast
Toaroha River	1717 AD	1720 ± 10 AD	1718 ± 10 AD	post 1665 AD ?1717 AD
Crane Creek	$1620 \pm 10 \text{ AD}$	-	1615 ± 10 AD	
Macgregor Creek*	-	1580 ± 10 AD	1578 ± 10 AD	
Geologists Creek	1425 ± 15 AD	1440 ± 15 AD	1428 ± 10 AD	1400-1600 AD
Muriel Creek	1220 ± 50 AD	1210 ± 30 AD	1224 ± 10 AD	1105-1220 AD
Roundtop	940 ± 50 AD	900 ± 100 AD	961 ± 10 AD	880 ± 110 AD
Waitaha River	595 ± 60 AD	$550 \pm 100 \text{ AD}$	-	
John O'Groats	$25 \pm 90 \text{ BC}$	-	-	
Waitaha 2*	÷	300 ± 100 BC	÷.	

 Table 6.1
 Comparison of earthquake chronologies from three sources, together with age ranges for events on the southern section of the fault from this study. There is no implication that the southern events are necessarily the same as the named events to the north.

§ Bull's revised lichenometric dates are pers. comm. to C Wright 1998, based on Bull 1996.

* new events proposed by Wright, 1998.

Comparing the paleoseismic data from the Haast-Turnbull area discussed above, the last event (Toaroha River event) is compatible with the last event in the south. The Crane Creek – Macgregor Creek events (which could conceivably be the same event – Wright et al., in preparation) are more difficult to correlate with events recorded south of Haast although the penultimate event here has such poor age constraints it could conceivably represent one or both of these northern events (depending on whether they are separate events or not). The Geologists Creek rupture is another possible correlative of the penultimate event in the south. Alternatively, the southern event may be a completely separate rupture and not correlate with either of these northern events.

The Muriel Creek event at around 1200 AD may be the same event as the earliest event recorded in the trenches south of Haast and represented by a major inundation of the South Turnbull Swamp. Unfortunately, the error bars on the radiocarbon ages are too large to rule out separate events in the north and south. The Roundtop event at c. 900 AD is compatible with the inception of subsidence in the South Turnbull Swamp at around 880 ± 110 AD. It is also possibly consistent with stabilisation of the gravel terrace surfaces at the Turnbull and their removal from the main river channel deposition. Once again, however, the age constraints are too broad to demonstrate exact contemporaneity of these events. The investigated record in South Westland does not go back any earlier so that the earlier events in Table 6.1 are not represented.

The data are tantalizing, as a case could be made for fault-length ruptures occurring every 300 years or so. In the south, this would be consistent with a slip rate of 27 mm/year (Norris & Cooper, in press) and a slip per event of 8 m (Berryman et al., 1998; Chapter 2). An extra event is required in the north during the last 800 years. Paleoseismological studies are more likely to miss events as a signal may be absent or too weak at a site to be recognised. This is particularly the case with strike-slip faults where sediment accumulation on the downthrown side may be small. Nevertheless, some degree of consistency is developing regarding ruptures on the Alpine Fault.

We conclude by outlining two outstanding problems relating to Alpine Fault-related seismic hazard.

Firstly, the imprecision of radiocarbon ages means that it is impossible to distinguish between a full length, magnitude 8 rupture on the fault and a series of smaller events spaced closely in time. The amount of movement on the fault south of Haast (8m in each of the last three events) strongly suggests that a reasonable length of fault broke in a single event (c. 200 km; Wells & Coppersmith, 1994), but this section could still rupture separately from the northern part studied by Yetton et al. (1998) and Wright et al. (in preparation). Of the methods used to date, only the use of properly cross-matched dendrochronology can resolve this problem, and even then, two events within a year would remain a possibility. The "worst-case" scenario of a magnitude 8 rupture from Hokitika to Milford Sound must be emphasized, but the alternative of two or more smaller events within a few years breaking the whole fault must also be considered when estimating hazards. Further dendrochronological work may help resolve this problem but our experience shows that such undertakings are difficult with New Zealand tree species.

Secondly, the total record of events on the Alpine Fault is still rather short, spanning about 1200 years. A longer record would assist in calculating probabilities, hazard levels and long-term behaviour of the fault. Investigations of long-term recorders of subsidence or displacement, such as the South Turnbull Swamp and similar features, may assist in extending the record backwards in time.

Clearly, the two problems are interlinked since, even at best, dendrochronology is unlikely to be usable prior to 1200 AD. Nevertheless, a longer chronology would be a valuable asset in understanding the fault behaviour.

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Appendix 1

Alpine Fault Trace Map Haast River – Arawhata River

ALPINE FAULT Haast River - Arawhata River Trevor Wright 2000









Appendix 1 Alpine Fault Trace Map Haast River - Arawhata River

Appendix 2

Turnbull Trench Log





South Turnbull Swamp Stratigraphy





