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Paleoseismic Investigation Of The North And West Wairau Sections Of The Alpine Fault South Island, New Zealand.

April 2002

PALEOSEISMIC INVESTIGATION OF THE NORTH AND WEST WAIRAU SECTIONS OF THE ALPINE FAULT, SOUTH ISLAND, NEW ZEALAND.

Report prepared for:

EARTHQUAKE COMMISSION RESEARCH FOUNDATION

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Date: April 2002

Earthquake Commission Research Report No. 99/353

REPORT SUMMARY

This report outlines the results of paleoseismic trenching at four different localities spread over an approximately 100 km length of the north and Wairau sections of the Alpine Fault. A total of 15 radiocarbon dates from 6 trenches provide information on the timing of pre-historic earthquakes on the Alpine Fault.

The most recent earthquake rupture at the Blue Grey River, near the southwest limit of the study area, was a relatively small event resulting in a horizontal offset of approximately 1.0 ± 0.3m and a vertical offset of 0.2- 0.4m. This earthquake rupture occurred after AD 1450, and is most likely to have occurred in the period soon after AD 1600 (and up to AD 1680). The most recent earthquake rupture at the Maruia River was also a relatively small event resulting in a horizontal offset of approximately 1.3 ± 1m and a vertical offset of 0.25 ± 0.1m. Based on the radiocarbon dates the best timing estimate is an earthquake that occurred sometime in the period between AD 1530 – 1700.

The Matakitaki 2 paleoseismic excavation at the Matakitaki River provides a well-constrained date for the most recent rupture of the Alpine Fault at this location. This rupture occurred after AD 1455 and before AD 1700, and it is most likely to have occurred between AD 1500 and 1670. No definite single-event horizontal offset can be inferred from this site but the evidence suggests the most recent horizontal offset was not larger than approximately 3m, and was quite possibly less. Assuming this is the same event as that recognised 50 and 60 km further southwest at the Maruia and Blue Grey River, then the best estimate of event timing for these three combined locations is the period between AD 1600 and 1670.

Previous work utilising forest age disturbance patterns in Westland and Buller indicate the most likely time of this earthquake was 1620±10 years. This is a good fit to the data from the three new sites but no forest age data is available in the current field area to better test this possibility. If this is the same earthquake event then this implies a surface rupture length of at least 320 km. However, in the absence of forest age data in the current study area there is still the possibility that the surface ruptures investigated at these three new sites are the result of a separate smaller earthquake with an approximately 100 km rupture length.

The Tophouse trench provides evidence of a rupture on the Wairau section of the Alpine Fault at some time between AD 200 and 1840 (European settlement). The new data from the Wairau section of the Alpine Fault is consistent with that obtained in recent paleoseismic excavations located 50 km further northeast of Tophouse Saddle (Zachariasen *et al.* 2001). If the most recent event identified in their Wadsworth trench is the same as that in our Tophouse trench, then the most recent rupture of the Wairau section of the Alpine Fault occurred between AD 200 and AD 1000 and probably closer to AD 200. This indicates that there is an Alpine Fault rupture segment boundary somewhere between Matakitaki River and Wairau Valley. This rupture boundary is most likely southwest of Tophouse Saddle and in the general vicinity of Lake Rotoroa.

For the north Alpine Fault the most recent event had relatively small horizontal surface displacements averaging around 1.3 m ± 0.6. The long term slip rates, and youngest possible date for the last event (AD 1700), suggest that it is likely that elastic strain of this order or more (2.0 – 2.5m) has already accumulated on this section of the fault. The north Alpine Fault could rupture in conjunction with the central (and south Westland?) section (rupture length 350 - 500 km, Moment magnitude **M** 7.8 – 8.2) or in a considerably smaller separate earthquake (Moment magnitude **M** 7.1-7.5).

An earthquake rupture of the Wairau section of the Alpine Fault is likely to generate an earthquake with a moment magnitude of approximately **M** 7.3-7.7. Previous estimates of single event horizontal offsets associated with earthquakes on this section of the fault are 5 ± 1.5 m. The long-term slip rates (4.5 ± 1mm/yr), and the youngest possible date for the last event (AD 1000), indicate it is likely that elastic strain of 3.5 – 5.5m has accumulated on this section of the fault. However, the radiocarbon dates suggest it is more likely that 1500 – 1800 years have elapsed since the last earthquake rupture with a corresponding accumulated strain of 6.3 –9.9m.

These new results suggest that sufficient elastic strain may have already accumulated on both these sections of the Alpine Fault to generate new earthquake ruptures with surface offsets comparable to those of the most recent events. On this basis, earthquakes on both these sections of the Alpine Fault must be considered a strong possibility within conventional planning time periods (i.e. 50 -100 years).

LAYPERSON'S ABSTRACT

PALEOSEISMIC INVESTIGATION OF THE NORTH AND WEST WAIRAU SECTIONS OF THE ALPINE FAULT, SOUTH ISLAND, NEW ZEALAND.

The Alpine Fault is the onshore boundary of the Pacific and Australian crustal plates in the South Island of New Zealand. The Alpine Fault commences at the southwest coast at Milford Sound and forms a major active fault line along the west boundary of the Southern Alps for approximately 400 km to the Lewis Pass area. It then continues as a less active fault a further 200 km through the Nelson Lakes area to the Pacific coast at Blenheim.

Although the Alpine Fault has the highest long term movement rate of any active fault in New Zealand there have been no historical earthquakes on any part of it including the most active central area. This project has been undertaken to determine the approximate timing of the most recent prehistoric earthquake on the Alpine Fault in the less active area in the north (the north section of the Alpine Fault) and in the northeast (the Wairau section of the Alpine Fault). By knowing the approximate timing of the most recent prehistoric earthquake, and how much the fault moved in the last earthquake, it is possible to estimate the likelihood of a future earthquake of a similar size.

Excavations have been undertaken at four locations, three on the north Alpine Fault southwest of Nelson Lakes, and one on the Wairau section of the fault near Tophouse. These excavations of the surface soil and gravel at the fault line have provided wood, charcoal and peat that can be radiocarbon dated to determine the approximate age of the soil and gravel, and in some cases the time of the last earthquake rupture.

The results from the three locations on the north Alpine Fault indicate that the most recent earthquake in this area was between AD 1440 and AD 1700. It is

most likely to have been between AD 1600 and 1670 and closely matches previous research on the fault further southwest that suggests a large earthquake occurred at around AD 1620 that extensively damaged the natural forests.

The results from the excavation on the Wairau section of the fault indicate there has been an earthquake in this area since AD 200, but the new results do not indicate when. If this is the same earthquake rupture that has been identified in previous work 50km northeast (which is likely) then the earthquake occurred between AD 200 and AD 1000.

Although the fault has been locked near the ground surface since these prehistoric earthquake ruptures, the steady movement of the plates at lower crustal depths has been accumulating strain near the fault. These new results suggest there is already sufficient stored energy to generate an earthquake of a similar size to the most recent earthquake rupture along virtually the entire Alpine Fault, including the Wairau section of the fault near Blenheim.

TECHNICAL ABSTRACT

PALEOSEISMIC INVESTIGATION OF THE NORTH AND WEST WAIRAU SECTIONS OF THE ALPINE FAULT, SOUTH ISLAND, NEW ZEALAND.

Detailed paleoseismic investigation of the Alpine Fault has been undertaken at four locations that bracket the north and Wairau sections, between the Blue Grey River and Tophouse Saddle. Six trenches and pits have been excavated at four localities along one hundred kilometres of fault strike and a total of fifteen radiocarbon dates provide age constraints on the timing of the most recent earthquake.

At the three localities along the north Alpine Fault (Blue Grey River, Maruia River, Matakitaki River) there is consistent evidence that the most recent earthquake occurred between AD 1450 and 1700, and it is most likely to have occurred between AD 1600 and 1700. This is in close agreement to the results obtained from previous paleoseismic excavations on this north section of the Alpine Fault at two localities further southwest. Previous analysis of the timing of forest disturbance suggests that the earthquake occurred in the southwest area in AD 1620 ± 10yr, and this may be the same earthquake that is recorded at these three new locations. The surface offsets at the fault scarp during the most recent event at the new locations were relatively small (horizontal offset 1.3 ± 0.6m, vertical offset 0.25± 0.1m).

The trench site at Tophouse Saddle on the Wairau section of the Alpine Fault indicates there has been an earthquake rupture since AD 200 but how long after this date can not be determined. If this is the same earthquake rupture as that recorded in previous work on this same section of fault, then the rupture occurred between AD 200 and AD 1000, and is likely to have been nearer to the AD 200 end of this range.

The new paleoseismic data from this investigation indicates there is an earthquake rupture segment boundary between the Matakitaki River and Tophouse Saddle. Long-term slip rates suggest sufficient elastic strain has accumulated since the last earthquakes to generate new earthquake ruptures with surface offsets at the fault scarp comparable to those of the most recent events. On this basis, earthquakes on both these sections of the Alpine Fault should be considered possible within traditional planning time periods (i.e. 50 -100 years).

CONTENTS

Section 1

INTRODUCTION

1.1 BACKGROUND

The Alpine Fault is the longest active fault in New Zealand with an overall length of more than 600 km. It also has the highest average long term slip rate of any active fault in New Zealand and a total cumulative dextral separation of at least 350 km. Despite this there have been no significant moderate or large earthquakes on the Alpine Fault since European settlement in New Zealand, and the earthquake data over the last 150 years show that only a small percentage of the strain accumulation across the Alpine Fault has been released seismically. It appears that the Alpine Fault is locked and has the potential to rupture in large earthquakes.

It is critical to establish the timing of the most recent prehistoric earthquake ruptures of the Alpine Fault as a first step in assessing the probability of future Alpine Fault earthquakes. This report outlines the results of paleoseismic excavations at four localities along the north and Wairau sections of the Alpine Fault. It continues the earlier investigation work of Yetton *et al.* (1998) and Yetton (2000) aimed at establishing the paleoseismic history of the central and north Alpine Fault from the Hokitika area to the Ahaura River.

This project provides a fundamental first step in the assessment and mitigation of earthquake hazard associated with the Alpine Fault in the northern South Island.

1.2 OBJECTIVES

This project has the following objectives:

- to define the approximate date of the most recent earthquake rupture at a range of locations along the strike of the north and Wairau sections of the Alpine Fault
- where possible to also define the approximate date of the penultimate event, and any earlier events which are able to be determined
- Assess the estimates of the average long-term fault slip rate
- Combine this information to provide a first order approximation of the likelihood of a future rupture of the north and Wairau sections of the Alpine Fault in the next 50-100 years.

The remainder of this section provides a brief introduction to the Alpine Fault describing its location, plate tectonic setting, general structure, and previous paleoseismic work. This is followed by an outline of the contents of the subsequent sections of the report.

1.3 INTRODUCTION TO THE ALPINE FAULT

1.3.1 Plate Tectonic Setting

The Alpine Fault is part of a transform fault zone through continental crust linking the west dipping subduction zone of the eastern North Island with the east dipping subduction zone of southern Fiordland.

Figure 1.1, from Walcott (1998), shows the major plates of the southwest Pacific and the plate tectonic setting of the Alpine Fault. The Pacific plate has rotated counterclock-wise relative to the Australian plate about poles (solid squares in Figure 1.1), the positions of which have changed progressively with time from 5d (17.5 Ma) to 3a (5.89 Ma) thereby increasing the component of shortening. The solid circle is the current NUVEL 1A pole (De Mets *et al.* 1994).

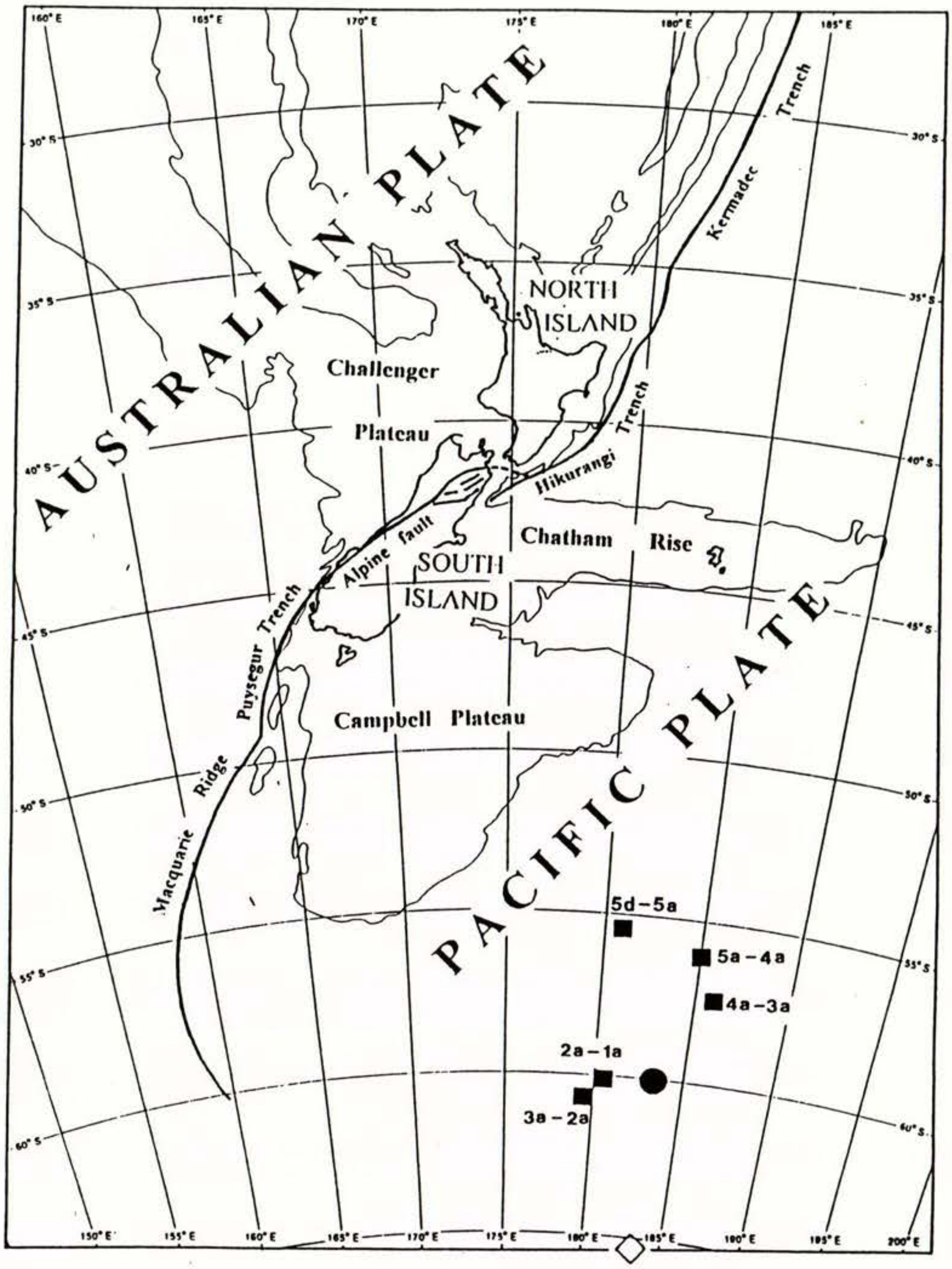

Figure 1.1 – The plate boundary of the Pacific and Australian plates with the Alpine Fault (labeled) forming the onshore boundary through the central and southern South Island (from Walcott 1998). The Pacific plate has rotated counter-clockwise relative to the Australian plate about poles (solid squares). The solid circle is the current Nuvel 1A pole obtained from seafloor spreading information (De Mets *et al.* 1994).

The Alpine Fault in the South Island is approximately 650 km long and extends from Blenheim, on the northeast coast, to Milford Sound on the southwest coast (Figure 1.2). For descriptive convenience this project broadly adopts the original geographic division of Berryman *et al.* (1992) into sections, but makes the clear distinction that these sections are not necessarily rupture segments. Figure 1.2 shows the divisions adopted and this descriptive classification is discussed in more detail in Section 2.

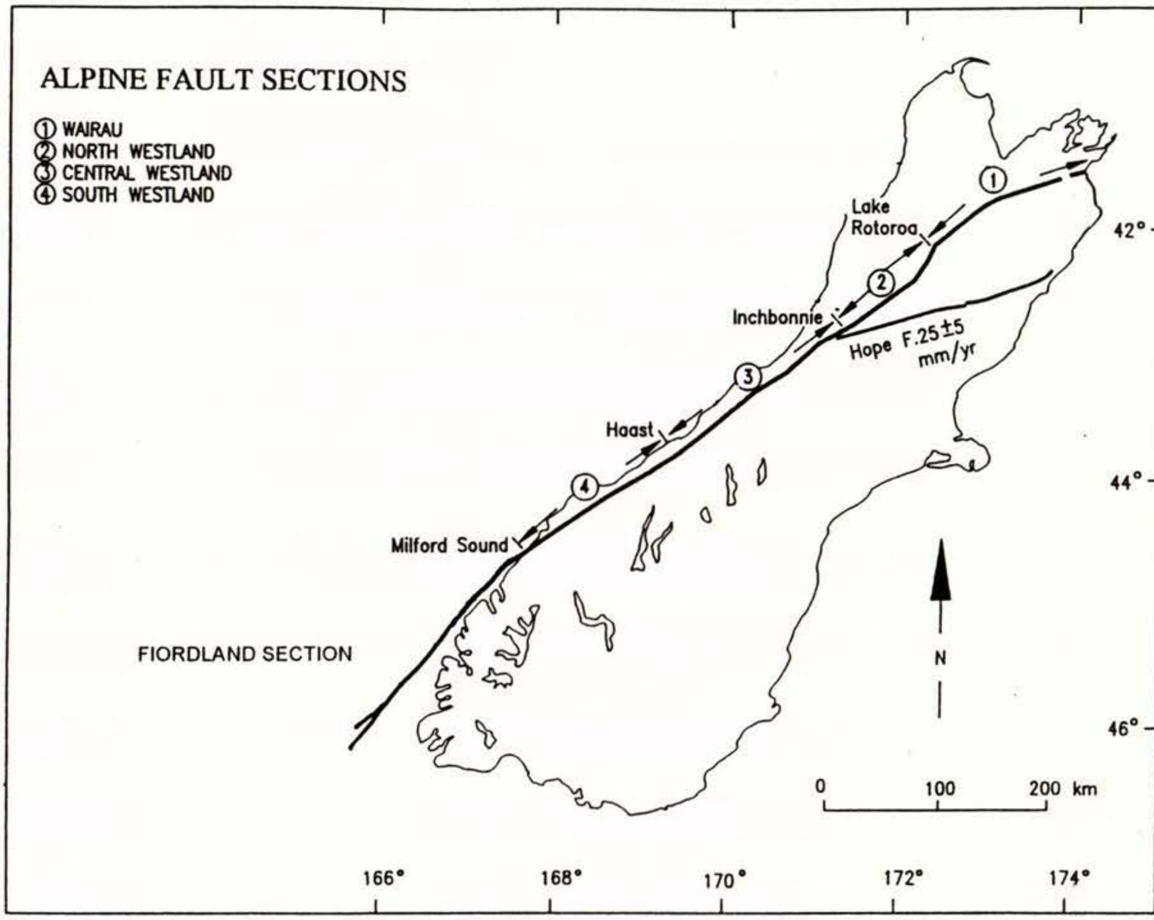

Figure 1.2 – Division of the Alpine Fault into four sections after Berryman *et al.* (1992), with the addition here of a Fiordland section based on Barnes, pers. comm., 1999. These sections are not necessarily fault rupture boundaries. Figure adapted from Berryman *et al.* (1992).

Although the Alpine Fault forms the main plate boundary feature through the South Island, its character changes along its length as plate motion is partitioned onto other structures, and in particular the strands of the Marlborough Fault Zone that coalesce with the Alpine Fault in the north section.

The NUVEL 1A pole position of De Mets *et al.* (1994) for the Pacific Plate is shown in Fig 1.1. At most locations along the central section and northern Alpine Fault south of the "big bend" this pole location predicts plate rates of around 37mm/yr at an azimuth of 071°. This resolves into a fault parallel dextral horizontal rate of 35.5mm/yr and fault normal horizontal rate of 10mm/yr.

The central Alpine Fault is therefore oblique to the plate motion, and in addition to the dominant dextral horizontal strain, there is a significant component of shortening at the plate boundary. The oblique motion at the boundary results in local segmentation of the fault trace into low angle more north striking thrusts with subvertical linking strike - slip faults sub-parallel to the plate vector (Norris & Cooper 1995). The component of shortening results in uplift on the southeast side of the Alpine Fault that is responsible for the formation of the Southern Alps. In most of the central area the Alpine Fault marks the western boundary of the Southern Alps range front.

The pattern of local segmentation noted by Norris & Cooper (1995) is generally absent in the north Alpine Fault (Yetton 2000), However, the fault in this area remains oblique to the plate motion vector, and there is still significant uplift on the southeast side. Some of this relative uplift is masked in the landscape by apparent higher regional uplift rates on the northwest side.

The progressive change in fault strike associated with the "big bend" increases the predicted relative component of shortening. The double bend has been the subject of considerable conjecture both as to its formation (e.g. Suggate 1979) and the kinematics of the area (e.g. Yeats & Berryman 1987; Lamb 1988). Although the geometry forms a restraining bend on the Alpine Fault, it is not associated with marked relative uplift (Wellman 1979). Geological mapping of the bends area (Rose 1986; McLean 1986) shows low angle thrust faulting to the west of the Alpine Fault of slivers of Mesozoic and older terranes over a Pliocene foreland basin, filled with schist debris shed across the fault from the uplifted Southern Alps adjacent to the Marlborough Fault Zone.

The Marlborough Fault Zone lies to the east of the north Alpine Fault and comprises a major system of northeast trending strike-slip faults that include the Hope, Clarence, and Awatere Faults as well as the continuation of the Wairau section of the Alpine Fault northeast of Lake Rotoiti. These faults are sub-parallel to the plate motion vectors and therefore generally purely strike-slip for most of their length.

The faults of the Marlborough Fault Zone splay and form a series of imbricate oblique thrust systems at their southeast junction with the Alpine Fault and the kinematics and details of the strain transfer in this transition area is currently being investigated (Langridge, pers. comm. 2001).

Estimates of average long term slip rates derived from Late Pleistocene and recent geological markers across the north and Wairau sections of the Alpine Fault are outlined and discussed later in Section 8 of this report.

1.3.2 Regional geology and total fault offset

The Alpine Fault separates the quartzofeldspathic dominated terranes of the eastern province, including the associated Haast Schist terrane, from Paleozoic granites and meta-sediments of the Buller terrane. Figure 1.4 summarises the basement geology of the South Island adopting the terrane classification of Bradshaw (1989).

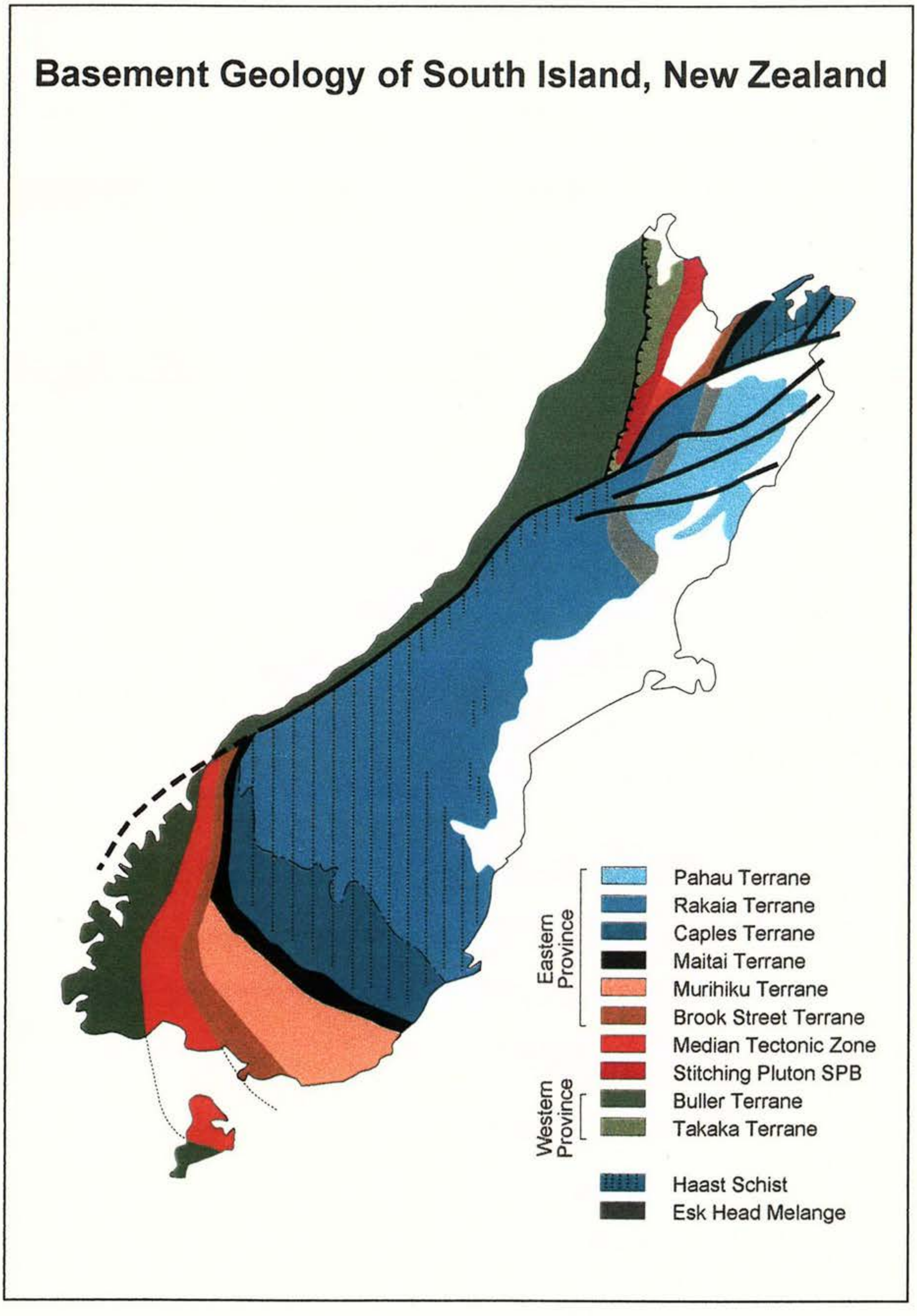

Figure 1.3 – The basement geology of the South Island, New Zealand adopting the terrane classification of Bradshaw (1989). Map courtesy of Anekant Wandres.

The Alpine Fault is recognised as one of the major strike-slip faults in the world. Wellman (1955a) first noted the lateral shift of the Permian rocks of the Brook Street terrane by the Alpine Fault from Fiordland to northwest Nelson (Figure 1.4). This is an apparent offset along the fault of approximately 460 – 480 km. While there has been some disagreement over this estimate (see for example Suggate 1963), and others have proposed alternative oblique-slip models resulting in some apparent offset rather than a pure strike-slip separation (Campbell and Rose 1996), most geologists accept at least 350 km of strike-slip movement has occurred along the Alpine Fault.

The timing of this movement is still in question. Whereas early workers favoured a Cretaceous initiation (Suggate 1963; Wellman and Cooper 1971), plate tectonic considerations and implications based on the sedimentary record from Cenozoic basins adjacent to the fault currently favour an early Miocene inception (Carter and Norris 1976; Norris *et al.* 1978; Kamp 1986; Cooper *et al.* 1987; Walcott 1998).

1.3.3 Geodetic and GPS surveys

Resurveys of 100 year old geodetic survey networks (Walcott 1978; Walcott 1984; Wood and Blick 1986) cross the Alpine Fault indicate elastic strain is accumulating over a broad zone in the rocks on each side of the fault at rates consistent with the plate tectonic predictions. It is likely that this accumulated elastic strain represents potential energy in storage for the next Alpine Fault earthquake.

Berryman *et al.* (1992) highlight the surprising consistency of the magnitude of the strain rate across the fault from South Westland to the Wairau section, despite the implied reduction in slip rate to the north. They also note that these rates alone, in conjunction with the definite absence of Alpine Fault earthquakes since at least 1840, suggest the observed strains can only continue to accumulate for one or two hundred more years before rock strength is exceeded and an earthquake occurs.

Aseismic creep has not been observed along any part of the Alpine Fault. The Alpine Fault trace crosses sealed roads in at least 10 locations and a concrete monitoring wall was constructed across the trace at Maruia River in 1964 (Section 4).

Beaven *et al.* (1998) report that small scale survey networks crossing the Alpine Fault indicate no significant near- surface aseismic fault slip on the central Alpine Fault over the past 25 years. Recently the first GPS (Global Positioning System) resurveys of the original triangulation network have been carried out between Christchurch and Hokitika (Pearson *et al.* 1995). The observed strain rates over a period from 1978 to 1992 are once again consistent with the De Mets *et al.* (1994) plate velocities, and indicate about two thirds of the plate motion is being taken up as elastic strain in the vicinity of the Alpine Fault. Further strain is accumulating east of the Alpine Fault in the Porters Pass - Amberley Fault Zone (Cowan *et al.* 1996), but this in turn may ultimately join the Alpine Fault, possibly in the vicinity of the Whataroa River (Anderson and Webb 1994).

More recently Beaven *et al.* (1998) have reported on the GPS resurveys from 1994 to 1998. Their results confirm more than 70% of the plate strain is occurring within a band from 5 km northwest to 20 km southeast of the Alpine Fault. The surface displacements in the high strain rate area are well fitted by a model in which 65 – 75% of the relative plate motion is accommodated by slip below 7 – 9 km depth on a southeast dipping Alpine Fault, with material above this behaving elastically and thus storing elastic strain in the region of the Alpine Fault (Beaven *et al.* 1998).

1.3.4 Historical earthquake record and modern seismicity.

Historical record

There has definitely been no rupture on any section of the Alpine Fault in the 160 year record since 1840. While it is possible an Alpine Fault earthquake may have gone unrecognised between 1800 and 1840, sealers and whalers were regularly working in the region and this is unlikely.

Modern Seismicity

New Zealand has had a reliable seismograph network sufficiently accurate to record small and medium earthquakes since around 1940. This early data for area along the central Alpine Fault suggested anomalously low levels of activity in relation to the importance of the structure although the levels of seismicity in the northern area are higher. This led to the suggestion by Adams (1980) that the central Alpine Fault is a "seismic gap" similar to sections of plate boundary in other parts of the world where large earthquakes have been predicted after low recorded seismicity (e.g. Sykes 1971; Sykes *et al.* 1981; Ward and Page 1989; Scholz 1990).

However, recent improvements in the seismograph network near the central Alpine Fault, and the deployment of portable networks, demonstrate that more seismicity is also occurring in this area than was being recorded in the old network. Eberhart – Phillips (1995) note that seismicity levels are comparable to the Mojave section of the San Andreas Fault, which last ruptured in 1857, and is estimated by Sieh *et al.* (1989) to have generated at least 10 large earthquakes in the last 1400 years. Leitner *et al.* (2001) also conclude that the seismicity rate on the Alpine Fault is comparable to locked sections of the San Andreas Fault and that there is potential for large earthquakes.

1.3.5 Previous paleoseismic work on the Alpine Fault

In view of the fundamental importance of the Alpine Fault to the seismology, geological structure and earthquake hazard in the South Island, paleoseismic investigation of the Alpine Fault was relatively neglected prior to 1990. This in part reflects the poor exposure of the fault; the very rapid active processes that tend to mask it; and the difficulty of working in such heavily forested terrain.

Adams (1980)

The earliest research on the paleoseismic history of the Alpine Fault is the work of Adams (1980). He collects together ten radiocarbon dates from landslides and aggradation terraces in central and South Westland and suggests the apparent coincidence of some of the radiocarbon dates is indirect evidence of the timing of large earthquakes on the Alpine Fault. Two or more dates which coincide within the radiocarbon dating error are considered by Adams to be sufficient evidence to infer a series of earthquakes at approximately 500 year intervals over the last 2000 years, with the most recent event around 550 years ago. However, Adams noted that the record may still be incomplete and that future dating may reveal intermediate age earthquakes.

Cooper and Norris (1990)

Cooper and Norris (1990) investigated Alpine Fault paleoseismicity along the South Westland section of the fault near Milford Sound. This involved the ^{14}C dating of material excavated from sag ponds near the fault scarp and estimates of the age of trees which appear to have lost their crowns as a result of earthquake shaking. The tree age estimates are based on circumference as opposed to the more reliable increment corer method, which samples actual tree rings. They conclude that the last large earthquake in this area due to movement of the Alpine Fault occurred in the period between AD 1650 and AD 1725. An incomplete record suggests a possible earlier event around 2000 years ago.

Bull (1996)

Bull (1996) infers a quite different pattern of past earthquakes on the central Alpine Fault to that of Adams (1980). Bull's approach is based on the lichenometric dating of rockfalls. These rockfall sites were all well east of the fault, the closest being approximately 18 km away, and the majority more than 25 km. The dating method is based on the assumption that lichen growth rates are uniform on new rock surfaces created during rock falls.

Bull infers regional peaks in lichen size modes of 43 mm, 84 mm and 125 mm are the result of earthquakes on the Alpine Fault at AD 1748 ± 10 yrs, AD 1489 ± 10 yrs and AD 1226 ± 10 yrs respectively. A less distinct size mode at 166 mm also suggests an event around AD 967 ± 10 yrs. The implied recurrence interval is a remarkably constant 261 ± 14 years.

Bull has subsequently revised his lichen based earthquake chronology (Norris *et al.* 2001) as follows: AD 1718 ± 10 yrs; AD 1615 ± 10 yrs; AD 1578 ± 10 yrs; AD 1428± 10 yrs and AD 224± 10 yrs. These dates now closely conform to the results of other paleoseismic work since 1996 and the implied earthquake recurrence interval is much more variable.

Yetton (1996); Yetton et al. (1998); Wells et al (1999); Yetton (2000)

Most of this work is mainly focussed on the central and north Alpine Fault in the area between Hokitika and the Ahaura River (Figure 2.1), but some of forest-based research extends as far south as the Paringa River (40 km northeast of Haast, Figure 1.2). Four potential paleoseismic indicators are used to determine the history of prehistoric earthquakes on the Alpine Fault, with particular emphasis on the last 500 – 1000 years.

Figure 1.4 summarises the four methods. The most direct and unambiguous method is paleoseismic trenching of the fault. Radiocarbon dating of wood samples in the fault zone defines possible date bands during which Alpine Fault earthquakes have definitely occurred. Attempts are also made to extend the earlier work of Adams 1980 by gathering more radiocarbon dates from aggradation terraces and landslides that may have been earthquake triggered. These show a pattern that is consistent with the trench date bands but do not significantly narrow these.

Significantly better calendric resolution is made possible by analysis of existing data on the age of forests in Westland. Previous historical earthquakes in similar terrain have showed the profound impact of earthquakes on tree mortality due in particular to landslides and burial by aggradation, but also liquefaction and shaking damage to limbs and roots. For example the Wairarapa Earthquake of 1855 (M_w 8.0 – 8.4) triggered landslides that killed one third of the forest on the western Rimutaka range as viewed from Wellington (Grapes & Downes, 1997). Analysis of forest age demonstrates only one major period of mortality within each of the trench date bands in which approximately 25 – 35% of the forest area has died and synchronously regenerated.

For the most recent period of forest damage at around AD 1715 sufficiently large numbers of trees are still living that have survived the earthquake. Tree ring studies of these trees allows refinement of the exact timing of the event. The tree ring data suggests the earthquake occurred in the growing season of AD 1717 and the shaking impacts were synchronous from Fiordland to the Haupiri River (located approximately 50 km northeast of Hokitika), a distance of approximately 400 km. The northeast limit of damage in the AD 1717 event based on the tree ring data coincides with the northeast limit of surface fault rupture established independently by the paleoseismic trench investigations.

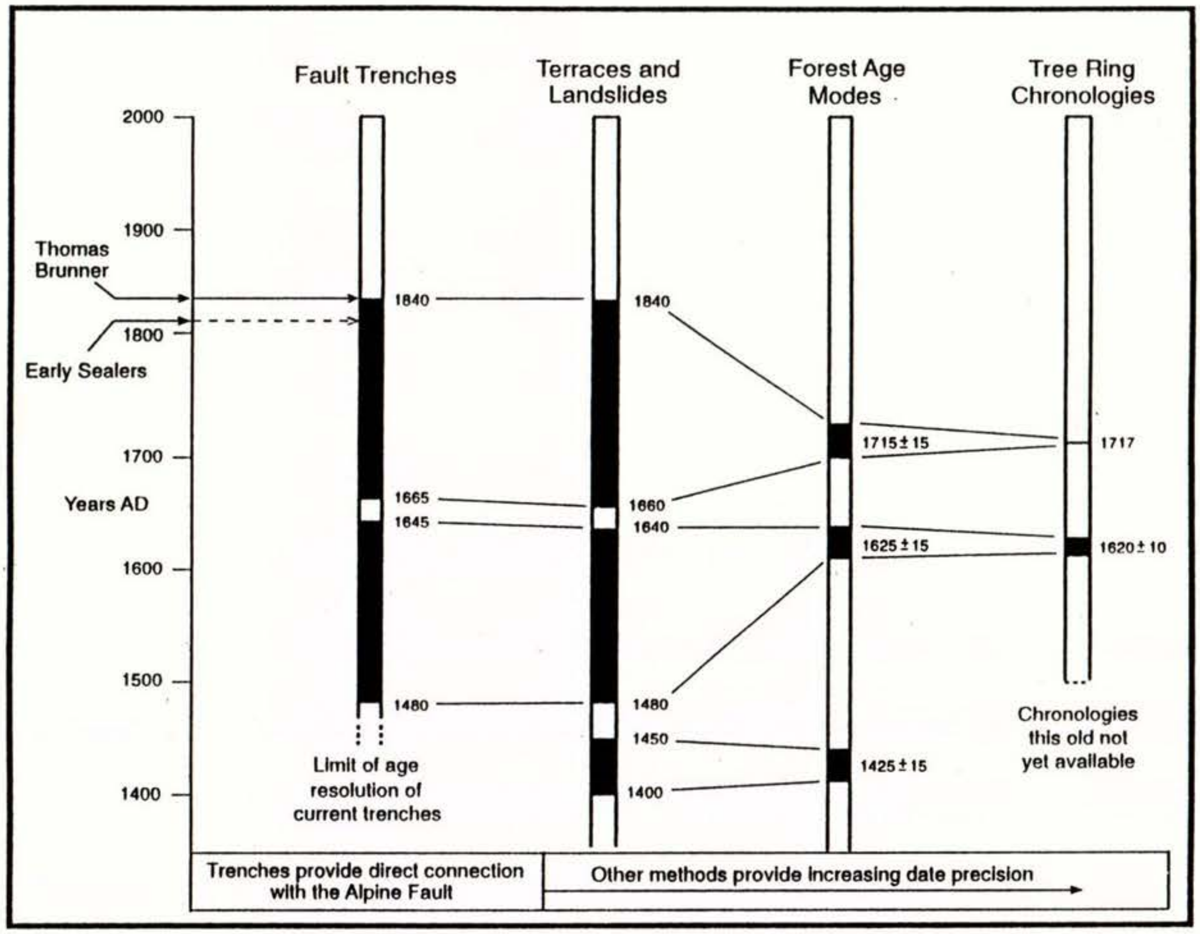

Figure 1.5: A summary of the four lines of independent evidence used in Yetton *et al.* (1998) and Yetton (2000) to establish the timing and extent of the most recent earthquakes on the central and part of the north Alpine Fault

The timing within a single growing season strongly suggests that the most recent earthquake rupture was a single synchronous event, as opposed to a series of smaller ruptures that progressively migrate along fault strike with intervals of a few years. For example the six events of M_w 7 – 8 which migrated westward over 750 km along the North Anatolian Fault (Turkey) in the 28 years between 1939 and 1967 (Barka and Kadinsky-Cade 1988).

Table 1.1 summarises the inferences regarding the timing and extent of the most recent three prehistoric Alpine Fault earthquakes. ***Toaroha River event***				
Evidence	Trenching	Landslide and terrace ages	Forest age	Tree ring chronologies
Estimate of Timing	Post AD 1665 probably 1700 –1750 AD	Post AD 1660	AD 1715 ± 15 yr	**AD 1717**
Rupture Length	Trenching and the landslide record suggest a minimum length of 375 km but a possible length of 450 km is suggested by the tree ring chronologies.			
Moment Magnitude Estimate	**M** = 8.05 ± 0.15 for 375 km and **M** = 8.15 ± 0.2 for 450 km			

Crane Creek event				
Evidence	Trenching	Landslide and terrace ages	Forest age	Tree ring chronologies
Estimate of Timing	AD 1480 – 1645	AD 1488 – 1640	AD 1625 ± 15 yr	**AD 1620 ± 10 yr**
Rupture Length	A minimum length of 200 km is suggested by trenching and the landslide record			
Moment Magnitude Estimate	**M** > 7.8 ± 0.1			

Geologists Creek event				
Evidence	Trenching	Landslide and terrace ages	Forest age	Tree ring chronologies
Estimate of Timing	Not yet recognised.	Ad 1420 – 1450	**AD 1425 ± 15 yr**	Current chronologies not old enough
Rupture Length	A minimum length of 250 km is indicated by forest age data			
Moment Magnitude Estimate	**M** > 7.8 ± 0.1			

Table 1.1: Summary of the key features of the most recent three Alpine Fault earthquakes from Yetton *et al.* (1998) and Yetton (2000). The best date estimate for the timing of each event is shown in bold text. The magnitude estimates come from published correlations between rupture length and moment magnitude (**M**) of Wells and Coppersmith (1994) and Anderson *et al.* (1996).

Wright et al. (1998) and Wright (1998)

The authors outline recent paleoseismic investigations at the Waitaha River, in the central Alpine Fault, which have involved trenching of sag ponds and dendrochronology. They infer at least four ground rupturing earthquakes in the last 900 years, and the most recent around AD 1720 ± 5.

Berryman et al. (1998)

The authors describe trenching in the Haast area along the South Westland section of the fault. They report clear evidence of three ground rupturing earthquakes in the last 900 years, each of around 8 m of dextral slip. They also consider the last event was probably at AD 1718 ± 5.

Synthesis

Table 1.2 is a synthesis of the available data on the timing of the most recent prehistoric earthquakes on the Alpine Fault.

EARTHQUAKE CHRONOLOGY COMPARISON			
Yetton (1996) & (2000); Yetton *et al.* (1998)	**Wright (1998) Waitaha River**	**Bull (revised) ***	**Berryman *et al.* (1998)**
AD 1717	AD 1720± 10	AD 1718 ± 10	> AD 1665, ?1717
AD 1620 ± 10		AD 1616 ± 15	
	AD 1580 ± 10	AD 1578 ± 10	
AD 1425 ± 15	AD 1440 ± 10	AD 1428 ± 10	AD 1400 –1600
AD 1220 ± 50	AD 1210 ± 30	AD 1224 ± 10	AD 1105-1220
AD 940 ± 50	AD 900± 100	AD 961 ± 10	AD 880 ± 110

Table 1.2: Comparison of available prehistoric earthquake chronologies for the Alpine Fault area south of the Ahaura River. * Designates data from Norris *et al.* 2001, pers.comm. Bull 1998.

The work to date shows significant consistency in the conclusions regarding the timing of most of these inferred earthquake events.

Zachariasen *et al.* (2001)

There has recently been one other paleoseismic investigation of the Wairau section of the Alpine Fault near the small settlement of Wairau Valley, approximately 50km northeast of the field area for this project (Figure 2.1). Three trenches have been excavated relatively close to one another. Although one trench did not expose datable material, the other two have helped constrain the timing of prehistoric earthquake events at this location.

The authors conclude the lapsed time since the last earthquake is at least 1400 years and at most 2600 years. An earlier event occurred between 2600 and 3300 years ago. Their results are discussed further in Section 8.

1.4 REPORT OUTLINE

This report outlines the results of paleoseismic excavations at four selected sites northeast of the previous limit of investigation by Yetton *et al.* (1998) and Yetton (2000).

Dendrochronology and forest age studies have not been undertaken in this new area that could potentially provide supporting data. This is because the forest along the Alpine Fault undergoes a significant change north of the Ahaura River and becomes dominated by nothofagus species (beech) as opposed to podocarp species. The beech species (mainly nothofagus fusca) have a considerably shorter life span than most podocarp species, averaging up to 350 years and only very rarely reaching 400 years (Wells pers. comm., 1999). As a result cross - matched tree ring chronologies are restricted to the period post AD 1650 and are generally not available in this more northern area. Furthermore analysis of the forest disturbance record in these more northern areas is restricted by the naturally short life span of the trees to the period after about AD 1650. Any earlier period of significant tree mortality and synchronous regeneration prior to AD 1650 has potentially been lost in the forest record near the fault.

For these reasons it was decided to undertake paleoseismic investigations by trenching as a first stage in this northern area to check the general timing of the most recent event. If there is evidence for an event post AD1650, or alternatively a significant area of podocarp forest can be identified close to the Alpine Fault, then subsequent forest age and tree ring studies may be justified as a subsequent stage of investigation (refer Section 11).

Section 2 of this report describes the fault trace in the study area and the rationale for the selection of the four paleoseismic trench sites. Sections 3 to 6 outline the results of the fieldwork and trenching work at each of the four localities.

Section 7 compares the results with earlier work and Section 8 reviews the estimates of long-term slip rate for this project area.

Section 9 is a discussion of the implications of the results in relation to seismic hazard for the northern and central South Island and Section 10 presents a summary and conclusions. Recommendations for further work are included as Section 11.

Section 2

DESCRIPTION OF THE ALPINE FAULT TRACE AND THE SELECTION OF TRENCHING SITES

2.1 Description of the Alpine Fault trace south of the project area

The Alpine Fault appears clearly on satellite images of the South Island with a very distinct, apparently straight trace at approximately 055° from Milford Sound northeast to the Taramakau River valley. On a more detailed scale the fault trace in this central section is frequently segmented into oblique thrust sections striking 020 ° - 050 °, that are linked by dextral strike –slip traces striking 065 ° - 090 ° (Norris and Cooper 1995; Wright 1997; Yetton 2000). Throughout the central section the Alpine Fault forms a prominent, forest covered, northwest facing range front reflecting the marked uplift on the southeastern side.

The fault then changes strike at the southeast end of the Taramakau River valley (Lynch Creek, refer Figure 2.1) to approximately 060 °, and thus becomes more closely aligned with the orientation of the plate vector. This essentially marks the beginning of the north section of the fault, although Berryman et al 1992 originally proposed the section boundary 10 km further northeast where the trace crosses the Taramakau River at Rocky Point near the sharp bend in SH 73.[1]

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[1] As noted in the introduction, for descriptive convenience this project broadly adopts the original geographic division of Berryman et al. 1992 into <u>sections</u>, but makes the clear distinction that these sections are not necessarily rupture segments. To avoid geographic confusion we have also dropped the adjective "Westland" from the original *north Westland section* and *central Westland section* classification of Berryman et al. 1992. Instead we refer to these simply as the *north* and *central section* of the Alpine Fault. This is because Westland District formally ends at the Taramakau River and by definition the north section of the Alpine Fault is located outside of Westland in the Grey, Buller and Tasman Districts.

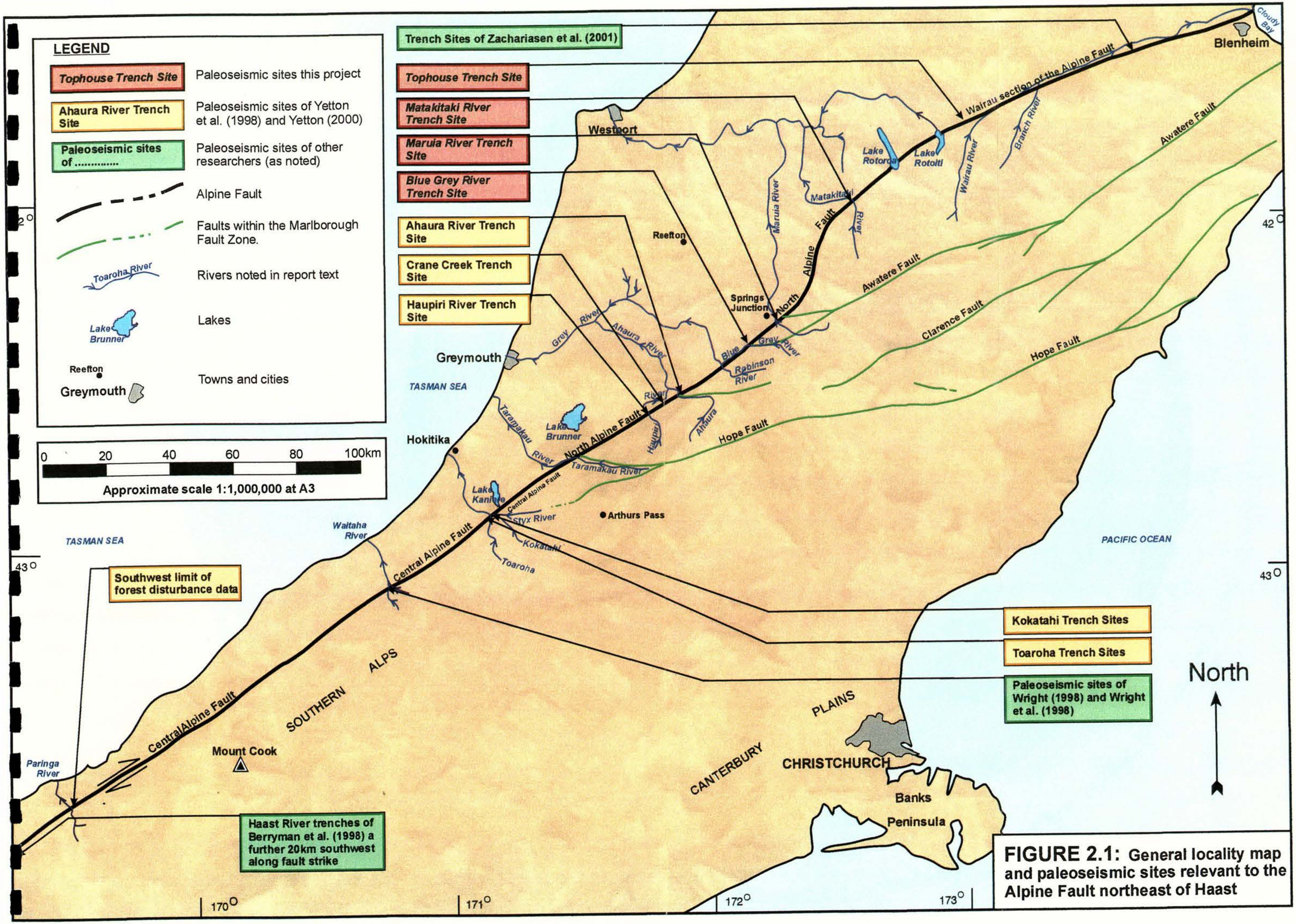


FIGURE 2.1: General locality map and paleoseismic sites relevant to the Alpine Fault northeast of Haast

The north section of the fault does not exhibit the same degree of local segmentation as the central section and at a detailed scale the recent traces maintain a more consistent strike. However, there are segments of the fault that, in map view, are convex to the north and commonly facilitate minor right steps in the fault trace. These right steps are generally on the scale of 10-100's of metres.

Uplift is still consistently on the southeast side and the fault continues as a prominent range front feature 50 km northeast to the Ahaura River (the northeast limit of previous paleoseismic investigation by Yetton (1996); Yetton *et al.* (1998) and Yetton (2000).

At this point the fault ceases as a simple rangefront-bounding feature and continues northeast as a prominent furrow over the Nancy Tass Saddle and on to the Robinson River. This relatively inaccessible saddle area has not been mapped since the early reconnaissance work of Munden (1951). The fault gradually changes strike as it crosses the Nancy Tass Saddle back to approximately 050° by time it reaches the Robinson River.

2.2 Description of the Alpine Fault trace between the Robinson River and Tophouse Saddle

This paleoseismic investigation commenced at the Robinson River, at the southwest end of Palmers Road, and extended northwest to Tophouse Saddle. This was not a mapping project but local mapping of the fault was necessary in areas adjacent to the potential trenching sites.

Figure 2.2 shows the Alpine Fault trace from the Robinson River to Tophouse Saddle, including the four sites finally selected for paleoseismic trenching. The fault trace details shown are from this project and the various other sources noted.

The fault continues northeast from the Robinson River as a relatively simple single trace with minor side steps and local strike variations (for detail refer

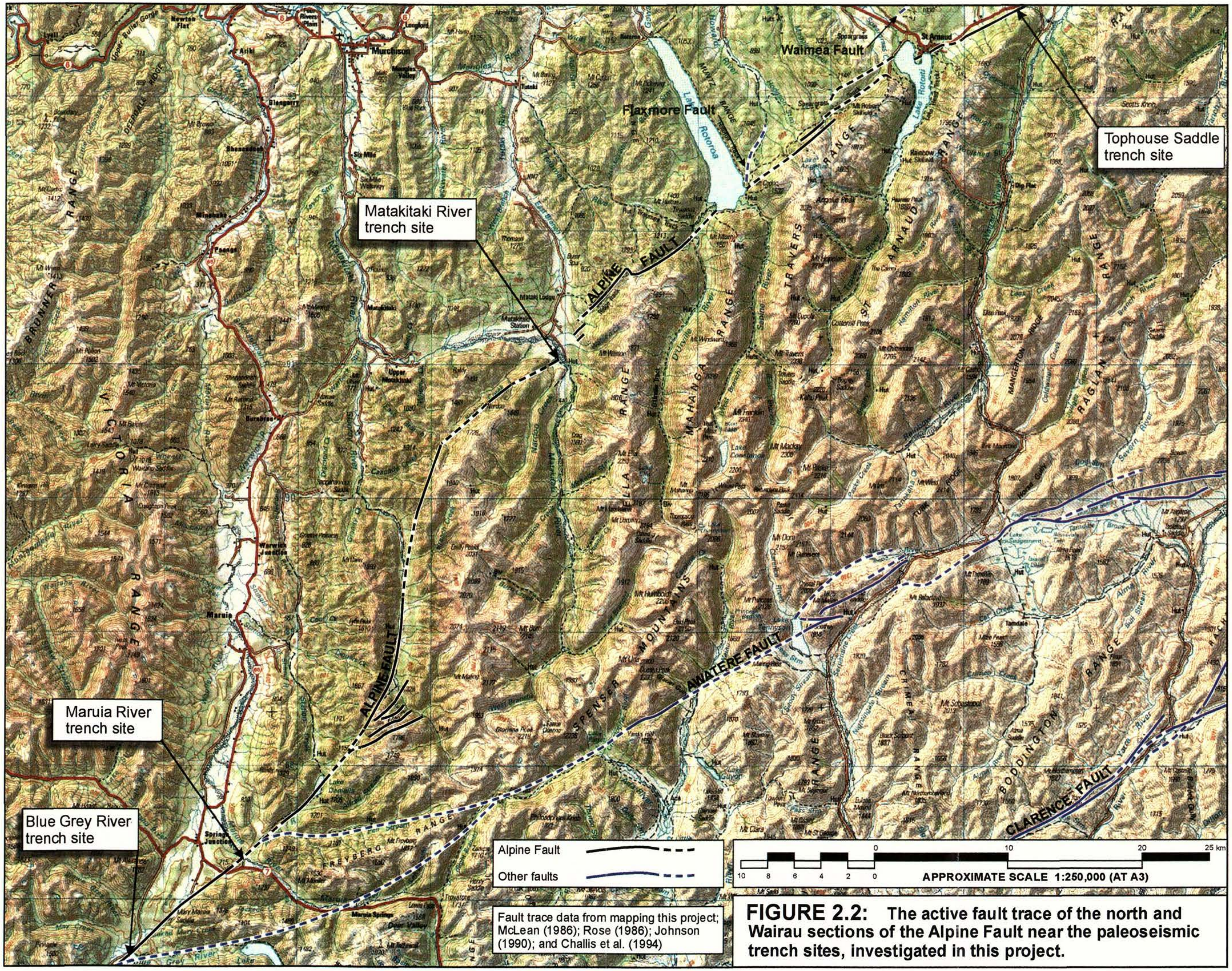


FIGURE 2.2: The active fault trace of the north and Wairau sections of the Alpine Fault near the paleoseismic trench sites, investigated in this project.

Figure 3.1) past the Blue Grey River to the Lake Daniels area. Although the mountains on the southeast side of the fault are no longer significantly higher than those on the northwest, the sense of vertical movement at the fault trace is still consistently up on the southeast side (for example the recent traces at the Blue Grey and Maruia River).

Approaching the Lake Daniels area there is a change in strike of a few degrees to the north that marks the beginning of the "bends" area and for the first time sections of the trace also exhibit uplift on the northwest side (for example the prominent trace immediately northeast of the Alfred River).

Three kilometres northeast of Lake Daniels the fault splays into a series of fault traces as it enters the Glenroy valley and the strike swings significantly northwards to approximately 005 °. Unfortunately the active trace of the fault in this area is poorly defined and generally masked by the numerous active forested fans associated with side creeks to the main river.

There is a gentle swing in strike across the main branch of the Glenroy River to the head of the east branch. Here there is an abrupt change in strike back to approximately 050 °, close to the general orientation of the central Alpine Fault, and by this point the double bend is essentially complete. The trace then maintains the approximate 050° strike across the Holocene river terraces of the Matakitaki River and over Mole Saddle (where there is local minor variation) to Lake Rotoroa and Lake Rotoiti.

At Lake Rotoiti there is an eastward bend in strike to approximately 065° that marks the transition to the Wairau section of the Alpine Fault and the junction with the Waimea Fault. This strike is maintained for 40 km over the Tophouse Saddle and down the Wairau Valley[2] until 10km northeast of the Wairau River junction with the Branch River. From this point the fault swings eastwards progressively over several kilometres to approximately 075 ° and continues to the Pacific coast. The Wairau section of the Alpine Fault has a total length of 110 km. The active trace along the Wairau section of the fault is essentially a purely dextral strike slip fault and it is not consistently up on the southeast side but varies with local changes in strike (Lensen, 1976).

2.3 SELECTION OF SITES FOR PALEOSEISMIC INVESTIGATION

The paleoseismic work outlined in this report has been carried out on the north and Wairau sections of the Alpine Fault, extending from the Robinson River (20 km southwest of Springs Junction) to the Tophouse saddle (10 km northeast of Lake Rotoiti).

In several locations within the study area there are large rivers that cross the fault. In some cases these have created flights of aggradation and degradational terraces which provide a potentially useful late Pleistocene and Holocene chronology that allows a detailed study of the fault zone geometry and the paleoseismic history. In other areas the fault trace can be identified crossing relatively young fan surfaces and these also provide potential paleoseismic trenching sites.

At such locations it is important to investigate the fault zone in sufficient detail to confidently identify the youngest traces on the Late Holocene fluvial surfaces where critical data include the timing of the most recent rupture event to provide

[2] Following recent conventions we include in our definition of the Alpine Fault the section of fault along the Wairau valley which has previously been referred to as the Wairau Fault. McKay (1892) originally named the fault in the Wairau Valley the "Wairau Valley Fault" and this name was retained by Wellman (1953) but extended to include a longer length of fault southwest as far as Lake Rotoroa (Figure 2.1). Lensen (1962) retained the name Wairau Fault for the fault in the Wairau Valley but Suggate (1978) subsequently referred to the section of the fault from Lake Rotoiti northeast to the Pacific Coast as the Wairau section of the Alpine Fault. Berryman et al 1992 follow this convention and recent map publications have adopted the name "Alpine (Wairau) Fault" for the fault in this area (for example Johnston 1990; Begg & Johnston 2000).

estimates of elapsed time. It is also important to identify, and generally avoid, those sections of fault trace that may be associated with other subsidiary branch faults or less active back-thrusts.

Not all the large rivers provide suitable potential paleoseismic sites. In some cases, for example the Glenroy River, active side streams and associated Late Holocene outwash fans have buried the fault trace at the critical locations. In other cases a fault trace may be present but there are no stratigraphic constraints to indicate a definite Late Holocene age.

Once an area that has a clear Late Holocene fault trace has been identified, the key requirement is to determine the relative and absolute ages of the various geomorphic and stratigraphic markers which may be offset in the fault zone. This normally requires the presence of suitable organic material for radiocarbon dating within the subsurface soil materials, either from natural exposures or paleoseismic trenches.

In Figure 2.2 a total of 8 sites are shown that were initially identified in the project proposal as having potential for paleoseismic investigation, and one site (Blue Grey River) that was subsequently identified. The proposal was to undertake paleoseismic excavation at the four most promising sites while ensuring a reasonable geographic spread along fault strike. In the section below we briefly describe each of the potential sites in turn commencing at the southeast end of the study area.

Robinson River

Although a major fault scarp exists on the southeast side of the high terrace on the north bank of the river there is no identifiable trace on the recent fluvial surfaces closer to the river. The main scarp on the north bank exposes bedrock on the upthrown side and is so steep that a considerable mantle of slope debris has accumulated on the down-thrown side, masking any recent trace at the scarp base. The entire area is covered in thick forest and is not accessible for excavation machinery, which would definitely be required for a site with slope debris on this scale. This site was not selected for trenching.

Blue Grey River

This was not considered initially because of concerns regarding human disturbance at the site and it's close proximity to the more promising Crooked Mary Swamp site. However, once land ownership difficulties became apparent at the Crooked Mary Swamp site, the Blue Grey River was selected as an alternative site that has provided good results (Section 3).

Crooked Mary Swamp

The area between Crooked Mary Creek and the Blue Grey River includes a thick peat swamp on downfaulted moraine immediately southwest of Little Mary Creek (refer Figure 3.1). The Alpine Fault forms the southeast margin of the swamp. There is potential at this site for detrital material to enter the swamp is pulses from fault scarp rejuvenation and uplift in successive earthquakes. Some radiocarbon dates have already been collected from the site (NZ 298-302, collected by P. Suggate and reported in Grant Taylor and Rafter 1963) that suggests steady peat accumulation over the last approximately 10,000 years.

Unfortunately the peat swamp near the scarp is located on private land. Despite successive attempts to convince the owners, they are not willing to give permission for paleoseismic investigation in this area, even by hand excavation or auguring.

Maruia River (Calf Paddock)

The Alpine Fault trace on the true left of the Maruia River was described initially by Wellman (1952) and more recently by Officers of the Geological Survey (1975). It is referred to locally as the Calf Paddock and in 1964 the site was chosen for construction of a concrete wall as a coarse indicator of possible creep displacement.

The terrace tread closest to the modern river channel shows evidence of a relatively recent rupture of the fault and this was selected as a possible trench site to determine the timing of the most recent rupture of the fault in this location (Section 4). The land is part of the Department of Conservation estate and a concession to undertake the paleoseismic excavation was successfully obtained. We are grateful to the Department of Conservation for their agreement to allow this research to be undertaken.

Matakitaki River

The Alpine Fault crosses the Late Holocene alluvial terraces on the true left of the Matakitaki River near Nardoo Creek. Officers of the Geological Survey 1975 have previously described the trace at this location. This site is the only possible trench site that has a clear Late Holocene trace in the "bends" area of the Alpine Fault and so it has particular importance in any paleoseismic assessment. Although the faulted Late Holocene gravels exposed by erosion by the active river channel are devoid of datable material, the decision was made to trench the site, in the hope that datable material would be found (Section 5). The land in this area is part of Mount Ella Station, a recent large diary conversion, and we are grateful to the owner (Mr Rick Monk), for permission to trench the site, and for his excavator which he made available for hire.

Southeast end of Lake Rotoroa

Challis *et al.* (1994) show the trace of the Alpine Fault at the southeast end of Lake Rotoroa. There is a short 400m section of trace that crosses a postglacial fan near Cedric Stream approximately 3 km northeast of the lake. Other short sections of trace can also be recognised nearby. In all cases the scarps are relatively high (generally 3 -8m) and no section could be clearly discerned as the product of a single-event rupture. This area is relatively remote and all excavations would have to be by hand.

In view of the subsequent conclusions of this project more work in this area may now be justified (refer Section 11), but at the time of original site selection these potential sites were not considered to be the best available targets.

Northwest end of Lake Rotoiti

The trace of the Alpine Fault crosses moraines of the last glacial advance at a small peninsula at the northwest end of Lake Rotoiti (Brunner Peninsula, also know locally as "the neck"). The scarp in this area varies in height from approximately 3 – 7m. There are no swamps or obvious pronounced fault furrows along the scarp base and there are many large moraine boulders scattered over the surface up to several metres in diameter. The area is densely forested with no vehicle access and is administered by the Department of Conservation. Once again any trenching would need to be by hand. Given the size of the moraine boulders this does not look a promising proposition.

Further northeast the trace passes through a Department of Conservation campground and several private holiday properties. These locations are accessible for machinery but none of them have swamps or permanently saturated areas and this makes the preservation of reliable organic material less likely. As noted in Section11, in light of the conclusions of this project these more limited targets may now be worth reconsidering.

Tophouse Saddle

Approaching Tophouse Saddle the Alpine Fault trace crosses a series of moraines and post glacial fans and forms an obvious Late Holocene trace in many locations. In several sections these fault traces cross fans that are covered in beech forest, and locally swampy ground, thereby increasing the chances of the preservation of organic material. In some cases sections of the trace are also accessible for machinery.

A promising site was identified near Northridge Farm, adjacent to SH 63, 3 km northeast of the SH63/Tophouse Road intersection. This is located on private land owned by Professor G. Guilford (Massey University) and we are grateful for Professor Guilford's permission and support in undertaking machine excavations on this property (Section 6).

2.4 Summary

The Alpine Fault trace forms the boundary of mountainous terrain associated with an actively rising range front. Because of rapid burial of the active trace under slope debris, landslides and active fans there are not many locations where the active trace can be clearly identified and investigated. We have identified and assessed a total of seven general locations distributed along approximately 100 km of fault strike where paleoseismic investigation may be possible. Of these seven locations, four have been selected to undertake detailed paleoseismic investigations. These are Blue Grey River, Maruia River (Calf Paddock), Matakitaki River and Tophouse Saddle. The four sections that follow outline the results of this research.

Section 3

PALEOSEISMIC INVESTIGATION OF THE ALPINE FAULT TRACE AT THE BLUE GREY RIVER

3.1 Fault trace description

Figure 3.1 shows the Alpine Fault trace from a few kilometres southwest of the Blue Grey River to Pell Stream, 3 km northeast of the Maruia River. The fault in this area has an average strike of 050^{o} and separates schist and indurated sediments of the Torlesse Supergroup on the southeast side of the fault, from generally older metamorphic rocks of the Mt Arthur Group and plutonic rocks of the Rotoroa and Karamea Suite on the northwest side.

In most cases the basement geology is inferred from regional mapping and there are very few exposures of bedrock at the fault. Most of the time the fault scarp is crossing Late Quaternary glacial deposits associated with the latest glacial advance (Reid Stream Advances of Mabin 1983) or the penultimate glacial advance (Creighton Advances). In other cases the trace can be followed across postglacial fans that in some more active areas completely bury the fault trace.

Immediately southwest of the Blue Grey River on the true left bank the trace forms a subdued 5m high scarp across a post glacial fan associated with side creeks that drain the local schist range front. Unfortunately the recent clearing of forest on this fan has removed any features that could have been used to reliably determine horizontal offsets, and may also be responsible for the rounded-off appearance of the scarp in this area.

However, on the true right bank there is a largely unmodified fault trace crossing a low terrace elevated approximately 3.5m above the average water level of the Blue Grey River. This was described by Officers of Geological

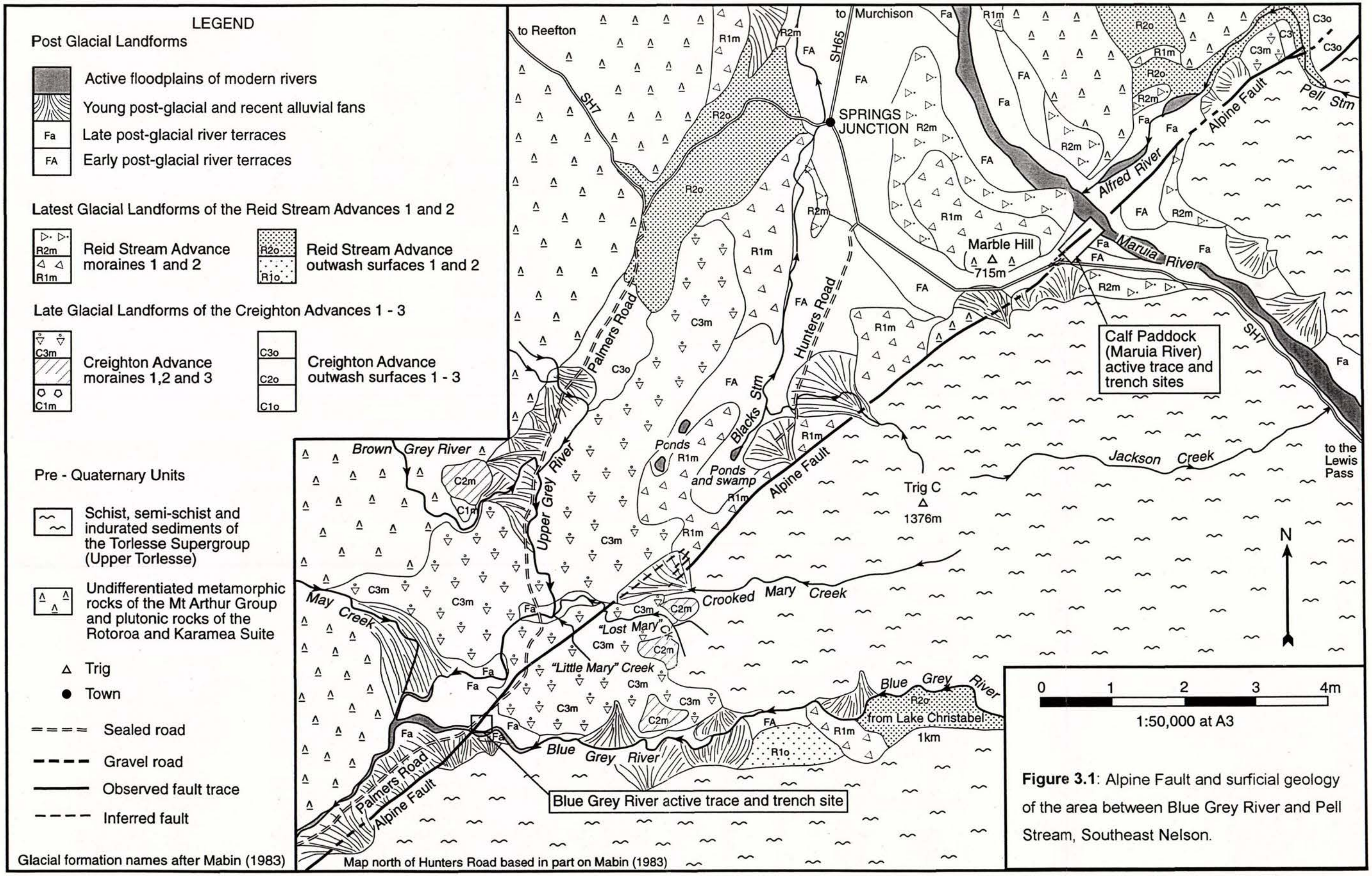


Figure 3.1: Alpine Fault and surficial geology of the area between Blue Grey River and Pell Stream, Southeast Nelson.

Survey (1975) during a general reconnaissance trip to known sites with active traces along the Alpine Fault. This fault trace is the most recent at this location and there is no sign of any trace on the next terrace down (elevated 1.6m above the Blue Grey River).

Figure 3.2 shows a map of the fault trace in this area. The main trace on the 3.5m terrace is only 0.2 – 0.4m high but it is clearly discernable. The fault scarp increases in height to approximately 1.4m at the next highest terrace to the northeast (the 4.5m terrace) but beyond the northeast limit of Figure 3.2 the scarp enters an area of old slumping and collapse and clear scarp definition is lost.

In detail the main trace starts on the 3.5m terrace, immediately northeast of the Department of Conservation track to Lake Christabel, and has two small curved subsidiary traces arranged crudely en echelon to the broader main trace.

The fault trace then crosses a shallow channel at the edge of the 3.5m terrace tread and offsets the riser between this and next higher 4.5m terrace. The horizontal offset of this riser is a relatively small 1 ± 0.3m ([3]). We cannot measure a corresponding horizontal offset of the true left side of this shallow channel because nothing can be discerned northwest of the fault in the matching area. However, there is some apparent dextral distortion of the channel edge in the area immediately southeast of the main trace associated with the subsidiary trace. It is also likely that erosion or deposition by post rupture flood occupation of the channel has masked or removed the continuation of the channel edge.

In contrast the 1± 0.3 m horizontal offset on the true right side of the channel is naturally protected against subsequent erosion (i.e. it is a *trailing edge* in the terminology of Bull (1991) in which the riser is displaced laterally away from the

[3] These estimates of vertical and horizontal displacement come from stadii survey and projections of piercing points across the trace but in reality their accuracy is generally limited by the landform definition. For comparison our estimates of H = 1.0 ± 0.3m and V=0.2-0.4m compare with Officers of Geological Survey (1975) estimates of H=0.8m and V=0.5m.

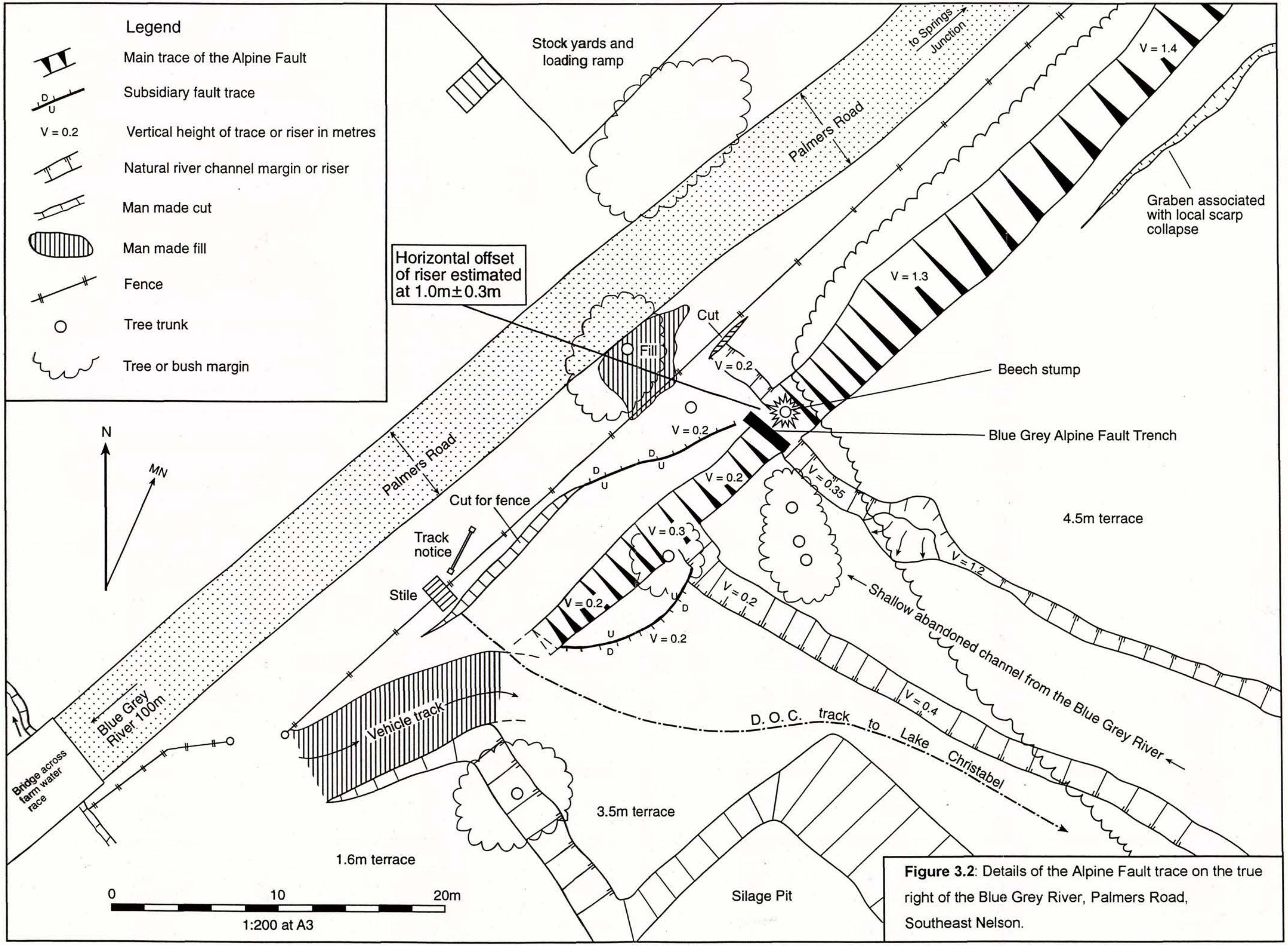


Figure 3.2: Details of the Alpine Fault trace on the true right of the Blue Grey River, Palmers Road, Southeast Nelson.

active channel c.f. to the *leading edge* on the other side). For this reason we consider this is reliable indicator of the horizontal single-event offset during the most recent rupture on this part of the fault. An offset of this order is considerably smaller than the inferred single-event offsets on the Alpine Fault further southwest.

3.2 Paleoseismic Excavations

Area selected for trenching

Most of this area of lower terraces is private land. There has been considerable recent human modification near the fault trace including cut and fill associated with Palmers Road and a farm access track, cuts for fencing, and the excavation of a farm silage pit.

The silage pit currently provides a good exposure of the fluvial sediments comprising the 3.5m terrace. These are medium to coarse schist gravels that continue right up to the base of a thin topsoil layer (100 –150mm) with no overbank silt or finer sediments in the upper soil horizons. These gravels do not show much stratification or imbrication and generally become coarser and less stratified with depth.

Our previous experience in paleoseismic trenching along the Alpine Fault indicates that generally little useful paleoseismic information comes from gravel sediments, unless there are either finer silts that can contain wood in the top few hundred millimetres, or organic material trapped in the shear zone near the ground surface. For this reason the decision was made to trench this site by hand in the expectation that any useful data would probably be in the top 1m, and the greater depth possible by machine would not be necessary. This method also avoided machine damage to several attractive beech trees at the start of the popular tramping track to Lake Christabel.

The dampest area at the base of the fault scarp was selected as a trench site (Fig 3.2). This is very close to the displaced riser edge and has a large beech tree stump at the north trench margin, which demonstrates that the area is unlikely to have been disturbed by forest clearing activities. Figure 3.3 is photograph of the site prior to trenching, showing the dextrally displaced riser, the old stumps, and general setting.

Trench Stratigraphy

Figure 3.4 is the face log on the northeast wall of the hand-dug trench. Gravels very similar to those exposed in the silage pit dominate the sequence. We identify two basic gravel units. The deepest, Unit 1, is a coarse well rounded schist gravel with minor sand in the matrix that is typical of the bedload sediment in the main channels of the modern Blue Grey River. There a gradational contact between this oldest unit and Unit 2, which is a finer gravel typical of floodplain gravels deposited in progressively decreasing river current. This is sandier and the gravel clasts are locally matrix supported.

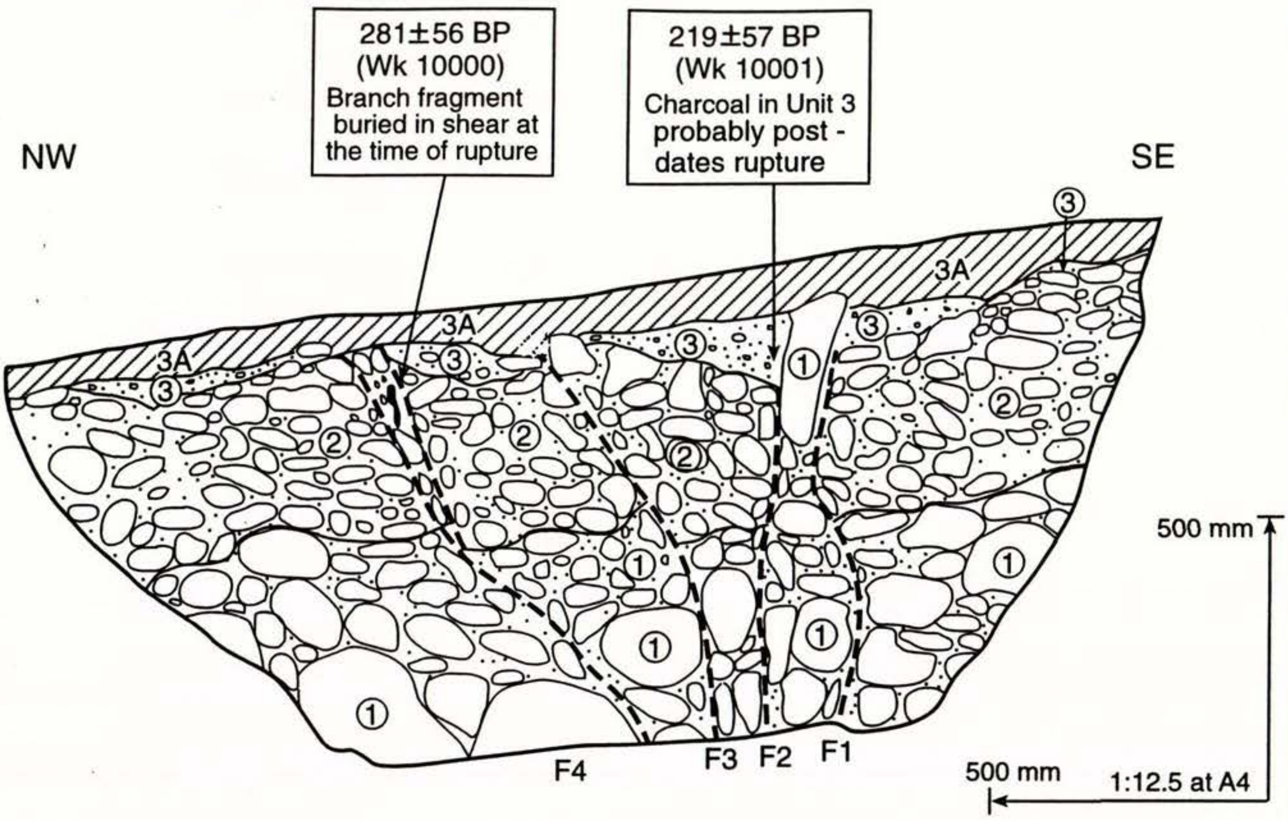
Unit 3 is silty sand containing very fine gravel and rare charcoal. This unit is not exposed in the nearby silage pit and we could not find it in several other shallow pits we dug away from the fault scarp. This is interpreted as a scarp related colluvium and slopewash material that has accumulated in the response to the erosion and smoothing of the fault scarp following its formation.
However, this can not be categorically determined, and we discuss the significance the alternative interpretation (i.e. that Unit 3 predates the faulting) in the section further below.

Faults exposed in the trench

For ease of reference we designate the faults in the trench F1 – F4. In reality we expect these individual shears coalesce deeper below the trench floor and in effect they define and enclose an upward flower structure. Within the zone F1 – F4 the gravel clasts have been jostled and moved out of their original

Figure 3.3: The Alpine Fault trace on the true right bank of the Blue Grey River. The fault trace runs from in front of the stump at the right of the photo across the 3.5m terrace and channel to the riser up to the 4.5m terrace. This riser is offset dextrally by 1.0± 0.3m. The trench was excavated in the slight depression immediately beside the moss-covered stump near the riser. Part of this stump can recognised in the subsequent Figure 3.6 that shows part of the trench.

Blue Grey River Alpine Fault Trench



Unit Symbol	Description	Interpretation	Event Horizon
3A	Soft brown organic clayey silt	Topsoil developed on Units 2 and 3	Earthquake rupture
3	Silty sand with very fine gravel and rare charcoal fragments	Colluvium and slope wash that have accumulated post rupture in local depositional settings	
2	Grey sandy medium matrix supported schist gravel	Floodplain sediment of the Blue Grey River	
1	Grey and brown medium to coarse schist gravel	Bedload sediment from the Blue Grey River	

Summary

- Rupture extends up to the topsoil
- Small vertical offset of approximately 300mm
- Rupture around 281± 56 BP (refer text for discussion of calendric date ranges)

Figure 3.4: Face log of the northeast side of the hand dug trench across the Alpine Fault trace on the 3.5m terrace on the true right of the Blue Grey River

sedimentary positions, with local clast realignment parallel to the main shears and associated local subsidence at the paleo-ground surface. Figures 3.5 and 3.6 show the upper few hundred millimetres of the trench wall, and in particular the large rotated schist clast between F1 and F2.

There is no stratigraphic or other evidence for more than one rupture event. Given the relatively small dextral offset, and the low scarp, we consider this trench records a single rupture event that is the most recent movement of the Alpine Fault at this location.

Radiocarbon dates and event timing

There are two dates that provide constraints on rupture timing. The first and most definitive date is from a short section of beech twig (6-12mm diameter, up to 14 growth rings i.e. up to 14 years "self-age") found aligned and trapped near the surface in F4. Both ends of the twig were broken and had silt pressed into and around the broken ends, demonstrating that this was definitely not an in-situ modern root. We infer that the twig became trapped in the shear as the ground dilated during the ground rupture.

The twig fragment (WK 10000) provides a date of 281 ± 56 BP[4] and the calendric conversion for this is shown in Figure 3.7. This graph shows the relative probability that the true calendric age of the branch fragment falls within the dark areas. It is absolutely certain that the rupture that trapped the branch fragment occurred post AD 1440 plus the branch age (up to 14 rings, say 10 years and therefore AD 1450). It is also certain that there has been no rupture of the Alpine Fault since European settlement in AD 1840. These are the absolute limits within which rupture has occurred. However, three time periods are more likely than others are i.e. the peak AD 1450 – 1600, the most

[4] Throughout this project radiocarbon dates are indicated by the conventional suffix BP. This is not simply "Before Present" but designates radiocarbon years before AD 1950 when atmospheric carbon around the world was modified by contamination from hydrogen bomb testing. Radiocarbon years do not simply equate with calendric years. We utilise here calendric conversions provided by University of Waikato Radiocarbon Laboratory based on Stuiver *et al.* (1998) and the NZ Delta-R correction of McCormac *et al.* (1998).

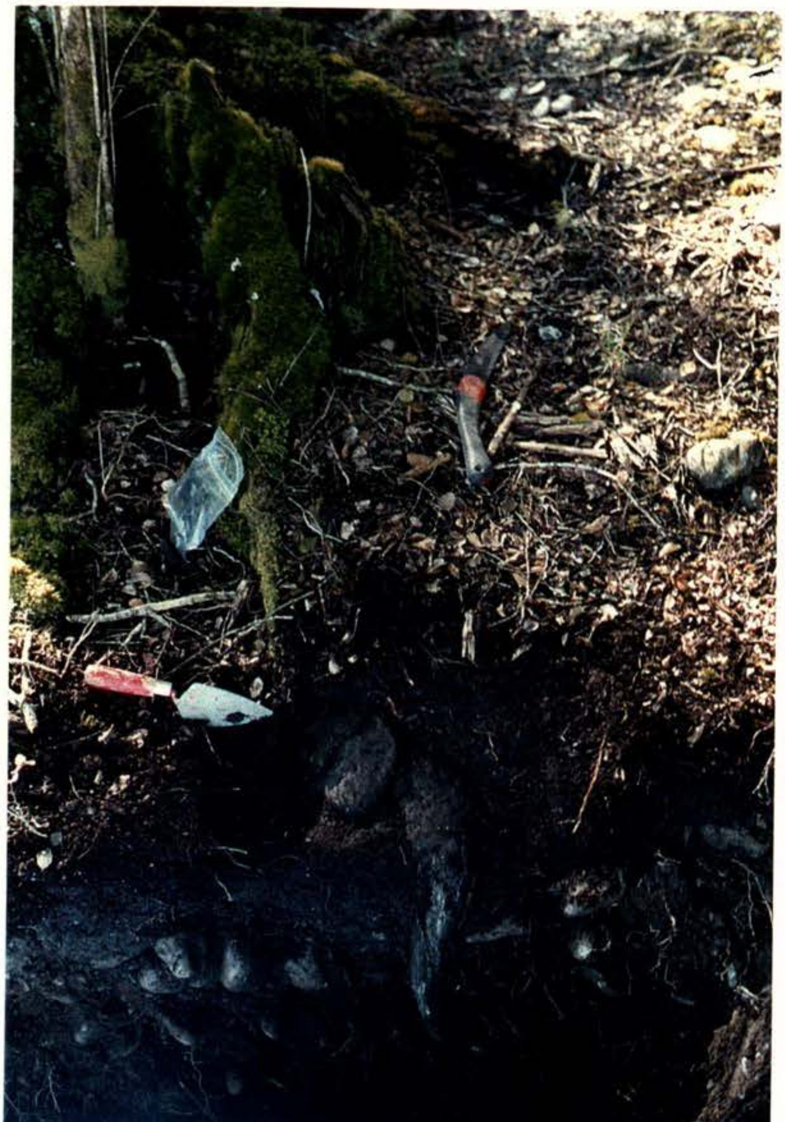


Figure 3.5: Part of the trench showing the shear rotated clast between F1 and F2. Also the small dark piece of wood in the F4 shear along the projection of the trowel and at about the trowel blade length from the tip.

Figure 3.6: Further excavation of the area near the shear rotated clast showing the local depositional areas created in the shearing either side of this large clast.

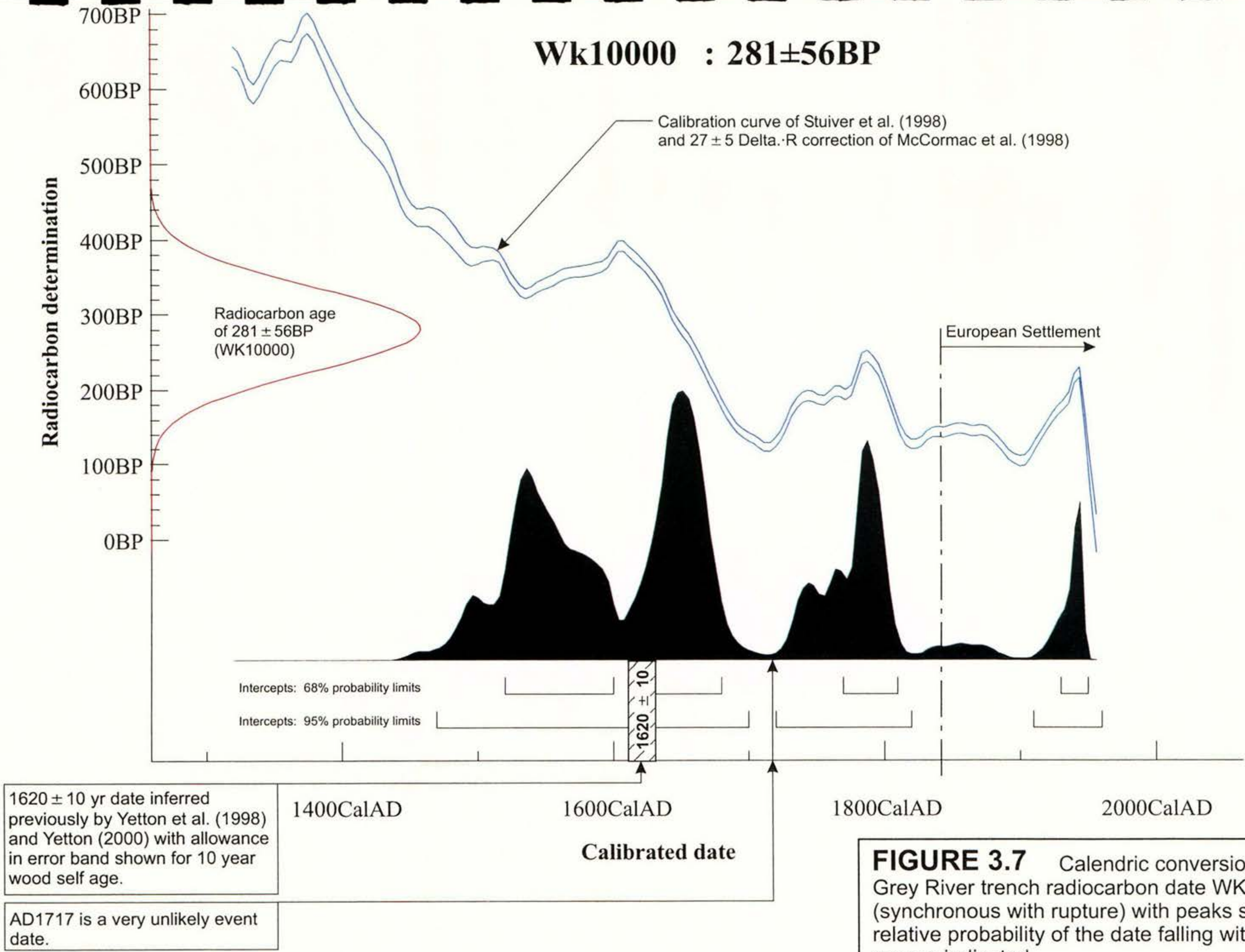


FIGURE 3.7 Calendric conversion of Blue Grey River trench radiocarbon date WK10000 (synchronous with rupture) with peaks showing relative probability of the date falling withing the age ranges indicated.

significant peak shortly following AD 1600 (AD 1600 – 1680), and the peak following approximately AD 1730 – 1840. On the basis of this sample alone there is no way to establish the timing any more precisely, but statistically the period post AD 1600 appears the most probable.

Most importantly (and quite fortuitously) this sample does indicate that it is very unlikely that this branch fragment was trapped in a ground rupture of the Alpine Fault trace in AD 1717, the generally accepted most likely date for the most recent earthquake rupture on the Alpine Fault further to the southwest. This is consistent with the previous work of Yetton *et al.* (1998) and Yetton (2000) that indicates the AD 1717 rupture did not progress much further northeast than the Haupiri River (refer Figure 2.1).

The second radiocarbon sample from this trench is Wk 10001 from an AMS radiocarbon date on a small fragment of charcoal near the base of Unit 3 adjacent to the rotated clast. Growth rings that were relatively planar could be discerned under the binocular microscope in the charcoal fragment, but this does not closely define self-age other than to suggest it came from the youngest outer area of a log or branch.

This charcoal provides a date of 219 ± 57 BP and we infer this unit accumulated soon after rupture in the local depositional hollows and ground irregularities associated with erosion of the rupture ground surface.

This best explains:

- the apparent absence of this unit away from the scarp area
- the major thickness variations exhibited by this unit that would otherwise require significant post rupture erosion
- the poor sorting within the unit

However, it is also possible (but less likely) that this unit is some form of overbank silt that predates rupture. We consider below each possibility in turn in relation to the calendric date ranges shown in Figure 3.8.

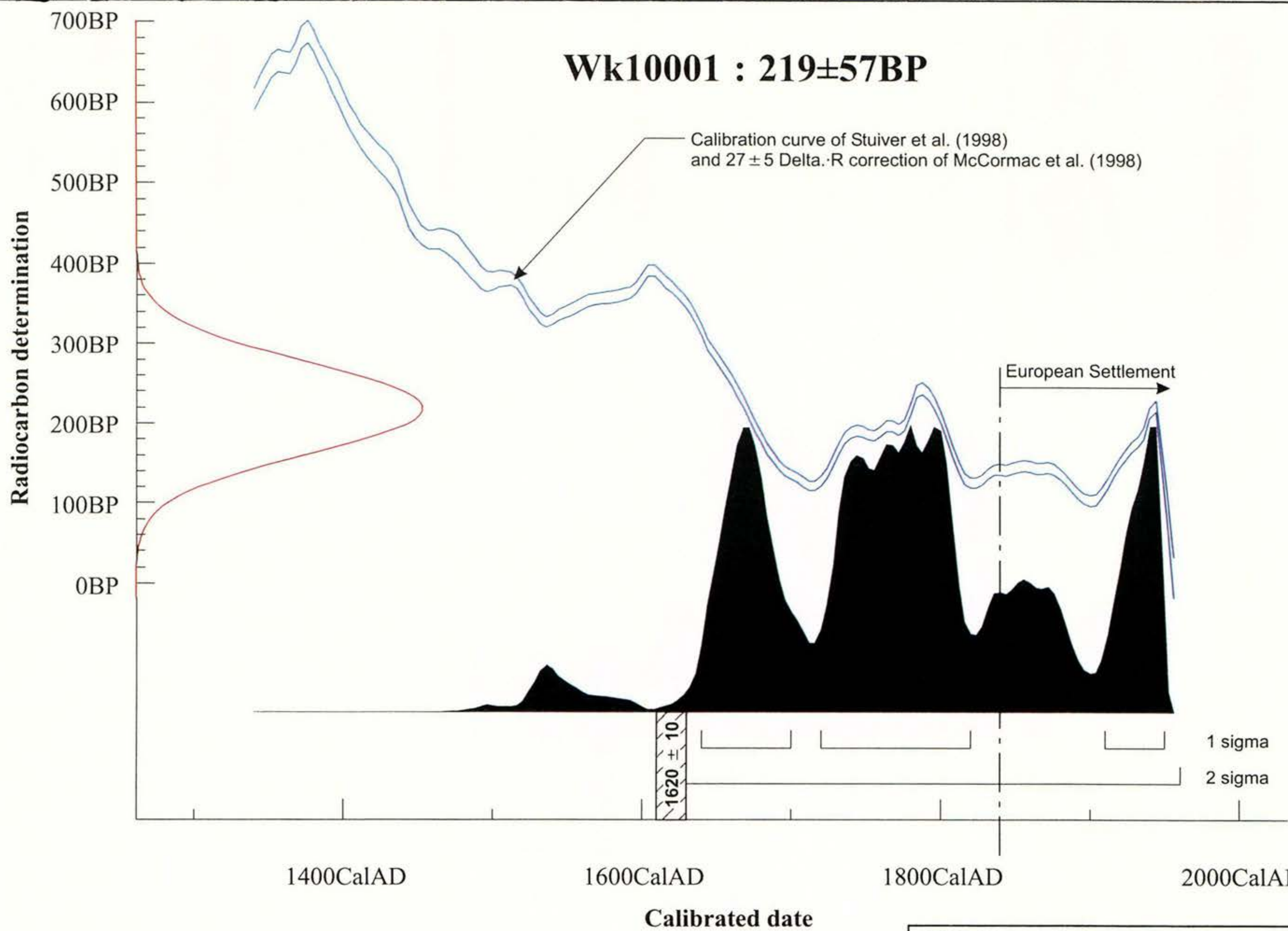


FIGURE 3.8 Probability distribution for calendric conversion of Blue Grey River trench date WK10001 inferred to closely post-date the most recent earthquake rupture at this location.

If the unit post dates rupture, then it is most likely to closely post-date the rupture i.e. accumulate with the first few years as the broken ground on the scarp is smoothed off by erosion. The probability distribution for this sample (Fig. 3.8) is a good fit to an earthquake event at around AD 1620 but not as good a fit to an event much earlier i.e. the period AD 1450-1600 which was one of the likely possibilities based only on WK 10000. This is particularly the case given the possibility of significant self-age in the sample (i.e. the charcoal fragment could come from older wood closer to the heart of a tree).

Alternatively if the unit pre-dates the rupture (less likely) then the possibility of the rupture event being in the period AD 1450 – 1600 is even less likely.

3.3 Summary

The most recent earthquake rupture at the Blue Grey River was a relatively small event resulting in a horizontal offset of approximately 1.0 ± 0.3m and a vertical offset of 0.2- 0.4m. This ground rupture and associated earthquake definitely occurred post AD 1450 and is most likely to have occurred either in the period soon after AD 1600 (AD 1600 – 1680), or later in the period AD 1730 – 1840. It is very unlikely to have occurred in AD 1717, the generally accepted date of the most recent earthquake on the Alpine Fault in the area southwest of the Haupiri River. This is consistent with the results of previous work that indicates ground rupture associated with the AD 1717 event did not extend far northeast of the Haupiri River.

Section 4

PALEOSEISMIC INVESTIGATION OF THE ALPINE FAULT TRACE NEAR SPRINGS JUNCTION AT THE MARUIA RIVER (CALF PADDOCK)

4.1 General description

The Alpine Fault trace on the true left of the Maruia River was first described by Wellman (1952), and more recently by Officers of the Geological Survey (1975) and Beanland (1987). It is referred to locally as the Calf Paddock and has been used intermittently for cattle grazing since early settlement of the area. Historically it has never had a significant forest cover (A. Blackadder, pers. comm. 1999).

In 1964 the site was chosen for construction of a concrete wall as a coarse indicator of possible creep displacement. Neither creep nor cracking of wall has occurred since construction. Geophysics Division of the D.S.I.R. in 1972 (Garrick and Hatherton,1974) undertook drilling and geophysical surveys at this site. They carried out seismic refraction profiles normal, parallel and oblique to the fault trace and a gravity profile across it.

The investigation concluded with the drilling of a vertical hole to a depth of 83m approximately 40m east of the fault trace. It passed through 26m of gravel and then greenschist, much of it broken and some of it sheared. Schistosity in the intact core dipped at 60 – 70 degrees but the crush zones were at a higher angle between 70 and 90 degrees. Because the drillhole was still penetrating schist at the maximum depth of 83m the minimum dip on the fault plane at this location is 65 degrees.

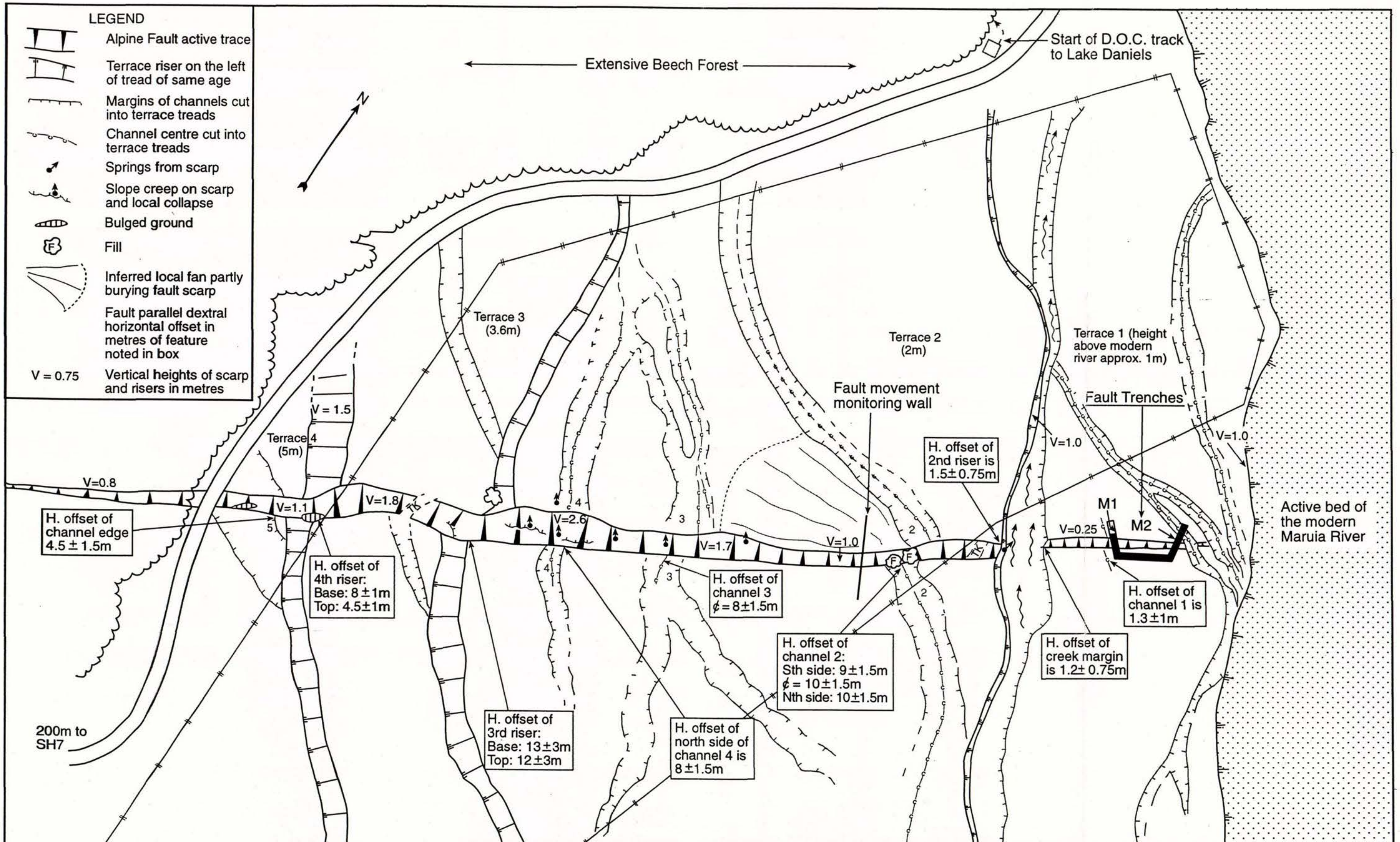


Figure 4.1: The Alpine Fault trace on the true left of the Maruia River (Calf Paddock) near SH7 (Lewis Pass) and Springs Junction. The paleoseismic excavations have been carried out on the lowest terrace (Terrace 1, 1m above river level) and the two face logs Maruia 1 (M1) and Maruia 2 (M2) form two legs of a continuos excavation. Offset channels that can be traced across the fault scarp are numbered 1 – 5, channels that post-date the faulting on the Terrace 1 surface near the river margin are not numbered.

4.2 Fault trace description

The earlier Figure 3.1 also shows the general location of this locality and the surrounding geological setting. The fault trace can be mapped between active fans from the Hunters Road area south of SH7 to a fault-truncated fan immediately southwest of SH7. Close to SH7 the fault appears to make two stepovers to the left, each of approximately 50m, an observation noted by Beanland (1987), but apparently overlooked by Wellman (1952) [5]. A new trace (approximately 1m high) can then be followed northeast out of dense beech forest, across a post glacial terrace elevated approximately 5m above the current Maruia River bed, into the clear pasture of the Calf Paddock. This is the section of the Alpine Fault trace that has been previously described in some detail by Wellman (1952) and Officers of the Geological Survey (1975).

Figure 4.1 shows the details of the fault trace in this area. Following from the southwest the trace <u>gains</u> in height to approximately 1.8m as it crosses down onto the next lower terrace (designated Terrace 3, elevated 3.6m above the Maruia River). There is another gain in height down onto Terrace 2 (2m) and in parts of this tread the scarp height locally reaches 2.6m. There is then a progressive reduction in scarp height back to approximately 1m before reaching the lowest terrace.

This lowest terrace is approximately 1m above modern river level and has a low fault scarp of approximately 0.25m that closely follows the strike projection of the much higher trace on Terrace 2. Figures 4.2 and 4.3 are photographs looking along the fault trace on the Terrace 1 & 2 tread surfaces respectively.

[5] Unfortunately the exact details of this stepover area are obscured by a combination of old earthworks associated with SH7 road formation and very dense regenerating beech forest.

Figure 4.2: The Alpine Fault trace at the Maruia River looking northeast along the fault scarp on the Terrace 2 surface with springs and associated slumping apparent at the fault. The concrete monitoring wall is visible in the middle ground. Note the high fault scarp in beech forest in the background on the true right of the river on the same fault strike.

Figure 4.3: The Terrace 1 surface in the vicinity of the subsequent paleoseismic excavations looking southwest along the low 0.25m fault scarp that passes between the two running children. The channel that post-dates the most recent rupture is visible in the middle distance with no dextral offset. The remnant Terrace 1 surface between this channel and next closest channel has been faulted.

4.3 Possible single-event offsets

As noted earlier the scarp height varies considerably across this site. At the southeast end near Terrace 4 the fault scarp height appears to be die out approaching the stepover zone near SH7. This height reduction could also in part reflect a possible increase in the thickness of terrace gravels, over more competent underlying strata, passing up progressively from Terrace 2 to Terrace 4.

Terrace and offset feature	Horizontal fault offset (m)	Vertical fault offset (m)	Interpretation
Terrace 1			Single-event offset of c. H= 1.3m and V=0.25m in the most recent rupture which is very similar to the Blue Grey River recent offsets.
Channel 1,c[1]	1.3± 1	0.25	
Creek edge	1.2± 0.75	0.25	
Riser	1.5± 0.75		
Terrace 2			Cumulative displacement of approx. 10m horizontal is a good fit within the errors. 2m vertical offset is affected by partial burial of true scarp base by fan material. 2 events minimum (H=1.5, H=8.5) but probably 3 or more (e.g. 3 say H=1.5, H= 4 – 4.5 etc).
Channel 2, sth	9 ± 1.5		
Channel 2, c[1]	10 ± 1.5	1.0	
Channel 2, nth	10 ± 1.5		
Channel 3, c[1]	8 ± 1.5	1.7	
Channel 4, nth	8 ± 1.5	2.6	
Riser, base	13 ± 3		
Top	12 ± 3		
Terrace 3			Probably beginning to be influenced by the approaching trace die out and stepover. Similar or slightly less cumulative displacement to terrace 2.
Riser, base	8 ± 1	1.8	
Riser, top	4.5 ± 1		
Terrace 4			Definitely affected by trace die out because despite being twice as high as terrace 2 there is much less horizontal and vertical scarp offset
Channel 5, nth	4.5± 1	1.1	

Table 4.1: Observed horizontal and vertical fault offsets for various fluvial features adjacent to the Alpine Fault on the true left of the Maruia River.

[1] Channel centre

[2] Note it is also possible that both terraces have been affected by the same number of events and faulting is not regular w.r.t. terrace formation

Table 4.1 summarises the observed horizontal offsets of channels and risers that can be traced across the fault. Offset channels are numbered from channel 1 on the lowest terrace tread 1, to channel 5 on terrace tread 4. Other channels that are not faulted (e.g. younger channels on terrace 1), or can not be traced across the fault, are also shown in Figure 4.1 but are not numbered.

The horizontal offsets of these features do not form a classic pattern (c.f. Lensen 1968) but reduce in both directions along the fault trace. Unfortunately all the terrace risers in a setting such as this (i.e. located on the true left a river in a dextral fault zone) form *leading edge*[6] offsets, so it is possible that some of the offset risers have been trimmed by stream erosion at some stage in their fluvial history. In principle the most reliable potential markers that can be recognised on both sides of the fault are the channel features. However, channels can also be easily modified by infilling on the downthrown side, and the edges of channels are often difficult features to accurately define.

Compilation of the various offsets (Table 4.1) indicates that the maximum offsets can be seen on the Terrace 2 surface where the scarp height is also the greatest. The best – fit cumulative horizontal offset for Terrace 2 is approximately 10m. Unfortunately there is no way to determine how many rupture events this cumulative offset represents but it is likely to be more than two (refer for discussion Table 4.1, terrace 2).

The Terrace 1 surface has a relatively small but consistent vertical offset of 0.25m and a horizontal offset of approximately 1.3 ± 0.75 – 1m. This is a similar scarp height and horizontal offset to the recent trace on the lowest terrace tread at the Blue Grey River, 10 km further southwest (Section 3). Once again we consider this is most likely to represent a single-event offset associated with the most recent rupture of the Alpine Fault at this Maruia River location.

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[6] Terminology of Bull 1991

4.4 Paleoseismic Excavations

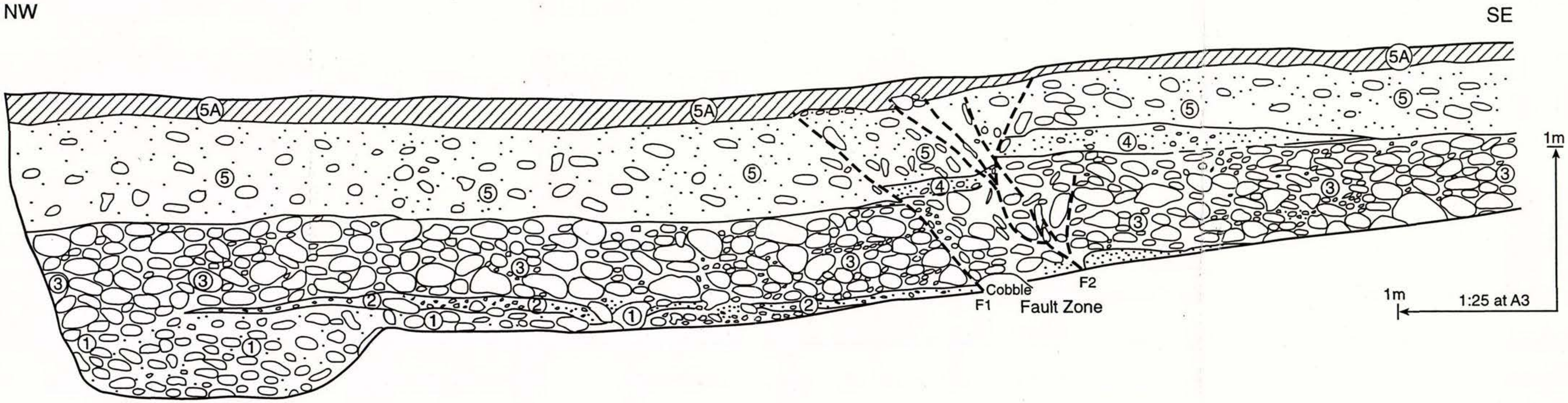
Area selected for trenching

The Terrace 1 surface was selected as the trench site most likely to define the timing of the most recent rupture. Unfortunately there are no swampy areas on the Terrace 1 tread near the fault, and historical accounts suggest that this terrace was never forested, making the presence of significant buried wood unlikely. However, prior to selecting this site the natural exposures of the terrace margin along the modern river channel were examined and these suggested a reasonable cover of overbank silt was present that might enclose datable material.

The trenches were designed to expose the maximum terrace tread surface in the hope that the tread could be dated from buried organic material. Figure 4.1 shows the trench configuration. Effectively two trenches approximately at right angles to the fault zone were joined on the up-faulted side by a section of trench parallel to the scarp, thereby exposing more of the tread surface. The northeastern leg of the U shaped trench (designated Maruia 2) was extended to cross a channel on the terrace 1 surface. This channel has no horizontal or vertical offset at the scarp and appears to postdate the most recent rupture. It was hoped that any datable material from within this channel might effectively bracket the rupture event.

Figures 4.4 and 4.5 are face logs of the two sections of trench that cross the fault. The section of trench parallel to the fault was also examined carefully for samples of organic material that could date the terrace tread, but no material was found and this was not logged in detail.

Maruia 1 Alpine Fault Trench

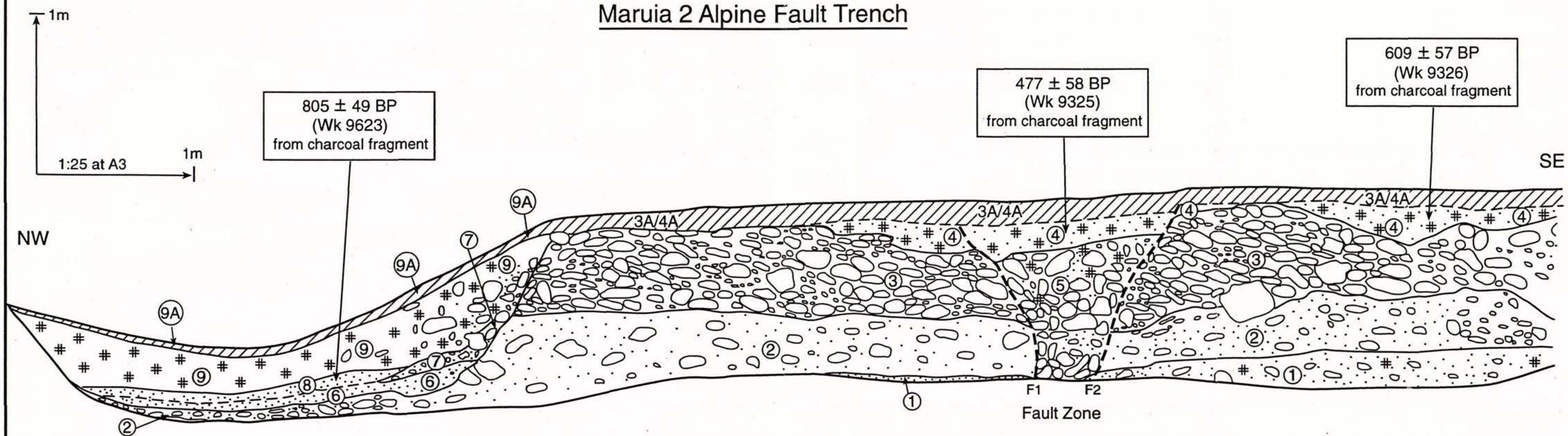


Unit Symbol	Description	Interpretation	Event Horizon
5A	Soft brown organic sandy silt	Topsoil developed since regular floods cease	← Earthquake event
5	Grey silty matrix supported medium gravel with silt more abundant towards the top	Sediments from flood inundation close to the time of terrace abandonment by the main river	
4	Grey pebbly coarse sand	Bedload and channel sediments of the Maruia River	
3	Grey coarse gravel (clast supported) with minor sand		
2	Grey coarse sand with minor fine to medium gravel		
1	Grey medium gravel (clast supported) with minor sand		

Summary

- Southeast dipping fault zone
- Single rupture extending all the way to the surface topsoil
- Small vertical displacement of approximately 250mm
- No datable horizons

Figure 4.4: Face log of the northeast side of the Maruia 1 leg of the trench excavation



Unit Symbol	Description	Interpretation	Event Horizon
9A	Soft grey brown organic sandy silt	Thin topsoil developed on relatively young channel fill	
9	Grey blue sandy silt with gravel becoming more abundant near the SE channel margin	Overbank silts accumulated in several floods with gravel emplaced from scour of SE channel margin	
8	Grey silty sand with rare charcoal	Fluvial channel sediments	
7	Grey silty sandy medium gravel	Slump of channel side into channel in response to scour	
6	Grey silty sand	Fluvial channel sediments deposited after channel cutting	
5	Grey sandy gravel with rotated and sheared appearance	Fault disrupted equivalents of units 1→3	← Event horizon
3A/4A	Soft grey brown organic sandy silt	Relatively thick topsoil developed on Units 3 (gravel) and 4 (silt)	
4	Grey blue dense sandy silt with rare charcoal fragments	Overbank silts from fluvial inundation close to the time of terrace abandonment	
3	Grey medium coarse gravel (clast supported) with minor sand	Bedload and channel sediments of the Maruia River	
2	Grey sandy matrix supported medium - coarse gravel		
1	Grey black sandy matrix supported medium gravel with some silt		

Summary

- Subvertical fault zone forming a small local scale graben structure
- Single rupture extending all the way to the surface topsoil
- Small vertical displacement of approximately 250mm
- Rupture post - dates the youngest tread age date (477±58 BP)
- Rupture pre - dates the channel formation (channel margins and base are not offset in the field), implying substantial charcoal self age for sample Wk 9623, but limiting the rupture to pre 1800 AD and probably pre 1700 AD (refer text discussion)

Figure 4.5: Face log of the northeast side of the Maruia 2 leg of the trench excavation

Trench Stratigraphy

Figure 4.4 (Maruia 1) provides a good exposure of the sediments that comprise the terrace 1 tread. In general this is a fining upward fluvial sequence. Medium and coarse sandy gravels alternate with coarse sands and gravelly sands in the lower trench units (Units 1 – 4). These are overlain by silt rich, matrix supported, medium gravel near the surface (Unit 5) and immediately underlying the surface topsoil. There is no clean silt in this southwest leg of excavation, and no organic material could be located for dating.

The northwest leg of the excavation (Figure 4.5, Maruia 2) reveals a similar basal sequence. Units 1 – 3 are similar to Maruia 1 but in this area a relatively clean sandy silt with rare charcoal fragments caps the gravel dominated sediments (Unit 4) and immediately underlies the topsoil (a soil A horizon, designated Unit 3A/4A).

At the northwest end of this trench there is a new group of units that reflect erosion of the main terrace 1 tread to form a younger channel (units 6-8). A silt-dominated upper unit (Unit 9) overlies basal depositional units associated with this channel. The topsoil that has developed on top of Unit 9 is noticeably thinner than the topsoil on the main terrace 1 tread, and is this designated Unit 9A in the trench log.

Faults exposed in the trench

In the Maruia 1 trench there is narrow southeast dipping fault zone defined by faults we designate F1 and F2. Unit 4 can be recognised on the southeast side of F2, and also within the fault zone, but it is absent northwest of F1 indicating strike slip movement. The apparent vertical displacement of the units is approximately 300mm and this is the same order as the relatively small vertical displacement of 250mm apparent at the ground surface. There is no evidence of more than one rupture event and all the fault strands reach the topsoil.

In Maruia 2 the fault zone is a more vertical flower structure enclosed by two bounding faults designated F1 and F2. Unit 5 is grey sandy gravel with a rotated and sheared appearance that occupies the lower fault zone and we infer this a fault-disrupted equivalent of fluvial Units 1 – 3. Both F1 and F2 have faulted Unit 4, and this unit appears thicker in the fault zone due to strike slip movement. F1 and F2 can be traced up to the topsoil, and F2 appears to extend a short distance into it. Once again there appears to be only one rupture event.

Radiocarbon dates and event timing

Radiocarbon dates for the sediments at this site could only be obtained from AMS dating of very rare and small (approx. 0.25 gm) pieces of charcoal found in the Maruia 2 trench. Small pieces of charcoal are problematic for dating because it is generally more difficult to tell what self-age the sample may have in comparison to dates from larger pieces of wood (rings and wood structure are more difficult to see). Radiocarbon dating of charcoal or wood from the heart of an old tree will date the time that the sample grew as sapwood under the bark, not the time of ultimate tree death and/or burning. Only the outermost sapwood and bark of a tree, or small branches, twigs and leaves have virtually no self-age.

In addition to self-age there is the question of *residence time* i.e. how long the charcoal or wood are resident in the natural environment before burial in the sediment record. In the wet humid environment of Westland wood rots quickly and charcoal also breaks down rapidly so residence time is not as much of an issue as self-age.

The effect of self-age is apparent in the charcoal samples from this trench. Two samples were obtained from close to the base of Unit 4, the overbank silt that caps the terrace 1 tread in the Maruia 2 trench. The oldest of these, Wk 9326, provides a date of 609 ± 57 BP. A second sample from an equivalent stratigraphic location and within the fault zone (Wk 9325) provides a younger date of 477 ± 58 BP. The difference in these dates is likely to be the result of more self-age in Wk 9326. However, the dates provide a reliable minimum tread age and the Unit 4 silt must be younger than the youngest of these two dates. Based on the youngest date of 477 ± 58 BP the tread age must be post AD 1330 and most likely AD 1390 – 1530.

After thorough and extensive hand excavation, a single small fragment of charcoal was obtained from Unit 8 in the channel floor (Wk 9623). The date obtained of 805 ± 49 BP is surprisingly old in view of the field and stratigraphic relationships that indicate the channel post-dates both the terrace tread and the fault rupture.

The possibility that the channel was faulted prompted further hand excavation in the floor of the channel along the projection of fault strike to check if faulting had occurred and was somehow masked. However, there is no sign of faulting in the subsurface channel sediments. This confirms the field evidence that the channel post-dates the most recent rupture based on the absence of vertical displacement of the channel floor and the absence of dextral displacement, particularly along the distinct and relatively planar southern channel side (Figure 4.3).

Furthermore there can be no doubt that the channel itself postdates the terrace 1 tread. This is indicated by:

- the channel floor elevation that is cut well below the elevation of the terrace 1 tread, and not far above modern river level
- the stratigraphic relationship between Units 6-9 and the terrace sediments (Units 1-4)
- the stratigraphic evidence of Unit 3 sediments being reworked and included in Units 6 – 9 in response to scour and undercutting at the steep south side of the channel

The clear implication of this field and stratigraphic evidence is that the charcoal sample taken from the channel has substantial self-age. The Maruia River drains a mono-species beech forest in which the only long lived species is *nothofagus fusca* (red beech). This tree species is seldom found more than 350 years old, and only exceedingly rarely approaches 400 years (A. Wells, pers. comm. 1998). Therefore the maximum possible self-age for the charcoal is 350-400 years.

The calendric conversion of the radiocarbon date from the charcoal indicates that the charcoal comes from wood that grew definitely prior to AD 1380, and very likely prior to AD 1300. Adding the maximum possible 400 year self-age this equates to the channel forming definitely pre – AD 1780 and very likely pre – AD 1700.

The rupture event is therefore bracketed by the tread age, which it post-dates, and the channel age that it pre-dates. The rupture event occurred after AD 1330 (and most likely after AD 1390 – 1530). It occurred before AD 1780 and very likely before AD 1700.

4.5 Summary and comparison with the Blue Grey River

The most recent earthquake rupture at the Maruia River was also a relatively small event resulting in a horizontal offset of approximately 1.3 ± 1m and a vertical offset of 0.25 ± 0.1m. This is a similar order of surface displacement to the most recent event 10 km further southwest at the Blue Grey River. This ground rupture and associated earthquake at Maruia River definitely occurred after AD 1330 and is most likely to have occurred after the period AD 1390- 1530. It occurred prior to AD 1780, and very likely prior to AD 1700. The best estimate is therefore an earthquake that occurred sometime in the period between AD 1530 – 1700.

This estimate of timing is compatible with the data from the Blue Grey River that indicates the most recent ground rupture at that location

definitely occurred post AD 1450 and is most likely to have occurred in period soon after AD 1600, or later in the period AD 1730 – 1840. If this is the same earthquake ground rupture event, which the marked similarity in observed ground displacement strongly suggests, then the best estimate of timing for the combined locations is the period AD 1600 – 1700.

Section 5

PALEOSEISMIC INVESTIGATION OF THE ALPINE FAULT TRACE AT THE MATAKITAKI RIVER.

5.1 General description

The Alpine Fault crosses the Late Holocene alluvial terraces on the true left of the Matakitaki River near Nardoo Creek. Officers of the Geological Survey 1975 have previously described the trace at this location. This site is the only possible trench site that has a clear Late Holocene trace close to the main bends area of the Alpine Fault and so it is of particular importance. The land forms part of Mount Ella Station, a large recent diary conversion, and permission was obtained by the owner Mr Rick Monk, who also made his excavator available for hire to undertake the trenching work.

Figure 5.1 is a summary geological map of the area surrounding the trench site. The Alpine Fault enters southwest of the map area with an average strike of approximately 050° (similar to the Blue Grey River and Maruia River sites) having essentially completed the double bend that results in a strike of a few degrees east of north along the Glenroy River. Across the high divide between Station and Nardoo Creeks, the fault changes strike from 050° to approximately 060°, which is then maintained through the trench area and on to the Nelson Lakes. This strike of 060° is more closely aligned with the plate convergence vector (Section 1) and therefore should result in less oblique convergence at the fault trace and a greater relative component of strike slip movement.

This area of Matakitaki River valley is not far from the end moraine associated with the penultimate advance of the Late Otiran glaciation (a few kilometres west of the map margin of 5.1). A prominent lateral moraine from this same advance closes the valley mouth to the Tutuki valley north of the trench area (near Mataki Lodge, Figure 5.1). Fault traces associated with the Alpine Fault zone cross the southeast end of this moraine but there appears to be a wide

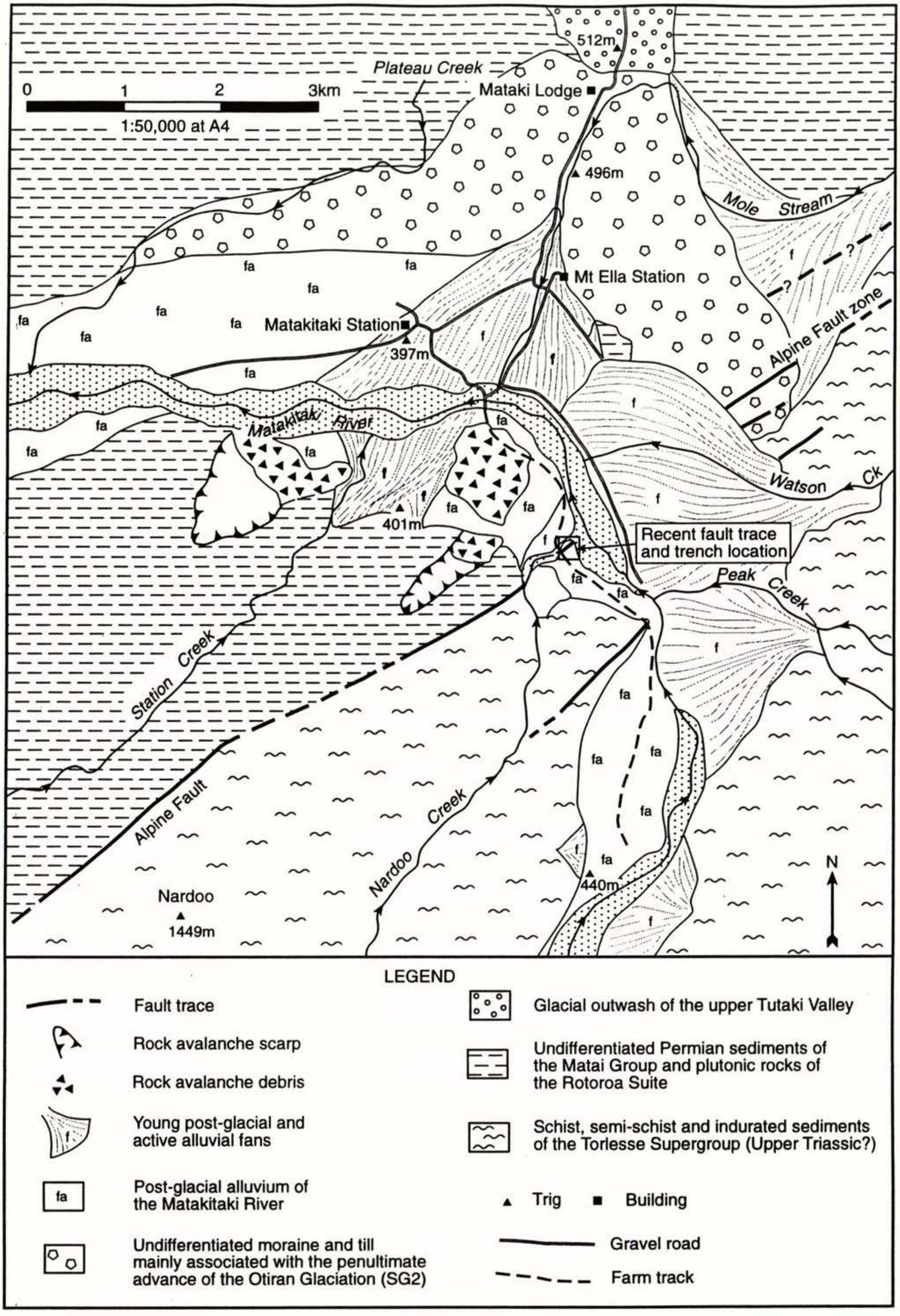


Figure 5.1: The geology of the Middle Matakitaki River valley in the vicinity of the Alpine Fault trace near the mouth of Nardoo Creek.

zone of deformation and multiple fault traces, some of which are in the local bedrock. None of these provide definitive potential trench sites.

At lower elevations below the lateral moraine there are post-glacial river terraces of the Matakitaki River, and numerous large Late Holocene fans associated with the major side creeks (Watson and Peak Creeks). At two locations on the true left bank of the Matakitaki River, immediately west of the trench area at Nardoo Creek, there are rock avalanche scarps in the bedrock on the northwestern side of the Alpine Fault (within Maitai Group sediments and Rotoroa Suite intrusives). Earthquakes, and quite possibly earthquakes on the nearby Alpine Fault, could have triggered these rock avalanches. Unfortunately from the point of view of dating any wood etc buried under the avalanches, the avalanche debris have been buried by subsequent aggradation of the Matakitaki River, and both rock avalanches appear to predate the faulted fluvial surfaces near Nardoo Creek.

The short 200m section of fault trace near Nardoo Creek is the only Late Holocene fault trace that can be identified in this area. There are no other fault traces northeast of the Matakitaki River crossing the major fan associated with Watson Creek. This fan has probably actively aggraded after the most recent Alpine Fault earthquake and buried any offset that may have been present.

5.2 Fault trace description

Figure 5.2 shows the fault trace in detail near the junction of Nardoo Creek with the Matakitaki River. The trace can be identified on two terrace treads of the Matakitaki River (designated the Matakitaki 1 and 2 surfaces respectively) but is not apparent on the relatively young Nardoo 1 surface further to the southwest. This Nardoo 1 surface has a few beech trees remaining after logging that are up to 1m in diameter but some larger trees could easily have been present prior to logging. Growth rings in cut stumps of *nothofagus fusca* on the nearby Matakitaki 1 surface are up to 1.4m diameter and indicate a tree age of 250

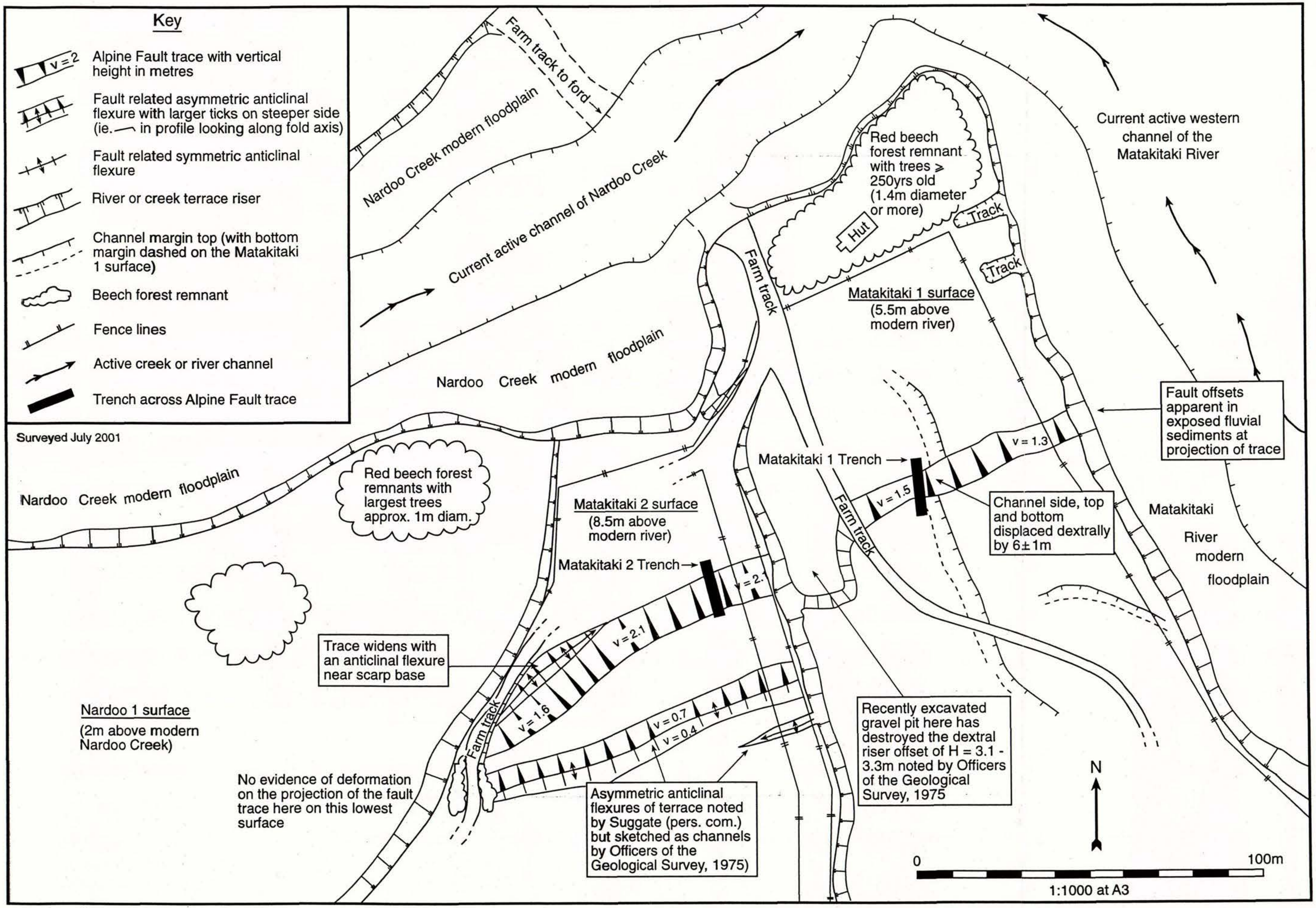


Figure 5.2: The Alpine Fault trace at Nardoo Creek on the true left bank of the Matakitaki River.

years in this location (refer Figure 5.1). Based on this age/diameter relationship we estimate the unfaulted Nardoo 1 surface is at least 200 years old.

The Matakitaki 1 surface is elevated approximately 5.5m above the Matakitaki River and is therefore likely to be a considerably older surface than those trenched previously at Maruia River and the Blue Grey River. The Matakitaki 2 surface is another 3m higher (8.5m). While the tree age on the Matakitaki 1 surface provides a minimum age (i.e. > 250 years) we suspect the surface is considerably older than this (i.e several thousand years).

The fault trace on the Matakitaki 1 surface grows in height from approximately 1.3m at the northeast end near the eroding terrace margin with the Matakitaki River, to 1.5m at the farm access track, after which point a recent gravel pit has destroyed the remainder of the trace on this lowest tread.

There is a single channel feature, the northeast side of which can be identified on both sides of the fault trace. Both the top and bottom of the channel side have been displaced dextrally by a total of 6 ± 1m.[7] Unfortunately the recent gravel pit excavation has destroyed a dextral displacement of the terrace riser between the Matakitaki 1 and 2 surfaces of 3.1-3.3 m (base and top respectively) that was noted by Officers of the Geological Survey (1975). Once again this terrace riser is a *leading edge* riser in the terminology of Bull (1991) and because this is offset less than the channel it appears to have been trimmed by subsequent stream erosion. There is currently no stream in this location on the terrace, or evidence of an old channel along the riser base. This suggests the inferred trimming occurred relatively early in the terrace history.

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[7] Officers of Geological Survey (1975) estimated a horizontal offset of the top of this channel edge of 7m (c.f. our 6± 1m) but also noted an offset of the base (centre) of the channel of 9m. In our opinion the channel base is not reliable at this location because it is very gently curved and scarp erosion appears to have filled the downstream side. In contrast the north side is distinct and both the top and bottom of the channel side are displaced by the same amount. There is no matching south side of this channel, which has probably been removed in track formation and forest clearing.

On the higher terrace the fault trace is generally approximately 0.5m higher than on the lower surface but there are also subsidiary traces (anticlinal flexures) indicating a wider zone of deformation and broader uplift. There are no markers that can be used to estimate the horizontal displacement on this older surface.

Single-event offsets

As noted above the height of both of these surfaces above the Matakitaki River suggests they are relatively old (i.e. several thousand years), and the trench evidence indicates at least two and probably more events. There is no definite single-event offset on either of the terrace surfaces and the maximum observed 6m offset off the channel edge could be as many as 5 or 6 rupture events (but is probably less).

Although it is tempting to presume that the approximately 3m dextral offset destroyed by the gravel pit could be a single-event offset, and the channel offset is then two events of the same order of horizontal displacement, this is unrealistically simplistic. The sites further south show that relatively small displacements of 1 – 1.5m horizontally and 0.25 vertically have occurred in the most recent ground ruptures. The 3m offset of the riser could just as easily be two events of 1m and 2m respectively, three events of 1m, or any other possible combination.

What can be inferred, based on the absence of evidence for recent trimming of the offset terrace riser, is that the single-event offset in the most recent event is unlikely to have exceeded 3m.

5.3 Paleoseismic excavations on the lowest terrace (Matakitaki 1)

Area selected for trenching

The Matakitaki 1 terrace edge at the eroding margin with the active Matakitaki River floodplain reveals a sequence of gravels and sands with fault offsets along several fault strands near the scarp. Although the terrace surface has a thin cap of finer silty sand and sandy silt thorough searching of several hundred metres of the terrace edge revealed no wood or datable material.

However, both the terrace surfaces were recently covered in mature beech forest, a remnant of which remains near the old hut beside Nardoo Creek. This forest was progressively removed between 1900 and 1960. Excavations along the Alpine Fault at similar sites that had forest cover during past earthquake ruptures have uncovered datable organic material trapped in the shear zone and this was hoped for at this new location.

A site near the centre of the offset channel was the lowest and wettest area of the terrace surface, with the best chance of the preservation of organic material, and this was selected for excavation of the first trench. Figures 5.3 – 5.5 are photographs showing the fault scarp on each terrace and location of both of the trenches.

Trench stratigraphy

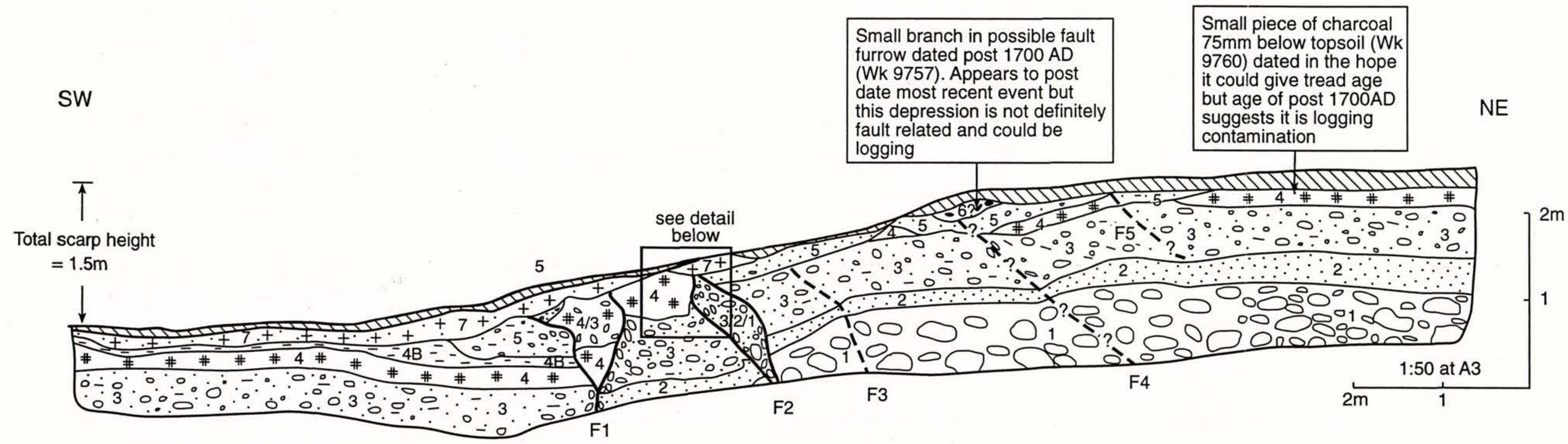
Figure 5.6 is the face log of the eastern side of the trench. This was selected for logging because the light was better on this side of the trench and the stratigraphy was similar on both sides. Figure 5.7 is a composite photograph of this side of the Matakitaki 1 trench. Note that by convention the face log has been reversed to show the trench face looking north, but unfortunately this makes correlation between the photographs and the face log more difficult.

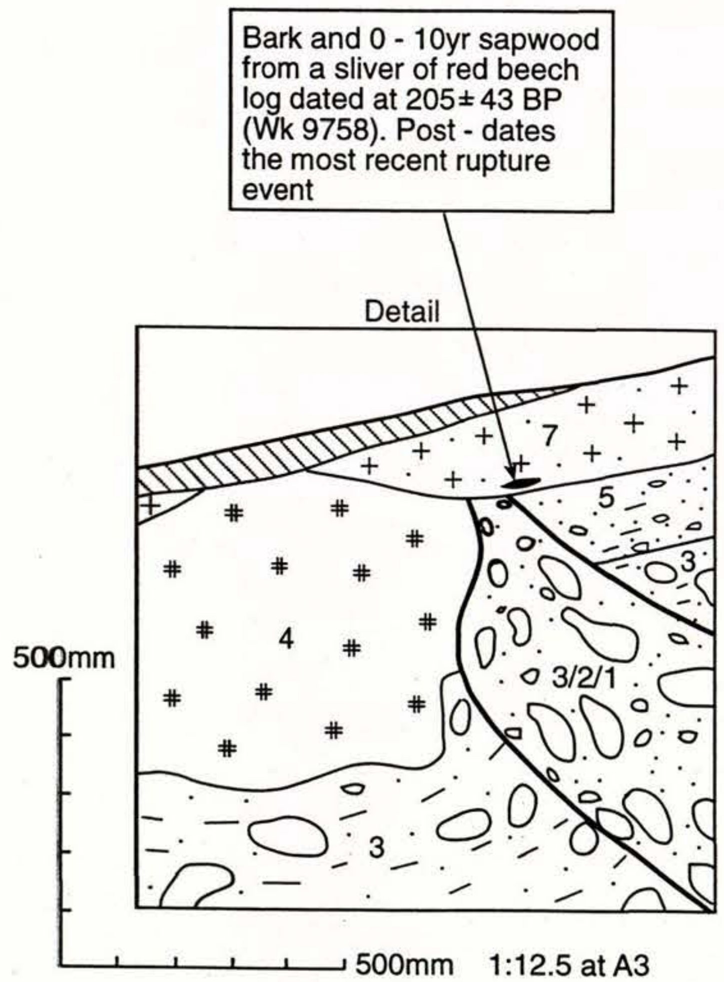
Figure 5.3: The Alpine Fault trace at the Matakitaki River. The first trench has been excavated and is visible on the lower terrace close to the dextrally displaced riser on the downthrown side. The second trench is being excavated on the higher terrace surface.

Figure 5.4: Another view of the Alpine Fault trace on the higher terrace looking towards the lower terrace. From this point a second lower scarp (bulge) is just visible above the main scarp running just uphill of the concrete stock trough.

Figure 5.5: The Alpine Fault trace on the higher terrace with the second scarp just visible above the main scarp.

Matakitaki 1 Alpine Fault Trench





Unit	Description	Interpretation	Event Horizon
(topsoil)	Soft brown organic clayey silt	Modern topsoil formed on a variety of older units	
7	Brown silty sand and sandy silt with some fine gravel	Scarp derived colluvium from most recent rupture	
6	Brown black organic clayey silt and wood	Buried forest litter in fault furrow or old stump hole	Most recent ← event
5	Brown and grey silty sandy fine gravel	Scarp derived colluvium from older rupture	Earlier ← event
4B	Brown sandy clayey silt with some sand	Soil B horizon formed on Unit 4	
4	Blue sandy silt with some sand	Overbank fluvial silts from the Matakitaki River	
3	Brown grey silty sandy fine to medium gravel	Various fluvial sediments from the Matakitaki River	
2	Blue grey coarse sand with some fine gravel		
1	Blue grey medium to coarse sandy gravel		

Summary

- At least two rupture events indicated by scarp colluviums and fault truncations (F1 and F2).
- Most recent event pre-dates sample dated at 205 ± 49 BP (Wk 9758).
- Date near top of scarp (Wk 9757) not definitely fault related because Unit 5 appears undeformed.

Figure 5.6: Face log of the Matakitaki 1 trench across the Alpine Fault trace on the lowest terrace.

Figure 5.7: Composite photograph of the southwest wall of the Matakitaki 1 trench. Note that after logging this wall the face log in Figure 5.6 has been reversed in keeping with viewing conventions. The main photograph shows the entire fault zone while the detail shows the area adjacent to F2 (between the yellow and red strings) with the unfaulted scarp- derived colluvium over this shear zone that yielded radiocarbon date WK 9758 (205 ± 43 BP).

There is a typical fining upward sequence of gravel and sand dominated fluvial sediments of the Matakitaki River capped by an overbank river silt. Four units can be recognised in this sequence (Units 1 – 4). At the base of the fault scarp there is an old buried soil profile (Unit 4B) in which all the organic material has been oxidised and only the old soil B horizon remains. We infer this burial is related to one or more episodes of fault displacement.

Above this unit at the base of the scarp, and at various other points higher up the scarp, there is brown and grey scarp-derived colluvium unit in which the schist pebbles are aligned down slope and the sorting is very poor. Near the base of the scarp this unit is faulted, and eroded, and a second scarp derived colluvium overlies it (Unit 7).

At the top of the scarp we show Unit 6, the origin which is unclear. At the time of trench logging we were of the view that this might be an area of buried forest litter preserved in a local fault related depression associated with a recent rupture. If correct this implies the organic rich unit predates Unit 7, the scarp-derived colluvium that has accumulated after rupture of the fault. However, there is only inferred evidence for a fault (designated nominally F4) below this "depression", based primarily on the local termination of Unit 4. Deeper stratigraphic units such as Unit 2 are not significantly offset. On reflection the depression containing the organic material could just as readily be the result of logging (i.e. an infilled stump hole), and this alternative explanation is supported by the young radiocarbon date (pre AD 1700) that has been subsequently obtained from this area (refer later discussion).

However, regardless of the origin of Unit 6, the recognition of two scarp-derived colluvium units indicates stratigraphic evidence of at least two rupture events.

Faults exposed in the trench

The fault strands exposed in the trench also indicate multiple rupture episodes. This is best demonstrated by the SW branch of F1, which offsets older scarp colluvium (Unit 5) and the buried soil horizon 4B, before terminating at the base of Unit 7. Unit 5 is also faulted at F2, and once again the faults do not enter Unit 7. While the presence of a concealed fault strand at F3 is highly probable, we are less confident of definite fault displacement at F4. Near F5 there is fault truncation of Unit 5 and an extensional area in which Unit 4 is absent and definite fault truncation of Unit 5. Tracing the continuation of this F5 fault plane deeper in the sequence is more difficult.

The trench log shows that there is local folding, faulting and disruption of the upper soil units extending over a relatively wide zone of deformation of approximately 6-7m. This is in contrast to the narrow fault zone (approximately 1m) at the Maruia River, where there appears to have been only one episode of faulting. The width of the fault zone at this location provides further indirect evidence that the scarp is the product of several rupture events.

Radiocarbon dates

Although a total of three radiocarbon dates were obtained from this trench the results are inconclusive. The first sample (Wk 9760) was a small piece of charcoal only 75mm below the topsoil near the top of Unit 4, the overbank silt capping the terrace tread. This was dated in the hope that it might reveal the tread age but the result of post AD 1700 indicates this was contamination from forest clearing.

We have already noted the questionable origin of Unit 6 comprising organic material near the top of the fault scarp. Wk 9757 was taken from a small section of branch in this organic material. Once again the resulting date is post AD 1700. This may post-date the most recent rupture but could just as easily be from logging disturbance in the early 1900's.

Finally there is one other date that is reliable from a stratigraphic perspective but does not significantly constrain event timing. Wk 9758 was taken from bark and a sapwood sliver of red beech near the base of Unit 7, the youngest scarp-derived colluvium. This returned a date of 205± 43 BP, and this date definitely post-dates the last rupture event, because Unit 7 truncates two strands of F2 immediately below the sample. However, the calendric conversion of this date is anytime between AD 1640 and the present day. Because of early settlement in AD 1840 this possible range can be reduced slightly to AD 1640 – 1840.

5.4 Paleoseismic excavations on the highest terrace (Matakitaki 2)

Area selected for trenching

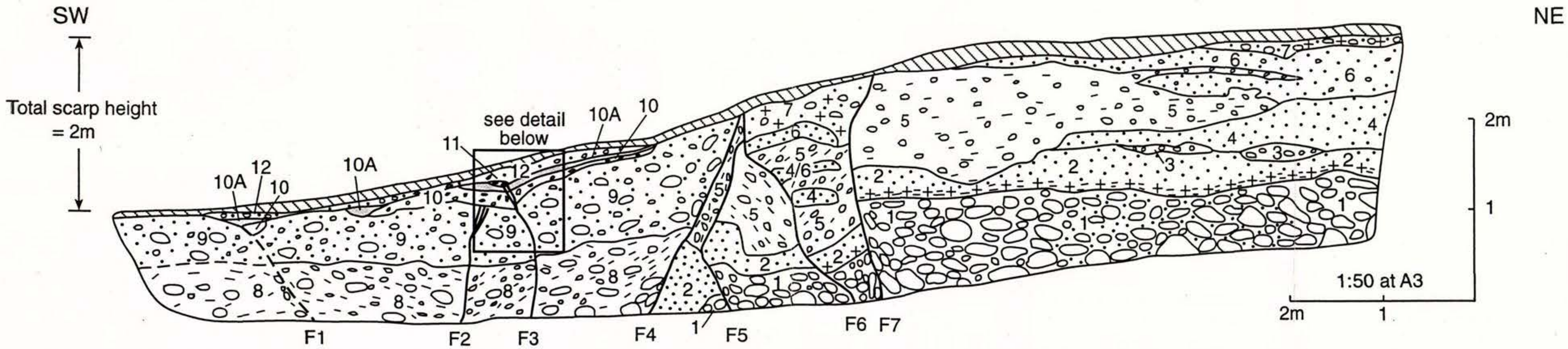
The scarp along the higher terrace has no depressions or obvious swampy areas and the site that was finally selected for trenching was located mainly to avoid inconvenience for the farmer. It became clear from the subsequent excavations that if the trench had been more than 1m either side of the final location, the key area that has provided a critical date would have been missed.

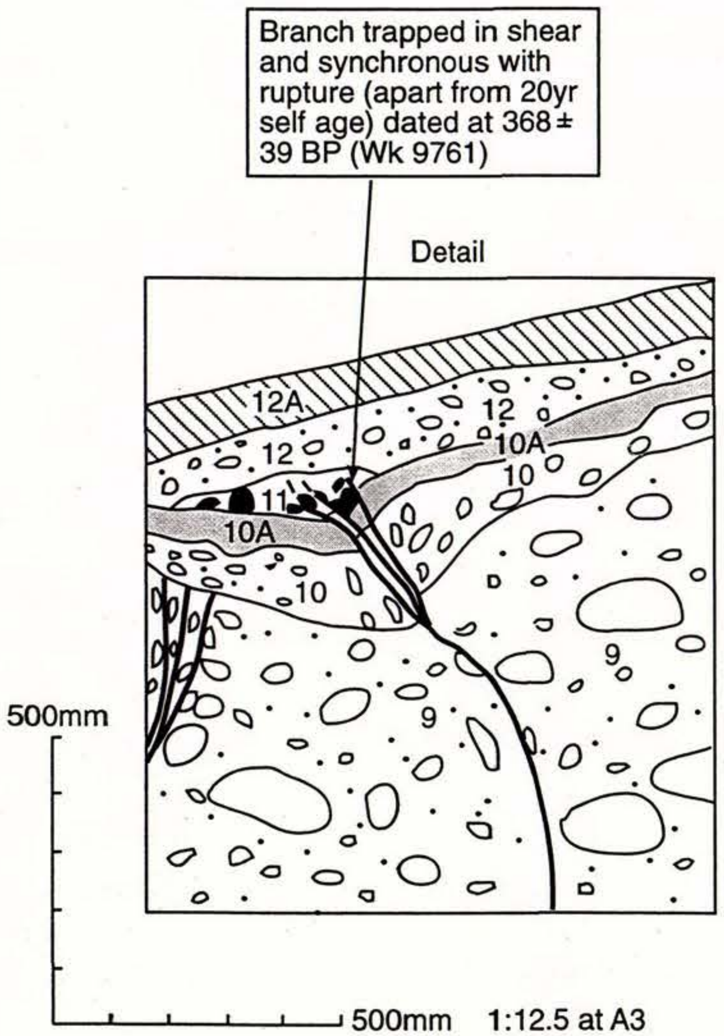
Trench stratigraphy

Figure 5.8 is the trench log of the southeast wall of the trench and Figure 5.9 is a composite photograph. Once again face log presentation conventions effectively reverse the log with respect to the photographs.

The units in this trench are similar to the deeper fluvial units in Matakitaki 1 except that on this higher terrace there is no overbank silt, and all the gravels are significantly more weathered. There are a greater number of fluvial units on the NE side of the scarp (Units 1-7), and there is not much correlation between the units across the fault because of the substantial dextral offset.

Matakitaki 2 Alpine Fault Trench





Unit	Description	Interpretation	Event Horizon
	Soft brown organic clayey silt	Modern topsoil formed on a variety of older units	
12	Brown silty sandy fine gravel	Scarp derived colluvium	
11	Branches and twigs in a peat matrix with some pieces charred from forest fire	Forest floor litter trapped and buried following F3 surface rupture	Earthquake event
10A	Dense black organic clayey silt	Buried topsoil pre - dating the most recent rupture	
10	Dark brown silty sandy fine gravel	Scarp derived colluvium	
9	Yellow brown silty sandy fine - medium gravel	Various fluvial sediments from the Matakitaki River	Earlier earthquake event indicated by the truncation of F2 at the top of Unit 9
8	Grey brown sandy fine - medium gravel		
7	Brown silty sandy fine to medium gravel		
6	Light grey sandy fine gravel		
5	Light grey silty sandy fine gravel		
4	Grey fine to medium sand		
3	Grey fine sandy gravel		
2	Dark grey fine to medium sand with silt beds common near base		
1	Grey brown locally sandy medium to coarse gravel		

Summary

- At least two ruptures demonstrated and more than two implied by the trench position on a higher terrace than Matakitaki 1
- Significant ground rupturing earthquake at around 368±39 BP (Wk 9761) which is probably the most recent event in both trenches

Figure 5.8: Face log of the Matakitaki 2 trench across the Alpine Fault trace on the highest terrace.

Figure 5.9: Composite photograph of the southwest wall of the Matakitaki 2 trench. Note that after logging of this wall the face log in Figure 5.8 has been reversed in keeping with viewing conventions. The main photograph shows the entire fault zone after some further excavation of the key area around F3. The arrow head shows one of the pre-burial broken ends of the branch from which WK 9761 was prepared for dating. This branch was the wood trapped lowest in the shear zone.

Because of this lack of correlation we define Units 8 and 9 on the SW side of the scarp as separate units, and show these as "younger" than Units 1-7, but they are most likely a similar age.

Units that relate to fault rupture commence with Unit 10, a scarp-derived colluvium, and Unit 10A, a buried topsoil associated with this. There is then a remnant forest litter (Unit 11) that in turn is covered by a younger scarp-derived colluvium (Unit 12), and this is immediately below the modern topsoil.

Once again the stratigraphy demonstrates at least two rupture events but the location of this scarp on a significantly higher terrace than Matakitaki 1 suggests that there have been more.

Faults exposed in the trench

The fault zone from F1 to F7 is a total of 7m wide and most of the displacement appears to have occurred in the middle of this area on the southwest dipping F4. There are clear truncations of some older fault strands (e.g. F2) at a scarp-derived colluvium (Unit 10) associated with an earlier event (or events). Most of the other fault strands can be traced all the way to the modern topsoil and appear to be associated with the most recent event.

In view of the date Wk 9761 from Unit 11 (discussed below) it is necessary to consider the possibility that there could have been a more recent rupture of the fault at this location since propagation of F4 into Unit 11. This appears unlikely based on:

- The proximity of Unit 11 to the modern ground surface
- The absence of any obvious younger scarp-derived colluvium than Unit 12
- The absence of evidence for any faulting of Unit 12

It is therefore reasonable to assume that estimates of earthquake event timing based on the age of wood contained in Unit 11 apply to the most recent rupture event.

Radiocarbon dates

The key area in this trench is enlarged in the detail in Figure 5.8 This is a local depression (furrow) near the base of the scarp associated with fault strand F3, which has ruptured all the way into Unit 11. Unit 11 is an old forest floor cover of branches, twigs and leaf litter that has been faulted, buckled, and densified by shearing of the underlying more competent topsoil layer (Unit 10A). This organic material closely pre-dates the most recent rupture of this fault strand. It may be few years older than the rupture event that preserved it, but there are very fast wood decay times on the forest floor of forests in the western South Island. The combination of high rainfall, invertebrates and fungi cause rapid decomposition of organic material in this temperate environment and twigs and small branches seldom survive intact on the forest floor for more than 10 years (A. Wells, pers. comm. 1998).

A fresh looking branch that was trapped between shears immediately above the underlying old topsoil was selected for dating because it:

- had ends that had clearly been broken prior to burial (i.e. it was not a root that grew later)
- had some recognisable sections with bark still attached.
- was in sound condition, particularly in the centre of the branch (spoors from rotting wood can affect apparent radiocarbon age and if possible only dense intact wood should be dated)
- was the lowest wood in this shear zone

This branch was cut into disc sections and the growth rings counted back from those locations that still had bark to the determine a maximum age of 27 years. A sample was then prepared for dating from the intact central section of the branch with growth rings spanning 15 –27 years (i.e. an approximately 20 year self-age).

This sample (Wk 9761) returned a date of 368 ± 39 BP and when corrected for self-age this date can be considered essentially synchronous with rupture. The date converts to a calendric age (including the 20 year self-age correction for the branch wood) of post AD 1455 and pre AD 1690 (and most likely AD 1500 to 1660). Arguably, this branch might have survived up to a maximum of approximately 10 years on the forest floor before burial and preservation. Therefore the timing of the most recent rupture event at this location is after AD 1455 but before AD 1700 (i.e. AD 1690 + 10 years) and most likely to be in the period between AD 1500 and 1670.

5.5 Summary and comparison.

The Matakitaki 2 paleoseismic excavation at the Matakitaki River provides a well-constrained date for the most recent rupture of the Alpine Fault at this location. The most recent rupture occurred after AD 1455 and before AD 1700, and it is most likely to have occurred between AD 1500 and AD 1670. No definite single-event horizontal offset can be inferred from this event, and although the evidence suggests this was not larger than approximately 3m, it could quite possibly have been less.

This timing estimate is consistent with the estimates obtained approximately 50 km southwest along fault strike at the Maruia River and a further 10 km southwest at the Blue Grey River. The best estimate of event timing for these combined locations is the period AD 1600 – 1700.

Section 6

PALEOSEISMIC INVESTIGATION OF THE ALPINE FAULT TRACE AT TOPHOUSE SADDLE.

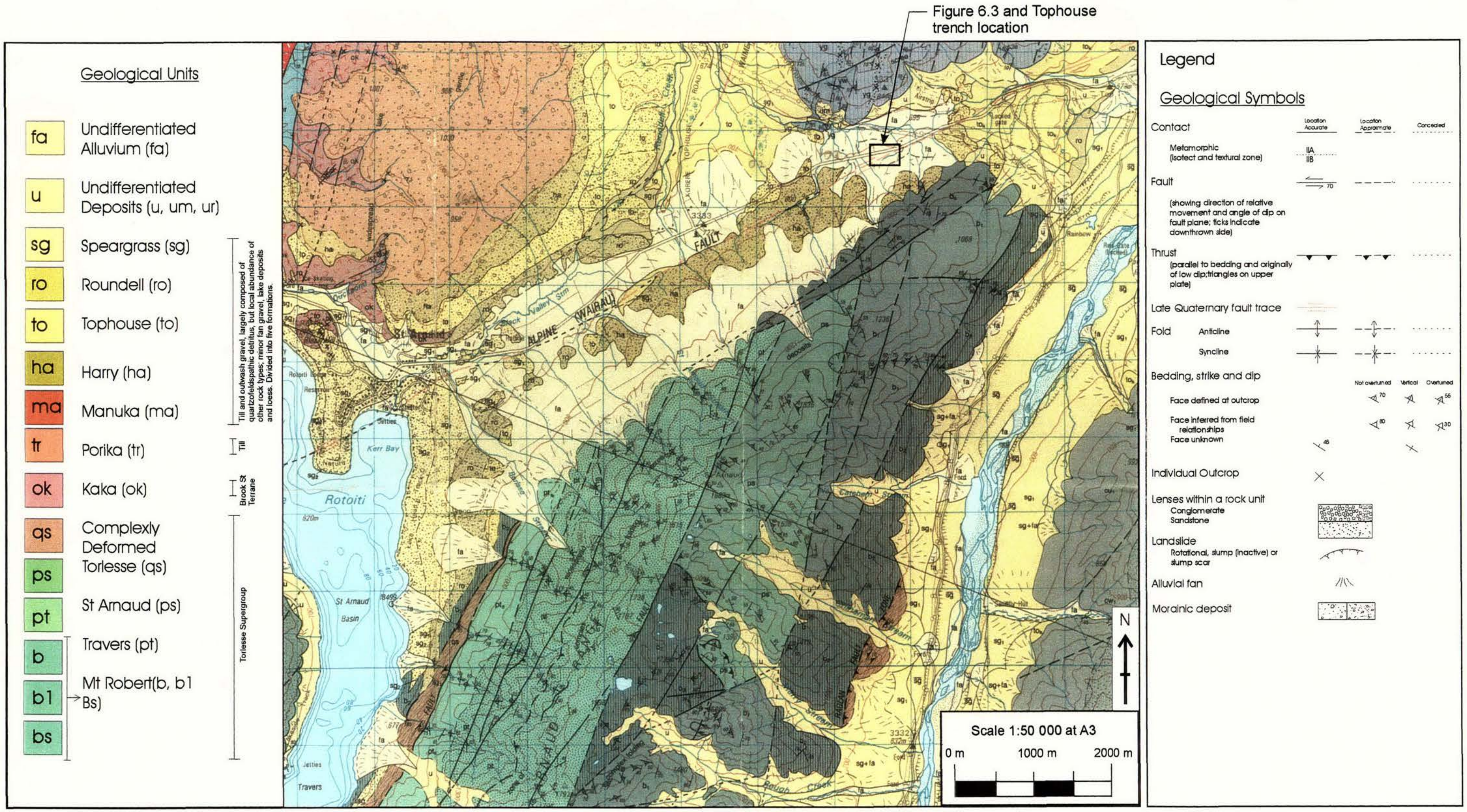
6.1 General description

Figure 6.1 shows the Alpine Fault trace in the vicinity of Tophouse trench site. Johnston (1990) has carried out geological mapping of the Lake Rotoiti and Tophouse Saddle area in considerable detail and part of this map is presented in Figure 6.2.

The active trace of the Alpine Fault can be identified crossing Brunner Peninsula at Lake Rotoiti at a strike of 065° where it offsets moraines associated with the latest glacial advance of the Late Otiran glaciation. There is approximately 70m of horizontal offset in this area and a scarp height across the displaced features that reaches around 7m (up on the southeast), although some of the height difference is the result of the strike-slip offset of an irregular landform.

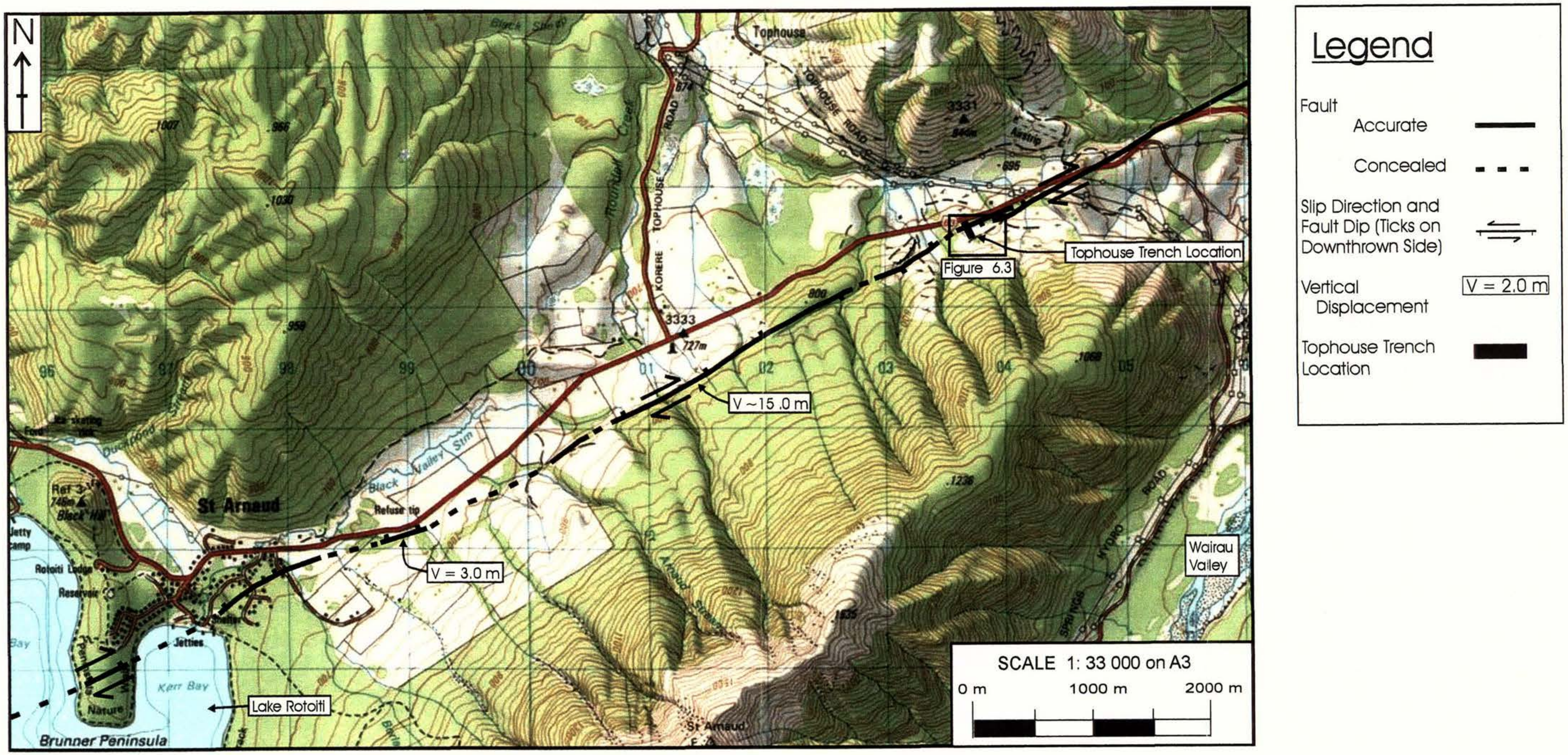
A 9m high fault scarp commences immediately northeast of the lake near the Department of Conservation campground and can be traced with generally decreasing height into the private properties of St Arnaud. There is local swing in strike and partial burial of the recent trace in young fan gravels before a clear 3m high trace is again apparent displacing moraine near the local refuse tip.

Once again the scarp is lost under fan gravels until northeast of St Arnaud Stream where there is a virtually continuous trace that can be followed all the way to the selected trench site. Through all of this area the fault is displacing Middle and Late Pleistocene moraine and Late Holocene fan deposits derived from the Torlesse Supergroup of the St Arnaud Range. The scarp is up to 15m high and there is clear dextral displacement of streams and fluvial features (up to approximately 170m). However, in some cases the apparent stream



Geological map of the Lake Rotoiti area (from Johnston, 1990)

FIGURE: 6.2



Map of the Alpine Fault Trace between Lake Rotoiti and the Wairau Valley

FIGURE 6.1

displacements are misleading because the streams have followed and exploited the fault zone. Unfortunately there are no reliable dated geomorphic markers in this area that can be identified on both sides of the fault.

No likely single-event displacements have been recognised along this section of the fault. The smallest definite horizontal displacement that can be observed is an approximately 13m horizontal offset of a small tributary of the Motupiko River, approximately 1km northeast along the fault trace from the Korere – Tophouse road junction with SH 63.

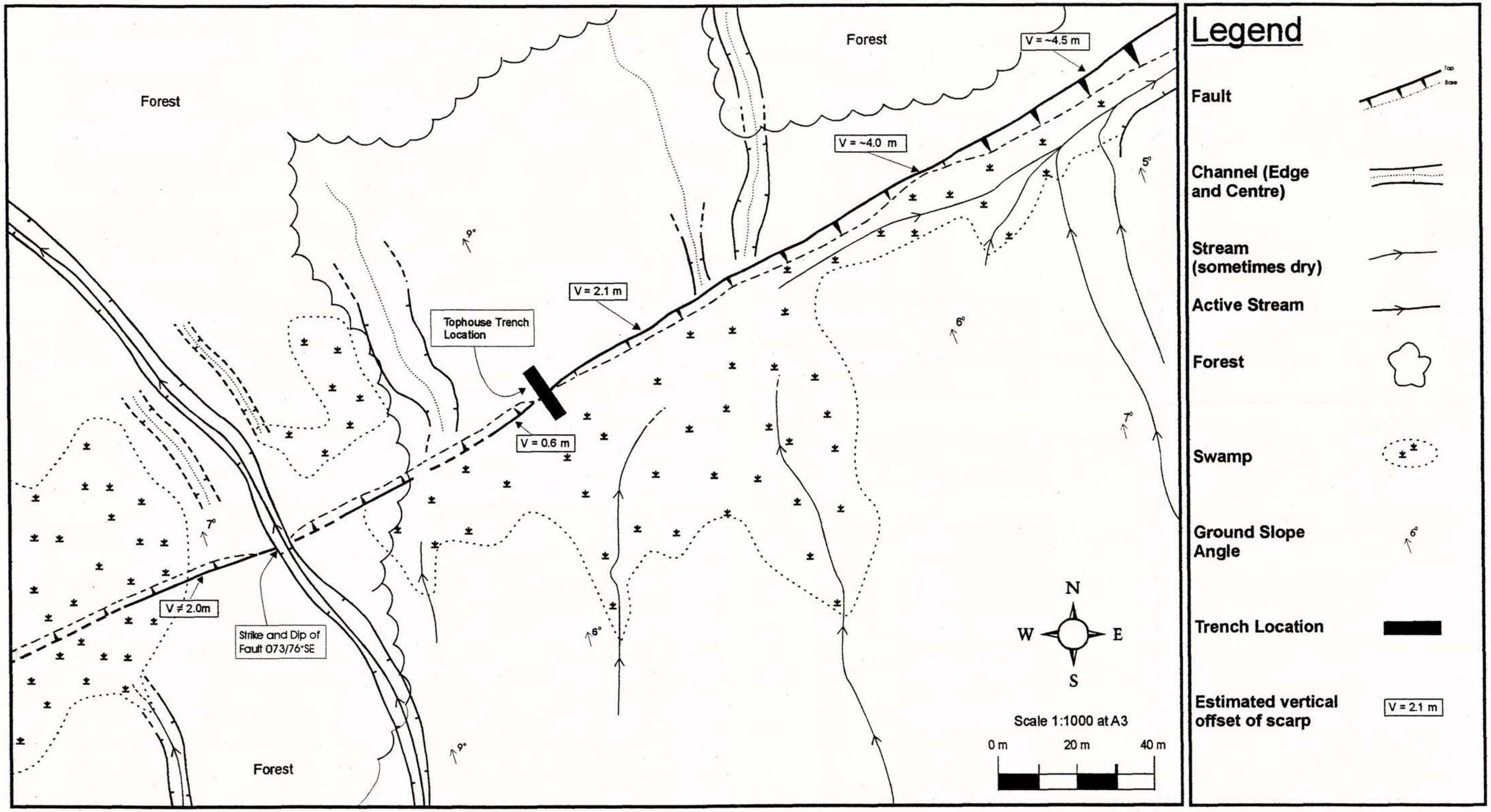
6.2 Fault trace description at the trench site

Figure 6.3 shows the fault trace in the vicinity of the trench site. A scarp approximately 3m high can be identified as the southwest of the area with a downhill-facing scarp (i.e. apparent uplift on the southeast side) and a strike of 068°. This trace reduces in height towards an active local fan and stream channel where the scarp is poorly defined and locally concealed.

Approximately 75m further northeast is the selected trench site. Here the active trace is beginning to reappear at the surface, this time in the form of an uphill-facing scarp (i.e. apparent uplift on the northwest). A swamp has formed against this 1m high scarp and this creates a local depositional basin. The trace continues to gain height to the northeast but the local drainage from the swamp and slopes above the sites becomes entrenched along the scarp. This has lead to scour and the potential removal of the youngest paleoseismic record and this area has been avoided.

Further northeast past the trench site a second arcuate downhill-facing fault trace becomes apparent (just within the northeast corner of the map in Figure 6.3), that is close to the main trace and defines the beginning of a broad graben feature between these traces[8].

[8] Lensen (1976) notes several wedges and tilted wedges of this general type along the fault trace in the area east of Tophouse Saddle and the Wairau Valley.



The Alpine Fault trace and the location of the Tophouse trench

FIGURE 6.3

Despite thorough examination there are no clear markers that can be recognised anywhere in this area of the fault scarp to determine either the cumulative or single-event horizontal offset at the fault trace.

The entire area shown in Figure 6.3 was covered in mature red beech (*nothofagus fusca*) and black and mountain beech (*nothofagus solandri*) up until partial logging in the 1960's. However, many beech trees still remain, particularly in the vicinity of the fault scarp.

6.3 Paleoseismic Excavations

Area selected for trenching

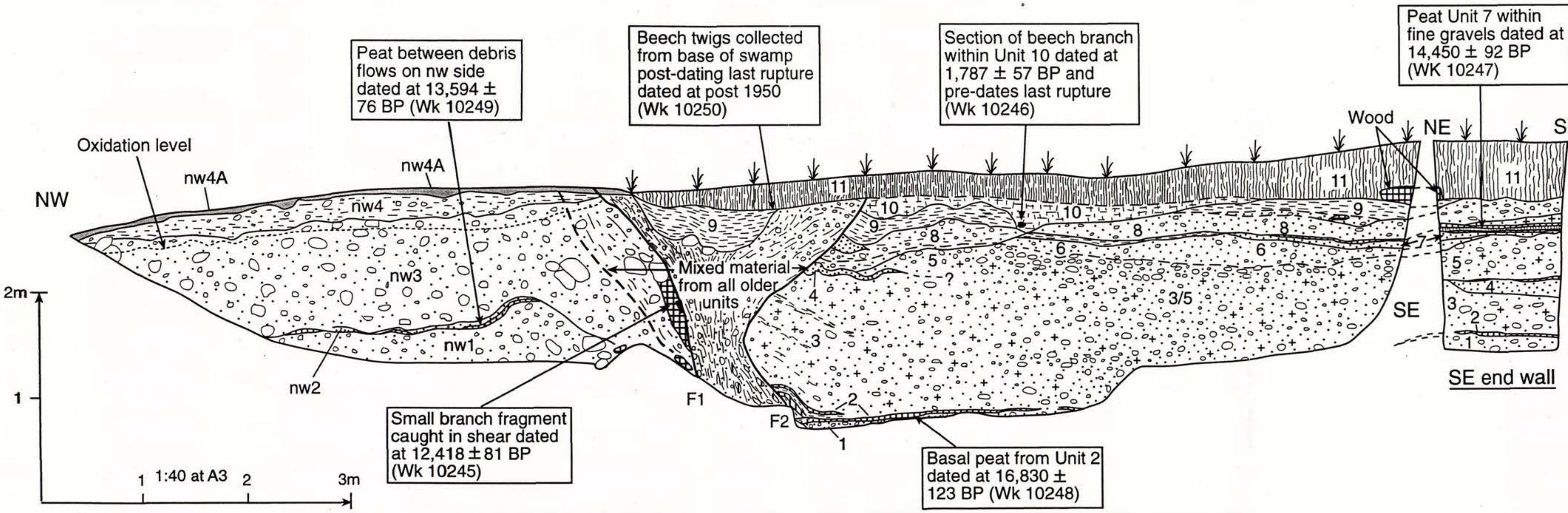
The area selected for trenching is an obvious sediment trap in which organic material is accumulating in a saturated state that should ensure good preservation.

Trench stratigraphy

Figure 6.4 is a face log of the southwest side of the trench. The basal sequence southeast of the fault is a series of fine silty sandy angular gravels derived from debris flows associated with landslides or major erosion episodes in the St Arnauds Range. Three major debris flow episodes can be inferred (Units 1, 3 and 5/6), each bounded by thin fluvial fine clean sand beds and peat (Units 2, 4 and 7).

Covering these debris flow units and intervening peats is a better sorted fluvial gravel and silt (Unit 8) that marks the cessation of debris flow incursions at this location. Overlying this is the first of two clay and silt dominated units (Units 9 &10) each with an upward increase in the relative proportion of organic material. The overlying surface unit (Unit 11) is a soft fibrous silty peat, with buried broken fallen twigs and branches.

Tophouse Alpine Fault Trench



Unit	Description	Interpretation
nw 4A	Grey brown organic silty sand	"A" horizon developed on Unit 4
nw 4	Grey moderately weathered silty clay with fine angular gravel	Debris flow sediments
nw 3	Grey blue fine to medium sandy gravel with a silty clay matrix	
nw 2	Black brown dense peaty sand and sandy peat	Swamp hiatus
nw 1	Blue grey fine to medium sandy gravel with a silty clay matrix	

Probable time correlation

Unit Symbol	Description	Interpretation	Event Horizon(s)
11	Black brown fibrous peat with twigs	Recent swamp deposits with twigs from trees growing in swamp	Event horizon
10	Grey clayey peat with some wood	Slopewash sediment and local peat and tree litter	
9	White grey silty clay locally with fine gravel and wood near base	Slopewash sediments following fan stabilisation	
8	Grey blue sandy fine angular gravel with some silt and local sand beds	Fan gravels from upslope stream systems	Numerous earlier rupture events displacing these units but no confirmed event horizons
7	Thin peat beds with grey blue silty clay and sand interbeds	Swamp deposits during hiatus in fan activity	
6	Grey blue sandy fine angular gravel with some silt and clay	Fan gravels from upslope stream systems	
5	Blue grey unsorted sandy fine subangular to subrounded gravel with a silty clay matrix	Debris flow sediments and associated minor fan gravels	
4	Grey medium sand with minor peat beds at the SE end of the trench	Fan sediments and minor swamp deposits	
3	Blue grey unsorted sandy fine subangular to subrounded gravel with a silty clay matrix	Debris flow sediments and associated fan gravels	
2	Dense brown uniform fine peat	Swamp deposits during hiatus in fan and debris flow activity	
1	Blue grey unsorted sandy fine gravel with a silty clay matrix	Debris flow sediments	

Summary

- Strike slip dominated fault zone with rupture confined to a narrow zone of repeated displacement.
- The most recent rupture post - dates 1,787 ± 57 BP, the date obtained from the faulted Unit 9.
- The date of post 1950 from the base of the swamp near the scarp indicates the swamp in this area is a very young feature.

Figure 6.4: Face log of the southwest wall of the Tophouse Alpine Fault trench.

Northwest of the fault more debris flow units can be recognised (Units *nw* 1, 3 and 4) and these also enclose a thin peat bed (Unit *nw* 2). In general the debris flow units northwest of the fault are more silt rich, more poorly sorted and have the appearance of being more distal from their source. A thin topsoil and more pronounced soil B-horizon (marked by oxidation staining) has developed on the surface of these units.

Faults exposed in the trench

In view of the age of the strata revealed by the dating (refer discussion below) the fault zone is remarkably narrow. Two steeply dipping bounding faults, designated F1 and F2, enclose a fault zone in which there is chaotic mixing of material from all the units adjacent to the bounding faults. At 2m depth the fault zone is less than 1m wide. Although there is some widening of the overall fault zone in the surface 1.5m to form a minor flower structure, even at ground level the fault zone is less than 3m wide.

Radiocarbon dates

Six radiocarbon dates were obtained from wood and peat in the trench. The oldest date is from the basal peat unit southeast of the fault (Wk 10248, Unit 2) that provides a date of 16,830 ± 123 BP. Approximately 1m higher in the debris flow sequence the peat from Unit 7 (Wk 10247) has a radiocarbon age of 14,450 ± 92 BP.

Northwest of the fault the peat between debris flows (*nw* 2, Wk 10249) has a radiocarbon age of 13,594 ± 76 BP. These dates indicate that the debris flows on the northwest side of the fault are younger features than those on the southeast side (refer probable time correlation in Figure 6.4) and that strike-slip movement along the fault has brought these sediments into relative juxtaposition.

All three of these peat dates are considerably older than we expected at the time of logging the trench. They suggest that in this area, located at the base of the St Arnaud Range, there was considerable slope instability and active erosion in the immediate post-glacial period. This may have been part of the geomorphic adjustment of the higher slopes in response to a warmer and wetter climate, and before the extensive beech forest became well established.

There are three dates that relate to the timing of faulting in the trench. By far the oldest is a date obtained from a 125mm x 25mm diameter broken branch fragment trapped in fault gouge associated with F1. This is dated at 12,418 ± 81 BP and indicates a rupture of the Wairau section of the Alpine Fault at this time. We do not consider a branch fragment of this type could have come from recycling of organic material during shearing of the old peats. All the old peats are uniformly fine and free of branch wood. The presence of wood trapped in the shear suggests that by this time a forest cover had become established at the site.

An interesting possibility is suggested by the similarity in the interval between the ages obtained from the various peat radiocarbon dates and the date from the branch trapped in the shear. It is possible that the debris flows could have been triggered by earthquake shaking associated with the Wairau section of the Alpine Fault at a time when the higher slopes were more sensitive to earthquake shaking. If this hypothesis is correct then the time interval between the debris flows may approximate to the recurrence interval of earthquakes on this section of the fault.

On the southeast side of the fault there is an approximately two thousand year interval between the basal peat and a peat date obtained two debris flows higher in the sequence (i.e. the interval between successive debris flows may be around one thousand years). There is also evidence for a debris flow about 1000 years later based on the peat date on the northwest side of the fault. Approximately another thousand years has then elapsed before fault rupture and an associated earthquake that is indicated by the trapped branch in the shear. Unfortunately this hypothesis is speculative and can not be readily proven. However, as more paleoseismic data becomes available for this section of the fault a more definitive pattern may emerge.

The date that most significantly constrains the timing of the most recent rupture of the fault is Wk 10246 taken from Unit 10. Unit 10 is on the northeast side of the trench and this is the youngest unit that has been faulted. The date obtained is 1787 ± 57 BP (this converts to the period AD 200 – 500) and the fault rupture of Unit 10 must have occurred after this. Once again this is an older date than we expected at the time of logging the trench. The presence of this faulted unit close to the surface at the top of the detrital sedimentary sequence indicates:

- that this area has been relatively stable and free of sedimentation for a substantial period since at least AD 500.
- that any detrital material from slope failures or erosion immediately following the last earthquake has bypassed this part of the fault scarp (i.e. there is no unfaulted sediment or scarp colluvium overlying the fault zone)

The final date from the trench is Wk 10250 (Unit 11) taken from a collection of twigs obtained from the very base of the peat overlying the fault zone. It is extremely unlikely twigs of the size selected could have fallen all the way through peat of the fibrous consistency of Unit 11 so we consider these twigs accurately date the time of swamp formation at the scarp. However, the dates obtained indicate these twigs are from trees that have grown since AD 1950 when atmospheric C_{14} became modified by early nuclear testing. This indicates the swamp is a modern feature, which could be the result of drainage disruption and stream modification associated with logging in the 1960's.

As a result the event timing on this section of the fault remains relatively poorly constrained. There is evidence of a recent fault rupture some time after the period AD 200 – 500 (i.e. definitely post AD 200) but, based only on this paleoseismic trench, there is no way to estimate how long after this period the fault rupture has occurred.

6.4 Summary

The Tophouse trench provides evidence of a rupture on the Wairau section of the Alpine Fault at some time between AD 200 and AD 1840 (European settlement). There is also evidence for a much older rupture of this section of the fault approximately 12,500 years ago. The activity of the fault implies there must also have been many other ruptures of the fault in the intervening period.

Section 7

COMPARISON OF NEW PALEOSEISMIC DATA WITH PREVIOUS WORK

7.1 Comparison of new data with previous paleoseismic work on the north Alpine Fault

The previous work of Yetton *et al.* (1998) and Yetton (2000) is summarised in Section 1. Most of the refinement in the estimates of event timing in this earlier work has come from forest disturbance data and tree ring chronologies that are either not possible in the area northeast of the Robinson River (due to forest type), or are not currently available. The most direct comparison that can be made between the results of the recent work and that done earlier is between the calendric date ranges obtained for the radiocarbon dating in the paleoseismic excavations.

Comparison of calendric age ranges for the most recent event with earlier equivalent trench data from the North Alpine Fault.

There are two trench sites that Yetton et al (1998) and Yetton (2000) have undertaken on the north Alpine Fault. The most southwestern site is located at Crane Creek (Fig.2.1), a distance of approximately 30 km along fault strike from the Taramakau River and the junction with the Hope Fault.

A small hand dug pit across a distinctive narrow furrow at the base of a high fault scarp provided dates of 360 ± 50 BP and 380 ± 25 BP for young twigs buried in scarp-derived colluvium that partly infilled the furrow in the most recent earthquake event. This was definitely the most recent event at this site based on the lack of faulting of this colluvium and the absence of higher colluviums. The calendric age conversions for radiocarbon dates obtained from the scarp-derived colluvium indicate a fault rupture immediately prior to the period AD 1480 to 1645. There is also landslide across the trace that post-dates the most recent event (i.e. it is not faulted) and this can be dated by trees that grow on it to the period prior to AD 1700.

A further 6 km northeast along fault strike the Alpine Fault trace crosses the post-glacial alluvial terraces of the Ahaura River. A machine excavated trench across the active trace and the area immediately northwest of the shear zone provides another date for the alluvial infilling of a fissured depression soon after the most recent rupture event. A radiocarbon date of 380 ± 60yrs comes from this alluvial material infilling the fissures. This corresponds to a calendric age range of AD 1440 to 1670.

In Figure 7.1 we plot these calendric age ranges along with the data obtained in this study of the three new sites on the North Alpine Fault. We also note if the ages are prior to rupture, synchronous with rupture, or postdate the rupture event.

It is apparent from Figure 7.1 that the new data is very good match to the results of the earlier work. There is consistent evidence of the most recent rupture of the North Alpine Fault occurring some time in the period between after AD 1440 and AD 1700. The best-constrained radiocarbon date is from Crane Creek and indicates fault rupture immediately before the period AD 1480 – 1645.

Comparison with timing refinements from forest disturbance and tree ring analysis

Forest disturbance studies and cross-matched tree ring chronologies from the podocarp-dominated forests southwest of the Robinson River provided Yetton *et al.* (1998) and Yetton (2000) with refined estimates of event timing.

There is good data that demonstrates that the most recent earthquake on the central section of the Alpine Fault (including a short 25 km length of the north

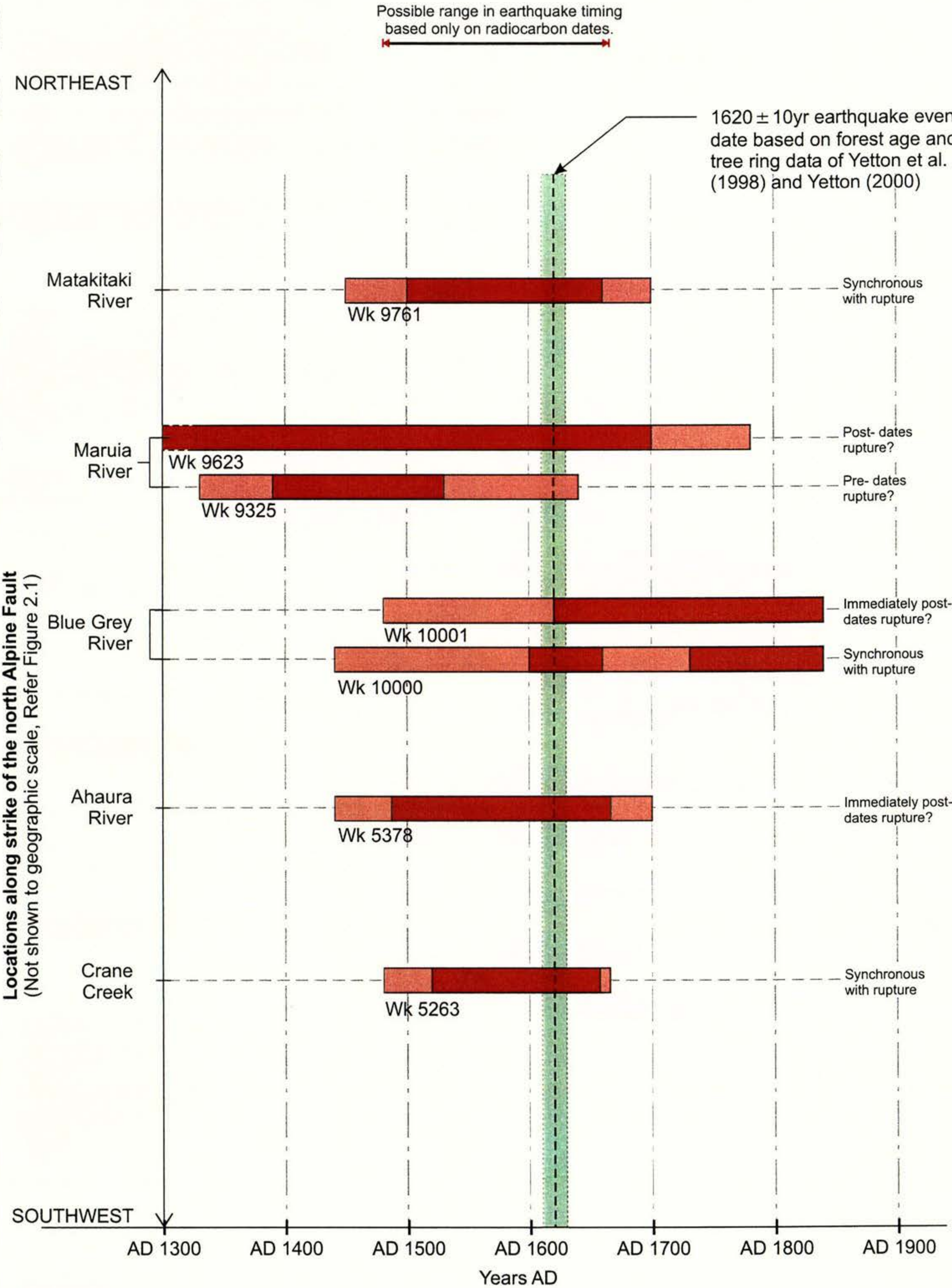


FIGURE 7.1 Comparison of all available radiocarbon dates that constrain estimates of timing of the most recent earthquake on the north Alpine Fault.

section as far northeast as Haupiri River) occurred in AD 1717. This surface fault rupture did not extend to Crane Creek or the Ahaura River.

Comparison of this AD 1717 date with the calendric age ranges from the new sites in this study (Figure 7.1) provides more evidence that the surface rupture in AD 1717 did not extend further along the north Alpine Fault. A postulated event in AD 1717 falls outside the possible age ranges at three of the five sites (Crane Creek, Ahaura River, and Matakitaki River) and is relatively unlikely at the other two (Blue Grey River, Maruia River).

The best estimate of the penultimate earthquake event along the central Alpine Fault, which is the most recent earthquake event at Crane Creek and Ahaura River, is AD 1620 ± 10 years (this has been referred to as the Crane Creek event for ease of reference in previous work). This timing estimate comes mainly from forest disturbance studies that indicate a large proportion of forest in Westland was destroyed at this time and a period of synchronous forest regeneration followed[9]. This was <u>the only period</u> of notable forest damage and regeneration within the possible calendric age range of the most recent earthquake at the Crane Creek and Ahaura Trenches.

Comparison of this estimate of AD 1620 ± 10 years with the age ranges for rupture at the new sites shows it is also a good fit to the new trench data. Unfortunately there is currently no equivalent forest age data to use to test the hypothesis that this is the same AD 1620 ± 10 yr event in these new areas. Although at present it can not be ruled out that some other earthquake event occurred in this more northern area at approximately this same time, the simplest explanation is that the trench evidence records the same event. In our

[9] Historical earthquakes in equivalent terrain to Westland and Buller have demonstrated the profound impact of earthquake shaking on forest mortality. For example it is estimated that one third of the forest cover of the Rimutaka range as viewed from Wellington was lost in the 1855 Wairarapa Earthquake, M_w 8.0 – 8.4 (Grapes and Downes 1997). Even smaller earthquakes such as the 1990 Lake Tennyson Earthquake [Ms 5.8] and the Mw 6.7 1995 Arthurs Pass earthquake caused significant forest damage in the epicentral areas (Downes 1995 and Allen *et al.* 1999 respectively).

opinion, in the current absence of evidence to the contrary, this is the most likely explanation.

If this is the correct interpretation then this extends the rupture length for the Crane Creek event from the previous minimum length estimate of approximately 200 km (Yetton *et al.* 1998; Yetton 2000) to approximately 320 km. This is the distance along fault strike from the Paringa River (the southwest limit of available forest age data but not necessarily fault rupture, refer Figure 2.1) to the Matakitaki River site (the site furthest northeast for which there is radiocarbon evidence of a rupture at approximately this time). The implications of this revised rupture length for earthquake magnitude and hazard estimates are discussed later in Section 9.

7.2 Comparison of new data with previous paleoseismic work on the Wairau Fault

Zachariasen *et al.* (2001) outline the results of paleoseismic trenching investigation of the Wairau section of the Alpine Fault. They trenched at three locations (designated Wadsworth, Dillons and Marfell) approximately 50 km northeast of the Tophouse trench site (refer Figure 2.1).

Of the three trenches excavated one provided no age constraints (Marfell), and one (Dillons) was rendered potentially ambiguous by virtue of it's location on one of two parallels fault strands i.e. it is possible that the most recent event bypassed this particular trench location.

However, the nearby Wadsworth trench was located on a section of the fault that has a single trace, and this provides useful results with evidence of up to three rupture events. Table 7.1 summarises the calendric ages (95% confidence limit) obtained from two samples of charcoal. These come from a similar stratigraphic position near the base of an unfaulted scarp-derived colluvium (Unit 49) that post-dates the most recent rupture. We include in the table the calendric date range for the youngest faulted unit in the Wadsworth trench (Unit 55). We also note the implications with respect to the possible self-age of the charcoal, adopting the tree species maximum life spans noted by Zachariasen *et al.* (2001).

Code and Unit	*C14 Date*	*Calendric Date range*	*Comments*
NZA 12461 from Unit 49	1530 ±55 BP	AD 470 to AD 700	Unfaulted colluvium, extent of possible self-age limited to less than 300yrs by the definite self-age of NZA 11643 below, and Totara trees in this area that live up to about 600yrs.
NZA 11643 from Unit 49	2025 ±60 BP	BC 130 to AD 168	Unfaulted colluvium, implied minimum 300yr self-age because this date is at least 300yrs younger than NZA 12461.
NZA 11642 from Unit 55	2531±55 BP	760BC – 364BC	Youngest faulted unit with an unknown self age, but up to about 600 years

Table 7.1: Calendric age ranges from critical samples that bracket the most recent fault rupture of the Wairau section of the Alpine Fault in the Wadsworth trench of Zachariasen *et al.* (2001).

This data suggests that the most recent earthquake rupture of the Wairau section of the Alpine Fault at this location occurred after 760BC and before AD 1000[10] (i.e. the AD 700 youngest age of NZA 112461 plus up to 300yrs of self-age).

In comparison the Tophouse trench described in Section 6 demonstrates a definite fault rupture after AD 200 (based on a date from the faulted Unit 10). If this rupture is the same event as that described a further 50 km to the northeast in the Wadsworth trench then the combined dates from these trenches suggest that *the most recent rupture event on the Wairau section of the Alpine Fault occurred between AD 200 and 1000.* Thus the lapsed time is at least 1000 years, but it is probably longer, because the AD 1000 date assumes the maximum possible self-age in the youngest charcoal sample from the unfaulted

[10] The youngest possible age for the rupture noted in text of Zacharaisen et al. (2001) is 1400 years ago (AD 600) but our interpretation of the maximum possible self-age in Table 8.1 suggests AD 770 is the true minimum age.

colluvium in the Wadsworth trench. The self-age is most likely to be less than this.

7.3 Summary

The calendric age ranges that come from the radiocarbon dates obtained from the three new paleoseismic excavations on the north section of the Alpine Fault compare very closely with those obtained previously at the two nearest locations further southwest (Ahaura River and Crane Creek). The combined trench data indicate the most recent rupture at these five locations occurred between AD 1480 and AD 1645.

Previous work utilising forest age disturbance patterns in Westland and Buller indicate the most likely time of this earthquake was 1620±10 years. This is a good fit to the data from the three new sites but no forest age data is available to better test this possibility. If this is the same event, which the available evidence suggests is likely, then this implies a surface rupture length in this earthquake of at least 320 km.

The new data from the Wairau section of the Alpine Fault is consistent with that obtained 50 km further northeast in recent paleoseismic excavations (Zachariasen *et al.* 2001). If the most recent event identified in their Wadsworth trench is the same as that in the Tophouse trench, then the most recent rupture of the Wairau Fault occurred between AD 200 and 1000 and probably closer to AD 200.

Section 8

ESTIMATES OF LONG TERM FAULT SLIP RATES INCLUDING NEW DATA FROM THE BLUE GREY RIVER AREA.

8.1 Previous data on slip rates on the north Alpine Fault

The horizontal slip rate near the start of the north section of the Alpine Fault in the area near the Taramakau River is estimated by Berryman *et al.* (1992) to be approximately 10 ± 2 mm/yr. This is based on unpublished weathering rind ages for terrace gravels at the fault of 1100 – 1300 years and dextral offsets of around 11-13m.

Yetton (2000) outlines the results of radiocarbon dating of an offset terrace tread at the Haupiri River, a further 25 km northwest along fault strike. The average horizontal slip rate over a relatively short 2000 year period was estimated to be 6.5 ± 2.5mm/yr. The high error in this estimate mainly reflects the substantial possible age range of the sample in comparison to the short time over which the estimate is made (the last 2000 years).

Up until now no other slip rate estimates have been available for the north Alpine Fault.

8.2 New estimates of long term slip rate from the Blue Grey River area

As part of the fieldwork associated with trench site selection for this project we have identified two offset streams close to one another that are located on faulted moraine associated with the late Otiran glaciation in the Maruia and Upper Grey valleys.

Figure 8.1 are maps of these offset streams and the earlier Figure 3.1 shows the geology and our interpretations of the glacial deposits of this area. Both

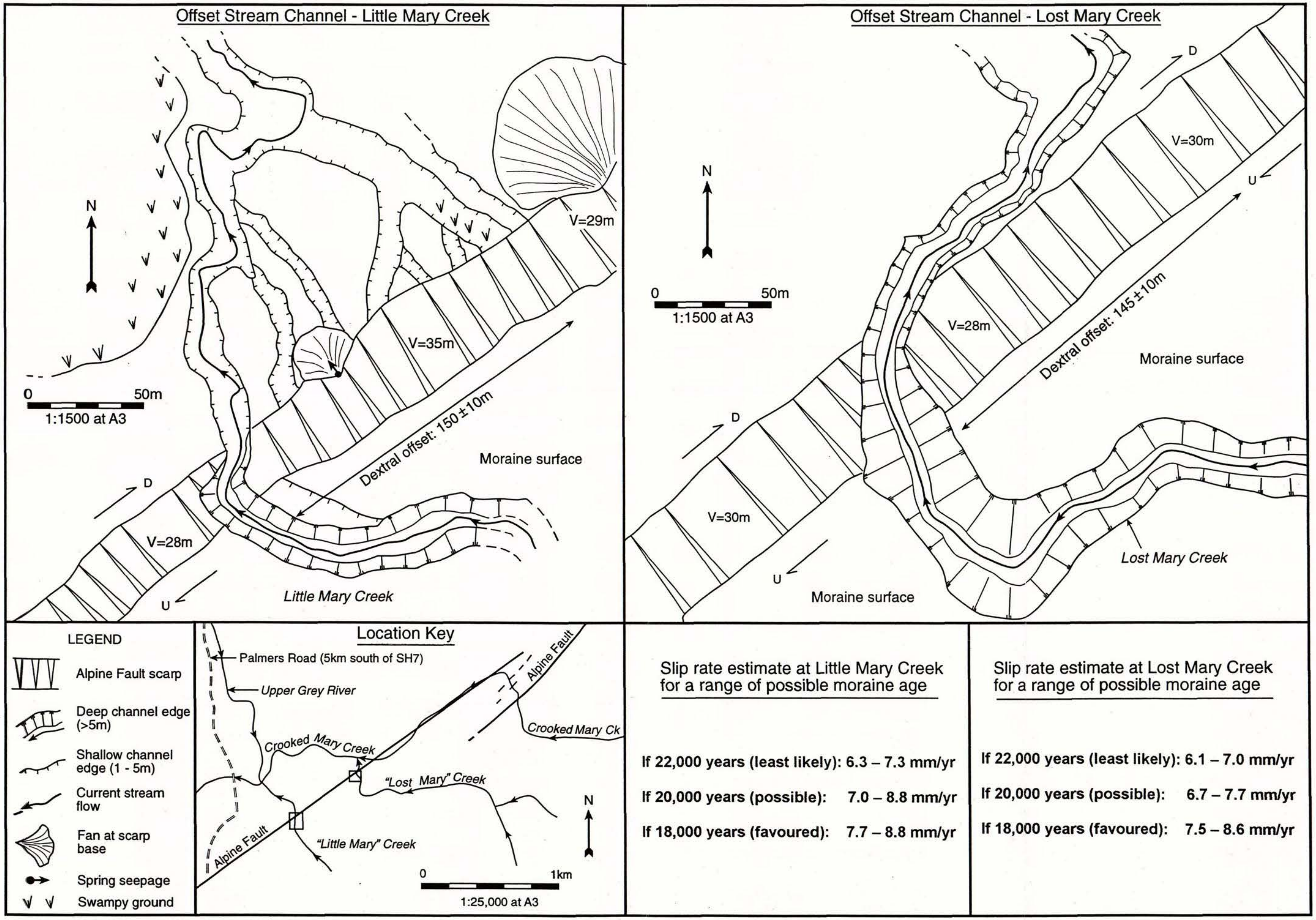


Figure 8.1: Fault offset tributaries of Crooked Mary Creek near Palmers Road and Upper Grey River.

these small creeks are tributaries of Crooked Mary Creek and we have informally named these Little Mary Creek and Lost Mary Creek for ease of reference.

While the offset of these two streams is virtually the same (i.e. approximately 150m) there is some difficulty in ascribing the correct age to the faulted moraine on which they have developed. Mabin (1983) has mapped the glacial advances of the Maruia Valley in some detail but this mapping does not extend to the Blue Grey River area. We have extended this work by assigning obvious moraines to the various advances that he defines.

The offset moraines are definitely associated with the penultimate advances of the Late Otiran glaciation of which three of closely similar age can be recognised in the middle Maruia Valley (Mabin, 1983). We tentatively assign the offset moraines to the Creighton 3 advance (the youngest and most obvious in this area) but it is also possible that they are from the slightly earlier Creighton 2 advance. It is unlikely to be associated with the earliest Creighton 1 advance that left moraines at much higher levels in this area.

The penultimate advances of the Late Otiran Glaciation occurred from the period of 22,000 years BP up to around 18,000 years BP (Suggate, 1990). The younger end of this possible range is preferred in this area on the basis of moraine elevation. In Figure 8.1 we show the range of slip rate estimates that derive from the full range of possible moraine ages. The preferred values from the younger ages provide the best estimate, and by combining these we conclude that a reasonable slip rate estimate for this area of the Alpine Fault near the Blue Grey and Maruia Rivers over the last approximately 20,000 years is 7.7 ± 1mm/yr.

8.3 Estimates of slip rate on the Wairau section of the Alpine Fault

The first detailed estimates of long term slip rate on the Wairau section of the Alpine Fault comes from the work of Lensen (1968) and Lensen (1976). Lensen (1976) notes the consistent dextral offset of approximately 70m on many different geomorphic markers located on the so-called Wairau Surface (Wellman, 1955). This extensive aggradation outwash surface can be followed almost continuously from the Tophouse area down the Wairau Valley to Renwick.

Lensen correlated this surface with the penultimate advance of the last glaciation and estimated an age of approximately 18,000 years. This corresponds to a slip rate estimate of 3.9 mm/yr. Suggate (1988) also supports this correlation and approximate age, based mainly on the similar extensive Speargrass surface of this age in the adjacent Buller catchment.

Grapes and Wellman (1986) take an alternative view of the age of the Wairau surface, suggesting this could be as young as 10,000 years old, and the slip rate as high as 7mm/yr. They also correctly point out that Lensen (1976) has discounted the possibility that the surface may be associated with the most recent glacial advance and therefore be 14 – 15,000 years old. If the Wairau surface is around this age then the long term slip rate increases slightly from the Lensen (1976) estimate to 4.7 – 5 mm/yr.

Kneupfer (1988) and Kneupfer (1992) describe the results of weathering rind dating of various fluvial surfaces in the Branch River area and the Wairau Valley. Kneupfer suggests a slip rate of 3-5mm/yr is reasonable estimate.

Most recently Zachariasen *et al.* (2001) estimate slip rates over the last four thousand years, based on displaced features and radiocarbon ages in trenches. There estimates are in the order of 4 – 5mm/yr and the authors note their consistency with other studies.

8.4 Summary

Long term slip rates for the north section of the Alpine Fault reduce progressively as slip is transferred to other faults in the Marlborough Fault Zone from an estimated possible maximum of approximately 10 ± 2mm/yr at the Taramakau River, to around 7.7 ± 1 mm/yr approaching the Maruia River. The general consensus amongst researchers for the estimated long-term slip rate for the Wairau section of the Alpine Fault is 4.5 ± 1 mm/yr.

Section 9

RELEVANCE OF THESE RESULTS TO SEISMIC HAZARD ASSESSMENT

9.1 North Alpine Fault

There appear to be two possible scenarios with respect to the most recent earthquake on the north Alpine Fault and each have different implications for the assessment of future hazard:

The central and north fault scenario

A single rupture of the Alpine Fault occurred at around AD 1620 ± 10 years from at least the Paringa River to the Matakitaki River (but not reaching Tophouse Saddle)

Based on the available evidence, including the 450 km length of synchronous rupture demonstrated by the tree ring analysis of the subsequent AD 1717 event in the south and central sections, this is the most likely scenario. If correct, this minimum rupture length of at least 320 km can provide an approximate estimate of the minimum earthquake magnitude.

The correlation's of Wells & Coppersmith (1994) suggest a moment magnitude (**M**) for an event of this length would be in the order of **M** 8 ± 0.2

The correlation of Anderson *et al.* (1995) suggest a slightly lower moment magnitude of **M** 7.9 ± 0.25

However, these estimates, though minimums with respect to rupture length, must also be considered in relation to the evidence at two localities for only a small single-event surface offset at the fault scarp. Both the Blue Grey River and the Maruia River localities indicate a horizontal offset in the order of 1 - 1.5m (average 1.3 ± 0.6m) and a vertical offset of 0.25m. Arguably these small offsets at the fault scarp may reflect the progressive die out of surface displacement from some maximum in the central section of the fault. However, single-event offset has also been correlated with earthquake magnitude, and based purely on these observed offsets, the correlation suggests a considerably lower magnitude of **M** 7.1± 0.2 (Wells and Coppersmith 1995).

Unfortunately single-event offset is a much less reliable indicator of magnitude because in historical earthquakes it has been observed to vary substantially. For example in the 1906 San Francisco (M_s 7.9) the surface offsets at the fault varied from 0.5 to 6m with irregular variations of up to 50% over relatively short distances (Thatcher *et al.* 1997).

The north – only scenario

A separate rupture episode occurred at about this same time as indicated by the trench dates, which only involved part of the north section of the Alpine Fault. This took place either before or after the AD 1620 ± 10yr event further to the southwest.

In this scenario we postulate a relatively short length of the fault in the area for which no forest or tree ring data is available (essentially from Ahaura River to Matakitaki River, a distance of approximately 100 km) ruptured in a separate earthquake either before or after the larger event of AD 1620 ± 10 yrs but in the period defined by the radiocarbon dates (i.e. AD 1480 –1645).

An estimate of magnitude can be made using both the shorter rupture length of approximately 100 km (**M** 7.4 ± 0.2, Wells and Coppersmith 1994; **M** 7.6 ± 0.2 Anderson 1996) and the single-event slip (**M** 7.1 ± 0.2, Wells and Coppersmith 1994). Although we consider this is less likely than the wider central fault scenario, in the absence of tightly constrained forest age or tree ring data this alternative must be considered a possibility.

Future scenarios

The possible future scenarios are a north-only earthquake event with a magnitude similar to that postulated above (i.e. **M** 7.1-7.6 ± 0.2) or rupture of this north section of the fault in combination with a wider Alpine Fault earthquake event. Based on the simultaneous AD 1717 earthquake rupture of both the central and south sections of the fault, it is possible that a future wider Alpine Fault earthquake would also include the southern section. This southern section has slip rates almost as high as the central section and has not ruptured since AD 1717. This "whole fault" scenario, should it occur, would involve a rupture length of 500 km and a corresponding moment magnitude estimate of **M** 8.1 ± 0.2 (Wells and Coppersmith 1994 and Anderson *et al.*1996).

A first order assessment of the likelihood of a future earthquake rupture on the north section of the Alpine Fault can be made utilising observed single-event offsets, long term slip rate, and lapsed time as follows[11]:

Lapsed time since the last event:
Maximum – 500 years
Minimum – 300 years

Predicted elastic strain available in the next rupture can be estimated from the maximum and minimum of the average long-term horizontal slip rate (adopting 7.7 ± 1 mm/yr as the best average estimate in the area where single-event offsets can be recognised although this may be a low estimate for the southwest end and high for the northeast). These slip rate estimates are then multiplied by the maximum and minimum time since the last event:

[11] This method has been adopted in numerical probability estimates of rupture, for example the Working Group on California earthquake probabilities (1988; 1990; 1995). In our view given the uncertainty in determining single event offsets, and the possibility that not all future events will have the same offset, it is not appropriate to estimate a numerical probability by this method however, a first order assessment of the relative likelihood of a similar rupture is reasonable.

Maximum strain available:- 4.3m
Minimum strain available: - 2.0m

This can be compared to the observed single-event offsets as the best available estimate of future offsets, in this case the offsets at Blue Grey and Maruia River of up to 1.5 ± 1m horizontally (average 1.3 ± 0.6m). Thus, based on the past observable horizontal offsets, a rupture of this order in the near future on the north Alpine Fault appears to be likely. A further 100 years of strain would increase the minimum strain to 2.7m (and the maximum to 5.2 m), which is about two to four times the offsets that can be reliably observed.

This crude assessment of the likelihood of future rupture is similar for both the central fault scenario and the north-only scenario outlined above. A more comprehensive estimate of conditional probability of rupture for this section of the fault will require considerably more data on the exact timing of several of the most recent earthquake events (and/or single-event offsets for penultimate events). Unfortunately, based on the trace preservation and limited number of potential paleoseismic sites in this area, establishing a more comprehensive record of this sort may not be feasible.

In reality, the likelihood of rupture on the north Alpine Fault may be controlled not so much by the strain that accumulates in this area, but by the behavior of the much more active central Alpine Fault. If, for example, the central Alpine Fault ruptures in two earthquakes relatively soon after one another, as appears to have been the case around AD 1620 and AD 1717, then the majority of the north section is unlikely to have sufficient stored elastic energy to rupture each time.

However, if the interval is 200-300 years (or more) then most of the north Alpine Fault may rupture. For example the observed small single-event offsets at the Blue Grey and Maruia Rivers equate to approximately 200 years of stored strain. This suggests that the previous earthquake may have been around AD 1420. There is an inferred earthquake at about this time on the central section of the Alpine Fault based on forest disturbance age (Wells *et al.* 1999); tilted trees at the fault scarp (Wright, 1998; Wright *et al.* 1998); and the terrace and landslide record (Yetton *et al.* 1998; Yetton 2000). This may have been the penultimate earthquake at the Blue Grey and Maruia sites on the north Alpine Fault.

9.2 Wairau section of the Alpine Fault

The work in this project (in conjunction with the trenching of the Wairau Fault by Zachariasen *et al.* 2001) demonstrates that there is a surface fault rupture boundary between the north Alpine Fault and the Wairau section of the Alpine Fault. This rupture boundary was operative in the most recent Alpine Fault earthquake and probably for several earthquake events prior to this. However, it should be noted that with the current level of data it can not be ruled out that on relatively infrequent occasions, when the Wairau section of the Alpine Fault is close to the end of it's seismic cycle, both adjacent sections of the fault could rupture in the same earthquake event.

The rupture boundary is most likely to be somewhere in the wider area between the Matakitaki River and Tophouse saddle, but this has not been categorically determined. The most likely general location for a surface rupture boundary from a structural perspective is the section of fault from Mole Saddle (located immediately southwest of Lake Rotoroa) to Lake Rotoiti, where there is a progressive change of fault strike and the junction with the Flaxmore and Waimea Faults. This area is a releasing bend for the Alpine Fault and there are several fault strands along which surface displacement could dissipate.

An estimate can be made of the possible maximum magnitude of a rupture of the Wairau section of the Alpine Fault based on this inferred rupture boundary. The distance from Lake Rotoroa to the coast near Blenheim is 120 km. Based on this maximum likely rupture length (and ignoring the possibility of rupture on offshore continuations of the fault) the moment magnitude estimates are **M** 7.5 ± 0.2, Wells and Coppersmith (1994); **M** 7.6 ± 0.15, Anderson *et al.* (1996)

It is important to note that there is currently insufficient evidence to assess if a complete rupture of the Wairau section of the fault is more likely than one or more shorter ruptures. However, there are three related lines of reasoning that suggest that a relatively long rupture may be the more likely scenario. These are:

- The relative lack of surface features along the fault trace that might otherwise indicate structural variation and complexity at depth (for example stepovers and en-echelon strands).

- The early geological history of the fault that indicates that for a very long period this was the main continuation of the Alpine Fault. It is likely that over this long period (10 – 15 million years) fault plane irregularities would have been smoothed and removed, and a well developed gouge zone developed which generally leads to less frequent but longer ruptures (i.e. the concept of strike- slip fault evolution, Wesnousky 1989).

- The rupture in 1848 of an approximately 100 km length of the nearby but "less evolved" Awatere Fault in the M_w 7.5 Marlborough Earthquake (Benson *et al.* 2001).

A first order estimate of the likelihood of a future rupture of the Wairau section of the Alpine Fault can be made using the Lensen (1968) estimates of single-event slip from the Branch River terraces, in conjunction with the minimum time since the last event, and the available estimates of the long term slip rate.
Lapsed time since the last event:

Maximum -	1800yrs
Minimum -	1000yrs

The predicted elastic strain available in the next rupture can be estimated from the maximum and minimum of the average long-term horizontal slip rates

(4.5±1.0 mm/yr) multiplied by the maximum and minimum time since the last event:

Maximum strain available: -	9.9m
Minimum strain available: -	3.5m

This can be compared to the best available estimate of past single-event horizontal offsets on this section of the fault by Lensen (1968) at the Branch River terraces of 3.4 - 6.6m.

Once again, based on the past observable horizontal offsets, a rupture of this order of offset in the near future on the Wairau section of the Alpine Fault also appears to be reasonably likely. However, because the strain is accumulating at a slower rate than in the north Alpine Fault, and the estimated single-event offsets could be as high as 6.6m, this crude assessment method suggests there could still be around 500 years until rupture. Countering this is the likelihood that the lapsed time since the last rupture was closer to the AD 200 maximum than the AD 1000 minimum. For example a last rupture time at AD 300, with the minimum slip rate, equates to 7.7m of strain.

This demonstrates the importance of better constraining the time of the last event on this Wairau section of the fault.

9.3 Implications for the central and northern South Island

The north section of the Alpine Fault at the Ahaura River is the closest part of the fault to Christchurch City, at a distance of approximately 120 km. In comparison the most active part of the Alpine Fault near Mt Cook is more than 200 km away. From the perspective of Christchurch City, the extent to which the north section of the Alpine Fault is involved in a future Alpine Fault earthquake is of particular importance.

The Wairau Fault is also relatively close to important regional trade and transport centres such as Blenheim (located directly above it), Picton (25 km), and Nelson (40 km at the closest approach). The active trace of the fault also passes through the small settlement of St Arnaud at Lake Rotoiti.

In addition to previous work that suggests there is a high probability of rupture of the central Alpine Fault, there is now new evidence of a high likelihood of rupture of the North Alpine Fault (although with relatively small fault displacements). There is also the suggestion that rupture on the adjacent Wairau section of the fault may also be likely (with larger surface displacements) but this is sensitive to assumptions about the exact time of the last rupture.

The best possible scenario would be three separate earthquakes in these three different areas, over a period of tens to hundreds of years, in which the north Alpine Fault event would be the smallest. However, it is probably more likely that there will be two earthquake events i.e. a large Alpine Fault earthquake either preceded, or followed by, a rupture of the Wairau section of the fault in a smaller moderate to large earthquake. These earthquakes may also be tens or hundreds of years apart. The most serious and least likely scenario (though still not impossible) would involve a single very large earthquake rupture along the entire onshore length of the Alpine Fault.

9.4 Summary

Long term slip rates, in conjunction with observed single-event fault displacements and the timing of the last earthquake rupture, can be used together to provide a first order estimate of the likelihood of a future earthquake rupture with a similar fault displacement.

This approach suggests an earthquake with relatively small fault displacements (i.e. 1 - 3m horizontal displacements) is likely over the next 50-100 years for the north Alpine Fault. The Wairau section of the fault

also appears to be close to, or approaching, the time of the next earthquake rupture but this inference is sensitive to the exact timing of the most recent event.

There are different possible earthquake scenarios depending on what sections of the Alpine Fault rupture together in the next event. There could be rupture of the north section in conjunction with the central (and south) Westland sections in a single large earthquake (Moment Magnitude of approximately M 8). Alternatively the north Alpine Fault could rupture in a smaller separate event at around the same time (Moment Magnitude 7.1 - 7.5 and within 50-100 years of a larger Alpine Fault event).

The Wairau section of the Alpine Fault is capable of generating an earthquake up to approximately Moment Magnitude 7.5. However, more paleoseismic work is required to check if possible rupture boundaries exist along this section of fault. Given the current situation with the Wairau section of the Alpine Fault apparently approaching the culmination of it's seismic cycle, there is also the possibility that the Wairau section of the fault could rupture in conjunction with the north Alpine Fault and other sections. At present there is insufficient data to determine how likely this might be.

Section 10

SUMMARY AND CONCLUSIONS

This report outlines the results of paleoseismic trenching at four different localities spread over an approximately 100 km length of the north and Wairau sections of the Alpine Fault. A total of 15 radiocarbon dates from 6 trenches provide information on the timing of pre-historic earthquakes on the Alpine Fault.

Sites on the north Alpine Fault

The most recent earthquake rupture at the Blue Grey River, near the southwest limit of the study area, was a relatively small event resulting in a horizontal offset of approximately 1.0 ± 0.3m and a vertical offset of 0.2- 0.4m. This ground rupture definitely occurred post AD 1450 and is most likely to have occurred either in the period soon after AD 1600 (and up to AD 1680), or later in the period AD 1730 – 1840. It is very unlikely to have occurred in AD 1717, the generally accepted date of the most recent earthquake on the Alpine Fault in the area southwest of the Haupiri River. This is consistent with the results of previous work that indicates ground rupture associated with the AD 1717 event did not extend far northeast of the Haupiri River.

The most recent earthquake rupture at the Maruia River was also a relatively small event resulting in a horizontal offset of approximately 1.3 ± 1m and a vertical offset of 0.25 ± 0.1m. This earthquake definitely occurred post AD 1330, and is most likely to have occurred after the period 1390- 1530 AD. It occurred prior to AD 1780, and very likely prior to AD 1700. The best estimate is an earthquake that occurred sometime in the period between AD 1530 – 1700.

If this is the same earthquake event as that recognised at the Blue Grey River, which the marked similarity in observed ground displacement strongly suggests, then the best-combined estimate of timing is the period AD 1600 – 1700.

The Matakitaki 2 paleoseismic excavation at the Matakitaki River provides a well-constrained date for the most recent rupture of the Alpine Fault at this location. This rupture occurred after AD 1455 and before AD 1700, and it is most likely to have occurred between AD 1500 and 1670. No definite single-event horizontal offset can be inferred from this event but the evidence suggests this was not larger than approximately 3m, and was quite possibly less. Assuming this is the same event as that recognised 50 and 60 km further southwest at the Maruia and Blue Grey River, then the best estimate of event timing for these three combined locations is the period between AD 1600 and 1670.

Previous work utilising forest age disturbance patterns in Westland and Buller indicate the most likely time of this earthquake was 1620 ± 10 years. This is a good fit to the data from the three new sites but no forest age data is available in the current field area to better test this hypothesis. If this is the same earthquake event then this implies a surface rupture length of at least 320 km.

In the absence of forest age data there is still the possibility that the surface ruptures investigated at these three new sites on the north Alpine Fault are the result of a separate smaller earthquake that occurred either shortly before, or soon after, the much larger AD 1620 ±10yrs event. If so this would have had a rupture length of approximately 100 km.

Tophouse Site

The Tophouse trench provides evidence of a rupture on the Wairau section of the Alpine Fault at some time between AD 200 and 1840 (European settlement). There is also evidence for a much older rupture of this section of the fault approximately 12,500 years ago. The activity of the fault implies there must also have been many other ruptures of the fault in the intervening period.

The new data from the Wairau section of the Alpine Fault is consistent with that obtained in recent paleoseismic excavations located 50 km further northeast of Tophouse Saddle (Zachariasen *et al.* 2001). If the most recent event identified in their Wadsworth trench is the same as that in our Tophouse trench, then the most recent rupture of the Wairau Fault occurred between AD 200 and 1000 and probably closer to AD 200.

This indicates that there is an Alpine Fault rupture segment boundary somewhere between Matakitaki River and Wairau Valley. This rupture boundary is most likely southwest of Tophouse Saddle and in the general vicinity of Lake Rotoroa.

Hazard Scenarios and assessment of the likelihood of future earthquakes

Long term slip rates, in conjunction with observed single-event fault displacements and the timing of the last earthquake rupture, can be used in combination to provide a first order estimate of the likelihood of a future earthquake of a similar displacement.

Long term slip rates for the north section of the Alpine Fault appear to reduce progressively from a possible maximum of approximately 10 ± 2mm/yr at the Taramakau River, to around 7.7 ± 1 mm/yr approaching the Maruia River.

For the north Alpine Fault the most recent event had relatively small horizontal surface displacements averaging around 1.3 m ± 0.6. The long term slip rates, and possible date ranges for the last event, indicate it is likely that elastic strain of this order or more (i.e.2.0 – 4.3m) has accumulated in this section of the fault. The north Alpine Fault could rupture in the next 50 – 100 years, either in conjunction with the central and south Westland sections (rupture length 500 km, Moment magnitude **M** 7.9 – 8.3) or in a considerably smaller separate earthquake (Moment magnitude **M** 7.1 – 7.6).

The estimated long-term slip rate for the Wairau section of the Alpine Fault is 4.5 ± 1 mm/yr. Previous studies suggest that surface displacements associated with earthquakes on the Wairau section of the Alpine Fault are larger than those inferred for the north Alpine Fault with estimates of single-event horizontal displacements of 5 ± 1.5 m.

These long-term slip rates imply elastic strain of between 4.9 and 8.5m has accumulated since the last earthquake rupture. Once again, based on the past observable horizontal offsets, a fault rupture of this order of offset in the near future on the Wairau section of the Alpine Fault also appears to be likely.

In comparison to the north Alpine Fault, this Wairau assessment is more sensitive to the substantial range in the possible lapsed time since the last event (1000 –1800 years). At the slowest likely rates several hundred years may still be required before strain reaches the largest possible estimates of single-event displacement (i.e. 6.5m). However, if the lapsed time is closer to the longest possible end of this range (and this is most likely based on the radiocarbon ages), then even at the slowest possible long–term slip rate, elastic strain of this order may have already accumulated.

Section 11

RECOMMENDATIONS FOR FURTHER WORK

North Alpine Fault

In our opinion there are two potentially useful areas of further paleoseismic research along this section of fault.

Forest age and tree ring investigations in areas further west but close to the Alpine Fault

We have noted in our report that the forest growing along the actual fault trace of the north Alpine Fault is nearly all beech forest and is not amenable to forest disturbance studies that extend back beyond the natural lifespan of the trees (generally less than 350 years).

However, there are smaller and more distant podocarp forests near Murchison and the Rahu Saddle that would have been affected by strong earthquake shaking in a north Alpine Fault event in the period around AD 1600. There is also a small area of podocarp forest growing close to the fault trace at the southeast of Lake Rotoroa. These forests, including the younger beech forests, would have been strongly affected by the 1929 Buller (Murchison) earthquake.

A forest and tree ring study in this area would be very worthwhile and should have the combined aims of:

- documenting the impacts of a large historical earthquake on forests in this area to allow calibration with the isoseismals from the 1929 earthquake and to better test the application of forest impact models to paleoseismic investigations

- establishing an older chronology of forest disturbance and tree ring studies sufficient to test the hypothesis that the Alpine Fault earthquake of AD 1620 ± 10 yrs was a synchronous single event.

Further paleoseismic excavation between Matakitaki River and Tophouse Saddle

This work has demonstrated that a likely rupture boundary exists between the north Alpine and Wairau section of the Alpine Fault somewhere northeast of the Matakitaki River. The most likely location is near Lake Rotoroa. There are only very limited sections of fault trace that can be recognised in this relatively inaccessible and densely forested area, but in light of the results of this work these sites take on a greater significance. We recommend more detailed mapping of the fault trace in this area, in conjunction with hand dug paleoseismic excavations. Similarly there is merit in reconsidering possible paleoseismic excavations at some of the more accessible sites near Lake Rotoiti.

Wairau section of the Alpine Fault

Further paleoseismic trenching of the fault trace

There is an urgent need to gather more paleoseismic information on this section of the fault because of its close proximity to important regional centres and the current indications that it is a long time since the last fault rupture.

Future work should aim to better constrain the timing of the most recent rupture and to test the hypothesis that the fault is not segmented but ruptures for the entire approximately 100 km length. To achieve these objectives more information is required from a range of trench sites that are well distributed along fault strike. This new work should include trenching the short section of the fault trace located at the coast to the northeast of Blenheim.

ACKNOWLEDGEMENTS

Funding for this project has primarily come from the Earthquake Commission Research Fund with additional assistance from West Coast Regional Council, Hurunui District Council and Tasman District Council. We are very grateful to these organisations for their support. The Department of Geological Sciences at the University of Canterbury have also contributed professional time and financial support for radiocarbon dating at the Tophouse site.

In a project such as this it is critical to get the permission and support of the landowners at the various paleoseismic excavation sites. We are very grateful for permission granted by Rodney Main (Blue Grey River); Department of Conservation, Greymouth (Maruia River); Mr Rick Monk of Mt Ella Station (Matakitaki River) [who also made his excavator available for hire and served up some delicious Nardoo Creek venison]; and Professor Grant Guilford (Tophouse Saddle), for both access to his land and the use of a site caravan. We would also like to thank Nelson College for permission to stay at their Mataki Lodge during fieldwork on Mt Ella Station.

A diverse group that includes geologists, farmers, and fine artists has provided great help with the field work in frequently inhospitable weather and challenging terrain. These are Howard Aschoff, Ben Yetton, Renee Yetton, Lisa Yetton, Dr Jarg Pettinga, Jocelyn Campbell, Sam Fougere and Paul Eyles. Richard Wise, Sam Fougere and Lee Leonard have also assisted with drafting work of a high standard.

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