Geoscience Society of New Zealand 2011 Conference

FIELD TRIP GUIDE


St Arnaud, Lake Rotoiti, Alpine Fault


Mt Owen marble massif


Marlborough Sounds


Awaroa Bay, Abel Tasman National Park

NELSON 27 November - 1 December 2011


Abel Tasman National Park

Geosciences 2011

Annual Conference of the Geoscience Society of New Zealand
Nelson, New Zealand

Field Trip Guide

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Nelson, New Zealand

Field Trip 1
Tuesday 29 November, 2011

Wairau Fault Late Quaternary displacements and paleoearthquakes

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HEALTH AND SAFETY

PLEASE READ!

There are certain inherent hazards in working along roads and on farms. Participants must heed and observe the warnings and time limitations imposed at certain stops by the trip leaders. Caution must also be exercised when crossing public roads, standing on the road reserve, or farm track locations where vehicles or machinery may be in use.

An average level of fitness and mobility is required for this trip; there will be some walking across farmland (perhaps up to 1 km at the Branch River stop).

Participants should carry any personal medications, including those for allergic reactions (e.g. insect stings, pollen, food allergies).

The weather in November can be variable, although we hope for warm sunny conditions! Participants need to be prepared for cold, warm, wet, and/or dry conditions. The expectation is that temperatures would be in the range 15–25°C. A sunhat, sun cream, sunglasses, waterproof and windproof raincoat, and warm clothing (layers) are essential. If the weather is warm, drink plenty of water to combat dehydration. Please don't underestimate the climatic variations that are possible or the potential to get sunburnt. A change of clothing may be useful to bring and to leave in the vehicles, as would a small hand towel.

During this field trip we will be stopping near roads and on farm tracks. When visiting roadside stops hi-visibility vests are to be worn, and zipped up, before exiting your vehicle. Please exit on the verge/left side of your vehicle if safe to do so. Do not stand on the road and beware of road traffic at all times. If you need to go onto the road surface itself ("live lane"), for example to take photos, you must ensure you have a traffic spotter whose full attention is solely to alert you to approaching traffic.

Introduction

In this field trip we will examine evidence for Late Quaternary strike-slip displacements and paleoearthquakes on the Wairau Fault between Renwick and St Arnaud. The field trip will visit locations showing fault displacements of tens to hundreds of metres, including those observed at the classic Branch River site and described by Lensen (1968, 1976). Changes in displacements through time will be related to paleoearthquakes on the fault where it has been trenched. The field trip will also consider the age of the faulted landscape, including river terraces, moraines and the drowned river valleys of the Marlborough Sounds.

The Wairau Fault is one of the four main active faults that make up the Marlborough Fault System (MFS) in the northern South Island of New Zealand (e.g. Lensen 1976; Van Dissen & Yeats 1991; Zachariasen *et al*. 2006). The fault is the northeastern continuation of the Alpine Fault and forms a discontinuous active trace which runs for about 140 km from southwest of St Arnaud to Cook Strait (Fig. 1.1). The location and geometry of the fault has been mapped along its length (e.g., Wellman 1953; Lensen 1976; Begg & Johnston 2000; Rattenbury *et al*. 1998, 2006; Barnes & Pondard 2010). Detailed geomorphic, fault-trenching and offshore seismic reflection studies provide information on the timing and slip during prehistoric earthquakes that ruptured the ground surface or seabed (Lensen 1968, 1976; Grapes & Wellman 1986; Knuepfer 1988, 1992; Berryman *et al*. 1992; Fougere 2002; Yetton 2003; Zachariasen *et al*. 2006; Barnes & Pondard 2010). These studies indicate Late Quaternary rates of strike slip on the fault of 3-7 mm/yr (mean ~4 mm/yr), earthquake surface fault rupture interevent-times ranging from <500 yrs to >5000 yrs (mean ~2200 yrs), and typical single event displacements of 5-10 m.

After a brief stop in Havelock to discuss the evolution of the Marlborough Sounds landscape we will travel westwards along the Wairau Fault. We propose to stop at five main locations along the fault to examine the geometry of the active trace, the timing of prehistoric surface-rupturing earthquakes, slip during these events and a large displacement (~300 m) on a Birchdale moraine near St Arnaud. This will be an opportunity to become more familiar with the fault and the evidence used to infer its paleoearthquake history. The approximate itinerary for the day is outlined below (for Stop locations see Fig. 1.1).

Depart:	Rutherford Hotel, 8am, Tuesday November 29th
Stop 1	Havelock. Summarise plan for the day. Discuss Marlborough Sounds landscape evolution.
Stop 2	Waihopai River/Bankhouse depression. Introduction to Wairau Fault and discuss geometry and displacements of fault at this site. Introduce fault avoidance zone concepts.
Stop 3	Wairau Valley Township. Comfort stop and evidence for paleo-shaking in the Richmond Range.
Stop 4a	Dillon trench site. Outline evidence for late Holocene displacements and the last few paleoearthquakes on the fault.
Stop 4b	Wadsworth trench site (time permitting). Outline evidence for the last 3 paleoearthquakes on the fault.
Stop 5	Branch River. Discuss fault displacements and implications for earthquake slip.
Stop 6	Tophouse Saddle. Discuss larger (>100 m) fault displacements and implications for fault history.
Stop 7	Comfort stop St Arnaud.
Return:	Rutherford Hotel, 5pm, Tuesday November 29th

Figure 1.1 Vertical aerial photograph (Google Earth 2011) showing the locations of field trip stops and the approximate position of the Wairau Fault.

Stop 1 Havelock – Marlborough Sounds Landscape

The Marlborough Sounds is a large and spectacular network of rias or drowned valleys (Figs. 1.2 & 1.3). The Sounds were formed by stream incision and dissection of uplifting bedrock followed by subsidence and marine incursion into the valleys (Cotton 1913, 1969; Campbell & Johnston 1992; Begg & Johnston 2000; Singh 2001; Nicol 2011). The Sounds topography started to submerge at ~1.5 Ma when the Wanganui Basin stepped southwards. This southward migration of the basin produced subsidence of ~0.3 mm/yr which was important for bringing strongly dissected topography close to sea level. Marine inundation and formation of the Sounds was primarily driven by eustatic sea-level changes which resulted in ephemeral submergence during interglacial periods when sea levels were highest (Nicol 2011). The present coastline in the Marlborough Sounds formed ~7 kyr ago, and similar high-stand sea-level configurations probably occurred about every 100 kyr throughout the Late Quaternary.

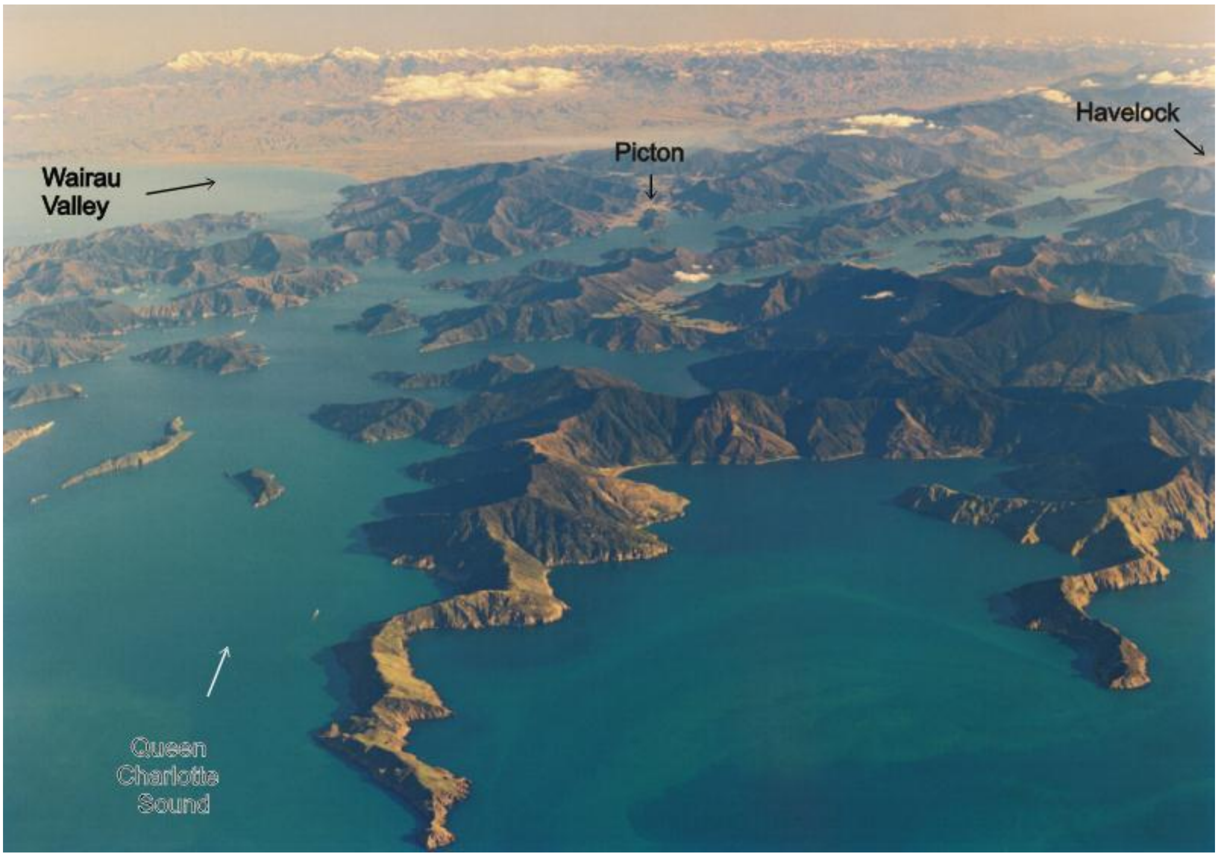

Figure 1.2 Oblique aerial photograph looking south across the Marlborough Sounds. Location of Havelock (Stop 1) indicated. Photograph by DL Homer, GNS Science.

The primary purpose of this stop is to discuss the age of the landscape which was occasionally drowned by rapid rises in sea level. In Marlborough Sounds the valley and ridge topography is inferred to have developed through a combination of uplift and drainage incision of mainly Mesozoic schist and greywacke basement rocks (Begg & Johnston 2000). This basement topography can be traced to the north of the Marlborough Sounds where it is buried by up to 4 km of sedimentary strata deposited in the Wanganui Basin (Anderton 1981; Lamarche *et al*. 2005; Proust *et al*. 2005).

To examine the relations between the geometries of the basement erosional surface in the Marlborough Sounds and Wanganui Basin, a contour map has been constructed for this surface by correlating paleovalleys and ridges between 2D seismic-reflection lines across the offshore

Wanganui Basin (Fig. 1.4). Inspection of Marlborough Sounds topography and paleotopography preserved beneath the Wanganui Basin suggests that the same valley and ridge system exists in both areas. The largest paleovalleys and ridges in Fig. 1.5 generally trend north-northeast and are the northern continuations of the main drowned valleys and emergent ridges in the Sounds. Three primary paleovalleys can, for example, be traced 70-90 km northwards from the Sounds. These paleovalleys are here referred to as PS, QCS and CS and are inferred to be the northern continuations of Pelorus Sound, Queen Charlotte Sound and Cook Strait, respectively (Fig. 1.5). Therefore, it is suggested that the Sounds topography formed at approximately the same time as the paleotopography beneath the basin and at least in part predates the onset of basin formation at ~5 Ma and may be as old as early Miocene (Nicol & Campbell 1990; Nicol 2011). The trend of the main paleovalleys together with the inferred position of the coast at ~5 Ma suggest that during the Miocene, sediment was eroded from the northern South Island (including the Sounds) and transported towards the north-northeast at least ~100 km across the offshore Wanganui Basin.

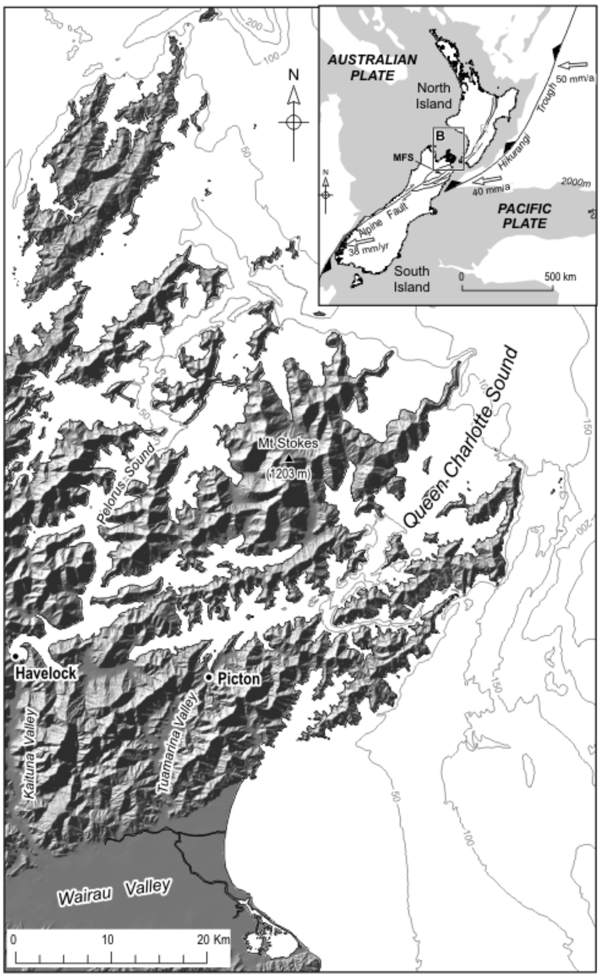

Figure 1.3 Morphology of the Marlborough Sounds. Main map is a sun shaded Digital Elevation Model of the Sounds with 50 m bathymetry contours from Begg & Johnston (2000). Inset map shows location of main map.

How much the topography of the Sounds has been modified since the onset of basin formation at ~5 Ma has important implications for the age of this topography. The maximum amplitude (i.e. ~1500 m) and hill slopes (i.e. ~5-35º) of paleotopography beneath the Wanganui Basin are similar to those of topography in the Sounds. Similarities in the amplitude of the topography of the eroded basement in the Sounds and beneath Wanganui Basin are consistent with the notion that the first order topography in both regions is part of the same system and may not have changed substantially in amplitude (e.g., no more than 400 m) or orientation in the past 5 Ma. For this to be true ongoing hill-slope erosion, as indicated by regolith failures during high intensity rain storms and the formation of small deltas at many stream mouths (e.g., Cotton 1913;

Nicol 2011), must have not occurred at sufficiently high rates to substantially modify the amplitudes, hill-slope angles or orientations of the main valleys and ridges in the Sounds. The low rates of erosion suggested by the absence of a change in the topography on the top basement surface across the outer margin of the Sounds (and the strong weathering of basement rocks) are consistent with the view that the Sounds were probably not a significant source of the < 5 Ma sediments deposited in the offshore Wanganui Basin.

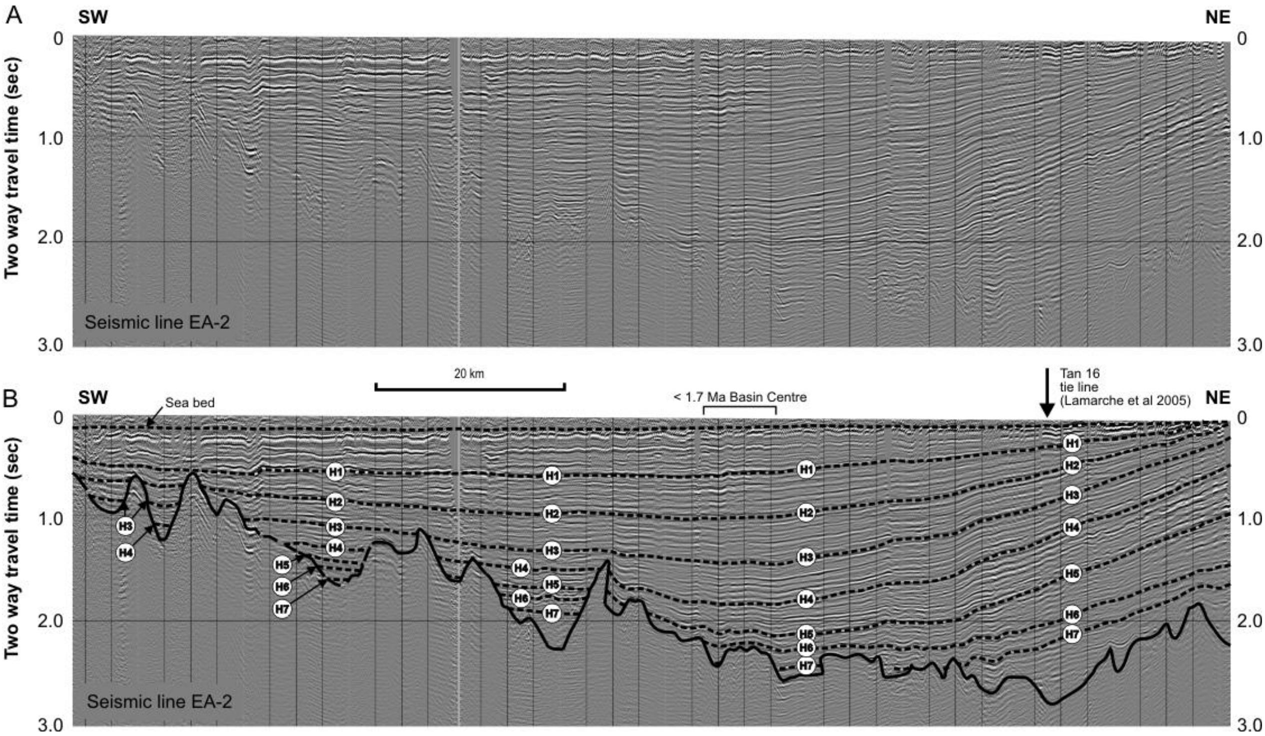

Figure 1.4 Uninterpreted (A) and interpreted (B) seismic reflection profile (line EA-2) across the offshore Wanganui Basin (see Fig 1.5 for location). Eight seismic reflectors (H1-H7 and top basement) have been interpreted in the seismic line with the age and location of the H1-H7 reflectors from cross line Tan 16 of Lamarche *et al*. (2005). Estimated reflector ages are; H1 120-260 ka, H2 620±100 ka, H3 1000±150 ka, H4 1750±300 ka, H5 2400±200 ka, H6 2600±200 ka, H7 3000±200 ka. Figure from Nicol (2011).

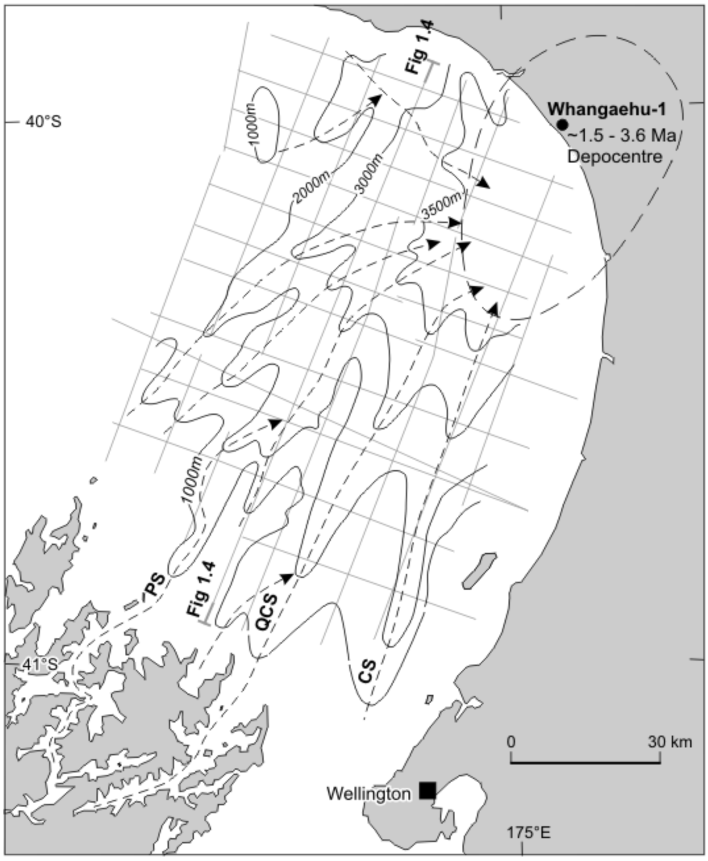

Figure 1.5 Contour Map showing the depth (in metres below sea level) to the top of basement beneath the offshore Wanganui Basin. Intermediate length dashed lines define the axes of paleovalleys incised into basement with arrows indicating the inferred paleoflow direction. PS, QCS and CS show the locations of paleovalleys inferred to be the north-northeast continuations of Pelorus Sound, Queen Charlotte Sound and Cook Strait, respectively. Thin grey lines show locations of seismic lines. Long dashed lines define the approximate location of the Wanganui Basin depocentre between ~1.5 and 3.6.

The coastal and offshore portions of the Wairau Fault

The first stop along the Wairau Fault in this field trip is at Bankhouse Station/Ara Vineyard (Stop 2; Figs. 1.1 & 1.6-1.9) about 60 km from the mapped eastern end of the fault. To add context for the trip and foster discussion farther up the valley, we discuss the coastal and offshore portions of the Wairau Fault in the following paragraphs.

East of Renwick, for c. 8 km, the location of the Wairau Fault is uncertain as it is concealed beneath the young floodplain of the Wairau River (Fig. 1.6). This is of concern with regards to characterising, and mitigating, the surface fault rupture hazard along this section of fault. Further to the east-northeast, closer to the coast, Grapes & Wellman (1986) map an active fault trace near Spring Creek, which was termed the “Spring Creek sub-section” of the Wairau Fault by Yetton (2003). This section of the fault displaces late Holocene beach ridges to within 800 m of the coast. The beach ridges were defined on the basis of many drill holes in the Wairau delta area. Marine shells radiocarbon dated by Gibb (1979) provided ages of c. 6600 and 4500 yr for the two most prominent faulted shorelines. Based on an assumed constant rate of coastal progradation, Grapes & Wellman (1986) estimate the age of the oldest unfaulted beach ridge to be c. 800 yr.

Much of the Cook Strait area was re-mapped by NIWA geologists as part of the It's Our Fault project (Barnes & Pondard 2010; Pondard & Barnes 2010; Van Dissen *et al*. 2010). In particular, the locations of offshore active faults in the strait, including the Wairau Fault, have been significantly improved using high-resolution seismic reflection profiles (Fig. 1.7). The Wairau Fault is now mapped as extending from near the coast for a further c. 40 km into Cook Strait to the edge of the continental shelf. Multi-beam data in water depths of >100 m show a prominent fault scarp on the seabed up to 10 m high (Pondard & Barnes 2010). Across the shelf, the fault has an overall east-west strike and is characterised by a large restraining bend in Cloudy Bay and a large releasing bend toward the shelf edge (Fig. 1.7). Barnes & Pondard (2010) use the seismic reflection profiles and sea-level rise records to estimate the timing of paleoearthquake events on the offshore section of the Wairau Fault. The last four-five events occurred at 2.0 ± 0.3, 2.9 ± 0.5, possibly 3.5 ± 0.4, 5.5 ± 0.8 and 7.4 ± 1.7 ka. Comparison of this record with the onshore, trenching-derived, paleoearthquake record will be made at Stop 4b.

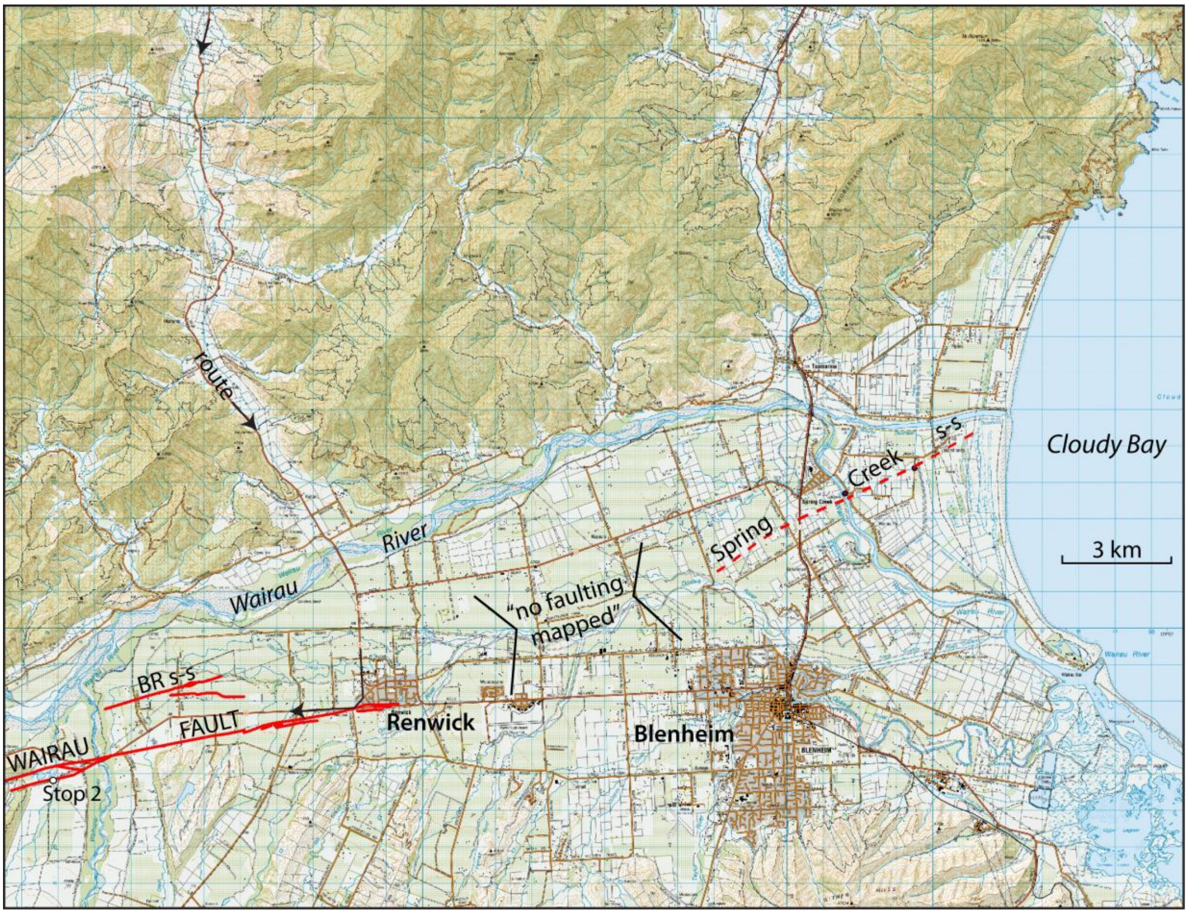

Figure 1.6 Map of the coastal portion of the Wairau Fault from Bankhouse Station (Stop 2) to Cloudy Bay. Abbreviations: BR s-s, Bedford Road sub-section; Spring Creek sub-section.

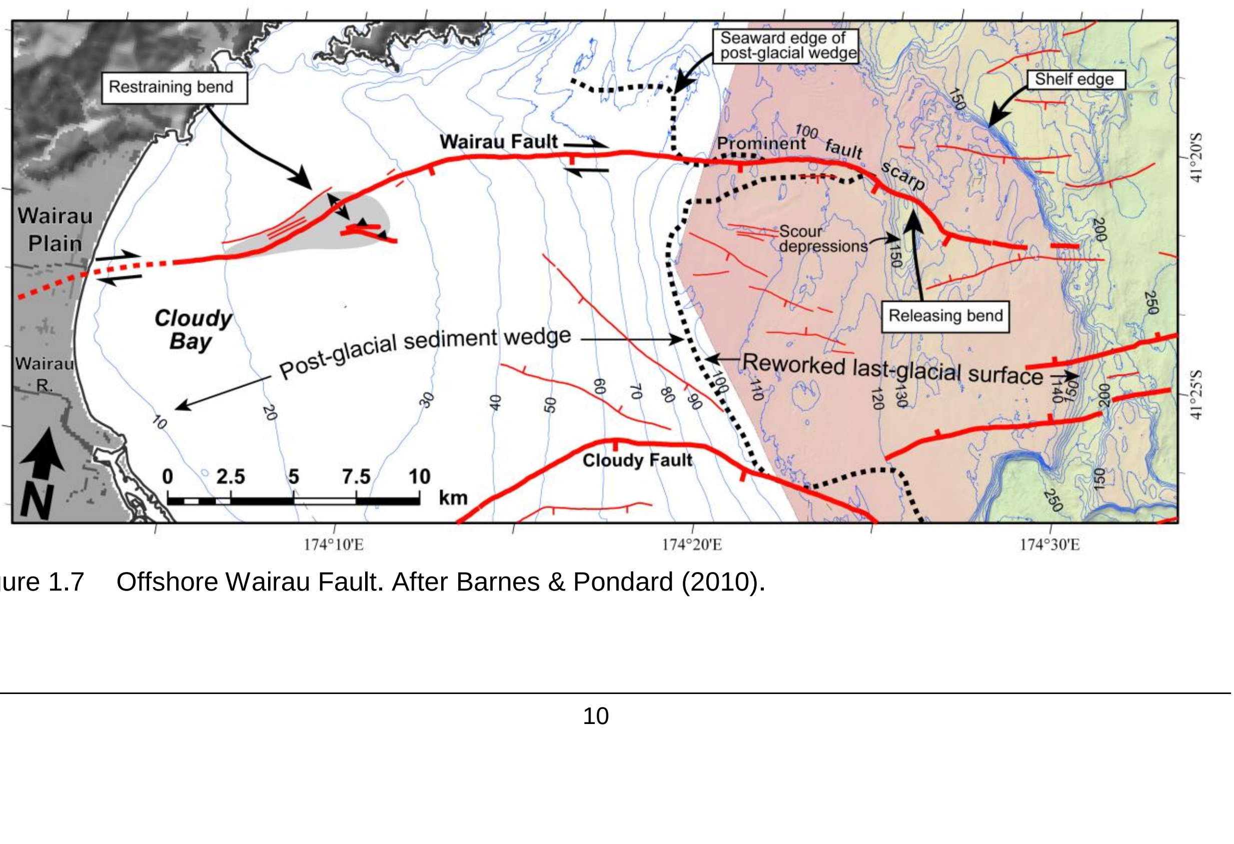

Figure 1.7 Offshore Wairau Fault. After Barnes & Pondard (2010).

Stop 2 Bankhouse depression fault location and geometry

Bankhouse Station and the Ara Vineyard are located c. 20 km west of Blenheim. The Ara Vineyard property covers some 16 km^2 of land adjacent to the true left bank of the Waihopai River, a major tributary of the Wairau River. The active Wairau Fault crosses the northern end of Bankhouse Station/Ara Vineyards near State Highway 63. The Wairau Fault Zone consists of a graben (Bankhouse depression) with two well-defined active traces that form the structural depression, one well-defined secondary trace, and other possible secondary faults and fold axes (Figs. 1.6, 1.8 & 1.9). At this stop, scarps of the Wairau Fault are visible across alluvial terraces of the Waihopai River and continue to the west through surrounding hill country south of the Wairau River. Three of the fault scarps have been previously mapped as active fault traces by Lensen (1976). The low hill country in the south of the Bankhouse property consists of upper Pliocene to lower Pleistocene Hillersden Gravels (Rattenbury *et al*. 1998) which are claybound and have clasts comprised predominantly of quartzo-feldspathic sandstone.

The main alluvial river terrace, upon which the majority of the property and Ara Vineyard are sited, has been termed the “Bankhouse Flat” terrace. This broad terrace was probably formed during the Last Glacial Maximum (LGM), and is designated as a Q2a surface (c. 19,000 ± 5000 yr) (Begg & Johnston 2000).

A development proposed by Ara Vineyards for this site involved the construction of an irrigation scheme that included an irrigation canal and a number of water storage ponds. In addition, water was to be channelised into and stored in the previously existing lake between the main fault traces of the Wairau Fault zone (Figs. 1.8 & 1.9).

Figure 1.8 Photograph of the Wairau Fault zone at Bankhouse Station/ Ara Vineyard. View to the west along the Bankhouse depression. Photograph by DL Homer.

Guidelines for Avoidance of Active Faults

The Ministry for the Environment (MfE) has published guidelines[1] concerning building practice in the vicinity of active faults (Kerr *et al*. 2003). The "MfE Guidelines" require three pieces of information to assess the resource consent activity for greenfield sites, such as at the Ara Vineyard property. These are: i) fault trace complexity; ii) building type; and iii) surface fault rupture recurrence interval. These three topics are discussed below:

Figure 1.9 shows the fault traces in the vicinity of the Waihopai River and Bankhouse Station, as mapped by Lensen (1976). In the Bankhouse area, the Wairau Fault has an average strike of c. 077º. Two of the three fault traces are major strands of the fault which collectively form a graben. Both of these scarps have heights of several metres, attesting to considerable local vertical movement since the abandonment of the Q2a surface. The right-lateral component of fault displacement (which is the dominant sense of displacement) for the Wairau Fault is difficult to discern, but is best expressed by the offset of the riser against the Bankhouse Flats terrace (34 metres) on trace 2 (Fig. 1.9), and the step in Bankhouse Stream from the south side of the graben to the north, a horizontal step of c. 100 m (also post-Q2a).

The third trace mapped by Lensen (1976) occurs between the two major fault traces and within the graben. The area to the east of the third trace is relatively upthrown with respect to the lake/marsh within the graben. Detailed geomorphic maps from Lensen (1976), and low-altitude aerial photographs taken by GNS along the Wairau Fault, have been used to identify other secondary faults, potential fault traces (mapped as lineaments), and a series of folds hinges related to "sags" and "highs" in the Bankhouse depression. The amount of vertical deformation caused by these secondary faults and folds is generally less than the throw on the main fault traces. However, the effects of deformation on secondary structures, which could include displacement, tilting, sagging or opening, would probably be large enough to cause damage to buildings and infrastructure constructed over these secondary structures.

The Wairau Fault, at present, has a Recurrence Interval (RI) class I (≤ 2000 yr) status. The following were recommendations made to the vineyard for development of a water retention lake within the graben with associated engineering structures that crossed the fault zone (Zhang *et al*. 2004):

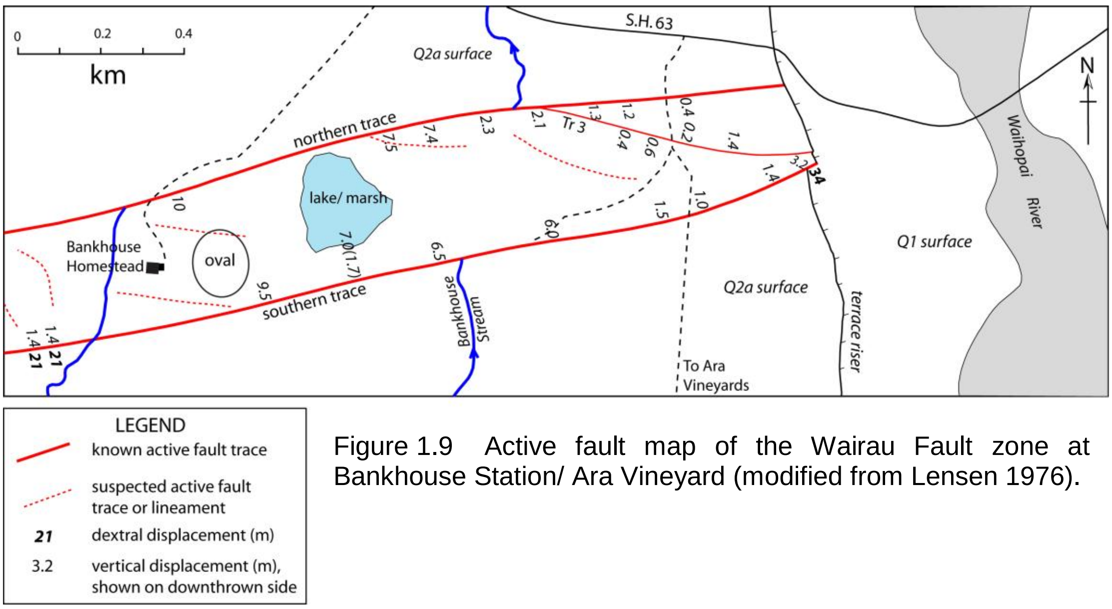

Figure 1.9 Active fault map of the Wairau Fault zone at Bankhouse Station/ Ara Vineyard (modified from Lensen 1976).

[1] Planning for Development of Land on or Close to Active Faults – An Interim guideline to assist resource management planners in New Zealand (Kerr *et al*. 2003).

"At its most restrictive, the MfE Guidelines require that a minimum 20 metre wide setback zone be placed either side of the known location of fault scarps associated with the Wairau Fault. This means that only BIC I structures [i.e. temporary structures] may be permitted within the designated Fault Avoidance Zone. Within the graben and excepting the three well-defined buffer zones, the fault is considered to be a distributed zone of deformation. In these areas, the consent activity status is "Discretionary" for BIC 2a structures [i.e. timber-framed residential structures], while BIC 2b structures remain "Non-complying" at greenfield sites. Better fault location and study could reduce the uncertainty concerning the consent status of this area".

Following these recommendations, Ara Vineyards constructed a new lake (Pinot Lake) about 3.4 km to the south of the Wairau Fault on the Q2a surface, relieving the need for any engineering structures across the fault zone. This is obviously a positive result in terms of the MfE Guidelines.

Stop 3 Wairau Valley township – Evidence of past strong ground motions

The township of Wairau Valley is about halfway up the valley between Cloudy Bay and Tophouse (Figs. 1.1 & 1.10) and provides an opportunity for us to stretch our legs and use the facilities.

Landslides and Rockfalls north of the Wairau River

In the Richmond Range, north of Wairau Valley, there are many landslides that could have been generated by shaking from a Wairau Fault earthquake, including landslide-dammed Lake Chalice and the slide on Mount Fishtail (Figs. 1.10-1.12; e.g. Johnston 1994; Rattenbury *et al*. 1998).

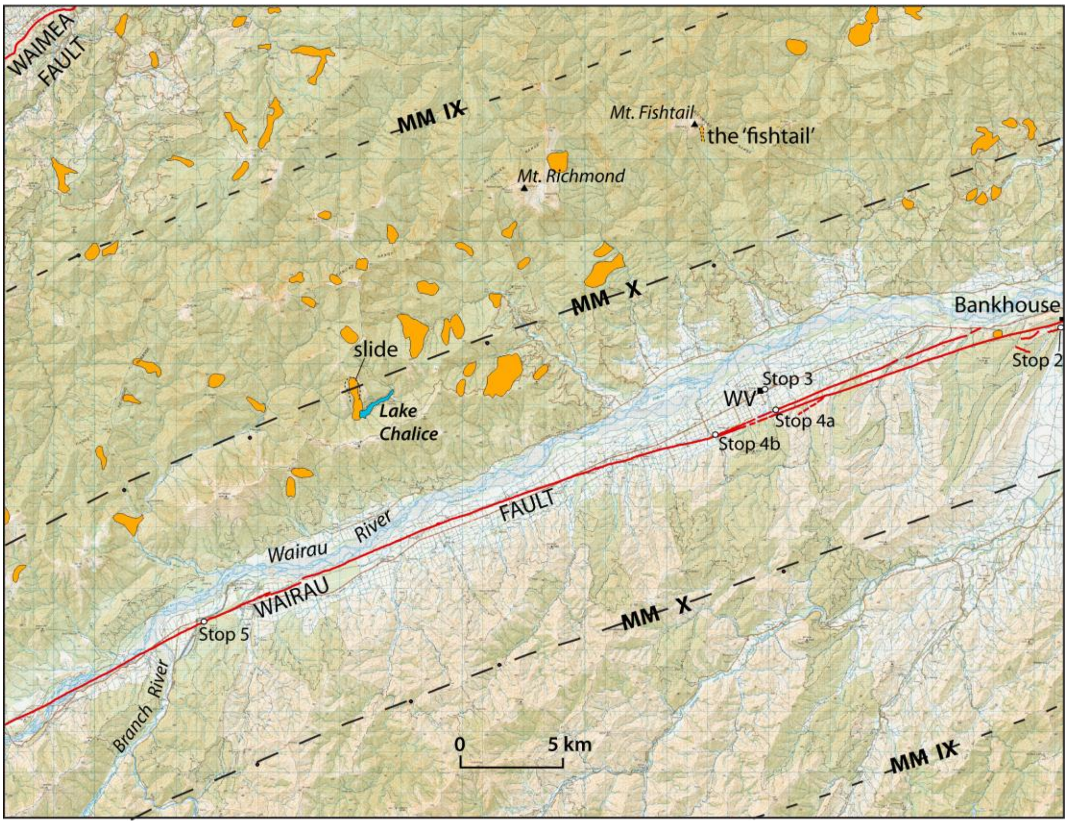

Figure 1.10 Earthquake shaking map of the central part of the Wairau Fault. Orange polygons are mapped landslide deposits. WV = Wairau Valley township. Contours are Modified Mercalli Intensity isoseismals based on Dowrick & Rhoades (1999).

Lake Chalice

Lake Chalice is located c. 15 km west of Wairau Valley (Figs. 1.10 & 1.11). It is c. 1.7 km long x 0.2 km wide and occurs at an elevation of c. 770 m a.s.l. The lake has formed behind a landslide dam that blocks the Goulter River (Adams 1981; Meredyth-Young & Pullan 1977). The landslide deposit is sourced from the collapse of Permian Caples terrane rocks (Star Formation sandstones) that typically have NW-SE striking foliation with shallow (20-25°) dips to the SW in the area around the slide scar (Johnston 1994; Rattenbury *et al*. 1998). The deposit resembles a massive, semi-contained dip-slope failure that has slid/dropped c. 250 m in elevation from a ridge crest summit above the valley forming a 100 m high barrier. At the outcrop scale, the landslide deposit consists of angular schistose rock debris in a clay-rich matrix (Johnston 1994).

Lake Chalice is probably more than 60 m deep and currently drains through the landslide deposit, which it has probably never overtopped. On the lake bottom stand 10 m high trees that were drowned as the lake formed. Two twig samples taken from the trees by divers have been radiocarbon dated at 2170 ± 70 and 2160 ± 80 yr B.P. (Meredyth-Young & Pullan 1977; Adams 1981). Recent re-evaluations of these dates by the Rafter Radiocarbon Laboratory at GNS Science yield a combined age of 2121 ± 60 yr B.P. which calibrates to an age of 1880-2300 cal yr B.P.

A correlation has been made between the timing of this landslide and the most recent faulting event observed in trenches across the Wairau Fault in the Wairau Valley (Zachariasen *et al*. 2006; and discussed below as part of Stop 4), suggesting a causal relationship between ground motions during Wairau Fault rupture and landslide formation. The source area for the Lake Chalice slide is c. 7.5 km from the trace of the Wairau Fault (Fig. 1.10). Applying the Dowrick & Rhoades (1999) MM attenuation relation, it is estimated that rupture of the Wairau Fault would generate close to MM IX shaking at the Lake Chalice site (assuming a magnitude 7.7 earthquake, a crustal thickness of 12 km, and a source to site distance of c. 7.5 km). In addition, shaking may have been further enhanced due to topographic effects, and slab failure of the rockmass may have been facilitated by the low angle of foliation (Johnston 1994).

Figure 1.11 Oblique aerial image of the Lake Chalice area, Richmond Range, viewed to the east. Wairau Valley and fault in the distance. Photograph by DL Homer.

Mount Fishtail

Mt. Fishtail is so named because of a fishtail-shaped scree deposit that is spread over 500 m relief between the summit ridge and native bush below (Fig. 1.12). Mt. Fishtail occurs in Permian Caples terrane indurated sandstones and siltstones. The rocks have NE-SW strikes and shallow foliation dips (c. 35° SE) (Rattenbury *et al*. 1998). The 'fishtail' can be seen from many points along the highway in the area of Wairau Valley. The deposit inundates native forest at the foot of the mountain and could well have been generated by earthquake shaking. However, there is no age data to assess whether this active scree deposit was generated by a Wairau Fault event. Re-activation of this slide may have occurred during nearby large historical earthquakes in 1848, 1855, or 1929 (G. Hancox, personal communication 2011). The Mt. Fishtail deposit occurs at a distance of c. 14 km from the trace of the Wairau Fault (Fig. 1.10). Using the Dowrick & Rhoades (1999) relation, the expected MM Intensity at Mt. Fishtail, resulting from a magnitude 7.7 Wairau Fault earthquake, would at least MM IX, certainly high enough to trigger slope failure.

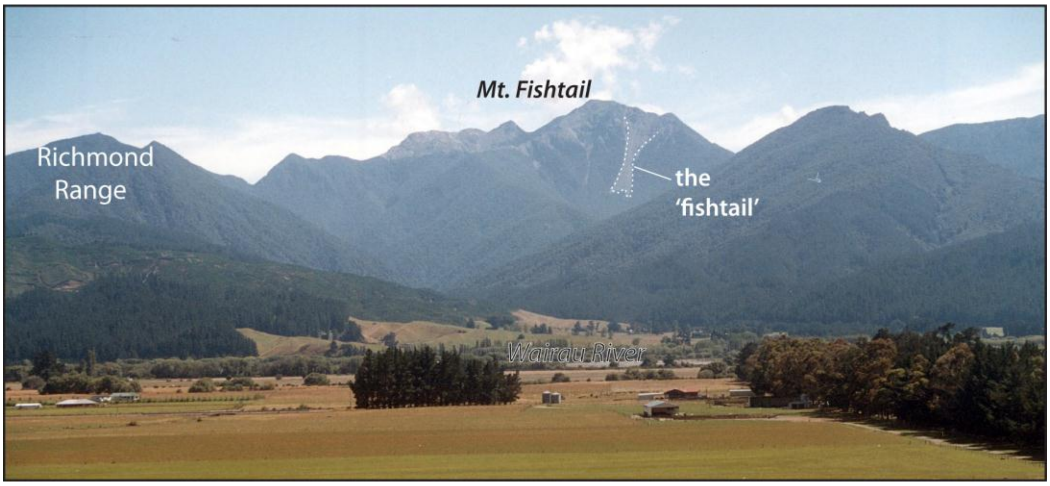

Figure 1.12 The Richmond Range and Mount Fishtail, from the Wairau Fault. Photograph by R. Langridge.

In summary, rupture on the Wairau Fault will cause very strong shaking in the region around the Wairau Valley (Fig. 1.10), and appears to have done so in the past. Many of the landslides mapped in the Richmond Range by Rattenbury *et al*. (1998) occur within the predicted MM IX shaking contour of a large Wairau Fault earthquake. It is no surprise that such strong ground motions would trigger slope failures, especially in areas of high topographic relief and in rocks that have pre-existing weaknesses susceptible to failure.

Stop 4 Trench Sites and Paleoearthquake timing

Three trenches were excavated across the Wairau Fault near Wairau Valley township by Zachariasen *et al*. (2006) (Figs. 1.1, 1.10, 1.13-1.19). In most of this area, the fault comprises two main strands. The northern strand traverses terraces on the south side of the Wairau River valley and along the base of a range of low hills composed of Pliocene Hillersden Formation (a weathered clay-bound quartzo-feldspathic gravel), and Mesozoic Torlesse sandstones and mudstones (Rattenbury *et al*. 1998; Begg & Johnston 2000). The southern strand, c. 50-300 m away, traverses the hills slightly upslope. The two strands flank a relatively down-dropped block, with the northern strand upthrown on the downhill side. This configuration produces an uphill-facing fault scarp at the base of the hill that blocks stream flow and causes ponding of water and deposition of sediment at the foot of the scarp. Local ponding of drainage along active faults is ideal for paleoseismic trenching, as sediment is deposited along the scarp. This sediment often contains organic material suitable for dating, which can be used to constrain the age of sediments and the timing of earthquakes that rupture through the collected sediments. Two trenches (Marfell and Dillon) were excavated across the northern strand, and the third (Wadsworth) was located where the strands merge (Zachariasen *et al*. 2006). The Dillon trench site will be our Stop 4a; the Wadsworth trench site (Stop 4b) will be visited if time permits. The Marfell trench is not described in this guide.

Stop 4a Dillon trench site

This trench was excavated at Lansdowne Station across the northern strand of the fault through a small ponded area formed at the foot of the scarp and fed by an intermittent stream that flows north (Fig. 1.13). The scarp here trends c. 66°, is c. 1 m high (north side up), and blocks the north draining stream (Fig. 1.14). Preserved on the scarp is an abandoned channel that was interpreted to have originally been an outlet for the stream. Lensen (1976) mapped this offset stream and reported a right-lateral displacement of 23 m.

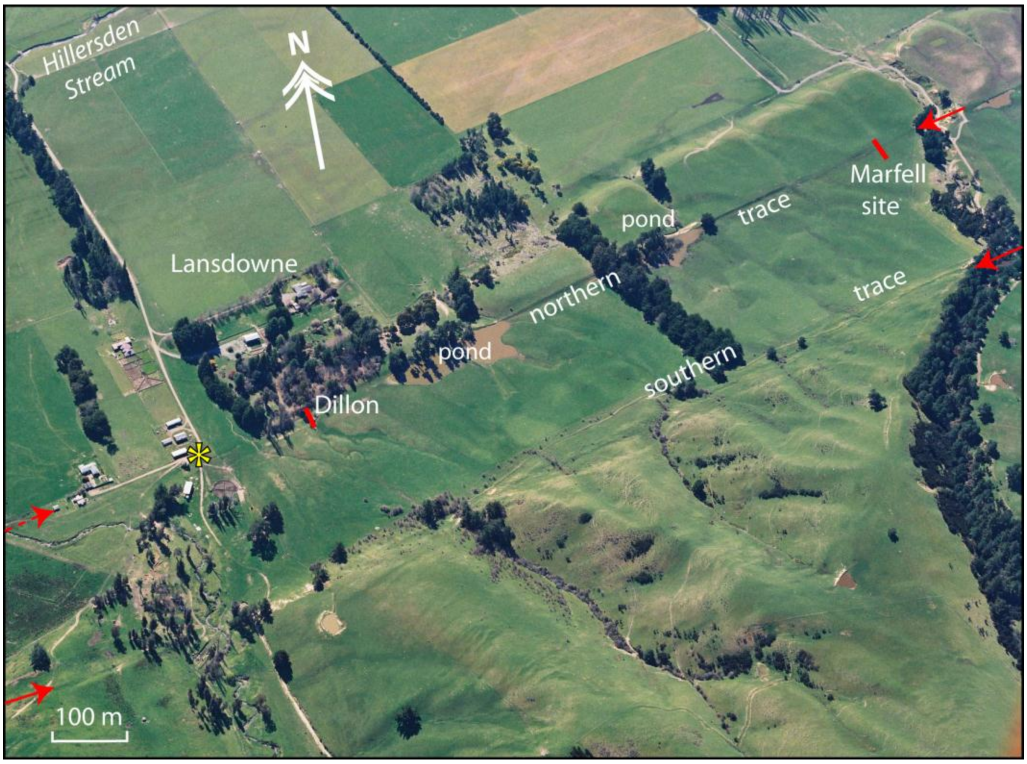

Figure 1.13 Oblique aerial photograph of the two strands of the Wairau Fault (red arrows) looking to the north across the Dillon and Marfell trench sites (red bars). Asterisk marks the bus stop.

Stratigraphy

The log of the western wall of the Dillon trench is shown in Fig. 1.15, and a photograph of a portion of the Dillon trench is shown in Fig. 1.16. In the trench, the sediments are primarily alluvial silts and gravels. These alluvial channel deposits occur on both sides of the fault and were probably derived from local streams sourced from the hills to the south. West of the trench site, the fault scarp is not discernible across a paddock, and its absence may indicate that the paddock surface postdates the last faulting event (Fig. 1.13). Several streams in the foothills deliver sediments to the paddock area and could be the source of some of the deposits exposed in the trench.

The sediments on the downthrown side of the scarp (metres 8-16) are dominated by pebble to cobble-sized gravels with silt and sand lenses, which may be partly alluvial and partly slope wash debris. The axis of scarp parallel streams on the downthrown block can be seen by the presence of channel cross-sections (e.g., units 8-12, 17, 21, 23 of Fig. 1.15) cutting across finer grained alluvial units in the trench walls. In the lower part of the trench, the gravels are poorly sorted and tend to have cobble- to boulder-sized clasts. Gravels are both matrix and clast supported, and the matrix ranges from silt to gritty sand. In addition to the gravels are several finer-grained alluvial deposits. Higher in the section, above the bench, a series of finer pebble gravels, silts, and sands (units 8-15) overlie the silts and larger clast gravels (units 16-21). They differ from the underlying units and the sediments on the upthrown side of the fault, in that they generally have smaller clasts, less matrix, better sorting, and a smaller scale channel structure. It appears that all of the exposed units on the south side of the fault scarp postdate the creation of the scarp and development of a pond, and probably the offset of the stream channel. The age of the oldest of the scarp-parallel units should be a minimum age for the blocking of the channel through fault rupture.

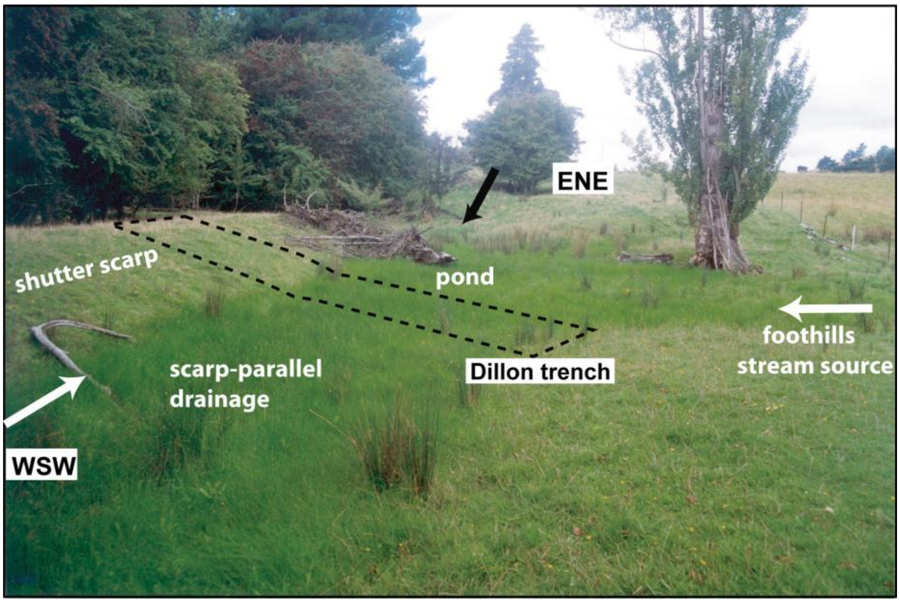

Figure 1.14 The Dillon trench site (within dashed box). The stream source from the southern foothills is ponded against the shutter ridge related to the northern trace of the fault.

Faulting

In the west wall of the trench (Fig. 1.15), there are two main zones of faulting exposed. The primary zone, at about metre 5, is 10-40 cm wide at the trench floor and splays upward and outward. Individual strands of the fault strike more easterly than the general 66° trend of the scarp and are steeply south-dipping. For example, strand F1 strikes 83° and dips 57°S, and strand F2 strikes 70° and dips 79°S. There are also numerous subvertical, gleyed zones on either side of the faults. These may be associated with faults or fractures and in places are correlated with zones of distributed shear (e.g., point A at metre 3.5).

A subsidiary zone of faulting occurs between metres 8 and 10 (F3-F6). The zone comprises several c. 50°-striking, steeply north-dipping fault strands, several of which have upward terminations that help constrain rupture event history. While the magnitude of displacement in this zone is unknown, the truncations and mismatch of channel and silt facies (units 17a, 20, 21a) in the lower part of the trench, suggests there is some lateral displacement across these faults. Given the location of these strands, south of the scarp and well in the down-dropped part of the zone, their discontinuous nature, and their northerly dip, it was concluded that these are secondary faults, accommodating minor lateral displacement and local extension.

The following is a rupture event history for the Dillon trench from Zachariasen *et al*. (2006). Several lines of evidence from the trench argue for the occurrence of at least two, and probably three, fault-rupture events. At the main fault zone, the oldest event is constrained by unit 4.5 (Fig. 1.15). This unit comprises poorly sorted silt to cobbles. The cobbles are derived from unit 4. The lack of sorting, the source of the cobbles, and the wedge shape of the unit lead us to interpret this unit as a colluvial wedge deposited at the foot of the fault scarp. The presence of this unit is evidence of a faulting event that generated a free face and a colluvial wedge (unit 4.5) of material ravelled off the scarp. This event horizon and overlying colluvial wedge unit are both faulted, indicating a second, younger event. There is no clear evidence of faulting in the units above unit 4.5 (units 1-3). Unit 3 is somewhat irregular, but no faults were observed within it. In addition, faults at metre-7 terminate at the base of, and do not displace, unit 2.5. There may be another earlier event that affected the lower part of unit 4 but preceded deposition of the upper part of unit 4. Fault F1 breaks unit 5 and disrupts the base of unit 4 but is overlain by the upper part of unit 4, which has a smooth undisturbed upper contact.

Evidence from the secondary fault zone supports the occurrence of three, and possibly four, events. The occurrence of the pond deposits (units 8-15) represents at least one rupture event, and is consistent with the continued development of the scarp, blocking of the channel, and consequent ponding at the foot of the scarp. Secondary fault strands F5 and F6 break through the pond deposits, indicating the occurrence of a second, younger event. Therefore, at least two events have occurred since the deposition of the lower channel silts and gravels (e.g., since deposition of units 29, 30, and 16). Fault terminations occur above unit 12 on strand F6 and below unit 2.5 on strand F5, respectively, identifying two clearly separate events.

Fault strand F4 may have some lateral offset across it in the lower part of the Dillon trench. Although the units are similar on either side, some discontinuities and juxtapositions were mapped within units 17 through 21, below unit 16. Unit 16 is less disturbed than the units below it; indeed, the top and bottom contacts appear to have little or no vertical separation. However, unit 12, above unit 16, is disrupted where a thin line of fine pebbles is vertically separated across the fault. In addition, dashed fault strand F4 terminates on the base of unit 16. From this configuration of sediments and faults, a third event is inferred at the Dillon trench (D_3), which occurred before deposition of unit 16.

Ages

The only organic material that was located for dating came from the secondary zone of faulting. The oldest radiocarbon sample in the trench (sample D-1), a piece of charcoal from the thick silt unit between the two fault zones (unit 28), has an age of 4835 ± 60 BP (5321-5611 cal yr BP). This unit has probably been involved in all the events that affected sediments exposed in the trench. In other words, there have been three or more events within the past c. 5600 yr. A charcoal sample from unit 30, which overlies unit 16, has a radiocarbon age of 4199 ± 55 BP (4445-4841 cal yr BP). If there was an event prior to the deposition of unit 16, then it should have occurred before deposition of that charcoal, i.e., between 4445 and 5611 cal. yr BP.

Unit 30 is immediately below the ponded sediments of unit 14. The development of the pond and the blocking of the channel by the fault scarp would have occurred after 4841 cal. yr BP. Therefore, at least two events have occurred in the past 4841 yr. Charcoal (D-10) from the charcoal-rich seam, unit 15, which is probably the lowest unit within the ponded sequence, has an age of 3769 ± 55 BP (3889-4236 cal. yr BP). It is likely, therefore, if there are two events post-unit 30, that the penultimate event at Dillon (D_3) occurred between 4841 and 3889 cal. yr BP.

Charcoal sample D-8 was sampled from unit 2.5 (probably equivalent to unit 2), a dark grey to brown mottled silt with abundant charcoal, root material and evidence of bioturbation, which directly underlies the modern topsoil. This unit, drapes the scarp, overlies the ponded gravel units, and appears to be unfaulted. The charcoal from this unit has an age of 2687 ± 55 BP (2618-2887 cal. yr BP), suggesting that the last event at this site (D_1) occurred before 2618 yr ago and after c. 4236 cal. yr BP, the age of charcoal from unit 15, which was faulted at least once.

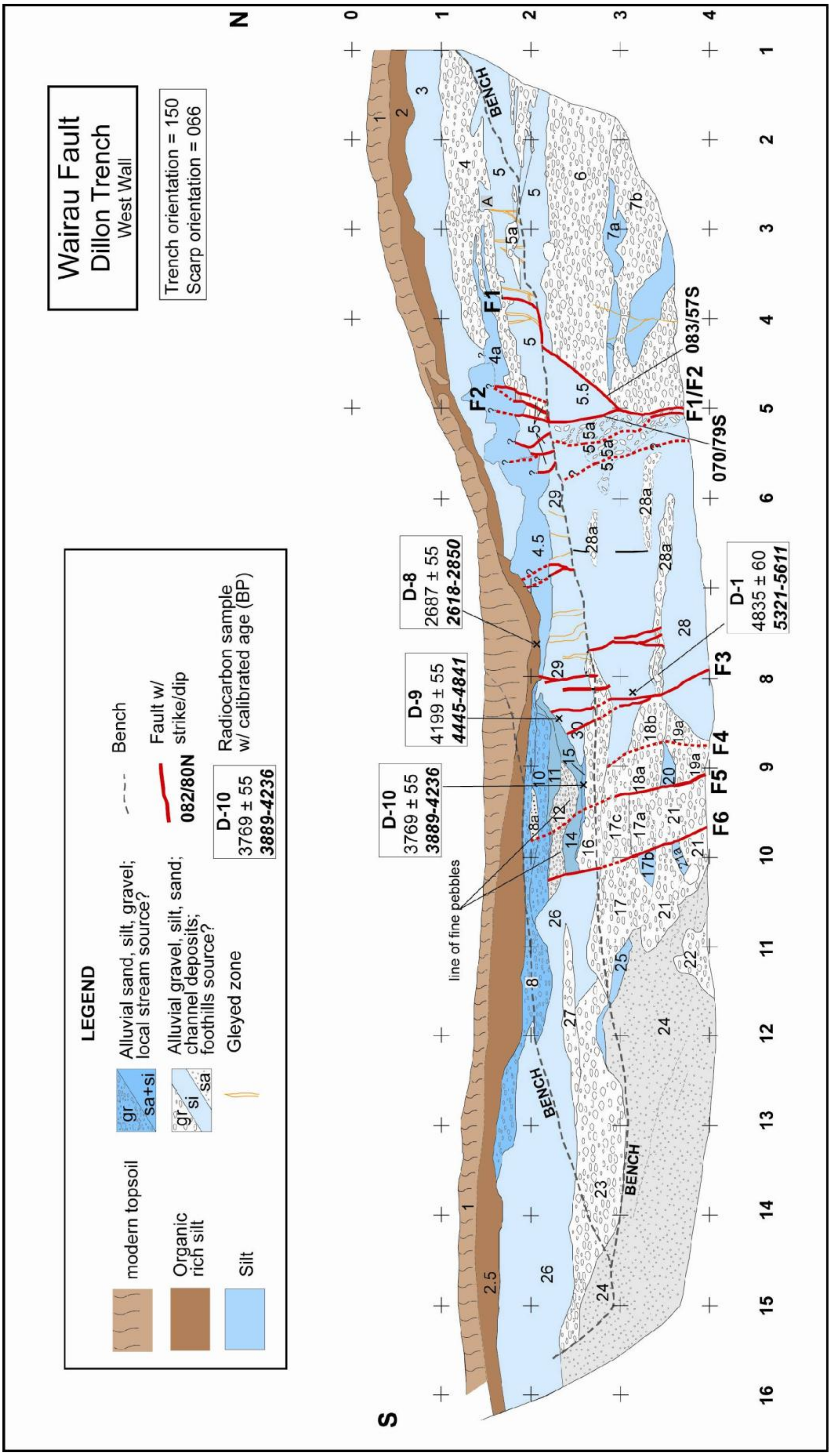

Figure 1.15 Log of the Dillon trench (modified from Zachariasen *et al*. 2006).

Figure 1.16 Fault scarp exposed in the west wall of the Dillon trench. Upper batter on the north side of the fault zone is displayed. Units are numbered according to Fig. 1.15.

Stop 4b Wadsworth trench site

The Wadsworth trench was excavated across a 3.2 m high fault scarp just southeast of Parsons Road (Figs. 1.12 & 1.17). The southern strand of the Wairau Fault dies out to the east or joins the northern strand at about this point (Fig. 1.17). A small stream, a tributary of Hillersden Stream, meets the fault scarp at the site and travels east along the foot of the scarp until it meets the main stream. The trench was excavated where the stream met the scarp (trend c. 075°), where it was likely that sediment and carbonaceous material would collect. The log of the western wall of the Wadsworth trench is presented in Figure 1.18, and a photograph taken during the early stages of excavation is shown in Figure 1.19.

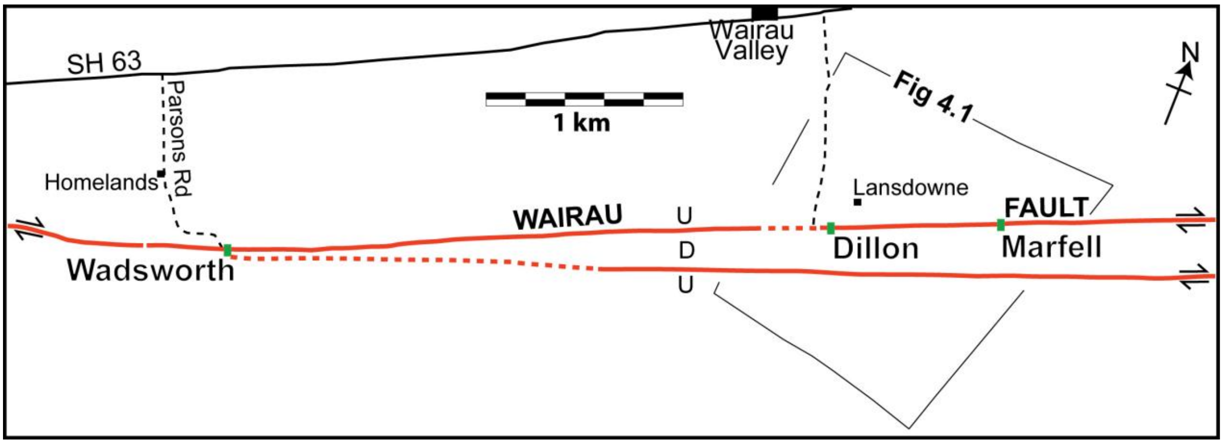

Figure 1.17 Location of the Wadsworth trench site close to the intersection of the northern and southern fault strands of the Wairau Fault, west of Wairau Valley township.

Stratigraphy

The sediments exposed in the trench are primarily alluvial gravels, sands, and silts on both sides of the fault. Lensen (1976) mapped the fault here as offsetting the late Otiran Stage (c. 18,000 yr) degradation surface. Those gravels presumably comprise the sediments on the northern, upthrown side of fault. These deposits, exposed in the trench between vertical metre marks 0 and 2, are pebble to cobble-sized gravels (Fig. 1.18). Channels are not evident in these units, and they appear as relatively uniform, subhorizontally bedded strata, dipping gently to the north.

At the southern end of the trench, between metre marks 6 and 14, the sediments are primarily cobble- to pebble-sized gravel with local silt interbeds. The stratigraphy indicates these are interfingering channel deposits from the active stream, and therefore significantly younger than the gravels north of the fault. As a group, these units tend to dip slightly to the north. Calibrated radiocarbon dates from this trench (see below) are consistent with a history of late Holocene local stream sedimentation on the south side of the scarp, deposited against older gravels.

Faulting

The zone of active faulting occurs between metres 2 and 7 (Fig. 1.18). Sediments in this part of the trench are similar in composition to those on either side but have a greater proportion of silt. The fault zone is pervasively sheared. However, there appears to be one dominant fault, the northernmost (F1 on log), and three or four other major faults. The fault scarp here trends at about 75°. Individual faults within the zone are in an *en echelon* pattern and strike more easterly, mostly between 78° and 86°. Fault dips are steep, most within 15° of vertical. The main fault dips 85°S; the others, farther south, dip steeply to the north.

The relationships between faults, their upward terminations, and the stratigraphy yield a faulting history with relative chronology that indicates the occurrence of at least three rupture events. The terminations highest in the stratigraphy probably represent the last event. These terminations occur on faults F1 and F2 at the base of unit 18, which is poorly sorted, matrix-supported, pebbly, cobbly gravel in silt. The lithology and shape of this deposit suggest it is a colluvial wedge, composed of material ravelling off the fresh scarp face and filling in the space at the foot of the scarp. The colluvial wedge and the units above it (19a, b, d) are all unfaulted; units below (e.g., 1d, 14, 17) are faulted. These relationships indicate that the last event occurred after deposition of units 1d, 14, 17 and before deposition of unit 18.

The penultimate rupture event is indicated by the termination of faults F3 and F4 below unit 16. Fault F3, which breaks through units 7 and 8a and up into unit 10, comprises two strands, both of which terminate below unit 16. F4 juxtaposes units 10 and 9 against units 11 and 15 and is overlain by unit 16. The penultimate event, then, occurred before deposition of unit 16 and after deposition of units 9, 10, 11, and 15.

The earliest event that can be identified in the trench is marked by the upward termination of F5 below unit 11, near metre 6. This fault termination is considered to represent an event horizon because the contact between the two distinctly different units 3 and 11 is not displaced across the fault, and there is no tectonic imbrication of unit 11 clasts up-dip of the mapped termination of F5. This event occurred after the deposition of unit 3 but before the deposition of unit 11. There are a couple of faults near metre 3.5 and 4.2 that cannot be followed above the bench. Whether these represent real upward terminations below unit 12 and, if so, how they relate to the termination below unit 11, is unclear. Near metre 4, two fault strands terminate near the top of unit 8c and appear to be overlain by unit 8e. This may also represent an event horizon, but it is not possible to relate the faulted stratigraphy here to the units (e.g., 3 and 11) near fault F5 and therefore determine if this represents an event distinct from the oldest event described above.

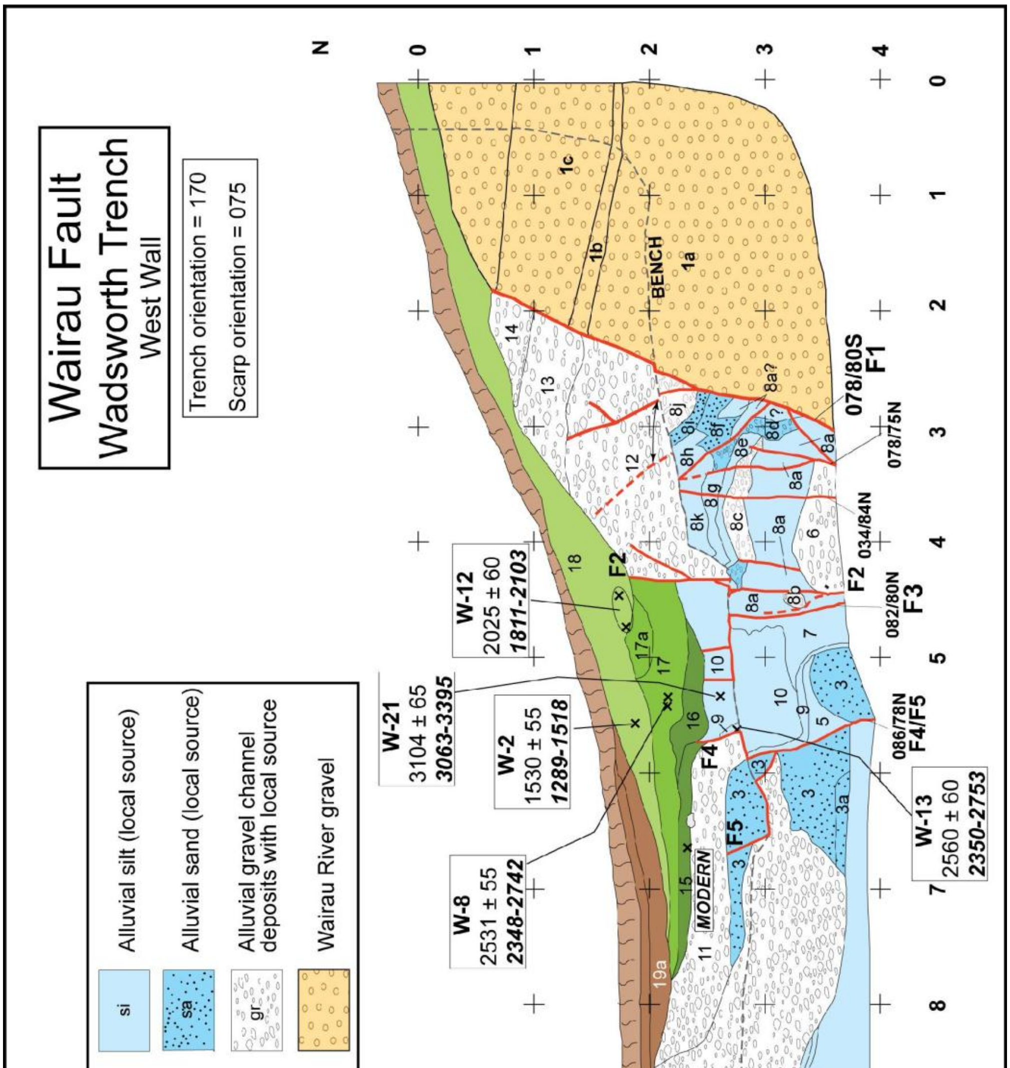

Figure 1.18 Log of the Wadsworth trench (modified from Zachariasen et al. 2006).

Figure 1.19 Excavation of the Wadsworth trench adjacent to Parsons Road; view to the west. Arrows follow the trend of the fault scarp. Photo spans metres 0-3 of log in Fig. 1.18.

Ages

Charcoal (sample W-12) from unit 18, the unfaulted colluvial wedge, has an age of 2025 ± 60 BP in radiocarbon years, or a calibrated age between 1811-2103 cal BP. A second charcoal sample (W-2) from slightly higher in this wedge has an age of 1530 ± 55 BP (1289-1518 cal BP). A sample of charcoal (W-8) from unit 17, faulted in the last event, has an age of 2531 ± 55 BP (2348-2742 cal BP), suggesting the last earthquake occurred between c. 1290 and 2740 cal BP. Two possible interpretations can be derived from these event relations: (1) the age of unfaulted materials indicate the Wairau Fault in this area has not experienced a ground rupturing event in the past 1290-2100 yr; or (2) as unit 18 was deposited immediately after the most recent surface faulting event, the age of the charcoal deposited at its base constrains the most recent event timing to around 1810-2100 cal. yr BP.

A charcoal sample (W-13) from the fault zone at unit 9, faulted in at least two events, has an age of 2560 ± 65 BP (2350-2753 cal. BP), statistically indistinguishable from the age of the charcoal in unit 17, faulted only once. At first glance, this suggests that the two events, the most recent and the penultimate, occurred in relatively rapid succession, at least within c. 400 yr of each other. However, the sample was collected from within the fault zone. As such, the charcoal may have been faulted into its position, rather than deposited, and it could be out of stratigraphic sequence and younger than other deposits at the same level in the sequence. To check this, another sample, of tree gum (W-21) from unit 10 was dated, which was also faulted in at least two events. The age of the gum is 3104 ± 65 BP (3063-3395 cal BP), which is consistent with the ages of overlying charcoal samples and its stratigraphic position except relative to the unit 9 fault sliver. These data and event relations suggest that the penultimate event occurred after c. 3300 yr ago (Table 1). The date on colluvial wedge units 16-17a (Wads-8; 2348-2742 yr BP) and infaulted charcoal Wads-13, most probably closely brackets the penultimate event. No dateable material was located to constrain the age of the third event back, though it must be older than the age of Wads-21 (i.e. ≥3065 cal yr BP.)

Event history

Utilising information from both trenches and insights from the landscape in the Wairau Valley area it is possible to develop a late Holocene rupture history for the Wairau Fault (Fig. 1.20).

Most recent event

Data from the Wadsworth trench indicate that the most recent event occurred before deposition of unit 18, the unfaulted colluvial wedge, and after deposition of unit 17. If it is assumed that the two charcoal ages reflect the time over which the colluvial wedge developed, then the older material should constrain the age of the preceding event, which implies the last event occurred between 1811-2742 cal. yr BP. This is the preferred geologic interpretation from the Wadsworth trench. However, in light of the uncertainties due to inherited age, one needs to consider a more conservative constraint for the timing of the last event of between c. 1290 and 2740 cal. yr BP from the trenches. The preferred interpretation for the Dillon trench is that it lacks key stratigraphic, structural or chronologic control to identify the most recent event there, or that the northern strand of the fault did not rupture during the youngest Wairau fault event.

One more piece of local data can be applied to our analysis of the most recent event age for the Wairau Fault, which are the dates on standing drowned trees from landslide-dammed Lake Chalice (combined age of 2121 ± 60 yr B.P.) (Adams 1981). Their calibrated ages (1880-2300 cal yr BP) overlap with the charcoal ages deposited in the colluvium after the most recent faulting event in the Wadsworth trench. From this data it is reasonable to assume that the most recent Wairau Fault earthquake generated the slide that formed Lake Chalice, as it can be both spatially and temporally linked to rupture of the Wairau Fault. Therefore, our combined preferred age estimate for the most recent rupture of the fault spans the age of the colluvial charcoal (W-12) and the Lake Chalice trees (i.e. 1810-2300 cal. yr BP) (Fig. 1.20).

Penultimate and older events

The penultimate event at the Wadsworth site definitely occurred between c. 2350 and 3395 cal BP. Assuming that the depositional age of the charcoal in the faulted colluvial wedge (unit 17) is correct and that the best interpretation for W-13 in unit 9 is as a fault-guided, charred root, then the preferred age range for the penultimate event is 2350-2755 cal. yr BP. The penultimate event at Wadsworth could be the equivalent of the youngest event identified in the Dillon trench (D_1), where sample D-8 comes from unit 2.5 that drapes across the fault scarp. This unfaulted unit covers the youngest event at Dillon and temporally (2620-2850 cal. yr BP) corresponds to the penultimate event at Wadsworth (W_2). At least one more event was identified in the Wadsworth trench, which can be constrained as being older than 3065 cal. yr BP. The equivalent event horizon at Dillon is older than 3890 and younger than 4840 cal. yr BP. The fourth event back can only be tentatively constrained at the Dillon trench. This event faulted units below the level of unit 16. Therefore this event occurred before the age of deposition of unit 15 and after the depositional age of unit 28, or between 4565 and 5610 cal. yr BP.

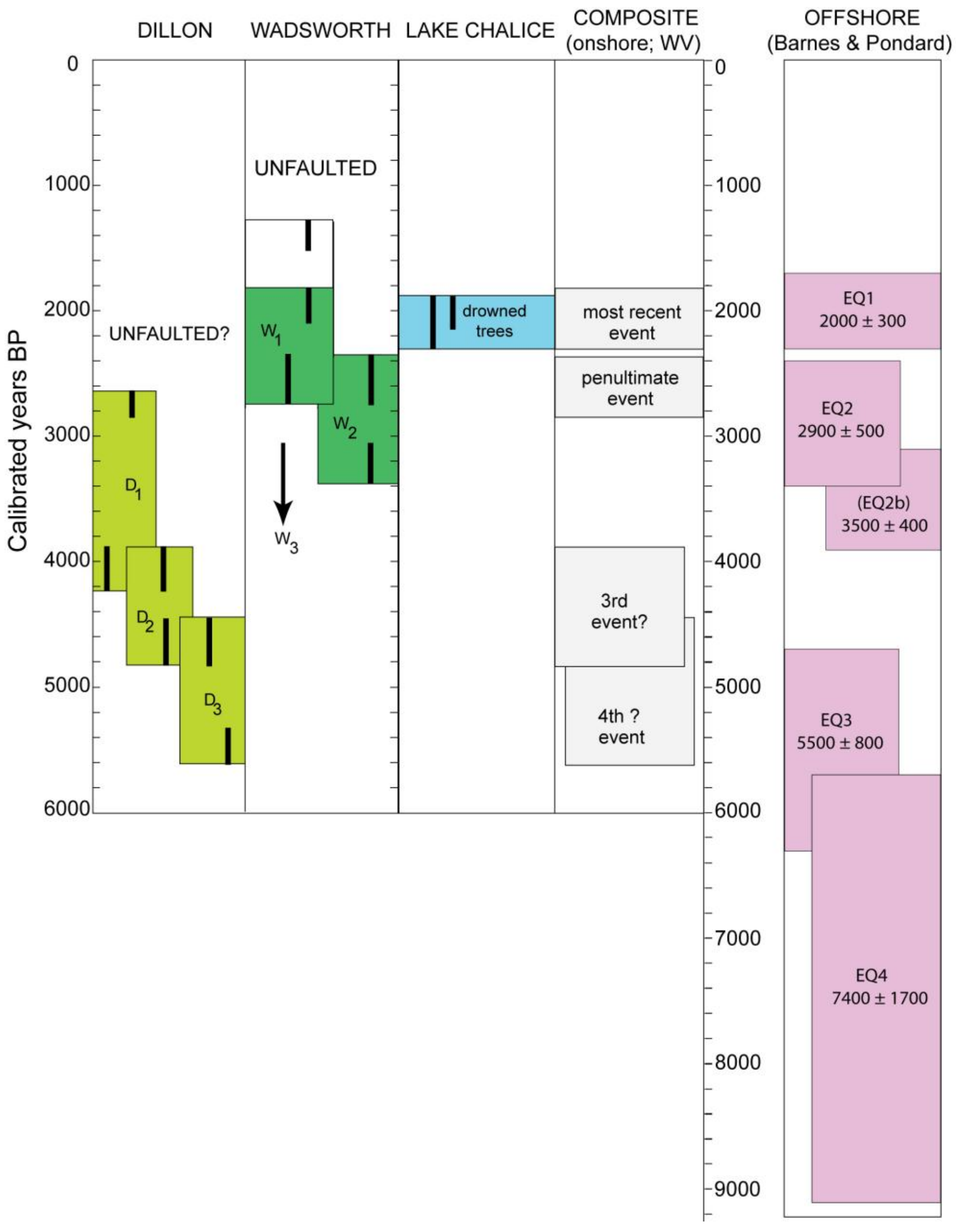

Figure 1.20 Combined onshore and offshore paleoearthquake record for the Wairau Fault. The left hand side of the diagram describes results from trenches in the Wairau Valley. These are combined with dates from Lake Chalice for the preferred onshore record from the Wairau Valley (WV) area. Offshore paleoearthquake data comes from Barnes & Pondard (2010).

Other outcomes of Wairau Valley trenching

The results of trenching in the Wairau Valley area suggest a maximum slip rate of 3.5-4.8 mm/yr on the northern strand of the fault near Wairau Valley (Zachariasen *et al*. 2006). This is consistent with previously determined average Holocene strike-slip rates of 3-5 mm/yr for the Wairau Fault. Given these rates, the elapsed time since the last event indicates that c. 5.5-11.5 m of elastic shear strain has accumulated on the Wairau Fault. This is of the same order as the best estimates of 5-7 m for single-event displacements. These data are consistent with the best estimates of single-event displacement determined from previous studies (e.g. Lensen 1976; Grapes & Wellman 1986; Knuepfer 1992). These results will be reviewed more critically in light of the new results from Branch River, described from Stop 5.

Stop 5 Branch River Displaced river terraces

This is a classic site on the Wairau Fault which has been studied in detail by Lensen (1968, 1976). The fault displaces a flight of degradation terraces formed by down-cutting of the Branch River (Figs. 1.21 & 1.22). Optically Stimulated Luminescence dates from silt at the base of paleochannels on the river degradation terraces indicate that these surfaces may have formed from about 18 to 7 ka (OSL samples collected by Nicol & Van Dissen and dated by the VUW lab, unpublished data). The fault has a sharp trace along which terrace risers and channels are displaced by up to 60 m right-lateral strike-slip and 1-2 m dip slip (down to the north). At this location a slip rate on the fault of 3.2±0.6 mm/yr averaged since formation of the highest degradation terrace at ~18 ka is consistent with previous estimates along the fault including Branch River (Lensen 1976; Knuepfer 1988, 1992; Zachariasen *et al*. 2006).

Figure 1.21 Aerial photographs looking east (A) and west (B) along the Wairau Fault at the Branch River site. Photographs by DL Homer.

At the Branch River site, strike-slip displacement of 15 reference lines were remeasured during this study and provide information on the number and single event displacement of surface-rupturing paleoearthquakes between 7 and 18 ka. These strike slip displacements where measured from a Digital Elevation Model (DEM) of the Branch River site generated using RTK GPS data with an estimated accuracy ≤ ±5 cm (Figs. 1.22 & 1.23). Each displacement was also estimated in the field using a tape measure. Maximum, minimum and preferred displacements were recorded for each displaced landform using both techniques. The resulting uncertainties on the displacement range from ±3.5 to 20% (mean 7%) of the preferred value, depending on the sharpness of the displaced feature, and the distance over which it was projected up to the fault plane.

Displacement of terrace risers and channels increases with terrace altitude and are consistent with the view that strike-slip displacements progressively increase with terrace age. Strike-slip displacements at the Branch River site range from 28±1 m to 57±4 m. To constrain the paleoearthquake history all displacements from this location have been plotted as filled black circles in ascending order of size (Fig. 1.24A). These displacements have been augmented by additional measurements (open circles) from up to 5 km east of the Branch site (Lensen 1976; Van Dissen & Nicol unpublished data 2011). Displacement data from 18-20 km west of Branch River on Rainbow Station have been used to construct Fig. 1.24B. For both figures, steps in the plots are inferred to reflect displacement that accrued in surface-rupturing paleoearthquakes. The stepped red lines in each plot represent the minimum number of paleoearthquakes (marked by the vertical segments of the line) required to account for the available measurements. On Fig. 1.24A the light blue stepped line incorporates the displacement observations from Rainbow Station and is our preferred model for the accumulation of slip during paleoearthquakes in the Branch River area. For this model, seven surface-rupturing earthquakes occurred on the fault since 18 ka, with single event displacements ranging from 5 to 11.5 m (average of ~8 m) and an average recurrence interval of ~2500 yrs (comparable to the 2500 yrs calculated for mean slip of 8 m and a slip rate of 3.2 mm/yr). Our range of single event displacements and average recurrence intervals are larger than the 5-7 m and 500-900 yrs, respectively, of Lensen (1976). An average recurrence interval of ~2500 yrs is, however, similar to the published estimates of 1000-2300 yrs and ~2200 yrs of Berryman *et al*. (1992) and Barnes & Pondard (2010), respectively.

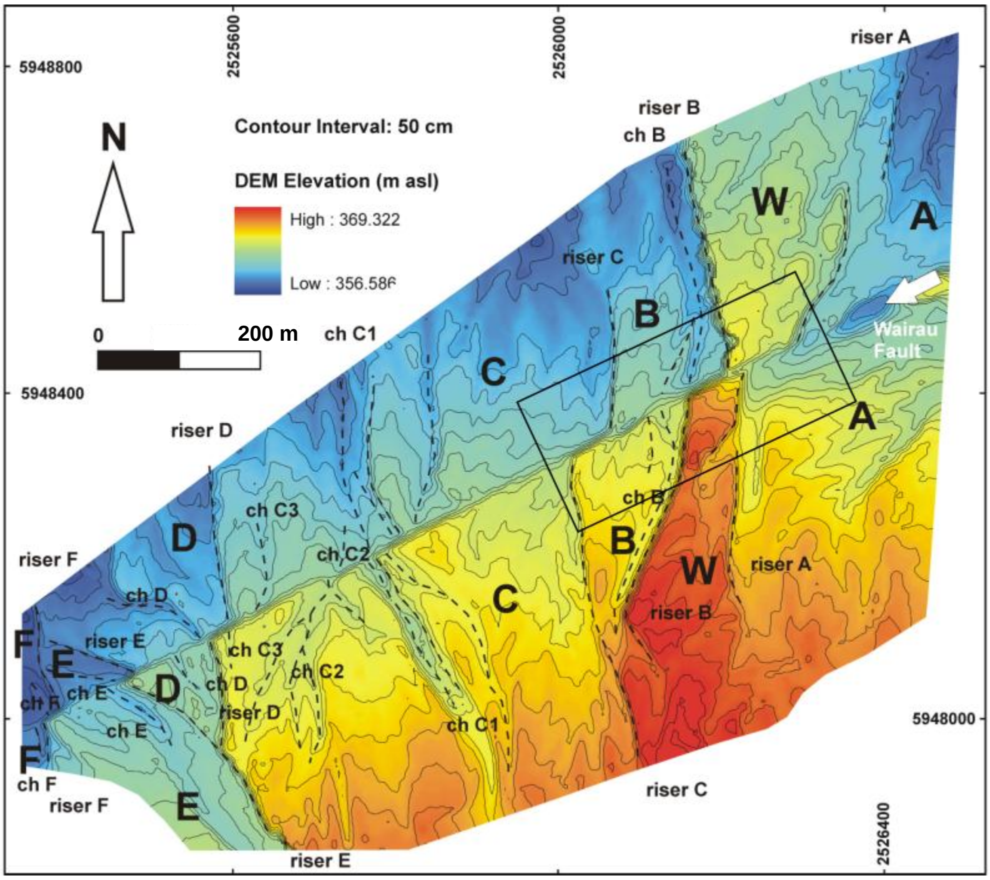

Figure 1.22 Digital Elevation Model (DEM) of the Branch River Wairau Fault site. DEM generated using RTK GPS surveying. Terrace surfaces are labelled A (highest) to F (lowest).The locations of channels (ch) and terrace risers (riser A-F) showing right lateral displacements are shown and marked by thick dashed lines. Rectangle marked by black solid line shows location of Fig. 1.23.

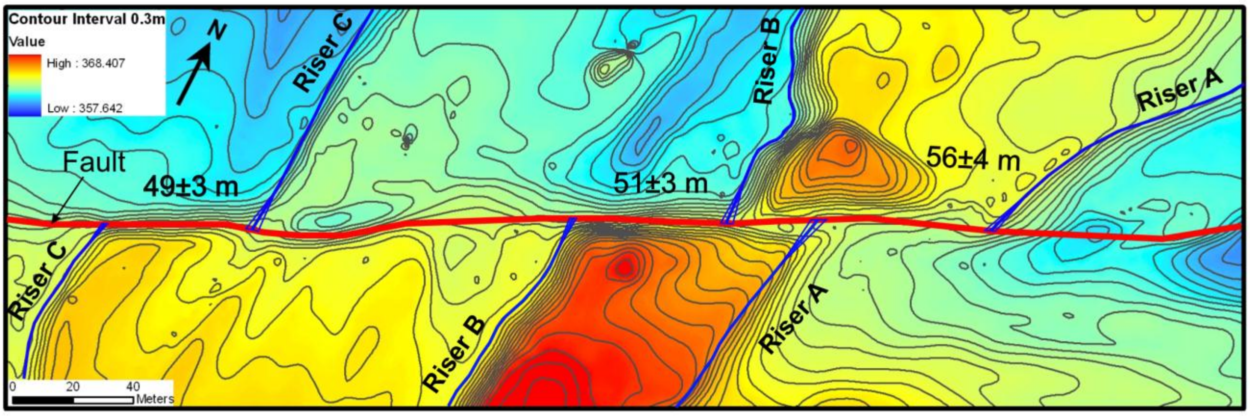

Figure 1.23 Detailed map of displaced terrace risers at the eastern end of the Branch River site. Triangular zones at the ends of risers indicate the uncertainty in their locations at the fault. See rectangular outline in Fig. 1.22 for location.

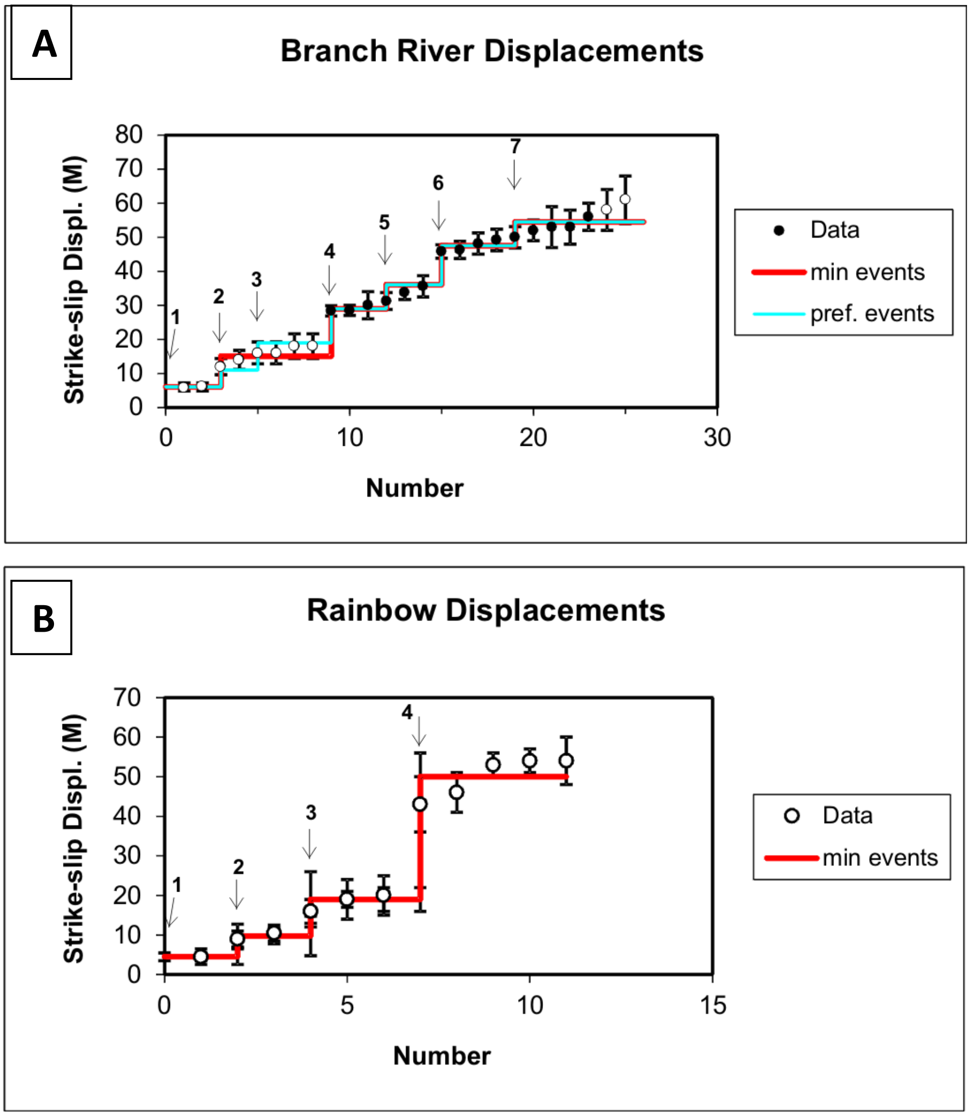

Figure 1.24 Displacement plots for Branch River (A) and Rainbow Station (B). At Branch River displacements measured from the area in Fig. 1.22 are indicated by the black filled circles, while the unfilled circles at displacements <20 m are from Lensen (1976) and >55m from Van Dissen & Nicol (unpublished data 2011).

We have used single-event displacements (this study) and individual inter-event times from multiple sources (Zachariasen *et al*. 2006; Barnes & Pondard 2010; Van Dissen & Nicol unpublished data 2011) to examine their variability since ~18 ka. The available data have been analysed by generating frequency histograms for earthquake slip and inter-event times (Fig. 1.25). These histograms were produced for the Wairau Fault by constructing Probability Density Functions (PDF) for the entire population of recurrence and slip measurements on the fault. The PDFs incorporate the variability between, and the uncertainty of, individual measurements. The histograms were produced by randomly drawing 1000 values from the PDFs for slip and recurrence interval. In this analysis, inter-event times between Wairau Fault surface ruptures range from <500 years to >5000 years and are approximately log normal, while single-event slip mainly ranges from 3 to 13 m and is approximately normally distributed. These data support the view that both recurrence interval and single-event slip vary on individual faults. Recurrence interval appears to show the greatest variability with a modal, or most common, recurrence interval of about 1000 years and a long tail on the distribution stretching out to >5000 years. Lastly, Fig. 1.25 (lower graph) provides insights into the likelihood of earthquakes on the fault in the near future (e.g., next 500 years) given the elapsed time since the last earthquake on the fault (~2000 yrs). Based on the recurrence histogram for values of ≥2000 years the chances of large magnitude surface-rupturing earthquake on the Wairau Fault over the next 500 years will be higher than subsequent 500 year time intervals.

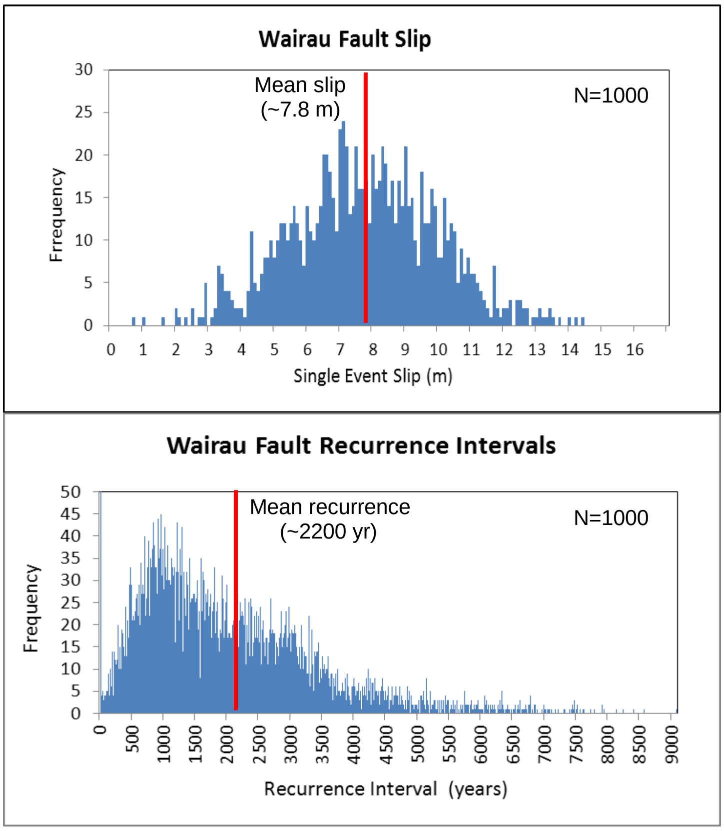

Figure 1.25 Frequency histograms for single-event slip (top) and inter-event times (bottom) of surface-rupturing paleoearthquakes on the Wairau Fault. Histograms were generated by randomly drawing 1000 values from Probability Density Functions derived from the original paleoearthquake data. The histograms take acount of the measurements and their uncertainties.The shapes of the histograms are broadly consistent with synthetic seismicity populations and suggest that for surface-rupturing earthquakes single-event displacements and inter-event times could vary by up to a factor of four, and in excess of an order of magnitude, respectively.

Stop 6 Top House Rd Displaced Moraines

In the St Arnaud area (Figs. 1.1, 1.26 & 1.27) the Wairau Fault displaces terminal moraines and outwash surfaces formed by glaciers which advanced northwards down the main valleys in Nelson Lakes National Park (Adamson 1964; Suggate 1965; Johnston 1990; Campbell 1992; Barrell 2011). These glacial deposits are offset by strike-slip displacements of 46 m to 10 km along the Wairau Fault (Campbell 1992). Displacements of 100s of metres to kilometres support the view that some of the glacial deposits are significantly older than the degradation terraces at Branch River. Although these glacial deposits have not been directly dated, their ages have been inferred from paleoclimate curves and could be up to million years (Adamson 1964; Suggate 1965; Campbell 1992).

Figure 1.26 Vertical aerial photograph (Google Earth 2011) of the displaced Birchdale moraine at Tophouse Saddle.

Of the displaced terminal moraines, the late Pleistocene Birchdale moraine at Tophouse Saddle is the most accessible (Fig. 1.26). The moraine appears to have been constructed by the eastern lobe of a glacier that occupied the Travers Valley and Lake Rotoiti to the west. The moraine forms the saddle and is displaced in a strike-slip sense by the Wairau Fault which is located immediately southeast of State Highway 63 (Fig. 1.26). Topographic profiles parallel to the fault and normal to the moraine ridge indicate 277±11 m horizontal and 28±3.5 m vertical displacement of the moraine by the fault (Fig. 1.27). These measurements by Campbell (1992) are consistent with displacements of 275±10 m and 22±5 m estimated using hand-held GPS to map the western edge of the moraine on both sides of the fault (Van Dissen & Nicol unpublished data 2011).

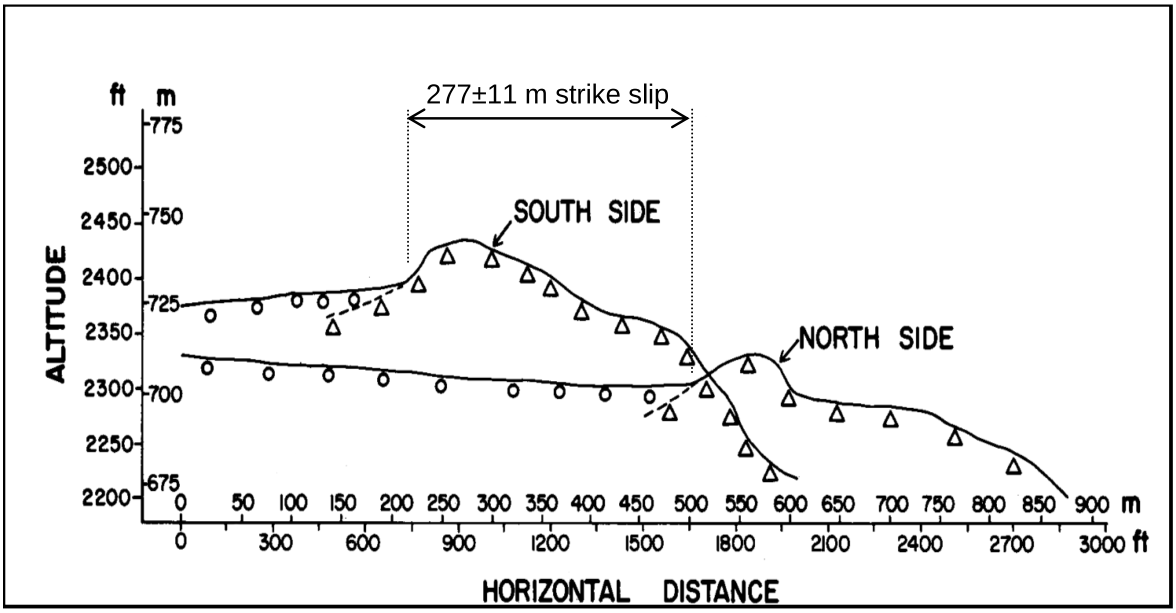

Figure 1.27 Topographic profiles across the Birchdale moraine north and south of the Wairau Fault trace at Tophouse Saddle (Campbell 1992).

The age of the Birchdale moraine has been inferred to be 35-40 ka (Suggate 1965) or 50-72 ka (Campbell 1973, 1992) based on correlations of the timing of moraine formation to different glacial periods in the global paleoclimate curve. For these two age estimates and a strike-slip displacement of 275±10 m the average displacement rates since formation of the Birchdale moraine are 7.4±0.8 mm/yr and 4.7±1 mm/yr. Strike-slip displacement of the Rotoiti and Black Valley glacial deposits near St Arnaud (Campbell 1973, 1992) together with data from Branch River (Fig. 1.24) suggest that the average displacement rates over the last ~18 kyr were ~3-4 mm/yr. Therefore, the younger of the two age estimates would require that displacement rates accelerated by a factor of three to four (i.e. 3 to 10-13 mm/yr) prior to 18 ka. Alternatively, the second age produces displacement rates of 3.7-5.7 mm/yr and, given the uncertainties, could be consistent with a constant displacement rate model. Discriminating between the alternative dates for the Birchdale moraine is critical for determining how displacement rates on the fault have evolved over the last 100 ka and has implications for plate boundary development in the northern South Island. Slowing of displacement rates on the Wairau Fault approaching the present (as is suggested by the younger age estimate), for example, provides support for a model in which displacement on the Wairau Fault has been transferred onto the more southerly faults in the MFS (Campbell 1973).

To constrain better the age of the Birchdale moraine we have submitted a sample from a silt bed, which rests directly on moraine deposits, for Optically Stimulated Luminescence dating. This date will provide a minimum age for the moraine and may assist in determining the true age of the moraine.

References

Adams, J. 1981. Earthquake-dammed lakes in New Zealand. *Geology* 9: 215-219.

Adamson, J.K. 1964. The Alpine-Wairau Fault System in the Lake Rotoiti area. Unpublished MSc (Hons) thesis, University of Canterbury, New Zealand.

Anderton, P.W. 1981. Structure and evolution of the South Wanganui Basin, New Zealand. *New Zealand Journal of Geology and Geophysics* 24: 39-63.

Barnes, P.M., Pondard, N. 2010. Derivation of direct on-fault submarine paleoearthquake records from high-resolution seismic reflection profiles: Wairau Fault, New Zealand. *Geochemistry, Geophysics, Geosystems* 11: Q11013, doi:10.1029/2010GC003254.

Barrell, D.J.A. 2011. Quaternary glaciers of New Zealand. In J. Ehlers, P.L. Gibbard, and P.D. Hughes (editors), *Developments in Quaternary Science* 15: 1047-1064, doi: 10.1016/B978-0-444-53447-7.00075-1.

Begg, J.G., Johnston, M.R. 2000. Geology of the Wellington area. Geological Map 10, 1:250 000. Lower Hurt, New Zealand, Institute of Geological & Nuclear Sciences.

Berryman, K.R., Beanland, S., Cooper, A.F., Cutten, H.N., Norris, R.J., Wood, P.R. 1992. The Alpine Fault, New Zealand: variation in Quaternary structural style and geomorphic expression. *Annales Tectonicae VI* (Special Issue, Supplement): 126-163.

Campbell, I.B., Johnston, M.R. 1992. Nelson and Marlborough. In: Soons JM, Selby MJ. ed. Landforms of New Zealand. 2nd edition Auckland, Longman Paul. p. 424-438.

Campbell, J.K. 1973. Displacement data from the Alpine Fault at Lake Rotoiti and its relevance to glacial chronology and the tempo of tectonism. IXth Congress INQUA [International Union for Quaternary Research] Abstracts: 57-58.

Campbell, J.K. 1992. The Wairau and Alpine faults – structure and tectonics of the S-bend junction. In: Campbell, J.K. (ed.) Field trip guides: joint annual conference of New Zealand Geophysical Society and Geological Society of New Zealand, Christchurch. Geological Society of New Zealand Miscellaneous publication 63B: 10-30.

Cotton, C.A. 1913. The Tuamarina Valley: a note on the Quaternary history of the Marlborough Sounds district. *Transactions and Proceedings of the New Zealand Institute* 45: 316–322.

Cotton, C.A. 1969. Skeleton islands of New Zealand and elsewhere. *Earth Science Journal* (Waikato Geological Society) 3: 61-76.

Dowrick, D.J., Rhoades, D.A. 1999. Attenuation of Modified Mercalli Intensity in New Zealand earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering* 32(2): 55-89.

Fougere, S.R. 2002. Paleoseismicity and active deformation, Lake Rotoiti to west Wairau Valley section of the Alpine Fault. Unpublished MSc thesis, University of Canterbury, New Zealand.

Gibb, J.G. 1979. Late Quaternary shoreline movements in New Zealand. Unpublished PhD thesis, Victoria University of Wellington, New Zealand.

Grapes, R.H., Wellman, H.W. 1986. The north-east end of the Wairau Fault, Marlborough, New Zealand. *Journal of the Royal Society of New Zealand* 16: 245-250.

Johnston, M.R. 1994. Geology of the Richmond Range. Scale 1:50,000. *Institute of Geological and Nuclear Sciences geological map 12*. Institute of Geological and Nuclear Sciences Ltd., Lower Hutt, New Zealand.

Kerr, J., Nathan, S., Van Dissen, R., Webb, P., Brunsdon, D., King, A., 2003. Planning for Development of Land on or Close to Active Faults: A guideline to assist resource management planners in New Zealand GNS Client Report 2002/124.

Knuepfer, P.L.K. 1988. Estimating ages of late Quaternary stream terraces from analysis of weathering rinds and soils. *Geological Society of America Bulletin* 100(8): 1224-1236.

Knuepfer, P.L.K. 1992. Temporal variations in latest Quaternary slip across the Australian-Pacific Plate boundary, northeastern South Island, New Zealand. *Tectonics* 11(3): 449-464.

Lamarche, G., Proust, J-N., Nodder, S.D. 2005. Long-term slip rates and fault interactions under low contractional strains, Wanganui Basin, New Zealand. *Tectonics* 24: TC4004, doi:10.1029/2004TC001699.

Lensen, G.J. 1968. Analysis of progressive fault displacement during downcutting at the Branch River terraces, South Island, New Zealand. *Geological Society of America Bulletin* 79: 545-556.

Lensen, G.J. 1976. Late Quaternary tectonic map of New Zealand, Hillersden & Renwick sheets. Wellington, New Zealand, Department of Scientific and Industrial Research.

Meredyth-Young, J.L., Pullan, S.G. 1977. Fisheries survey of Lake Chalice, Marlborough acclimatisation district, South Island: New Zealand Ministry of Agriculture and Fisheries, Fisheries Technical Report 150.

Nicol, A., Campbell, J.K. 1990. Late Cenozoic thrust tectonics, Picton, New Zealand. *New Zealand Journal of Geology and Geophysics* 33: 485-494.

Nicol, A. 2011. Landscape history of the Marlborough Sounds, New Zealand. *New Zealand Journal Geology Geophysics* 54(2): 195-208.

Pondard, N., Barnes, P.M. 2010. Structure and paleoearthquake records of active submarine faults, Cook Strait, New Zealand: Implications for fault interactions, stress loading, and seismic hazard. Journal of Geophysical Research 115 (B12320): doi:10.1029/2010JB007781.

Proust, J-N., Lamarche, G., Nodder, S., Kamp, P.J.J. 2005. Sedimentary architecture of a Plio-Pleistocene proto-back-arc basin: Wanganui Basin, New Zealand. *Sedimentary Geology* 181: 107-145.

Rattenbury, M.S., Cooper, R.A., Johnston, M.R. (compilers) 1998. Geology of the Nelson area. Geological Map 9,1:250 000. Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences. 67p.

Rattenbury, M.S., Townsend, D.B., Johnston, M.R. (compilers), 2006. Geology of the Kaikoura area. Institute of Geological & Nuclear Sciences 1:250,000 Geological Map 13. GNS Science, Lower Hutt, New Zealand.

Singh, L.J. 2001. Late Quaternary sea level and tectonic history of Marlborough Sounds. Unpublished PhD thesis, Victoria University of Wellington, New Zealand.

Suggate, R.P. 1965. Late Pleistocene geology of the northern part of the South Island. New Zealand. *New Zealand Geological Survey Bulletin* 77.

Suggate, R.P. 1988. Quaternary deposition and deformation in the Buller and tributary valleys. *New Zealand Geological Survey Record* 25: 51 p.

Van Dissen, R., Barnes, P., Beavan, J., Cousins, J., Dellow, G., Francois-Holden, C., Fry, B., Langridge, R., Litchfield, N., Little, T., McVerry, G., Ninis, D., Rhoades, D., Robinson, R., Saunders, W., Villamor, P., Wilson, K., Barker, P., Berryman, K., Benites, R., Brackley, H., Bradley, B., Carne, R., Cochran, U., Hemphill-Haley, M., King, A., Lamarche, G., Palmer, N., Perrin, N., Pondard, N., Rattenbury, M., Read, S., Semmens, S., Smith, E., Stephenson, W., Wallace, L., Webb, T., Zhao, J. 2010, It's Our Fault: better defining earthquake risk in Wellington. *in proceedings,* 11th IAEG Congress, Auckland, New Zealand, 5-10 September, 2010: 737-746.

Van Dissen, R., Yeats, R. S. 1991. Hope fault, Jordan thrust, and uplift of the Seaward Kaikoura Range, New Zealand. *Geology* 19: 393-396.

Wellman, H.W. 1953. Data for the study of Recent and late Pleistocene faulting in the South Island of New Zealand. *New Zealand Journal of Science and Technology* 34B: 270-288.

Yetton, M. 2003. Paleoseismic trench investigation of the active trace of the Wairau section of the Apline Fault, Renwick Area, Marlborough District. Consultancy report prepared for Marlborough District Council (reference: 1490).

Zachariasen, J., Berryman, K.R., Langridge, R.M., Prentice, C., Rymer, M., Stirling, M., Villamor, P. 2006. Timing of late Holocene surface rupture of the Wairau Fault, Marlborough, New Zealand. *New Zealand Journal of Geology and Geophysics* 49: 159–174, doi:10.1080/00288306.2006.9515156.

Zhang, J.J., Langridge, R.M., Cousins, W.J. 2004. Assessment of seismic and fault hazards at Bankhouse, Marlborough. GNS Confidential Client Report 2004/127.