S&G 3706 – Recent rupture of the Tararua section of the Wellington Fault and relationships to other fault sections and rupture segments (97/248)

- Kelvin Berryman, Russ Van Dissen, Vasiliki Mouslopoulou, GNS (May 2002)

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Earthquake Commission Research 97/248

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Executive Summary

We present the results of an investigation into the fault rupture history of the section of the Wellington Fault that is located within the Tararua Ranges. To do this we also need to consider data on the Wellington Fault from both south and north of the ranges. The southernmost 75 km-long part of the fault, from offshore in Cook Strait to the c. 2 km-wide right side-step at Kaitoke at the southern end of the Tararua Ranges, has been interpreted to represent a rupture segment of the fault, the *Wellington-Hutt Valley segment*. Based on geographic location, and the structural position of the fault within the mountains, the next part of the fault has been called the Tararua section, extending 55 km from Kaitoke to Putara. To the north of Putara, the fault is again a range-front feature, and the Pahiatua section of the fault extends northeast to Woodville. This section is 45 km long. We use the terms segment and section with the intention of differentiating between parts of the fault that are inferred to represent past (and therefore possible future) surface ruptures (earthquake sources), from purely geographic parts that possibly have no correlation to fault rupture segments.

In this study we compiled existing published and unpublished information on the location and geology of the recent trace of the Wellington Fault in the Tararua Ranges, and used aerial photographs to locate potential sites for detailed field studies. We completed field inspections of potential sites, investigating natural exposures, and obtained several samples for radiocarbon dating from sites in the Tararua Ranges. We also compiled data obtained from seven fault trenches excavated in the early 1990's along the Pahiatua section of the Wellington Fault immediately northeast of the Tararua section, to compare with the data available from the Tararua section, and further south, with the Wellington-Hutt Valley segment.

The Wellington fault has a major impact on the physiography of the Tararua Ranges, including the formation of dextrally (right-lateral) deflected sections of the main rivers flowing from the east side of the Tararua Range, and intervening low saddles. The consistent dextral deflection of the river courses along the fault is suggestive of dextral displacement. A reconstruction with 7±1 km of dextral motion brings many rivers and streams into alignment. At current rates of dextral movement of 6-7.6 mm/yr the present-day strike-slip nature of the Wellington Fault may be no older than 0.8-1.3 million years.

We obtained four radiocarbon ages from organic debris trapped within a hillside fissure located upslope of the Wellington Fault adjacent to the walking track leading to Powell Hut. Such hillside fissures are very common throughout the Tararua Ranges and elsewhere in mountain areas in New Zealand. They are usually inferred to be formed during earthquakes by gravitational collapse of ridge crests under high seismic shaking intensity. The results of radiocarbon dating of the deposits from this particular hillside fissure extend back to at least 2000 years before present.

At Totara Flats, along the Waiohine River there are natural exposures and field relationships that indicate these terrace flats owe their existence to a relatively recent aggradation event that buried a substantial forest. We dated two trees that have been buried by, and presumably killed by, the coarse alluvial gravel that comprise the deposits of this aggradation event. The aggradation event along the Waiohine River occurred at 1650-1450AD, in the same age range as the best estimate for the timing of the most recent surface rupture of the Wellington-Hutt Valley segment of the Wellington fault (1640-1440AD). This suggests to us that aggradation in the Waiohine was probably linked with rupture of the Wellington fault in the Wellington area. Whether the aggradation was initiated by earthquake shaking generated by rupture of only the Wellington-Hutt Valley segment of the fault, or was related to rupture that also extended along the Tararua section as well, cannot, unfortunately, be determined from information available from the Tararua Ranges. The distance from Kaitoke, at the northern end of the Wellington-Hutt Valley segment, to Totara Flats is less than 25 km, which is well within the range where earthquake shaking would still be expected to be strong enough to cause extensive landsliding and consequent river aggradation. The ages we have obtained do not coincide with the 1855 rupture of the Wairarapa Fault.

Along the Pahiatua section of the fault, between Putara and Manawatu Gorge, two trenches (Bennett and Hughes 2) were excavated with the intent of obtaining data for slip rate calculations. The remaining five trenches were primarily excavated to investigate the recent rupture history of this section of fault. Two trenches (Death 1 & 2) were located about 6 km from the southwest end of the Pahiatua section near the geometric "boundary" with the Tararua section, and the remaining three were located 16-20 km to the northeast. Most trenches were located at or adjacent to sites where the dextral displacement of topography was known and often where the scarp was upthrown to the southeast, thus tending to pond the southeast flowing drainage. Throughout this section of fault, the single event dextral displacement is about 4±1 m.

In summary, the data obtained from the Death trenches are;

- There has been no faulting here since at least 1260 AD and possibly since 1020 AD.
- The most recent faulting event (MFE) is identified as a young ponding event in Death trench 1 and faulting of the PFE unit in Death trench 2. The time of this event is best estimated at 1260-1020AD.
- The penultimate faulting event (PFE) is interpreted to have in the interval 700-600AD.

The Hughes and Ebbett trenches reveal data to constrain the following timing of past surface rupture events;

- The best estimate for the timing of the most recent faulting event (MFE) is 1860-1670AD.
- The penultimate faulting event (PFE) was probably at or about 1160-890AD, although another sample also interpreted to have experienced the PFE has an age of 990-690AD, and the use of this second date suggests a more refined estimate of the PFE in the range 990-890AD.

- The 3rd most recent event in the area occurred at c. 150-400BC (Hughes trench data).
- The 4th event is well constrained in Ebbett trench 1 by two samples at 1960-2560BC, and in the Hughes trenches by three samples from in-situ leaves and twigs at 1880-2130BC. These two age ranges overlap for the period 1960-2130BC, and this is our best estimate for the timing of the 4th event.
- An older event, almost certainly not in consecutive order from the 4th event above, is inferred at c. 8560-9220 BC.

Thus, the timing of the MFE and PFE at the Death trench sites at the southwest end of the Pahiatua section do not appear to be the same as at the Hughes/Ebbett sites. If the MFE event at the southwest end of the Pahiatua section did not extend northeast as far as the Ebbett and Hughes trenches c. 20 km away, then it seems likely that the MFE at the Death trench site must have ruptured into or from the Tararua section of the fault in order to attain a rupture length consistent with a single-event displacement of 4±1 m. If that rupture were indeed 60 km or more long this would include the whole length of the Tararua section, and this would imply the last rupture of the fault in the Waiohine Valley was at 1260-1020AD (the best estimate for the MFE timing at Death site). Consequently, we suggest that the c. 1650-1450AD aggradation episode observed in the Waiohine Valley was related to shaking from the more distant rupture of the Wellington-Hutt Valley segment, which did not extend into the Tararua Ranges. To explain the difference in fault rupture timing between the Death and Hughes/Ebbett sites we propose that at least a partial or "soft" rupture segment boundary exists somewhere between the trench sites, and, as a consequence, the chronology of faulting at the Death trench sites may at least partially characterise the rupture history of the Tararua section of the Wellington Fault.

Thus, we infer that for the past two rupture cycles on the Wellington Fault in southern North Island three rupture segments have existed. The northern rupture segment includes the Hughes and Ebbett sites, that is part of the Pahiatua section that has ruptured twice since 890AD. The distance from the proposed segment boundary between the Death and Hughes/Ebbett sites to Woodville at the northern end of the Pahiatua section of the fault is only about 30 km, so we expect that this rupture segment extends perhaps an equal distance further north. We tentatively name this the *Woodville segment* after the name of the major town near the fault. The southern 10 km or so of the Pahiatua section has probably ruptured with most or all of the Tararua section twice since c. 700AD, and we tentatively name this *the Tararua-Putara segment*, for evident geographical descriptive reasons. In this interpretation we infer that the *Wellington-Hutt Valley segment* has been the rupture segment for the past two events in the south at 1640-1440AD, and about 1290-940AD.

We also make some estimate of both the short term (c. 4000 years) dextral slip rate and size of average amount of dextral faulting per event from the Hughes and Ebbett trenches. From the Bennett trench we obtained an average dextral slip rate over the past c. 8,500 years of 4.6-7.2 mm/yr. At Ebbett trench 1 we interpret a dextral slip rate of 3.6–4.9 mm/yr, somewhat lower than calculated from the Bennett site. The paleoseismic analysis reveals four surface rupture events in the past c. 4000 yrs, suggesting an average recurrence interval for surface rupture in the vicinity of the Ebbett and Hughes trench sites of about 800-1000 yrs.

Based on the similar single event dextral displacement and suggested rupture length for each of the fault segments we expect that the estimate of earthquake magnitude proposed for the Wellington-Hutt Valley segment of M_w 7.4-7.8 by Van Dissen & Berryman (1996) may also be appropriate for the Tararua-Putara segment and the Woodville segment. We do not make more specific calculations for these latter two segments because the part of the Tararua-Putara segment in the ranges appears to be more reverse in character than the 10 km-long northern part, and we do not know the northern limit of the proposed Woodville segment yet.

Because the rupture history for the last cycle involving the three southern segments of the Wellington Fault appears to different in each segment, this suggests that temporally clustered activity or increased static stresses near the ends of strike-slip rupture has not resulted in triggered slip on adjacent segments. However, the MFE on the Tararua-Putara segment overlaps with the PFE on the Wellington-Hutt Valley and Woodville segments and the possibility exists that this may have been a much longer single rupture (implying larger earthquake magnitude) or that coulomb stress triggering may have played a role in a possible cascade of linked events. Based on the elapsed time since the last event compared with average recurrence interval we conclude that the Wellington-Hutt Valley segment of the fault is not "overdue" for rupture as is commonly reported but is "within the window" if the observed factor of two to three variation about the mean recurrence is a useful criteria for the probability estimate of rupture. The Tararua-Putara segment apparently has not ruptured for at least c. 1100 years, and although an average recurrence interval has not been obtained for this segment, it is unlikely to be much different to the segments north and south. The prior interval on the Tararua-Putara segment was apparently only one-third to one-half of the present elapsed time, so we suggest that, of the three fault rupture segments discussed in this report, this is the segment that is the most "likely" to rupture in the future.

Technical Abstract

The slightly arcuate, concave to the SE, southern-most 75 km long section of the Wellington Fault was identified ten years ago as the *Wellington-Hutt Valley segment (W-HV)*. Here, we tentatively define the next two rupture segments to the north, based on dated natural exposures along the slightly arcuate, concave to the NW, Tararua section of the Wellington Fault, and seven trench exposures on the relatively straight Pahiatua section further to the north.

At Totara Flats, along the Tararua section of the fault, a young aggradation event that inundated and killed a forest is dated at 1650-1450 AD. This is in the same age range as the best-estimate timing for the most recent rupture of the *W-HV,* and suggests that aggradation at Totara Flats was probably directly linked with rupture of the *W-HV.*

Along the Pahiatua section, the timing of ruptures recorded in two adjacent trenches located 6 km north of the Tararua Range is different from the rupture timing derived from the remaining five trenches located a further 16-20 km to the NE. Because single event dextral displacement along the Pahiatua section of the fault is consistently recognized to be about 4±1 m, we expect such displacement to correspond to rupture lengths in excess of many tens-of-kilometres. Therefore, we conclude that the trench sites on the southern part of the Pahiatua section, that exhibit a different rupture history to those nearer the Manawatu Gorge, must rupture with the Tararua section of the fault in order to attain a rupture length consistent with single-event displacement size. We refer to this segment as the *Tararua-Putara rupture segment (T-P)*. The remaining part of the Pahiatua section, extending northeast to at least the Manawatu Gorge, is interpreted to belong to a different rupture segment which we refer to as the *Woodville segment (W)*.

Average dextral slip rate estimates for the *W-HV segment* and the *W segment* are 6-7.6 mm/yr and 4.6-7.2 mm/yr, respectively. Single event dextral displacement is c. 4±1 m for both *W-HV* and *W*, and also for the northern part of *T-P* that is north of the Tararua Range. From these data, indicative average recurrence intervals for the *W-HV* and the *W* of c. 600 yrs and c. 800-1000 yrs, respectively, are obtained. Indicative elapsed time since the most recent rupture on each of the three segments is 400, 1150, and 250 yrs for *W-HV*, *T-P*, and *W,* respectively. Of the three segments of the Wellington Fault discussed in this report, the Tararua-Putara segment is the most "likely" to rupture in the future, with the elapsed time at or probably exceeding the average recurrence interval. Earthquakes of approximately M_w 7.4-7.8 are expected on each of the segments based on the above rupture parameters, or larger, if two or more segment were to rupture together.

In the most recent cycle of events none of the fault rupture events so far identified on the Wellington Fault overlap in time with adjacent segments, indicating that rupture has not extended onto adjacent segments, and has not given rise to stress-triggered, along-strike, segment failure. However the most recent surface rupture on *T-P* overlaps in time with the

penultimate surface rupture on *W-HV* to the south and *W* to the north. Therefore, the possibility exists that this may have been a much longer single rupture (implying larger earthquake magnitude) or that coulomb stress triggering may have played a role in a possible cascade of linked events in prior cycles.

1.0 Introduction

The Wellington Fault (and its continuation north of the Manawatu Gorge as the Mohaka, and Whakatane faults) can be followed as a structural feature from about 20 km south of the Wellington south coast (Carter et al. 1988) northeastward through Wellington City and the Hutt Valley to the Tararua Range and beyond (Figure 1). It is a major structural feature of the North Island, throughout most of which it has a dominantly dextral sense of movement (Berryman & Beanland 1988). In the southern North Island, the ratio of horizontal to vertical slip exceeds 10:1 (Ota et al. 1981; Berryman 1990). With respect to this project, three parts of the fault in southern North Island are pertinent. The southern-most, 75 km long part, from offshore in Cook Strait to the c. 2 km-wide right side-step at Kaitoke has been interpreted (Berryman, 1990; Van Dissen & Berryman, 1996) to represent a rupture segment of the fault, the *Wellington-Hutt Valley segment (W-HV)*. Based on geographic location, and the structural position of the fault within the mountains, the next part of the fault has been called the Tararua section, extending 55 km from Kaitoke to Putara. To the north of Putara the fault is again a rangefront feature, and the Pahiatua section of the fault extends northeast, at least to Woodville. This section is 45 km long. We use the terms segment and section with the intention of differentiating between parts of the fault that are inferred to represent past (and therefore possible future) individual surface ruptures, from purely geographic parts that possibly have no correlation to fault rupture segments.

While the southern section of the Wellington Fault, in the Hutt Valley and Wellington peninsula have been the subject of geological research for a long period, and provided the examples for classic geological papers by Cotton (e.g. 1912), the Tararua section has received little attention (Figure 1). The only published paper on the Wellington Fault within the Tararua Ranges is Lensen (1958), which was based on a photo-geological study supplemented by only 5 days of fieldwork (Grindley, 1956). The compilation of geological data for the 1:250,000 scale map (Kingma, 1967) contained very few data from within the ranges. The Tararua section of the Wellington Fault has also been recently mapped as part of the regional compilation of Wellington geology (Begg & Johnston, 2000), and data from that work have been incorporated in this study.

Recent published work on the Wellington-Hutt Valley segment of the fault includes Berryman (1990), Van Dissen et al (1992), and Van Dissen & Berryman (1996). These studies have concluded that the long term average slip rate is 6-7.6 mm/yr (see also section 4.4 for discussion of Pahiatua section slip rate) and the most recent rupture of that section of the fault was about 1640-1440AD, with a prior event about 1290-940AD. At a few sites along this section of the fault, such as near Te Marua and Long Gully (south of Wellington City) the size of the displacement in individual surface rupture events has been observed to be in the range of 3.8-4.6 m. This single event displacement size is on the high side of the range of what empirical relationships of rupture length and displacement (e.g. Wells & Coppersmith, 1994) would suggest for the 75 km long Wellington-Hutt Valley segment (Figure 1). Therefore, although the right-step in the fault at Kaitoke has been argued to represent a segment boundary on the fault (Berryman, 1990), the data are not so robust as to rule out the possible co-rupture of all or part of the fault extending into the Tararua Ranges. If rupture could extend through the apparent segment boundary at Kaitoke then the magnitude of the earthquake associated with that rupture may have been underestimated in the past.

To the northeast of the Tararua Ranges, some preliminary interpretation of fault trench data from the Wellington Fault have been reported by Beanland & Berryman (1991), and Beanland (1995). We present and analyse that information more fully in this report.

2.0 Objectives of the Study

Rupture of the Wellington-Hutt Valley segment of the Wellington Fault (Berryman, 1990; Van Dissen et al., 1992) is the usual scenario for insurance industry Probable Maximum Loss (PML) earthquake models for New Zealand. Recent studies by Van Dissen & Berryman (1996), Robinson & Benites (1995), and Robinson et al. (1997) have demonstrated, from two points of view, that rupture of one of the upper-plate faults in the Wellington Region has not, and on most occasions will not, result in triggered rupture of an adjacent fault. However, Robinson & Benites have shown in their modelling studies that along-strike triggering of another segment of the same fault is a possibility for the Wellington region faults. Thus, rupture of the Wellington-Hutt Valley segment of the Wellington Fault might be accompanied by, or triggered by, rupture of the along-strike Tararua section of the fault. This scenario would result in different, and more severe PML models.

The principal objective of this project is to compile data on the Tararua section of the Wellington Fault pertaining to its recent movement history, so as to evaluate from field data whether the Tararua section of the fault has ruptured with, or in close temporal association with the Wellington-Hutt Valley segment of the fault. We also wish to compare data from the Tararua section with the Pahiatua section to postulate possible past (and future) rupture scenarios for the whole of the Wellington Fault from the south coast to Woodville.

3.0 Activities

- 3.1 We have compiled existing published and unpublished information on the location and geology of the recent trace of the Wellington Fault in the Tararua Ranges. This project has made use of the recent geological mapping completed by Begg & Johnston (2000) which included delineation of bedrock faults, geological structure, and some active faults.
- 3.2 We used aerial photographs to locate potential sites for detailed field studies. These were generally at locations where river terraces of major tributary streams and rivers cross the fault position at a high angle. At these sites we anticipated that river terraces aligned at a high angle to the fault may record the progressive movement of the fault, in the fashion of faulted terrace sequences described, for example, at Waiohine River and Branch River (Lensen & Vella, 1971; Lensen, 1968).

- 3.3 We have completed field inspections of potential sites, investigating natural exposures, and obtained several samples for radiocarbon dating.
- 3.4 In addition to the stated objectives of the original proposal we have compiled data obtained from seven fault trenches excavated in the early 1990's along the Pahiatua section of the Wellington Fault immediately northeast of the Tararua section, to compare with the scant data available from the Tararua section (Figure 1).
- 3.5 We present here a discussion of the recent rupture history of the Tararua section of the fault in comparison with the Wellington-Hutt Valley segment and Pahiatua section. We assess whether our field data provides any precedent data to assess the synthetic seismicity modelling experiments of Robinson & Benites, and from this evaluate the possibility of multi-segment rupture of the Wellington Fault in a larger earthquake than is usually the basis of a Wellington PML model.

4.0 Results

4.1 Aerial Photograph Interpretation

Sets of aerial photographs taken in the 1940's (scale ~1:16,000) and in the 1960's (scale ~1:50,000) provide good coverage of the Tararua region. These coverages show the Wellington Fault very well as a regional structure. The fault has a major impact on physiography as has been described many times (e.g. Stevens, 1974). The fault typically coincides with northeast-deflected sections of the main rivers flowing from the east side of the Tararua Range, and across intervening low saddles (Figure 2). The consistent dextral deflection of the river courses along the fault is suggestive of dextral displacement. A reconstruction with 7±1 km of dextral motion brings many rivers and streams into alignment (Table 1 & Figure 2). For example, 8 km of dextral motion restores the upper and lower reaches of the Tauherenikau River across the fault. Assuming that the onset of drainage formation within the Tararua Ranges was a consequence of uplift, and that those "markers" were in place at the initiation of the present-day phase of strike-slip motion, then at current rates of dextral movement of 6-7.6 mm/yr the present-day strike-slip nature of the Wellington Fault may be no older than 0.8-1.3 million years.

4.2 Compilation of Existing Data

Although the Tararua Ranges are in close proximity to Wellington and are often visited, the dense forest cover and relative lack of outcrop means that few detailed observations have been made of active faulting the in the area. Lensen (1958) listed a number of places where fault features were observed. These were usually in fault controlled saddles where scarps were preserved on relatively gentle slopes. In a few locations an apparent dextral displacement of ridges and spurs in the range of 60-100 m were documented. Begg & Johnston (2000) mapped the geology in the southern part of the ranges, including active fault traces of the Wellington Fault. They mapped an active trace of the Wellington Fault near the valley floor northeast of Totara Flats Hut, but in our field inspection we interpret the feature to be a terrace riser of the Waiohine River. Near the south end of the Tararua section of the fault a clear fault trace is observed on aerial photographs in the vicinity Smith's Creek, a southern tributary of the Tauherenikau River (Figure 2). Lensen (1958) recorded several dextral offsets in the range of 7-40 m. However this site does not lend itself to detailed investigation of recent rupture history because of steep, potentially unstable slopes where landsliding could modify the apparent fault displacements, and is very close the end of the fault section, and thus, may not be representative of that section of fault.

Table 1 Apparent kilometre-scale dextral river displacements across Tararua section of Wellington Fault

Upstream of Fault	Downstream of Fault	Possible Dextral Offset (km)
Tauherenikau River	Tauherenikau River	8
Waiohine River	Clem Creek	6
Atiwhakatu Stream	Carrington Stream	7
South Mitre Stream	Atiwhakatu Stream	7
Waingawa River	Waingawa River	7.5
Upper Mangatainoka River	Ruamahanga River	8
Upper Ruamahanga	Ruamahanga River	4.5?

Note: Considering that deflection and apparent displacement of rivers can result from a number of different causes, including mis-correlation, diversion, deflection, and tectonic displacement, there is a remarkable consistency in the values reported above. Because of this consistency, we consider that tectonic displacement is the likely predominant cause of mis-alignment, and propose that 7±1 km of dextral displacement has occurred on the Wellington Fault since establishment of the major drainage pattern in the Tararua Ranges.

4.3 Tararua Field Inspections

In the course of this project we have attempted detailed fault inspection in the Waiohine, Atiwhakatu, and Mangatainoka valleys, and on the ridge between the Waiohine and Atiwhakatu valleys. We obtained samples for radiocarbon dating from the Waiohine Valley and from hillside fissures located upslope of the Wellington Fault from near Powell Hut (Figure 2). We discuss these sites in more detail below.

Our inspections generally revealed that the active trace of the Wellington Fault is not located along the valley floors through the Tararua Ranges, where it might be expected to offset fluvial terraces. Instead we found evidence in landslide exposures for the fault to be at the break in slope west of the valleys. In this position, the fault trace(s) have been buried by landslide and scree deposits at the base of slopes, and cross the main valleys at the downstream ends of prominent gorges where no terraces are preserved. Thus, our fundamental premise that recent traces of the fault would displace fluvial terraces has not been found to be correct, and thus the potential to obtain a recent fault history for the Tararua section of the fault by earthquake geology techniques does not exist. The map pattern of the Wellington Fault in the Tararua Ranges also gives some clue to the change in nature of the fault in that the fault strike in the Tararuas is commonly in the range of 025-040°, whereas to the south of the ranges the fault strike is 040-065° (Figure 2). Thus, within the ranges an increased reverse component of motion is not unexpected. The high peaks of the Tararua Ranges (with the exceptional of the Mt Hector massif in the south) are all clustered on the inside of the northward curving, restraining bend in the northern part of the Tararua section of the fault.

We obtained four radiocarbon ages from organic debris trapped within a hillside fissure located upslope of the Wellington Fault adjacent to the walking track leading to Powell Hut (Figure 2). Such hillside fissures are very common throughout the Tararua Ranges and elsewhere in mountain areas in New Zealand. They are usually inferred to be formed during earthquakes by gravitational collapse of ridge crests under high seismic shaking intensity (e.g. Beck, 1968). In the absence of primary fault scarps for establishing the recent rupture history of the fault we sought other indirect evidence for the timing of possible earthquake-induced features. The results of radiocarbon dating (Table 2) of the deposits from this particular hillside fissure extend back to at least 2000 years before present. Because two ruptures of the Wellington-Hutt Valley segment of the fault have occurred within the past 1000 years, and the average recurrence interval that might be expected to apply to the Tararua section is about 600 years, we infer that the hillside fissure was not formed in association with the most recent large earthquakes in the area. There may have been a rejuvenation of the feature in more recent times, but there were no stratigraphic markers to support such an interpretation.

At Totara Flats, along the Waiohine River, there is a relatively wide, and picturesque expanse of river terrace flats. There are natural exposures and field relationships that indicate these terrace flats owe their existence to a relatively recent aggradation event that buried a substantial forest (Figure 3). We dated two trees that have been buried by, and presumably killed by, the coarse alluvial gravel that comprise the deposits of this aggradation event. Exposed in the west bank of the Waiohine River, at grid ref. S26/121271 (Site TF1), are buried tree stumps in growth position (Figure 4). These tree stumps are rooted in a horizon that is buried by c. 1.5 m of coarse alluvial gravel. The buried root horizon is also about 1.5 m above current river level. We collected, and dated, roots (ca 5-12 mm in diameter) from these buried stumps, and these have an age of 276±46 yr BP (Table 1; 1670-1450 cal AD). About 350 m to the southwest, at grid ref. S26/118269 (Site TF4), is another buried, in-growth-position tree stump, ca 1 m in diameter, exposed adjacent to the Totara Flats walking track on the west side of the Waiohine River (Figures 3 & 4). We collected, and dated, wood from the outside of the stump, and it has an age of 309±46 yr BP (1650-1450AD). We consider it highly likely that the above two samples were buried by, and killed by, the same aggradation event at 1650-1450AD. Also, in the Totara Flats area there are a number of dead trees (snags) sticking up through the grassed and lightly forested terrace surface. Though we have not dated these snags, we suggest that it is quite likely that most, if not all, were buried, and subsequently killed by the above aggradation event at 1650-1450AD.

Despite the lack of direct data constraining the timing of recent ruptures of the Tararua section of the Wellington Fault, it is intriguing to note that the timing of the newly discovered aggradation event along the Waiohine River (1650-1450AD) is in the same age range as the best estimate for the timing of the most recent surface rupture of the Wellington-Hutt Valley segment of the Wellington Fault (1640-1440AD; Van Dissen et al. 1992) (Table 2). This suggests to us that aggradation in the Waiohine was probably linked with rupture of the Wellington fault in the Wellington area. Whether the aggradation was initiated by earthquake shaking generated by rupture of only the Wellington-Hutt Valley segment of the fault, or was related to rupture that also extended along the Tararua section as well, cannot be determined from the available data. The distance from Kaitoke, at the northern end of the Wellington-Hutt Valley segment, to Totara Flats is less than 25 km, well within the range where earthquake shaking would still be expected to be strong enough to cause extensive landsliding and consequent river aggradation (Hancox et al., 1997). The ages we have obtained do not coincide with the 1855 rupture of the Wairarapa Fault.

4.4 Pahiatua Section of the Wellington Fault

From Putara northward the Wellington Fault is located at the eastern edge of the Tararua Range and is quite accessible in open farm land (Figure 5). Its strike from Putara to the Manawatu Gorge averages 035°. There is a 15° eastward (clockwise) change in strike between the northern end of the Tararua section and the southern end of the Pahiatua section. This change coincides with the change from the fault being within the range to the south, and bounding the eastern flank of the range to the north. Within the Tararuas the fault appears to have a significant up-to-the-west reverse-oblique sense of displacement. North of the Tararuas the fault has a predominantly dextral strike-slip sense of displacement, sometimes with a small normal component so that the fault is upthrown on the southeast side at some locations.

Along the Pahiatua section of the fault, between Putara and Manawatu Gorge, the fault has been mapped in some detail (Kelsey et al., 1995) and seven trenches (named after the local landowners) have been excavated to investigate the recent history of surface rupture and to obtain average fault slip rates. Apart from a preliminary description of four trenches by Beanland & Berryman, 1991, and inclusion of one of the trenches in Sarah Beanland's thesis of 1995, these trenches have not been reported previously. Two trenches (Bennett and Hughes 2) were excavated with the express intent of obtaining data for slip rate calculations. The remaining five trenches were primarily excavated to investigate the recent rupture history of this section of fault. Two trenches (Death 1 & 2) were located about 6 km from the southwest end of the Pahiatua section near the geometric "boundary" with the Tararua section, and the remaining three were located 16-20 km to the northeast (Figure 5). Most trenches were located at or adjacent to sites where the dextral displacement of topography was known and often where the scarp was upthrown to the southeast, thus tending to pond the southeast flowing drainage.

Table 2. Summary of radiocarbon samples, Tararua section of the Wellington fault

Location, Field reference & (site number)	Lab No.	Radiocarbon age (yr BP)	Calibrated age cal BP 1 σ range	Calibrated age cal BP 2 σ range	Calibrated age AD/BC 2 σ range	$\delta^{13}C$ (‰)	Grid reference, material & significance
Totara Flat							
Totara Flat ^{14}C -4	Wk-9521	276±46	300-460	280-500	1670-1450 AD	-28.0	S26 121271. Roots (ca 5-12 mm diameter) from buried, in-growth-position tree stump on west bank of Waiohine River about 0.6 km NE from new Totara Flats hut. Buried root horizon is ca 1.5 m below present ground surface and ca 1.5 m above current river level.
Totara Flat ^{14}C -1	Wk-9519	309±46	310-460	300-500	1650-1450 AD	-23.9	S26 118269. Wood from outside of buried, in-growth-position tree stump (ca 1 m diameter) on west side of Waiohine River about 250 m NE from new Totara Flats hut. Totara Flat ^{14}C samples 1 & 4 were probably buried by the same aggradation event.
Totara Flat ^{14}C -2	Wk-9520	406±43	340-530	320-540	1630-1410 AD	-24.9	S26 116263. Charcoal from river-bank exposure on east bank of Waiohine River about 200 m NNE of Sayer hut.
Mountain House							
Mountain House ^{14}C -1	NZA 13458	537±60	530-640	510-650	1440-1300 AD	-27	S26 ca 146329. Twig fragments (wood/root?) from 1.4 m depth from 1st auger-hole in fissure/rent located NW from, uphill from, main trace of Wellington fault between Mountain House and Powell hut.
Mountain House ^{14}C -2a	NZA 13459	607±65	550-650	530-670	1420-1280 AD	-25.7	S26 ca 146329. Wood fragment (branch/root?) from 1.2 m depth from 2nd auger-hole in same fissure/rent as above.
Mountain House ^{14}C -3	NZA 13460	960±65	790-560	740-1050	1210-900 AD	-25.3	S26 ca 146329. Wood fragment (branch/root?) from 1.4 m depth from 2nd auger-hole in same fissure/rent as above.
Mountain House ^{14}C -2	Wk-9518	2013±48	1900-2100	1870-2130	80 AD - 180 BC	-29.2	S26 ca 146329. "Bulk" sample (sediment, soil, wood fragments) from 1.2 m depth in 2nd auger-hole in same fissure/rent as above. Mountain House ^{14}C samples 2 & 2a come from the same auger bucket full.

Lab number: Wk, University of Waikato, New Zealand; NZA, Institute of Geological & Nuclear Sciences Rafter Radiocarbon Laboratory, New Zealand

Radiocarbon age: Conventional radiocarbon age before present (AD 1950) calculated using Libby half-life of 5568 years, and corrected to $\delta^{13}C$ of –25 ‰. Quoted error is ± 1σ.

Calibrated age: Calendar years before present (AD 1950) and calendar years AD/BC using C-14 calibration programme CALIB 4.3 (Stuiver, Reimer & Reimer: http://depts.washington.edu/qil/calib). A Southern Hemisphere offset of –27 radiocarbon years has been applied to all samples prior to calibration (McCormac et al., 1998). A lab error multiplier of 1.0 has been applied to NZ and NZA samples, and 1.217 for Wk samples. Age ranges listed are minimum and maximum values of the calibrated age range based on a radiocarbon age error of either 1σ or 2σ.

Grid reference: Given on NZMS 260 topomap sheet S26 as easting (first three digits) and northing (last three digits)

4.4.1 Slip Rate sites

A) Bennett Trench

Beanland (1995) discussed one site (Bennett trench – Figures 5 & 6) where a 50±10 m dextral displacement of a ridge has resulted in progressive deflection of a stream (Figure 7). A trench was excavated at the fault where initial stream gravel, related to the c. 50 m dextral offset, could be expected to be encountered (Figures 8 & 9). This gravel is overlain by an organic-rich silt unit that is interpreted as the slack water deposits resulting from initial offset-induced ponding of the drainage by up-to-the-east fault displacement. A radiocarbon age of 7737±68 yrs BP (6440-6750 BC at 95% confidence limits) has been obtained from this basal organic unit (Table 3). Therefore, assuming we are correct in the interpretation that this organic unit was deposited when the shutter ridge began to move across in front of the drainage, then the 50±10 m of displacement has occurred since 6440-6750 BC yielding an average dextral slip rate over that period of 4.6-7.2 mm/yr. This rate is very similar to the 6-7.6 mm/yr calculated for the Wellington-Hutt Valley segment of the fault (Berryman, 1990; Van Dissen & Berryman, 1996).

B) Hughes Trench 2

The Hughes 2 trench (Figures 5, 6 & 10) was excavated with the intention of dating the back edge of a terrace associated with a 70±10 m dextral displacement. The trench revealed a sequence of gravel and slope wash interbedded with two woody organic silt units (probably either co-seismic or ponded deposits) cut against Pliocene siltstone bedrock. The lower of the two woody organic silt units has an age of 2013±49 yrs BP (65AD-170BC) (Table 3). The age appears not to relate to the formation of the terrace, and the 70 m dextral displacement, because it implies an impossibly high slip rate of c. 35 mm/yr. We presume therefore that there is a major unconformity between the dated horizon and the alluvial gravel, or that there are deeper and older layers of alluvium below the trench floor.

Table 3. Summary of selected radiocarbon dates that constrain the timing of the most recent ruptures on the Wellington fault both south and north of the Tararua section.

Location	Lab No.	Radiocarbon age (yr BP)	Calibrated age: cal BP 1 σ range	Calibrated age: cal BP 2 σ range	Calibrated age: AD/BC 2 σ range	Original reference†	Material & significance
South of Tararua section:							
Wellington-Hutt Valley segment							
Long Gully trench 6, sample I	Wk-1746	340±50	320-500	310-510	1640-1440 AD	2	Wood (branch) buried by most recent scarp-derived colluvial wedge. Probably closely dates the timing of the most recent surface rupture on this section of the Wellington fault.
Long Gully trench 6, sample H	Wk-1747	480±70	470-640	320-660	1630-1290 AD	2	Wood (root) from same buried tree as above. Sample age is probably slightly older than timing of most recent surface rupture.
Long Gully trench 1, sample B	NZ 7775	683±48	570-690	560-730	1390-1220 AD	2	Detrital wood from a peat-dominated unit with some gravel. This unit is unfaulted and unconformably overlies two of the four fault strands that comprise the fault zone in this trench.
Long Gully trench 1, sample A	Wk-1556	980±50	790-970	770-1060	1190-900 AD	2	Detrital wood from a tectonically mixed fault zone unit, overlain by the unit that contains sample B. Long Gully samples A and B bracket the timing of a surface rupture event, interpreted to be the penultimate event.
Long Gully trench 2, sample C	Wk-1561	3250±60	3400-3630	3360-3690	1410-1740 BC	2	Wood (detrital?) from a fissure-fill unit within the fault zone. Sample is inferred to closely date the timing of a surface rupture event that is older than the penultimate event.
Manor Park	NZ 8222	293±31	310-430	310-460	1640-1490 AD	4	Detrital wood from an alluvial terrace that is interpreted as both crossing the fault and unfaulted. It is inferred that the most recent surface rupture on the fault is older than this date.
Te Marua	NZ 7769	80±51	30-260	0-280	1950-1680 AD	2	Charcoal from an unfaulted alluvial terrace that crosses the fault. Most recent surface rupture is older than this.
Te Marua	NZA 711	356±82	320-510	290-550	1660-1410 AD	2	Charcoal from a faulted alluvial terrace. Most recent surface rupture is younger than this sample.
Kaitoke trench 2, sample L	Wk-1748	800±50	680-790	660-910	1290-1040 AD	2	Wood from outer part of a growth position tree that is buried by a faulted alluvial/colluvial gravel unit. Gravel influx inferred to relate to hillslope destabilisation during and shortly following large earthquake. Age of sample interpreted to closely date, or to be no more that ca 100 yrs younger than, timing of penultimate event.
North of Tararua section:							
Pahiatua section							
Death trench 1, sample 1-1	Wk-1796	1330±50	1190-1330	1170-1390	780-560 AD	1	Buried peat and other plant material from base of a unit that is interpreted to be "ponded" behind a scarp generated by a recent surface rupture event. Ponding (and sample) may closely date timing of this event. Sample is from same stratigraphic horizon as sample Death 1-2.
Death trench 1, sample 1-2	Wk-10066	1565±43	1420-1530	1350-1570	600-380 AD	5	Detrital wood from base of a unit that is interpreted to be "ponded" behind a scarp generated by a recent surface rupture event. Ponding (and sample) may closely date timing of this event. Sample is from same stratigraphic horizon as sample Death 1-1.
Death trench 2, sample 2-3	Wk-1798	860±55	730-910	690-930	1260-1020 AD	1	Plant material (wood fragments, seeds and, leaves) from an unfaulted unit that unconfomably overlies the fault zone. Most recent surface rupture is older than this date.
Death trench 2, sample 2-1	Wk-1797	1140±50	990-1170	950-1260	1000-700 AD	1	Peat and small wood fragments from a faulted organic-rich gravel. Most recent surface rupture is younger than this sample, and the unit itself may represent deposition resulting from an additional surface rupture.
Death trench 2, sample 2-4	Wk-1799	1320±50	1180-1310	1090-1350	860-600 AD	1	Wood fragments from a faulted unit comprised of tectonically mixed peat, detrital wood, gravel and sand. At least one surface rupture younger than this sample. Death trench 2 samples 2-1 and 2-4 come from the same unit.
Bennett trench, sample 1-2	NZA 3568	7737±68	8450-8590	8390-8700	6440-6750 BC	3	Twigs from base of an organic-rich silt unit that directly overlies an alluvial gravel unit. The organic-rich silt and alluvial gravel units are associated with a 50±10 m dextral stream misalignment.

Hughes trench 1, sample 1-12	NZ 8054	83±58	25-270	0-280	1950-1670 AD	5	Fibrous reeds in an organic-rich gravelly silt. Sample is from same stratigraphic unit as sample Hughes 1-13.
Hughes trench 1, sample 1-1	Wk-10068	1014±64	800-1060	790-1170	1160-780 AD	5	Wood from a faulted silty gravel. At least one surface rupture younger than this sample.
Hughes trench 1, sample 1-13	Wk-10071	2051±69	1630-2150	1870-2310	70 AD–360 BC	5	Wood from an organic-rich gravelly silt. Sample is from same stratigraphic unit as sample Hughes 1-12.
Hughes trench 1, sample 1-8	NZ 8052	2197±62	2150-2330	2100-2350	150-400 BC	5	Twigs (and leaves?) from a faulted organic-rich gravelly silt. At least one surface rupture younger than this sample, and the unit itself may represent deposition resulting from a surface rupture.
Hughes trench 1, sample 1-4	Wk-10070	2552±47	2500-2770	2470-2780	520-830 BC	5	Wood from a faulted organic-rich gravelly silt. Probably at least two surface ruptures younger than this sample, and the unit itself my represent deposition resulting from a surface rupture. Sample is mapped as coming from the same unit as Hughes 1-2.
Hughes trench 1, sample 1-10	NZA 3604	3426±63	3640-3830	3550-3870	1600-1930 BC	5	Wood pieces from a faulted organic-rich gravelly silt. At least one surface rupture younger than this sample, and the unit itself may represent deposition resulting from a surface rupture.
Hughes trench 1, sample 1-2	Wk-10069	3551±60	3730-3980	3690-4090	1740-2140 BC	5	Wood from a faulted organic-rich gravelly silt. Probably at least two surface ruptures younger than this sample, and the unit itself my represent deposition resulting from a surface rupture. Sample is mapped as coming from the same unit as Hughes 1-4.
Hughes trench 1, sample 1-15	NZ 8049	3564±59	3780-3980	3720-4080	1770-2130 BC	5	Twigs, bark and seeds from a faulted organic-rich unit within the fault zone. At least one, and probably two or more, surface ruptures younger than this sample.
Hughes trench 1, sample 1-9	NZ 8051	3600±53	3840-4070	3780-4090	1830-2140 BC	5	Bark and twigs from a faulted organic-rich gravelly silt. At least one, and probably two or more surface ruptures younger than this sample. Unit itself my represent deposition resulting from an additional surface rupture
Hughes trench 1, sample 1-7	NZ 8053	3603±48	3870-2100	3830-4090	1880-2140 BC	5	Seeds, leaves, twigs and bark from a faulted organic-rich (peat) unit. At least one, and probably at least two surface ruptures younger than this uni
Hughes trench 1, sample 1-3	NZ 8050	9481±110	10,600-11,070	10,500-11,160	8560-9220 BC	5	Wood and bark from a faulted organic-rich unit.
Hughes trench 2, sample 2-2a	NZ 8055	2013±49	1930-2060	1890-2120	65 AD - 170 BC	5	Wood and bark from an organic-rich silt that overlies alluvial gravel.
Ebbett trench 1, sample 1-2	Wk-1800	1010±50	800-1050	790-1070	1160-890 AD	1	Wood from an organic-rich gravelly silt/clay that is faulted. Most recent surface rupture is younger than this date, and the unit itself my represent deposition resulting from an additional event.
Ebbett trench 1, sample 1-5	Wk-1802	3740±70	3980-4250	3910-4410	1960-2460 BC	1	Wood from an organic-rich gravelly silt/clay that is faulted. At least one, probably two (and possibly more) surface ruptures younger than this sample, and the unit itself my represent deposition resulting from a surface rupture event.
Ebbett trench 1, sample 1-6	Wk-1803	3810±70	4100-4410	3980-4440	2030-2550 BC	1	Wood from tree stump sampled near base of trench.
Ebbett trench 1, sample 1-3	Wk-1801	3840±60	4160-4410	4090-4510	2140-2560 BC	1	Tree stump (20 cm diameter, in growth position) from same stratigraphic horizon as sample Ebbett 1-5.
Ebbett trench 2, sample 2-2	Wk-1804	280±55	300-460	150-510	1800-1440 AD	1	Wood from an unfaulted peat that is ponded behind the fault scarp. Most resent surface rupture is inferred to be older than this date.
Ebbett trench 2, sample 2-5	Wk-1806	1160±60	990-1220	970-1260	990-690 AD	1	Detrital wood within a faulted silt/clay unit. At least one surface rupture is younger than this sample.
Ebbett trench 2, sample 2-3	Wk-10067	6287±61	7100-7410	7020-7420	5070-5470 BC	5	Wood from a faulted clay-rich unit.
Ebbett trench 2, sample 2-4	Wk-1805	30,300±750				1	Detrital wood, seeds, and bark from an organic-rich gravelly silt/clay.

Radiocarbon age: Conventional radiocarbon age before present (AD 1950) calculated using Libby half-life of 5568 years, and corrected to $\delta^{13}C$ of −25 ‰. Quoted error is ± 1σ.

Calibrated age: Calendar years before present (AD 1950) and calendar years AD/BC using C-14 calibration programme CALIB 4.3 (Stuiver, Reimer & Reimer: http://depts.washington.edu/qil/calib). A Southern Hemisphere offset of −27 radiocarbon years has been applied to all samples prior to calibration (McCormac et al., 1998). A lab error multiplier of 1.0 has been applied to NZ and NZA samples, and 1.217 for Wk samples. Age ranges listed are minimum and maximum values of the calibrate age range based on a radiocarbon age error of either 1σ or 2σ.

† Original reference: 1, Beanland & Berryman (1991); 2, Van Dissen et al. (1992); 3, Beanland (1995); 4, Van Dissen & Berryman (1996); 5, This study.

4.4.2 Paleoseismology Sites

A) Death Trenches

At the Death trenches in the southern part of the Pahiatua section of the fault, the sites were located across uphill-facing scarps 0.5-2 m high that have resulted in ponding and accumulation of sediments against the scarp (Figures 5, 11, & 13). Death trench 1 exposed a sequence of coarse alluvial gravel, fan deposits and woody peat deposits on the downthrown side of the fault, interbedded with fine silty gravel (Figure 12). Two fault planes, about 1 metre apart disrupt the sequence. Fault 1 appears to have moved in the most recent event forming the c. 0.5 m high scarp. Fault 2 does not appear to have ruptured in the most recent event because it does not coincide with the surface scarp. Radiocarbon ages of 1330±50 yrs BP (780-560AD - 95% confidence limits) and 1565±43 yrs BP (600-380AD) (Table 3) have been obtained from peat samples from the lower part of what we interpret to be the oldest ponded unit overlying Fault 2. If the recent ponding was induced by fault rupture and formation of a barrier across the local stream drainage as surface geomorphology suggests (Figure 11 & 12), then the time of the faulting event is just older than the age of the peat sample from the ponded deposits, that is, just older than 600-380AD. The existence of a higher and presumably younger peat deposit may indicate a more recent ponding event (?=fault rupture on Fault 1), but this has not been dated at this trench.

Death trench 2 is associated with a shutter ridge dextral displacement of 22±4 m, and was excavated at a site where the surface scarp is about 2 m high, upthrown to the southeast, potentially ponding local drainage (Figures 5 & 13). The exposure revealed a complex sequence of alternating fan gravel, organic silts, and organic-rich gravels, faulted against gouge and broken greywacke bedrock that is overlain by thin gravel colluvium (Figure 14). Three fault planes were mapped, and these bound wedge-shaped mixed zones, one of which is composed of a woody peaty gravel, the other of a clayey gravel. These units, and the fault planes are overlain by sub-horizontal units of peaty organic silt, organic mud, and organic silty sand intercalated with fine fan gravel. A wedge shaped sandy gravel extends out from the fault scarp and appears to result from erosion of the fault scarp. This scarp-derived unit is intercalated between some of the ponded organic rich deposits. Two radiocarbon ages from peat and detrital wood samples from the mixed wedge of material between Fault 1 and Fault 2 are 1140±50 yrs BP (1000-700 AD) and 1320±50 yrs BP (860-600AD) respectively (Table 3). From the overlying, unfaulted organic silt deposit an age of 860±55 yrs BP (1260-1020AD) has been obtained from a peat sample. The age difference of c. 100-150 years between the 1140 yrs BP peat and 1330 yrs BP detrital wood samples may represent the time that the detrital wood resided in the environment prior to being incorporated into the deposit (although the ages overlap by c. 170 yrs at 95% confidence limits).

The peaty and organic-rich gravelly sand that the older samples were obtained from is similar in composition to other units in the same trench and to units in other trenches from this area that we present later. The organic gravelly silt and sand units are reminiscent in composition to units described by Van Dissen & Berryman (1996) in fault trenches from elsewhere on the

Wellington Fault and on the Wairarapa Fault where they concluded that the combination of leaf litter, seeds, broken branches, and some in-situ stumps, combined in a gravelly silt probably represented a co-seismic deposit. They proposed that earthquake shaking destabilised many slopes and broke many trees, bringing together the unusual mixture of gravel, and forest litter in a silt or sand matrix. Therefore, radiocarbon ages from short lived leaf litter or the outside of branches and trunks from these unique units are inferred to be close in age to the timing of a paleo-earthquake.

In Death trench 2 the faulted mixed organic gravel deposit, and the thin organic silty gravel overlying Fault 1, that appears to be a lateral equivalent of the Death 2/3 sample are interpreted to be "co-seismic" deposits. The organic sandy gravel unit to the northwest of Fault 1 (Figure 14) may also have a similar origin, but has not been dated.

The relationship of un-faulted peat overlying faulted deposits provides a clear bracketing of the timing of recent faulting at this site at between 1260-700AD (representing the bounding ages of the faulted and unfaulted deposits respectively - Table 3). We can also assert, assuming our interpretation of "co-seismic" deposits is correct, that fault rupture occurred immediately prior to the formation of the units. With certainty we can show that no faulting has occurred since 1260-1020AD, but the most recent rupture event may have occurred immediately prior to this, and the next older (penultimate) event may have occurred at 1000-600AD (the range in age of the two "co-seismic" deposits).

In summary, the data obtained from the Death trenches indicate there has been no faulting here since at least 1260 AD and possibly since 1020 AD. The penultimate faulting event (PFE) is interpreted to be represented by a ponding event in Death trench 1, and formation of a co-seismic unit in Death trench 2. Although there is no overlap between all four radiocarbon ages obtained from the deposits that are inferred to have formed immediately after the penultimate faulting event, the best fit is in the range 700-600AD. The most recent faulting event (MFE) is identified as a young (but undated) ponding event in Death trench 1 and faulting of the penultimate PFE unit in Death trench 2. The time of this event is best constrained by the lateral equivalence of an un-faulted organic silty gravel (?co-seismic unit) with the un-faulted dated horizon at 1260-1020AD. So, although this sample most confidently places an upper constraint on the elapsed time since the MFE, it is also inferred to be close in time to the MFE.

B) Hughes & Ebbett Trenches

The Hughes and Ebbett trench sites (two trenches at each site – Figures 5, 6, 15) are located on a 4 km long section of the fault 16-20 km northeast of the Death trenches. The surface trace of the fault has a similar freshness at both the Hughes and Ebbett sites (compare Figures 6 & 15). The Hughes 1 trench (Figure 16) revealed a sequence of organic-poor colluvium, and silts, interbedded with several of the unique organic-rich gravelly silt ("co-seismic") units.

Three principal fault planes separate the alluvial and colluvial deposits from crushed greywacke bedrock on the upthrown, southeast, side of the fault.

As in the Death trenches, the distinctive deposits in the Hughes trenches (and the faulted peaty mixed wedge unit in Death Trench 2 as discussed above), and in the Ebbett trenches described next, are hypothesised to be co-seismic deposits, and therefore radiocarbon ages from short lived leaf litter or the outside of branches and trunks from these units are inferred to be close in age to a paleo-earthquake.

In the Hughes 1 trench there are a total of eleven radiocarbon dates from these "co-seismic" organic-rich gravelly silts. Five of the dates cluster at c. 3400-3600 yrs BP (1600-2140BC - 95% confidence limits), and there are three dates in a range of 2050-2550 yrs BP (830BC-70AD). An older sample from a peat (but a lateral equivalent of an organic-rich gravelly silt in the opposite wall of the trench) has an age of 9500 yrs BP age (8560-9220 BC) (Table 3). Faulting extends through the deposits to beneath the present topsoil. In a channel-shaped unit on the south wall a fault plane extends upward to beneath the uppermost, apparently "co-seismic", deposit and ages of 83±58 yrs BP (1950-1670AD) and 2051±69 yrs BP (70AD-360BC) (Figure 16, Table 3). This unit was not separated out from the upper peat unit in the opposite wall. Although correlation of units and faults is difficult from one trench wall to the other, the structural relationships indicate recent rupture of all but the uppermost peaty soil and possible co-seismic unit. The uppermost apparently "co-seismic" deposit with one sample with an age of 83±58 yrs BP (1950-1670AD) may represent the age range of the MFE, and the sample with an age of 2051±69 yrs BP (70AD-360BC) may have been reworked during faulting from the older co-seismic deposit that has ages of c. 2200 and 2550 yrs BP. The c. 3500 yr BP radiocarbon ages cluster, indicating event-dominated deposition, and the nature of the organic-rich gravelly silt/sand units suggest those units were also formed in response to faulting and landscape instability.

The Ebbett trenches (Figures 5 & 15) are located a few kilometres northeast of the Hughes sites and were excavated across small dextrally-displaced ponded scarp sites. The Ebbett 1 site is associated with a 18±2 m dextral displacement of a small hillside channel, and the Ebbett 2 site is associated with a 9±1m dextral channel displacement.

In Ebbett trench 1, two organic-rich gravelly clay units (postulated "co-seismic" units) are interbedded with sparsely gravelly silty clays, and collectively these are faulted against a wedge-shaped packet of units including another strongly deformed peaty gravel, and grey brown siltstone (Figure 17). Radiocarbon samples from the two organic-rich gravelly clay units have ages of 1010±50 yrs BP (1160-890AD) and c. 3800 yrs BP (1960-2560BC – range for two samples, a 3rd sample from the outside of an apparently in-situ tree has the same age but comes from a lower elevation). The older age range overlaps with that of a "co-seismic" unit in the Hughes trench 1 (Table 3). The uppermost organic-rich gravelly silt "co-seismic" deposit at the Ebbett site has an age 1160-890AD, but the fault plane displaces this unit, implying a more recent fault rupture. Therefore, the 1160-890AD age is one estimate for the timing of the penultimate (PFE) event (Figure 18, Table 3), and the timing of the MFE must be younger than this. We found no evidence for a co-seismic deposit between the two organic-rich gravelly silt/sand units discussed above which might be expected to correlate with the unit dated at the c. 150-400BC in Hughes trench 1 only a few kilometres to the southwest. We expect that the accumulation of the so-called "co-seismic" deposits depends on the local conditions at the time of the earthquake, so they may not be formed at every site in every event.

We do not specifically recognise the 3rd event in the Ebbett Trench 1, 4th but if the correlation of the "co-seismic" units is correct then we have good definition of the event at 2140-2550BC (overlap of 95% confidence limit range for two in-situ wood samples - 3840±60 & 3810±70 yrs BP, one sample from detrital branch material was not considered because of uncertainty in environmental age).

The Ebbett trench 2 site is in a small ponded drainage associated with a 9±1m dextral displacement (Figure 15). The stratigraphy exposed was relatively simple with a sandy gravel and clay overlying, and faulted against, sandstone bedrock (Figure 18). Beneath, and adjacent to the gravel alluvium are two fault-bounded, wedge-shaped units, one of peaty gravelly silt from which a radiocarbon age of 30,300 yrs BP has been obtained, the other a clay containing wood with an age of 6287 yrs BP (Table 3). These are much older ages than anything else obtained from trench excavations reported here. They come from in-faulted slivers of units similar to those elsewhere considered to be "co-seismic". This exposure and these ages suggest that in packages of sediment entrained by the fault there is a partial record of the older rupture history of the Wellington Fault.

In the southwest wall of the trench a recent peat lies across the top of the upper termination of the fault. A sample from the same peat has been dated from the northeast wall at 280±55 yrs BP (1800-1440AD), limiting the timing of the most recent event to older than 1800AD. One further radiocarbon age was obtained from this trench, from organic material in the faulted clay overlying alluvial gravel in the north wall of the trench (1160±60 yrs BP – 990-690AD, Table 3). This age overlaps with the age of the youngest faulted co-seismic unit in Ebbett trench 1 (1160-890AD). As with the Ebbett trench 1 this age horizon is displaced but the 1800-1440AD horizon is not. Therefore the MFE is certainly bracketed between 1800-890AD.

We can make some estimate of both the short term (c. 4000 years) dextral slip rate and the average amount of dextral faulting per event from the Ebbett trenches. If the lower co-seismic unit of 2140-2550BC is the first event initiating the 18±2 m dextral displacement now observed at the Ebbett Trench 1 then a short-term (last c. 4000 years) dextral slip can be estimated at 3.6–4.9 mm/yr, somewhat lower than calculated from the Bennett site. We caution the use of this value however, because of the susceptibility to large variation in rates because of the short period and dependence on the timing of events. Ebbett trench 2 contains evidence for only two events forming the 9±1 m of dextral displacement, and this suggests single event dextral displacement of about 4.5 m per event.

In summary, the Hughes and Ebbett trenches reveal data to constrain the following timing of events;

- The most recent faulting event (MFE) is poorly determined in the Ebbett trenches to be older than 1800AD and younger than 890 AD, but a single age of 1950-1670AD is an estimate of the timing in the Hughes trench 1. We have no evidence for historic (c. 140 years locally) rupture on the Pahiatua section of the fault. Therefore, the best estimate for the age of the MFE is 1860-1670AD.
- The penultimate faulting event (PFE) was probably at or about 1160-890AD (95% confidence limit range for one sample, but perhaps a little older than the event because of possible environmental age of the detrital wood sample). A sample (E2/5 – Table 3) from Ebbett trench 2 that is interpreted to have experienced both faulting events at that site has an age of 990-690AD, and overlaps with the one firm determination of the PFE. The use of this second date suggests a more refined estimate of he PFE in the range 990-890AD.
- The 3rd most recent event in the area at c. 150-400BC is identified in Hughes trench data, but is not observed in the Ebbett trenches. It can be inferred to occur in the Ebbett trenches by the c. 4.5 m single event displacement calculation from the Ebbett trench 1 divided into 18±2 m of displacement in the past c. 4000 yrs observed a few hundred metres along the fault in Ebbett trench 2. An age of 65-170BC was obtained from sample Hughes 2/3 (Figure 10 & Table 3) within a unit that might be interpreted as a ponding unit (although no fault relationship was observed in that trench) and this age overlaps with the proposed event of 150-400BC
- The 4^{th} event is well constrained in Ebbett trench 1 by two samples at 1960-2560BC, and in the Hughes trenches by three samples from in-situ leaves and twigs at 1880-2130BC. These two age ranges overlap for the period 1960-2130BC, our best estimate for the timing of the 4^{th} event.
- An older event, almost certainly not in consecutive order from the 4^{th} event above, is inferred at c. 8560-9220 BC. An extremely old age of c. 30,300 yrs was also obtained from Ebbett trench 2 from a sliver of organic-rich gravelly silt near the base of the trench resembling other "co-seismic units". Whether this sample indeed records the timing of an earthquake far back in the late Pleistocene, or whether the unit has been "assembled" from different units during the expected c. 150 m of dextral motion (c. 5 mm/yr for 30,000 yrs) that the fault has undergone in that time is unknown.

5.0 Discussion

The principal objective of this study has been to characterise the recent rupture history of the Tararua section of the Wellington Fault, and to compare that history with sections and proposed rupture segments of the fault to the north and south. Not as much information has been obtained from the Tararua section of the fault as we would have desired. The combination of the dense forest cover and the location of the fault not being in the floor of valleys as expected, means that the potential to obtain a high resolution chronology of surface faulting on the Wellington Fault within the Tararua Ranges is not likely to exist. We did, however, obtain data from the Totara Flats area in the Waiohine Valley that suggests an aggradation event in the valley was coincident with the most recent faulting event (MFE) on the Wellington-Hutt Valley (W-HV) rupture segment, and implies either faulting extended onto the Tararua section of the fault on that occasion, or that shaking associated with rupture of only the W-HV segment was sufficiently strong to initiate extensive landsliding in the Waiohine Valley. Both options are possible. Further effort in dating recent aggradation episodes in other Tararua catchments (if such aggradation occurred) may result in a preference for one or other of the fault rupture or shaking scenarios.

Data from the trenches excavated on the Pahiatua section of the Wellington Fault provide some constraints and insights into the rupture history of Tararua section as well. In Figure 19 we illustrate constraints on the timing of rupture events deduced from the W-HV rupture segment, the Tararua section, and from the Death, Bennett, Hughes and Ebbett sites on the Pahiatua section. The figure illustrates the synchroneity of the MFE on the W-HV segment with aggradation at Totara Flats. The timing of the MFE and PFE at the Death trench sites at the southwest end of the Pahiatua section do not appear to be the same as at the Hughes/Ebbett sites. Because the amount of single event displacement in the vicinity of the Death trench sites is of the order of 4±1 m, then the fault rupture can be expected to be of the order of many tens-of-km long, similar to estimates of the W-HV segment rupture (Wells & Coppersmith, 1994; Berryman, 1990). If the MFE event at the Death trench sites did not extend northeast as far as the Ebbett and Hughes trenches, c. 20 km away, then it seems likely that the MFE at the Death trench site must have ruptured into or from the Tararua section of the fault in order to attain a rupture length consistent with a single-event displacement of 4±1 m. If that rupture were indeed 60 km or more long this would include the whole length of the Tararua section, and this would imply the last rupture of the fault in the Waiohine Valley was at 1260-1020AD (the best estimate for the MFE timing at Death site). Consequently, we suggest that the 1650-1450AD aggradation episode observed in the Waiohine Valley was related to shaking from the more distant rupture of the W-HV segment, which did not extend into the Tararua Ranges.

To explain the difference in fault rupture timing between the Death and Hughes/Ebbett sites we propose that at least a partial or "soft" rupture segment boundary exists somewhere between the trench sites, and, as a consequence, the chronology of faulting at the Death trench sites may at least partially characterise the rupture history of the Tararua section of the Wellington Fault (Figure 19). The preliminary chronology of surface rupture events that emerge from this analysis are summarised in Table 4.

Table 4 **Fault rupture history of Wellington Fault in southern North Island**

	Fault Segment/Section			
Rupture History	Wellington-Hutt Valley	Tararua (aggradation)	Pahiatua (Death)	Pahiatua (Hughes & Ebbett)
MFE	1640-1440AD	1650-1450AD	?1260-700AD[1] ?1260-1020AD[2]	1860-890AD[1] or ?1860-1670AD[2]
PFE	1290-940AD	no data	780-700AD	1160-890AD
3rd Event	no data	no data	no data	150AD-400BC
4th Event	no data	no data	no data	1880-2130BC or 2140-2550BC or 2000-2200BC[2]

Notes: [1] more conservative interpretation, [2] more speculative, but preferred interpretation.

Thus, we infer that for the last rupture cycle on the Wellington Fault in southern North Island three rupture segments have existed. The northern segment includes the part of the Pahiatua section that has ruptured twice since 890 AD. Using the same rupture length for single event displacement argument as advanced above, we expect that this rupture segment is also many tens-of-kilometres long. The distance from the proposed segment boundary between the Death and Hughes/Ebbett sites to the Woodville at the northern end of the Pahiatua section of the fault is only about 30 km, so we expect that this rupture segment extends perhaps an equal distance further north. We tentatively name this the *Woodville segment* after the name of the major town near the fault. Neall & Hanson (1995) suggested a young event on the Wellington Fault at least 20 km north of Woodville with displacement of an horizon dated at 257±44 yr BP (1649-1737AD), and perhaps as young as 211±63 yr BP (1676-1802AD). This perhaps suggests that the MFE observed at the Ebbett trench sites may belong to a surface rupture extending at least 50 km, but more intense investigation north of Woodville is required to confirm these suggestions.

The southern 10 km or so of the Pahiatua section has probably ruptured with most or all of the Tararua section twice since c. 700AD, and we tentatively name this *the Tararua-Putara segment*, for evident geographical descriptive reasons. In this interpretation we infer the *Wellington-Hutt Valley segment* has been the rupture segment for the past two events in the south as proposed by Van Dissen & Berryman (1996).

An estimate of the inter-event intervals and elapsed times for each of the three rupture segments is developed from the data presented in Table 4 and is presented in Table 5, and graphically in Figure 19. Although this analysis is developed from limited paleoseismic data with only a few events constrained by multiple age determinations, it is nevertheless instructive to look at the indications of event recurrence variability in each rupture segment with respect to average estimates of the recurrence interval. For the Wellington-Hutt Valley segment and for the Woodville segment recurrence intervals up to two-three times as long as the average recurrence interval are indicated. This factor of two to three variation about the mean recurrence interval is similar to that obtained for the Awatere Fault by Benson et al. (2001) and Benson et al. (2001). It may be that for seismic hazard calculations incorporating the strike-slip faults of central New Zealand that a probability density function on recurrence interval that utilises this factor of two to three variability would be a useful approach. Table 5 also suggests the Wellington-Hutt Valley segment of the fault is not "overdue" as is commonly reported but is "within the window" if a factor of two to three variation about the mean recurrence is a useful criteria for the probability estimate of rupture. The Tararua-Putara segment apparently has not ruptured for at least c. 1100 years, and although an average recurrence interval has not been obtained for this segment, it is unlikely to be much different to the segments north and south. The prior interval on the Tararua-Putara segment was apparently only one-third to one-half of the present elapsed time, so we suggest that, of the three fault rupture segments discussed in this report, this is the segment that is the most "likely" to rupture in the future.

Based on the similar single event dextral displacement and suggested rupture length for each of the three fault segments we expect that the estimate of earthquake magnitude proposed for the W-HV segment of M_w 7.4-7.8 by Van Dissen & Berryman (1996) may be appropriate for the Tararua-Putara segment and the Woodville segment. We do not make a specific calculations for these latter two segments because the part of the Tararua-Putara segment in the ranges appears to be more reverse in character than the northern-most 10 km part for which we have event timing and displacement data, and we do not know the northern limit of the proposed Woodville segment yet.

The analysis presented above addresses one of the principal objectives of this project – to evaluate whether there is geological evidence for past rupture involving more than just the Wellington-Hutt Valley segment of the Wellington Fault either as rupture in a single event extending into or from the Tararua section, or as a triggered event because of, for example, increased coulomb failure stresses at the end of a strike-slip rupture. We must emphasise that our analysis is tentative because of the paucity of data from the Tararua Ranges itself, and because the timing of ruptures deduced from the trenches on the Pahiatua section of the fault has been interpreted from the so-called "co-seismic" units is uncertain. However, we can make the following conclusion: The summary interpretation of Table 4 and Figure 19 indicates that for the MFE on the southern Wellington Fault there has been no temporal clustering or coulomb stress triggering upper plate fault behaviour (such as is commonly interpreted for the North Anatolian Fault in Turkey). However the MFE on the Tararua-Putara segment overlaps with the PFE on the Wellington-Hutt Valley and Woodville segments and the possibility exists that this may have been a much longer single rupture (implying larger earthquake magnitude) or that coulomb stress triggering may have played a role in a possible cascade of linked events.

Table 5 Elapsed time and inter-event interval for Wellington Fault rupture segments

Rupture Segment	Average Recurrence Interval (yrs)	Elapsed Time Since MFE (yrs)	Inter-event Intervals (yrs)		
			MFE-PFE	PFE-3rd	3rd–4th
Wgtn-Hutt Valley	635±135[1]	400±100[4]	425±275	no data	no data
Tararua-Putara	no data	1140±120	400±160	no data	no data
Woodville	755±335[2]/1000[3]	235±95	740±230	1150±400	1975±375

Notes:

1. Calculated using a 3.8-4.6 m average dextral displacement and long term average dextral slip rate of 6-7.6 mm/yr (Van Dissen & Berryman, 1996).
2. Calculated using a 4±1 m average dextral displacement and c. 8000 year average dextral slip rate of 4.6-7.2 mm/yr obtained from the Bennett trench 2 site.
3. Calculated from trench data with 4 events in the past c. 4000 yrs.
4. All intervals and elapsed times calculated by taking the midpoint of the age range within which the faulting is interpreted to have occurred, taking the difference in the mean values as the central estimate and summing the difference between midpoints and range bounds of the pairs of dates to obtain an estimate of uncertainty. For example, the midpoint of the range for the MFE on the W-HV segment is 1540AD with an uncertainty of ±100 years. The midpoint of the range for the PFE is 1115AD with an uncertainty of ±175 yrs. Therefore the interval between the MFE and PFE is 1540-1115 = 425 years and the uncertainty is 100+175 = 275 years.

6.0 Conclusions

The ability to find and map the recent trace of the Wellington Fault in the Tararua Ranges has proven more difficult than anticipated at the outset of this project. This situation arises primarily because we found the fault within the ranges to have a more pronounced reverse component, such that its position was usually high on valley sides and hidden beneath local fan deposits rather than in the valley floor and cutting terrace deposits as anticipated. Nevertheless, within this project we obtained radiocarbon material from hillside trenches that may have been initiated by earthquake shaking (although in this case apparently older than the very recent fault history that we were searching for). In the Waiohine Valley we obtained information on an extensive aggradation episode that occurred within the same time frame as the most recent faulting event on the Wellington-Hutt Valley segment of the fault. Without other data we could not differentiate between aggradation induced by earthquake shaking associated with rupture of only the Wellington-Hutt Valley segment or aggradation resulting from instability where rupture extended along all or some of the fault within the ranges.

When we assess the data from a series of seven trenches excavated about 10 years ago on the Pahiatua section of the fault, we find that the southern two trenches have a different rupture history to the remaining five, located a further 16-20 km to the northeast. Because the amount of single event displacement at several locations along the Pahiatua section of the fault are about 4±1 m dextral, then the rupture length associated with these events was probably at least several tens-of-km. Therefore, the Death Trench sites on the southern part of the

Pahiatua section must belong to the rupture segment comprising the Tararua section of the fault, and we define this portion of the fault as the Tararua-Patara segment. The event timing observed in the Death Trenches is not the same as the aggradation episode in the Waiohine Valley, therefore that aggradation event was probably related to shaking from rupture of just the W-HV segment, not including any rupture of the Tararua section. The remaining five trenches on the Pahiatua section generally provide evidence for similar timing of events at all sites. This set of events is unique, indicating the existence of a rupture segment boundary somewhere in the vicinity of where the Managahao River crosses the fault. This northern rupture segment of the fault is referred to as the Woodville segment. The segment boundary appears to have operated in the last cycle of faulting, but the evidence is equivocal for the next older cycle because of the overlap in ages of the MFE on the Tararua-Putara segment and the PFE on the Woodville segment. Because the fault length between the proposed segment boundary around the Mangahao River to Woodville is only about 30 km, we expect that this segment extends further north, but no data yet exist to define its northern boundary.

In the MFE on the southern Wellington Fault there has been no temporal clustering or coulomb stress triggering upper plate fault behaviour (such as is commonly interpreted for the North Anatolian Fault in Turkey). However the MFE on the Tararua-Putara segment overlaps with the PFE on the Wellington-Hutt Valley and Woodville segments and the possibility exists that this may have been a much longer single rupture (implying larger earthquake magnitude) or that coulomb stress triggering may have played a role in a possible cascade of linked events.

7.0 Future Studies

While it is difficult to obtain high resolution data from the Tararua Ranges area, our study indicates that the southernmost part of the Pahiatua section (Death trench area) and south is at least sometimes part of a Tararua rupture segment. Therefore, further characterising the fault in this Putara area will provide data on the otherwise hard-to-study Tararua section. Consequently, further mapping and trenching is suggested to try and define the nature of the segment boundary between the Death and Hughes trench sites. Also, in the Putara area, obtaining better definition of the timing and size of the two events recorded in the Death Trenches and extending the record back in time to older surface rupture events are worthwhile objectives.

From the preliminary information obtained on the paleoseismology record of the proposed Woodville segment of the fault from the Hughes and Ebbett Trenches, it is clear that a more refined story could be available with a focussed trenching study. We also propose the Woodville rupture segment probably extends north of the Manawatu Gorge (where the fault is known as the Mohaka Fault), and further work is required to define the timing and size of individual rupture events in that area, and the nature of fault rupture segmentation to the north. Identification of this northern segment boundary may indicate a more appropriate location for a fault nomenclature change.

8.0 Acknowledgements

We would like to acknowledge the Earthquake Commission, and the Public Good Science Fund for financial support for this study. The trenching studies on the Pahiatua section of the fault were carried out with Sarah Beanland and Alan Hull. The credit for obtaining useful data on past surface rupture on this section of the fault belongs with them as well, but the present authors accept responsibility for the interpretation presented here. We thank Janet Arnst for assistance with graphics. Robert Langridge and John Begg (GNS) provided review comments on the report, and we thank them for their time and interest.

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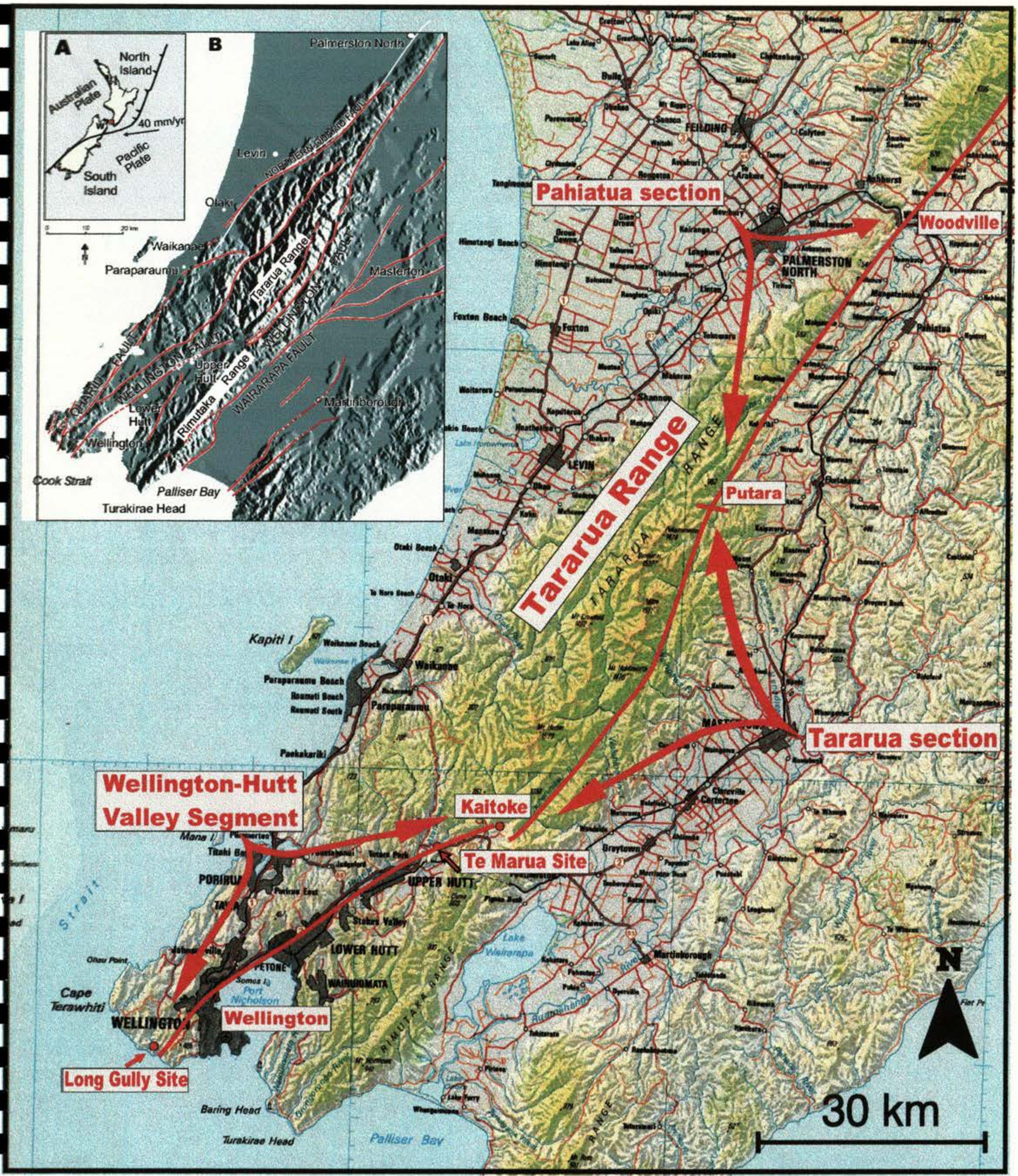


Figure 1. General geographical map of the study area showing localities mentioned in the text, and sections of the Wellington Fault. Inset A shows the plate tectonic setting of the study area in central New Zealand. Inset B shows the location and names of other active faults in the Wellington Region.

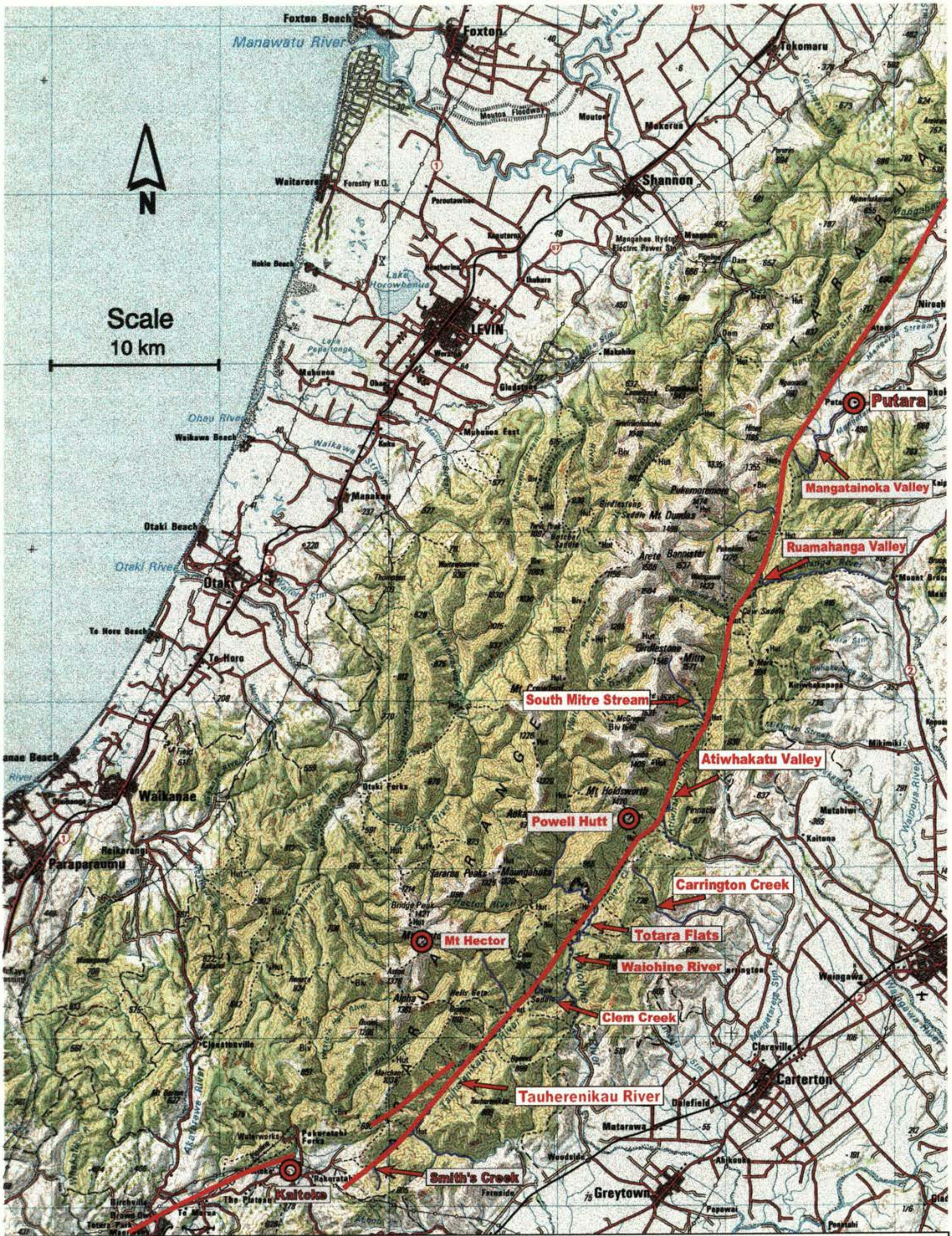


Figure 2. Map of the Tararua section of the Wellington Fault showing place names referred to in the text. The 2 km right side-step at the Kaitoke Basin at the boundary between the W-HV segment and Tararua section is shown at bottom left.

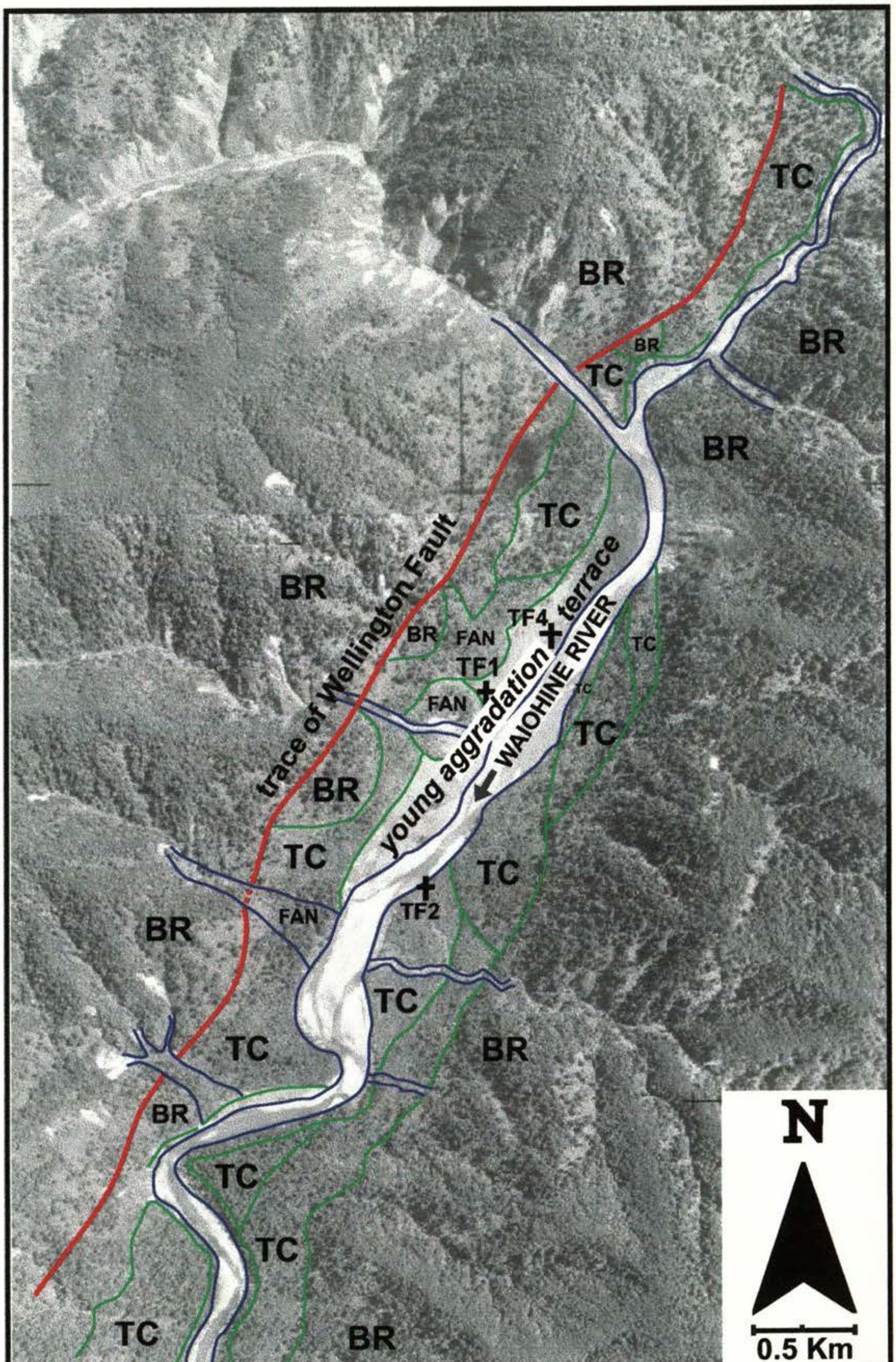


Figure 3. Interpretation of terrace and fan distribution in the vicinity of Totara Flats, Waiohine Valley. Location of young aggradation terrace, interpreted to have formed in association with the last rupture of the W-HV rupture segment of the Wellington Fault, and the radiocarbon sampling sites (TF1 etc) on that terrace are shown.TC=terrace, BR=bedrock.

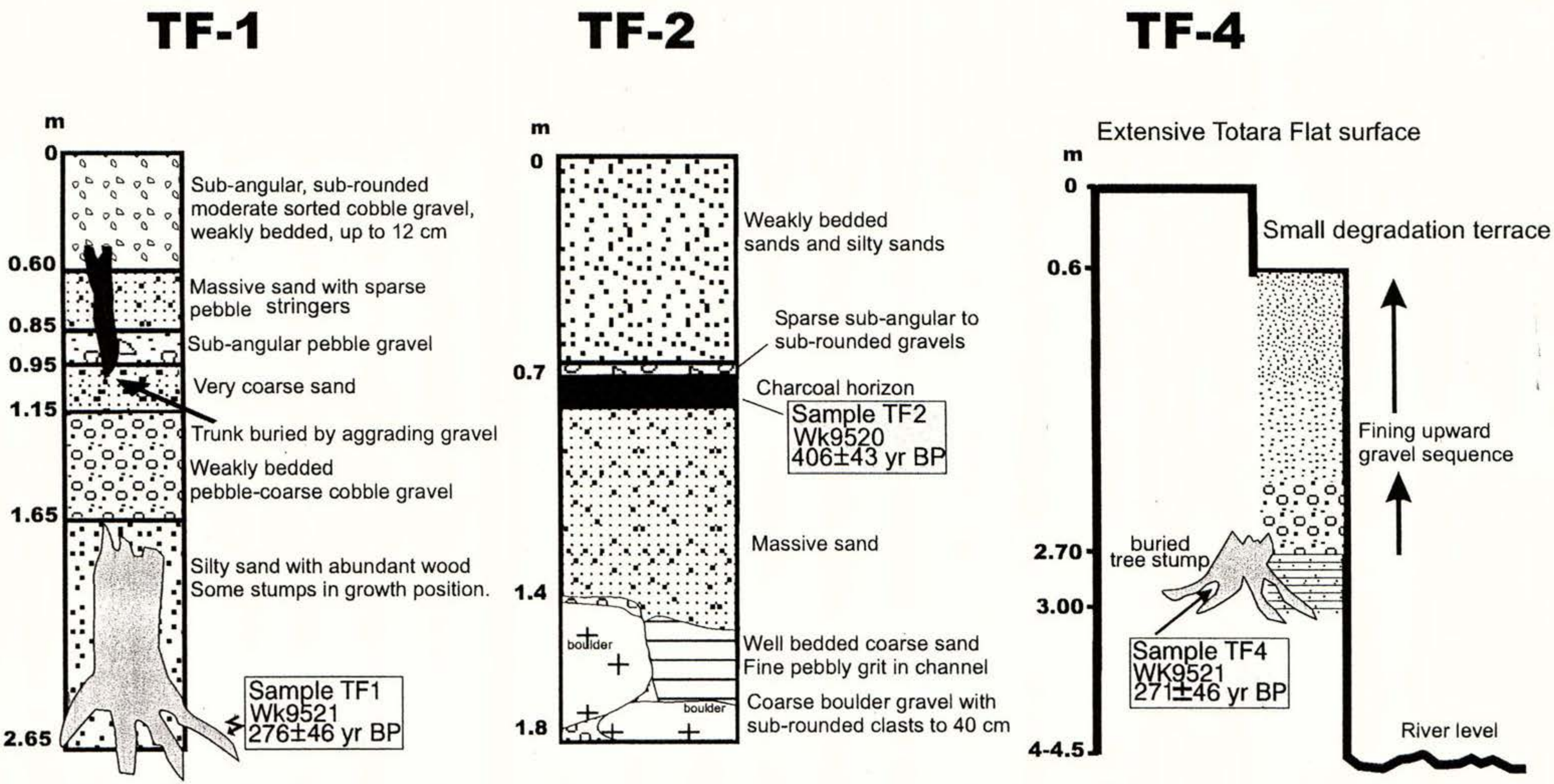


Figure 4. Stratigraphic columns from young aggradation terrace at Totara Flats, Waiohine Valley. Sample locations are shown on Figure 3.

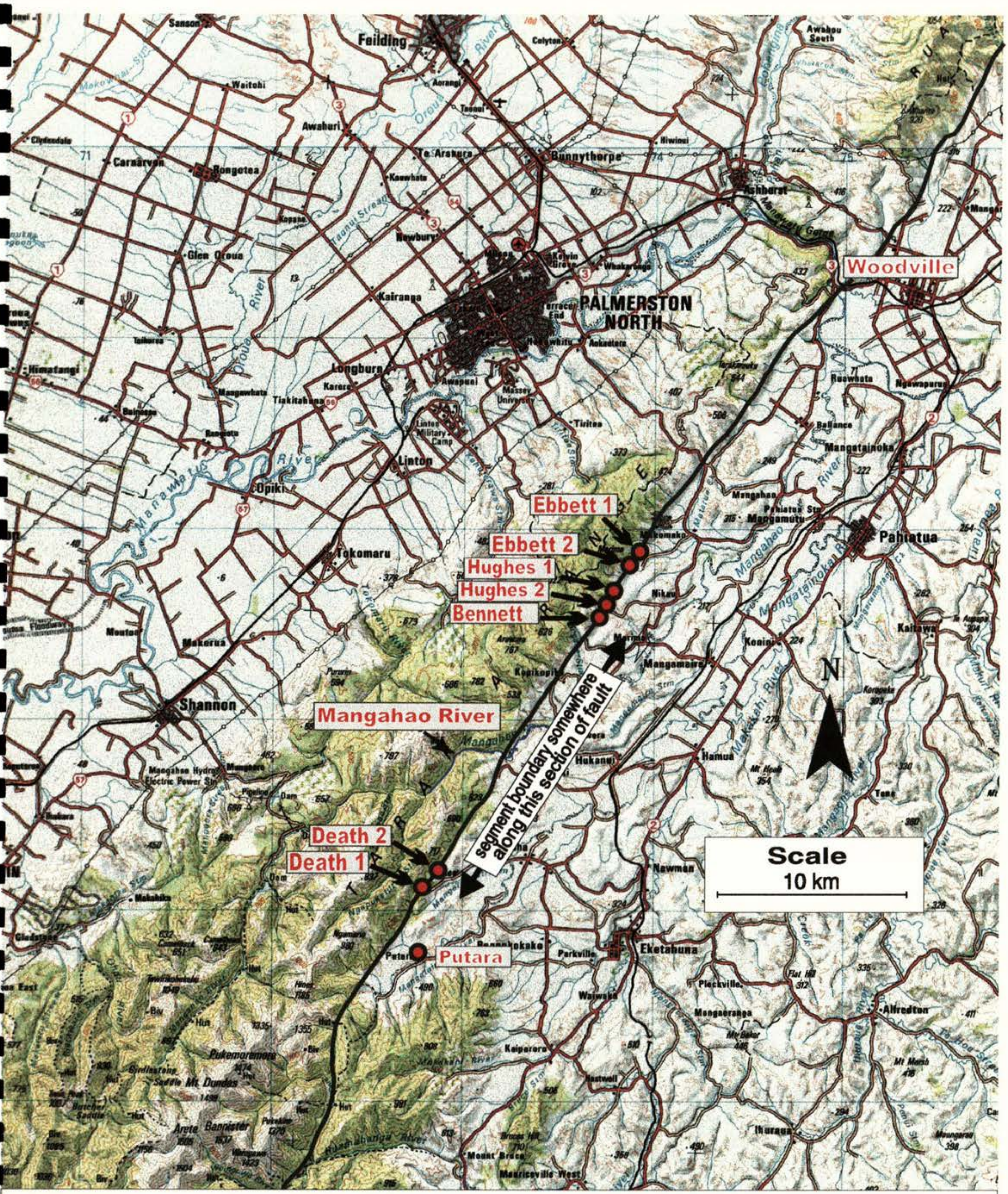


Figure 5. Map of Pahiatua section of the Wellington Fault, showing localities and trench site locations.

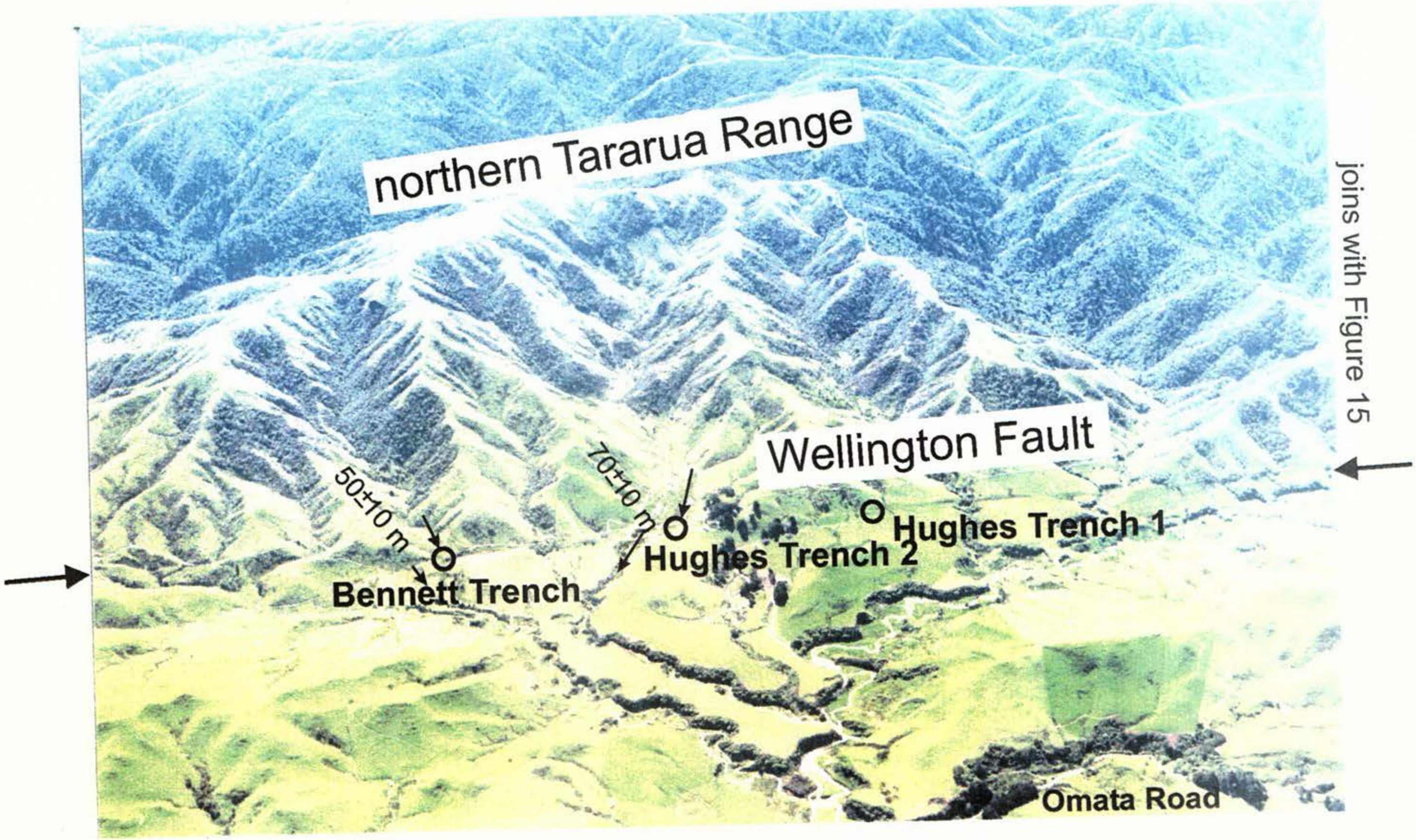


Figure 6. Photograph of part of Pahiatua section of the Wellington Fault, showing the location of the Bennett and Hughes trench sites, and prominent dextral offsets of topography in the vicinity. Photo: D.L. Homer, GNS.

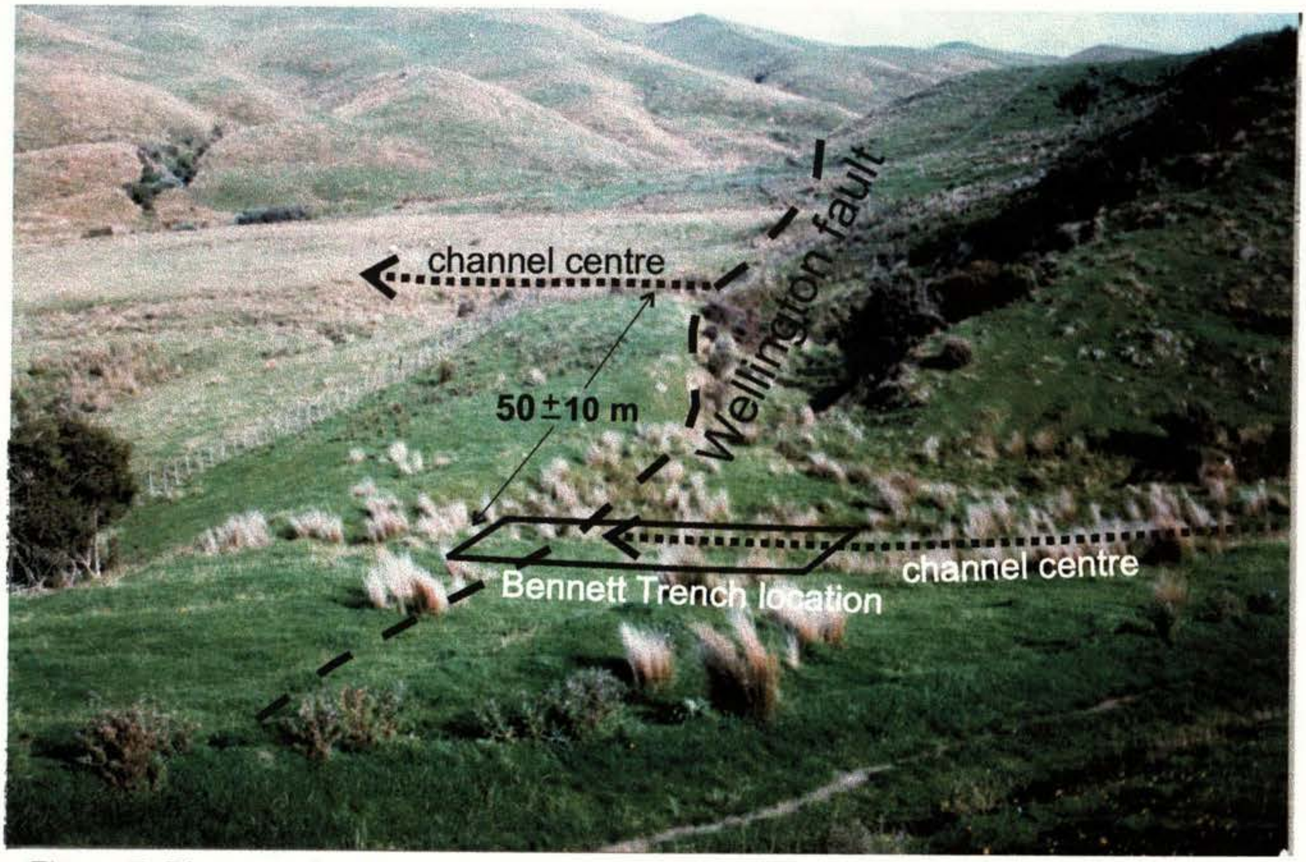


Figure 7. Photograph of the Bennett trench site, looking southwest, with the c. 50 m dextrally displaced drainage entering from the right, and exiting left from the end of the shutter ridge.

Figure 8. Photograph looking into the Bennett trench toward the fault scarp. Two faults are sketched to the right of the person in the trench. Numbers correspond to grid numbering of the trench log, presented in Figure 9.

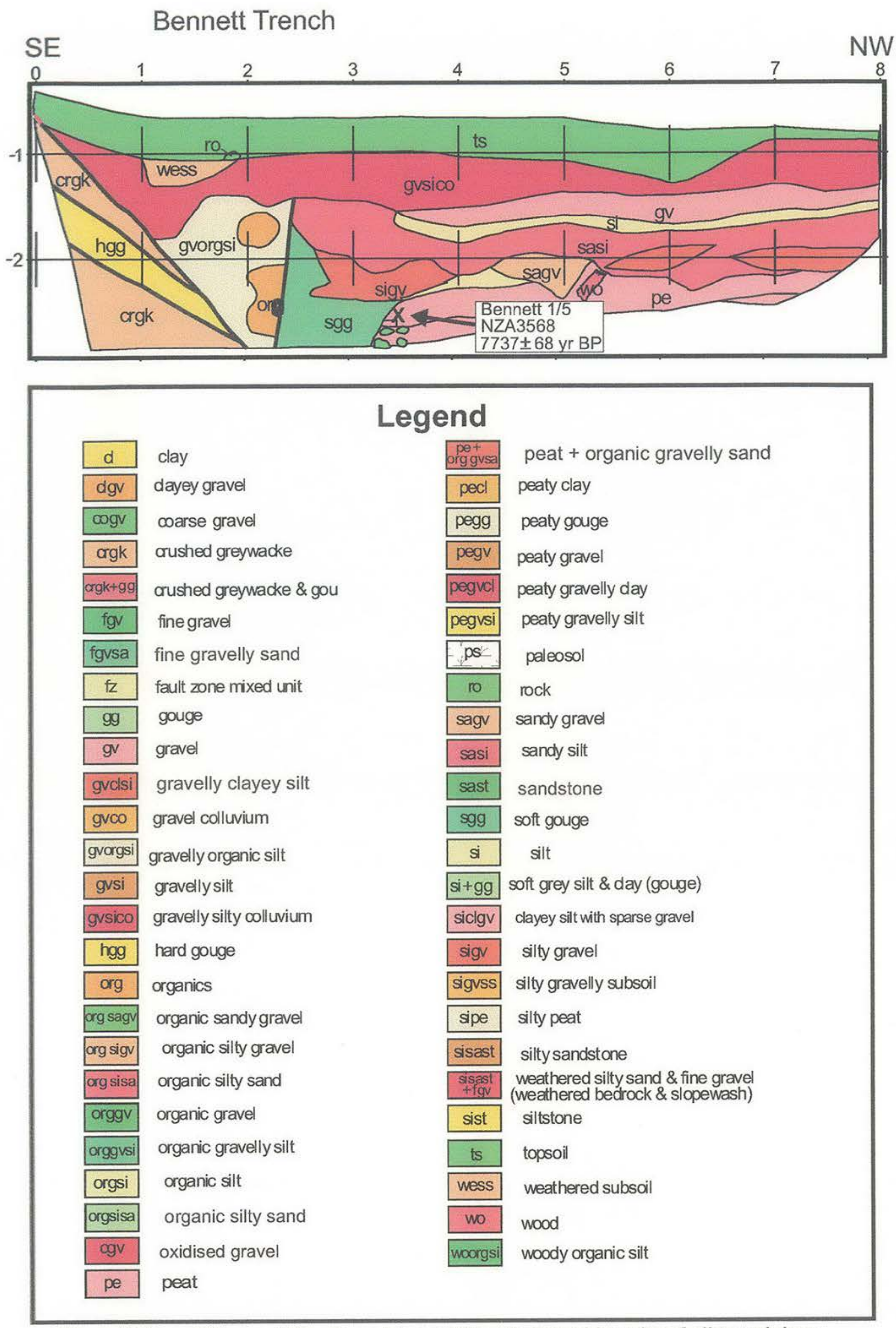


Figure 9. Log of Bennett trench and legend for stratigraphic units of all trench logs. See Figures 7 & 8 for field photographs.

Hughes 2 trench log

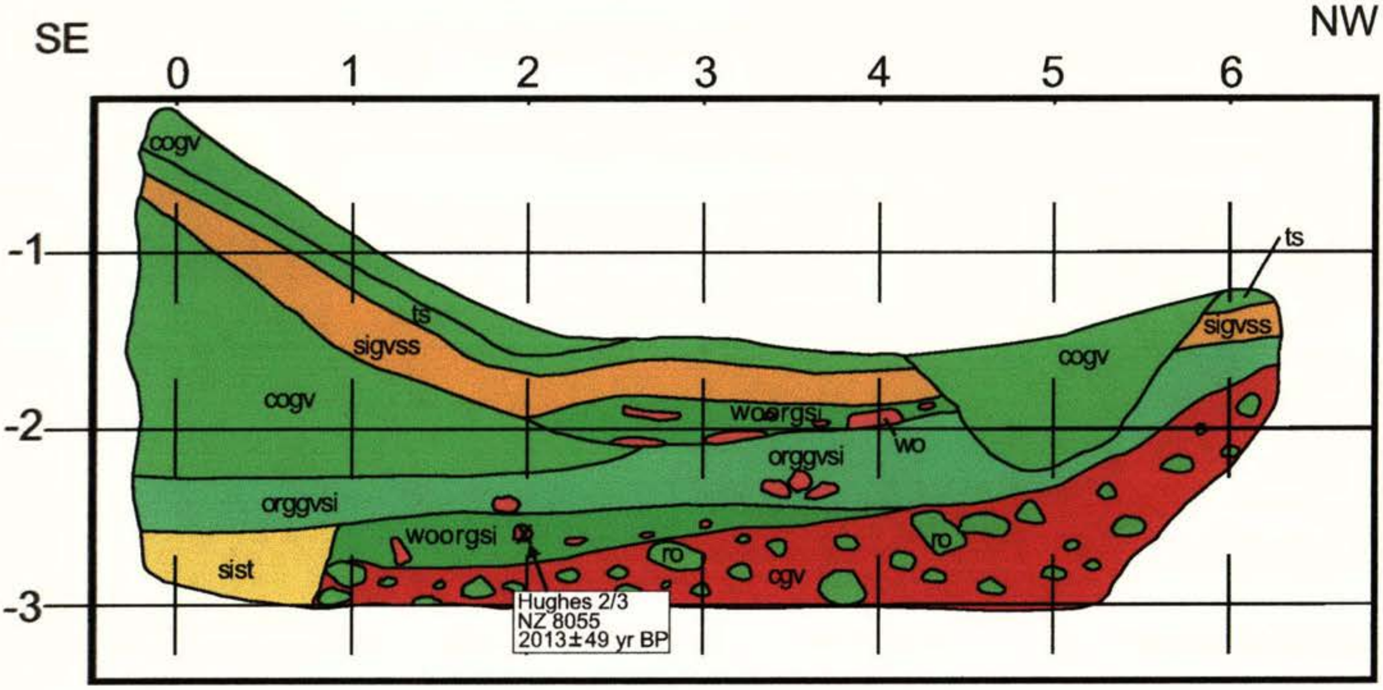


Figure 10. Hughes 2 trench log. Site was excavated into a terrace riser searching for deposits associated with the initiation of 70+/- 10 m of dextral displacement of the adjacent channel. See Figure 6 for location. Unit descriptions are shown in Figure 9. Grid is 1 metre.

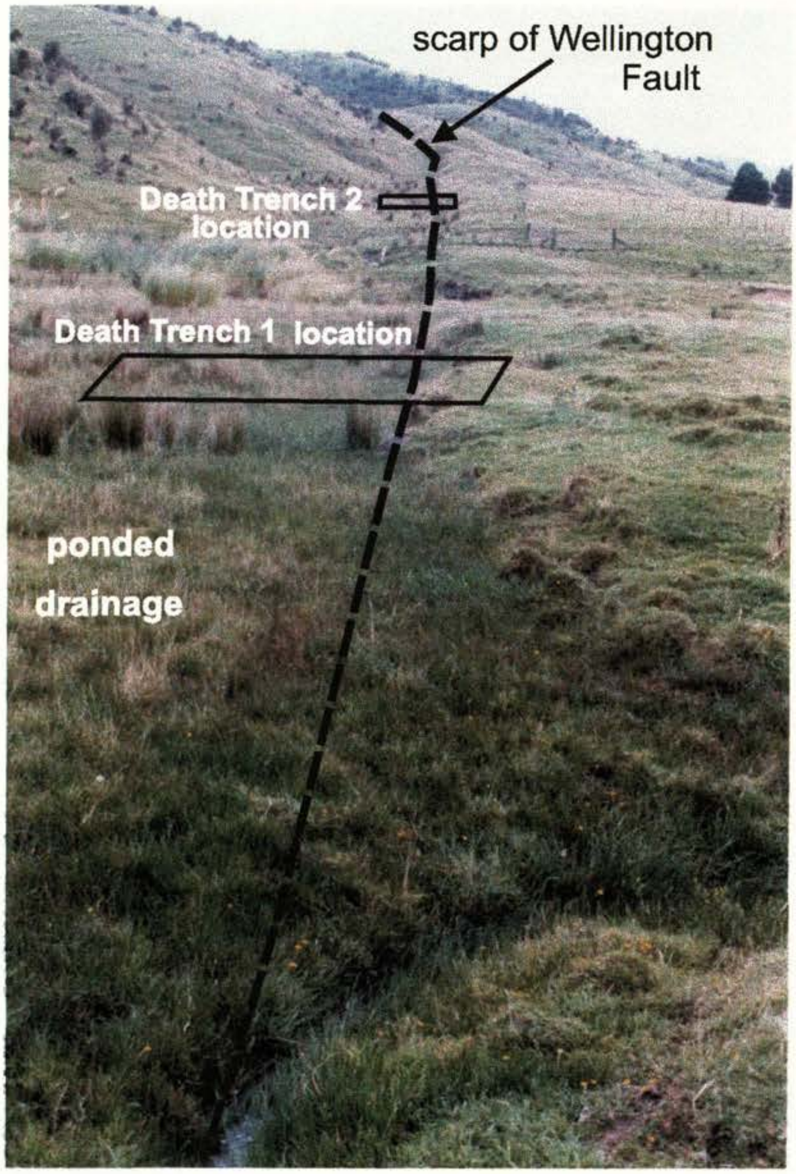


Figure 11. Photograph looking northeast along the trace of the Wellington Fault. Locations of Death 1 and Death 2 trenches are shown. See Figure 5 for location.

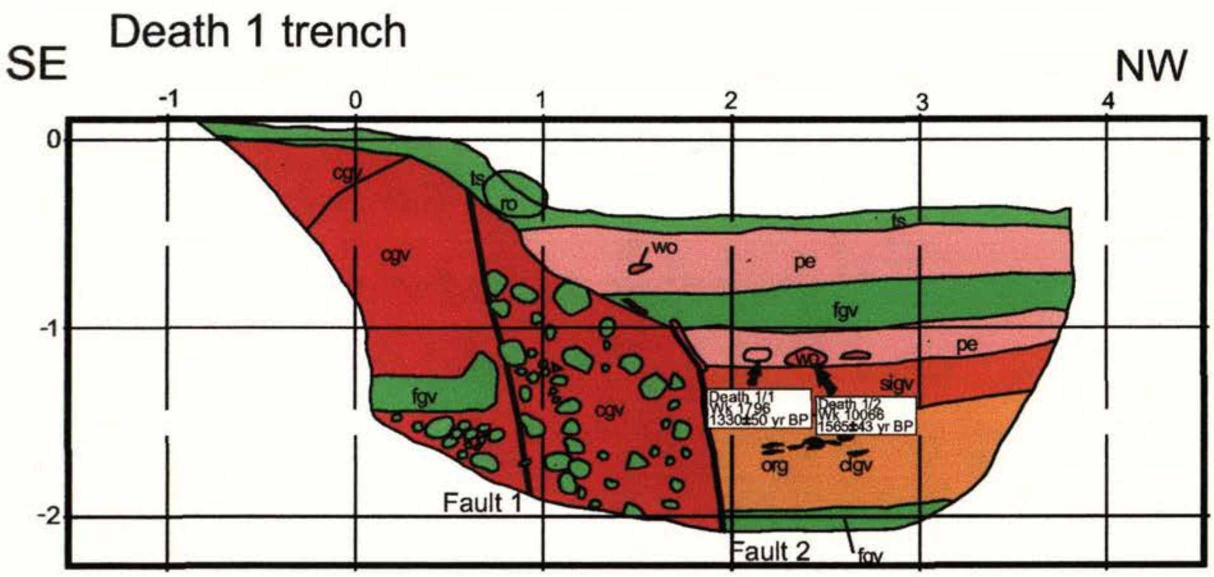


Figure 12. Log of northeast wall of Death 1 trench. See location of surface scarp and ponded drainage in Figure 11.

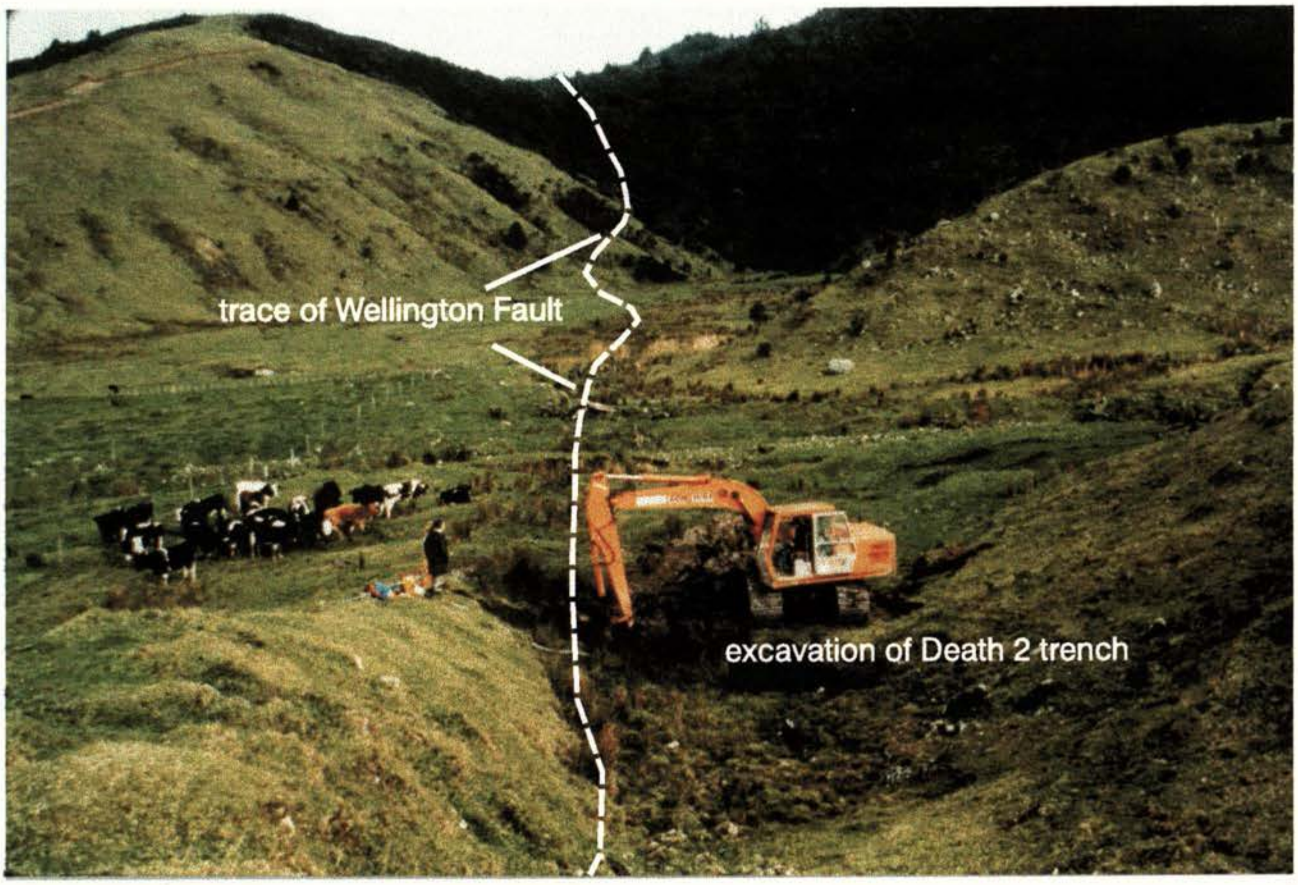


Figure 13. Photograph looking southwest along the trace of Wellington Fault and excavation of Death 2 trench.

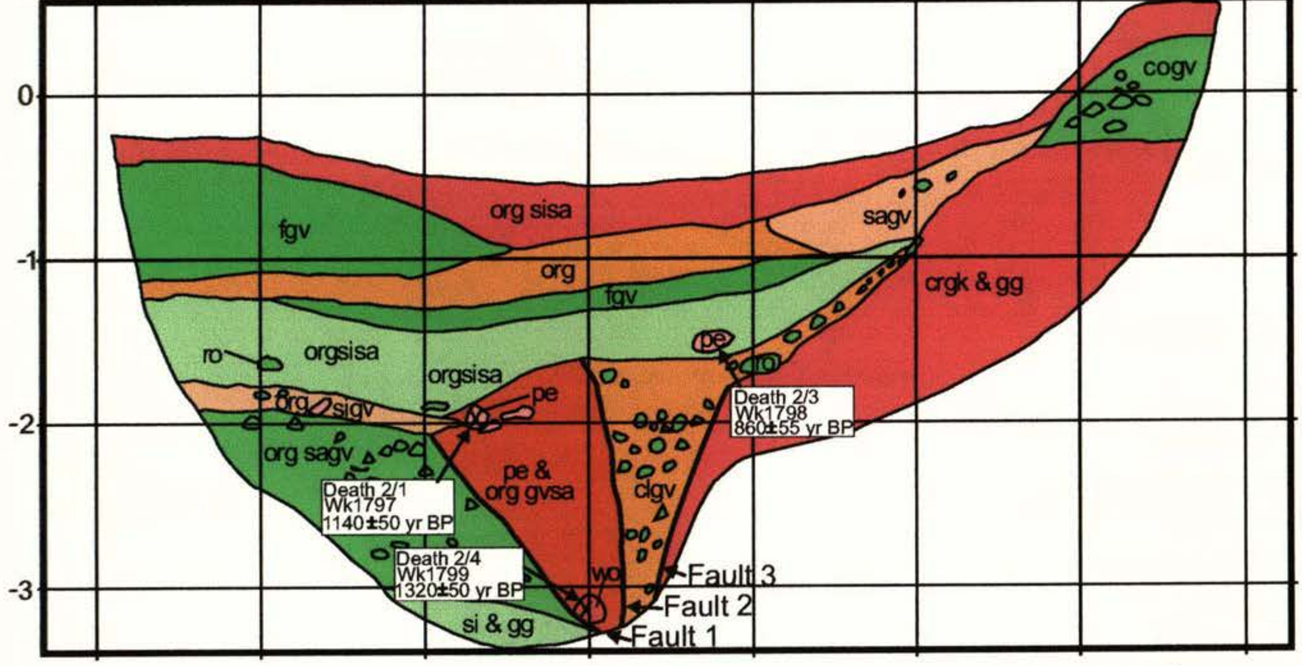


Figure 14. Log of northeast wall of Death 2 trench. See photograph above, and Figure 5 for location.

joins with Figure 6

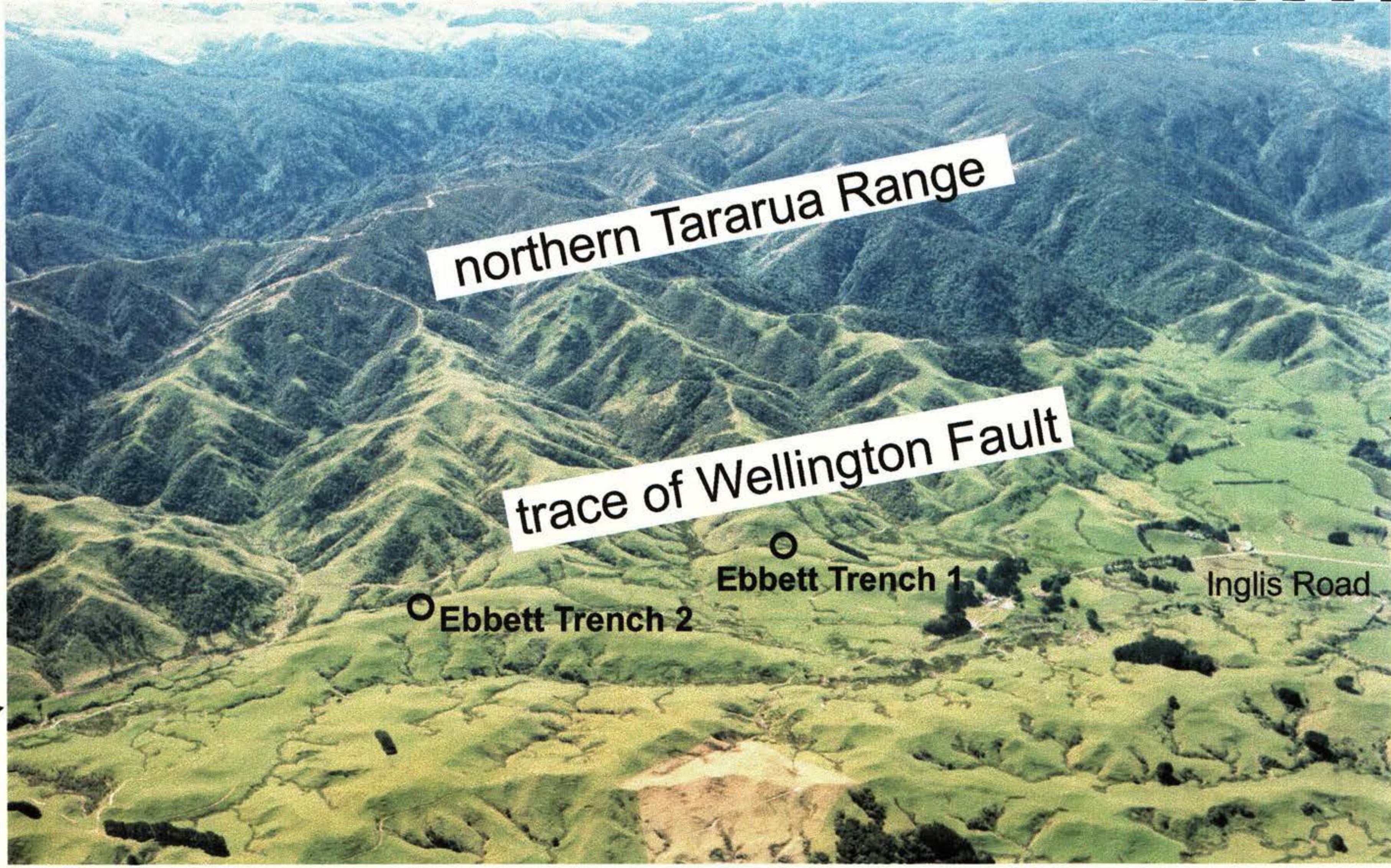
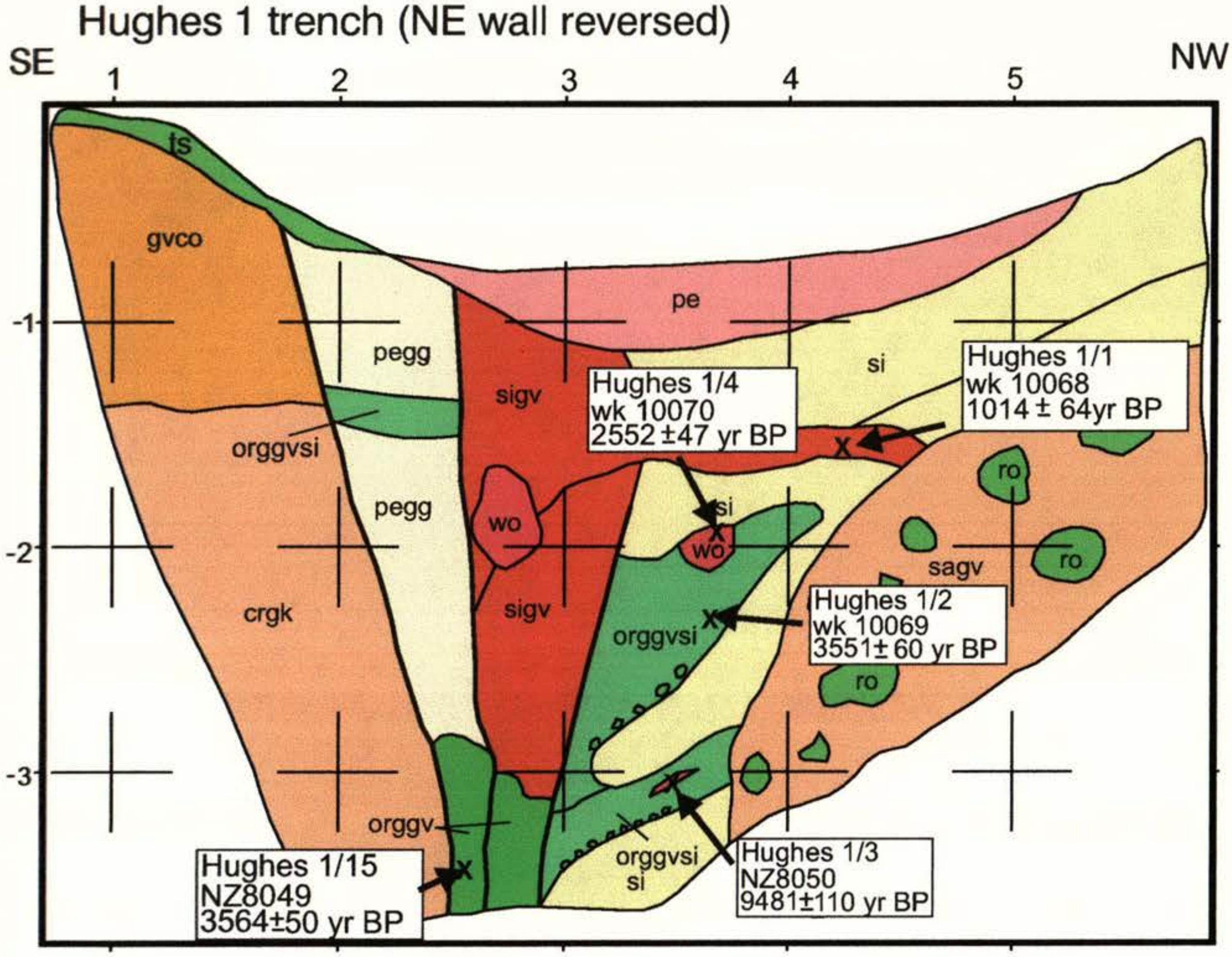


Figure 15. Photograph of part of the Pahiatua section of the Wellington Fault showing the location of the Ebbett trench sites. Numerous dextral displacements of ridges and drainages are visible along this section of fault. Photograph - D.L. Homer, GNS.



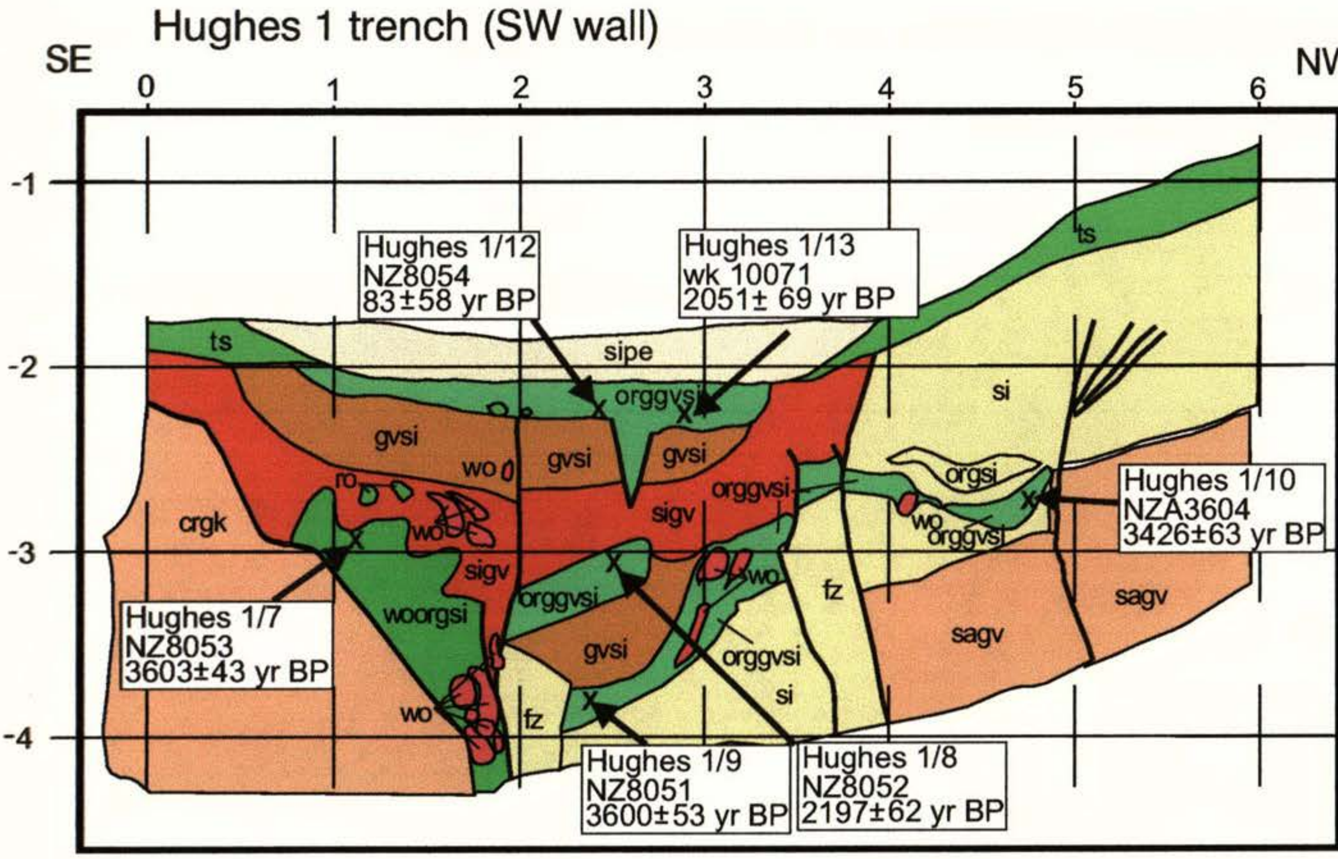


Figure 16. Hughes 1 trench trench log.

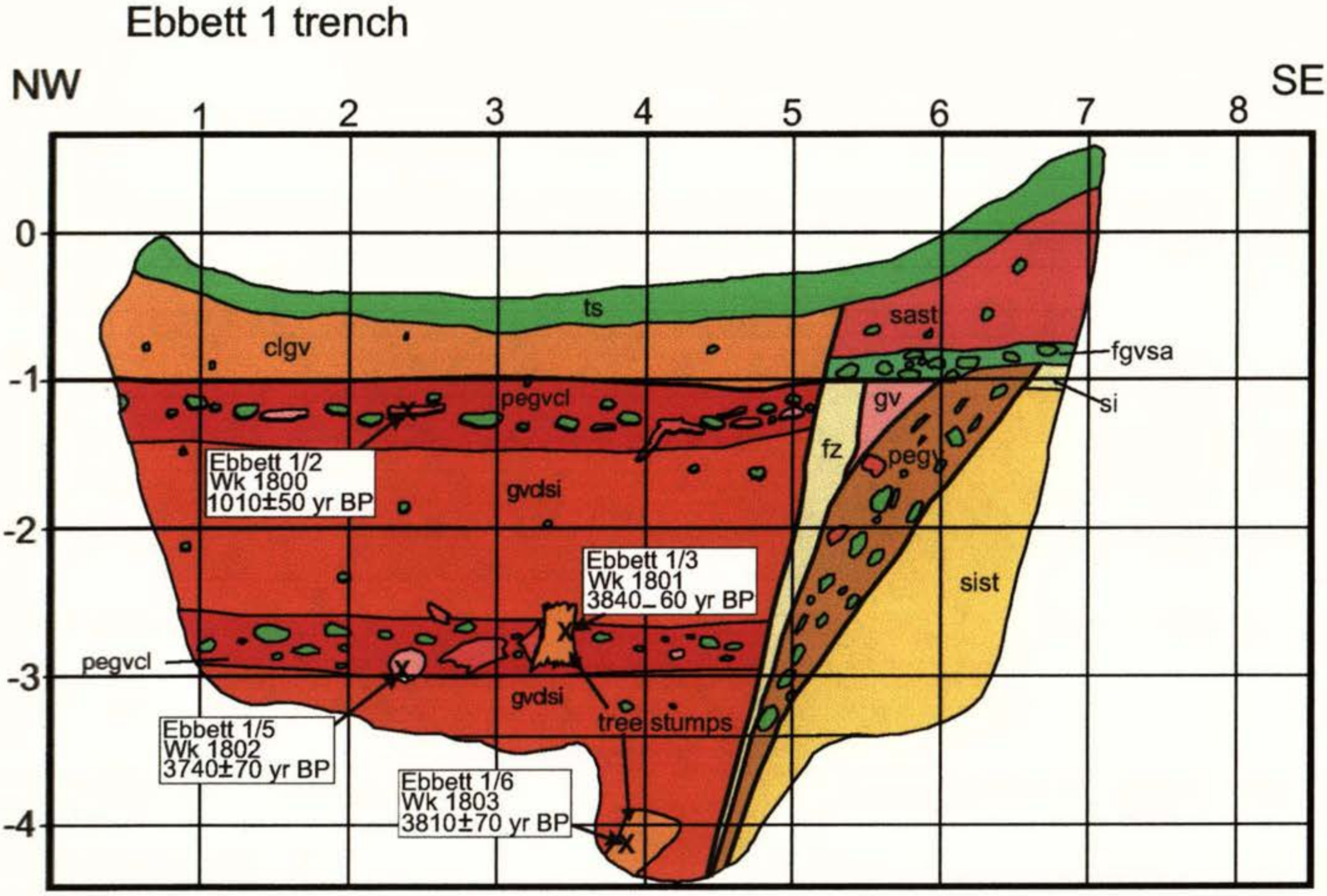
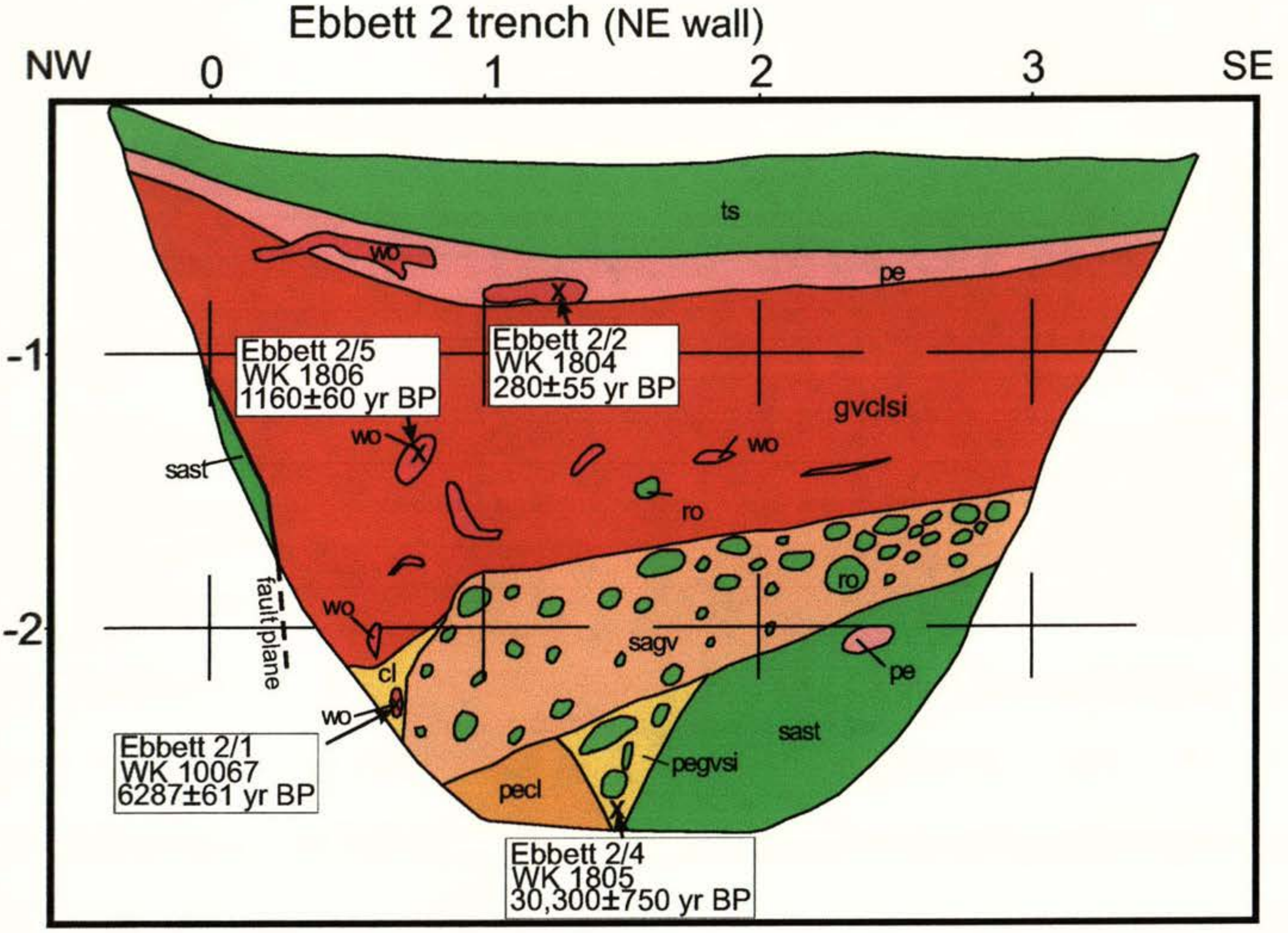


Figure 17. Log of northeast wall of Ebbett 1 trench.



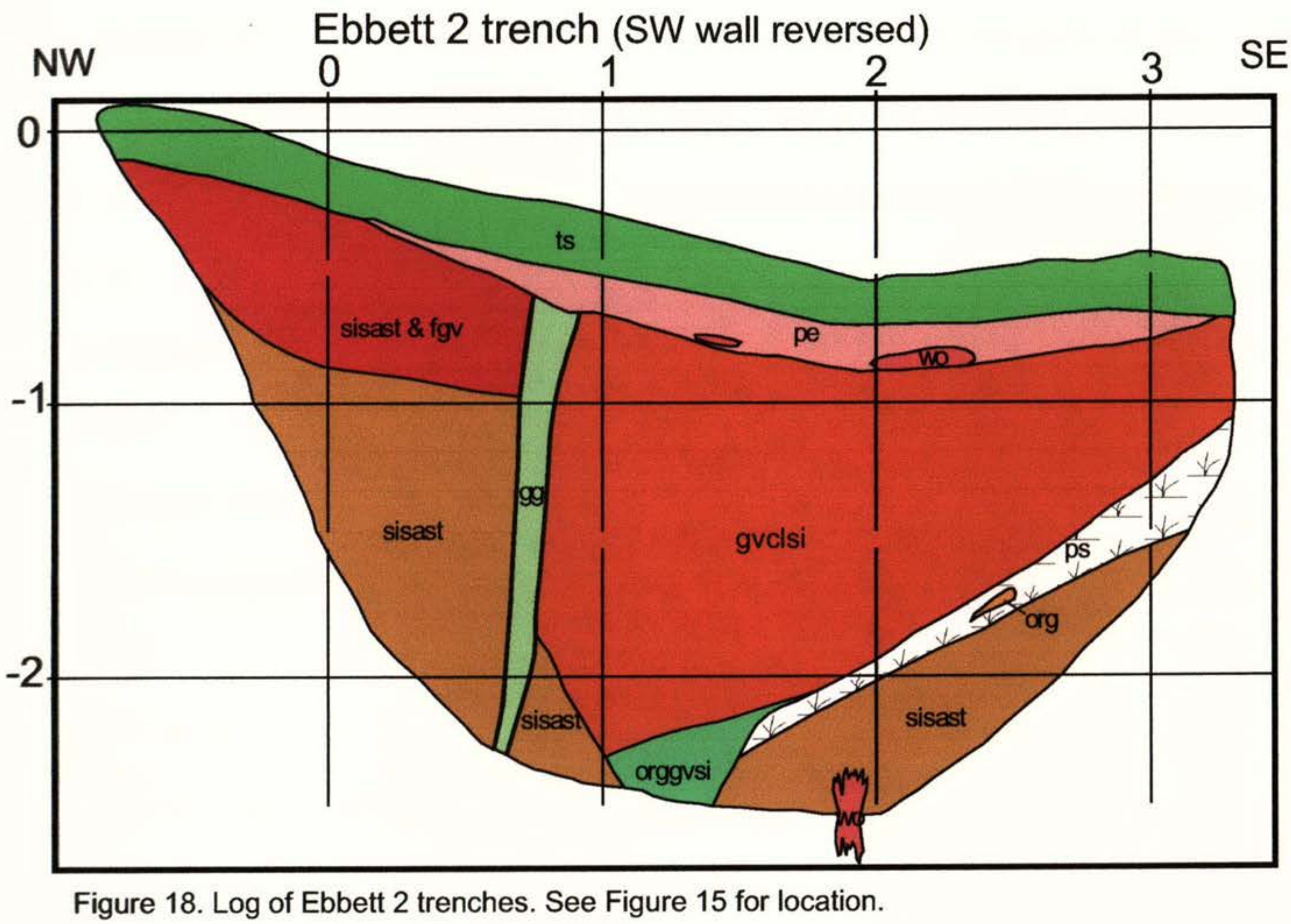


Figure 18. Log of Ebbett 2 trenches. See Figure 15 for location.

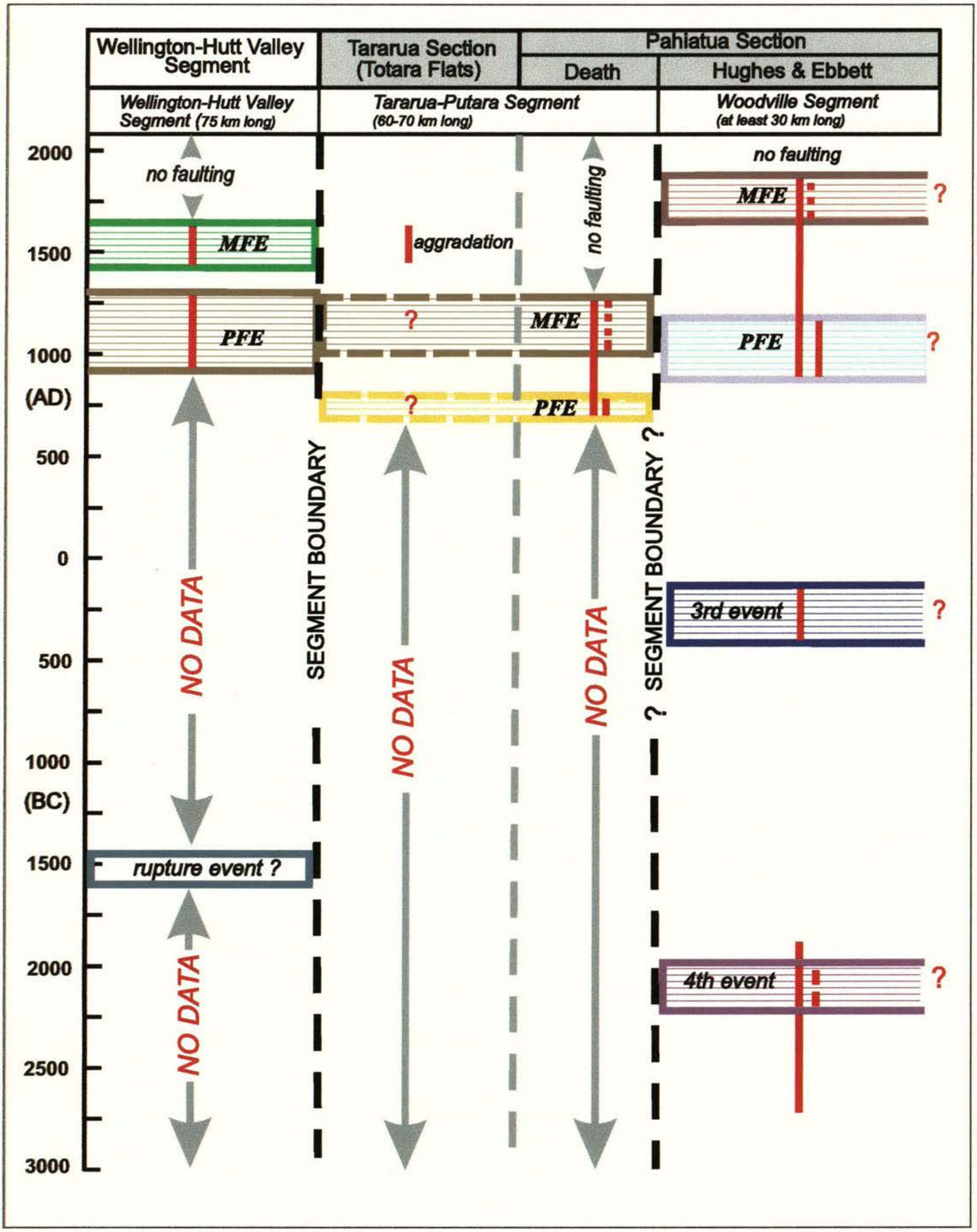


Figure 19. Summary figure showing fault rupture data for the past c. 5000 years presented in Table 4. The relationships between sections and interpreted rupture segments is illustrated. Most recent faulting events and penultimate faulting events are designated *MFE* and *PFE*, respectively. The earlier event on the W-HV segment is defined by Van Dissen et al. (1992).

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