FIELD TRIP 1

Wellington Fault: Neotectonics and Earthquake Geology of the Wellington-Hutt Valley Segment

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- photo caption -
Fault-line scarp of Wellington-Hutt Valley segment of the Wellington Fault. View looking NE, with Thorndon in foreground, Wellington Harbour (Port Nicholson) in middle distance, and Hutt Valley in background.
Photo: Annie Douglas.

- bibliographic reference -
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Neotectonics and Earthquake Geology of the Wellington-Hutt Valley Segment

Trip Summary

This all-day fieldtrip encompasses visits to key localities along the Wellington-Hutt Valley Segment of the Wellington Fault (Fig. 1) including, especially, sites where recent investigations have yielded new insights into the fault's rupture history and behaviour. We will examine and discuss its scarp and late Quaternary surface displacements, its relationship to the Hutt Valley basins, and the expression of its fault zone in bedrock. Visited sites will include, depending on weather and time constraints, some combination of the following (south to north): Te Kopahou/Long Gully, Thorndon overbridge, Petone foreshore, Te Mome Road (fault scarp through Lower Hutt), Manor Park, Trentham Memorial Park, California Park/Harcourt Park, Te Marua, Stuart Macaskill Lakes, and Kaitoke.

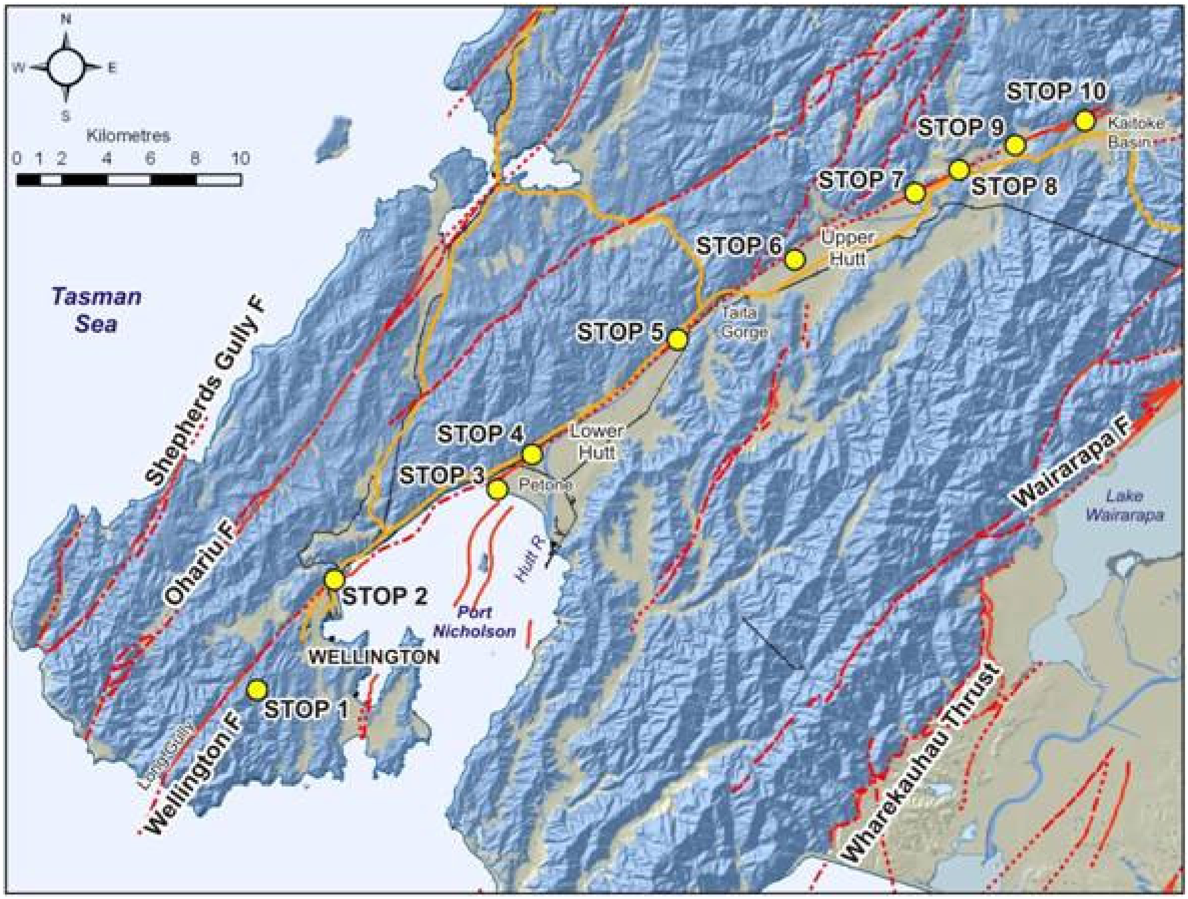


Figure 1. On-shore Wellington Fault, Wellington Hutt-Valley segment. Field trip stops are indicated, as are major Pleistocene to Recent depocentres (light shaded) in the region east of the Wellington Fault, including the Lower Hutt, Upper Hutt and Kaitoke basins. Development of the Port Nicholson/Lower Hutt, Upper Hutt and Kaitoke basins is described here in terms of active tectonics. The Wairarapa Fault (southeast of this map) is discussed in Field Trip 5 (Little et al, this volume).

Introduction

This field guide, in essence, provides an update of a popular Wellington Fault field guide published by the Geological Society of New Zealand in 1997 (Begg et al. 1997). There are many sites common to both guides and for those, the information presented here supersedes that in the earlier guide.

1997 was a fitting time to publish a Wellington Fault field guide as it marked the culmination of noteworthy earth science and earthquake engineering efforts in the Wellington Region and on the Wellington Fault itself. For example, the 1:50,000 scale geological map of Wellington had just been published (Begg & Mazengarb 1996), a summary paper detailing the paleoseismicity of the regions most hazardous strike-slip faults had just been published (Van Dissen & Berryman 1996), and the earthquake retrofit of the Thorndon overbridge was well advanced (Billings & Powell 1996). 2008 marks a fitting time to update the Wellington Fault field guide as significant new work has been undertaken along the Wellington Fault in recent years. This new work has been largely undertaken at Te Kopahou/Long Gully, Manor Park, Te Marua, and Kaitoke; and its importance with regards to better understanding and characterizing earthquake hazard in the Wellington region will be detailed in Stops 1, 5, 8 and 10, respectively (see Fig. 1) (see Langridge et al. this conference, Little et al. this conference). In fact, a highlight of this field guide is that it is the first place where the results of these new investigations are presented in some depth in a publicly available document.

This field guide starts with a brief summary of the It's Our Fault programme – the source of funding for much of the new Wellington Fault work reported here. Then it proceeds with a summary of the tectonic setting of central New Zealand and the Wellington Fault. The field guide then begins in earnest with each Stop covered sequentially, from southwest to northeast.

It's Our Fault

The overall goal of the "It's Our Fault" programme is to see Wellington positioned to become a more resilient city through a comprehensive study of the likelihood of large Wellington earthquakes, the size of these earthquakes, their effects and their impacts on humans and the built environment (see Van Dissen et al. 2007 & this conference). The It's Our Fault programme was launched three years ago, is jointly funded by EQC, ACC & Wellington City Council, and comprises four main phases - Likelihood, Size, Effects and Impacts. Work to date has been focused within the first phase (Likelihood). The three main aspects of the Likelihood Phase are: 1) geological investigations to extend and further constrain the sequence of surface rupture earthquakes on the major Wellington region faults (including, importantly, the Wellington Fault), and to better constrain their location and rate of movement; 2) GPS studies of the Wellington region to constrain the extent of the currently locked portion of subduction thrust under Wellington; 3) synthetic seismicity modelling of the Wellington region to investigate the stress interactions of the major faults, and specifically to assess the rupture statistics and interactions of the Wellington-Wairarapa fault-pair. A number of talks at this Geosciences '08 conference will be presenting exciting results from specific investigations that comprise the Likelihood phase (Barnes et al. this conference, Langridge et al. this conference, Little et al. this conference, Wallace et al. this conference, Wilson et al. this conference).

Tectonic environment

New Zealand sits astride the active transpressional boundary zone between the Pacific and Australian plates (Fig. I.1). The plate boundary through New Zealand is complex, with westward-directed subduction of the Pacific Plate beneath the Australian Plate under the North Island, and eastward directed subduction of the Australian Plate beneath the Pacific Plate to the south of the South Island. These two subduction zones are linked through the South Island by the predominantly strike-slip Alpine Fault and Marlborough fault system.

In more detail in the Wellington region, subduction of the oceanic Pacific Plate beneath the continental Australian Plate commences at the Hikurangi Trough about 150 km east of Wellington City off the Wairarapa coast (Fig. I.2). Plate convergence in the Wellington region is about 40 mm/yr at an azimuth of about 260°. The gently northwest-dipping subduction interface lies at a depth of about 25-30 km beneath the city (Fig. I.3).

Deformation resulting from the convergent collision between the Pacific and Australian plates is largely partitioned into plate margin-normal and plate margin-parallel components, with strain mostly stored and released in the North Island part of the boundary zone between the Hikurangi Trough and the western side of the New Zealand landmass. A significant portion of the margin-parallel strain component, especially in the southern North Island, is carried to the surface along a series of northeast-striking strike-slip faults known as the North Island Fault System (Fig. I.2). At least some of these faults, including the Wellington and Wairarapa faults, are thought to propagate all the way from the subduction interface to the surface (Fig. I.3).

The only two major geological units exposed in the Wellington area are the largely Mesozoic basement greywacke (Rakaia terrane of the Torlesse composite terrane), and a Mesozoic zone of similarly lithified but more deformed rocks, the Esk Head melange, a unit derived from the Mesozoic process of suturing of Rakaia and the slightly younger Pahau terrane (see Begg & Johnston 2000 and references cited therein). The only other widespread geological units in the Wellington region are those of Pleistocene and Holocene age. These geological units, some old landforms and their chronology, are the principal tools available to understand Wellington's geological past and the history of the Wellington Fault.

Post-Pliocene deposition in the Lower Hutt and Upper Hutt valleys reflects interplay between the active tectonic processes of the region during the ?Early Pleistocene to Holocene, and global sea level change. Sedimentation and deformation in the area are influenced primarily by the Wellington Fault, an active dextral strike-slip fault with varying uplift and subsidence along its southern extent (Fig. I.4).

The Wellington Fault

The Wellington Fault is one of the longest and most laterally persistent of New Zealand's on-shore active faults. From its southernmost known location in Cook Strait (Barnes et al.

2008 & this conference), it can be followed for some 420 km more or less continuously northwards past the south Wellington shoreline, through Wellington and the Hutt Valley, through the Tararua Range to the Manawatu River. Beyond the Manawatu River the fault changes only by name and continues northwards to the coastline of the Bay of Plenty (Fig. I.2) close to where it is truncated by the active faults of the Taupo Rift.

Along its southern part, the Wellington-Hutt Valley segment, it has a high lateral slip rate (ca 6-7.6 mm/yr) (Berryman 1990) and varying rates of throw. Here, several significant bends (ca 10-15^{o}), when combined with the fault's predominantly dextral sense of displacement, have resulted in development of a series of basins adjacent to the fault (see Fig. 1). The characteristics of the fault plane are known from relatively few exposures, but the comparatively straight scarp, even where crossing topography is consistent with known exposures, and indicates a steeply dipping to vertical plane. In general, the upthrown side of the fault is to the west, but locally there are traces and scarps upthrown to the east (e.g. Thorndon seabed; Te Marua).

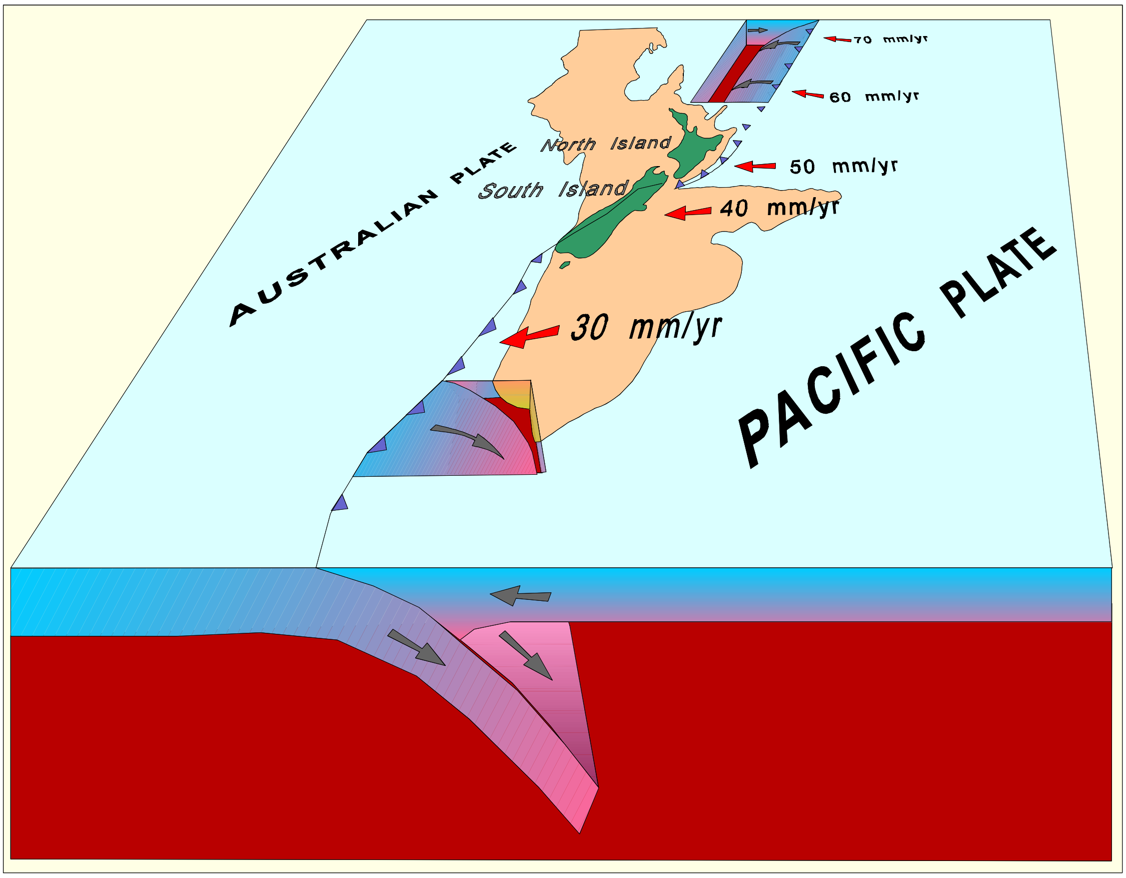


Figure I.1. Cutaway representation of the plate boundary configuration in the New Zealand area. Offshore areas with medium shading (light brown) are underlain by continental-type crust. Note that the Pacific Plate is subducted beneath the Australian Plate in northern New Zealand, while the Australian Plate is subducted beneath the Pacific Plate in the south (after Stevens 1974). Arrows and numbers indicate value and azimuth of the plate convergence vectors.

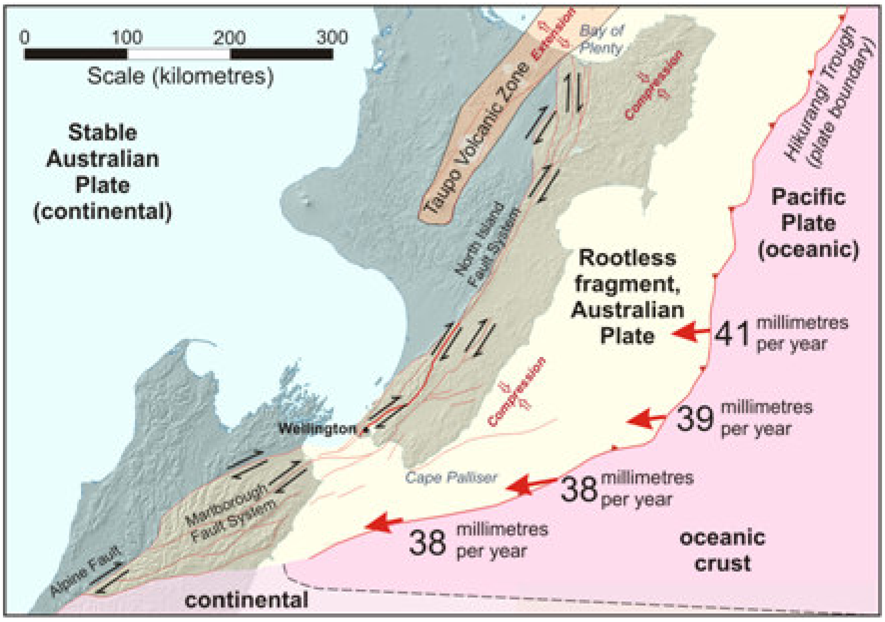


Figure I.2. Important plate boundary features of North Island and northern South Island, New Zealand. East of the North Island, the Pacific Plate is oceanic in origin, and converges with the continental Australian Plate at rates marked beside red arrows. The rootless eastern edge of the Australian Plate rides on top of the down-going Pacific Plate. Resulting plate margin-normal strain is accommodated as deformation between the Hikurangi Trough and the North Island Fault System, perhaps mainly as slip on the subduction interface. Margin-parallel strain in southern North Island is, in large measure, transferred from the plate interface to the North Island Fault System and released there. The Taupo Volcanic Zone is a fast-spreading rift and is associated with the eastward rotation of the Raukumara peninsula. After Begg et al. (2008).

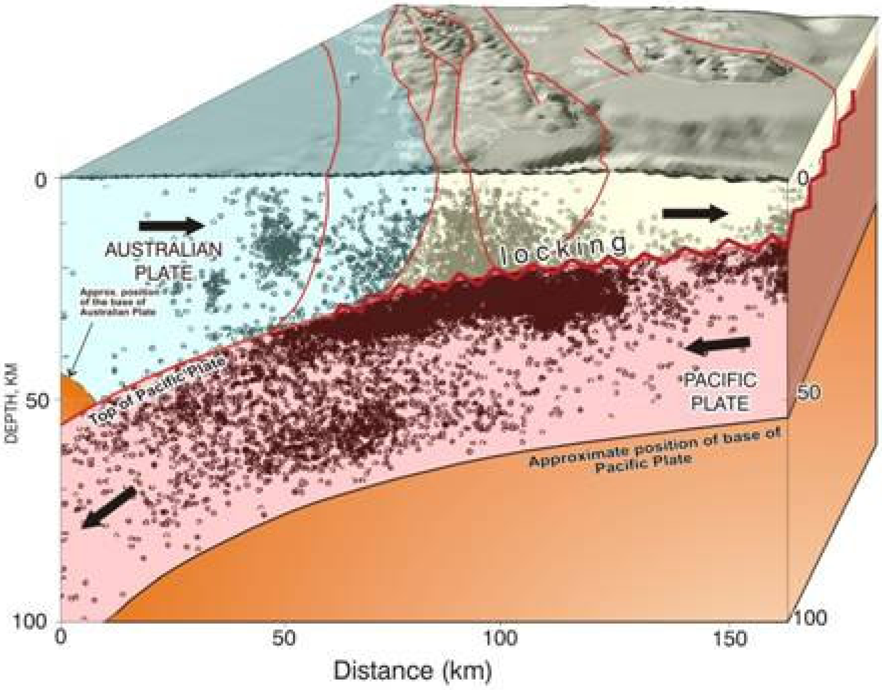


Figure I.3. Scaled diagram illustrating the location of the subduction interface beneath Wellington City and possible relationships between some of the active faults of the North Island Fault System (after Begg & Johnston 2000; extent of subduction zone locking after Wallace et al. manuscript in prep.). The cloud of dark spots represent microearthquakes recorded between 1987 and 1993 from a zone within 20 km of the section plane, and allows a relatively accurate estimation of the location of the subduction interface. The largest of the microearthquakes measured is M 4.

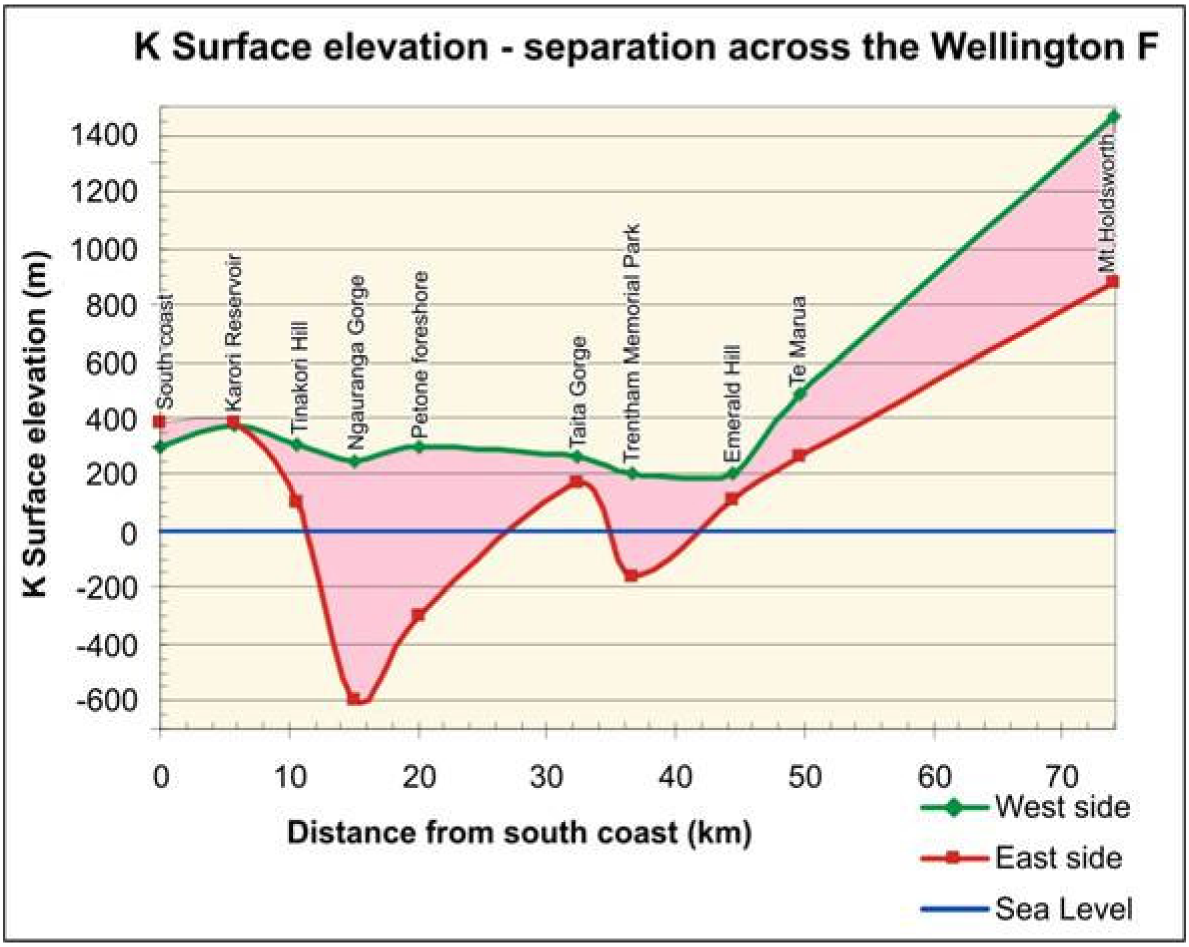


Figure I.4: Two profiles on the basement greywacke surface, one each side of the Wellington Fault, from the Wellington south coast (left) to the southern end of the Tararua Range, illustrating cumulative vertical offset of the K-Surface. Elevations of the K-Surface (or equivalent) on the eastern side of the fault near Ngauranga Gorge and Trentham Memorial Park are based on seismic profiles (Wood & Davy 1992; Melhuish et al. 1997), and at the Petone foreshore from the Gear Meat drillhole. Sea level is marked as a blue line, and the apparent vertical separation is highlighted in pink. Note that except for the first six kilometres, the surface is downthrown on the southeastern side, and that most of the variation in elevation is also on the southeastern side of the fault. Note also that the base of the Port Nicholson/Lower Hutt and the Upper Hutt basins extends well below the elevation of the edge of the continental shelf.

Stop 1: Brooklyn Wind Turbine – an overview of the Wellington Fault

The Brooklyn Wind Turbine is a good place to begin this field trip. Here, we get an impressive overview of Wellington City and Port Nicholson (see Frontispiece) and get an impression of how the Wellington Fault dominates the physiography of the national capital. Just beyond the wind turbine is the mammal-proof fence that surrounds the Karori Wildlife Sanctuary, another area traversed by the Wellington Fault. In addition, from here we can discuss new Wellington Fault paleoearthquake investigations to the south in Long Gully Station that have been undertaken as part of the 'It's Our Fault' project.

Te Kopahou trench site

The Te Kopahou trench site is located at Long Gully Station and overlooks Cook Strait, south of Wellington City (Fig. 1.1) (grid ref. R27/522835). Two new paleoseismic trenches were excavated across the Wellington Fault there in 2007 at a site where a shutter ridge had been displaced right-laterally across (and deflecting) a drainage. Surveyed points along this drainage indicate it is right-laterally deflected by ca 47 m, and the mean lateral displacement from the 5 spurs and gullies shown in Fig. 1.1 is ca 52 m. As the shutter ridge was laterally displaced, the drainage became ponded behind and internally drained and a swampy pond developed adjacent to the fault. The aim of both trenches was to span the fault zone from the shutter ridge across into alluvial and swamp deposits of the shutter basin. In both trenches we exposed the trace of the Wellington Fault as a ca 50° SE-dipping fault plane adjacent to the shutter scarp. The fault has a strike of ca 050° in this area.

Te Kopahou trench-1

Te Kopahou trench -1 (TK-1) was sited across a modern peat swamp adjacent to the shutter ridge, separated by the trace of the Wellington Fault. TK-1 exposed repeated sequences of colluvial/scree deposits interbedded with peat/ soil units (Fig. 1.2). Buried peats within the shutter basin graded laterally into soils towards and across the fault, as observed at the ground surface today.

The peats and soils are interpreted as having formed over long stable periods of time, which we correlate with inter-seismic periods (estimated to be many centuries in length) between surface rupturing earthquakes. Interbedded with the peat are thick, scarp-derived colluvial deposits sourced from the shutter ridge to the NW, and angular scree deposits sourced from the steep hillslopes of the Te Kopahou rangefront directly above the shutter basin to the SE. The greywacke adjacent to the fault in the shutter scarp is highly fractured and pre-conditioned to being reduced to colluvium under strong shaking. There are 4 distinct scarp-derived colluvial packages identified in TK-1. Light brown, buried soils were formed on colluviums -4 (unit 4c1) and -3 (unit 3c) and a modern soil was forming on unit 1c at the ground surface on the scarp. We consider the colluvial and scree units formed rapidly following each surface faulting event as a consequence primarily of very strong ground motions and, for the scarp derived colluvial units, possibly also free-face collapse. We interpret this stacked sequence of peat/ colluvium units as a series of inter-seismic/co-seismic depositional couplets in the shutter basin.

Assuming that the peat/colluvium couplets are earthquake rupture generated, this trench, with its many peats, soils and wood, provides an abundance of radiocarbon dating opportunities with which to characterise the timing of earthquake events on the Wellington Fault, discussed below. Eight AMS radiocarbon samples were submitted for dating. Small, 3-4 cm sized twigs were selected from within the peat samples for dating. In some cases the outer part of larger tree branches or trunks were dated. Four levels within the 4p peat near the base of the trench (Units 4sp-4p-4ps) were sampled for dating. The deepest of these (sample TK1-1), a twig from the basal, stony peat (4sp), yielded an age of 2565 ± 30 radiocarbon yr BP (2460-2740 cal yr BP at 2 sigma level) (Fig. 1.2). The uppermost of the four dates from the 4p peat complex yielded an age of 2369 ± 30 yr BP (TK1-4; 2208-2355 cal yr BP). Thus, this thick peaty unit formed over a period of at least 100 yr and possibly >500 yr. Sample TK1-7, a twig from the base of the youngest peat horizon yielded an age of 889 ± 30 radiocarbon yr BP (688-794 cal yr BP). Based on this date, peat 1p formed over at least 740 yr at an average accumulation rate of ca 0.6 mm/yr. Three other samples located stratigraphically between peats 1p and 4p were dated in this study. These gave ages in stratigraphic order, providing confidence that no obvious recycling of organic fragments has occurred through the section.

Te Kopahou trench-2

Trench TK-2 was sited about 15 metres to the south of trench TK-1. In this trench, the Wellington Fault, expressed as a NE-striking, SE-dipping clay-rich gouge zone juxtaposes clastic colluvial units against sheared bedrock. TK-2 had a similar stratigraphic sequence to TK-1, with at least 3 distinct, scarp-derived colluvial wedge packages grading outward from the shutter scarp and across the shutter basin to interfinger with rangefront-derived, angular scree units. However, trench TK-2 lacked significant organic horizons and exhibited only weak paleo-soil horizons on each colluvial package.

Faulting exposed in Te Kopahou trenches and sense of displacement

Both trenches are characterised by a moderately dipping (ca 45° SE) fault zone that has higher-angle splays which propagate into the basin deposits. In TK-1, these splays comprise 2 faults with dips of 60-85° (faults F1b and F1c; Fig. 1.2). In TK-2, the zone of splay faulting was wider (up to 2 m) and formed a graben with bounding fault dips of 60-75° E and 42-75° W. One slickenside measurement was recorded within the dcm-wide, dipping gouge zone of the main fault in trench TK-2. The rake of the slickensides was ca 1°, confirming that the movement is essentially pure strike-slip.

Paleoseismic Event History

The Te Kopahou site provides radiocarbon age constraints for the last 4 surface-rupturing earthquakes on the Wellington-Hutt Valley segment of the fault. The paleoseismic event evidence is closely tied to the generation of wedge-shaped, scarp-derived colluvial deposits. These are believed to be generated during, and subsequent to, violent shaking at the time of Wellington Fault displacement events. Under this model, the base of each colluvial package should correspond with an earthquake event horizon. As these colluvial units generally overlie a paleosol or peat horizon, the top of those dateable units become maximum (or equivalent) age marker horizons for each seismic event. In no place do the peats approach the fault zone, so the package boundaries are used to establish the relationship with the faulting.

Most recent event

The most recent earthquake event is defined by the upward termination of the main fault bounding the greywacke shutter scarp by colluvium 1c which drapes the scarp and the tip of this fault (Fig. 1.2). Unit 1c is thin and has formed in part from the re-mobilisation of colluvium 2c and its soil on the scarp (note: colluvium 2c is faulted - sheared between two fault strands and against the shutter ridge - while colluvium 1c is unfaulted). A medium brown soil (1s) is currently forming on colluvium 1. The construction of a farm track has somewhat disturbed colluvium 1 and its soil. The most recent event cannot be easily dated at this trench because colluvium 1c does not extend as far as the datable unit 1p peat. From these observations it is clear that unit 2c was present and faulted during the most recent event, while colluvium 1c was generated as a consequence of the earthquake. A maximum age for the most recent event comes from sample TK1-7w, which comes from the base of peat 1p. The age of this sample was 889 ± 25 radiocarbon yr BP (688-794 cal yr BP). Van Dissen et al. (1992a) suggest an age of ≤300-450 cal BP (AD 1500-1650) for this event from Trench 6 at Long Gully, ca 1.8 km to the NE.

Faulting in the secondary zone (F1b and F1c) appears to disrupt the base of colluvium 2c. This disruption may have occurred during the most recent event or possibly during the previous event as a depositional relationship against a fault free-face against which colluvium 2c was deposited.

Event II

The thick Unit 2c is interpreted as a scarp-derived colluvial wedge generated in response to strong ground shaking during Event II (colluvial wedge 2c). Unit 2c is at least 0.5 metre thick across a 9 metre length of the trench and reaches a metre in thickness at the fault zone. At its distal end, unit 2c overlies Unit 2x, which is composed of angular, cobble sized blocks of greywacke. Unit 2x thins to the SE and must have originated from the rangefront slope and is interpreted as a scree fan deposit. Event II is interpreted to have occurred at the base of unit 2c. Here, this unit overlies a silty gravel unit and does not directly overlie a buried peat/soil horizon. In this case we believe that the silty units 2g and 2z2 covered the soil some time before the earthquake event. At the fault zone there is independent evidence for Event II. Faults F1b and F1c have displaced pre-existing units (e.g. unit 2z2, 3ps and 3c), but the base of younger unit 2c2 shows only minor disruption across these faults. In summary, Event II involved rupture on Faults 1b and 1c (and certainly the main fault plane as well) and resulted in displacement of pre-existing beds and the deposition of colluvium 2.

Three radiocarbon samples (TK1-6, -7 & -10) have been dated from units 2p (peat) and 2z1 (silt) that overlie the colluvium (2c) and scree (2x) deposits and therefore post-date Event II. Twiggy sample TK1-6 from immediately above Unit 2x within peat 2p yields an age of 996 ± 30 yr BP (788-928 cal yr BP). This date provides the best minimum age of Event II from trench TK-1. From Trench 1 at Long Gully, Van Dissen et al. (1992a) present an age of 790-930 cal yr BP for material that was probably faulted during Event II. This age range is essentially the same as for material unfaulted by Event II at trench TK-1 and implies a tight age constraint of ca 790-930 cal yr BP for this event.

Event III

Faulting relationships are more difficult to follow for older events. However, based on the presence of another colluvial wedge (unit 3c) a third paleoseismic event is inferred. The minimum age for this event comes from a piece of charred wood (sample TK1-5) within the paleosol unit 3ps, which formed on colluvium 3c. This sample post-dates Event III faulting, pre-dates Event II (because it underlies unit 2c), and yielded an age of 2033 ± 30 yr BP (ca 1833-1996 cal yr BP). A maximum age for Event III is provided by two samples (TK1-3 & TK1-4) from near the top of unit 4p peat which underlies the unit 3c colluvium. These samples yield ages of 2277 ± 30 yr BP and 2369 ± 30 yr BP, respectively. The maximum 2-sigma calibrated range for sample TK1-3 (2131-2338 cal yr BP) is slightly younger than that for sample TK1-4 and is used here as the maximum age for Event III faulting. Collectively these data constrain the timing of Event III to be older than 1833 cal yr BP and younger than 2338 cal yr BP.

Event IV

Based on our adopted model of strong shaking generating colluvial wedges from the shutter scarp, a fourth rupture event is implied by the presence of the thick colluvium unit 4c beneath the 4p peat complex. This is supported by the presence of the same overlapping scree/colluvium relationship between units 4x and 4c, as found in units 2x and 2c, and associated with Event II. The minimum age for Event IV comes from Sample TK1-1 from unit 4ps at the base of the 4p peat complex which yielded a radiocarbon age of 2565 ± 30 yr BP (2460-2740 cal yr BP). No datable material was found at a lower level in this trench so it is not possible to define a maximum age for the Event IV at this site.

Recurrence Interval Estimate

Four paleoseismic events have been interpreted and dated from trench TK-1 at Te Kopahou. This represents a significant improvement in knowledge of the timing of past rupture events on the Wellington-Hutt Valley segment of the Wellington Fault.

The results described above in combination with single event displacement and slip rate data allow calculation of recurrence interval for the Wellington-Hutt Valley segment. Monte Carlo simulations reported in Langridge et al. (2007) using all available paleoseismic data for the Wellington Fault at that time generated a Mean Recurrence Interval of 641 yr (range 332-1107 yr). Subsequent to that work, single event displacements for the fault at Te Marua (see Stop 8) have been reassessed and are now thought to be ca 20% greater than that previously published. This will lead to a ca 20% increase in the recurrence interval estimate reported above (i.e. ca 770 yrs compared with 640 yrs).

Figure 1.1. Oblique aerial view of the Wellington Fault above Cook Strait. The ca 042°-striking fault trace is marked by red arrows. White lines mark ridgelines (spurs), while blue lines mark adjacent streams. The Te Kopahou trenches (yellow box) were sited behind a prominent shutter ridge (offset spur). *Image from Google Earth*.

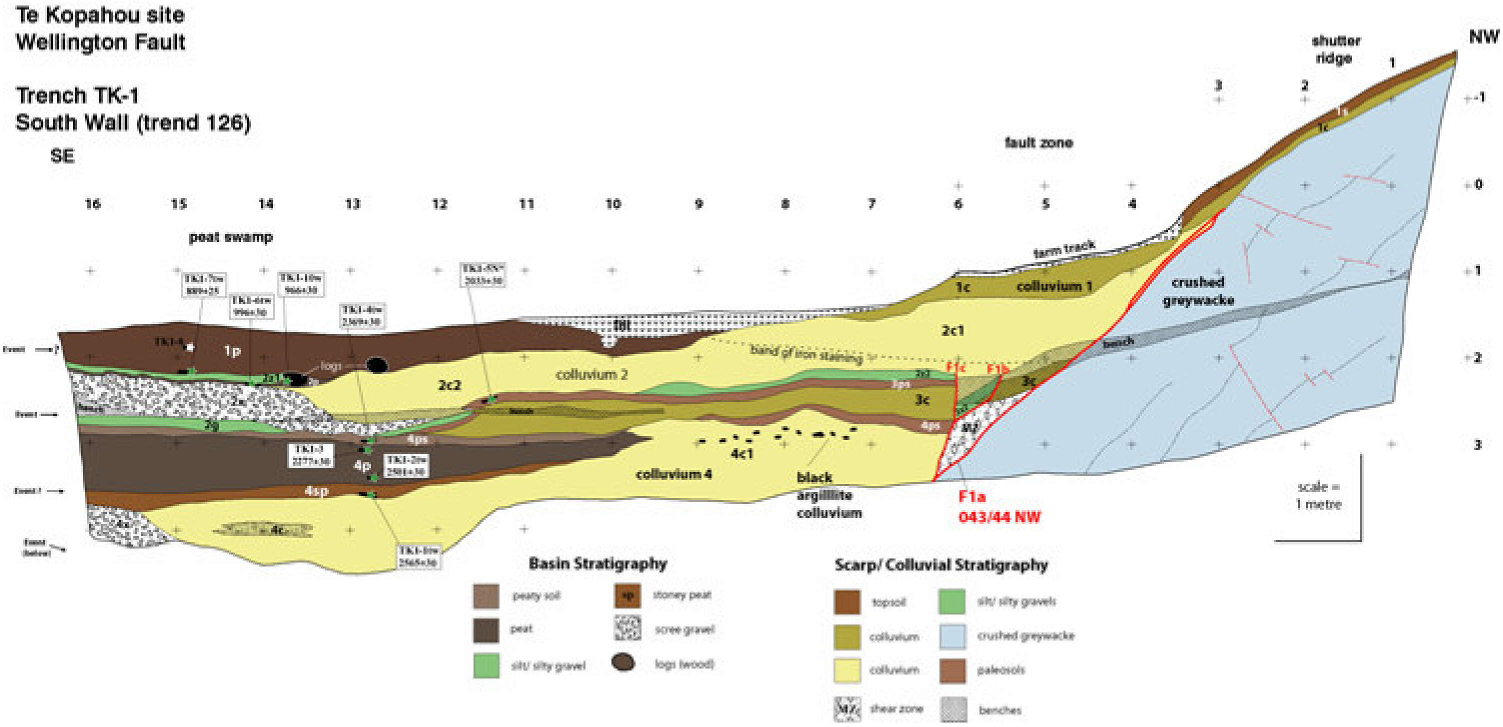


Figure 1.2. Log of the south wall of Te Kopahou trench-1 in Long Gully Station. Faults are marked as red lines. Uncalibrated AMS radiocarbon dates are shown within boxes and locations marked by green stars.

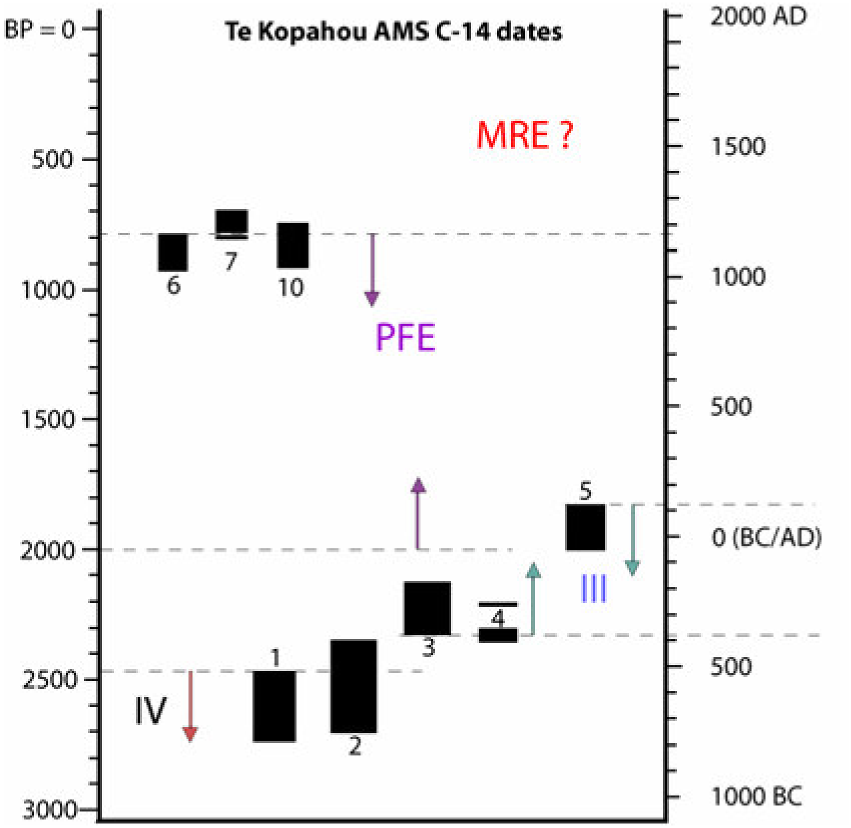


Figure 1.3. Graph of the calibrated ages of radiocarbon dates (shown as black bars) from Te Kopahou trench-1. Arrows show 'Event older than/ younger than' age relationships. MRE = most recent event, PFE = penultimate faulting event. III = faulting event prior to PFE, and IV = the fourth faulting event.

Stop 2: Thorndon Overbridge

The Thorndon Overbridge is a twin three-lane motorway linking Wellington City with northern city suburbs, and the rest of the North Island, and is a critical structure on State Highway 1. It is 1.3 km long and spans an area of dense development, including the route for many of the infrastructural elements essential for the functioning of the city (e.g. rail, road and ferry transport; water reticulation; telecommunications cabling etc). It is also dissected by the Wellington Fault. In this stop, we discuss efforts to mitigate the earthquake hazards of strong ground shaking and rupture of the Wellington Fault to the bridge using retrofitted engineering.

The Thorndon Overbridge is founded partially on natural land (uplifted during the 1855 Wairarapa Earthquake) and partially on artificially reclaimed land. When the overbridge was designed and built in the late 1960's, the location of the Wellington Fault was well known south of Wellington City but information on its location through the city itself was, at best, sketchy (Lensen 1958). Two truncated spurs identified from old aerial photographs along Tinakori Road were already modified by urban development and difficult to locate. The northwestern side of Port Nicholson was assumed to represent the eroded faultline scarp.

The age of reclamation and its engineering quality vary significantly in the Thorndon area, from hydraulically dredged marine silt to properly engineered rock fill (see Murashev & Palmer 1998). The Thorndon Overbridge is sited upon reclamation that dates from between 1882 and 1932 (the latter comprising mostly hydraulic fill of high liquefaction susceptibility). Fill thickness varies from 2 to 12 m and rests on unconsolidated beach sand and nearshore marine silt of Holocene age. These are in turn underlain by non-marine gravel, colluvium and swamp deposits of Last Glacial age.

Following the poor performance of bridges of similar design in large earthquakes in California (1989 Loma Prieta and 1994 Northridge earthquakes) and Japan (1995 Kobe Earthquake), the decision was made to assess critical vulnerabilities of the Thorndon Overbridge and to undertake a programme of retrofit strengthening to markedly increase its post-earthquake functionality (see Billings & Powell 1996). The risk of loss of life and serviceability of the bridge due to 300-1000 year return time strong ground shaking alone was assessed as high. Key areas of vulnerability were the pier pilecaps (e.g. inadequate strength; non-reliability in development of a "plastic hinge"; loss of foundation strength due to liquefaction, lateral spreading and/or settlement), and span collapse owing to Wellington Fault displacement between piers.

During the years between the bridge's construction and subsequent retrofit, the Wellington Fault through Thorndon had been more accurately located (e.g. Ota et al. 1981; Figure 2.1). From western Kelburn, the Wellington Fault passes just west of Glenmore Street and across the base of Tinakori Hill (Upper Witako No. 2) at Harriett Street to the lower Thorndon area, where its trend swings 18^{o} to the east to an orientation of about 055^{o}. Lewis (1989) recorded the position of a sea floor fault scarp beneath the wharf north of the ferry terminal with upthrown side to the southeast indicating a reversal of throw for recent ruptures. Its location in the lower Thorndon area, through the railway yards and under the overbridge was established using three dimensional modelling of drillhole information (Perrin 1993; Figure 2.2). These investigations provided enough characterisation of the

Wellington Fault surface rupture hazard under the overbridge for it to be accommodated in the retrofit program.

Engineering works to earthquake retrofit the Thorndon Overbridge were completed in the mid-1990s. Retrofit measures included supplementing the existing pier piles with additional piles designed to reduce vulnerability to liquefaction and lateral spreading, and the tying together of adjacent pier piles. Steel column jackets were fitted in the "plastic hinge" zone to existing reinforced concrete piers to ensure reliable seismic performance under strong levels of earthquake shaking. The pilecaps have been strengthened by adding a concrete overlay (the overlays are connected to the existing pilecaps using drilled and grouted dowels) and/or cored through post-tensioning. Individual 23 m deck spans are not continuous to reduce the possibility of failure of the entire structure. To support the roadway-superstructure, and prevent span collapse resulting from Wellington Fault surface rupture, extended seat frames have been installed under the pier caps to catch the roadway if it is pulled off the existing pier cap seats. (Figure 2.3).

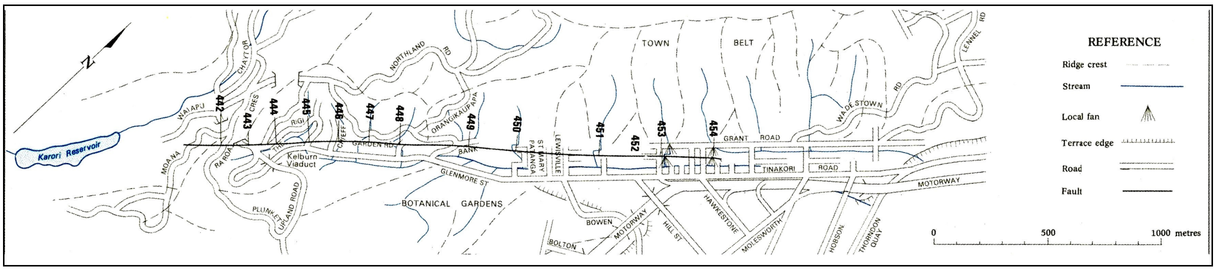


Figure 2.1. Ota et al. (1981) constrained the location of the Wellington Fault in the upper Thorndon area by locating a number of offset and fault-related geomorphic features (from Inset C of Ota et al. 1981). More recently, Perrin & Wood (2003) have provided a quantified characterisation of the location of the Wellington Fault through the entire city in a fashion consistent with the Ministry for the Environment's "Active Fault Guidelines" (Kerr et al. 2003).

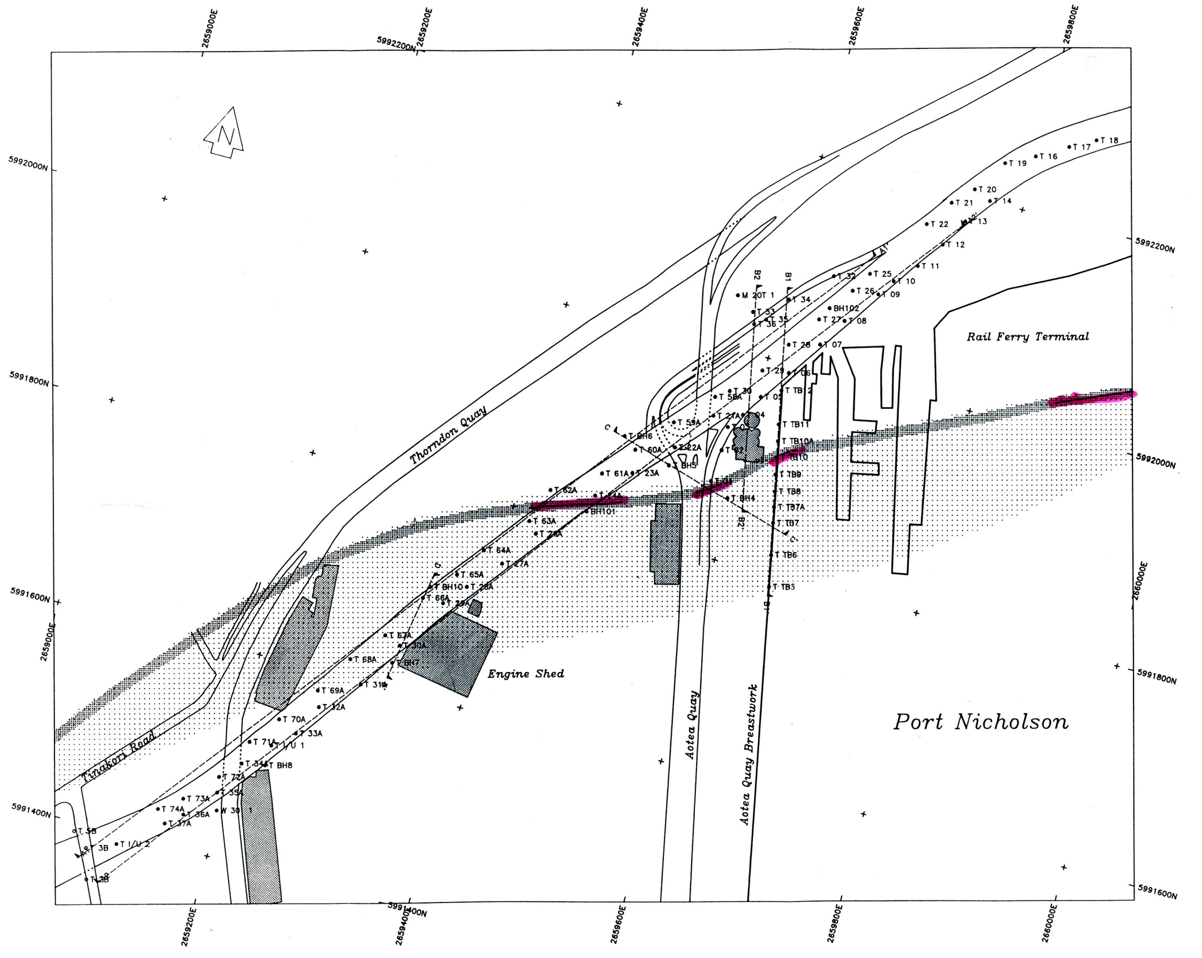


Figure 2.2. Location of the Wellington Fault in the Thorndon Overbridge area (Perrin 1993). The position of the fault is determined from correlation of sediments within drillholes located on the map. Logged drillholes are marked with a solid circle, holes without logs are marked with open circles. Confident location of the fault is marked by darker lengths on the line of the fault and the extended lightly stippled area marks the zone of deformation. The fault's position to the northeast was established by Lewis (1989). Grid is a 200 m grid based on the NZMG.

Figure 2.3. Column piers either side of where the Wellington Fault cuts the line of the Thorndon Overbridge have retrofitted "catch frames" with the capacity to accommodate lateral fault displacement of the order of 4-5 m between piers and prevent span collapse in the event of surface rupture of the fault. Photos: Billings, I.J. and Powell, A.J. (1996).

Stop 3: Petone Wharf

The Hutt Valley/Port Nicholson Basin is broadly wedge shaped, tapering from its widest extent of 9.5 km within Port Nicholson, to about 5 km wide at the Petone foreshore, to a narrow point of a few hundred metres wide at the Taita Gorge (Fig. 3.1). Low to moderately high hills make up the eastern and western flanks of the basin, while the basin surface itself is topographically of low relief (also largely flat bathymetrically). A notable structural high within the basin is Somes Island which is the crest of a largely submarine ridge that traverses the basin obliquely. On the basis of seismic stratigraphy (Wood & Davey 1992) the margins of the ridge are faulted, and these faults displace shallow, presumably relatively young, sediments (0.1 TWT) (Fig. 3.2).

Hill crests on the eastern and western sides of the valley are similar in height (summit height accordance). The ridge crests are remnants of a flat erosion surface (the "K Surface") that may have existed more or less intact until about 1 million years ago. On the western side of the valley the surface rises from about 250 m (Puketirotiro) opposite Petone to about 380 m opposite Taita Gorge (Haywards). From the west of the abrupt faultline scarp, the K Surface steps up to the ridgecrest, perhaps with a little back-tilting. On the eastern side of the valley, the ridge crest (probably close to the original K Surface) rises from about 350 m in the southeast (Towai) to about 440 m (Trig 16093) near Taita Gorge. Here, deeply weathered rocks (possibly sub-remnants of the K-surface) appear to dip towards the fault, particularly in the Silverstream area. The eastern side of the harbour and perhaps the eastern valley wall may be defined by faulting, although (apart from identification of some possibly active faults on the eastern side of Port Nicholson - Wood & Davy 1992; Davy & Wood 1993) there is little supporting evidence for this inference.

The northwestern side of Port Nicholson and the Hutt Valley is a long, gently curved, steep scarp that is the eroded faultline scarp of the Wellington Fault. Early vertical aerial photographs display a series of prominent fault facets at the lower end of spurs from the western Hutt hills. Note that the northwestern side of the fault is uplifted, the southeastern side down-faulted; it is reasonable to assume that on the southeastern side of the fault, basinal sediments lie upon the eroded equivalent of the K Surface. Basinal sediments are at least 300 m thick near the Petone foreshore (Gear Meat drillhole; Stevens 1956) (see Figs. 3.3 & 3.4) and, further south, near the mouth of the Ngauranga Gorge, are believed to be about 600 m thick (seismic reflection, Wood & Davy 1992) (Fig. 3.2).

In late January 1855 the Wellington region was shaken by New Zealand's largest historical earthquake, the M 8.1-8.2 Wairarapa earthquake, associated with surface rupture on the Wairarapa Fault, 25 km to the east. In this earthquake, a block of land from at least the Wairarapa Fault to west of the Wellington Fault was uplifted, tilted and folded. Uplift was about 6 m at Turakirae Head (Hull & McSaveney 1996, McSaveney et al. 2006) and ca 1.5 m in the Wellington City area. The Western Hutt motorway and the railway line beside it are built on a raised beach and wave-cut platform uplifted and tilted in 1855. In the Petone area, the net result of the earthquake was uplift of ca 1.2 m in the west and ca 1.5 m in the east. This uplift caused a substantial amelioration of drainage problems around the Hutt River estuary, and in doing so, created a landscape in a state of disequilibrium (Fig. 3.5).

Core obtained from the Petone Wharf by Victoria University of Wellington provided a record of environmental changes in the very recent past (ca 200 years) (e.g. Barrett et al.

1993, Dunbar et al. 1997, Goff 1997). The present day depositional environment at the harbour head consists of a series of distinctive zones: the subtidal zone (silt, sand and minor gravel); tidal zone (sand and gravel); supra-tidal zone (windblown and storm beach); back-beach swamp (now tectonically and artificially reclaimed, but consisting of sand, carbonaceous silt, grit and minor gravel); and an alluvial floodplain (rounded gravel and minor poorly sorted sand and silt).

Pre-existing coastlines had a similar zonation, the signature of which can be tracked using drillhole logs. These marginal marine sediments are covered by increasing thickness (representing an increasing period of time) of Holocene non-marine sediments between Wakefield Street and beyond Lower Hutt City. Similar marginal marine facies of Last Interglacial age (128-71 ka) can be identified in drillhole logs, but only as far north as Wakefield Street. At a deeper level, Karoro Interglacial (245-186 ka) marginal marine sediments are found only at the Gear Meat drillhole. Figures 3.3 & 3.4 show an interpretive correlation of these sediments in the Hutt Valley Basin based on palynostratigraphy and climatic succession (Mildenhall 1995; Begg & Mazengarb 1996). A notable feature is that in spite of the uplift in the Hutt Valley associated with the 1855 Wairarapa Earthquake, geological markers require long term basinal subsidence.

On the basis of the oxygen isotope sea level curve (Imbrie et al. 1984) and correlation of marine incursions into the Hutt Valley, calculated long term subsidence rates for the western side of the Hutt Valley average ca 1.06 m/ka for 125 ka (start of Last Interglacial); 0.97 m/ka for 240 ka (Karoro Interglacial); and 0.6 mm/yr for 340 ka ("Brunswick" Interglacial). Seismic (Port Nicholson; Wood & Davy 1992) and drillhole data show sediments thicken to the west and dip westwards progressively more steeply with age suggesting that the Wellington Fault plays a significant role in this net subsidence and that this process is cumulative. Drillhole data indicate that nett subsidence on the western side of the valley is taking place roughly 1.5 times as fast as that at the eastern side of the valley (Figs. 3.3 & 3.4).

The most plausible conclusion is that vertical deformation at Petone comprises components relating to a number of seismic sources, including the Wellington Fault, Wairarapa Fault and possibly the underlying subduction zone. Vertical deformation associated with the 1855 Wairarapa Earthquake, the only historical event, involved uplift. There is limited existing information on absolute vertical displacement associated with Wellington Fault or subduction zone earthquakes, but a plausible and logical reconciliation of historical information and long term stratigraphic data is possible using a series of assumptions.

A. By making three assumptions, the component of vertical deformation at Petone attributable to Wairarapa Fault earthquakes can be calculated for the last 125,000 years.

***Assumption 1*:** Recurrence interval for Wairarapa Fault uplift-generating earthquakes is 1200 (min; Little et al. in press) to 2200 (max; McSaveney et al. 2006) yrs. (See below for more detail.)

***Assumption 2*:** The 1855 uplift of 1.2 (west)-1.5 (east) m at Petone is typical for Wairarapa Fault ruptures. (See McSaveney et al. 2006)

Assumption 3: The recurrence interval of the Wairarapa Fault has remained constant for 125,000 yrs.

	max recurrence interval	min recurrence interval	Time interval
Wairarapa Fault	2200*	1200+	yrs
Earthquakes in time interval	**57**	**104**	125,000

* Recurrence interval of McSaveney et al. (2006)
\+ Recurrence interval of Little et al. (in press)

McSaveney et al. (2006) examined raised beach ridges in the Turakirae Head area using a series of high resolution profiles and radiocarbon dates (some derived from stranded marine invertebrates still attached to rock surfaces). They concluded that the stranded beach ridges at Turakirae Head are a proxy for uplift events on the Wairarapa Fault, the last of which, in 1855, was more or less typical. They recognised four uplift events during the last ca 7 ka. The mean recurrence interval for the Wairarapa Fault uplifts derived by McSaveney et al. (2006) is 2194±117 yrs (~2200 yrs).

Recent trenching work on the Wairarapa Fault (Little et al. in press) has identified a composite surface-rupture history including at least five events in the last ca 5.2 ka. Of these five events, three correspond in age with events recognised at Turakirae Head. The other two, the penultimate event (prior to 1855) and the fourth last event, are not recognised by stranded beach ridges at Turakirae Head. The recurrence interval of Wairarapa Fault earthquakes using data of Little et al. (in press) is ca 1200 years.

It is unnecessary to assume that one of these two data sets is wrong. It is possible that Wairarapa Fault earthquakes may not always result in 1855-type uplift, thereby sometimes leaving no beach ridge expression at Turakirae. But for our purposes, it is prudent to use both estimates as bounds to constrain likely subsidence in Petone associated with a Wellington Fault earthquake.

Minimum and maximum cumulative uplift from Wairarapa Fault earthquakes in the Petone area over the last ca 125,000 years can be estimated as follows:

Cumulative Wairarapa F earthquake uplift	West Petone	East Petone	
Single event uplift (as occurred in 1855)	1.2	1.5	m
Total cumulative uplift (min) (57 events)	**68**	**85**	m
Total cumulative uplift (max) (104 events)	**125**	**156**	m

B. By making two further assumptions it is possible to calculate a value of subsidence at Petone in a single Wellington Fault surface rupture earthquake.

Assumption 4: Vertical deformation in Petone is largely attributable to a combination of Wellington and Wairarapa fault earthquakes.

Assumption 5: The recurrence interval for the Wellington Fault of ca 770 yrs (see Stop 1) has remained constant over the last 125,000 yrs.

	recurrence interval	Time interval
Wellington Fault	770	yrs
Earthquakes in time interval	**162**	125000

Additional information needed for the calculations includes: 1) sea level in the early Last Interglacial was the same as it is today (± 5 m); and 2) based on drillhole data, the base of the Last Interglacial marine beds is currently at an elevation of 105 m below mean sea level in the west of Petone and 65 m in the east.

Cumulative subsidence in Petone attributable to Wellington Fault earthquakes over the last ca 125,000 years can now be estimated as follows:
West Petone
= 105 m + 68 m (min. value for Wairarapa Fault earthquake uplift) = **173 m**; to
= 105 m + 125 m (max. value for Wairarapa Fault earthquake uplift) = **230 m**
East Petone:
= 105 m + 85 m (min. value for Wairarapa Fault earthquake uplift) = **190 m**; to
= 105 m + 190 m (max. value for Wairarapa Fault earthquake uplift) = **295 m**

Dividing these cumulative values of subsidence attributable to Wellington Fault earthquakes by the calculated number of earthquakes over that period (162 earthquakes) provides an estimate for subsidence per earthquake:

Single event subsidence estimated for each Wellington Fault earthquake

	West Petone	East Petone
min	**1.1 m**	**0.9 m**
max	**1.4 m**	**1.4 m**

Using these data points, it is also possible to extrapolate an age for the oldest sediments in the Lower Hutt Valley, providing a minimum age for onset of deformation linked to the "current phase of activity" on the Wellington Fault. The calculation is crude, but does provide a useful "ball park" estimate. Inherent in the calculation is that initiation of deformation coincided with initiation of sedimentation, and that extrapolation of subsidence rates backwards through time is reasonable. Particularly through variation of the latter factor, the value derived is more likely to underestimate the age of onset of sedimentation.

Sediment depth at Petone: 300 m			estimated age (ka)
Subsidence rates:	125,000 yr average	= 0.8 mm/yr	366
	240,000 yr average	= 0.7 mm/yr	417
	340,000 yr average	= 0.6 mm/yr	500

Minimum age for onset of sedimentation/deformation = ca 350,000 to 500,000 yrs.

The rates cited all consist of two components, a tectonic and a compaction component. Although none of the calculations have taken sediment compaction into account, Begg et al. (2002) show that compaction values are low.

As a result of a strong earthquake, either centred on the Wellington Fault, or elsewhere, significant liquefaction and/or ground shaking amplification is anticipated in the Petone area (e.g. Van Dissen et al. 1992b, Benites & Olsen 2005).

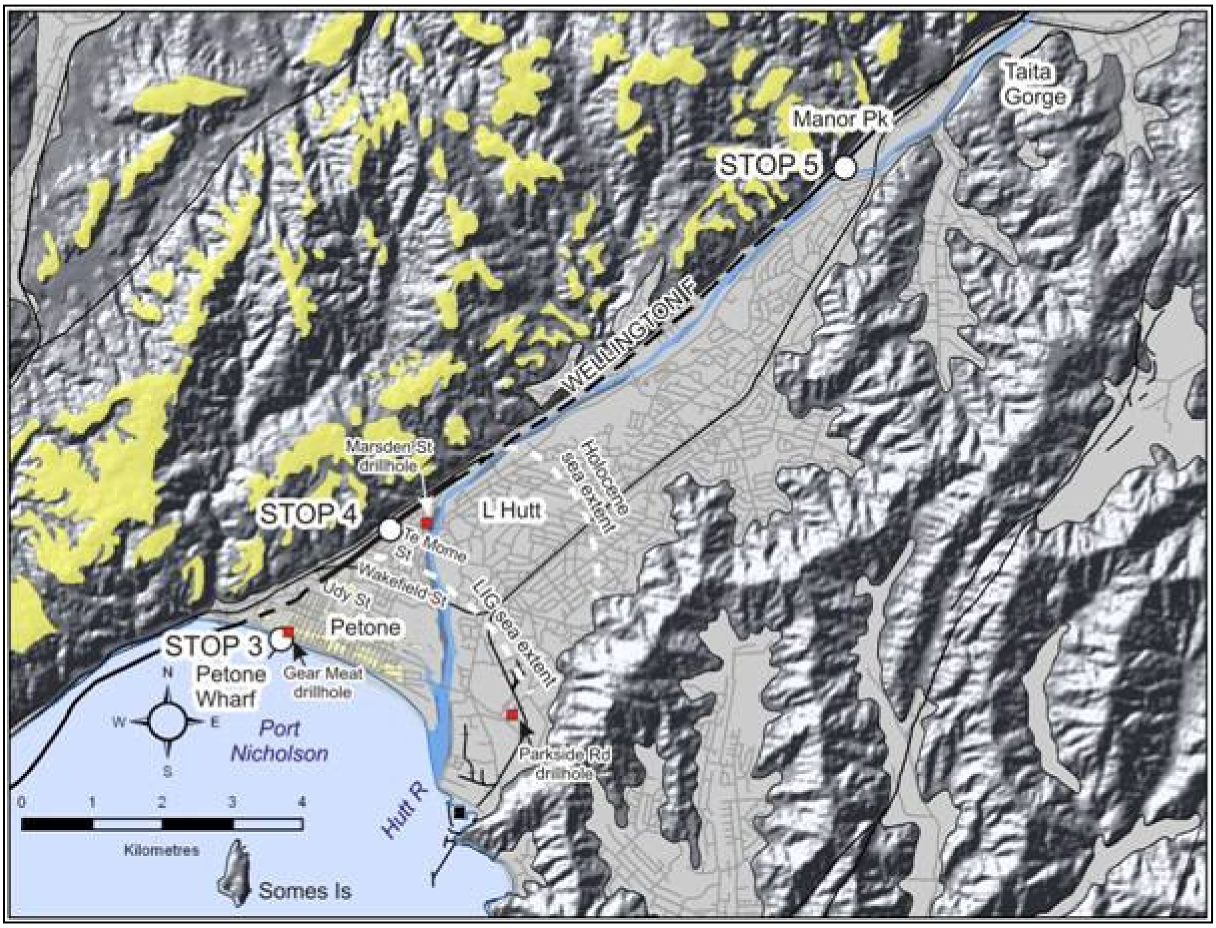


Figure 3.1. Map of the Port Nicholson to Taita Gorge section of the Wellington Fault. The lightly shaded areas are underlain by Quaternary sediments and shading on hill crests delimits selected areas of the K Surface. The landward extent of the Holocene (6,500 years) and Last Interglacial (LIG; 125,000 years) marine incursions are marked. Marginal marine beach ridges in the Petone foreshore area are shown in a light yellow shade. The Wellington Fault is marked as a solid line where its location is reasonably well constrained. Note the location of the Gear Meat, Parkside Rd and Marsden St drillholes (see Fig. 3.4).

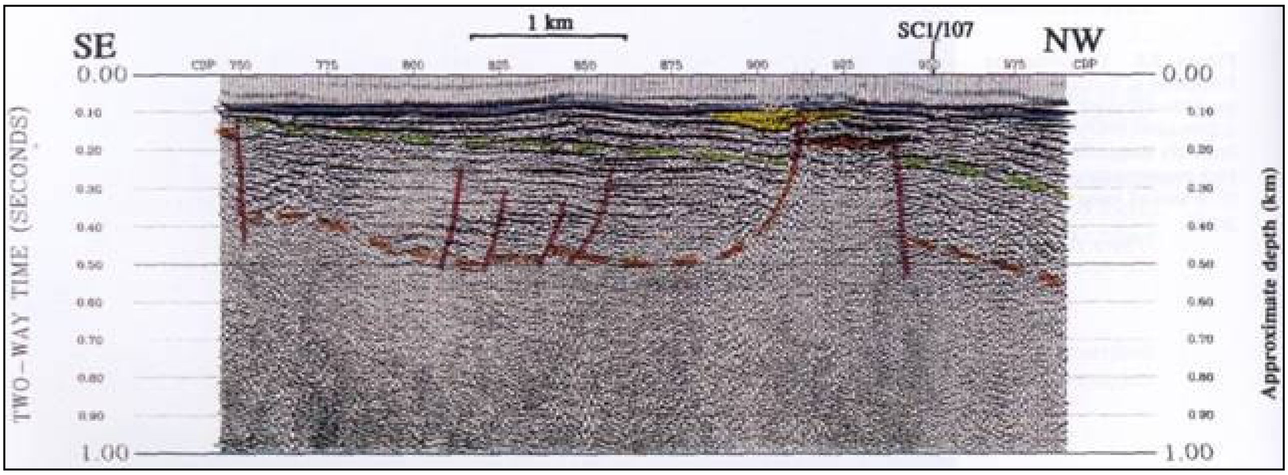


Figure 3.2. A multichannel seismic reflection line across Port Nicholson (R27/693917 to 650957) shows two sub-basins separated by the Somes Island Ridge which is fault bound at least on its NW side. Reflecting layers dip NW towards the Wellington Fault, just off the end of the profile to the right. (From Wood & Davy 1992).

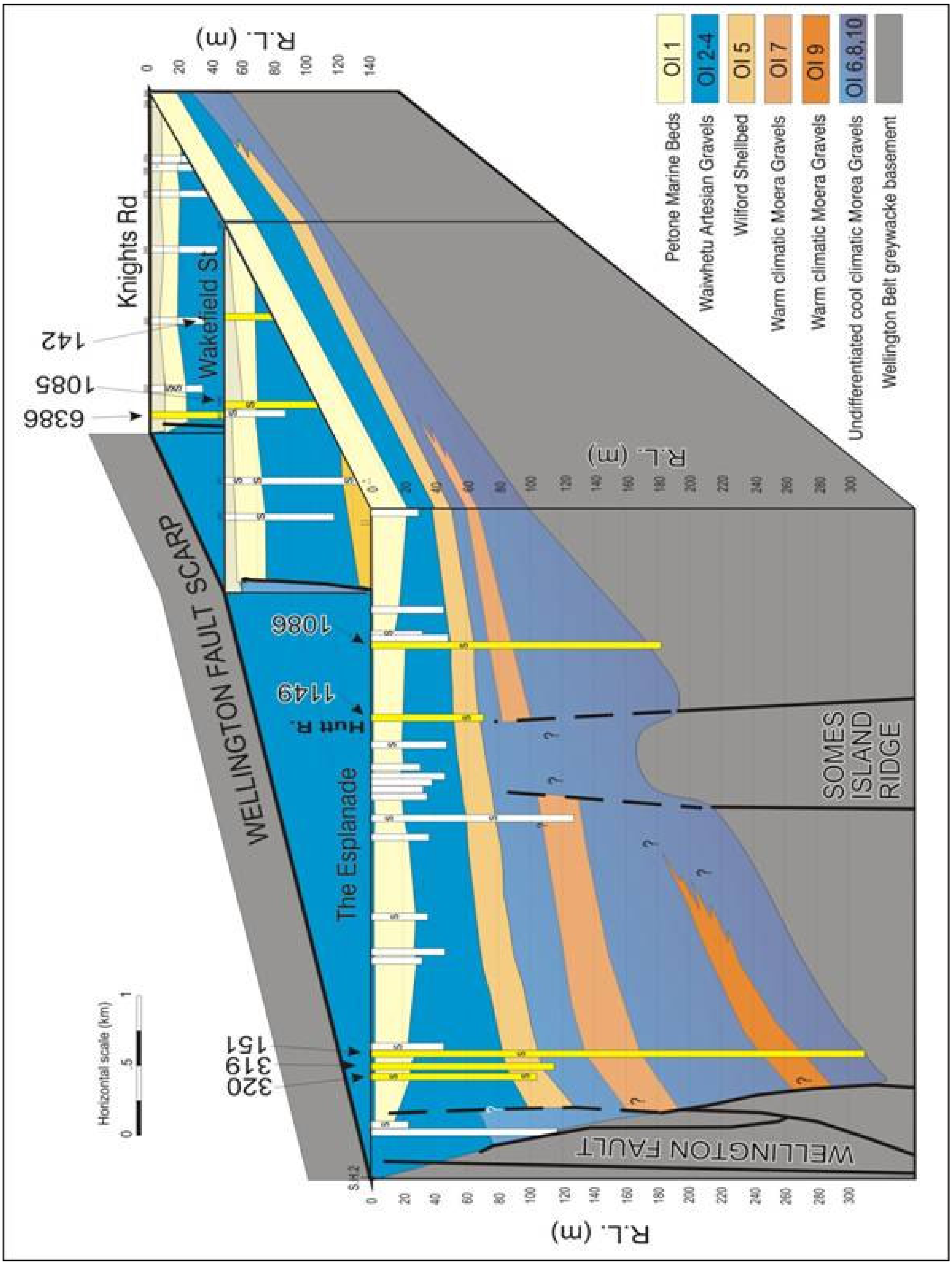


Figure 3.3. Three dimensional representation of sediments of the Lower Hutt basin from the Petone foreshore to Knights Rd, based on drillhole logs. Basement greywacke is shown densely shaded, interglacial sediments as yellow to orange shaded and glacial Pleistocene sediments are blue shades. The position of the Somes Island Ridge is based on onshore gravity and seismic data from Port Nicholson. (After Begg & Mazengarb 1996).

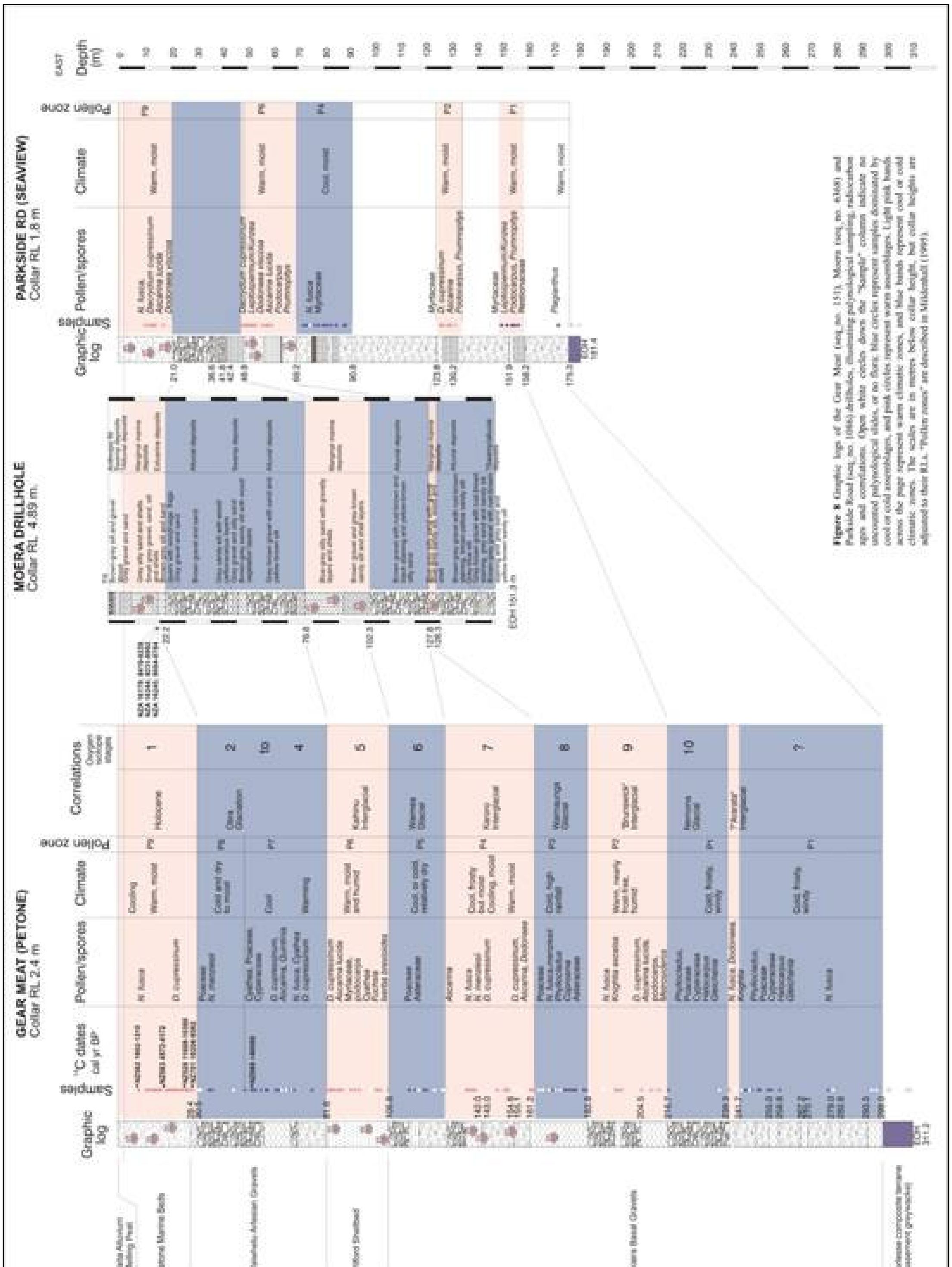


Figure 3.4. Logs to basement for three Lower Hutt Valley bores, the Gear Meat, Parkside Road and Marsden St drillholes. The Gear Meat drillhole is located on the western side of the valley, but east of the Wellington Fault (see Fig. 3.1). The Parkside Rd drillhole is on the eastern side of the valley. The Marsden St drillhole is close to the Wellington Fault near Lower Hutt City. Note the change in unit thicknesses from west to east and inland to the Marsden St drillhole. Correlation is based on superposition of warm and cold climate palynofloras and marine incursions.

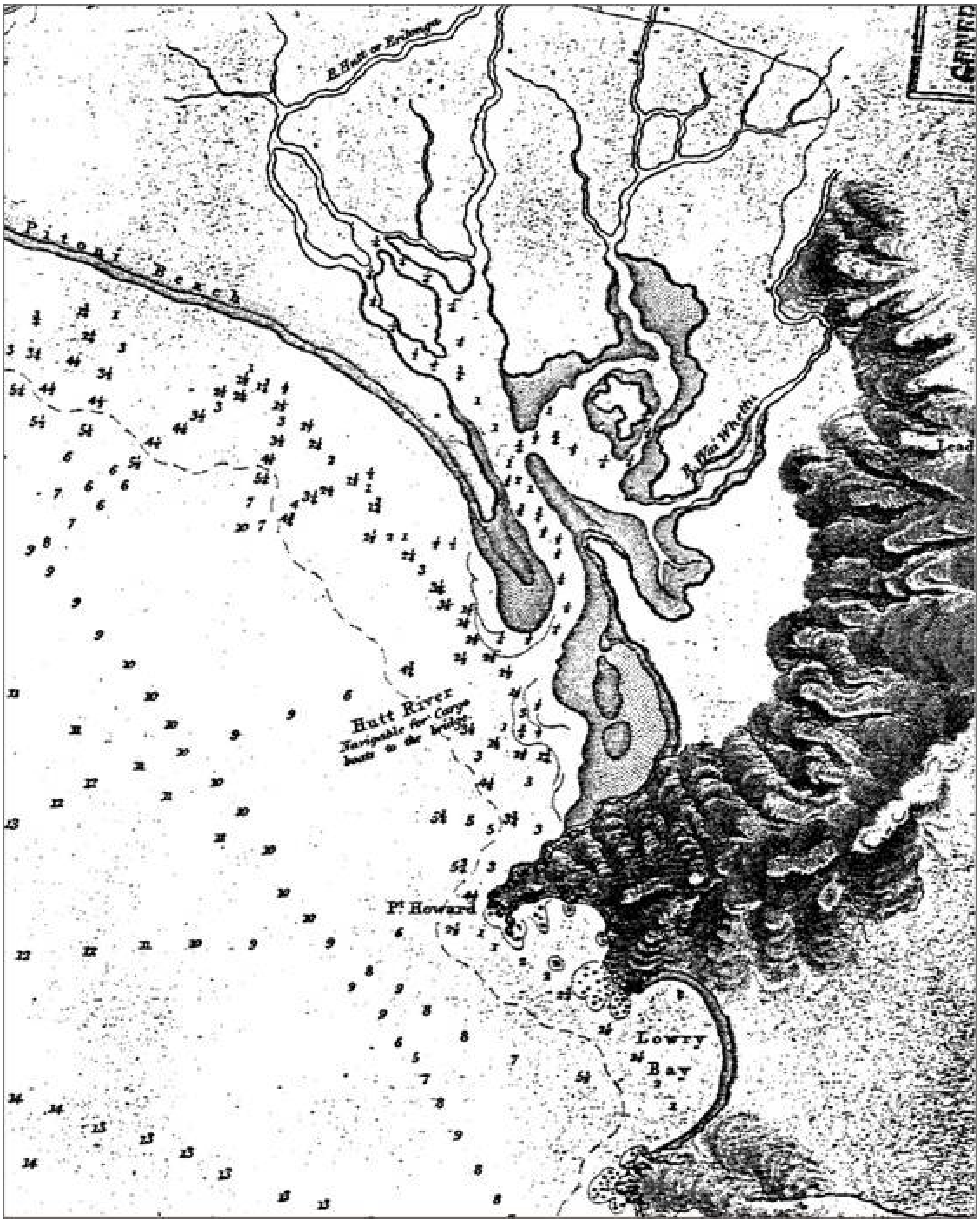


Figure 3.5. Chart of the Hutt River mouth surveyed before the uplift associated with the 1855 Wairarapa Earthquake. Note the development of an extensive estuary at the Hutt River mouth. Waiwhetu Stream, the southernmost eastern tributary of the river was navigable by quite substantial vessels to the Gracefield bends.

Stop 4: Te Mome Road - a well-developed urban fault scarp

A ca 4 m high southeast-facing slope 30 m from the Te Mome Road/Hutt Road junction represents the active trace of the Wellington Fault. The trace can be followed south almost as far as Jackson Street and northwards as far as the junction of Marsden and Pharazyn Streets. The upthrown side of this trace is to the west. The trace increases in height from Gear Street to Te Mome Road and decreases in height from Te Mome Road to its northern extremity in Pharazyn Street. A possible explanation is that at Te Mome Road, the scarp represents multiple (?three) events, while at each end, the scarp may be younger (i.e. the result of fewer earthquake ruptures) because of river erosion and deposition (to the northeast) and by marginal marine erosion and deposition (to the southwest).

Note that the recent fault trace is up to 200 metres east of the major topographic faultline scarp. This may be due (at least in part) to the erosion of the scarp back from the position of the fault by the Hutt River and by wave erosion when the lower part of the valley was occupied by the sea (Stevens 1973, 1974). Another possible explanation is that the fault displacement steps out at depth into the Quaternary valley fill deposits which lap against and across the eroded faultline scarp.

Prior to a study by Grant-Taylor (1967), the Wellington Fault was considered to be located close to the northwestern valley wall through the Lower Hutt Valley. Grant-Taylor recognised this feature at Te Mome Road as a trace of the Wellington Fault and mapped it between Udy Street (c. 1.5 km south of this stop) and Pharazyn Street (c. 140 m north of here). Recognition of the feature as a fault trace therefore, substantially post-dated most of residential and commercial development along its length.

Hundreds of active faults have been recognised by geologists throughout New Zealand over many decades, but it wasn't until 2003 that the Ministry for the Environment (Kerr et al. 2003) issued guidelines aimed at planners to assist them in managing avoidance and/or mitigation of fault rupture hazard. These guidelines were developed by a joint working group of the NZ Society for Earthquake Engineering and the Geological Society of NZ. The two defining fault-avoidance criteria in the guidelines are accuracy of fault location, and average recurrence interval of surface rupture. The guidelines also recognise existing use rights, and influence the proposed structure has, in terms of life safety, on the level of risk. The guidelines recommend that controls on proposed development are greater for areas where faults are well located, recurrence intervals are shorter, and proposed structures are of greater hazard to life.

In hazardous areas that are already developed, such as the fault scarp here at Te Mome Road, existing land use is a complicating factor in implementing hazard mitigation. The community may have an expectation to continue living as before, and be prepared to live with the risk despite the potential for damage, or worse. An existing use right under the Resource Management Act means that when an existing building across a fault is damaged or burnt down, or requires rebuilding for whatever reason, it can be rebuilt, even once the risk has been realised. In the case of the fault scarp through Petone, hazard could be mitigated, somewhat, by having the district plan modified to ensure that the risk is not increased by intensified land use or redevelopment of existing properties.

Stop 5: Manor Park

Work to locate the Wellington Fault has been undertaken recently at Manor Park (Beetham et al. 2008). Field work in the Hutt Valley during the last few years has identified a number of localities of hard fault gouge close to the expected location of the Wellington Fault. These include two localities at Manor Park (Fig. 5.1), one at the foot of Haywards Hill, one at Mein's Rock ca 1.5 km above Silverstream Bridge and one beneath the Moonshine Bridge. In each locality gouge is grey and steeply dipping. Both exposures of steeply dipping fault gouge at Manor Park appear to have sub-planar upper surfaces that are overlain by alluvial gravel. The next exposure of bedrock upstream along the banks of the Hutt River is 2.5 km upstream, three quarters of the distance to the Silverstream Rail Bridge. It is likely that alluvial gravel increases in depth on the eastern side of the Wellington Fault between that exposure and the Taita Rail Bridge. Constriction of the valley at Taita Gorge has allowed the Hutt River to utilise the whole width of the valley, eroding relatively soft, brecciated rock and gouge on the western side of the fault, resulting in an alluvial bench. This provides an opportunity to better locate the Wellington Fault in the area.

About 500 m to the east of Manor Park, drillholes for the foundations of the Taita Rail Bridge (Fig. 5.2) encountered the top of basement rock at relative elevations of ca 2 m below sea level, suggesting the Wellington Fault traverses the interval between these points and the rock bench at Manor Park to the west. Other drillhole logs in the area were examined in an attempt to better define the location of the fault. An additional five drillholes intersected greywacke at shallow depths (all about RL 28-30 m). These were judged to be on the western side of the Wellington Fault, and confirmed the presence of a buried sub-horizontal bedrock surface on the western side of the fault.

Trenches were excavated in the western river bank to try to locate more accurately the main plane of the Wellington Fault. The trenches were excavated across the strike of the fault, starting from a position certain to be on the west side of the fault. The sub-horizontal surface on sheared basement rock was encountered at an RL of ca 20 m, and formed the floor of the trench. At about 30 m east of the start of the trenching, a diagonal lip across the floor of the trench, striking parallel with the strike of the Wellington Fault (Fig. 5.2) is interpreted as a fault plane of the Wellington Fault. Here, at the lip, bedrock entirely consisted of soft gouge. This softness indicates that the gouge here has not been subject to the annealing process of that to the west in the trench and is taken as evidence that this is the location of the main plane of the Wellington Fault. High groundwater levels thwarted attempts to dig deeper below the lip on the southeastern side of the fault, but it was possible to demonstrate that there was at least a 1.5 m greater thickness of alluvial gravel southeast of the lip (i.e. southeast of the fault) compared to northwest of the fault. No indication of faulting through overlying alluvial gravels indicates that they post-date the last rupture.

To test these results, and to follow the continuity of the lip/fault further to the northeast, a series of three microgravity profiles were run across the valley (Fig. 5.3). Density contrast between bedrock greywacke and alluvial gravel was calibrated at the Taita Rail Bridge drillhole sites. The resultant profiles were plotted on the map and modelled the location of the fault in a position in agreement with other techniques outlined above.

Figure 5.1. Sheared and veined greywacke sandstone and lithified fault gouge on the western Hutt River bank at Manor Park. Gouge is structurally aligned with similar material 30 m away in the bed of the river and with similar material on the western bank ca 300 m downstream. Photo: R.D. Beetham.

Figure 5.2. The Manor Park trench exposure of the Wellington Fault, showing the bench cut on sheared greywacke rock and lithified gouge, soft gouge near the lip of the surface, and unfaulted alluvial gravel overlying the bench. Note the obliquity between the trench wall and the strike of the fault (strike ca 44°).

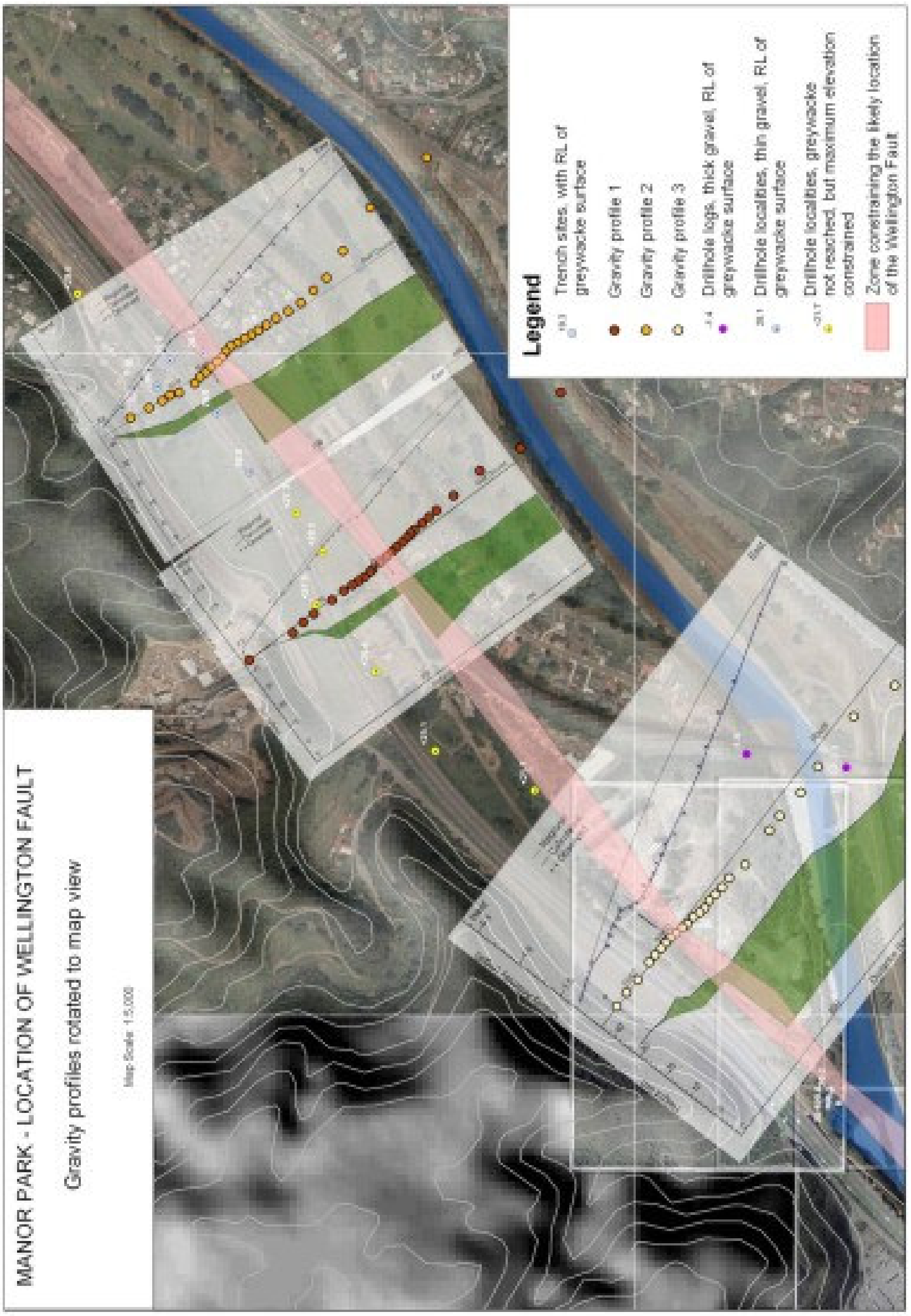


Figure 5.3. A zone (pink) defining the likely location of the Wellington Fault in the Manor Park area is derived from three independent datasets: 1) rock exposure, both natural and in trenches, 2) drillhole data, and 3) microgravity profiles. Profiles are illustrated rotated about the mapped line of profile points; green represents the modelled thickness of alluvial gravels. Note the marked change in the microgravity values close to the Wellington Fault. White dotted grid is the 1 km NZMG.

Stop 6: Trentham Memorial Park

About 1.5 km northeast of Silverstream Bridge, Mein's Rock, a prominent exposure on the northwest side of the Hutt River (Fig. 6.1), consists of crushed rock of the hanging wall of the Wellington Fault. Trentham Memorial Park lies about 3 km northeast of the Taita Gorge, but by here the Upper Hutt valley has widened to 3 km. The valley floor is flat, bounded again on the northwestern side by the Wellington Fault, and surface deposits lap against the eastern valley wall without terrace risers. This onlapping relationship is confirmed by seismic reflection data (Melhuish et al. 1997; Fig. 6.2). The Witako Valley, a wide, low relief tributary valley of the Upper Hutt valley forms a sub-basin on the southern side of the main basin. On the northwestern side of the valley the K Surface lies at an elevation of about 450 m, while the ridge crest on the southeastern side of the valley, possibly a remnant of the same surface, is at about 250 m elevation.

Closely spaced drillhole logs right across the valley in the Silverstream Bridge area define the elevation of the greywacke basement surface at about 20 m asl (Fig. 6.3). A groundwater stratigraphic drillhole at Trentham Memorial Park (WRC1510017) intersected the basement surface at 204 m below the surface (158 m bsl). Gravity and seismic reflection studies across the valley near Trentham Memorial Park (Cowan & Hatherton 1968, Melhuish et al. 1997) provide an estimation of maximum subsurface depth of the basement surface of 360-480 m. The deepest part of the basin probably lies just northeast of Trentham Memorial Park. It is difficult to conceive of any explanation other than tectonic for development of a valley of alluvial origin with an upstream-facing basement gradient.

The stratigraphy of this part of the basin consists of alternating beds of variable thickness, of alluvial gravel and sand, and mud/peat units (Fig. 6.4). The upper ca 50 m consists of coarse to fine alluvial gravel and sand, overlying ca 15 m of carbonaceous mud and peat of early Last Glacial age on the basis of pollen (Mildenhall 1994). If the pollen correlation is correct, the Trentham Memorial Park sequence is the thickest post-Last Interglacial sequence known in the Wellington region and represents a subsidence rate of ca 1 mm/yr (or vertical component amounting to ca 15% of the Wellington Fault's horizontal slip rate). Although ages of the alternating units below this horizon are unknown, a similar crude calculation as that used to estimate the age of the lowermost Quaternary deposits in the Lower Hutt basin yields a minimum basinal age of 360-480 ka.

Seismic reflection data allow a two-fold subdivision of the Quaternary sediments on the basis of reflective character and reflection dips at the western side of the basin (Melhuish et al. 1997). The lower unit (Unit B) is restricted to the western side of the valley and is characterised by mainly weak, discontinuous and low amplitude reflections, dipping to the west close to the Wellington Fault. Unit A overlies Unit B unconformably, is present right across the basin and reflections are characteristically continuous and of high amplitude. A possible interpretation of these data is that deposition of seismic Unit B pre-dates development of constriction at Taita Gorge, and that the lateral continuity of the Unit A reflections are attributable to ponding effects resulting from choking of drainage at the Taita Gorge.

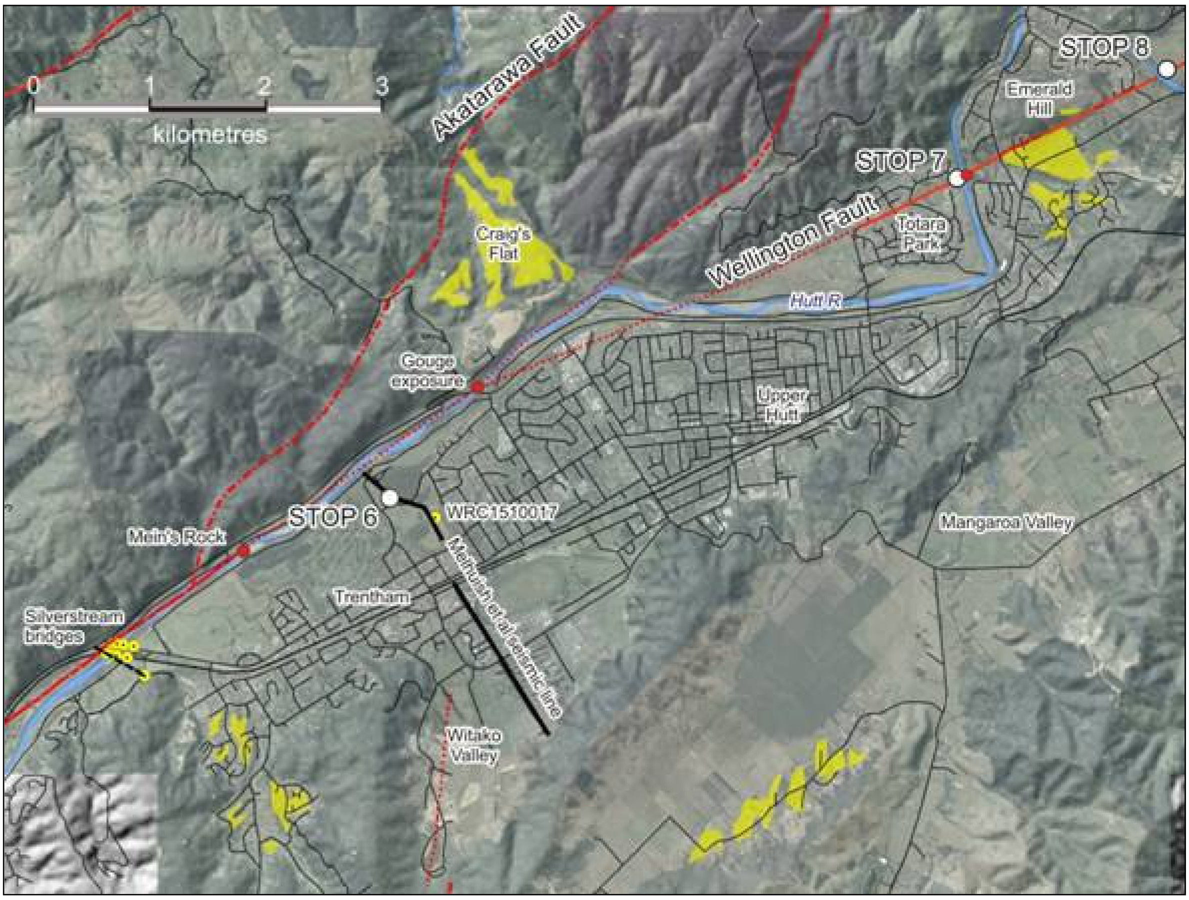


Figure 6.1. This map provides a reference for three stops planned in the Upper Hutt Basin. Elevated yellow surfaces are Pleistocene alluvial deposits of >24 ka age. Drillholes used in compiling this information are indicated as yellow spots with a black dot in the centre; exposures of gouge are shown as red spots; the location of the Upper Hutt seismic profile of Melhuish et al (1997) is shown as a black line. Where it is recognised as a trace at the surface, the Wellington Fault is shown as a heavy solid line; where reasonably well located, as a heavy dashed line; and where obscured by young deposits it is located approximately as a dotted red line. The approximate location of other faults, notably splays of the Akatarawa Fault are shown as dashed and dotted lines.

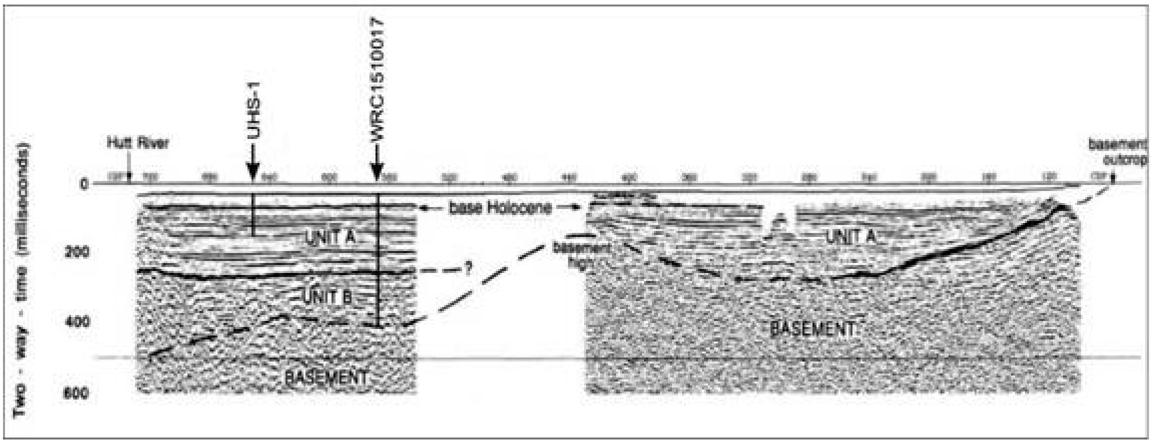


Figure 6.2. Seismic reflection profile across the Upper Hutt basin (from grid ref. R27/799066 to 818041). Lines indicate the approximate position of the contact between greywacke basement and overlying sediments, and a boundary between two distinct seismic units. The seismic line does not reach the position of the Wellington Fault at the left of the figure (After Melhuish et al. 1997).

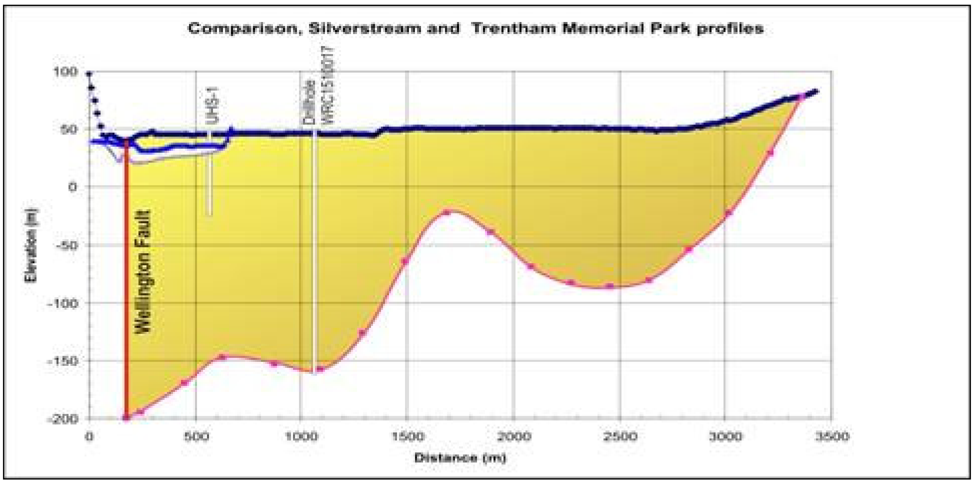


Figure 6.3. A scaled comparison of the surface profile and Pleistocene valley fill at Silverstream Rail Bridge (ground surface = bright blue, alluvial gravel = pale yellow), and Trentham/Witako (surface profile = dark blue, valley fill = darker yellow). The depth of alluvial fill at Silverstream is well constrained by numerous bore holes for the road and rail bridges. The thickness of valley fill at Trentham/Witako is known from drillhole WRC1510017 (basement rock surface at 204 m), and is here estimated from the seismic line of Melhuish et al. (1997), using WRC1510017 for calibration. Note that the base of the valley fill close to the Wellington Fault is at about the same elevation (or lower) than the edge of the continental shelf.

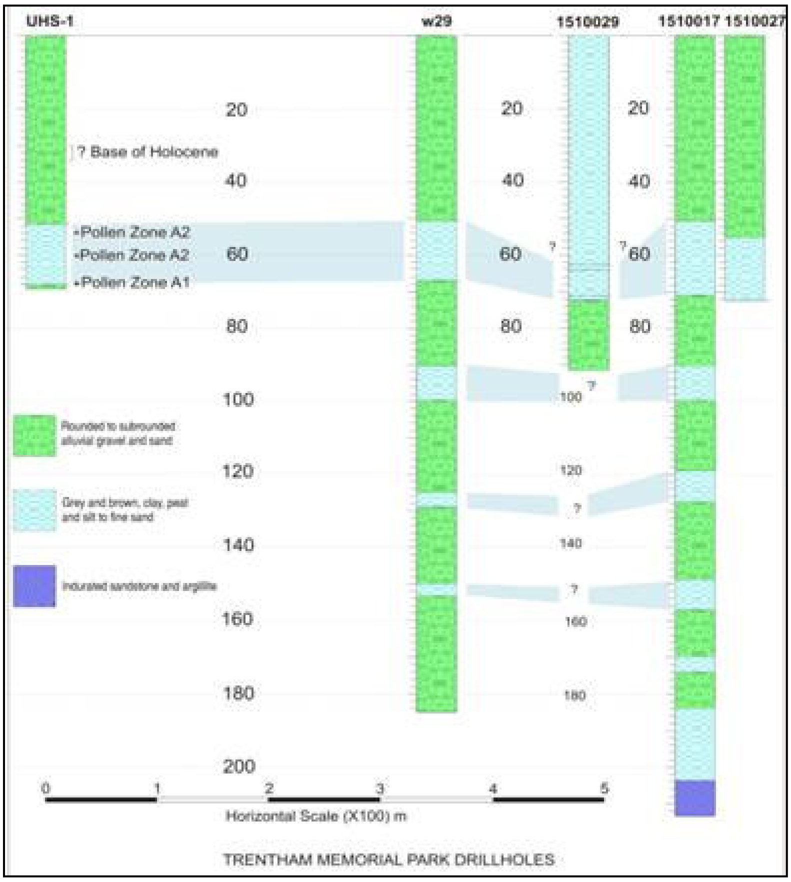


Figure 6.4. Correlation of summary drillhole logs in the Trentham Memorial Park area, Upper Hutt Basin. Individual beds are laterally continuous in the top two thirds of the drillholes, and the sequence consists largely of gravel horizons, alternating with silt, mud and peat units. Pollen zones A1 and A2 are correlated with the early part of the Last Glaciation (Mildenhall 1994). Drillhole WRC1510017 intersected greywacke basement at 204 m depth (158 m below sea level) (after Melhuish et al. 1997).

Stop 7: Totara & Harcourt Parks

Through much of the Upper Hutt Basin, the position of the Wellington Fault has been obscured by river modification since the last rupture event. At the northern end of the basin in the Brown Owl, Totara Park and Harcourt Park area, older Holocene and Last Glacial alluvial terraces rise from beneath Holocene gravel forming terraces dipping to the SW. Here, the active trace of the fault is preserved, passing through Totara Park, California Park, across the Hutt River, through Harcourt Park and across older terraces to Birchville (see Berryman 1990)(Figs. 7.1, 7.2 & 7.3).

Surface rupture hazard mitigation measures were incorporated into the layout and design of the Totara Park suburb (Fig. 7.1). Houses were kept away from the surface trace of the Wellington Fault by locating the centre of a dual carriageway, California Drive, along the fault trace (Fig. 7.2).

In the late 1970's when little was known about the characteristics of the Wellington Fault, a small aperture precise surveying network was established to test for creep in California Park area (Fig. 7.3). The network is being used in conjunction with regional GPS networks to try to define strain across the Wellington Fault. However, results from the precise surveying network are difficult to interpret in any way other than that there is some instability in one or more of the pillars (Des Darby pers. comm.). Ground penetrating radar investigations have also been conducted in the California Park area to better define the shallow-subsurface character of the Wellington Fault (Gross et al. 2004; Fig. 7.4).

The terrace surfaces at Totara Park, and California Park, are considered Holocene in age (Berryman 1990). Their fault displacement is well expressed as a distinct scarp that extends northeastward to the south bank of the Hutt River. In the northeast bank of the Hutt River, the Wellington Fault is well exposed (Fig. 7.5; see also Fig. 8 of Berryman 1990). Here the fault comprises two sub-parallel fault planes that have sub-vertical dips. The upstream fault plane separates crushed and sheared bedrock to the NW (upstream) from a fault-bound packet of blue-grey ?late Pleistocene-age alluvial gravel. There is little, if any, expression of this fault plane at the ground surface. The downstream fault plane separates flat-lying light-brown Holocene alluvial gravel to the SE (downstream) from the fault bound blue-grey ?late Pleistocene-age gravel. The downstream fault plane corresponds to the topographic fault scarp that extends to the northeast through Harcourt Park.

Downstream from the Wellington Fault exposure at the Hutt River, alluvial gravels are known to be greater than 40 m thick from foundation drillholes for the footbridge across the river. From the footbridge, deformed greywacke basement rock is visible in the river bank more than 1 km downstream (Brown Owl corner) indicating that alluvial gravel fills a wedge-shaped basin between the Wellington Fault and Brown Owl.

In the late 1970's a storm-water pipeline was installed that ran through Harcourt Park. The pipeline runs parallel to the Hutt River, not far from the northeast bank of the river, and crosses the Wellington Fault at about a right-angle (Fig. 7.6). In the excavation for the pipeline, the fault plane was exposed. It has a sub-vertical dip and separates coarse alluvial gravel to the NW from massive silt (presumably alluvial overbank deposits) to the SE.

At Harcourt Park, offsets of Holocene and Last Glacial terrace risers indicate cumulative dextral slip on the fault with individual offsets ranging from ca 10 m (youngest) to several tens of metres (oldest). Vertical displacement at Harcourt Park is comparatively large, about 10-20 % of the horizontal displacement. Older terrace risers are dextrally and vertically displaced by the Wellington Fault approximately 1 km northeast of Harcourt Park at Emerald Hill. Here, Berryman (1990) provides estimates for the ages and amounts of offset of the Ohakea (ca 15 ka), Porewa (ca 70 ka), and Marton (ca 140 ka) terraces, and calculates a mean horizontal slip rate 6.6 mm/yr (+ 1 mm/yr; - 0.6 mm/yr). Vertical displacements at Emerald Hill are only a few percent of the horizontal displacements.

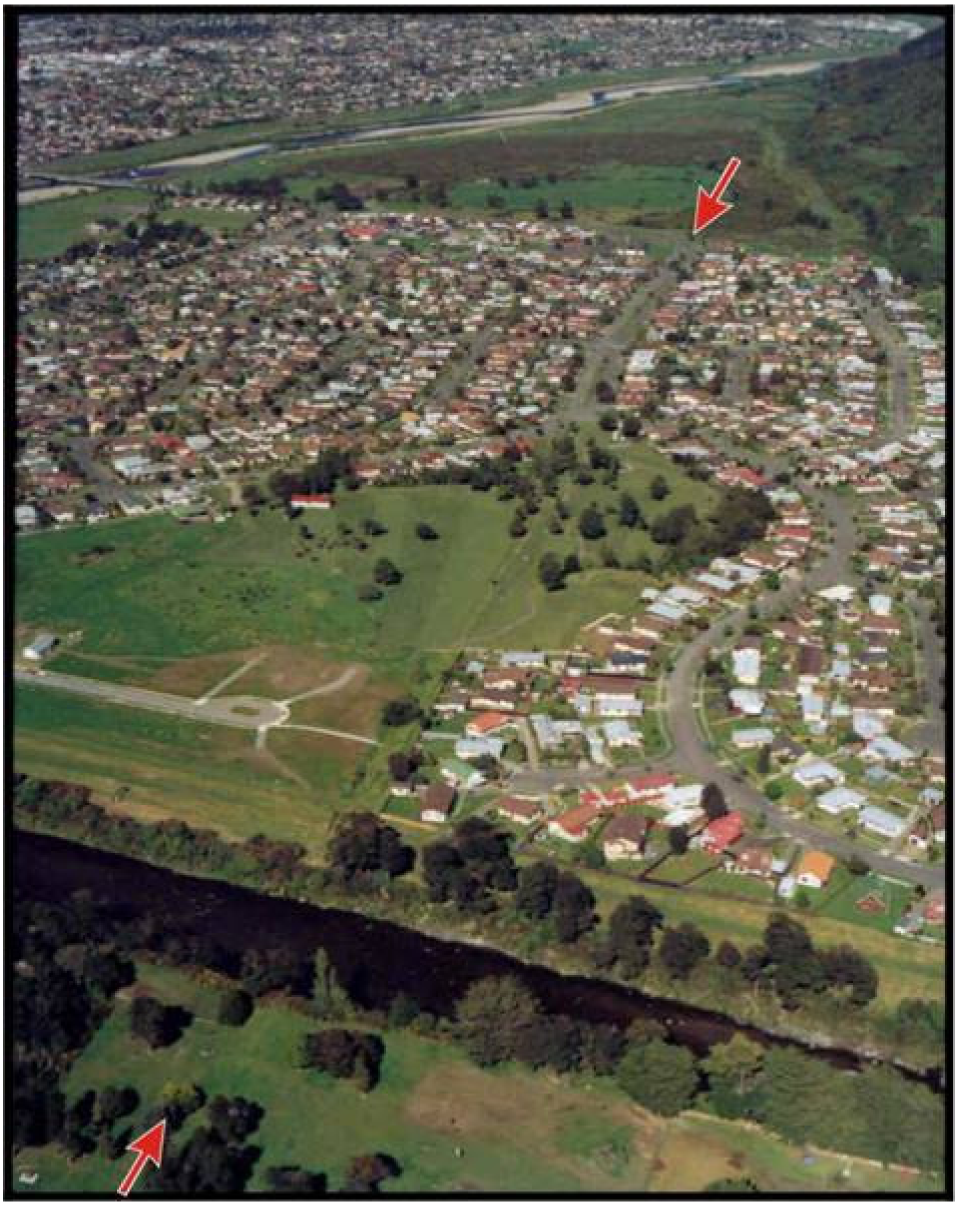


Figure 7.1. The location of the Wellington Fault (between arrows) at Totara Park was known before development of the subdivision. Note the dual carriageway of California Drive with houses on each side set back from the fault. California Park, a recreational reserve (see also Figs. 7.2 & 7.3), is also used to mitigate rupture hazard. In the foreground on the northern side of the river, preservation of the Wellington Fault scarp was one of the wishes of the person who donated Harcourt Park to Upper Hutt City Council.

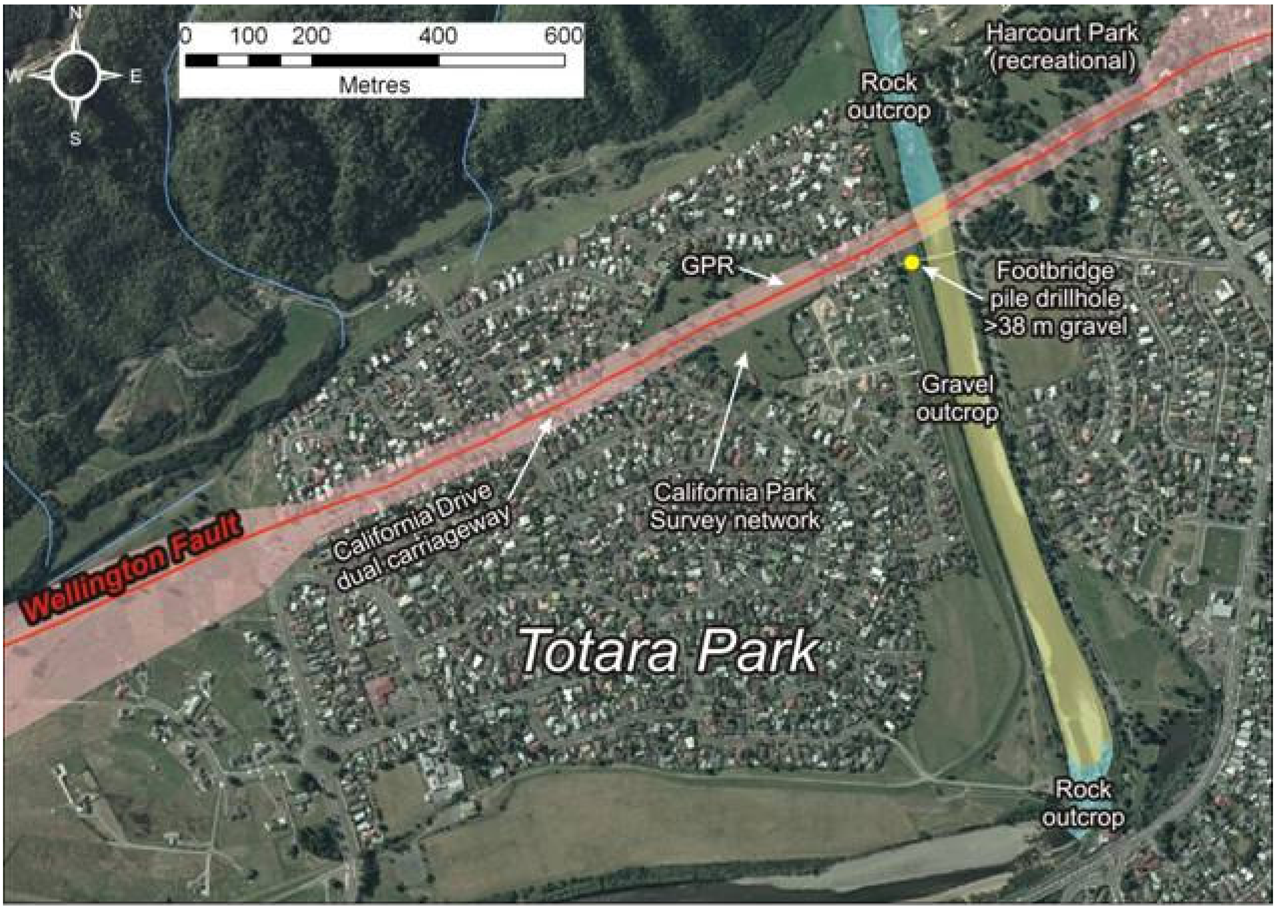


Figure 7.2. The location of the trace of the Wellington Fault at Totara Park is tightly constrained, as indicated by the narrowness of the Avoidance Zone defined by Van Dissen et al. (2005). At either end of the trace, the location of the fault is less well-known, and the width of the Fault Avoidance Zone is consequently substantially broader.

Figure 7.3. The surface trace of the Wellington Fault at California Park is clearly visible in this aerial photo taken with low evening sun illumination. Photo: D.L. Homer.

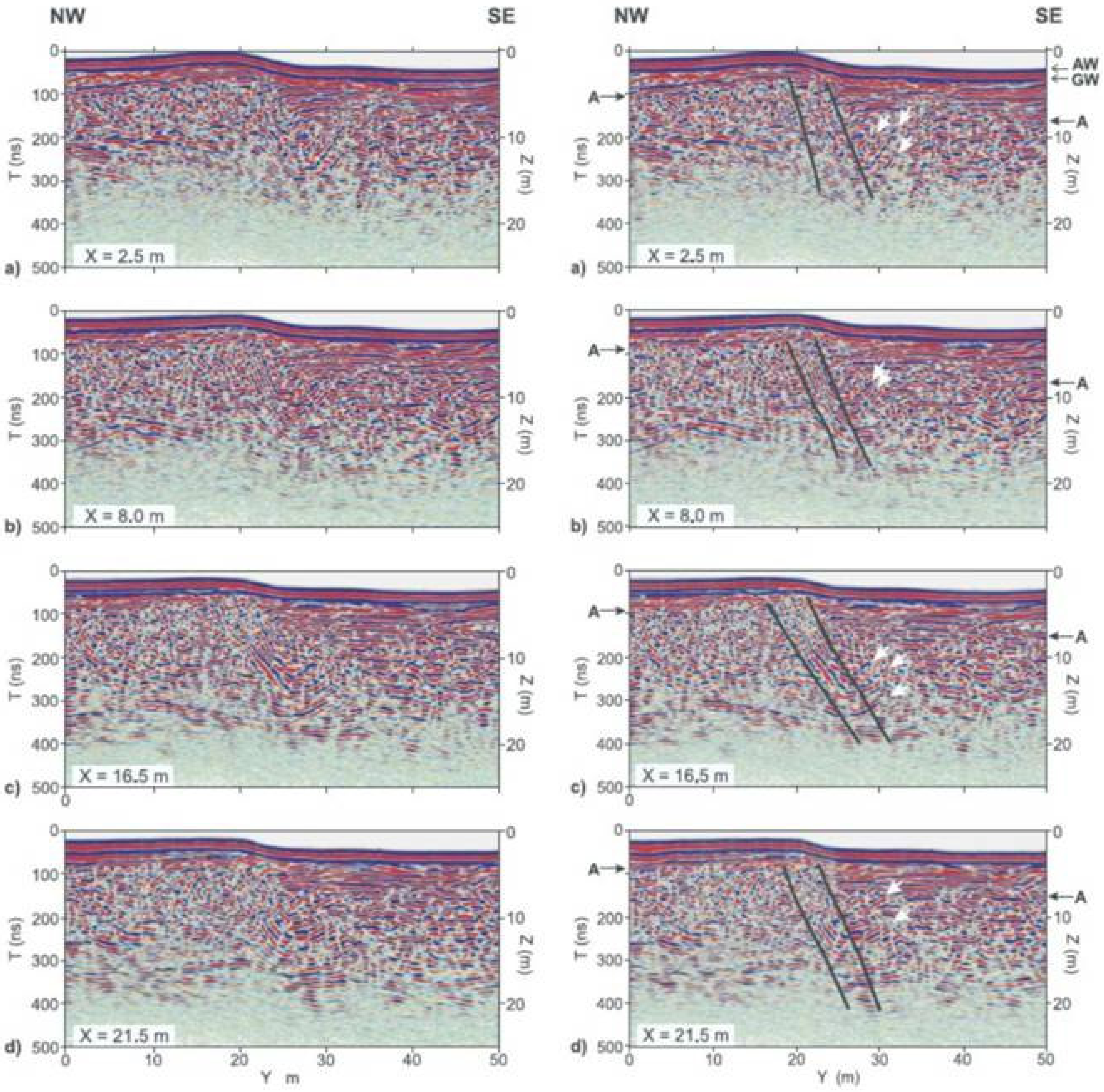


Figure 7.4. Ground penetrating radar profiles, taken from a 3D array, across the Wellington Fault in northern California Park image the Wellington Fault to a depth of ca 15 m (Gross et al. 2004). Right hand profiles show adopted interpretations. Note the scarp at the surface, the dip of the fault to the SE and the presence of two fault planes (compare with Fig. 7.5).

Figure 7.5. Exposure of the Wellington Fault, NE bank of Hutt River at Harcourt Park. Dayglow dots at waist height on the river bank are ca 1 m apart. The Wellington Fault juxtaposes bedrock greywacke and Pleistocene? and Holocene alluvial gravels across two splays. The western splay has little visible surface expression on the overlying terraces, and the eastern splay marks the location of the active trace.

Figure 7.6. ***Top photo***, Storm-water pipeline excavation across the Wellington Fault scarp at Harcourt Park (view looking west-southwest). ***Bottom photo***, exposure of Wellington Fault in pipeline excavation. Fault has a sub-vertical dip and separates coarse alluvial gravel in the background (NW) from massive silt in the foreground (SE) (view looking west-northwest). Photos: Ken Thorpe.

Stop 8: Te Marua terraces – paleoseismicity and single-event displacements

In the Upper Hutt area there are a number of sites along the winding section of the Hutt River where co-seismic displacements can be assessed from offset late Pleistocene to Holocene alluvial terrace features (e.g. Berryman 1990). At the Te Marua Terraces site, located to the NE of Harcourt Park and Emerald Hill (Figs. 1, 6.1, 8.1; grid ref. ca R26/876104), there is a well preserved flight of a dozen or so late Pleistocene to Holocene alluvial terraces (Figs 8.2-8.4). The youngest eight of these terraces cross the Wellington Fault, and are progressively dextrally displaced by the fault (Figs. 8.5-8.7).

The Te Marua Terrace site is important as it offers perhaps the only opportunity to assess both the single event displacement related to the most recent surface rupture of the Wellington-Hutt Valley segment and also progressive displacements resulting from the last several surface rupture earthquakes on this portion of the fault (see Little et al. this conference, Van Dissen et al. 1992, Berryman 1990). The Te Marua site is also close to the Emerald Hill locality (Fig. 8.1) where a Late Quaternary dextral slip rate of the fault (6-7.6 mm/yr) was estimated by Berryman (1990), so the site also provides an opportunity to develop a recurrence interval of faulting that is independent of the on-fault paleoseismic records. The It's Our Fault project has given us the chance to re-assess the Te Marua data and to undertake new research on the age and displacement of the alluvial terraces there.

The terrace sequence and co-seismic displacements

The Wellington Fault is rather subtly expressed where it crosses a southward projecting peninsula in a meander loop of the Hutt River near Te Marua, an area of open farmland near Wooster's Farm, accessed off Gillespies Road (Figs. 8.2, 8.3, 8.5 & 8.6). The lack of a conspicuous scarp across the Holocene terrace surfaces at this site is the result of its fault-slip vector being almost perfectly horizontal, essentially parallel to the local ca 067° strike of the fault. At the SW corner of the farm the fault crosses the Hutt River from Birchville and can be followed across the flight of low terraces and their associated risers and channels, labeled terraces T1 through T8 on Figs. 8.2, 8.4, 8.5 & 8.6. In this scheme, T1 represents the lowest unfaulted terrace, excluding the modern river bed, and successively higher terraces are assigned successively larger numbers.

This site has been surveyed with GPS-RTK to construct a detailed topographic map (Fig. 8.6) which has been used to document and accurately measure terrace displacements and to construct a record of sequential fault rupture displacements (Fig. 8.7)(Little et al. this conference, and manuscript in prep.). Also, three trenches were excavated in 2008 to attempt to better understand the nature of the terrace stratigraphy and to obtain carbonaceous material with which to date the terraces (and associated earthquake rupture displacements)(Langridge et al. 2008). In addition, 16 optically stimulated luminescence (OSL) samples have been dated from this site by Little et al. (manuscript, in prep.); the locations and ages of the samples are schematically depicted in Figure 8.4. From terrace T6 through to older terrace T12 OSL ages are consistent with stratigraphy and range from ca 4.5 ka for T6 to ca 13-15 ca for T12. However, for the younger terraces, OSL ages are not stratigraphically consistent. The reasons(s) for this are not yet well understood, but may have involved mass wasting of the deeply incised, older aggradational gravels (especially of T12), followed by rapid deposition at nearby overbank sites downstream of a mixture of recycled sedimentary particles that had been only variably to poorly bleached by light prior to their redeposition.

Little et al. (this conference, and manuscript in prep.) recognise three clusters of dextral displacement values from the Te Marua Terraces site. The smallest cluster, which includes displacements of two small channels on terrace tread T2 and the subdued ridge between them, and the riser separating T2 and T3 (denoted R2 on Fig. 8.5b, or T_{2-3} on Fig. 8.7), has a mean displacement of 5.3 ± 0.4 m (Fig. 8.7). Trench 1 (TMT-1) was excavated into one of these offset channels, while trench TMT-2 was excavated a few metres to the west through the unfaulted terrace riser separating T2 from T1 (Figs. 8.5b & 8.6). Stratigraphic and age results from these trenches constrain the timing of the displacement (earthquake rupture) and are discussed separately below. It is interesting to note that Berryman (1990) identifies a handful of other ca 5 m dextral displacements on the fault, most of which are now, unfortunately, destroyed. The cluster of dextral displacements of ca 5 m represents the smallest displacement increment identified along this portion of the fault, and are regarded as having resulted from the most recent surface rupturing earthquake.

A second cluster of displacements, with a mean of 14.0 ± 1.0 m (Fig. 8.7), is based on measured lateral displacements of two adjacent terrace risers (denoted R3 & R4 on Fig. 8.5b, or T_{3-4} & T_{4-5} on Fig. 8.7). If ca 5 m dextral displacement is typical for this section of fault, then a displacement of ca 14 m probably represents the cumulative displacement from three surface ruptures. This three-event interpretation is strengthened by noting that at Harcourt Park, ca 2 km to the SW of Te Marua (Fig. 8.1), an intermediate displacement of ca 10 m, albeit with large uncertainty, has been measured (Fig. 8.7) (Little et al. manuscript in prep.); and also that Berryman (1990) reported two other ca 10 m displacements between Emerald Hill and Te Marua. These may represent two-event displacements. To further test the three-event interpretation of the ca 14 m dextral displacement cluster at Te Marua, trench TMT-3 was excavated across the fault, between displaced sections of the R3 riser (Fig. 8.5a & 8.6). Results from this trench, like those from trenches TMT-1 & TMT-2, are outlined below.

The third displacement cluster at Te Marua is based on the lateral displacements of risers R5, R6 and R7, and of channels on the surface of T6 and T7; the mean value of this cluster is 19.8 ± 0.9 m (Fig. 8.7). This cluster of offsets is likely to represent four co-seismic displacements. If this is the case, then the last four ruptures of this section of the Wellington Fault have been remarkable consistent in size, generating single-event displacements averaging 5.0 ± 0.9 m (1 σ)(Little et al. this conference, Little et al. manuscript in prep.).

Te Marua trench-2 (TMT-2)

Te Marua trench 2 (TMT-2) was excavated close to the Hutt River through riser R1 and the deposits of terrace T1 and T2 (Figs. 8.5 & 8.6; grid ref. R26/875103). The base of this trench, and that of TMT-1 (see below), consisted of bouldery gravel, inferred to represent the same aggradational surface of terrace T2. Because there is no fault scarp across the T1 terrace surface, the deposits that comprise T1 are interpreted as unfaulted and these consist of ca 1.4 m of cobbly sand to silt, onto which a thin soil has developed.

Two new AMS radiocarbon dates from detrital charcoal collected from terrace T1 deposits (samples TMT-2/1 and TMT-2/7; 835 ± 30 yr BP and 428 ± 25 yr BP, respectively) and one earlier charcoal date from Van Dissen et al. (1992) (NZ 7769; 80 ± 51 yr BP) confirm that this unfaulted terrace is very young. A spread in ages for these samples can be expected due to the possibility of inherited age of charcoal (e.g. from the middle of an old tree), and also the possibility of significant residence time, including re-working from older deposits. In such cases, when several pieces of detrital charcoal are dated from a given unit it is likely that the youngest date best reflects the true age of the deposit. Accordingly, we regard the T1 terrace surface to be ≤ ca 270 cal yr BP (the maximum of the calibrated age range of 80 ± 51 radiocarbon yr BP). This is consistent with the fact that this terrace surface still occasionally gets inundated by Hutt River flood waters.

Deposits comprising the edge of terrace T2 (the R1 riser) were also exposed in TMT-2 and consists of well-bedded sand and sandy silts. One charcoal radiocarbon sample was collected and dated from these T2 deposits yielding an age of 975 ± 25 yr BP (sample TMT-2/10), which is consistent with the age results of other charcoal samples collected from T2 deposits in trench TMT-1 (see below).

Te Marua trench-1 (TMT-1)

Trench TMT-1 was excavated only 10 m to the NE of, and end-on from, trench TMT-2 (Figs. 8.5 & 8.6). TMT-1 was investigated to help better understand the deposits and age of terrace T2 and in particular, surficial channels on T2, which are displaced by ca 5 m (Fig. 8.2, 8.5, 8.6 & 8.7). The base of TMT-1 is sandy bouldery gravel, interpreted to be the same unit that floors trench TMT-2. The boulder gravel in trench TMT-1 is overlain by 1-1.3 m of massive to chanellised cobbly to sandy alluvium into which a brown soil is developed. The offset surficial channel is incised by up to 15 cm, and we found no deposits relating to it. The soil on T2 is deeper and better developed than that on T1.

The youngest feature exposed in the trench, apart from the soil, is the surficial channel, and because this channel is offset, all deposits related to terrace T2 must also be faulted and all radiocarbon dating samples from within these deposits should predate the most recent faulting event (assuming no young carbon has been introduced into the system). Five radiocarbon samples, three from the lower part of the trench and two from the upper part, constrain the age(s) of deposits encountered in trench TMT-1. The deepest sample, TMT-1/13 has a radiocarbon age of 1761 ± 90 yr BP, substantially older than all other dates from terrace T2 and is inferred to represent a piece of reworked charcoal or one with significant inherited age. It provides a maximum age for terrace T2 deposition. Samples TMT-1/1 and TMT-1/7, also from the lower part of the trench, yield radiocarbon ages of 861 ± 30 yr BP and 1049 ± 30 yr BP, respectively. These are similar in age to sample TMT-2/10 (975 ± 30 yr BP) collected from T2 deposits exposed in trench TMT-1. We infer that deposition of terrace T2 began at or before ca 675 cal yr BP (the minimum of the calibrated age range of 861 ± 30 yr BP).

Two dates come from charcoal collected from the upper part of the trench. Both samples are from depths 20-30 cm below the ground surface and yielded ages of 324 ± 25 yr BP (sample TMT-1/10), and 260 ± 25 yr BP (sample NZA 29483). Also, Van Dissen et al. (1992) reports an age of 356 ± 82 yr BP (NZA 711) for a charcoal sample collected at ca 15 cm depth from T2 on the opposite side of the fault, several tens of metres SE from trench TMT-1. If these samples represent charcoal deposited during the waning stages of T2 construction, then the abandonment of T2 occurred ≤310 cal yr BP (the maximum of the calibrated age range of the youngest sample). From these data we infer that the most recent faulting event (the event that displaced the surficial channels on T2 and underlying deposits) must be younger than 310 cal yr BP; it must also be older than the recorded historic period in New Zealand (ca AD 1840). Our currently preferred interpretation for the timing of the most recent rupture of the Wellington Fault at this site is sometime before AD 1840 and after AD 1640.

The cutting of riser R2 (see R2 on Fig. 8.5b, and T_{2-3} in Fig. 8.7) pre-dates deposition of terrace tread T2, but both the riser and the tread (T2 tread displacement is defined by the offset of the surficial channels) share the same displacement. This indicates that the last surface rupturing event post-dates both features, and the previous rupture (Event II) pre-dates them. The timing of the cutting of R2 and initiation of T2 deposition thus provides a minimum constraint on the timing of Event II faulting (the penultimate event). In summary, we consider that T2 deposition began at or before ca 675 cal yr BP, so Event II must pre-date this age (i.e. $\geq$675 cal yr BP).

Te Marua trench-3 (TMT-3)

A third trench, TMT-3 (grid ref. R26/876104), was excavated about 70 m east of TMT-1, across a ca 1 m high, NW-facing fault scarp of the Wellington Fault. At this location the tread of terrace T3 is faulted against the tread of T4, where the riser between T3 and T4 is dextrally displaced by ca 14 m (Figs. 8.5, 8.6 & 8.7). The vertical component of slip along the Wellington Fault here is close to zero, the scarp height resulting from juxtaposition of terrace treads of differing age (and height).

Terrace T4 deposits exposed on the SE end of the trench were composed primarily of cobble to boulder gravel capped by a thin silt cover. Materials exposed on the on the T3 side of the fault consisted of a number of facies in a fining-upward sequence of cobble gravel to fine sandy silt alluvium and fine colluvium. A fault zone 1.5 to 3 m wide separates T4 and T3 deposits. The primary zone of faulting is exposed beneath the steepest part of the scarp. In this area at least 4 near-vertical faults displace through most of the section. In addition, 3 distinct colluvial packages have been shed across the scarp, and we interpret these as resulting from co-seismic displacement on the fault. The oldest of these is a wedge-shaped silty cobble gravel. It is disrupted by a number of fault strands, some of which terminate at the top of the unit. A second colluvium overlies the oldest one and comprises yellow brown pebbly silt. This colluvium is itself cut by two fault strands, which terminate at the unit's top. The third and youngest colluvium is volumetrically the smallest and comprises little more than a stone-line that drapes unfaulted across the fault zone.

Three very small samples were submitted for AMS radiocarbon dating from trench TMT-3. All were from the T3 side of the trench, either from T3 deposits, or from the oldest colluvium (overlying T3 deposits). Two sample returned unrealistically young ages (both less than several hundred radiocarbon years, and though both these samples were small and black they, on reflection, were not detrital charcoal as was hoped at the time of their collection and submission for dating). The third sample (sample TMT-3/3), collected from within T3 gravel consists of rooty material that presumably post-dated abandonment of T3. Its age of 1725 ± 35 yr BP (ca 1420-1695 cal yr BP) provides a minimum age for deposition of terrace T3, deposits of which have been faulted three times.

Preliminary paleoearthquake record and recurrence interval from Te Marua

A major goal of the trenching at Te Marua was to characterise the timing of the most recent surface rupturing earthquake event. By trenching faulted and unfaulted terrace deposits we have been able to constrain the age of terraces T1 and T2 at Te Marua and of the last rupture event. Radiocarbon dates from within the uppermost facies of T2, combined with historical data, indicate the most recent event occurred between ca 110-310 cal yr BP (AD 1840-1640). A dextral slip of ca 5.3 ± 0.4 m was associated with this event.

Similarly, a preferred minimum age on the penultimate faulting event (Event II) comes from the age of the lower facies of T2. From these dates, we infer that Event II is >675 cal yr BP.

The last four surface rupture earthquakes at Te Marua have resulted in dextral slip averaging 5.0 ± 0.9 m each (see Fig. 8.7). This data combined with the previously published dextral slip rate of Berryman (1990) of 6.6 mm/yr (+1 mm/yr, -0.6 mm/yr) allows an estimated average recurrence interval of ca 760 years to be calculated, with an indicative minimum of ca 540 years, and a maximum of ca 980 years. Note, investigations are currently underway to re-evaluate the late Quaternary slip rate of this part of the fault (D. Nines, Victoria University of Wellington). If these warrant revision of the above slip-rate, then they too would warrant a revision of the above slip-rate derived recurrence interval.

Figure 8.1. Wellington Fault through the Harcourt Park, Emerald Hill and Te Marua Terraces area (after Berryman 1990, modified by Little et al manuscript in prep.). Terrace names: Po, Porewa; Ma, Marton; Bu, Burnand. Dashed-box around Te Marua Terraces area denotes location of Figure 8.2 and approximate location of Figure 8.3.

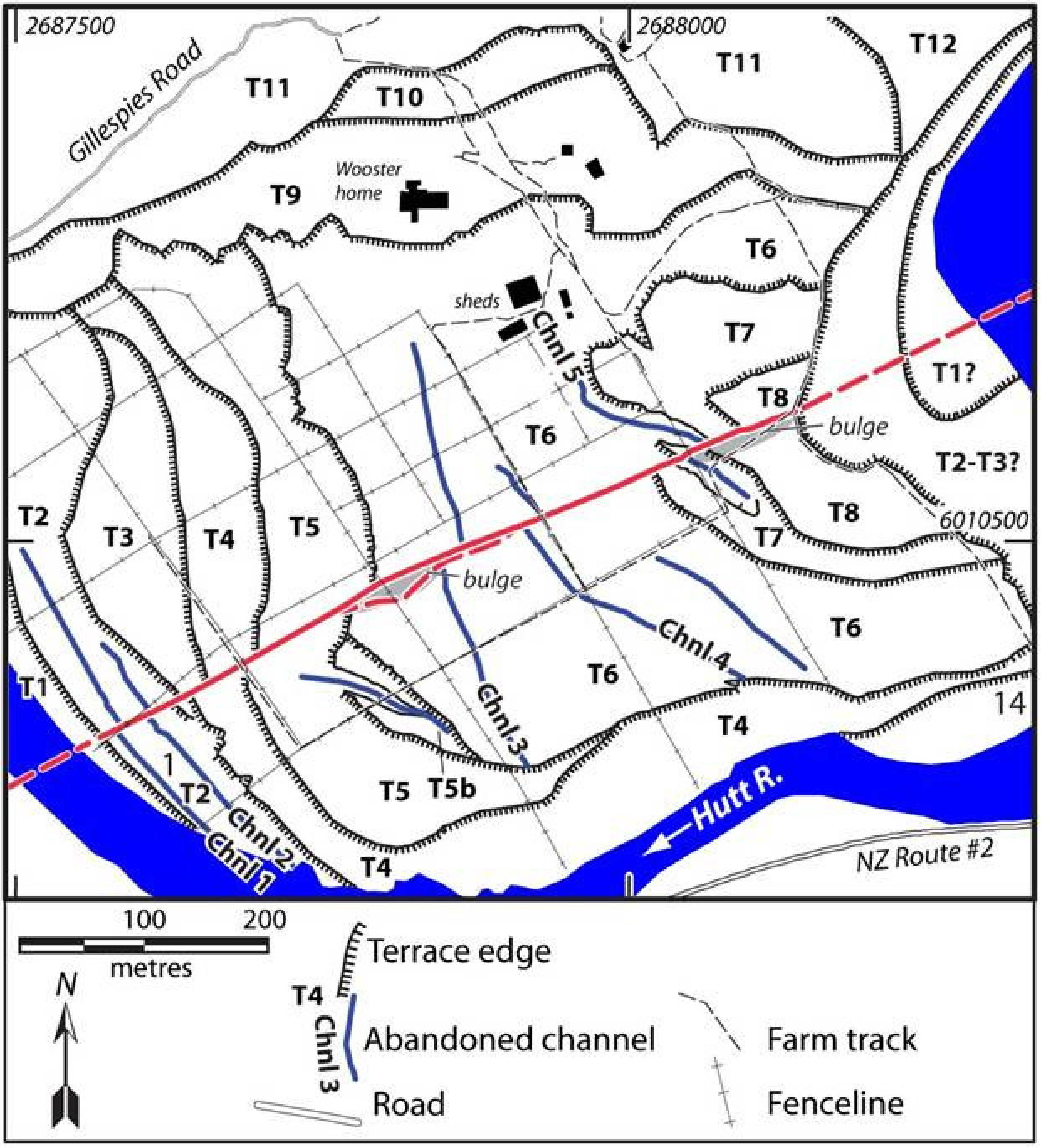


Figure 8.2. Wellington Fault through Te Marua Terraces area (from Little et al. manuscript in prep.). See Figure 8.1 for location; Figure 8.3 for an aerial perspective (see also Fig. 8.5); Figure 8.4 for schematic cross-section of these terraces depicting their relative elevational position and location of specific dating results; and Figure 8.6 for detailed topographic map of the fault and associated terrace and channel offsets.

Figure 8.3. Oblique aerial view to the SW along the Wellington Fault (arrowed) at Te Marua. The Hutt River winds through this area and has left behind a flight of abandoned river terraces, which are progressively dextrally displaced by the fault. Box shows area of Figures 8.5b & 8.6a. Photo: D.L. Homer.

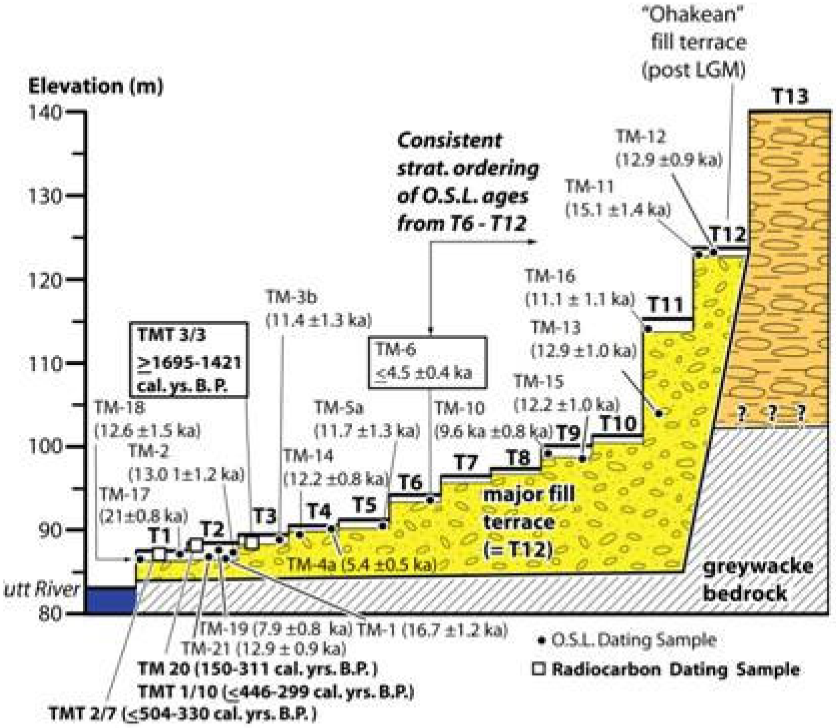


Figure 8.4. Schematic cross-section of Te Marua Terraces site showing relative elevational position of each terrace, and select dating results. All O.S.L. dating results are shown, but only the most relevant radiocarbon results are depicted. Below terrace T6, O.S.L. ages show no consistent stratigraphic ordering; whereas, above T6 they do (see text for additional discussion regarding this point). (from Little et al. manuscript in prep.)

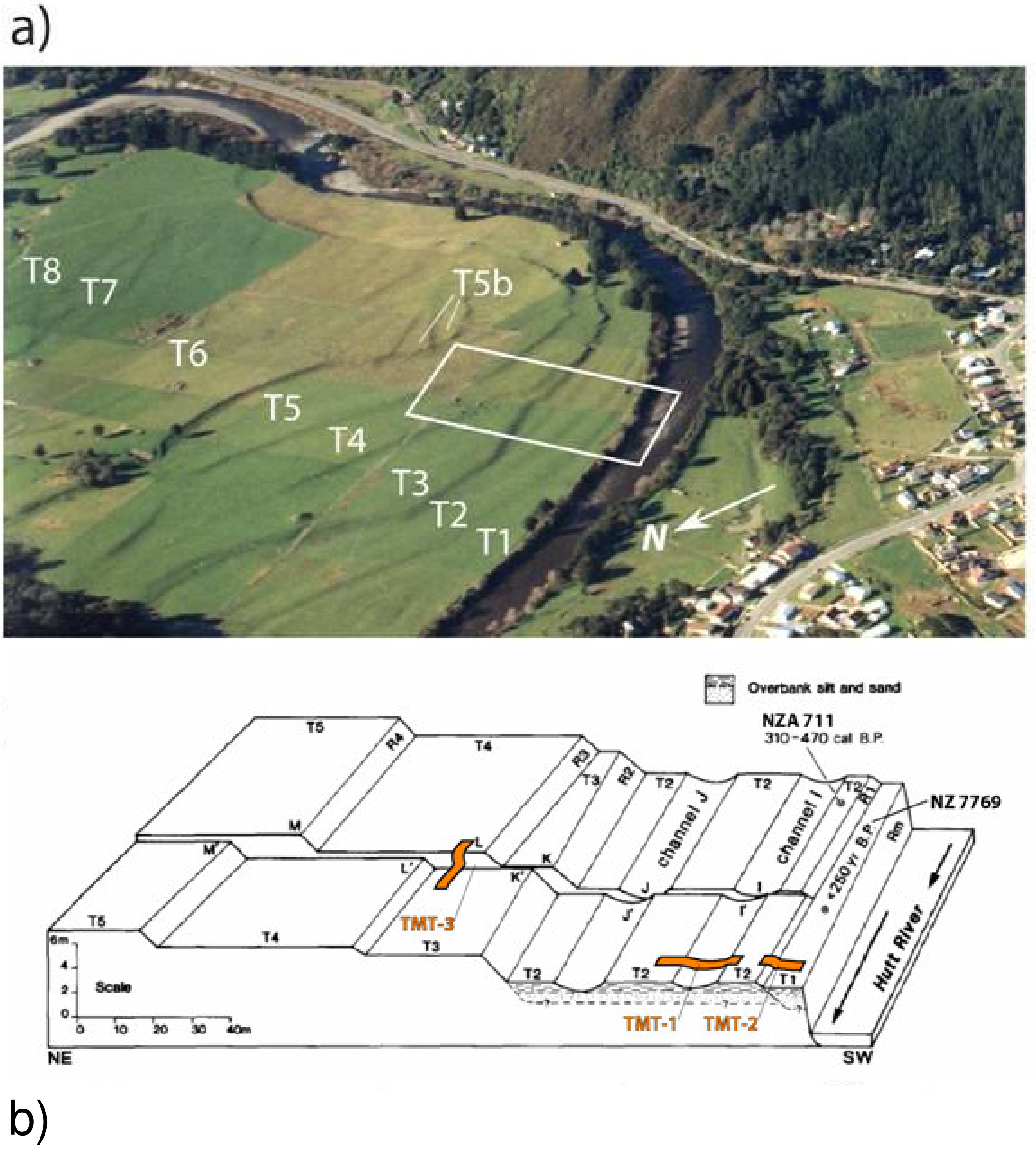


Figure 8.5. **a**) Oblique aerial view to the SE of the Te Marua Terrace area. Naming of Holocene terraces, T1 to T8, is the same as that shown on Figures 8.2, 8.4, & 8.6. White rectangle shows location of Figure 8.5b. Photo: D.L. Homer. **b**) Perspective scale drawing of displaced fluvial channels and terraces at Te Marua (after Fig.11 of Van Dissen et al. 1992). The three trenches excavated at the site are shown along with the two previous radiocarbon dates from the site. Locations of the most relevant radiocarbon dates obtained as part of the current investigation are depicted on Figure 8.4.

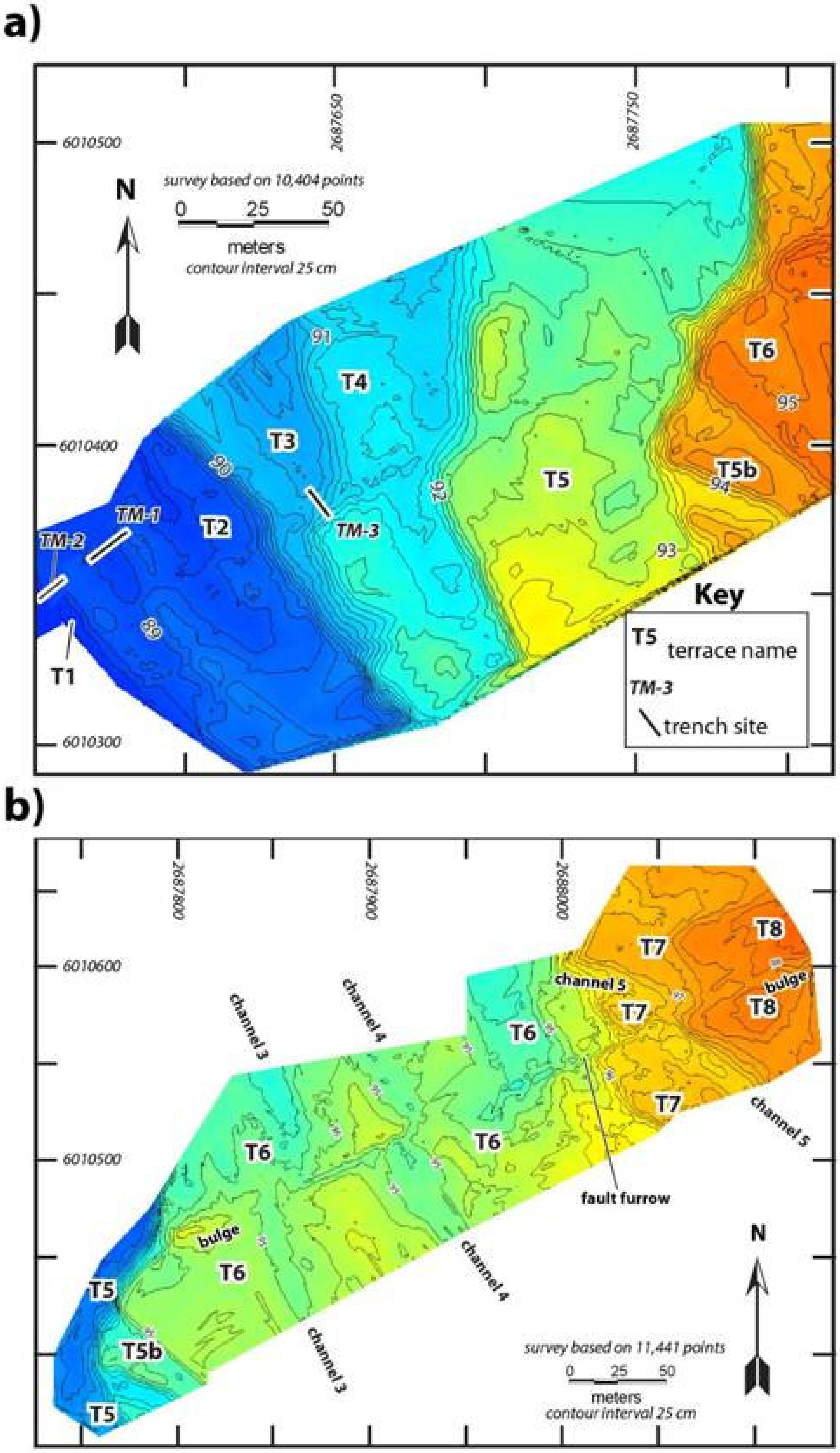
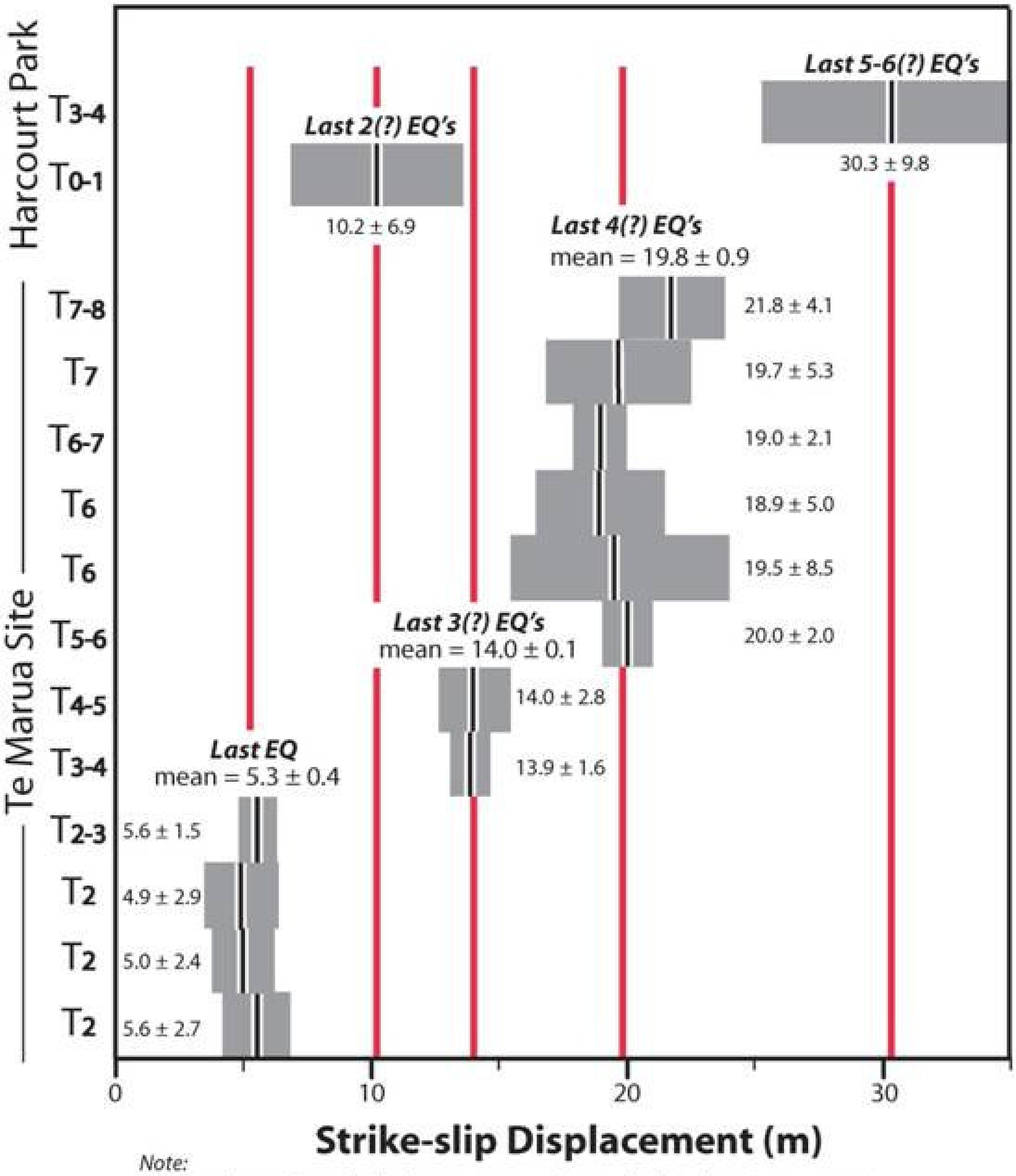


Figure 8.6. Detailed topographic map of the Te Marua Terraces site (see Figures 8.2 & 8.5 for location). Abandoned Holocene terraces of the Hutt River are labelled T1 (youngest) through to T8 (oldest). Trenches are shown by black bars, e.g. TM-1. (from Little et al. manuscript in prep.).



Note:
1) Quoted errors for each displacement are at 2 sigma level (= the written ± errors)
2) Where these were asymmetrical on either side of the best-fit displacement, the larger of the two half-ranges was applied to both sides to make a pseudo-symmetrical distribution
3) Grey areas depict 1 sigma uncertainties
4) Quoted mean values for the aggregated displacements (Last EQ, Last 3 EQ's, and Last 4 EQ's) are standard errors at the 2 sigma level.

Figure 8.7. Wellington Fault strike-slip displacements measured at Harcourt Park and Te Marua grouped according to size. Individual displacements appear to cluster around multiples of ca 5 m. If the assumption is made that each cluster represents an individual earthquake rupture, then the last four ruptures of this section of the Wellington Fault have been remarkable consistent in size, generating single-event displacements that average 5.0 ± 0.9 m (1 σ). (Little et al. this conference, Little et al. manuscript in prep.).

Stop 9: Stuart Macaskill Lakes

The Stuart Macaskill Lakes (Fig. 9.1; formerly Te Marua Lakes) provide water supply and storage for the greater Wellington urban area. Their main function is to provide clear water for times when the Hutt River, the regions primary water intake, is running too turbid for efficient treatment and distribution. The lakes are sited on abandoned river terraces of the Hutt River, and immediately adjacent to the Wellington Fault. The ages of these terraces are estimated to be several thousand to several tens of thousands of years old (Berryman 1990, Begg & Johnson 2000). The scarp of the Wellington Fault is clearly visible on aerial photographs taken prior to construction of the lakes (Figs. 9.2 & 9.3), crossing these alluvial terraces and close to the future location of the lakes. The scarp has a general strike of 067°E, displaces the terraces in a predominantly right lateral sense, and has a subordinate and variable vertical component of offset. In detail, the scarp is composed of, in places, a series of left-stepping en-echelon traces and, at these locations, has a width of up to ca 40-50 m measured perpendicular to the general strike of the fault. Construction of the Stuart Macaskill Lakes has completely destroyed the scarp of the Wellington Fault in the immediate vicinity of the lakes, as well as much of the original fluvial geomorphology of the site.

During construction of the lakes, a 10 m deep trench excavated to install a drain to reduce groundwater pressure under the lining for the southwestern lake crossed the Wellington Fault roughly perpendicular to its strike. Greywacke bedrock in the trench was crushed and sheared over a zone ca 70 m wide; the 75-80° SE dipping fault plane consists of clay fault gouge, up to ca 40 cm thick, extending through the alluvial gravels, and aligning with the currently active fault scarp (Figure 9.4; see Figures 9 & 10 of Berryman 1990). Rupture on the fault has occurred repeatedly at the same place over a period of at least 10,000 years (the estimated age of the gravel). The trench also provided evidence that there has been change in the upthrown side of the fault through time. The surface scarp shows a vertical displacement of about 0.5 m, upthrown to the SE, while the bedrock strath below the terrace gravels, thought to have been cut about 30,000 years ago, has a vertical throw of about 3 m, NW side up.

Prior to backfilling of the trench, a strainmeter was installed across the fault (Fig. 9.5). The strainmeter consists of: 1) five 5-8 m long stainless steel rods that cross the fault in a braced-x pattern, fixed to pillars founded on bedrock on one side of the fault, but with free ends on the other side of the fault; and 2) fixed reference marks, also founded on bedrock, near the free ends of the rods. Deformation (strain) is monitored several times a year by measuring the gap between the free ends of the rods and the fixed reference points which are accessed via two 9 m deep manholes. Measured engineering shear-strain rate parallel to the fault trace is about 3 ppm/yr (or a “creep” rate across the 5 m width of the array of about 27 µm/yr). This rate is three orders of magnitude lower than rates commonly referred to as fault creep, although its sense is entirely in accordance with regional GPS strain measurements. These data are consistent with a conclusion that displacement on the Wellington Fault is accommodated via episodic large earthquakes.

Near the Stuart Macaskill Lakes, main water supply lines cross the Wellington Fault making water supply failure almost inevitable in the event of a Wellington Fault surface rupture. At these crossings, automatic shut-off valves are currently being installed in conjunction with easily repaired smaller-diameter surface by-pass pipes designed to speed restoration of (at least partial) water supply. Despite these and other measures that add tangible robustness to the water supply network, post-event supply of water will be one of the most significant challenges facing the region. It is an issue that deserves continued high-priority planning and vulnerability reduction.

Figure 9.1. High altitude oblique aerial photograph of the Kaitoke to Wellington area, looking southwest. Location of Stuart Macaskill Lakes is show, as is the approximate location of the Wellington-Hutt Valley segment of the Wellington Fault (denoted by bold dashed red line). Photo: D.L Homer.

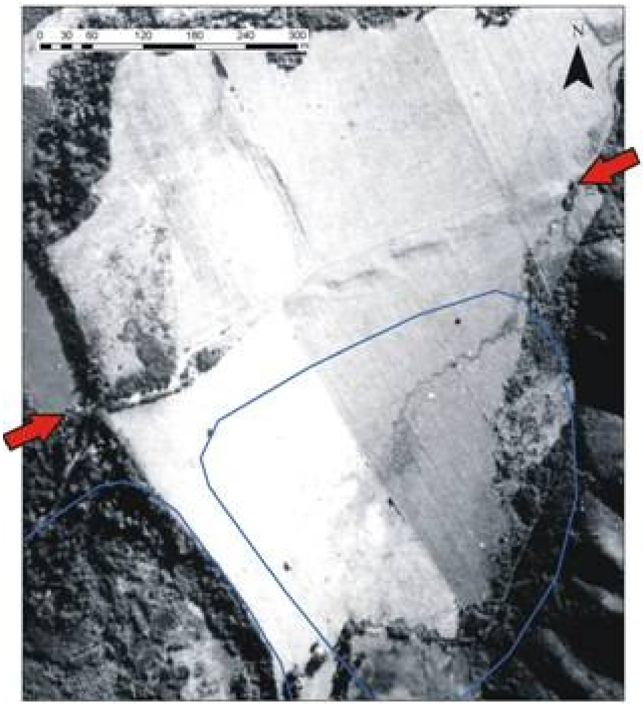


Figure 9.2. Orthorectified vertical aerial photograph (321/32 taken on 21 May, 1942) of the Wellington Fault scarp (denoted by bold arrows) extending across abandoned alluvial terraces of the Hutt River near the future site of the Stuart Macaskill Lakes. Approximate location of reservoir area of the Stuart Macaskill Lakes is denoted by the line in the lower right. Most of the reservoir area of the northeastern lake is encompassed by this image, but only a portion of the southwestern lake.

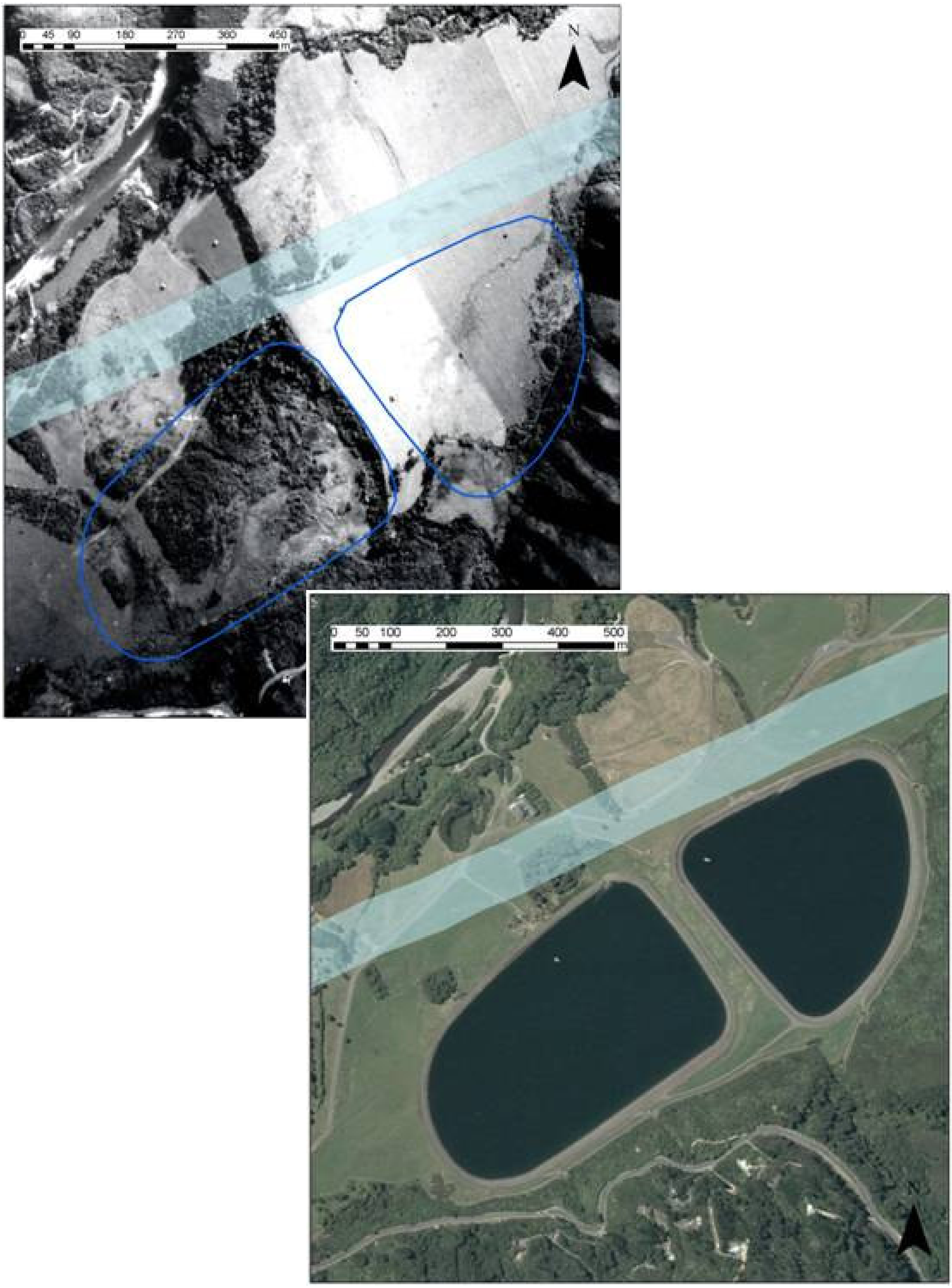


Figure 9.3. Vertical orthorectified aerial photographs showing location of Wellington Fault deformation zone (light blue shading; comparable to Fault Avoidance Zone defined by Van Dissen et al. 2005) in relation to the Stuart Macaskill Lakes. Width of deformation zone accounts for uncertainties in photo rectification, the width of visible fault scarp, and possible sub-resolution deformation that may extend further than the visible fault scarp. ***Top photo***, pre-construction image, part of aerial photograph 321/32 taken on 21 May, 1942; lines denote approximate outline of reservoir area of the lakes. ***Bottom photo***, post-construction image taken in early 2000's.

Figure 9.4. The trench at the future site of Stuart Macaskill Lakes exposed the Wellington Fault.

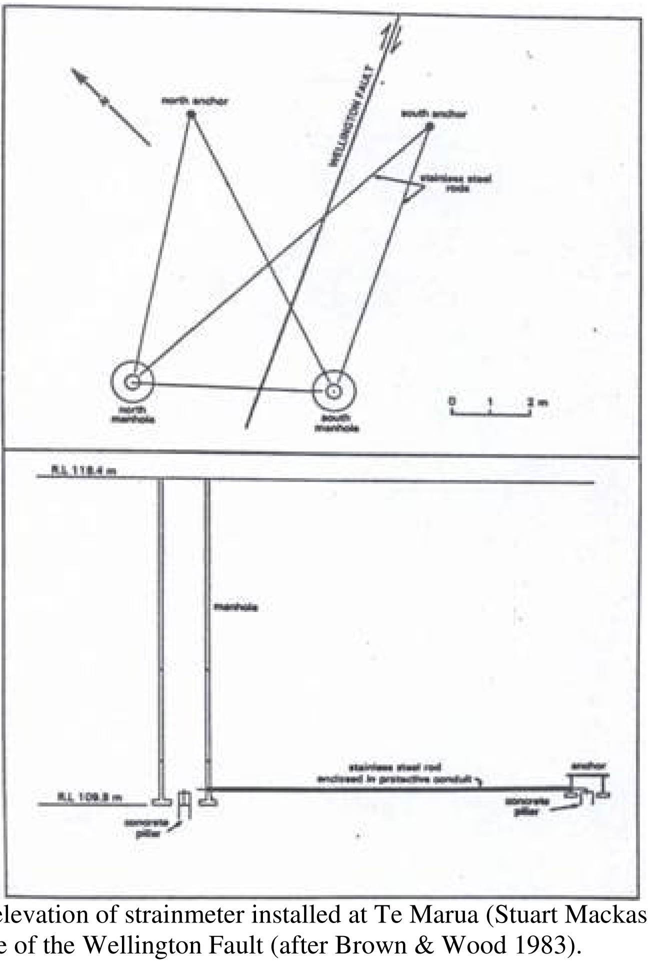


Figure 9.5. Plan and elevation of strainmeter installed at Te Marua (Stuart Mackaskill Lakes), and its relationship to the trace of the Wellington Fault (after Brown & Wood 1983).

Stop 10: Kaitoke AgResearch Farm – new trenching

The Kaitoke Farm trench site is located near the NE termination of the Wellington-Hutt Valley segment of the fault (Figs. 1 & 10.1). Prior to 2008, Berryman (1990) had mapped this stretch of the fault, and recognized a significant, ca 2 km right stepover in the Wellington Fault at the southern foot of the Tararua Range – termed the Kaitoke stepover. Also at that time, two paleoseismic trenches were opened in the area, ca 1.4 km west of the new site, and these are presented in Van Dissen et al. (1992a).

At the Kaitoke Farm trench site, the Wellington Fault is well expressed across open farmland. A clear E-W striking, north-facing scarp marks the main trace of the fault. This uphill-facing scarp causes deflection and ponding of small streams, and creates conditions favorable for the accumulation of peats against the fault trace (Fig. 10.1). For these reasons (i.e. datable material in close proximity to the fault trace) the Kaitoke Farm site was viewed as a prospective site for trenching investigations aimed at assessing the timing of paleoseismic events on the Wellington Fault (Langridge et al. 2008). Three trenches were excavated across this trace in 2008 as part of the Its Our Fault project, and are briefly described below.

In addition to the trenched uphill-facing scarp at this site, there is a downhill-facing rangefront scarp to the north near the bushline.

Kaitoke Farm trench-1

Kaitoke Farm Trench 1 (KAF-1) was excavated at grid ref. S26/932126, near the barn that can be seen from State Highway 2. Natural geomorphology at this site is extremely modified as a result of farm excavations in the early 1960’s. One of three large hillocks of Kaitoke gravels (ca 1 Ma) has been completely removed from the area of the barn and used to level the surrounding area. These hillocks are shutter ridges that have been translated along the Wellington Fault. The current topography of the site is now dominated not by a peat-ponding hillock shutter ridge, but rather by a farm drain that runs sub-parallel to the original, now buried, fault trace (Fig. 10.1). In trench KAF-1, a thick wedge of recent man-made fill material is exposed between the buried scarp and the farm drain (Fig. 10.2). Beneath the fill is a section of interfingered Holocene peats and colluvial deposits. The peaty deposits relate to the ponding of drainage against the fault scarp, and colluvial units relate to the shedding of debris from the former hillock of Kaitoke gravel (Fig. 10.3). The peat and colluvium intervals grade into each other across a 4 m-wide zone of high-angle faulting.

Trench KAF-1 was excavated in two stages. In the first stage a southern (upper) suite of faults was recognized and mapped (faults F9-F14). When the trench was deepened, faults F1-F8 were more fully uncovered and mapped.

Most recent event & event II

North of the trench and farm drain a modern peat swamp forms a surface equivalent to the top of the fill-buried peat 1 in trench KAF-1. This peat is a dark brown to black, massive peat with tree stumps at its top surface. At least the base of this peat is faulted by fault F1. Fault F1 also faults a colluvium (Unit 4) that extends across the middle part of KAF-1, and underlies peat 1. This colluvium is also faulted by fault F12. These relationships suggest the occurrence of two surface rupturing earthquake events: one which generated the Unit 4 colluvium; and a younger event that faulted it and the base of peat 1.

Two peat samples were collected from either side of a clear contact between the base of peat 1 and the top of peat 38 (samples KAF-1/18 and KAF-1/13, respectively). These two peats immediately overlie and underlie Unit 4 colluvium, and their ages are inferred to bracket the timing of Event II (the penultimate event). The ages from the base of peat 1 and the top of peat 38 respectively are 667 ± 20 radiocarbon yr BP (555-649 cal yr BP at 2-sigma), and 916 ± 20 radiocarbon yr BP (731-896 cal yr BP) respectively. This constrains the timing of Event II in this trench to between 555-896 cal yr BP. A previous estimate of 670-830 cal yr BP for the timing of this Event II earthquake in the Kaitoke region comes from Van Dissen et al. (1992a) though this age is somewhat interpretive in nature.

The relevance of these results will be discussed in context below with the updated results from the Te Kopahou/ Long Gully areas and Te Marua site.

There is no distinct colluvium related to the most recent faulting event, nor is there a distinct upward termination of Event I faulting observed in the trench (presumably this fault termination - event horizon - is located somewhere within peat 1). Therefore, we are not able to constrain the age of the youngest paleoseismic event in this trench, other than to say that it is certainly younger than Event II (i.e. younger than 555-896 cal yr BP).

Older events

Dating of trench KAF-1 deposits, show that units in the lower part of the trench are 7000-12,000 yr old, indicating a depositional hiatus of ca 6000 yr between these older units and those units that constrain the timing of the two most recent faulting events. This hiatus occurs about at the location of units 39/40. The missing time could be explained by one, or a combination of the following: (i) a lack of surface faulting and consequent colluvial unit generation between ca 1000-7000 yr BP; (ii) erosion and removal of that part of the stratigraphic section; (iii) no source of colluvium or development of peat over that period; and/or (iv) a wider zone of faulting than exposed in KAF-1 such that between ca 1000-7000 yr BP surface rupture displacement occurred on faults outside the bounds of the trench exposure for example, either on the rangefront fault, or unmapped faults closer to the trench.

However, the interbedded peat and colluvial stratigraphy of the lower part KAF-1 can be used to identify a number of distinct earthquake event horizons in the time interval between ca 7000-12,000 yr. The stratigraphic model used here is similar to that described from trench TK-1 (see Stop 1). That is, peats and soils typically form during stable periods when there is a lack of sedimentation at the site. This site was probably under forest and swamp vegetation over this time interval. At the time of large earthquakes on the fault, displacement and strong ground motions offered the opportunity of releasing colluvium from the former-steep-sided hillock of Kaitoke gravel. These may have occurred as shallow landslips that included soil, peat and vegetation.

Five to six older paleoearthquake events are recognized from the older portion of the trench on the basis of peat/colluvium couplets and the upward-termination of faults observed in the middle of the trench (Fig. 10.3). Five radiocarbon samples were submitted from this section. The highest and lowest samples yield the youngest and oldest ages, respectively. The youngest age is 6514 ± 30 yr BP (7291-7431 cal yr BP) from sample KAF-1/8 within colluvial unit 18, and the oldest age is 9984 ± 35 yr BP (11,233-11,600 cal yr BP) from sample KAF-1/23 from within a unit interpreted as a peaty colluvium (Unit 48a). Some of the dates between these two samples are out of stratigraphic order, suggesting that there has been some reworking of the section. The occurrence of 5-6 earthquake ruptures between ca 7300-11,600 yr BP yields a maximum recurrence interval over that time interval of ca 1,000 years.

Kaitoke Farm trench-2

A second trench, KAF-2 (grid ref. S26/931126), was excavated ca 40 m to the west of trench KAF-1 (Fig. 10.1). In this area there was an expectation that faulted and unfaulted deposits related to the most recent earthquake on the Wellington Fault could be dated. KAF-2 intercepted a series of probably Holocene gravels and silts in the footwall of the fault scarp. Ponded and faulted against this scarp are a sequence of massive to silty peat units. Sharp fault relations confirmed the location of active faulting along this scarp where it was unmodified by farm activities. A log of trench KAF-2 can be viewed in Langridge et al. (2008).

Kaitoke Farm trench-3

A third trench, KAF-3 (grid ref. S26/930125), was excavated near the western end of the Kaitoke Farm site. In this area the prominent uphill-facing scarp approaches within ca 50 m of the rangefront trace of the fault. Here, the scarp has deflected a small stream that is cut into an intermediate level fan surface that projects into the fault scarp (Fig. 10.1). The uphill-facing scarp corresponds to a geomorphic surface that is higher in the landscape than the Q2a (Ohakean) surface mapped in this area (Berryman 1990, Begg & Johnston 2000).

The log of the west wall of KAF-3 is shown in Figure 10.4. The stratigraphy comprised a series of clastic units that can be divided into 4 packages: (i) older fan/alluvial facies that occur in the uphill-facing scarp and within the fault zone (Units 10-13); (ii) younger alluvial deposits that comprise fan and stream units that are deposited against the scarp (Units 3-9); (iii) scarp-derived colluvium (Unit 2); and (iv) soils and historically modified surface units (fill/debris). Within the fault zone, the older fan/alluvial deposits comprise interbedded sandy, pebble ‘chip’ gravels (Unit 11g) and clayey silt facies (Unit 11z), overlain by very poorly sorted, angular medium gravel (Unit 10). Farther up the scarp, Units 12 and 13 are moderately weathered clayey silt and sandy gravels, respectively. Colluvium (Unit 2b) and soil (Unit 1) drape the fault scarp but are unfaulted.

The stratigraphy of the downthrown side of the fault comprises alluvial deposits that grade to a younger outlet fan south of the scarp. Most of the units on the north side of the fault project into, and are truncated by the fault zone. The lowest exposed units are poorly sorted angular cobble gravels (Unit 9). They are overlain by a series of generally fine-grained, clay and clayey silt units (Units 5-8) that likely represent ponding against the fault scarp. Unit 6 is defined by a paleosol formed within the light brown coloured top of this silty unit. Units 3 and 4 are channel fill deposits within a fault-parallel trough incised into Units 5 and 6, outside of the fault zone. The uppermost units are overlain by a fine sand deposit (Unit 2a) and a recent soil (Unit 1), formed on a sandy silt.

Three charcoal samples were submitted for radiocarbon dating from trench KAF-3. Charcoal sample KAF-3/2 from a depth of ca 1 m and within the basal fan gravel (Unit 9) gave an age of 246 ± 20 yr BP. This date does not represent the true age of this unit. Sample KAF-3/6 was collected from near the top of silty Unit 5. This date should provide a maximum age on possibly the last two earthquakes at this site. The third sample, KAF-3/5, comes from the lower part of the Unit 6 paleosol and has an age of 3774 ± 40 yr BP (3924-4227 cal yr BP). This age represents a maximum for at least two rupture events, most likely more (see below).

Older surface rupture event(s) may be inferred by the shift of the geomorphic axis of channel deposition adjacent to the scarp. This describes a time when two important changes took place in the stratigraphy of the trench: (i) the termination of soil formation in the Unit 6 paleosol caused by deposition of Unit 5; and (ii) the shift from deposition against the edge of the current scarp, to that point where Units 3 and 4 were deposited at the current topographic low adjacent to the fault scarp (Fig. 10.4). Also, units 5-8 are sharply truncated by the northern-most fault exposed in the trench, but probably once extended south past this fault. If there was once a record of rupture events preserved in association with the southern extent of these units, this record is now lost. Accordingly, this trench is probably best viewed as preserving only a minimum number of rupture events over the time period represented by the exposed deposits.

Combined paleoearthquake history – Wellington-Hutt Valley segment

Most recent rupture

There has been no rupture of the Wellington-Hutt Valley segment of the Wellington Fault within the time of European settlement of the region (i.e. since ca AD 1840). Two sites along the segment provide maximum constraints on the timing of the most recent rupture. At Te Kopahou/Long Gully (Stop 1) the most recent rupture is ≤450 cal yr BP, and at Te Marua (Stop 8) it is ≤310 cal yr BP. Our best estimate for the timing of the most recent rupture of the Wellington-Hutt Valley segment is therefore younger than 310 cal yr BP and older than European settlement. Note, all of these dates are presented at the 2-sigma level of calibration.

Event II

There are a number of sites along the Wellington-Hutt Valley segment that add meaningful constraints as to the timing of Event II rupture: Te Kopahou/Long Gully (790-930 cal yr BP; Stop 1), Te Marua (>675 cal yr BP; Stop 8), Kaitoke (670-830 cal yr BP), Kaitoke Farm site (730-900 cal yr BP; Stop 10). Taken collectively, and acknowledging that the 670-830 cal yr BP age estimate is more interpretive than the others, our best estimate for the timing of Event II is 790-895 cal yr BP.

Event III

At Te Marua, deposits that have been faulted three times have a minimum age of 1420 cal yr BP, but the best constraint for the timing of Event III is 1830-2340 cal yr BP from the Te Kopahou/Long Gully area.

Event IV

Constraints on the timing of Event IV are poor. At the Te Kopahou/Long Gully area Event IV has a minimum age of 2460 cal yr BP (i.e. Event IV is older than 2460 cal yr BP). To date, however, no positive maximum age constraints for Event IV have yet been unearthed.

Older events

At the Kaitoke Farm site (Stop 10), in particular, older rupture events have been recognized, though these do not necessarily follow on temporally in unbroken order from the above mentioned youngest four events. Here, between ca 7300-11,600 yr BP, at least five rupture events have been identified. Constraining the timing of individual events in this sequence has been hampered by suspected sample reworking and inherited-age issues, but collectively they provide a well constrained maximum recurrence interval ca 1000 years for the fault over this time interval.

Recurrence interval estimates

An average recurrence interval of 760-1120 years is estimated by considering the above constraints on the timing of the most recent event and Event III. However, it is questionable how representative this recurrence interval estimate is with regards to the long term behaviour of the fault, given how few (only two) inter-event times it is based on. Similarly, a perhaps non-representative minimum recurrence internal of ca 720 years is estimated through consideration of the timing constraints for the most recent event and Event IV.

Despite our reservations regarding the long term representativeness of these recurrence interval estimates, the values (760-1120 years; >720 years) are comparable to the independently derived recurrence interval estimates calculated from the Te Marua / Emerald Hill area based on single-event displacement and slip-rate considerations (mean of ca 760 years; indicative minimum & maximum of ca 540 years & ca 980 years, respectively) (see Stop 8).

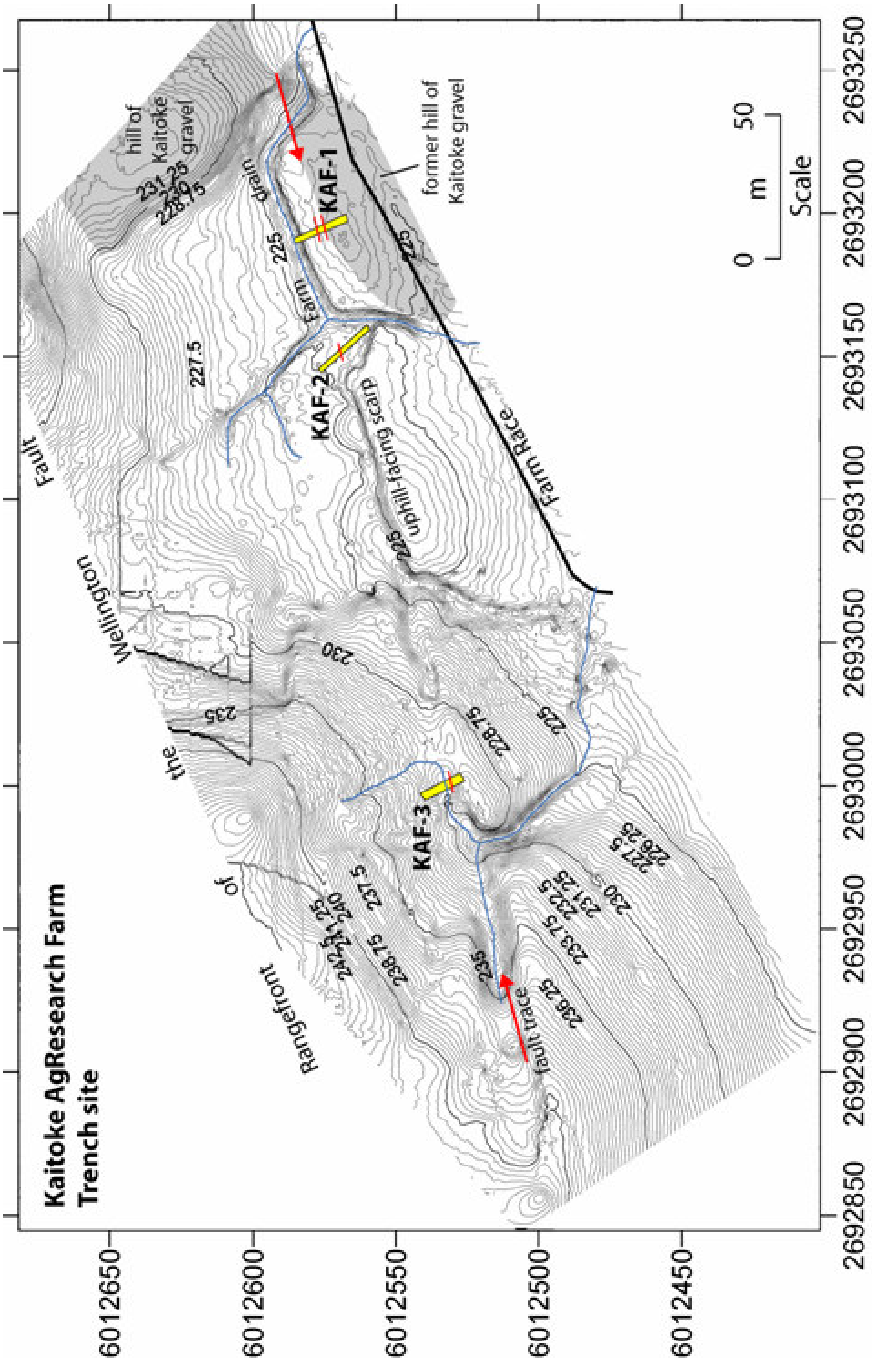


Figure 10.1. Detailed topographic map of the Kaitoke AgResearch Farm site, contour interval 25 cm. A somewhat modified uphill-facing scarp south of the rangefront marks the main trace of the Wellington Fault here (strike ca 076°). The fault location from trenches (yellow bars) and former geomorphology is shown by the red markers. In the early 1960's, at the location of trench KAF-1, a hillock of Kaitoke gravel (ca 1 Ma; grey shading) was entirely removed from the site, and a farm drain was excavated parallel to the fault trace.

Figure 10.2. Deepened south end of trench KAF-1 at the Kaitoke farm site, west wall. The upper metre comprises fill unit Ø, which drapes over a modern black peat, and across a former scarp to the right of painted #4. Dark peaty swamp units at left grade into peaty colluvium and colluvium at right. See Figure 10.3 for log of this wall.

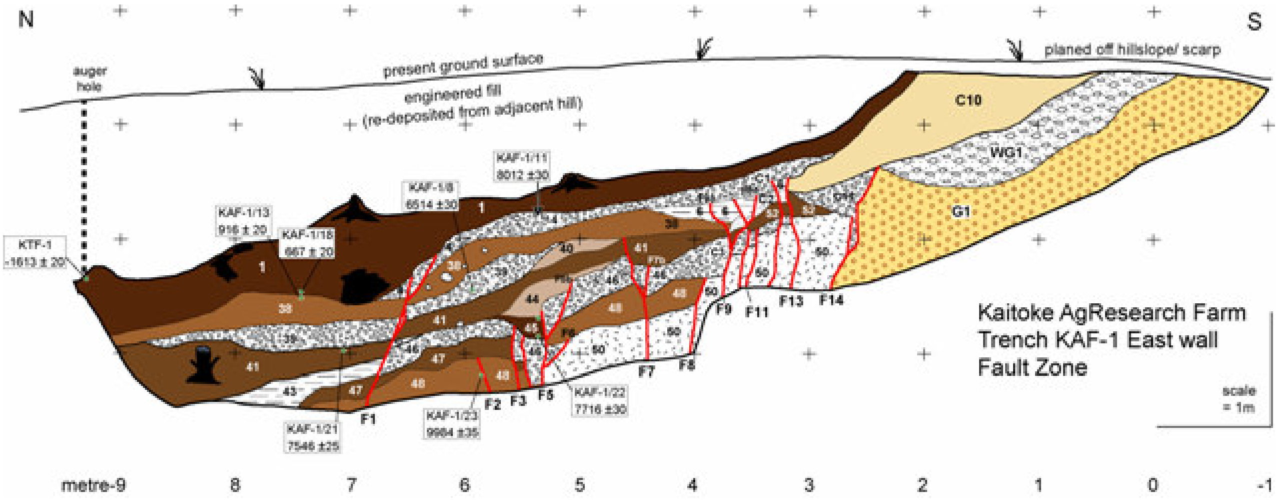


Figure 10.3. Detailed log of the zone of faulting in trench KAF-1 at Kaitoke farm. Fill units Ø and 1 have been removed from view. Brown units are peats and peaty colluviums; stippled patterns are colluvial units. A broad zone of faulting occurs from the former edge of the hillock of Kaitoke gravels (G1) into the peaty sequence that accumulated against the uphill-facing scarp here.

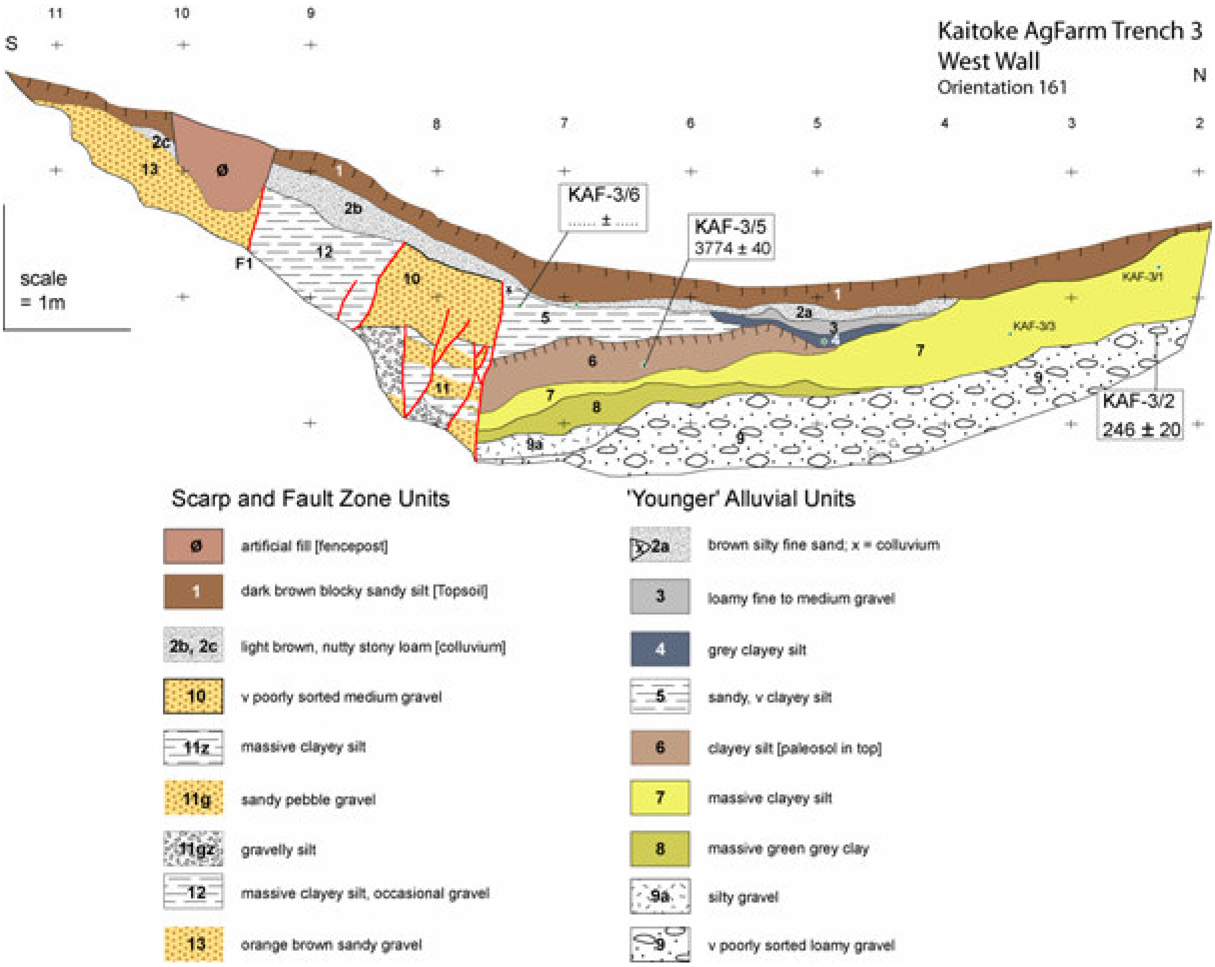


Figure 10.4. Graphic log of the west wall of trench KAF-3, Kaitoke Farm. The uphill facing scarp is at left; rangefront to the right. Holocene fan and alluvial deposits (Units 2-9) have abutted, and are faulted against the scarp across the Wellington Fault.

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