GeoPRISMS
Graduate Student Symposium
for the New Zealand Primary Site
FIELDTRIP

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

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

Trip Summary

This half-day fieldtrip encompasses visits to key localities along the Wellington-Hutt Valley Segment of the Wellington Fault (Fig. 1) including 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): Thorndon overbridge, Petone foreshore, Te Mome Road (fault scarp through Lower Hutt), California Park/Harcourt Park, Meins Rock, and Te Marua. Much of this fieldtrip guide is adapted from Begg et al. (2008a).

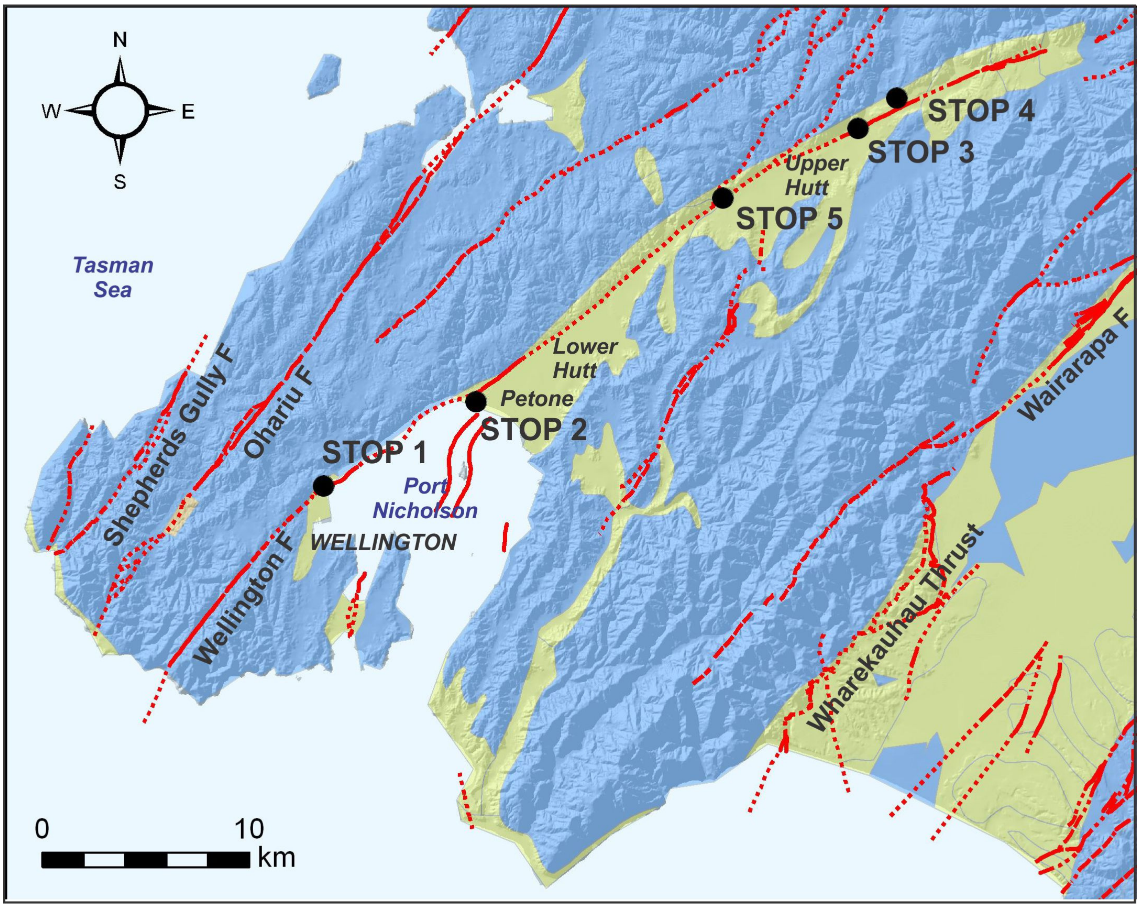


Figure 1. On-shore Wellington Fault, Wellington Hutt-Valley segment. Field trip stops are indicated, as are major Pleistocene to Recent depocentres (yellow shaded) in the region east of the Wellington Fault, including the Port Nicholson, Lower Hutt and Upper Hutt basins. The Wairarapa Fault, which ruptured in 1855, is shown on the east of the map. Active faults from the GNS Science New Zealand Active Faults Database (http://data.gns.cri.nz/af/).

Introduction

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 (e.g. Van Dissen & Berryman 1996), is carried to the surface along a series of northeast-striking strike-slip faults known as the North Island Dextral Fault Belt (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 (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 (Pondard &

Barnes 2010), 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. 6.3 mm/yr) (Ninis et al. 2013) 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 (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).

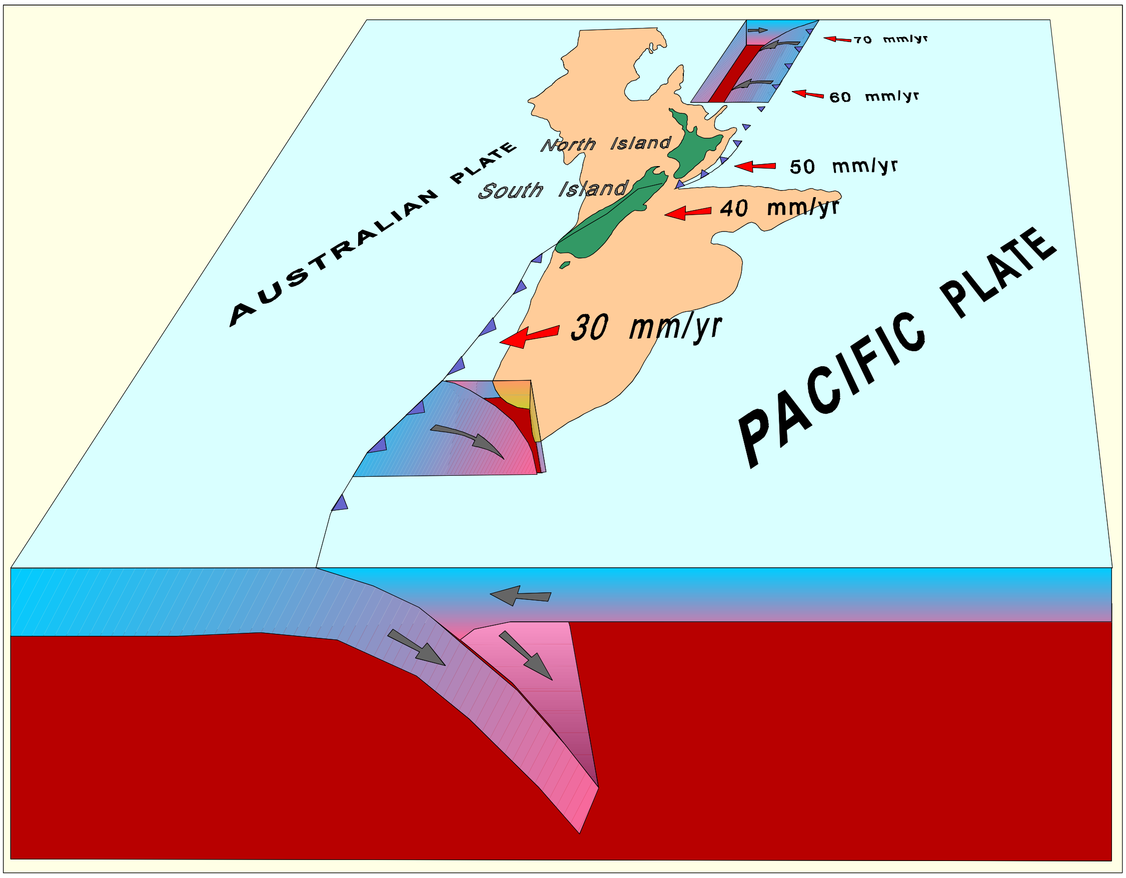


Figure I.1. Cutaway representation of the plate boundary configuration in the New Zealand area. Offshore areas with medium shading (light brown) are underlain by continental-type crust. Note that the Pacific Plate is subducted beneath the Australian Plate in northern New Zealand, while the Australian 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.

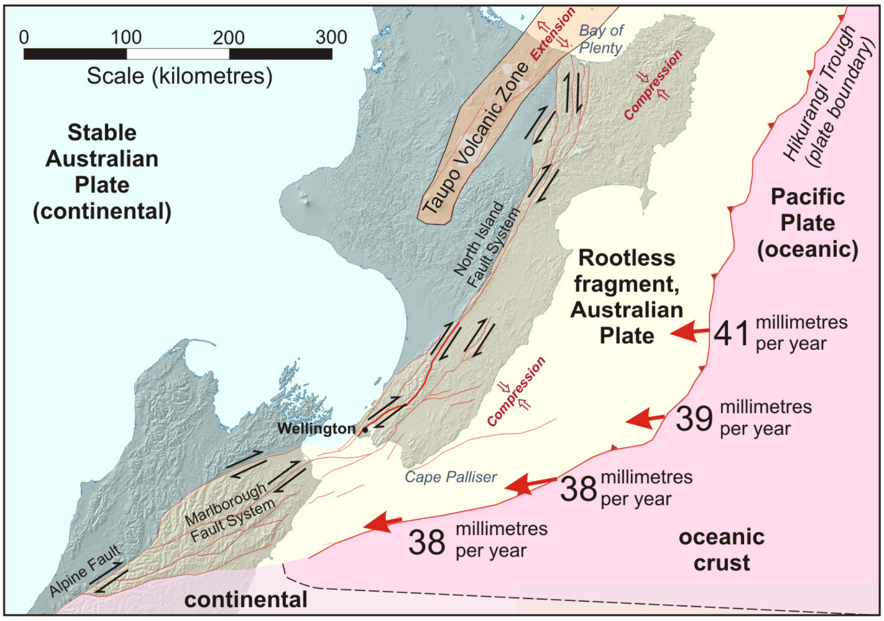


Figure I.2. Important plate boundary features of North Island and northern South Island, New Zealand. East of the North Island, the Pacific Plate is oceanic in origin, and converges with the continental Australian Plate at rates marked beside red arrows. The rootless eastern edge of the Australian Plate 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. (2008b).

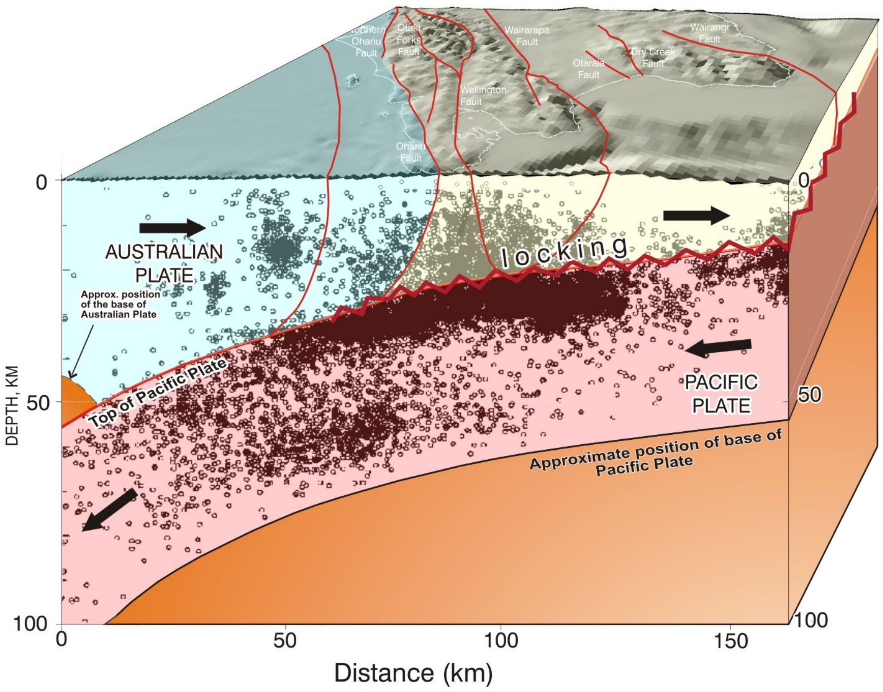


Figure I.3. Scaled diagram illustrating the location of the subduction interface beneath Wellington City and possible relationships between some of the active faults of the North Island Fault System (after Begg & Johnston 2000; extent of subduction zone locking after Wallace et al. 2009). The cloud of 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.

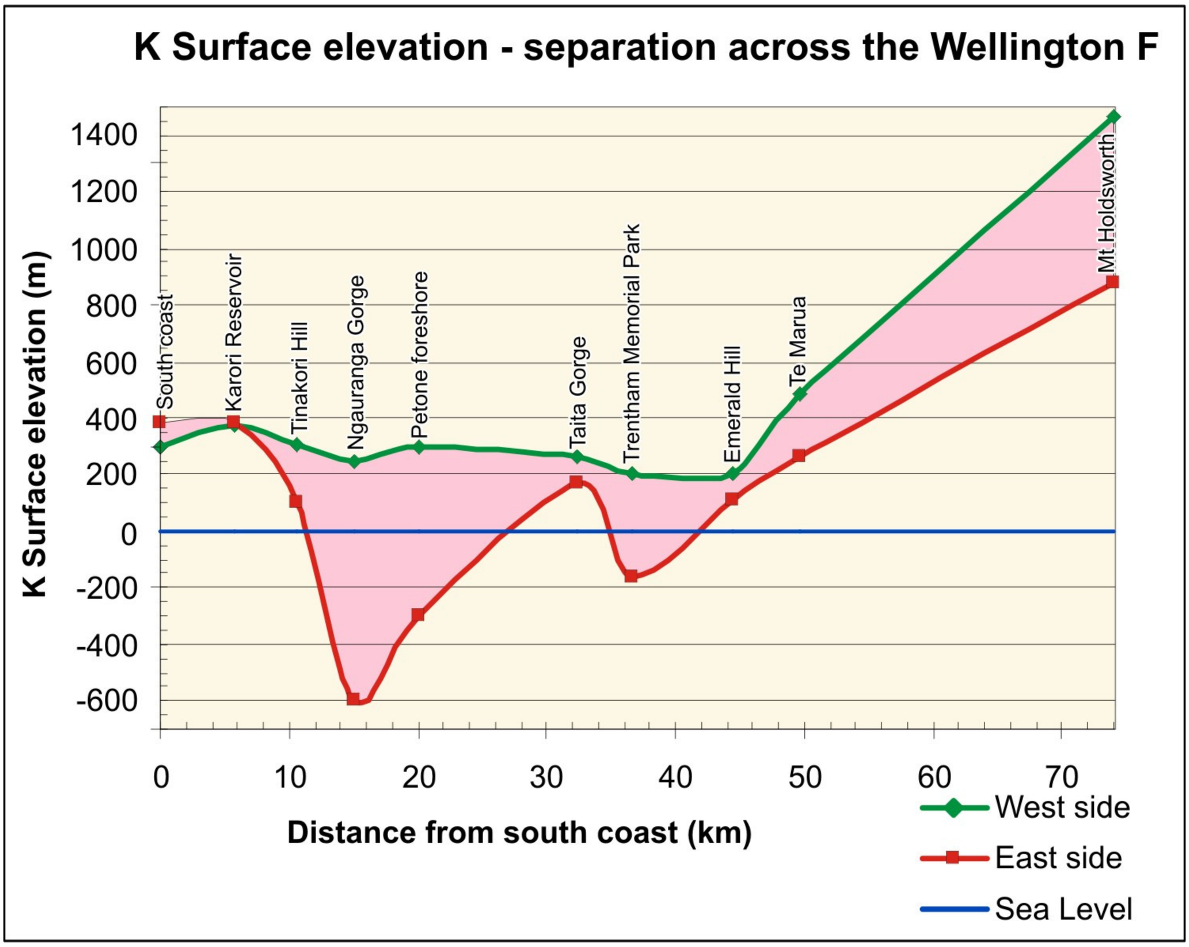


Figure I.4: Two profiles on the basement greywacke surface, one each side of the Wellington Fault, from the Wellington south coast (left) to the southern end of the Tararua Range, illustrating cumulative vertical offset of the K-Surface. Elevations of the K-Surface (or equivalent) on the eastern side 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: 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 (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 (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; Fig. 1.1). 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; Fig. 1.2). 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 (Fig. 1.3).

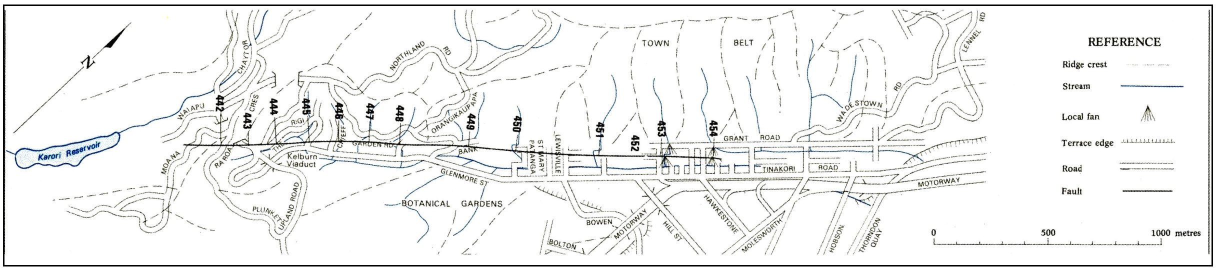


Figure 1.1. Ota et al. (1981) constrained the location of the Wellington Fault in the upper Thorndon area by locating a number of offset and fault-related geomorphic features (from Inset C of Ota et al. 1981). More recently, Perrin & Wood (2003) have provided a quantified characterisation of the location 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).

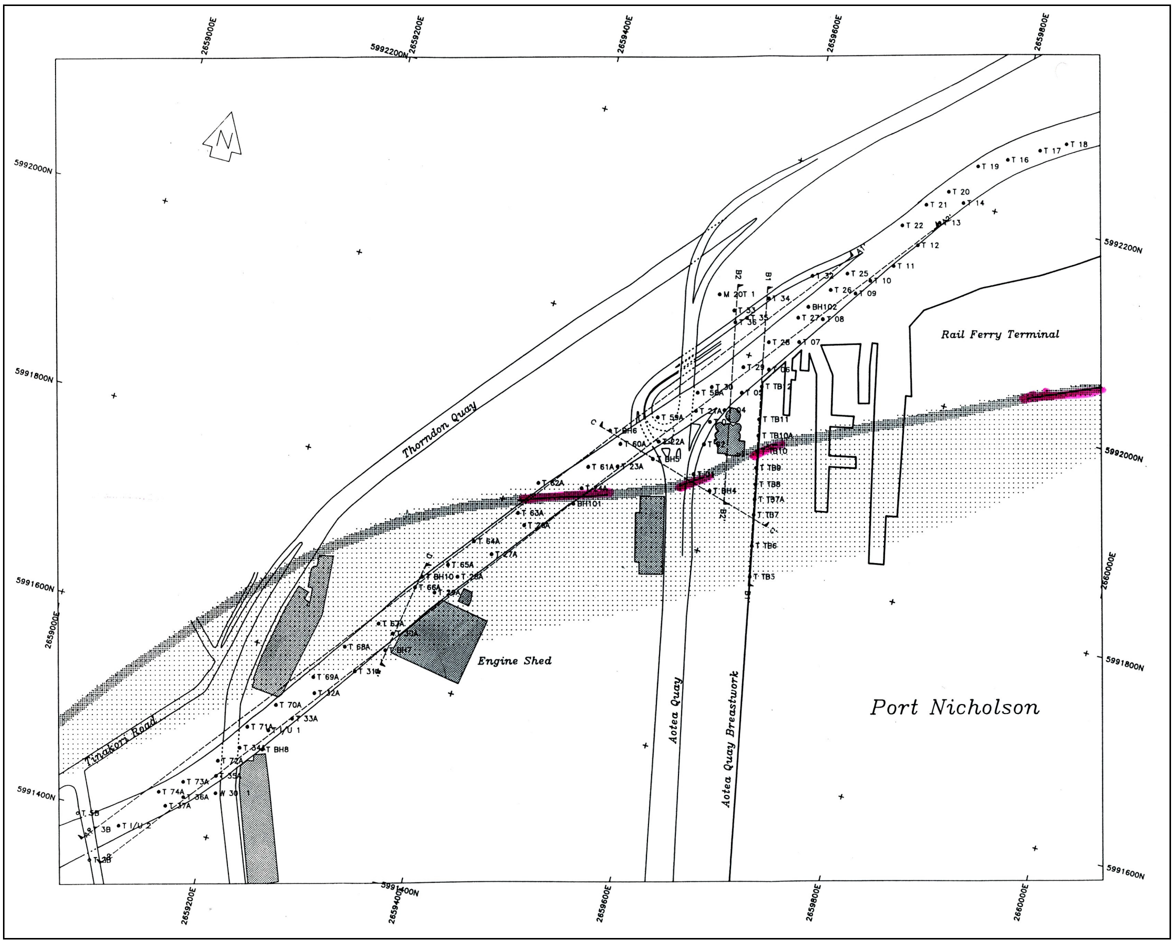


Figure 1.2. Location of the Wellington Fault in the Thorndon Overbridge area (Perrin 1993). The position of the fault is determined from correlation of sediments within drillholes located on the map. Logged drillholes are marked with a solid circle, holes without logs are marked with open circles. Confident 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 1.3. 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 & Powell (1996).

Stop 2: 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. 2.1). 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. 2.2).

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) (Figs. 2.3 & 2.4) and, further south, near the mouth of the Ngauranga Gorge, are believed to be about 600 m thick (seismic reflection, Wood & Davy 1992) (Fig. 2.2).

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 (e.g. Grapes & Downes 1997). 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. 2.5).

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 2.3 & 2.4 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. 2.3 & 2.4).

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. 2009) 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. (2009)

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).

Trenching work on the Wairarapa Fault (Little et al. 2009) 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. (2009) 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 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. 1992a; Benites & Olsen 2005).

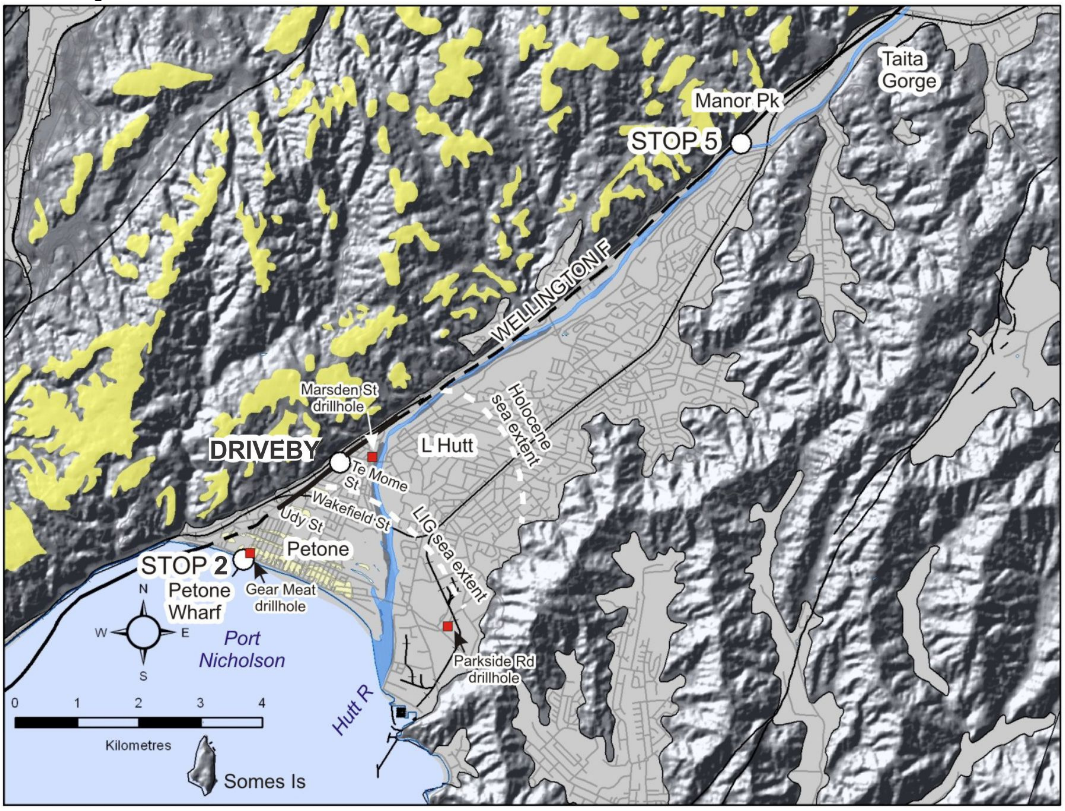


Figure 2.1. Map of the Port Nicholson to Taita Gorge section of the Wellington Fault. The lightly shaded areas are underlain by Quaternary sediments and shading on hill crests delimits selected areas of the K Surface. The landward extent of the Holocene (6,500 years) and Last Interglacial (LIG; 125,000 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 (Fig. 2.4).

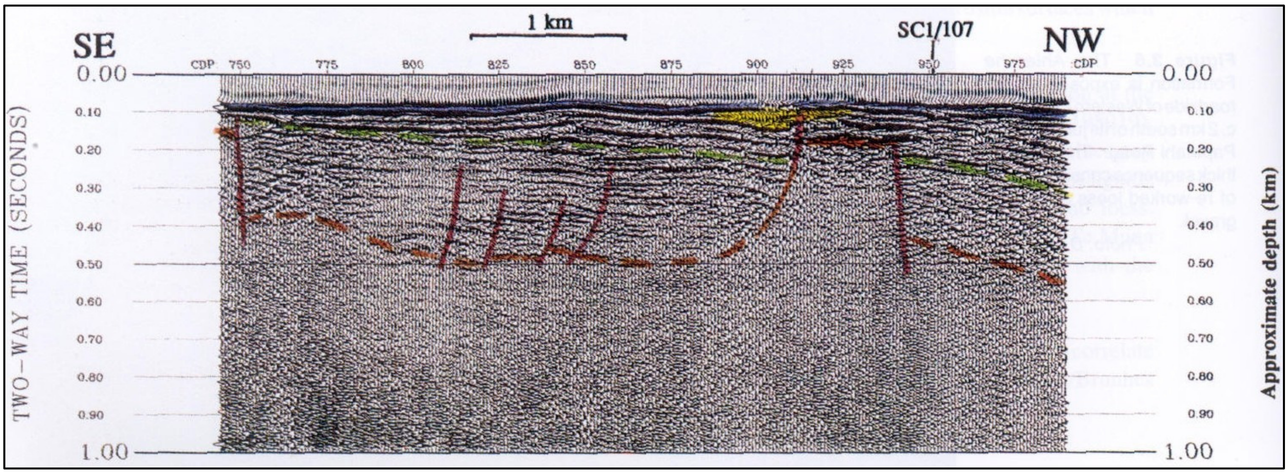


Figure 2.2. A multichannel seismic reflection line across Port Nicholson (R27/693917 to 650957) shows two sub-basins separated by the Somes Island Ridge which is fault bound at least on its NW side. Reflecting layers dip NW towards the Wellington Fault, just off the end of the profile to the right. (From Wood & Davy 1992).

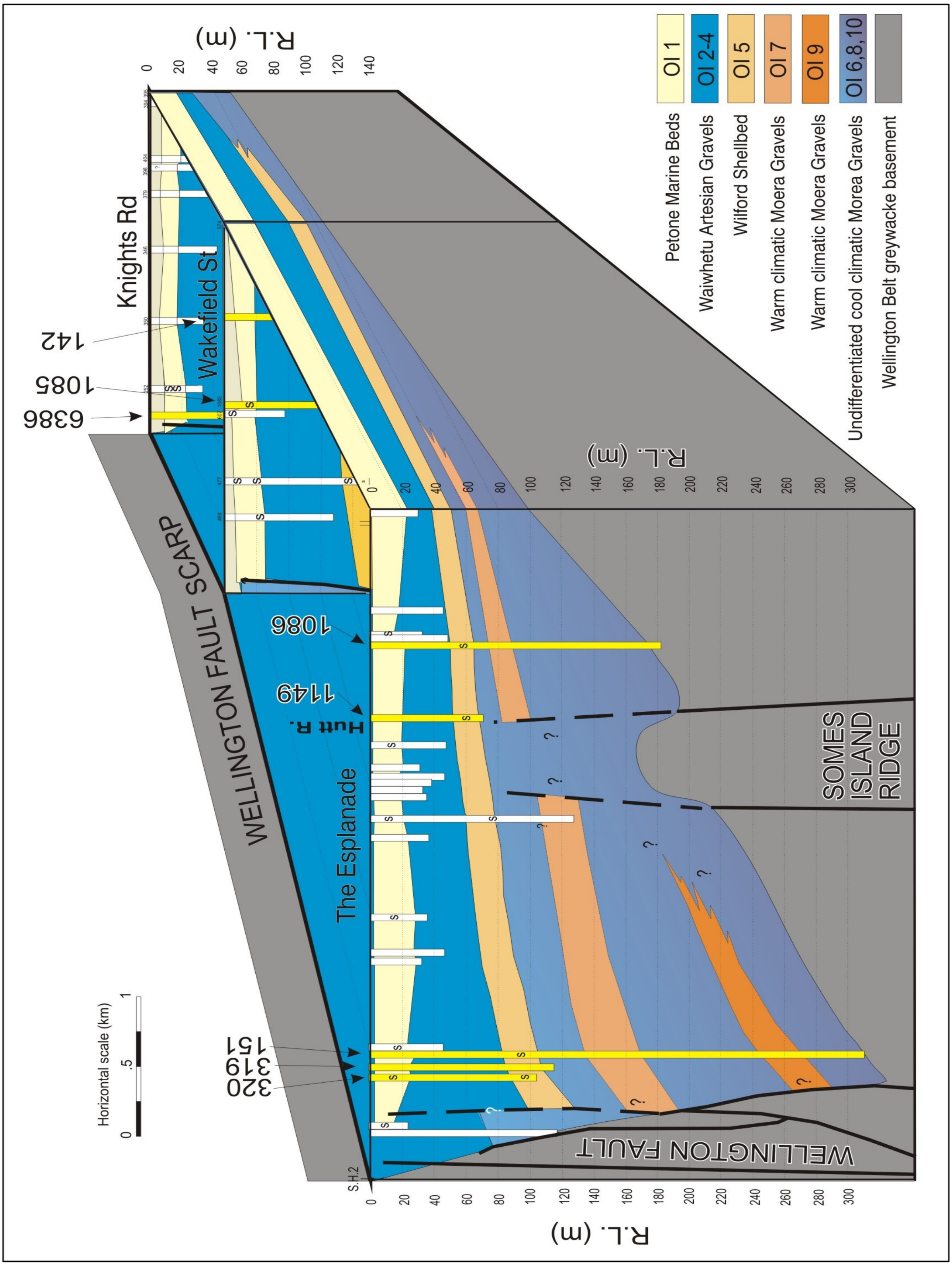


Figure 2.3. Three dimensional representation of sediments of the Lower Hutt basin from the Petone foreshore to Knights Rd, based on drillhole logs. Basement greywacke is shown densely shaded, interglacial sediments as yellow to orange shaded and glacial Pleistocene sediments are blue shades. The position of the Somes Island Ridge is based on onshore gravity and seismic data from Port Nicholson. (After Begg & Mazengarb 1996).

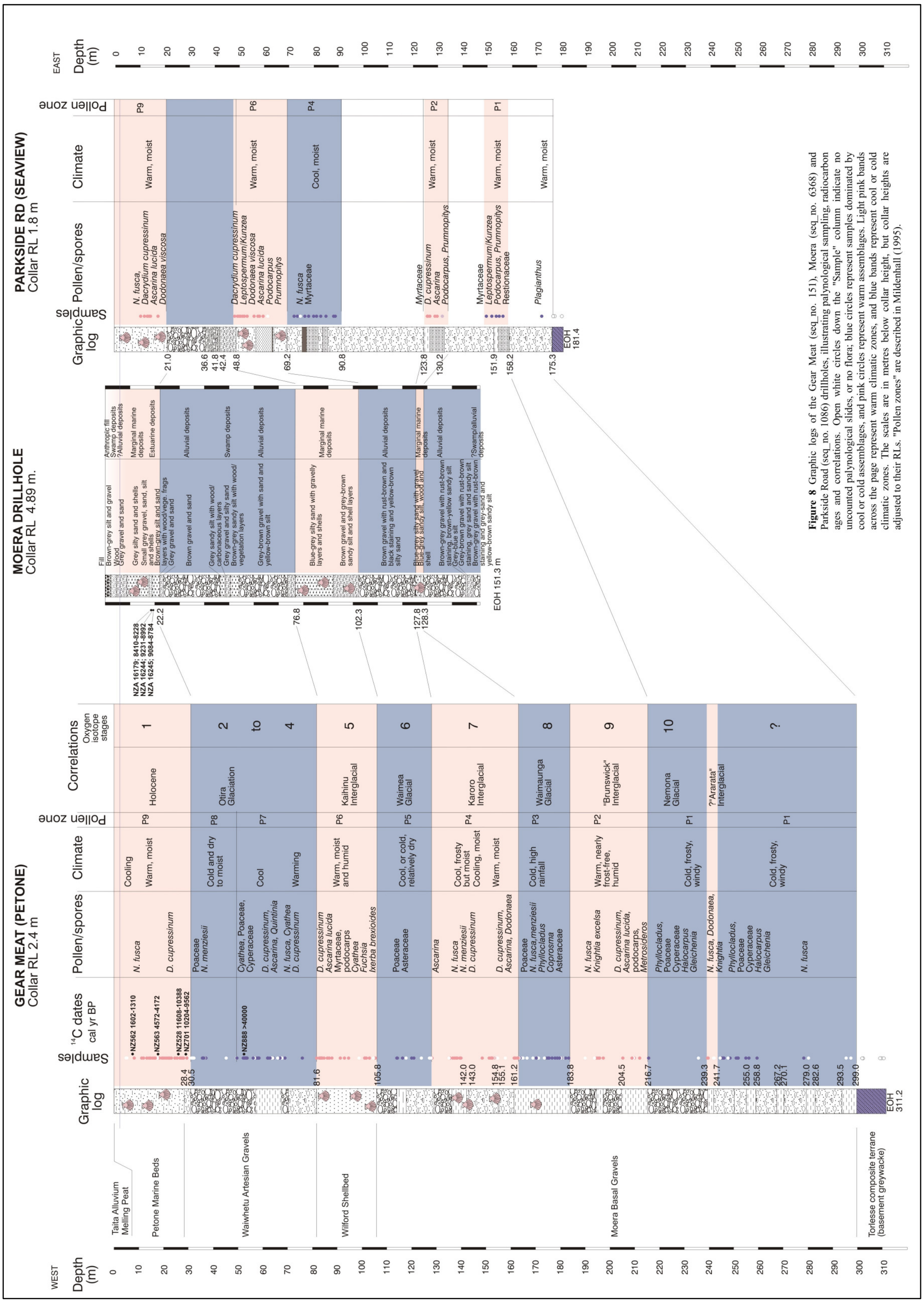


Figure 2.4. Logs to basement for three Lower Hutt Valley bores, the Gear Meat, Parkside Road and Marsden St drillholes. The Gear Meat drillhole is located on the western side of the valley, but east of the Wellington Fault (Fig. 2.1). The Parkside Rd drillhole is on the eastern side of the valley. The 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.

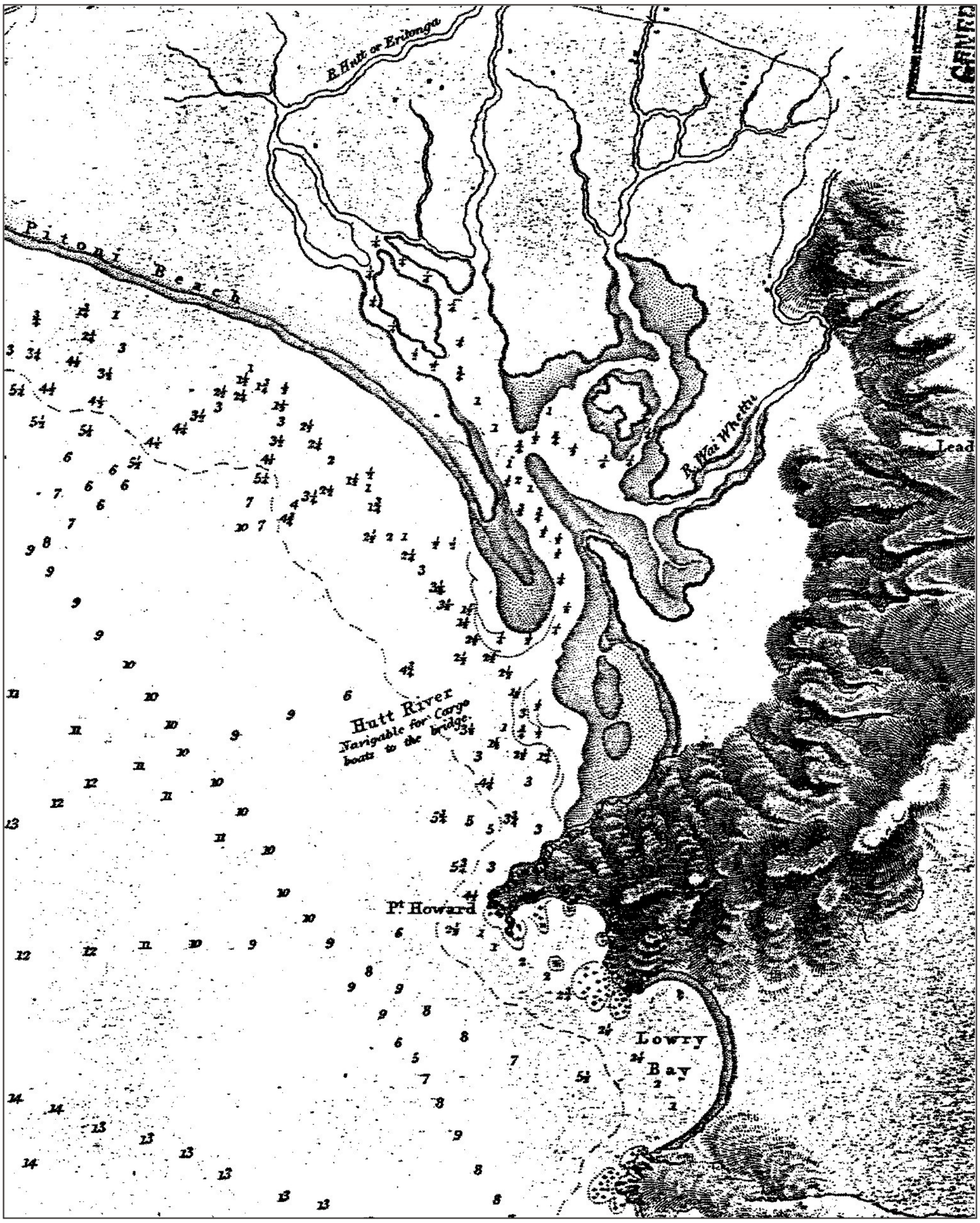


Figure 2.5. Chart of the Hutt River mouth surveyed before the uplift associated with the 1855 Wairarapa Earthquake. Note the development of an extensive estuary at the Hutt River mouth. Waiwhetu Stream, the southernmost eastern tributary of the river was navigable by quite substantial vessels to the Gracefield bends.

Discuss while driving: 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 3: 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 (Berryman 1990; Figs. 3.1, 3.2 & 3.3).

Surface rupture hazard mitigation measures were incorporated into the layout and design of the Totara Park suburb (Fig. 3.1). 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. 3.2).

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. 3.3). 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. 3.4).

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. 3.5; 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. 3.6). 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, Ninis et al. (2013) have dated terraces using optically stimulated luminescence, and calculates a mean horizontal slip rate 6.3 mm/yr (+ 1.9 mm/yr; - 1.2 mm/yr). Vertical displacements at Emerald Hill are only a few percent of the horizontal displacements.

Figure 3.1. 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 (also Figs. 3.2 & 3.3), 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.

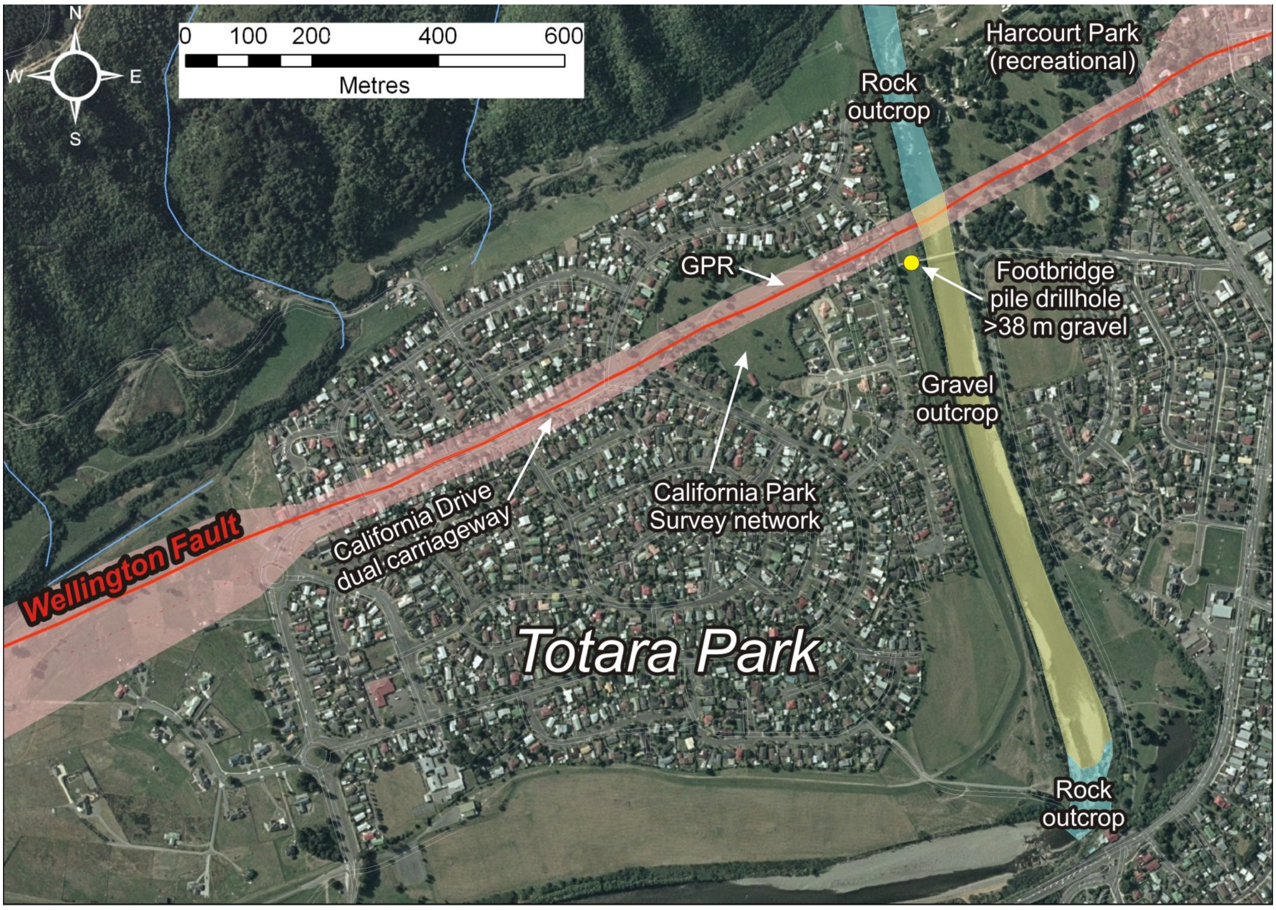


Figure 3.2. The location of the trace of the Wellington Fault at Totara Park is tightly constrained, as indicated by the narrowness of the Avoidance Zone defined by Van Dissen et al. (2005). At either end of the trace, the location of the fault is less well-known, and the width of the Fault Avoidance Zone is consequently substantially broader.

Figure 3.3. 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.

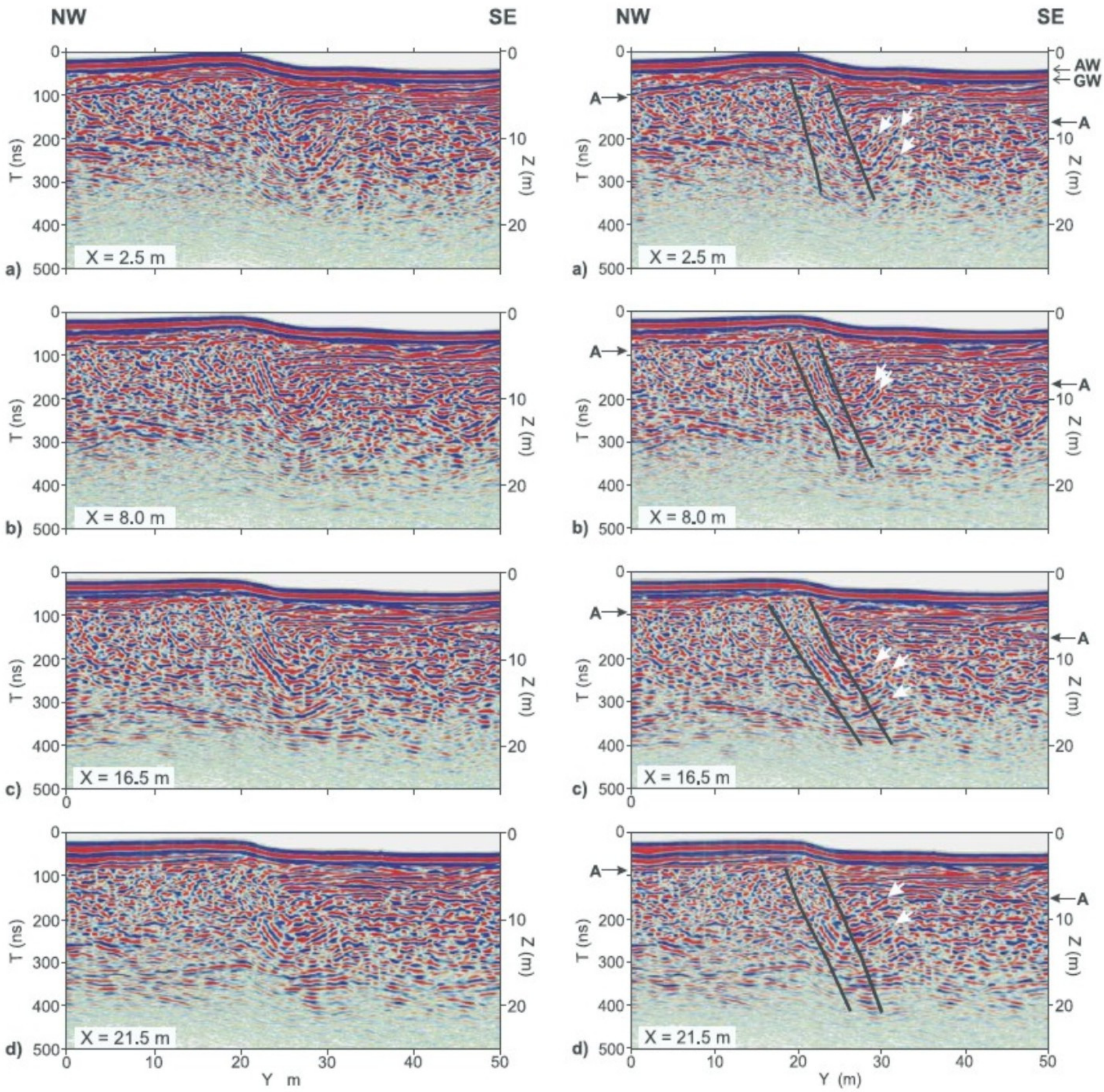


Figure 3.4. Ground penetrating radar profiles, taken from a 3D array, across the Wellington Fault in northern California Park image the Wellington Fault to a depth of ca 15 m (Gross et al. 2004). Right hand profiles show adopted interpretations. Note the scarp at the surface, the dip of the fault to the SE and the presence of two fault planes (compare with Fig. 3.5).

Figure 3.5. 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 3.6. ***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 4: 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 (Fig. 1; grid ref. ca R26/876104), there is a well preserved flight of a dozen or so late Pleistocene to Holocene alluvial terraces (Figs. 4.1, 4.2, 4.3, 4.4). The youngest eight of these terraces are Holocene in age and cross the Wellington Fault at Te Marua, where they are progressively dextrally displaced by the fault (Figs. 4.5, 4.7).

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 (Little et al. 2010, Van Dissen et al. 1992b, Berryman 1990). The Te Marua site is also close to the Emerald Hill locality (Fig. 4.1) where a Late Quaternary dextral slip rate of the fault of 6.3 (+ 1.9 mm/yr; - 1.2 mm/yr) has recently been estimated by Ninis et al. (2013) on the basis of: 1) new terrace riser displacement estimates based on a photogrammetrically derived Digital elevation model (DEM) of the pre-developmental topography of Emerald Hill; and 2) from Optically Stimulated Luminescence (OSL) ages of the terraces. Abandonment of the oldest dated terrace at Emerald Hill (EH-T5) was dated by OSL to have occurred prior to 93.2 ± 20 ka. This riser cut by this terrace has experienced a dextral-slip of 586 ±15 m (Ninis et al., 2013). Immediately across the river to the east of Emerald Hill, the terrace flight at the Te Marua, mostly of Holocene age, preserves many other terrace riser offsets that were measured by Little et al (2010) and dated by them using OSL. The progressively displaced geomorphology of the Te Marua site provides an opportunity to develop a recurrence interval of faulting that is independent of on-fault paleoseismic records (see below). Most recently, the latter has been undertaken by Langridge et al. (2011), who excavated three trenches at Te Marua (see below).

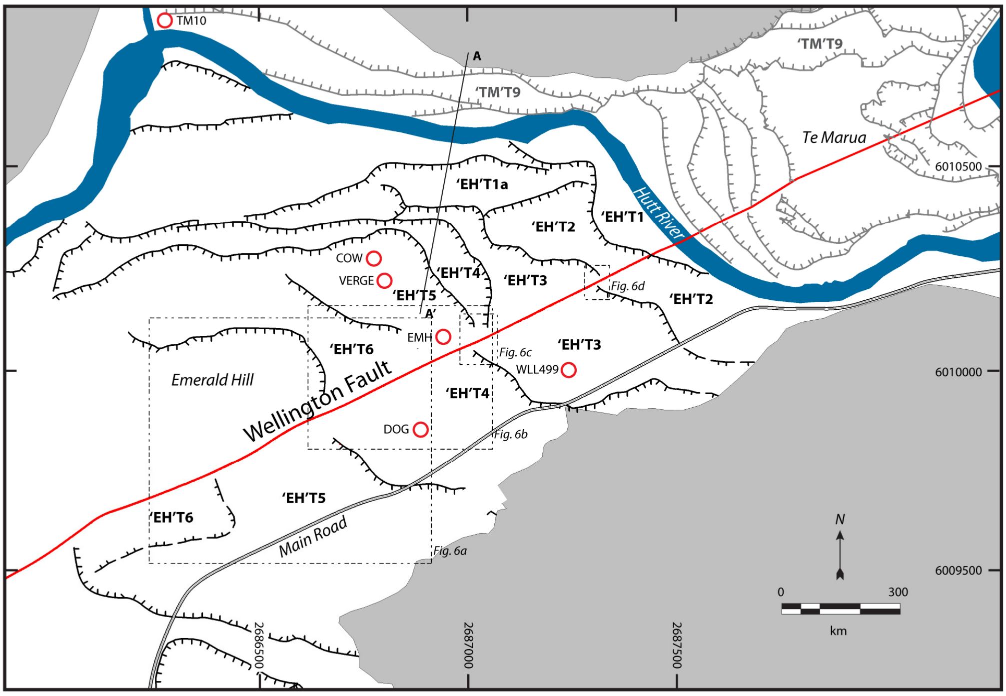


Figure 4.1. New map of terraces at Emerald Hill (black-from Ninis et al., 2013) and Te Marua (grey - after Little et al., 2010). Map also shows location of new OSL sample collection sites (red open circles). Hutt River flows from east to west. Figure also shows location of terrace riser offsets presented that were analyzed by Ninis et al. (2013). Grid marks are New Zealand Map Grid (Geodetic Datum 1949).

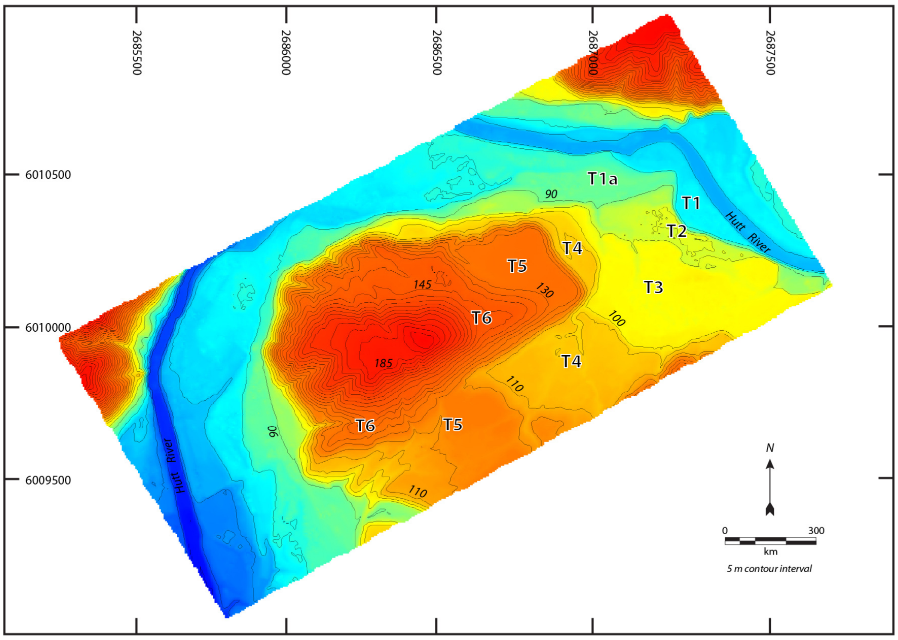


Figure 4.2. Pre-developmental DEM of the Emerald Hill region, based on elevation data created from photogrammetric processing of historic aerial photography. These data were used by Ninis et al. (2013) to estimate terrace riser displacemenst at Emerald Hill. Topographic contours are at 5 m intervals,elevation is relative to mean sea level. From Ninis et al. (2013).

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. 4.4, 4.5, 4.7 & 4.8). 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. 4.4, 4.6, 4.7 & 4.8. 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. 4.8) which has been used to document and accurately measure terrace displacements and to construct a record of sequential fault rupture displacements (Fig. 4.9) (Little et al., 2010). 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. 2011). In addition, 18 optically stimulated luminescence (OSL) samples have been dated from this site by Little et al. (2010); the locations and ages of the samples are schematically depicted in Figure 4.6. 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. (2010) 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. 4.5b, or T_{2-3} on Fig. 4.9), has a mean displacement of 5.3 ± 0.4 m (Fig. 4.9). 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. 4.7b & 4.8). 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. 4.9), is based on measured lateral displacements of two adjacent terrace risers (denoted R3 & R4 on Fig. 4.5b, or T_{3-4} & T_{4-5} on Fig. 4.7). 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. 4.3), an intermediate displacement of ca 10 m, albeit with large uncertainty, has been measured (Fig. 4.9) (Little et al. 2010); 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 (Figs. 4.7a & 4.8). 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. 4.9). 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. 2010).

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. 4.7 & 4.8; grid ref. R26/875103; Langridge et al. 2011). 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. (1992b) (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. 4.5 & 4.6; Langridge et al. 2011). 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. 4.4, 4.7, 4.8 & 4.9). 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. (1992b) 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 (R2 on Fig. 4.7b, and $T_{2\text{-}3}$ in Fig. 4.9) 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. ≥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 (Langridget et al. 2011). 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. 4.7, 4.8 & 4.9). 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.

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 (Fig. 4.9). This data combined with the Ninis et al. (2013) dextral-slip rate of ~6.3 mm/yr (+1.9 mm/yr, -1.2 mm/yr) allows an estimated average recurrence interval of ca 800 years to be calculated.

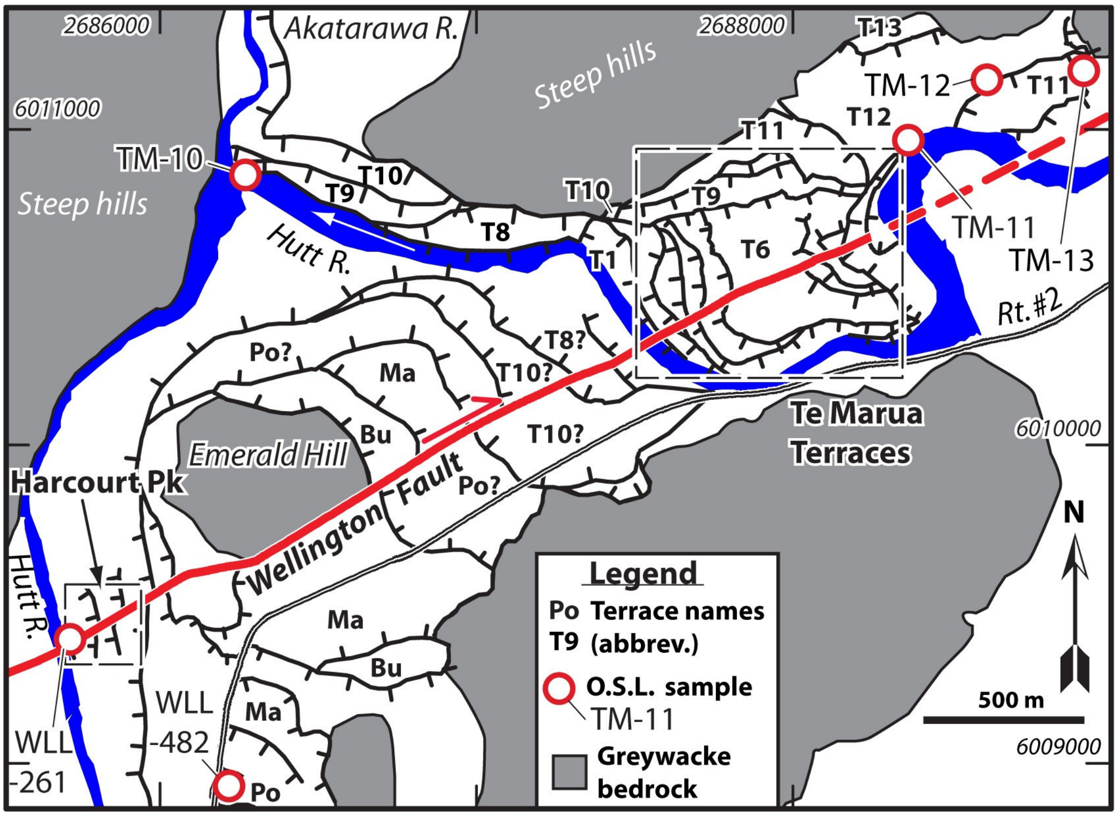


Figure 4.3. Wellington Fault through the Harcourt Park, Emerald Hill and Te Marua Terraces area (after Berryman 1990, modified by Little et al 2010). Terrace names from Berryman (1990): Po, Porewa; Ma, Marton; Bu, Burnand. Dashed-box around Te Marua Terraces area denotes location of Figure 4.4.

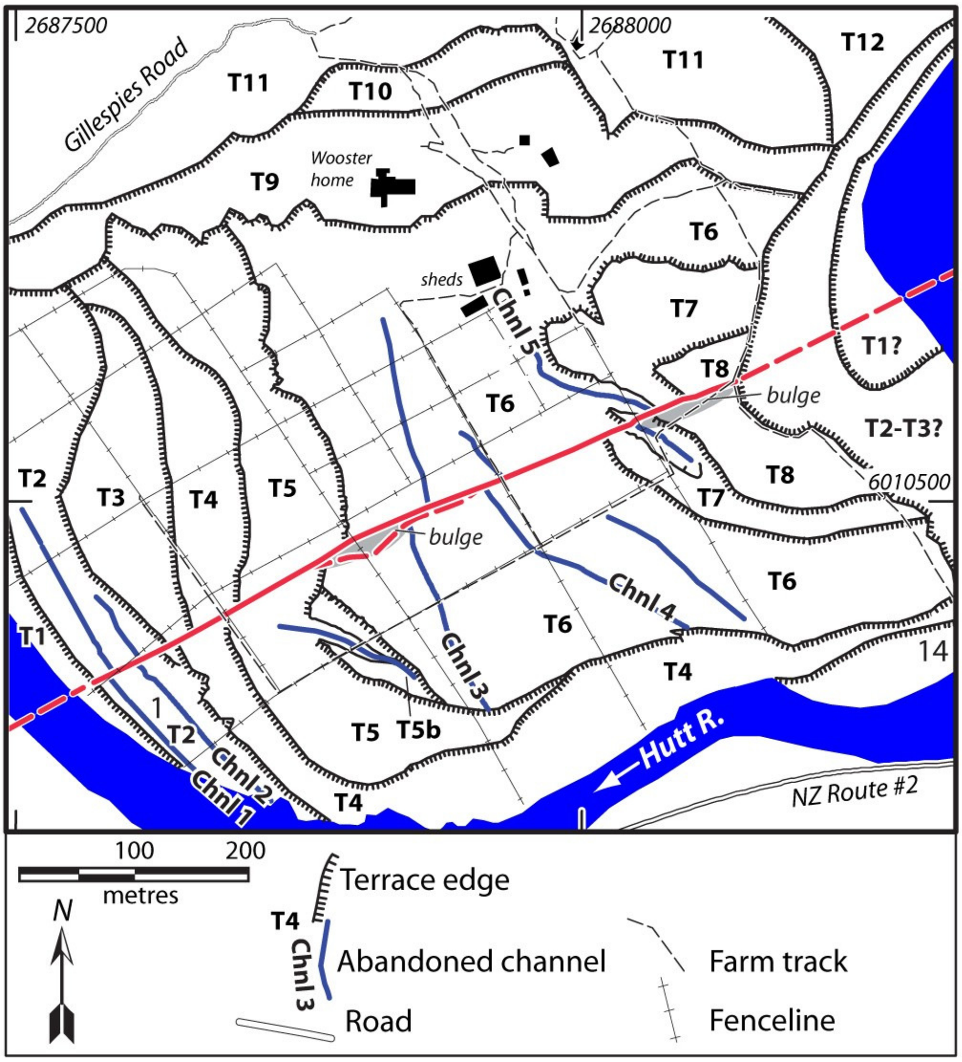


Figure 4.4. Wellington Fault through Te Marua Terraces area (from Little et al. 2010). See Figure 4.1 for location; Figure 4.3 for an aerial perspective (also Fig. 4.5); Figure 4.4 for schematic cross-section of these terraces depicting their relative elevational position and location of specific dating results; and Figure 4.6 for detailed topographic map of the fault and associated terrace and channel offsets.

Figure 4.5. 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 4.7b & 4.8a. Photo: D.L. Homer.

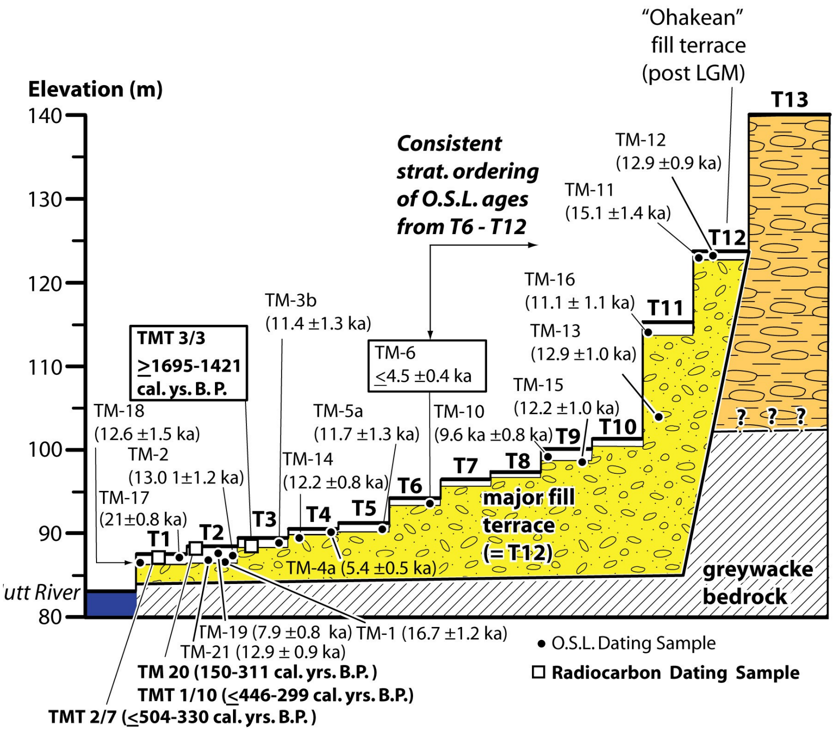
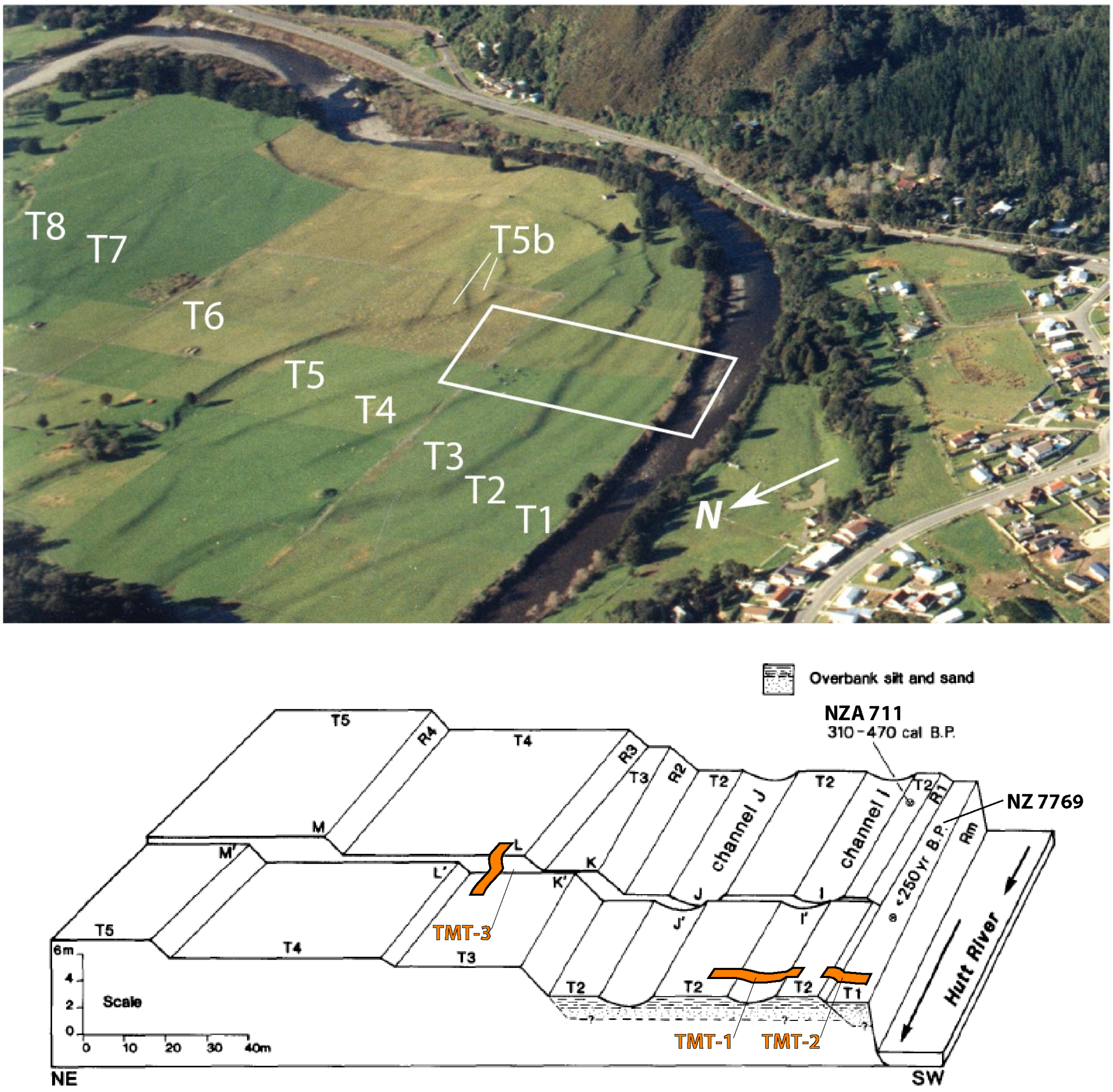


Figure 4.6. Schematic cross-section of Te Marua Terraces site showing relative elevational position of each terrace, and select dating results. All O.S.L. dating results are shown, but only the most relevant radiocarbon results are depicted. Below terrace T6, O.S.L. ages show no consistent stratigraphic ordering; whereas, above T6 they do (see text for additional discussion regarding this point). (from Little et al. 2010)

a)



b)

Figure 4.7. **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 4.4, 4.6, & 4.8. White rectangle shows location of Figure 4.7b. 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. 1992b). 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 4.6.

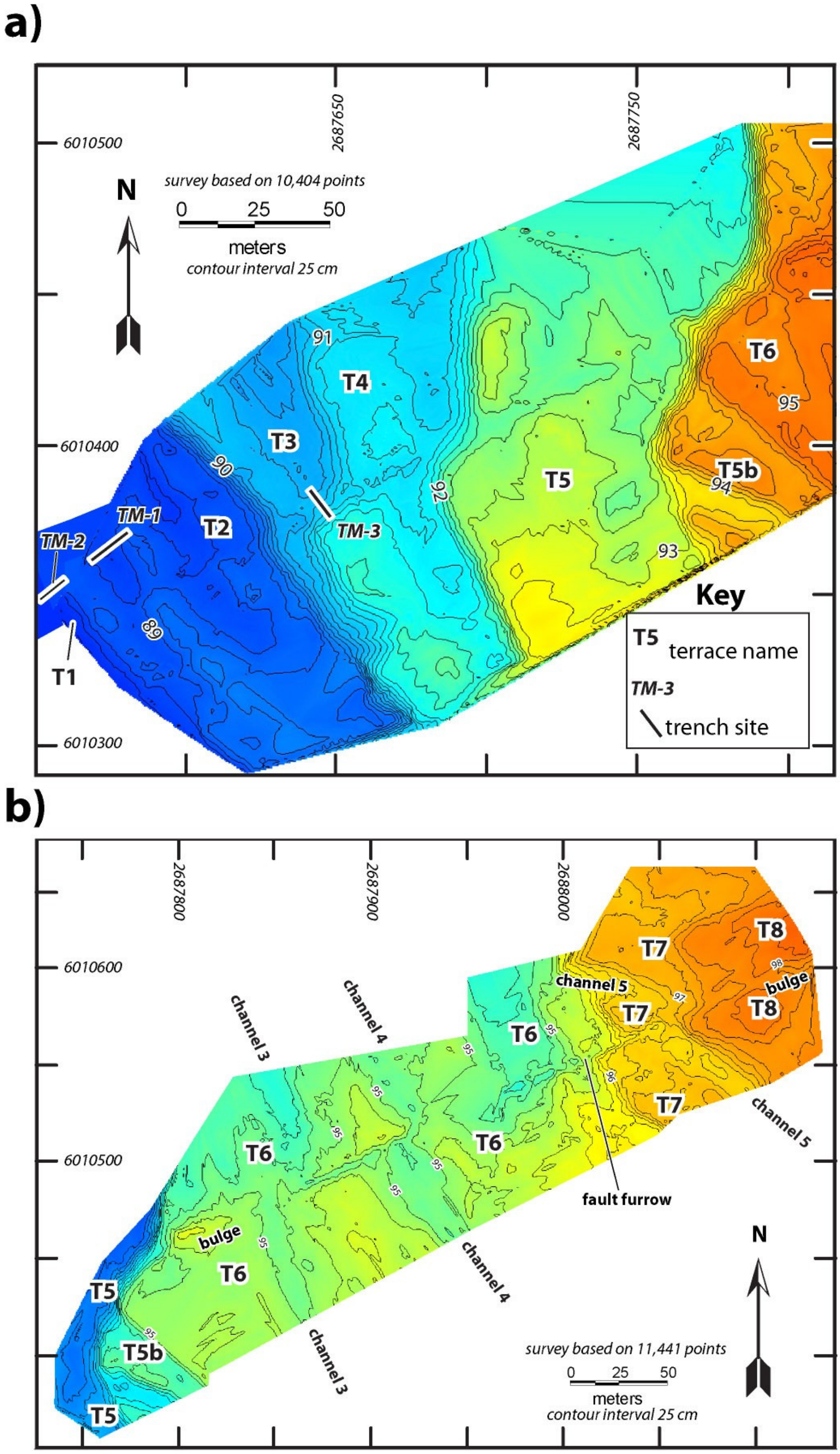


Figure 4.8. Detailed topographic map of the Te Marua Terraces site (see Figures 4.4 & 4.7 for location). Abandoned Holocene terraces of the Hutt River are labelled T1 (youngest) through to T8 (oldest). Trenches are shown by black bars, e.g. TM-1. (from Little et al. 2010).

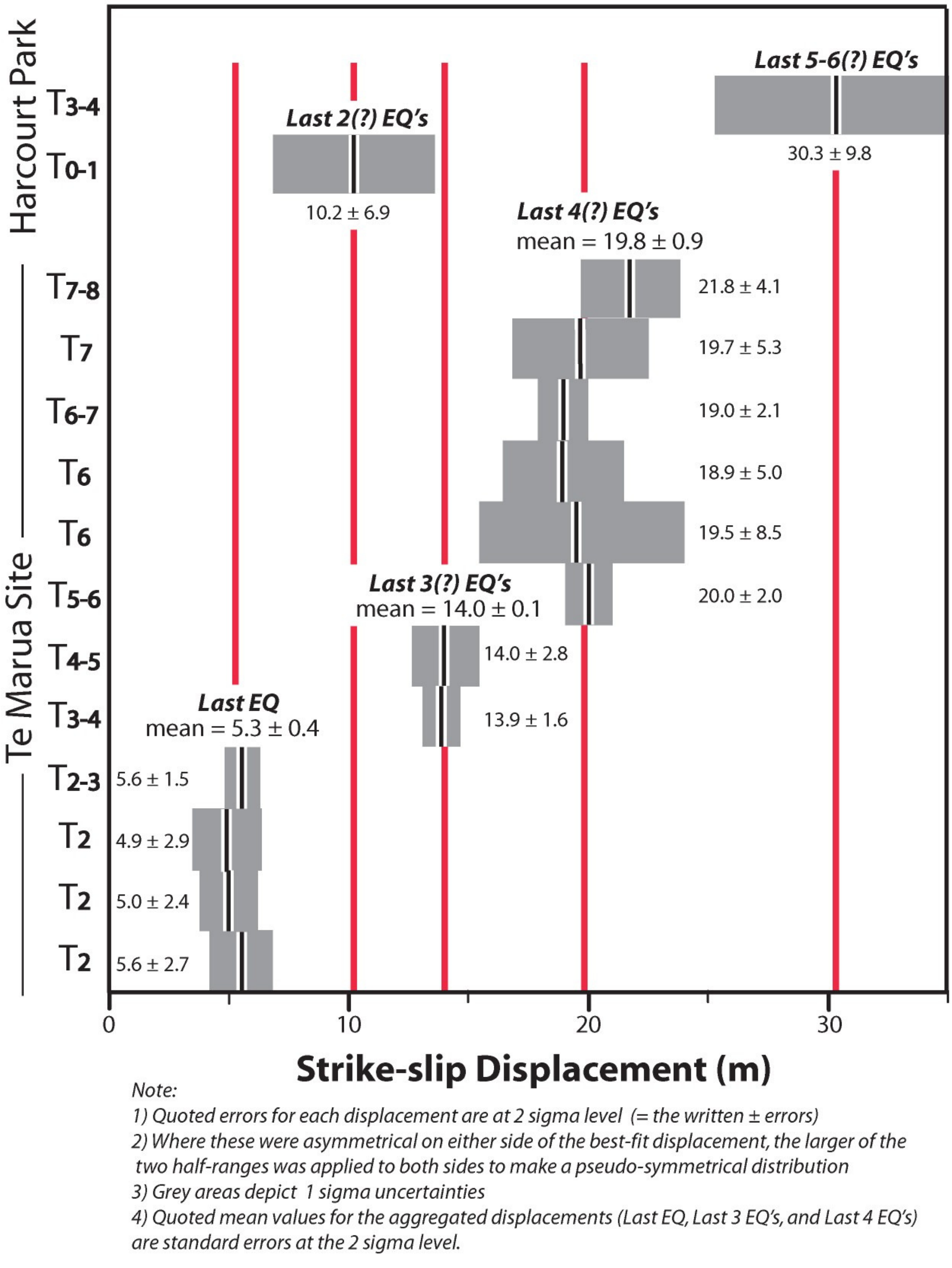


Figure 4.9. Wellington Fault strike-slip displacements measured at Harcourt Park and Te Marua grouped according to size. Individual displacements appear to cluster around multiples of ca 5 m. If the assumption is made that each cluster represents an individual earthquake rupture, then the last four ruptures 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). (from Little et al. 2010).

Stop 5: Mein's Rock: Exposure of the Wellington Fault zone on the Hutt River

This stop along the Hutt River in Taita Gorge between Upper and Lower Hutt provides an opportunity for us to examine variably brecciated Torlesse greywacke and related cataclasites and ultracataclasites that occur immediately adjacent to the Wellington fault. The currently active trace of the Wellington Fault trace lies submerged in the river immediately to the east of the outcrop platform (Fig. 5.1).

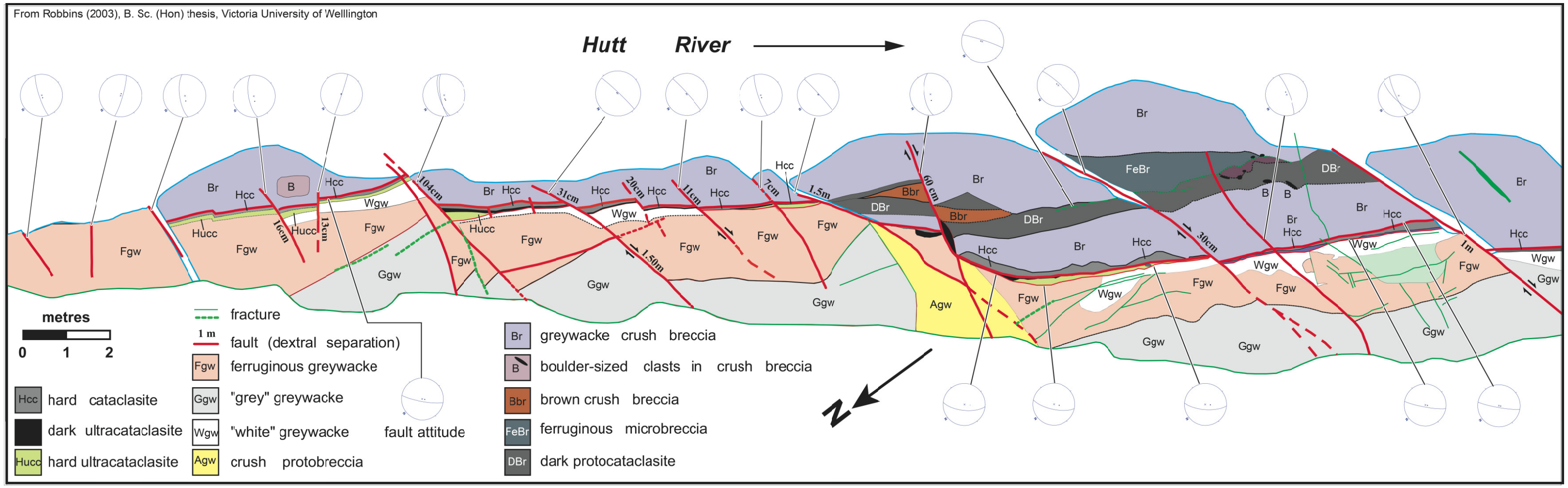
The rock platform exposes part of the damage zone of the Wellington Fault (Fig. 5.2). Embedded within this zone is a now-inactive strand of the Wellington Fault. Robbins (2003) called this inactive structure the "main" fault. It strikes ~046° similar to the active strand of the Wellington fault in this area. The *protolith* is essentially undeformed host rock. At Mein's Rock, the unit closest to protolith is relatively undeformed Torlesse greywacke, though fracturing is evident even in this rock. A *damage zone* is a region of enhanced wall-rock deformation adjacent to a fault, and is characterised by an increased concentration of fractures, veins, secondary faults and grain-scale deformation. At Mein's Rock this is at least 4 m wide. Pervasive fracturing in the damage zone has here led to the local development of elongate fragments of greywacke that are aligned at circa 120°. Within it, veinlets of quartz, calcite, and zeolite (probably laumontite) have cemented the greywacke fragments together to form indurated microbreccias and cataclasites. These occurrence of these hydrothermal veinlets indicate that the structures in the rock platform, which occur on the uplifted western side of the Wellington Fault, have been exhumed from greater depth, perhaps as much as several km. A *fault core* is the highly deformed portion of rock where the majority of slip has accumulated. At Mein's Rock the core of the "main" fault consists of extremely fine-grained ultracataclasites (composed of >90% matrix) an is mostly <15 cm thick. These demark the location of the *Principal Displacement Zone* (PDZ) of the inactive "main" fault at Mein's Rock.

The "main" fault is conspicuously cut and offset by a series of younger Riedel dextral-slip faults. These secondary faults make angles of ~35° and 65° (clockwise) to the main fault's strike and offset that older trace dextrally. These secondary (Riedel) faults are 20-55° more discordant in strike to the larger fault with which they are associated than than is typical of major strike-slip faults (typically this angle is only ~15°.

Perhaps at Mein's Rock, the Riedel faults may have formed ahead of a dynamically rupturing slip patch on the Wellington Fault during earthquakes. The dynamic stresses associated with the propagating earthquake rupture may here have reoriented theregional directions of due to compression and extension in a clockwise sense. Alternatively, slip on th Riedel faults may have accumulated during a series of *aftershocks* associated with Wellington fault earthquakes.

Figure 5.1. Photograph (looking south) of variably brecciated Torlesse greywacke and related cataclasites. Mein's Rock is the prominent bluff that occurs just downstream of the outcrop. The rock platform exposes part of the damage zone of the Wellington Fault, and a currently inactive strand of the Wellington Fault (note colour change across it). <10 cm-thick dark-coloured bands of ultracataclasite are developed along this inactive, "main" fault. Note that "main" fault is cut and offset by a series of younger Riedel dextral-slip faults. The currently active trace of the Wellington Fault trace lies submerged at 1-2 metre's depth in the river immediately to the left of the outcrop's margin on the left of the photograph. For scale, the white notebook on outcrop is A4 sized.

Figure 5.2 (next page). Simplified log of the fault rocks exposed at Mein's Rock, Taita Gorge, Wellington. Modified from Robbins (2003).


From Robbins (2003), B. Sc. (Hon) thesis, Victoria University of Welllington
Hutt River
N
metres
0 1 2
fracture
1 m
fault (dextral separation)
Fgw ferruginous greywacke
Hcc hard cataclasite
Ggw "grey" greywacke
dark ultracataclasite
Wgw "white" greywacke
Hucc hard ultracataclasite
Agw crush protobreccia
fault attitude
Br greywacke crush breccia
B boulder-sized clasts in crush breccia
Bbr brown crush breccia
FeBr ferruginous microbreccia
DBr dark protocataclasite
16cm
13cm
104cm
31cm
20cm
11cm
7cm
1.5m
1.50m
60 cm
30cm
1m

Brief Explanation of Units for Fig. 5.2

- **Ggw:** Light grey, highly fractured greywacke. This is the furthest unit from the main fault at Mein's Rock. It may therefore be the closest representative of undeformed host rock. Common fracture planes strike at 240° and 150°, and dip steeply. These planes bound blocks with average dimensions of 4 cm. The greywacke is indurated and shows little iron-staining in contrast to Fgw.

- **Fgw:** Hard greywacke that is redder and darker grey in colour than Ggw and other greywacke units. The contacts are mostly gradational and indistinct against adjacent units (except where bounded by fractures). The rock is a hard, homogeneous, fine sandstone. Grain-size reduction and increased fracturing density relative to Ggw may be related to the unit's proximity to the main fault. Most fracture strikes and clasts tend to align at 124 or 034°.

- **Wgw:** Whiter and more fault-proximal than the other greywacke units. More crumbly than Fgw or Ggw, and shows no signs of block fracturing. A structural grain is defined by the elongation of grain fragments that end to trend at 120° (similar to the clast fabric in Fgw). Its contact to other units further from the main fault is gradational over a decimetre scale.

- **Hcc:** Occurs adjacent to the main fault on its eastern flank, though it varies in thickness. A distinctive feature is the cross-fracturing perpendicular to the main fault trace. This fault-hardened rock is extremely indurated, a fact which is reflected in the unit protruding higher above the platform surface and being less weathered than surrounding units. The planar bounding surfaces to this unit provide an approximation of the main fault plane, and in places preserve slickenlines. No obvious clasts are visible. Veins of quartz have formed in the fractures perpendicular to the fault.

- **Ducc (black unit):** Dark black, flaky, crumbly ultracataclasite occuring as a 1-12 cm layer coincident with the PDZ of the main fault. The rock fractures primarily on planes parallel to the main fault, but also locally orthogonally to it.

- **Hucc:** Occurs as a distinct band along the core of the main fault. Similar in colour to Ggw but extremely fine-grained.

- **Gucc:** a green-white extremly hard layer ~2 cm-wide, occurring as lenses within the Ducc unit along the main fault. Extremely fine-grained and clay-rich with a rough weathering texture.

- **Gbr:** Resembles Ggw (into which it grades). The unit appears to preserve earlier stages of brecciation than do other units to the SE of the fault. This unit it is inferred to have been deformed in association with slip on the cross-cutting (Riedel) faults, to which this unit is proximal. Fragments are up to 5 cm in diameter and are dispersed in a comminuted greywacke-derived matrix.

- **Br:** Light-grey, hard, greywacke crush breccia containing angular fragments of greywacke that locally reach a maximum diameter of 10 cm. Average clast size 5-10 mm. Clast alignment is preferentially towards ~116°.

- **B:** Local cobble or boulder-sized fragments of greywacke host rock enclosed within other units (where differentiated).

- **Bbr:** Iron-stained greywacke-derived breccia. Soft or crumbly in texture. Sharp contacts with FB unit. Matrix is pale-orange-grey, conssiting of greywacke clasts that average about 1 cm in diameter (max., 3 cm). Massive fabric.

- **FeBr**. Occurs as relatively hard lenses of dark-orange coloured breccia that are enclosed in lighter greywacke-derived breccias. Fragments are often preferentially aligned sub-parallel to the strike of the eastern fault and may be as coarse as 40 cm in diameter.

- **Dbr**: Dark grey protocataclasite. Preferred clast alignment at 240°. These are commonly 3-5 cm in diameter in a finer-grained matrix.

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