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Defining the Wellington Fault within the Urban area of Wellington City

Client Report
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by N. D. Perrin & P. R. Wood



Frontispiece: Wellington and the Wellington fault. The Wellington fault line scarp is prominent in the photo, running between the arrows from Cook Strait (at bottom left) along the western (left) side of the Wellington Harbour and then along the western side of the Hutt Valley. The fault line scarp has eroded back from the location of the actual fault (Photo: D.L. Homer, GNS CN 15236-28).

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by N. D. Perrin & P. R. Wood

Prepared for

Wellington City Council

**Institute of Geological & Nuclear Sciences client report 2002/151
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**The data presented in this Report are
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EXECUTIVE SUMMARY

The purpose of this study is to provide Wellington City Council (the Council, WCC) with:

- ♦ a definition of “Active Fault”;
- ♦ an assessment of the activity of the Wellington fault;
- ♦ a compilation and assessment of information on the location of the Wellington fault through the urban area of Wellington City – the study area; and
- ♦ a definition of a fault rupture hazard zone for the Wellington fault.

Information about the location of the Wellington fault has been compiled for the urban areas of Wellington City. The compilation has been used to establish a fault rupture hazard zone for the Wellington fault within the urban area of Wellington City, approximately from Aotea Quay to the lower Karori Reservoir, including parts of the suburbs of Thorndon, Northland, Kelburn, and Karori. The hazard zone is for reference in the operation of the Wellington City Council District Plan. WCC engaged the Institute of Geological and Nuclear Sciences (GNS) to undertake this work.

The Wellington fault is an active fault, by at least New Zealand and Californian standards. It has a probability of an earthquake-generating ground surface fault-rupture occurring of about 10% in 50 years, equivalent to the criteria used in assessing wind and earthquake loadings on buildings by the NZ Standards Loadings Code NZS 4203. Proposed active fault planning guidelines (Kerr *et al*, in prep) for development of land on or close to active faults would have the Wellington fault in the most active class, a *Class I* active fault.

The location of the Wellington fault has been re-defined by this study through use of the new compilation of information but with little new fieldwork. Very few observations of the fault itself are known of in the study area. As a result, the location of the fault has been determined through both direct and indirect evidence and, equally importantly, evidence of its absence.

For the length of the Wellington fault studied, its location is presented as two zones around the likely position of the fault and with allowance for the apparent width. The inner zone defines the *likely fault rupture hazard zone* that varies in width from 10 to 50 metres. With due regard to the uncertainties in location, a 20-metre buffer has been added to define the outer zone, the GNS recommended *hazard zone*. This wider zone is recommended for reference in planning and development in the affected area. It varies in width from about 50 to 90 metres. The fault rupture hazard zones are supplied in a digital GIS form, for use in a geographic information system (GIS) at a maximum scale of 1:500.

The fault rupture hazard zones should be reviewed from time to time, as new information relevant to locating the Wellington fault will become available. Additional work specifically designed to directly observe the fault and thereby better define the *likely fault rupture hazard zone* should be considered.

1.0 INTRODUCTION

1.1 Purpose

The purpose of this study is to provide Wellington City Council (the Council, WCC) with:

- ♦ a definition of “Active Fault”;
- ♦ an assessment of the activity of the Wellington fault;
- ♦ a compilation and assessment of information on the location of the Wellington fault through the urban area of Wellington City – the study area.
- ♦ a definition of a fault rupture hazard zone for the Wellington fault.

In doing so, WCC will:

- ♦ increase its understanding of the likely extent of the fault and the associated fault rupture hazard;
- ♦ improve the quality of the information that locates the fault;
- ♦ be able to apply this additional knowledge when developing policy and undertaking planning related to the hazard of the Wellington fault.

The Council engaged the Institute of Geological & Nuclear Sciences Limited, (GNS) for this study.

1.2 Background

The area administrated by WCC lies on the Southwest tip of the North Island of New Zealand, between Cook Strait and Wellington Harbour. This area is one of the more tectonically and seismically active parts of New Zealand, being on the eastern edge of the Australian plate and underlain by the subducting Pacific plate. The area is measurably undergoing deformation, is exposed to strong earthquake shaking, and in addition, is traversed by several active faults that are significant on a world-wide scale, such as the Wellington fault. As a consequence of the tectonic setting, the region is characterised by steep topography (See Figure 1) and natural hazards that include earthquake ground shaking, liquefaction, fault rupture, landsliding, tsunamis, seiching, and flooding.

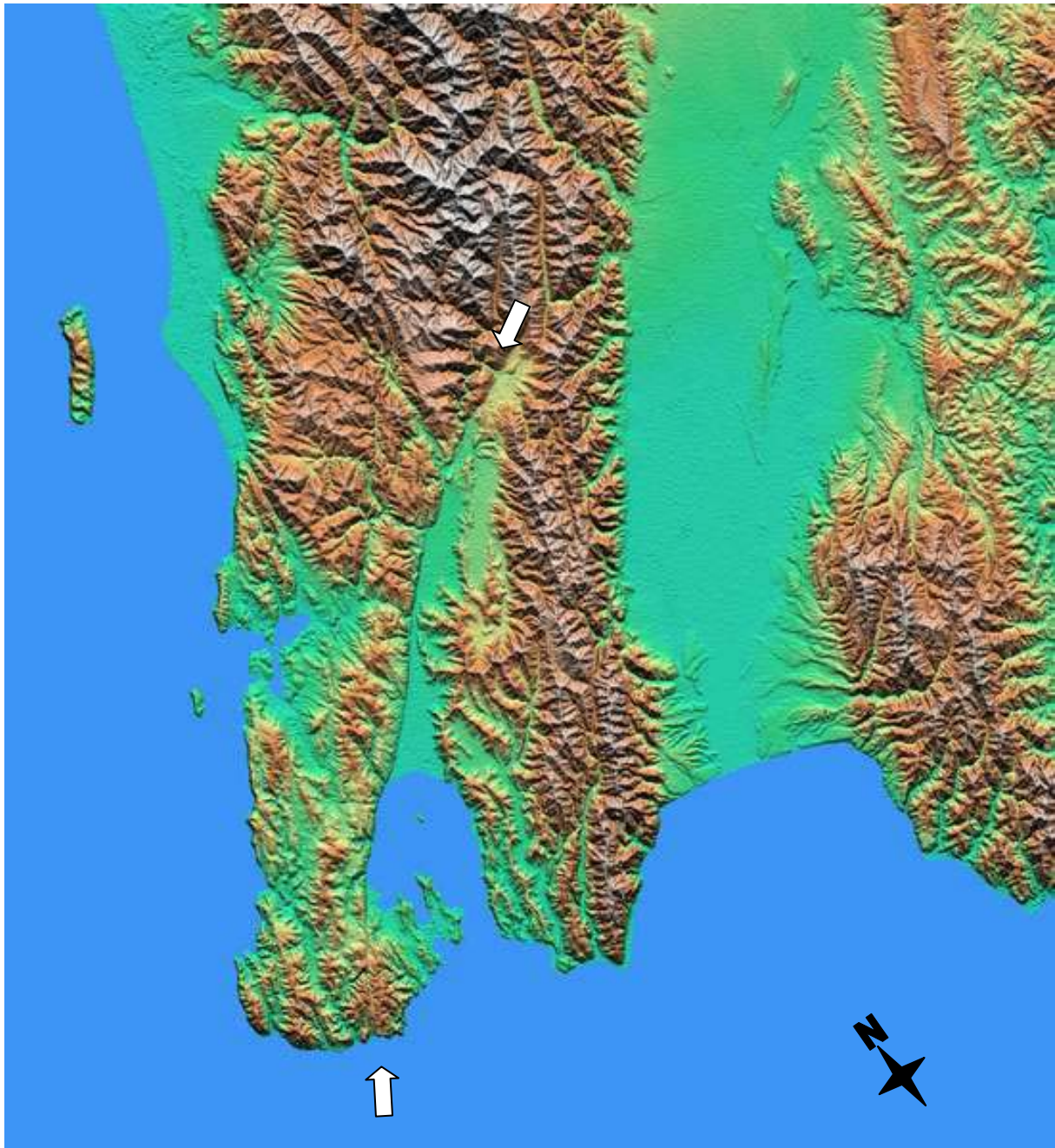


Figure 1 Topography of the Wellington region. The Wellington fault line scarp (arrowed) is the prominent linear landform bounding the western side of the Wellington Harbour in this digital terrain model image, where colour represents height. The fault line scarp has eroded back from the Wellington – Hutt Valley Segment of the Wellington fault, which lies up to 600 m to the east (right). The variation in cumulative vertical displacement across the Wellington fault is evident, being least about Brooklyn and most about Ngauranga (*image of 20-Feb-2000 from NASA/JPL/NIMA Shuttle Radar Topography Mission, sourced from <http://visibleearth.nasa.gov/cgi-bin/viewrecord?1142>, accessed Dec 2002*).

Earthquake shaking is the most common and extensive seismic hazard for the Wellington region. Wellington City is exposed to ground shaking generated by a number of earthquake sources including the Wellington fault; the Wairarapa, Ohariu, and Shepherd's Gully faults; (Figure 2); faults in the upper South Island; and the subduction zone, which lies some 25-30 km below Wellington City (where the Pacific Plate is being subducted beneath the Australian Plate).

Associated with the relatively brief periods of ground shaking associated with earthquake, there can also be "permanent" displacement of the ground. For example, the Wellington City area is known to have risen in elevation by 1.5 – 2 m following the great earthquake on the Wairarapa fault in 1855 (Grapes & Downes, 1997). Conversely, from geological evidence, ground levels have generally fallen to the east of the Wellington fault relative to the west, for Wellington fault earthquakes (Begg, pers. comm.). The maximum vertical slip across the Wellington fault is perhaps about Ngauranga, where the cumulative slip may be about 600 m over more than 1.4 million years, diminishing along the fault to the south-west and to the north-east.

The Wellington fault was recognised as a hazard after the settlement of Wellington City. The fault had long been known of as one of the major faults of the North Island. McKay (1891) said "...(it) forms the abrupt western shore of Wellington Harbour between Kaiwara and Petone..." and correlated it with the Awatere fault across Cook Strait. Bell (1909) described the physiography of Wellington Harbour, and provided "Proof of the great fault along the western side of Wellington Harbour". Almost immediately afterwards, Cotton (1911) corrected some of Bell's errors but was in general agreement with him as to the existence of the fault and its effect on the landscape. Cotton (1911) does not mention horizontal fault offsets, and evidence of these do not seem to have been recognised on the Wellington fault until the 1950s (Lensen, 1958). The horizontal, strike-slip, displacement is now estimated to be up to about four times the vertical (Van Dissen & Berryman, 1996).

The dislocation of the ground surface by fault slip constitutes the fault rupture hazard, the focus of this report. During an earthquake, the ground surface can be dislocated by fault slip of several metres or tens of metres. For the Wellington fault, both vertical and horizontal slip (along the fault) is likely to be more than a metre but less than ten.

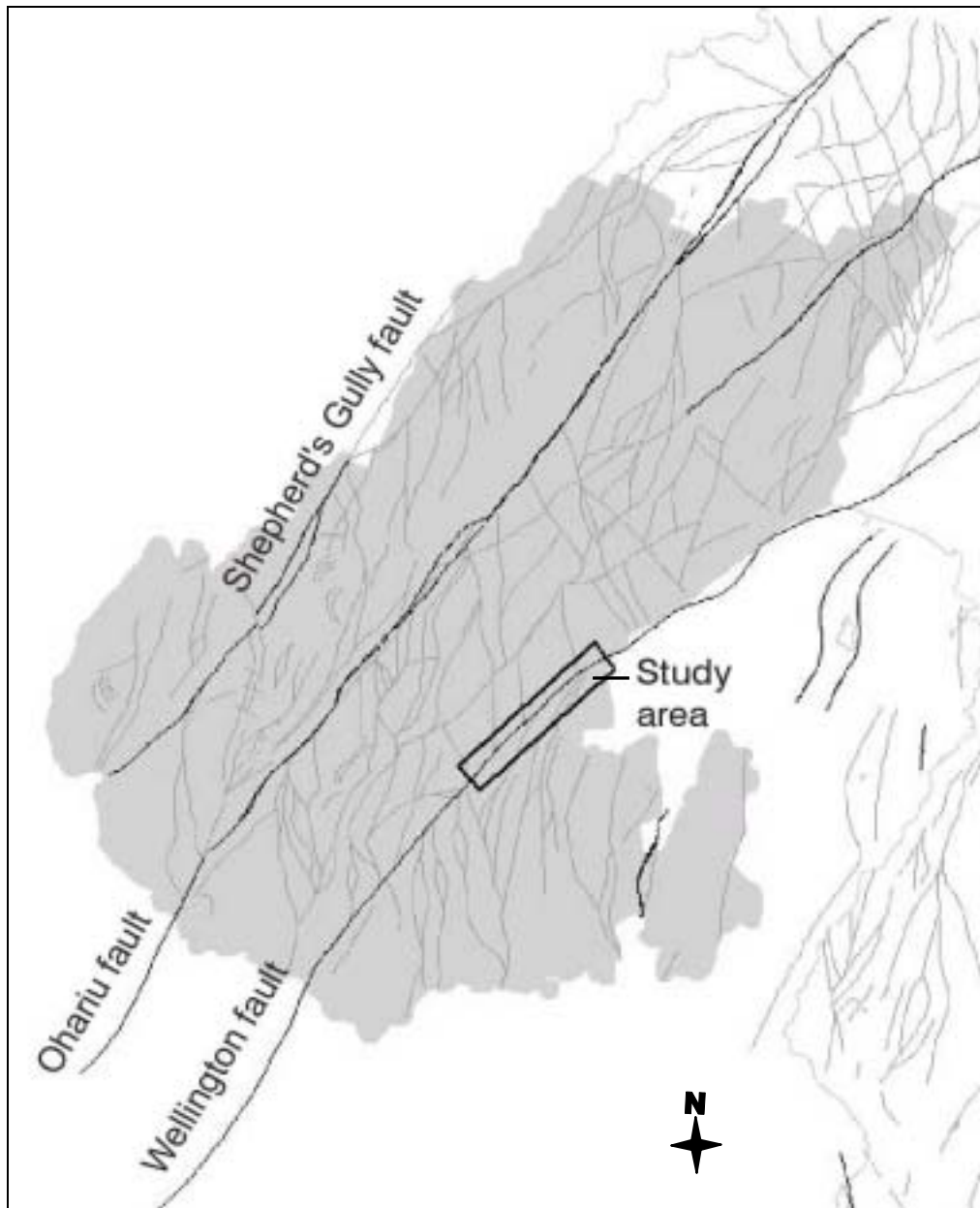


Figure 2 Location of the study within the WCC area (grey), with active faults (dark), and inactive (light). (after Begg & Mazengarb (1996))

Within the Wellington City area, GNS staff and others have investigated many sites along the Wellington fault. The results of some of these investigations are “open-file” and the important conclusions have been published. However, as well as these results, GNS and other consultants occasionally make additional site-specific investigations for private developers, under normal commercial contracts. The results from these contracts are generally not “open-file”, although some results may have been reported to Council in support of applications for developments. Consequently, not all information on the Wellington fault is in the public domain. The information reported to Council has been accessed for this study.

GNS and its predecessor, the New Zealand Geological Survey have researched the occurrence and nature of earthquake hazards of the Wellington City area for over 100 years. This has included systematic recording of earthquakes and mapping of active faults as well as the general geology. The concept of what is an “Active Fault” has evolved since the last published New Zealand definition (Grant Taylor *et al.*, 1979). Current practices tend to use definitions that are demonstrable within particular geological and geomorphic environments and that are judged relevant for the nature of the developments at risk. The Wellington fault as an active fault is discussed in Section 3.

1.3 Mitigating earthquake and fault rupture hazard

The Resource Management Act (1991) requires local authorities, such as WCC, to provide for the avoidance or mitigation of natural hazards. The earthquake shaking hazard is largely mitigated through the Building Act (including reference to the NZ Standards Loading Code NZS 4203), seismic resistant designs (e.g., base isolation systems), Local Authority earthquake risk building inventories, seismic retrofitting, and ground treatment. The Wellington City Council addresses its responsibilities in a number of ways; such as having an active programme of reducing the number of earthquake risk buildings, and having mechanisms in its District Plan that acknowledge hazards such as fault rupture.

Although Council fault rupture hazard mitigation planning initiatives exist in the District Plan, exposure to the fault rupture hazard of the Wellington fault is evident in Thorndon, Northland, Kelburn, and Karori where elements of the built environment have developed across it (buildings, roads etc). Further, it has been recognised recently that the fault rupture hazard areas shown on District Plan maps are based on information that is not up-to-date. This study addresses this issue.

1.4 Overview of the work

This report presents the set of information used here to define the location of the Wellington fault and describes the work undertaken and its limitations and uncertainties. The work updates the Council with definitions of active faulting and refines previous definitions of the location of the Wellington fault through the Wellington City urban area. These are the areas that are exposed to the fault rupture hazard from the Wellington fault. Those areas of the city exposed to rupture hazard from other faults are not addressed (e.g. the Ohariu fault; the Shephards Gully fault).

1.5 Procedure

The steps undertaken for this work, included:

1. Preparation of a statement that defines “Active Fault” for use by the Council. This has then been applied in a discussion on the Wellington fault.
2. Compilation of GNS records that show, in the vicinity of the Wellington fault in the Wellington City urban area, either: (i) evidence of faulting, or (ii) no evidence of faulting. Both these categories of information contribute to the spatial definition of the fault. The information was plotted onto prints of 1:500 scale digital orthophotos and summarised to show certainty of faulting, accuracy of location, and the availability of the information for the study. Some information was confidential.
3. Some limited field checking was undertaken.
4. Observations that constrain the location of the Wellington Fault were digitised and attributed with descriptions related to the faulting evidence such as: the original source of the information; ownership of the information, who currently holds the information (e.g. GNS); and the status of the information (e.g. not confidential). The resulting digital information constitutes the *GIS data coverage*.
5. By reference to the *GIS data coverage*, the *GIS fault rupture hazard coverage* was developed by applying the expert opinions of GNS staff. The *fault rupture hazard coverage* shows the areas where fault rupture hazard is judged to exist. The areas have been interpolated as necessary.
6. The initial fault rupture hazard coverage was reported to Council (Perrin & Wood, 2002) and then used by Council staff to identify Council property records that may contain additional information relevant to the location of the fault.
7. The additional Council information has been added to the *GIS data coverage* and used to revise and finalise the digital *GIS Likely fault rupture hazard coverage* (or zone) as reported here.
8. Finally, because of inherent uncertainties with the data available, such as the few direct observations of the fault and the subjectivity of some of the indirect evidence, a conservative precaution has been taken by extending the width of the *fault rupture hazard coverage* by 20m. This extension is equivalent to some previous practices in New Zealand e.g. Grant-Taylor *et al* (1979) and is also encouraged by Kerr *et al.* (in prep). The resulting area is referred to as the “hazard zone”.

2.0 FAULTS, FAULT RUPTURE HAZARD, AND ACTIVE FAULTS

2.1 What is a fault?

A fault is a fracture in the crust of the earth along which rocks on one side have moved, or “slipped”, relative to those on the other side. Most large faults (such as the Wellington fault) are the result of repeated displacements over a long period of time. A few faults in the world “creep”, that is they slip almost continuously. In New Zealand no “creeping” faults have been conclusively identified. Instead, New Zealand faults appear to slip episodically, in earthquake-generating events. The size of the displacement or slip for a single slip event is often of the order of metres and can exceed ten metres. Slip along the Wairarapa fault in 1855 was up to 12 metres horizontally, parallel to the strike direction of the fault. The vertical slip was up to about 3 metres at the fault (e.g. at Pigeon Bush). The associated earthquake had a magnitude estimated as greater than M8 (Grapes & Downes, 1997).

Repeated displacement of rock on either side of a fault crushes and shears hard rock. Consequently faults are characterised by zones of mechanically weakened rock. The width of the zone varies between faults and along a fault; it also varies through geological time as the fault develops from the original fractures to a through-going principal displacement zone. For the Wellington fault, the fault zone has been observed in basement rock at a number of localities from Cook Strait to Kaitoke. Although the rock appears to have been fractured up to 500 metres from the fault, the most intensely sheared rock is typically observed only within a metre or two of the fault (e.g. Brown & Wood, 1983). Typically there is a distinctive clay-gouge zone in the rock at the fault. An example of this can often be seen in the banks or bed of the Hutt River at Harcourt Park where the river has exposed the zone of the Wellington fault and also at Mains Rock at Hutt River 1.2 km upstream from Silverstream Bridge. Less well defined examples (exposures) occur within Wellington City, as at the eastern portal of the Karori tunnel.

2.2 What is fault rupture hazard?

Surface rupture of a fault occurs when a large slip event starts kilometres deep within the earth, breaking along the fault and upwards through to the earth’s surface, releasing seismic energy (an earthquake) and rupturing and deforming the ground surface. The abrupt rupture and deformation occur within a few seconds and may be measured in metres to tens of metres. Any structure or object on the ground in the vicinity of the fault will be shaken by the earthquake and subject to local ground deformations, but those situated across the fault will be additionally subject to fault rupture displacement and deformation – the fault rupture hazard (Figure 3).



Figure 3 The 1987 fault rupture of the Edgcumbe fault at McCracken Road (Photo: D.L. Homer, GNS GNS10115-37).

In New Zealand, examples of the consequences of fault rupture on the built environment are restricted to broken roads, fences, and similar (e.g. Glynn Wye 1888, Murchison 1929, Napier 1931, Inangahua 1968, Edgcumbe 1987). Recent overseas examples include damaged and destroyed buildings in Turkey from the Izmit, August 1999, and Duzce, November 1999, and earthquakes in Taiwan from the Chi-Chi earthquake of 1999. Fault rupture in Taiwan also severely damaged bridges and a concrete gravity dam. In some rare situations buildings can survive fault rupture, as for the 1992 Landers earthquake, California (Murbach *et al.*, 1999) and for some buildings in Turkey in 1999 (e.g. Sharpe *et al.*, 2000).

Defining and mapping fault rupture hazard zones (active faults) is part of an earthquake mitigation strategy. However, defining such a zone does not exclude the possibility of some fault rupture occurring outside of the zone (because of some unknown complexity in the mapped fault or due to an unknown fault). Nor does defining a fault rupture hazard zone exclude other ground damage such as localised deformation or warping, fissuring, lateral spreading, liquefaction, or landsliding also occurring outside the zone. These result from tectonic deformation and from ground failure under earthquake shaking. However, where an active fault can be located, minimising development across it (although not necessarily prohibiting) is the simplest, most effective, risk reduction measure.

2.3 What is an active fault?

Simply put, an “Active Fault” is a fault for which there is evidence of repeated fault slip in the recent geological past, thereby giving expectation of future slip.

Faults can become inactive, through changes such as the re-orientation of the tectonic stress field. Through geological time these faults can be “healed”. There are many such faults in the Wellington City area (Figure 2).

Inactive faults do not generally constitute a hazard, by definition (although they may be associated with weak rock and consequent susceptibility to ground failure). Active faults do constitute a hazard, although there is every degree of fault activity between active and inactive so that the boundary is necessarily arbitrary but often defined in accord with a specific purpose. It is difficult to argue that an active fault has stopped its episodic slipping. Hence, mitigation of the hazard that an active fault presents (ground shaking and fault rupture) should be considered in any hazard mitigation programme.

Basement rock is frequently masked by variable thickness of younger sediments, including alluvium and colluvium deposited by stream and slope processes. In the Wellington City area these can be tens of metres thick, elsewhere, as in the Hutt Valley, they can be more than several hundred metres thick. However, fault displacements do rupture up through the overlying sediments, and can leave a trace on the ground surface. The rupture almost always follows the zones of weakness of pre-existing faults. Fault rupture demonstrably and repeatedly displaces the ground surface along the fault trace. Topographic features, such as hill-slopes, ridges, stream valleys, and river terraces are offset. As these features are typically of different geological ages, the size of their displacements indicates the cumulative displacements for different time periods. These are the principal criteria for defining an *active* fault – recent, repeated displacements. The timing of the last and prior displacements (almost always pre-historic), require displaced features of known age. Dated sediments or landforms that have been ruptured provide one common method of proof.

Mapping active faults can identify fault rupture hazard zones, but always with various levels of uncertainties. These qualify the extent and characteristics of the rupture and the timing of past events. Criteria are required to set limits on such work, including which active faults are to be mapped and in what detail.

A number of active fault classification schemes have been developed. In California legislation the Alquist-Priolo Earthquake Fault Zoning Act (1972) defines an active fault for the purposes of the Act as one that has ruptured the ground surface in the last 11,000 years (Hart & Bryant, 1997)¹.

In New Zealand two classification schemes have been published, the first by Officers of the Geological Survey (1966) and a revision by Grant-Taylor *et al.* (1979). The principal criteria were (i) age of last displacement, and (ii) frequency of displacement. The most active class, Class I, required evidence of repeated movement in the past 0 – 5,000 years. *The Wellington fault has repeated movement in the last 5,000 years.*

Recent practice in seismic hazard assessment and seismic aspects of building codes has been to use fault slip-rate, both for specific studies for critical structures, such as hydro-electric dams, and for regional and national probabilistic seismic hazard assessments. A probabilistic seismic hazard assessment of California by Petersen *et al.* (1996) categorised faults into two classes. *Class A* faults generally have slip rates greater than 5 mm/yr and well constrained paleoseismic data. The *Class B* faults include all the other faults lacking paleoseismic data necessary to constrain the recurrence intervals of large events. *The Wellington fault has a slip rate of about 6 mm/yr and well-constrained paleoseismic data by world standards.*

The 1997 International Uniform Building Code (IUBC97) seismic loading provisions refer to *A* faults, *B* faults, and *C* faults. An *A* fault is the most destructive and a *C* fault is the least destructive. The slip rate and maximum magnitude of earthquakes associated with a fault are the basis for the categories. Category *A* faults exhibit magnitudes of 7.0 or greater and slip rates of at least 5 mm/yr. Category *B* faults fall in the magnitude 6.5 to 7.0 range with slip rates varying depending on maximum magnitude (Division of Mines and Geology, 1998). *The Wellington fault has an estimated maximum magnitude of 7.5 and a slip rate of about 6 mm/yr and would be a category A fault by IUBC97 criteria.*

The New Zealand classification of active faults is currently under discussion (Kerr *et al.*, in prep). Consideration is being given to risk based criteria equivalent to building codes, such as the current Loading Standard NZS 4203 (under revision, as a joint NZ/Australian loading

¹ The following notes on the Californian Alquist-Priolo Earthquake Fault Zoning Act are after Hart & Bryant (1997).

The Alquist-Priolo Earthquake Fault Zoning Act's main purpose is to prevent the construction of buildings used for human occupancy on the surface trace of active faults. The Act only addresses the hazard of surface fault rupture and is not directed toward other earthquake hazards. The Seismic Hazards Mapping Act, passed in 1990, addresses non-surface fault rupture earthquake hazards, including liquefaction and seismically induced landslides. Surface rupture is the most easily avoided seismic hazard. If an active fault is found, a structure for human occupancy cannot be placed over the trace of the fault and must be set back from the fault (generally 50 feet [c. 15 metres]).

Alquist-Priolo Earthquake Fault Zones are regulatory zones around active faults. The zones are defined by turning points connected by straight lines. Most of the turning points are identified by roads, drainages, and other features on the ground. Earthquake Fault Zones are plotted on topographic maps at a scale of 1 inch equals 2,000 feet [1:24,000]. The zones vary in width, but average about one-quarter mile wide [c. 400 metres].

standard). NZS 4203 stipulates that stability assessments are to allow for a 10% probability of an action being exceeded during the design life of a building, taken as 50 years. This is the equivalent of an event with a return period of about 500 years. The preparation of new guidelines for the development of land on or close to an active fault has led to a revision of classifying active faults in New Zealand (Van Dissen *et al.*, in press). *The Wellington fault has a return period estimated at about 600 years and fits the most active category - Class I of the proposed new NZ active fault classification.*

3.0 THE WELLINGTON FAULT

3.1 General description

The Wellington fault is one of the longest of New Zealand's on-shore active faults. From its southernmost known location in Cook Strait, the Wellington fault 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 essentially changes only by name and continues northwards to the coastline of the Bay of Plenty and beyond. The 75 km length of the fault between Cook Strait and Kaitoke is known as the *Wellington-Hutt Valley* segment (Berryman 1990). The *Wellington-Hutt Valley* segment is the length of the Wellington fault judged likely to rupture in a Wellington fault earthquake in this area. A Wellington fault earthquake on some other segment of the Wellington fault may not cause rupture of the *Wellington-Hutt Valley* segment – but will cause ground shaking in the Wellington City area.



Figure 4 Wellington City – Hutt Valley. The *Wellington-Hutt Valley* segment of the Wellington fault runs from Cook Strait, through the suburb of Thorndon at the bottom left of the photo, north-east through the ferry terminal area and then offshore to Petone and onshore through Hutt and Upper Hutt Cities. The fault-line scarp, eroded back some hundred or so metres from the fault, is a prominent landform along the western margin of Wellington harbour, it has eroded to the west (left) up to 600 m from the fault (Photo, DL Homer, GNS).

3.2 Characteristics and activity of the Wellington fault

The Wellington fault has produced many examples of topography that it has displaced in the recent geological past. Clear examples are seen along the Wellington-Hutt Valley Segment of the fault, from the south of Wellington City at Long Gully (Van Dissen *et al*, 1992), to the offset Hutt River terraces at Te Marua (Berryman 1990). The predominately right-lateral strike-slip displaced topography shows the cumulative effect of some c. 200 episodic slip events over c. 140,000 years – all associated with a rupture zone of limited geographic width, only metres to tens of metres wide (Van Dissen & Berryman 1996).

In Hutt City, the Wellington fault trace has been mapped across the ground surface, between Melling and Petone (e.g. Begg & Mazengarb, 1996). The fault has been exposed there by fault-investigation trenches (e.g. Ian R Brown Associates Ltd, 1995). Even though the sediments in the Hutt Valley that overlie the basement-fault are more than a hundred metres thick, the fault demonstrates repeated rupture through to the ground surface, along a zone that is generally of only a few metres width. Evidence of the Wellington fault through the urban areas of Wellington City is outlined in Section 3.3 and detailed in Section 4.

Along the Wellington-Hutt Valley Segment of the Wellington fault, the fault has a high right-lateral slip rate which, although episodic (recurrence interval of large earthquakes of 500-700 years), gives a long-term average of c. 6 mm/yr. (Berryman, 1990). Rates of throw (the vertical displacement component) vary along the fault. The characteristics of the fault's trace together with rare exposures of the fault itself indicate that it dips steeply to vertical. In general, the upthrown side of the fault is to the west, but locally there are traces and scarps that show up-throw to the east (e.g. Thorndon seabed; Te Marua). Episodic fault slip, with rupture offsetting the ground surface ~ 4-5 m right-lateral and ~1 m vertical, are to be expected. Associated earthquakes will be large with magnitudes of the order of M7.6. The last surface rupture of the Wellington-Hutt Valley Segment is estimated at c. 340–450 years ago (Van Dissen & Berryman, 1996). This together with the recurrence interval gives a probability of fault rupture in the next 50 years of about 10%.

The Wellington fault is an active fault by any of the previous criteria (Section 2.3), having had the following estimates published (Berryman, 1990; Van Dissen & Berryman, 1996):

- ♦ a slip rate of c. 6 mm/yr
- ♦ well constrained paleoseismic data;
- ♦ capable of generating an earthquake of magnitude c. 7.6
- ♦ a recurrence interval for large surface rupturing earthquakes of ~ 500 – 700 years;
- ♦ elapsed time since the last event of 340 – 450 years ago.
- ♦ average displacement of ~ 3.8 – 4.6 metres.

Under the proposed active fault planning guidelines (Kerr *et al*, in prep), the Wellington fault would be a Class I active fault (Van Dissen *et al*, in press), Class I is the most active Class.

3.3 Nature of the Wellington fault in Wellington City

Repeated displacements along the Wellington fault are responsible for many of the large-scale topographic features within Wellington City. The fault-line scarp is a prominent topographic feature more or less along the line of the Pipitea Stream between Raroa Crescent, the Kaiwharawhara ferry terminal, and to the north-east along the north-western margin of Wellington harbour and beyond, along the Hutt Valley (Figure 1; Figure 4). It forms the steep and dissected ESE facing slopes of Northland, Tinakori Hill, Wadestown, Khandallah, and Newlands. The fault-line scarp has been eroded to the west of the surface trace of the Wellington fault by up to 600 metres. The vertical offset of the bedrock surface along the fault increases in a north-easterly direction from almost zero at Raroa Crescent, to several hundred metres at the ferry terminal, with a maximum of c. 600 metres opposite the Ngauranga Gorge.

There are fewer than ten locations in the Wellington City urban area where the fault has been observed directly. Much of the additional evidence for the location of the fault comes from indirect observations, including aerial photographs taken in 1941 or 1942, showing topography now modified and masked by subsequent development. The photos show topographic lineaments consistent with faulting. In many places, particularly where rock is absent near the ground surface, the fault appears to comprise a narrow zone of many fractures and deformed sediments, not more than c. 20 metres wide. The fault appears to be near vertical.

Of historic interest is the observation that a number of minor streets have sections of roading aligned parallel to, and between, Tinakori and Grant Roads (the central dog-leg in Cottleville Terrace, Burnell Avenue, Goring Street, Little George Street). There are similar alignments south-west of Harriett Street (Pitarua St, Upper Lewisville, upper Patanga Crescent). These sections of roading were probably formed on local topographic highs or topographic benches, attractive to road construction in the early years of the establishment of Wellington. These topographic features are interpreted as being indicative of the fault location, and the roads may very well have been constructed unwittingly over or adjacent to the fault trace. Support for this suggestion comes from the alignment with the other indicators of the Wellington fault.

Within the Wellington City urban area the Wellington fault has three distinct alignments. To the north-east, *the harbour section* of the fault is aligned approximately ENE-WSW, the central *Tinakori Road - Karori Tunnel section* is NE-SW, and *the Long Gully section* to the south through the Karori Reservoirs and Long Gully is aligned more NNE-SSW.

4.0 EVIDENCE FOR THE WELLINGTON FAULT IN WELLINGTON CITY

This section presents the information that has been used to locate the Wellington fault. The information is from the area of the Wellington City urban area, between the Lower Karori dam in the south and Wellington Harbour in the north.

Both WCC and GNS files have been searched for information relevant to fault location, this included:

- i. Outlines of the map extent of relevant investigations;
- ii. Locations of specific investigations and observations such as drillholes, ground penetrating radar survey lines, seismic survey lines, investigation trenches and fault exposures;
- iii. Areas of unfaulted rock exposed close to the fault;
- iv. Fault traces mapped from aerial photographs;
- v. Approximate limits of areas showing stream deflections or other fault-related features;
- vi. Areas of topographic scarps interpreted as fault scarps.

The locations of the information have been numbered and manually plotted on to a large-scale (1:500) orthophoto base (NZ Map Grid Projection). WCC supplied the orthophoto images and digital elevation data used (contours, with 1 metre contour interval). The plotted information was digitised and then used in a GIS to produce the *data coverage*.

Each location has been classified as to the fault being:

1. *Certain*,
2. *Possible*,
3. *Unlikely*, and
4. *No fault observed*.

In addition, the locational accuracy has been assigned to one of three accuracy classes:

- i - location established to +/-5m*
- ii - location inferred +/- 20m*
- iii - location inferred +/- 60m*

The appended maps (*Maps 1 – 9*) have been printed from the GIS coverages developed for this study. Numbers on the map faces refer to the locations described in the following sections 4.1 – 4.3. The locations are further described in *Appendix 1. Compiled information*.

4.1 Harbour section to Tinakori Road

(Maps 1-2)

This section of the fault is characterised by offset sediments and a steep fall-off in the bedrock surface at depth. The hill slopes of the fault-line scarp project downward below the harbour or alluvial and marine sediments, such that the near vertical fault is some distance out from the foot of the fault-line scarp, just as at Lower Hutt and Totara Park to the north-east. The on-shore part of this section is mainly reclaimed land that post-dates the last fault displacement.

Lewis (1989) established the location of the fault in Wellington Harbour, using marine seismic methods with a positional accuracy stated to be +/-5 m. Lewis's southwest-most location of the fault was adjacent to the Ferry Terminal and is shown as location 1. This location is consistent with a fault identified (at location 5) by Adkin, 1950, in drilling that was undertaken for construction of the Aotea Quay breastwork.

Earlier work by Hochstein (1971) (at location 2) attempted to locate the fault in relation to the Johnsonville railway bridge over Thorndon Quay. At that time the fault was thought to pass through the railway bridge, but no such fault was found by the geophysical survey undertaken.

In an assessment of drilling records in the Wellington railway yards, an interpretation of the position of the fault was based on a lithological contrast between more or less oxidised mainly terrestrial sediments with peat layers on the upthrown side and mainly non-oxidised predominantly marginal marine sediments on the downthrown side. The location of the fault is considered to be constrained to an accuracy equivalent to the spacing between the adjoining drillholes in the railway yards.

Ground penetrating radar failed to find evidence of the fault in the railway yards (location 15 (Audru *et al*, 1999)), but it appears the line did not extend far enough to the north-west, because it was not possible to undertake the survey across the main railway tracks.

The continuation of the fault to the south-west is inferred to pass near the intersection of Tinakori Road and Thorndon Quay, in the vicinity of Stowe Hill (location 16). Here there is an exposure of possibly deformed gravel layers in a road cutting above Tinakori Road adjacent to an area of shotcrete (which may conceal the fault).

Further evidence constraining or defining the location of the fault includes two possible right-lateral offsets of a stream adjacent to Cottleville Terrace. The stream, (location 79 in Appendix 1) appears to be offset at locations 80 and 81. These apparent offsets, which are shown in a 1934 plan, are consistent with a dividing of the fault at a change in strike between two segments. The smaller offset (location 80) appears to be a continuation of the straight section between Harriett St and Cottleville Terrace while the larger offset (location 81) is probably a continuation of the harbour section of the fault.

Other observations and building records in the Cottleville Tce area show rock in the foundations for Mansfield Towers (location 82), Grosvenor Flats (location 83) and a new excavation for a car park (location 84). At Newman Court Flats (location 85) the ground conditions are typical of those on the south-east (downthrown) side of the fault.

4.2 Tinakori Road – Karori Tunnel Section

4.2.1 Tinakori Road to Premier House (Maps 3-5)

This section of the fault is characterised by offset fans of at least last-glacial age (>12,000 years old). The partially infilled-valley of the paleo-Pipitea Stream is aligned along the fault zone. The stream was probably dammed by a landslide from upper Newman Terrace and diverted to its historical route (now culverted) to Pipitea Point.

The fault is inferred to change direction to a more southerly trend from location 16, but no firm evidence for the location of the fault plane has been found between location 16 at Stowe Hill and just south of Park Street (locations 19 to 23). Ground penetrating radar surveys (locations 17 Cottleville Terrace and 18 Newman Terrace) failed to find evidence for the fault. However, the contour plans confirm that these radar lines are on a broad semicircular fan previously identified on aerial photographs in the vicinity of the lower part of Newman Terrace. The source of this fan is a deep bite in the flank of Tinakori Hill at the upper part of Newman Terrace, and it may be landslide debris, perhaps resulting from an earthquake-induced landslide, possibly from the earthquake of the last fault rupture event. All the other fans at the foot of Tinakori Hill show fault offsets, but since this fan does not appear to be offset, it is inferred to date from or after the last Wellington fault slip event. However, Hull (1979) recorded a possible fault scarp at the north end of Burnell Avenue. This just encroaches onto the southern margin of the fan. The more recent detailed contour information used for this work show a probable 1.5 to 2 m high scarp at the north end of Burnell Avenue (Location 78), consistent with Hull's interpretation. It is highly likely that the fan surface is of different ages.

Further evidence that the fan centred on Newman Terrace is landslide debris was found in a WCC file on piling at 3 Newman Terrace (location 86). It was reported that there were difficulties in excavating pile holes because of the presence of blocks of rock, and the material was referred to as "natural loose old slip debris, depth unknown".

The fault has been observed from both a Ground Penetrating Radar survey and a fault investigation trench that was excavated some 6 metres deep at the former Thorndon Bowling Club site, Goring Street (locations 19-23). The trench (excavated in 2001 by Ian R Brown Associates Ltd) showed, at location 20, faulted fan gravels overlain by unfaulted gravels (Figure 5 - Figure 7). The zone of inferred faults appeared to be not more than about 4 m wide.



Figure 5 Fault investigation trench at former Thorndon Bowling Club site Goring Street. Photos: N.D. Perrin, 19 July 2001, courtesy of Ian R Brown Associates Ltd.



Figure 6 Fault location in trench. Photos: N.D. Perrin, 19 July 2001, courtesy of Ian R Brown Associates Ltd.

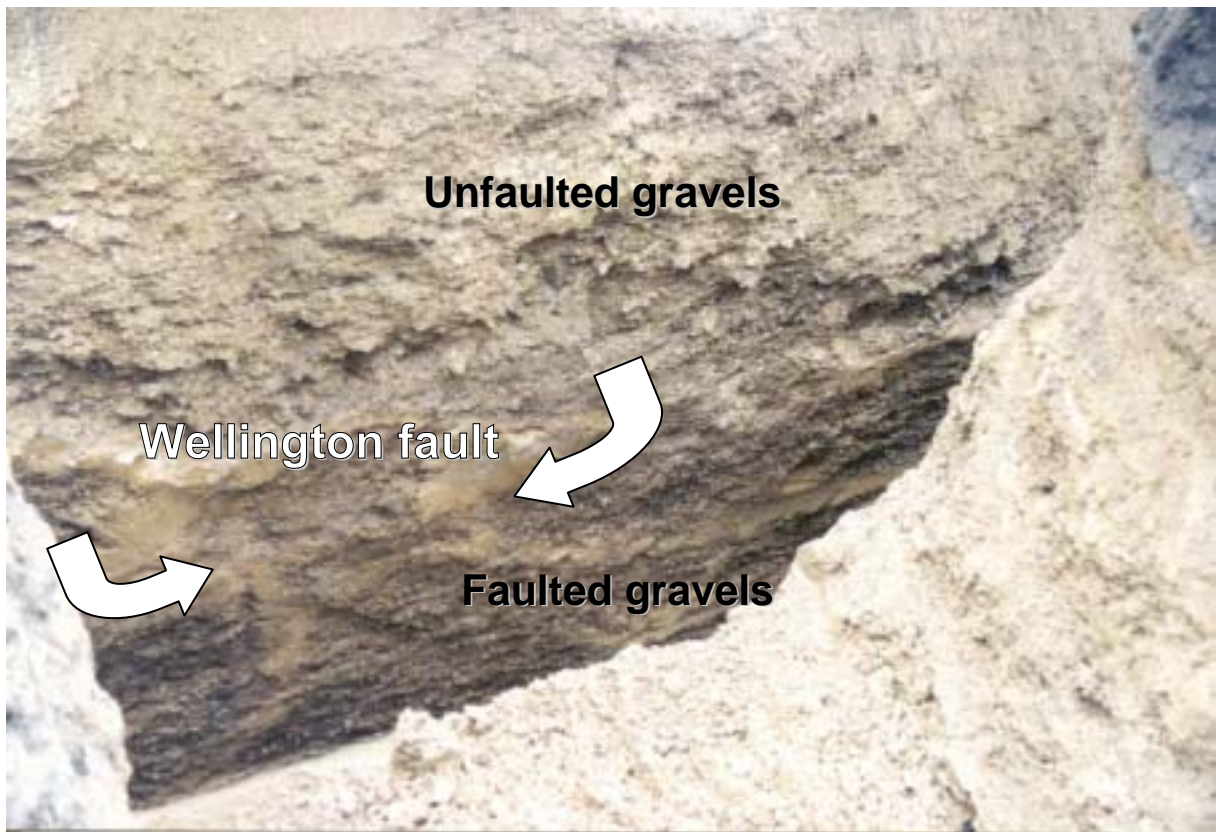


Figure 7 Inferred fault location indicated by disruption of a silt layer indicative of predominately horizontal fault rupture. There is a single, gently dipping layer to the left (west) of the photo (seen in Fig 5). It is contorted and disrupted where the “Wellington fault” is indicated. The upper gravel appears unfaulted and post-dates the last fault rupture event. Photos: N.D. Perrin, 19 July 2001, courtesy of Ian R Brown Associates Ltd.

At George Street, a drilling investigation comprising 4 drillholes was undertaken to locate the fault there in 1976 (locations 27-30). It was established that there is a deep channel in the bedrock surface along the inferred line of the fault (Williams, 1976), and it was considered that the fault was located within an 18m wide zone. A radar survey (location 25) by Audru *et al* 1999 has been interpreted to show a fault offset of subsurface sediments at location 26, close to the north-western edge of the 18 m wide zone.

At Malcolm Lane, Ota *et al.* (1981) recorded a fan truncated by the fault (location 454). A trenching investigation about the same location by Wood *et al.* (1988) (locations 31 to 37) found a continuous peat layer 2 m thick at a depth of 2 m below the surface east of this truncated fan. A fault is inferred where the peat layer terminates abruptly against fan deposits at location 35.

A ground penetrating radar survey by Audru *et al.* (1999) in Aorangi Terrace (locations 38 to 42) identified four possible faults in a zone 27 m wide. Although none of these possible fault planes coincided exactly with the projection of known or inferred locations to the north-east and south-west, the centre of the zone containing them is the best fit position for the fault from interpolation from the other locations. It is possible that there are multiple strands of past surface rupture at this location.

Investigations at Harriett Street included a trenching investigation by Beanland 1987 (location 43-44) and a ground penetrating radar survey by Audru *et al.* (1999) (locations 45 to 49). These sites are adjacent to location 453 of Ota *et al.* (1981), who recorded a scarp displacing a local fan and a beheaded stream. The trenching investigation was hampered by the constraints of building structures at the site and the presence of fill for most of the depth of the trench, but evidence of a narrow zone of surface ruptures was postulated as being indicative of proximity to the fault. This location was confirmed at the time by a ground penetrating radar survey in Harriett Street by Atkins (pers. comm. 1987). Audru *et al.* (1999) recorded four possible fault offsets in a zone 45 m wide, one of which corresponds almost exactly with the Beanland and Atkins position, in line with the north-west kerb of Pitarua Street at its intersection with Harriett Street. The apparent step in topography across Pitarua Street, up to the north-west, is inferred to be a fault offset.

In the grounds of Premier House, a fault trace displacing a local fan by 0.7 m vertically (up to the south-east) was recorded by Ota *et al.*, (1981) (location 452), this has subsequently been modified.

4.2.2 Premier House to Garden Road (Maps 5-7)

This section of the fault is characterised by rock close to the inferred fault location on the north-west (upthrown) side and Pleistocene to Holocene sediments on the south-east (downthrown side). Fault traces are preserved in a few places. The fault location is parallel to, and about 50m north-west of the valley of Pipitea Stream.

In the vicinity of Upton Terrace, Ota *et al.* (1981) recorded a stream offset (location 451), but it is difficult to locate the position of the fault plane more precisely than within a zone 60 m wide.

At Patanga Crescent (location 51), Berryman (1994) outlined a zone 20 to 25 m wide which was estimated to include the fault location. Ota *et al.* (1981) recorded a stream offset (their location 450) within this zone which defines the fault location to within +/-20 m. A trenching investigation at 31A Patanga Crescent (location 87) in 1995 did not encounter the fault.

Various studies in and around the Sharella site by Wood and Fellows (1988), Berryman (1994), and Wood and Perrin (2000) have located the fault within a zone 25 to 30 m wide (locations 53 to 56). Two fault traces were mapped from aerial photographs and ground inspection (locations 55 and 56). These two traces are separate strands of the fault, indicating a zone of possible rupture and deformation at least 15 m wide.

At Bank Road, Ota *et al.* (1981) recorded a stream offset (their location 449). Recent observations show rock on one side (locations 57 and 58), and bedded Pleistocene gravels and silts on the other side, constraining the fault to a position down the centre of Bank Road at its intersection with Garden Road. An excavation at 85 Garden Rd in April 1998, (location 88) behind 70 Glenmore St revealed unfaulted Pleistocene and Holocene sediments.

4.2.3 Garden Road to Karori Tunnel (Maps 7-8)

In this area the fault is characterised by the presence of rock on both sides of the fault and right-lateral stream offsets of 50 to 100 m between Garden Road and The Rigi.

Obvious right-lateral stream offsets at locations 59 (Garden Road), 448 (Orangi Kaupapa), 447 (below Garden Road), 446 (Crieff Street) and 445 (The Rigi) constrain the fault location to within a zone with a width of between 20m and 60m, but further constrained by the presence of rock exposures at locations 60, 61, 63 and 64. At location 62 an area of slumping is considered to represent the location of the fault.

Other evidence for the presence of the fault in the area adjacent to location 63 at 7 Orangi Kaupapa Rd (location 89) is a record of seepage and a slip. WCC analysis of the seepage proved it to be groundwater and not sewage or stormwater. Such seepages are typical in the presence of crush zones and clay seams passing through rock.

At location 90, an independent geologist's report gave an estimate of the location of the fault zone in relation to a proposed subdivision of 126 Glenmore St and 12 Crieff St, and at location 91, "unusual" subsurface conditions were reported for a deck at 3 Crieff St, adjacent to location 62.

South of the Rigi, rock exposures (locations 65 and 72), combined with the Ota *et al.* (1981) identification of a scarp displacing the slope (location 444) constrain the fault location to a zone about 20 m wide at the Northland Road/The Rigi/Glenmore Street intersection. Further information on the original topography at The Rigi Flats shows a possible truncated stream at location 92.

At 156 Glenmore St/27 The Rigi, (location 93) two trenching investigations revealed bedrock right across the site. This, and other evidence on Northland Rd constrains the fault to beyond the south-eastern end of the trenching investigation.

A new exposure of bedrock in an excavation for a new home at 3 Northland Rd (location 94) showed no evidence of major faulting. This location, and other observations of bedrock along Northland Road constrain the fault to a location a few metres to the southeast of No 3 Northland Road.

An excavation for car parking at 196 Glenmore St (location 95) encountered seepages and poor ground conditions. Although an engineer's report did not specifically mention the fault, the evidence is consistent with the fault being present close to, or possibly within this excavation.

At the east portal of the Karori Tunnel (Figure 8) an exposure of rock (location 66), a crush zone (location 67), and a record by Ota *et al.* (1981) of a fault trace with gouge (at location 443), all constrain the fault location within 20 m.



Figure 8 Crushed rock of the Wellington fault is exposed, at power pole, at the eastern portal of Karori tunnel (Photo: N.D. Perrin, Dec 2001).

4.3 Long Gully Section

4.3.1 Karori Tunnel to Lower Karori Reservoir (Maps 8-9)

There is bedrock close to and on both sides of the fault in this section. The fault crosses the drainage divide between the Pipitea Stream and Kaiwharawhara Stream at Raroa Crescent/Moana Road and forms a steep west-facing scarp along Waiapu Road.

At Raroa Crescent, Ota *et al.* (1981) recorded a fault trace (fault trench) at location 442. Observations in this area, including rock exposures either side of this (locations 73 and 74), constrain the fault location to within 10 m. Further rock exposure around Moana Road and Waiapu Road (locations 75 to 77) constrain the fault to a zone about 15 m wide between rock outcrops. From this point the fault is extrapolated southwards to pass through the Lower Karori dam between the centre and the right (east) abutment (Perrin & Wood, 2002).

At 29 Waiapu Rd (location 96), a scarp behind the block of flats is inferred to be a slightly modified fault scarp. The gap in the rock exposure between locations 75 and 76 through which the fault is thought to pass is substantiated by the foundation design for the flats, in which piles were not planned to be founded in bedrock. It is inferred that there is a considerable thickness of alluvium in a channel eroded into the fault zone by a former stream that has been truncated by the fault. Examination of the face behind the flats (about location 104) is required to further refine the location of the fault here.

At location 97, a recent study of the tunnels under the Lower Karori Dam (Perrin & Wood, 2002) was carried out to investigate the location of the fault with respect to the dam and other structures and services. As expected, the most likely location of the zone containing the fault is in an area of brick and concrete tunnel lining (locations 105D & 105E). The rock exposure in adjacent unlined portions of tunnel (shown in green on Map 9) and unfaulted surface rock exposures (locations 77 and 101) preclude the possibility of the fault zone being located in those areas.

From the inferred location of the fault to the north-east and south-west of the Lower Karori Dam, the most likely location containing the fault zone is a ten metre long zone of lined tunnel shown as “probable fault” on Map 9 (location 105E).

Outside the mapped area, but of interest in establishing the position of the fault, are plans of the floor of the upper reservoir where features consistent with stream offsets can be recognised (location 98 in Appendix I, but not shown on the maps). There are also the reported Wellington fault investigations, including trenches, to the south-west including those in Long Gully (Van Dissen *et al.*, 1992).

5.0 DISCUSSION AND CONCLUSIONS

The Wellington fault is a most active fault (Class I), according to the draft active fault planning guidelines (Kerr *et al*, in prep). This is on the basis of several independent criteria and from observations of the fault previously reported.

Information on the location of the Wellington fault through the urban area of Wellington City has been compiled. The information, from WCC and GNS files and archives, has been digitised into a geographic information system and subjected to study and some related field observations. This has resulted in:

- ♦ An attributed GIS *data coverage* of the data sources used for the study;
- ♦ Two attributed GIS *fault rupture hazard coverages*, defined from reference to the *data coverage* and with the *fault certainty* and *locational accuracy* in mind.
- ♦ The *hazard coverages* are presented as *Likely fault rupture hazard zone* and *Recommended hazard zone*.

For the length of the Wellington fault studied, the *Likely fault rupture hazard zone* varies in width between about 10 and 50 metres. According to the draft active fault planning guidelines (Kerr *et al*. in prep.) the fault complexity is “A well-defined”. To allow for the uncertainties in the location and width of the fault rupture hazard, the width of the *Likely fault rupture hazard zone* has been increased with a 20-metre buffer on each side, making a total width of about 50 to 90 metres. This wider zone, the *Recommended hazard zone*, is the one recommended for reference in planning and development in the affected area.

The Wellington fault has been reasonably well located for an urban area. The information used in this study confirms the continuity of the Wellington fault, and of a fault rupture hazard. However, it is certainly possible that the fault could be better located with additional work, such as an in-depth field survey of geological exposures and deep and fully documented fault investigation trenches, none of which have as yet been made within the study area. Some of the probable fault locations could be confirmed by investigating vegetated, steep, concrete lined, or shotcrete surfaces. Such locations include the:

1. lined section of the delivery tunnel at the Lower Karori Dam (location 105E);
2. exposures at the eastern portal of the Karori road tunnel (locations 66 & 67); and,
3. shotcrete road cut at Stowe Hill (location 16).

Fault investigation at these three locations would require site-specific investigation programmes, including, for (2) and (3) at least, partial or complete road closures.

The fault rupture hazard zones (*Likely* and *Recommended*) are supplied to Council as GIS coverages and are shown on the maps that accompany this report. It is intended that this information should be considered alongside the proposed active fault planning guidelines (Kerr *et al*, in prep; King *et al.*, 2003; Van Dissen *et al.*, 2003 a & b).

The zones should be reviewed from time to time, as new information relevant to locating the Wellington fault becomes available. Additional work, specifically designed to better define the fault rupture hazard zone, should be considered.

Finally, this work has addressed only that portion of the Wellington fault that lies within the urban area of Wellington City. It has not addressed the Wellington fault south of the lower Karori dam, nor the other known active faults within Wellington City.

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APPENDIX 1: COMPILED INFORMATION

<i>Location ID</i> ²	<i>Comment</i>	<i>Reference</i> ³	<i>Fault?</i> 1. Certain; 2. Possible; 3. Unlikely; 4. No fault observed,	<i>Accuracy</i> ⁴
0	Cross section, Aotea Quay breastwork	Adkin 1950	1	ii
1	Fault location from off-shore seismic	Lewis 1989	1	i
2	Seismic line, Sar St to Ferry terminal	Hochstein 1971	4	
3	Fault in relation to Aotea Quay Breastwork	Adkin 1950, Perrin 1993	1	i
4	Drillhole TB10A	Adkin 1950	4	
5	Drillhole TB10	Adkin 1950	1	i
6	Drillhole TB9	Adkin 1950	4	
7	Drillhole T01	Adkin 1950	4	
8	Drillhole BH4	Adkin 1950	4	
15	Radar line, Railway yards - no result	Begg, pers comm., Audru <i>et al</i>	4	
16	Observation of possible fault zone, Stowe Hill	Perrin obs	2	ii
17	Radar line, Cottleville Tce - no result	Begg, pers comm., Audru <i>et al</i>	4	
18	Radar line, Newman Tce - no result	Begg, pers comm., Audru <i>et al</i>	4	
80	Right-lateral stream offset 10 m	1934 WCC plan	2	ii
81	Right-lateral stream offset 30 m	1934 WCC plan	2	ii
83	Grosvenor Flats, 19 Cottleville Tce	WCC	4	
84	Crib Wall, Grant Road	NDP obs, July 2002	4	
85	Sediments not faulted, Newman Court flats	WCC	4	
86	Landslide debris 3 Newman Tce	WCC	4	
78	Fault trace, Burnell Ave	Hull 1979	2	i
19	Trench, Thorndon Bowling Club	Ian R Brown Assocs 2001	1	i
20	Fault location in trench, Thorndon Bowling Club	Ian R Brown Assocs 2001	1	i
21	Radar line, Thorndon Bowling Club	Ian R Brown Assocs 2001	2	ii
22	Radar line, Thorndon Bowling Club	Ian R Brown Assocs 2001	2	ii

² Sorted in order from north-east to south-west.

³ Refer to section 6 REFERENCES.

⁴ Accuracy of location: i - ± 5 m; ii - ± 20 m; iii - ± 60 m

<i>Location ID</i> ²	<i>Comment</i>	<i>Reference</i> ³	<i>Fault?</i> 1. Certain; 2. Possible; 3. Unlikely; 4. No fault observed,	<i>Accuracy</i> ⁴
23	Radar line, Thorndon Bowling Club	Ian R Brown Assocs 2001	2	ii
25	Radar Line, George St	Audru <i>et al</i>	2	ii
26	Fault on radar line, George St	Audru <i>et al</i>	2	ii
27	DH1, George St	NZGS files	4	
28	DH2, George St	NZGS files	4	
29	DH3, George St	NZGS files	4	
30	DH4, George St	NZGS files	4	
31	Trench T1, Malcolm Lane	Wood <i>et al</i>	4	
32	Trench T2, Malcolm Lane	Wood <i>et al</i>	4	
33	Trench T4, Malcolm Lane	Wood <i>et al</i>	1	ii
34	Trench T3, Malcolm Lane	Wood <i>et al</i>	4	
35	Fault location in trench, Malcolm Lane	Wood <i>et al</i>	1	i
37	Fault zone from Malcolm Lane report	Wood <i>et al</i>	1	ii
454	Truncated local fan, Malcolm Lane	Ota <i>et al</i>	1	iii
38	Radar Line, Aorangi Tce	Audru <i>et al</i>	1	ii
39	Fault on radar line, Aorangi Tce	Audru <i>et al</i>	2	ii
40	Fault on radar line, Aorangi Tce	Audru <i>et al</i>	2	ii
41	Fault on radar line, Aorangi Tce	Audru <i>et al</i>	2	ii
42	Fault on radar line, Aorangi Tce	Audru <i>et al</i>	2	ii
43	Trench, Harriett Street	Beanland	1	ii
44	Fault location inferred, Harriett St trench	Beanland	1	i
45	Radar Line, Harriett St	Audru <i>et al</i>	2	ii
46	Fault location inferred, Harriett St radar line	Audru <i>et al</i>	2	ii
47	Fault location inferred, Harriett St radar line	Audru <i>et al</i> , Aitken (pers com)	1	i
48	Fault location inferred, Harriett St radar line	Audru <i>et al</i>	2	ii
49	Fault location inferred, Harriett St radar line	Audru <i>et al</i>	2	ii
453	Scarp displacing fan and truncated stream, Harriett Street	Ota <i>et al</i>	1	ii
452	Scarp, Premier House	Ota <i>et al</i>	1	i
451	Stream offset, Upton Tce	Ota <i>et al</i>	1	iii
51	Fault zone, Patanga Cres	Berryman 1994	1	ii
87	Fault trenching investigation 31A Patanga Cres	WCC	4	
450	Stream offset, Patanga Cres	Ota <i>et al</i>	1	ii
54	Fault zone	Wood and Fellows 1988	1	ii
55	Fault Trace, Bank Rd to Patanga Cres	Wood and Fellows 1988	1	i

<i>Location ID</i> ²	<i>Comment</i>	<i>Reference</i> ³	<i>Fault?</i> 1. <i>Certain</i> ; 2. <i>Possible</i> ; 3. <i>Unlikely</i> ; 4. <i>No fault observed</i> ,	<i>Accuracy</i> ⁴
56	Fault Trace, Bank Rd to Patanga Cres	Wood and Fellows 1988	1	i
57	Rock outcrop, Bank Rd	Perrin obs	4	
58	Rock outcrop, Bank Rd	Perrin obs	4	
449	Stream offset, Bank Rd/Garden Rd	Ota <i>et al</i>	1	ii
59	Stream offset, Garden Rd	Perrin obs	1	ii
88	Excavation, Garden Rd April 1998	NDP obs	4	
448	Stream offset, Orangi Kaupapa	Ota <i>et al</i>	1	iii
447	Stream offset, Garden Rd	Ota <i>et al</i>	1	iii
446	Stream offset, Crieff St	Ota <i>et al</i>	1	iii
60	Rock outcrop, Glenmore St	Perrin obs	4	
61	Rock outcrop, Crieff St	Perrin obs	4	
62	Slumping fault scarp, Crieff St	Perrin obs	1	ii
63	Rock outcrop, Orangi Kaupapa	Perrin obs	4	
89	7 Orangi-Kaupapa, slip and seepage	WCC	1	ii
90	126 Glenmore St, 12 Crieff St, 24 Garden Rd - fault location mapped	WCC	1	ii
91	3 Crieff St deck stability- "unusual" subsurface conditions	WCC	2	ii
92	Rigi Flats -truncated stream	WCC	1	i
64	Rock outcrop, The Rigi	Perrin obs	4	
93	156 Glenmore, 27 The Rigi trenching investigation in rock	WCC/NDP obs	4	
445	Stream offset, The Rigi	Ota <i>et al</i>	1	iii
444	Scarp displacing slope, The Rigi	Ota <i>et al</i>	1	ii
94	3 Northland Rd rock excavation	NDP obs, July 2002	4	
65	Rock outcrop, Northland Rd	Perrin obs	4	
95	196 Glenmore -excavation and engineers report	WCC	2	ii
443	Trace with gouge, Karori Tunnel	Ota <i>et al</i>	1	ii
66	Rock outside Karori tunnel portal	Perrin obs	4	
67	Crush zone outside Karori tunnel portal	Perrin obs	1	i
442	Fault trench, Raroa Crescent	Ota <i>et al</i>	1	i
71	Rock outcrop by Talavera Tennis Club	Perrin obs	4	
72	Rock outcrop by old school site	Perrin obs	4	
73	Rock outcrop, Moana Rd/Raroa Crescent	Perrin obs	4	
74	Rock outcrop, Raroa Crescent	Perrin obs	4	
102	Rock exposure, Moana Road	NDP obs	4	
103	Rock exposure, Moana Road	NDP obs	4	
75	Rock outcrop, Waiapu Rd	Perrin obs	4	

<i>Location ID²</i>	<i>Comment</i>	<i>Reference³</i>	<i>Fault? 1. Certain; 2. Possible; 3. Unlikely; 4. No fault observed,</i>	<i>Accuracy⁴</i>
76	Rock outcrop, Waiapu Rd	Perrin obs	4	
77	Rock outcrop, Waiapu Rd	Perrin obs	4	
104	Rock exposure, north end of No 29 Waiapu Rd	PRW obs	4	
96	29 Waiapu Rd, no rock, possible offset stream channel	WCC	2	ii
99	Rock exposure, Waiapu Rd	NDP/PRW obs	4	
100	Rock exposure, steps to house south of 29 Waiapu Rd	NDP/PRW obs	4	
97	Karori Lower Reservoir dam	WCC	1	iii
99	Rock exposure, Waiapu Rd	NDP/PRW obs	4	
101	Rock exposure behind pump house at lower Karori Dam	NDP/PRW obs	4	
102	Rock exposure, Moana Road	NDP obs	4	
103	Rock exposure, Moana Road	NDP obs	4	
104	Rock exposure, north end of No 29 Waiapu Rd	PRW obs	4	
105a	Karori lower dam, scour tunnel, lined	Perrin & Wood, 2002	3	
105b	Karori lower dam, unlined sections, scour and delivery tunnels	Perrin & Wood, 2002	4	
105c	Karori lower dam. Unlined chlorination tunnel	Perrin & Wood, 2002	4	
105d	Karori lower dam, lined delivery tunnel from valve tower	Perrin & Wood, 2002	2	i
105e	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	2	i
105f	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
105g	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105h	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
105i	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105j	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
105k	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105l	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
105m	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105n	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
105o	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105p	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	

<i>Location ID</i> ²	<i>Comment</i>	<i>Reference</i> ³	<i>Fault?</i> 1. <i>Certain</i> ; 2. <i>Possible</i> ; 3. <i>Unlikely</i> ; 4. <i>No fault observed</i> ,	<i>Accuracy</i> ⁴
105q	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105r	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
105s	Karori lower dam, lined section of delivery tunnel to Aro St	Perrin & Wood, 2002	3	
105t	Karori lower dam, unlined section of delivery tunnel to Aro St	Perrin & Wood, 2002	4	
98	Karori Upper Reservoir dam, original stream course	WCC	1	ii

APPENDIX 2: MAPS

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