Active Fault Mapping and Fault Avoidance Zones for Horowhenua District and Palmerston North City

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REVIEW DETAILS

This report was completed December 2018. The final report includes corrections following review comments from Horowhenua District Council.

CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

APPENDIX TABLES

EXECUTIVE SUMMARY

GNS Science has been contracted by Horizons Regional Council ('Horizons') to provide active fault hazard information for its districts. The Horizons Region straddles the active Australia-Pacific plate boundary in the southern North Island and has a history of large earthquakes and many known active faults.

New active fault mapping and Fault Avoidance Zones are presented for the districts of Horowhenua and Palmerston North City. These districts are traversed by active strike-slip and reverse faults (and associated active folds) that pose a surface rupture (or ground deformation) hazard to buildings and infrastructure. Following the Ministry for the Environment's (MfE) Guidelines – "Planning for Development of Land on or Close to Active Faults" (Kerr et al. 2003; the "MfE Guidelines") – fault traces have been mapped to develop Fault Avoidance Zones (FAZs) that buffer the active faults at a scale that is suitable for district planning use. In terms of life safety, the "MfE Guidelines" focus on: (i) the location and complexity of faulting; (ii) the characterisation of recurrence interval of surface faulting; and (iii) the building importance category of the structure(s) that may be impacted by fault rupture ground deformation. Fault Awareness Areas (FAAs) have been developed for areas where the scale of mapping is small.

Active fault trace mapping was undertaken in both districts using hill-shade models developed from airborne Light Detection and Ranging (LiDAR) data and from review of active fault mapping from QMAP (the Geological Map of New Zealand project), the New Zealand Active Faults Database (NZAFD), a regional scale 8-m Digital Elevation Model (DEM) and orthophotographs. Fault mapping was undertaken at scales between c. 1:5000 and 1:10,000 where LiDAR data is available. Active faults have been mapped in a Geographic Information System (GIS) with traces being attributed as accurate, approximate, or uncertain. These terms are used to help characterise the fault complexity, i.e. how the fault deformation is expressed at the Earth's surface. Fault complexity can vary from well-defined to distributed or uncertain. The accuracy and complexity terms are further used to define the width of FAZs.

In Horowhenua District, the active faults recognised and mapped are the Northern Ohariu, Otaki Forks, Tokomaru (new), and Poroutawhao (new) faults. Two further short active traces – the 'Cluain traces' (new) and the 'Oturoa trace' (new) have been identified. FAZs have been defined for these active faults according to the MfE Guidelines. FAAs have been developed for parts of these faults that have been mapped at scales between 1:50,000 and 1: 250,000. FAAs are distinct from FAZs and carry no requirements related to the MfE Guidelines. The axes of active folds have also been re-mapped for the Levin, Shannon, Foxton (re-named), and Oturoa (new) anticlines. This study does not present avoidance zones for active folds because fold axes are not typically associated with life-safety threatening ground deformation.

We review and in some cases present new recurrence interval (RI) class assessments for active faults in Horowhenua District as follows: Northern Ohariu Fault (RI Class II; >2000 to ≤3500 years); Tokomaru, and Poroutawhao faults and 'Oturoa trace' (RI Class IV; >5000 to ≤10,000 years); and the 'Cluain traces' (RI Class V; >10,000 to ≤20,000 years). Fault Avoidance Zones have been developed for these faults, and a FAA has been defined for the Otaki Forks Fault (RI Class III; >3500 to ≤5000 years).

In Palmerston North City (PNC), the active faults recognised and mapped are the Northern Ohariu and Tokomaru faults. FAZs have been defined for these active faults according to the MfE Guidelines. Two other features, the Forest Hill Road Fault and 'Turitea trace', are identified as "possibly active" faults. These two faults are provided with FAAs to acknowledge that they may be active (though they have no proven activity during the last 125,000 years). The location

of the axis of an active fold (the Pohangina Anticline) has been updated and defined within PNC as part of this study. However, as for the folds mentioned above, we do not present a FAZ for the Pohangina Anticline. An unnamed and inferred fault, which was shown sub-parallel to the axial trace of the Pohangina Anticline in the NZAFD, has no known surface trace in PNC. This fault will be removed from the NZAFD, and no FAZ is supplied for it.

Recurrence interval classes for active faults in Palmerston North City have been revised as follows: Northern Ohariu Fault (RI Class II; >2000 to ≤3500 years) and Tokomaru Fault (RI Class IV; >5000 to ≤10,000 years).

We recommend that the active fault mapping and FAZs developed for Horowhenua District and Palmerston North City during this study should be adopted for use with regards to future planning decisions. In the supplied GIS dataset, the FAZs are attributed according to their Fault Complexity: well-defined, distributed and uncertain, and according to Recurrence Interval Class. As outlined in the MfE Guidelines, this information, when combined with land use status (i.e., is the site a Greenfield site or an Already Developed/Subdivided site) and intended or existing Building Importance Category (BIC), provides a risk-based rationale for making land use planning decisions pertaining to the development of land close to, or on, active faults. To assist planners, Appendix 3 presents a suite of “test case” examples of how the MfE Guidelines can be applied for various combinations of Fault Complexity, Recurrence Interval Class, land use status and Building Importance Category.

We recommend that the MfE Guidelines be treated as a standard reference when considering resource consent applications in these districts. In addition, we recommend that GIS data for FAZs, which can be used at an individual property specific scale, be provided on LIM reports so that buyers and sellers of land can be made aware that a ground surface fault rupture hazard may exist on a given property.

1.0 INTRODUCTION

The southern North Island straddles the boundary between the Australian and Pacific tectonic plates (Figure 1.1 inset). This plate boundary is associated with large earthquakes, ground-surface fault rupture (causing permanent ground deformation), and volcanism. The area administrated by Horizons Regional Council (Horizons Region) straddles one of the more seismically active parts of this tectonic boundary zone, overlying the subducted Pacific Plate, and includes the North Island Dextral Fault Belt (NIDFB) and the transition to an area of extension in the north known as the Taupo Rift (Beanland 1995; Villamor and Berryman 2006a). The Horizons Region is crossed by numerous active crustal faults (and folds) that have ruptured and deformed the ground surface in the past. These faults include the Wellington, Northern Ohariu, Leedstown, Ohakune and Makuri-Waewaepa faults. Previous studies indicate that several of these faults, including the Wellington Fault, have a moderately high rate of activity (i.e. relatively short recurrence interval, on the order of 2000 years or less), and are capable of generating large earthquakes (moment magnitude M_w >7.0) associated with large (i.e. metre-scale) single-event ground surface rupture displacements (e.g., Langridge et al., 2006; Schermer et al., 2004; Van Dissen et al., 2003).

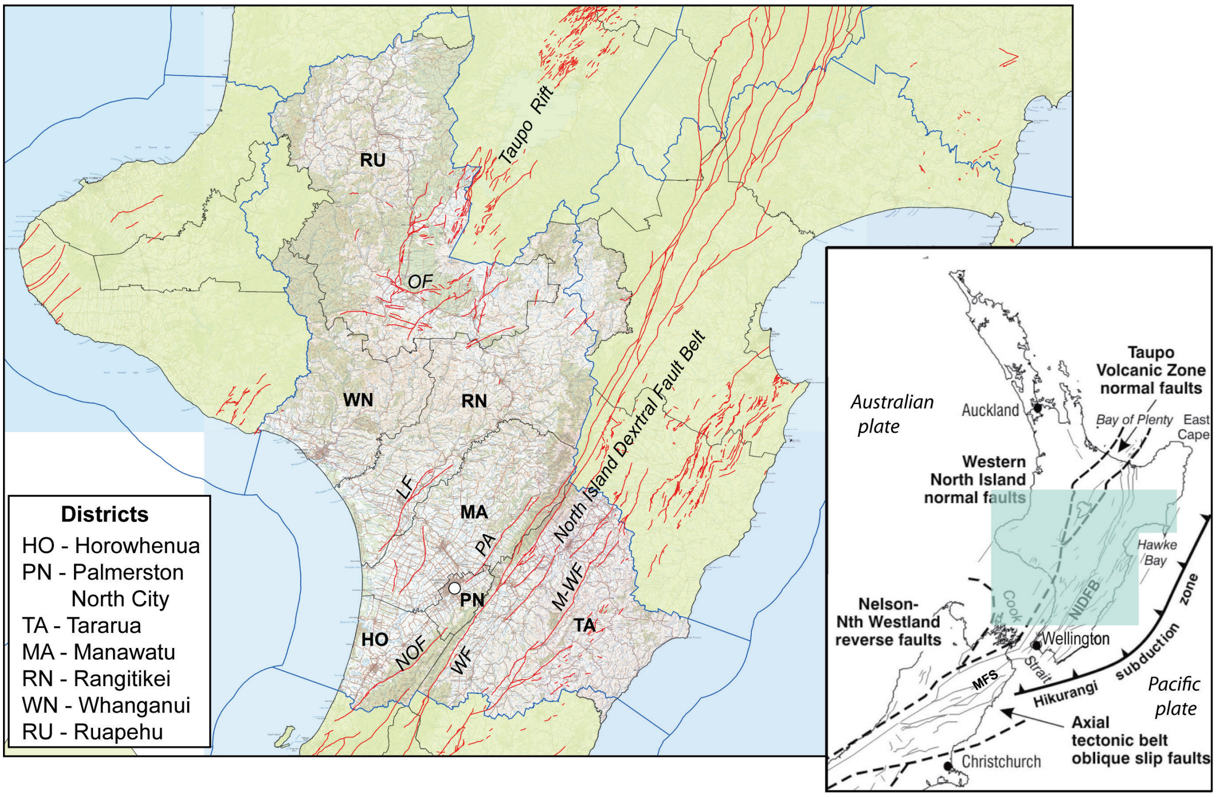


Figure 1.1 The area administered by Horizons Regional Council, showing its various districts.Onshore active faults (red) within the lower North Island area sourced from the New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al., 2016) prior to this studyFault names in italics are: LF, Leedstown Fault; NOF, Northern Ohariu Fault; M-WF, Makuri-Waewaepa Fault; OF, Ohakune Fault; and WF, Wellington Fault. Inset: Active tectonic map of central New Zealand with seismotectonic regions. NIDFB = North Island Dextral Fault Belt; MFS = Marlborough Fault System. Shaded area shows the location of the larger map.

Ground surface rupture of an active fault will result in a zone of intense ground deformation as opposite sides of the fault move past or over each other during an earthquake. Property damage can be expected, and loss of life may occur where buildings, and other structures, have been constructed across, or in the immediate vicinity of, the rupturing fault. In addition to the effects of strong ground motions, the 1931 Hawke's Bay, 1987 Edgecumbe, 2010 Darfield and 2016 Kaikōura earthquakes provide examples of the types of impacts caused by ground-surface fault rupture (e.g. Hull, 1990; Beanland et al., 1989; Van Dissen et al., 2011, 2018).

1.1 Scope of Work

GNS Science (GNS) have been contracted by Horizons Regional Council ('Horizons') to conduct a region-wide active fault and fold mapping programme in order to improve understandings of the effects of, and mitigation design for, hazards resulting from surface fault rupture deformation associated with large earthquakes. The fault mapping will be undertaken in a style that will facilitate application of the Ministry for the Environment's guidelines regarding "planning for development of land on or close to active faults" (hereafter called "the MfE Guidelines"; Kerr et al., 2003). This project builds upon, and supersedes, previous active fault studies in the region and the New Zealand Active Faults Database (NZAFD; https://data.gns.cri.nz/af/) coverage to date. The Horizons fault and fold mapping program has begun in the two southernmost districts within the Horizons Region: Horowhenua District and Palmerston North City. In coming years, this work will be extended to the other districts within the region.

The main objective for this work is to produce high-quality digital geospatial data and maps suitable for planning use at scales that are relevant to the current and expected future land use requirements in the Horizons Region. A significant improvement in the accuracy of mapping active faults is possible due to the advent and acquisition of airborne Light Detection and Ranging (LiDAR)-derived topographic data across much of the coastal plain and riverine areas (especially within Horowhenua and Palmerston North City), and analysis of LiDAR data within a Geographic Information System (GIS).

To improve understanding of the hazard posed from surface faulting and to update the quality of fault mapping for Horizons Region – with this report focusing on Horowhenua and Palmerston North City – the scope of work is as follows:

- Provide a review on active tectonics, seismicity and faulting in Horizons Region.
- Where airborne LiDAR-derived topographic data exists, map and attribute active fault traces at 1:10,000 scale or better. This effort has been facilitated by the acquisition of several airborne LiDAR datasets funded by Horizons and provided to GNS.
- Where LiDAR is not available or coverage is poor, incorporate active fault line work and attributes from other mapping studies, such as Begg and Johnston (2000); (i.e. part of the QMAP Geological Map of New Zealand Project; Heron, 2018), previous GNS reports, and review data within the NZAFD (1:50,000 to 1:250,000 scale).
- Improve the geospatial accuracy of fault line data upon review of previous mapping datasets and through use of georeferenced orthophotograph imagery within a GIS.
- Develop Fault Avoidance Zones (FAZ) based on the updated fault line data described above. The goal is to provide Horizons with up-to-date geospatial datasets that are valid for planning purposes and wholly compatible with application of the MfE Guidelines.
- Map active folds in order to better locate and characterise their tectonic activity[1].

[1] It may not be plausible to create avoidance zones for active folds, however, better characterisation of them is useful.

- Undertake a limited field review of active fault and fold features in order to attempt to better characterise recurrence interval information for active faults identified in the two districts.
- Provide an update on active fault recurrence interval data for Horowhenua District and Palmerston North City, where possible, so that more informed future research and planning decisions can be considered.
- Compile the results in this report and present those results to Horizons Region and District planning staff.

Chapter 2 of this report describes the tectonic and seismic character of the Horizons Region, including a record of historical earthquakes, district by district.

Chapter 3 introduces the fundamental elements of the MfE Guidelines. It also includes an introduction to what active faults and folds are, why they should be mapped for hazard purposes, outlining the history of recent active fault mapping in neighbouring regions. Chapter 3 concludes with a summary of previously known active fault recurrence interval information for the Horizons Region as relevant to the MfE Guidelines (Kerr et al., 2003).

Chapter 4 describes the methodologies used for fault and fold mapping, and how Fault Avoidance Zones (FAZs) were developed and attributed according to the Fault Complexity terms defined in the MfE Guidelines (i.e. well-defined, distributed, uncertain), fault activity (recurrence of fault rupture), building type (single storey timber framed house, cinemas, hospitals etc.), and resource consent activity status in relation to these three parameters.

Chapter 5 deals specifically with results and implications for active faults and folds within Horowhenua District and provides updated recurrence intervals for each of the active faults.

Chapter 6 deals specifically with results and implications for active faults and folds within Palmerston North City and provides updated recurrence intervals for each of the active faults.

Chapter 7 provides a summary of the results of this work, and Chapter 8 contains recommendations for implementing this work in future planning decisions.

The appendices to this report provides a background of styles of faulting throughout the Horizons Region, with descriptions of different types of geologic faults, and examples of how the MfE Guidelines could be applied in real world examples.

The report is accompanied by digital geospatial data including active fault mapping and Fault Avoidance Zones (polygons), as well as data on locations of fold axes. These should facilitate the direct incorporation of Fault Avoidance Zones into District Plans, which, in turn, will facilitate application of the MfE Guidelines and provide a rational, risk-based approach for dealing with land use decisions pertaining to the development of land on, or close to, active faults.

2.0 HORIZONS REGION

The Horizons Region includes seven Territorial Authorities that span an area encompassing many different landscape types across the central to southern North Island (Figure 1.1). The physiography of the region is diverse and varied. In the north, the region borders onto the extensional Taupo Rift and Volcanic Zone (Villamor and Berryman, 2006a, b) in the Ruapehu District. In the southwestern North Island, large rivers drain from the elevated central and southern parts of the island across a broad coastal plain (e.g. Whanganui, Rangitikei, Palmerston North and Manawatu districts). These settings extend and taper into the southern part of the Horizons Region, covering the Horowhenua District and Palmerston North City. Lastly, in the southeast, Tararua District covers an area from the elevated Tararua Ranges to the east coast of the North Island.

The primary earthquake hazards include seismic shaking (ground motion), ground-surface fault rupture, uplift, liquefaction, earth movement (e.g. rock fall and landslides), subsidence, and tsunami. This report focuses on active fault mapping in Horowhenua District and Palmerston North City and deals with the hazards relating to ground surface fault rupture deformation, including surface faulting and folding. This report also focuses on the effects/impacts of surface fault rupture on the built environment, specifically in terms of planning for, and mitigating against, the impacts of surface fault rupture hazard. To augment this discussion of earthquake hazard, we also present a compilation of large historical earthquakes in these districts.

2.1 Tectonic Setting

The lower North Island straddles the Australia-Pacific plate boundary which, at the location of the Horizons Region, forms part of the Hikurangi Subduction Margin (HSM). Figure 2.1 shows a plate-scale cross-section across the region. The HSM comprises: a subduction interface (the fault between the down-going Pacific Plate and the overlying Australian Plate); a forearc dominated by reverse, oblique and strike-slip faulting; axial ranges dominated by strike-slip, oblique and reverse faulting; a volcanic arc dominated by normal faulting (not indicated in figure); and a back-arc region dominated by reverse faulting and folding (Berryman and Beanland, 1991; Little et al., 2009). Thus, a diverse suite of active tectonic styles of faulting and deformation[2] is reflected in the broad area covered by Horizons Region.

Technically, the largest fault in the region is the Hikurangi subduction interface (HSI; Figure 1.1 and Figure 2.1), where the Pacific plate subducts to the northwest under the Australian plate, beneath the North Island. The HSI is considered capable of generating a ‘great’ earthquake (M_W >8) and possibly a megaquake (M_W >9). In such a scenario, surface rupture of the HSI (i.e. as a gently-dipping thrust fault) would occur at the seafloor off the east coast of Tararua District (Figure 2.1) and a significant tsunami would be generated that would impact the east coast. In addition, a magnitude M_W 8–9 earthquake on the HSI would generate severe ground shaking throughout much of the central New Zealand and beyond.

[2] Descriptions and diagrams of these types and styles of faulting are described in Appendix 1.

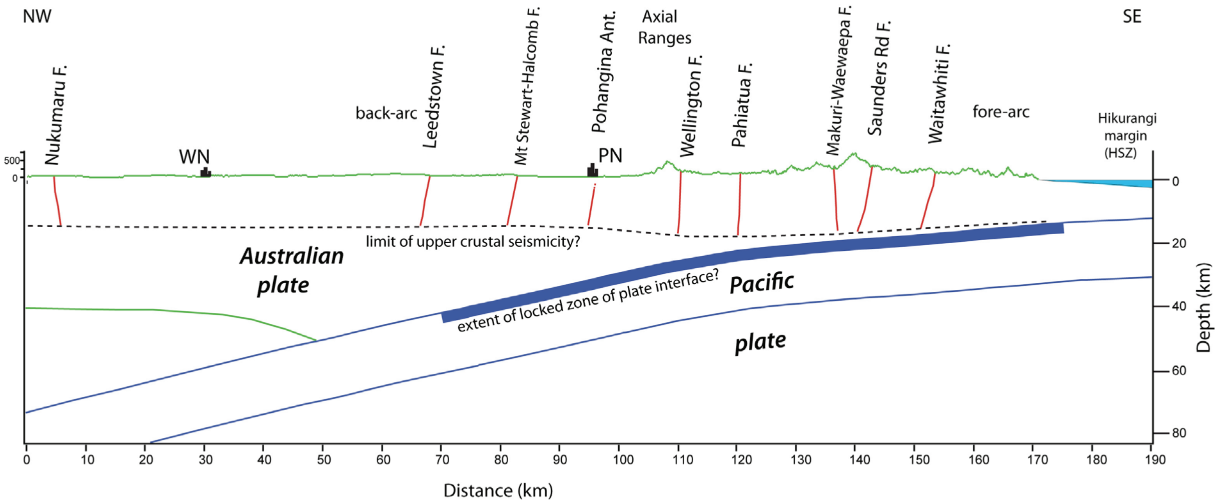


Figure 2.1 Simplified tectonic cross-section of the Horizons Region from offshore of Akitio in the east to near Whanganui (WN). The cross-section intercepts several well-known active upper crustal faults and includes the Hikurangi subduction zone (HSZ). The location of Palmerston North (PN) is also indicated. Ant, anticline; F, fault.

2.2 Regional and Historical Seismicity

The Horizons Region has a well-documented record of historical earthquakes that have been both damaging and destructive. Figure 2.2 shows the epicentres of shallow (<30 km depth) historical earthquakes with magnitude M_w >6 throughout central New Zealand. These represent significant earthquakes that caused shaking damage and for a subset of these events, ground surface-rupturing earthquakes. The Horizons Region boundary is shown in dark blue to highlight large earthquakes that have occurred within or close to the region itself.

From 1840 to 1870 three significant large earthquakes impacted the region. Firstly, in July 1843, a M_W ~7.6 earthquake, formerly the 'Wanganui earthquake' occurred – it was so called because of the heavy damage it caused in Wanganui (Downes, 1995). A more recent historical earthquake compilation that includes shaking intensity reports from further afield, places the epicentral area of this event in the axial ranges of Hawke's Bay. Thus, this 1843 event has been renamed the Western Hawke's Bay earthquake (Downes and Dowrick, 2014).

Downes and Dowrick (2014) offer two suggestions for the possible location of the epicentre of the 1855 M_W 8.1 Wairarapa earthquake. One of these possible locations is in South Wairarapa c. 50 km south of Horowhenua District. Shaking intensities of Modified Mercalli Intensity (MMI) 7–9 were recorded in Horowhenua and Wanganui in the 1855 earthquake (Downes and Dowrick, 2014).

In February 1863, the M_W ~7.5 Waipukurau earthquake occurred, and is believed to have originated on a reverse fault in the vicinity of Waipukurau (Grouden, 1966; Downes and Dowrick, 2014). The 1863 earthquake produced strong ground motions across the region, particularly in Tararua District.

In June 1881 a magnitude M_W 6.7 earthquake occurred, with an epicentre very close to Palmerston North where it was strongly felt.

The August 1904 Cape Turnagain earthquake was a shallow (16 km) M_W 7.2 earthquake that caused heavy regional damage to the landscape and personal property and resulted in one death. Shaking intensities (MMI 8–9) were most strongly felt on the eastern coast of Tararua

District near Cape Turnagain. Shaking intensities decreased in all directions form this area but ranged from MMI 5–7 across much of Horizons Region.

The August 1917 M_W 6.8 Castlepoint (Tinui) earthquake was felt throughout the North Island, being most strongly felt (MMI 7–8) near Castlepoint. Shaking intensities ranged from MMI 5–7 across much of the southern part of Horizons Region in this event.

During the first half of the 20th century, Hawke's Bay and surrounding regions were rocked by a number of large earthquakes, including the 1931 M_W 7.6 Hawke's Bay earthquake which killed 256 people and destroyed the cities of Napier and Hastings. During this event, felt intensities of 'damaging' to 'very damaging' (MMI 6–7) were reported across the Horizons Region. The Hawke's Bay earthquake was followed by a damaging aftershock in 1931 and the 1932 M_W 6.9 Wairoa earthquake (Figure 2.2).

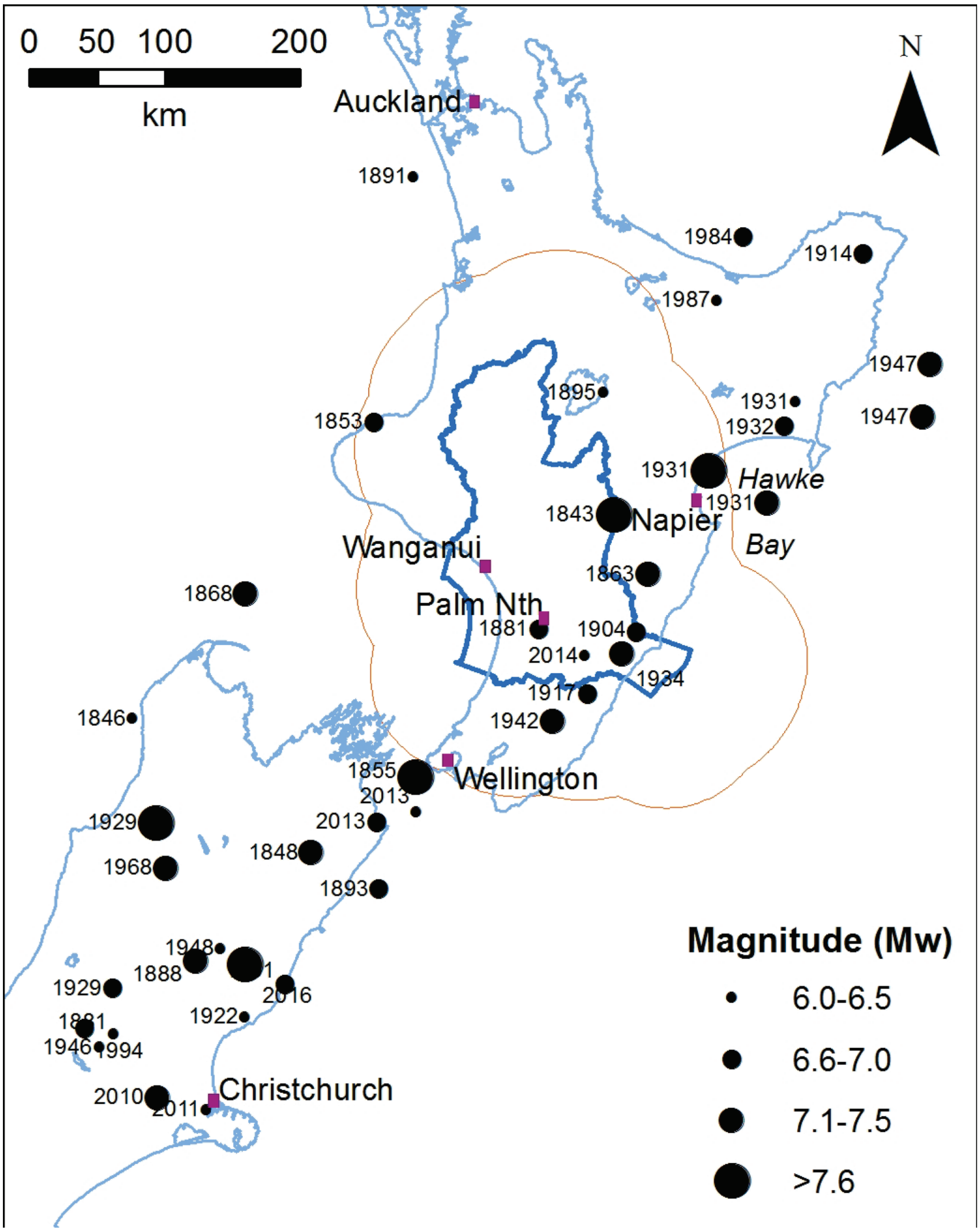


Figure 2.2 Epicentres of significant shallow (< 30 km depth) earthquakes in central New Zealand that have occurred since 1843.highlighted in dark blue and the red line is an area that extends a further 75 km around the region to consider impacts from earthquakes outside of the region. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

The 1934 M_W 7.4 Pahiatua (Horoeka) earthquake is probably the best example of a large earthquake in the Horizons Region that caused ground surface rupture. Geologic studies show that this earthquake caused surface rupture on the Waipukaka Fault, which had at least two other Holocene surface rupturing earthquake events (Schermer et al., 2004). The earthquake caused extensive damage from the northern Wairarapa to Hawke's Bay, particularly between Porangahau and Castlepoint. The worst damage was noted in Pahiatua, the largest town near the earthquake epicentre. There were no deaths caused by this earthquake, although one person required hospitalisation.

In 1942, two earthquakes shook the lower North Island on 24 June and 2 August. They were large and shallow with the epicentres located close together east of Masterton in the Wairarapa area. The June earthquake was sometimes referred to as the Masterton earthquake, but both caused damage over a wide area, from Dannevirke and Eketahuna to Wellington, Whanganui and Otaki. There was one death in Wellington relating to the 24 June earthquake (Downes 1995; Schermer et al. 2004).

The largest earthquake to occur within the Horizons Region this century was the 2014 M_W 6.2 Eketahuna earthquake (Figure 2.2 and Figure 2.3). This event occurred at a depth of c. 34 km and was felt strongly across the country, from Auckland to Dunedin, with more than 9,000 reports submitted by the public to GeoNet. The Eketahuna earthquake resulted in three injuries. Ground motions at Hokowhitu Lagoon in Palmerston North were reported to have caused damage leading to water leaking away from the oxbow lagoon into the subsurface.

As a comparison to the record of large historical earthquakes in Figure 2.2, Figure 2.3 shows the seismicity of the Horizons Region over the last 5 years (August 2013 to August 2018). The seismicity ($M > 2.6$; depth < 40 km) shows almost 2000 earthquakes, and apart from the M_W 6.2 Eketahuna earthquake and its aftershocks, the map also highlights clusters of seismicity related to the HSM and local earthquake swarms, including a long-lived swarm offshore of Whanganui.

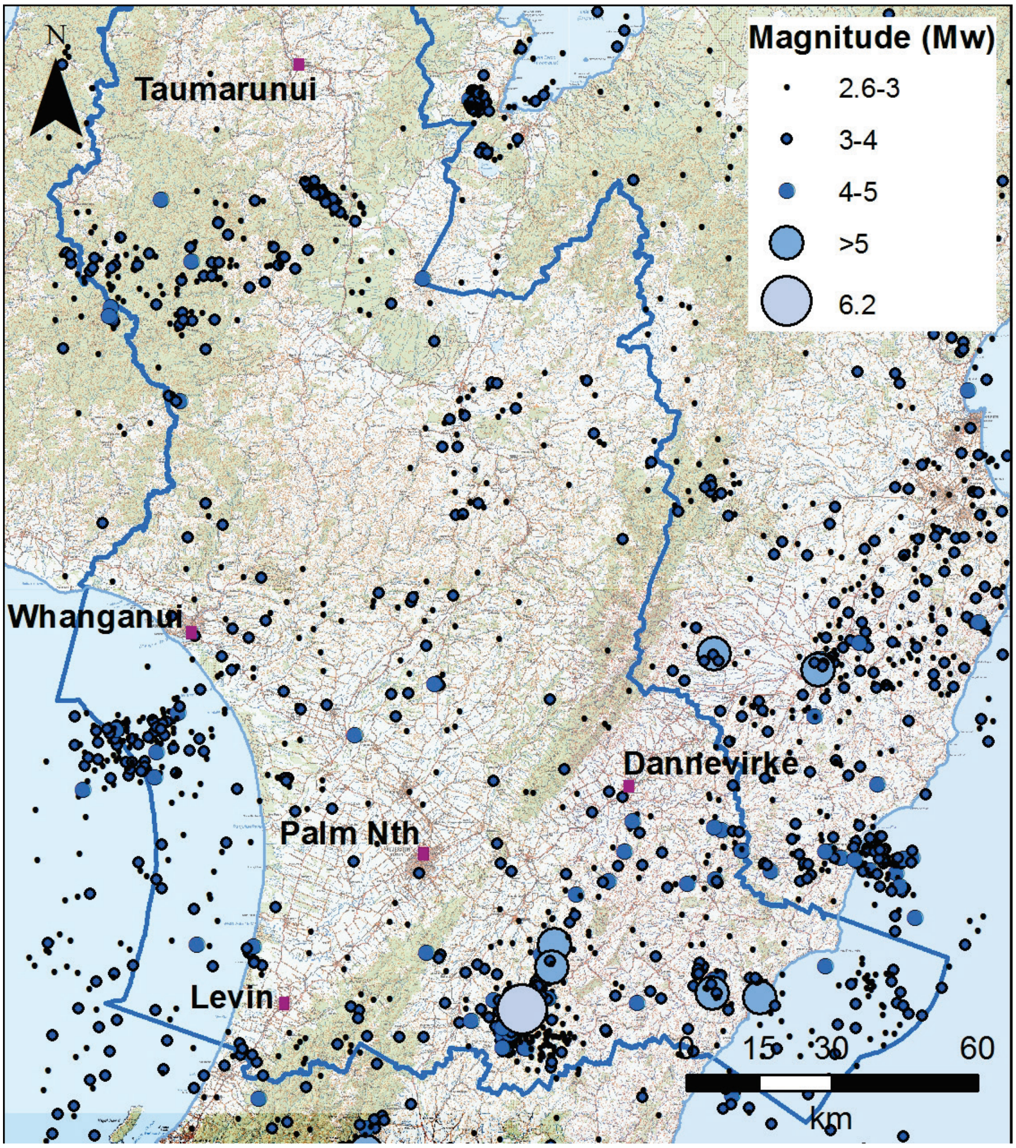


Figure 2.3 Epicentral locations of shallow (<40 km) earthquakes of M_w >2.6 that occurred between August 2013 and August 2018 in the Horizons Region (marked in dark blue) and the surrounding areas.Earthquakes are colour coded in magnitude bands. The largest event is the 2014 M_w 6.2 Eketahuna earthquake. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

3.0 ACTIVE FAULTS AND THE MFE GUIDELINES

The Horizons Region has a large number of active faults, which have previously been mapped mostly at scales of >1:10,000 (1:250,000 - see Heron 2018, or 1:50,000 - Langridge et al., 2016 - NZAFD; http://data.gns.cri.nz/af/) (Figure 1.1). The locations of active faults mapped at scales of >1:10,000 have significant locational uncertainty and accordingly have more limited use for planning purposes. This project draws on the significant coverage of airborne LiDAR across the southern part of the Horizons Region (in Horowhenua and Palmerston North City) to refine active fault locations and to produce Fault Avoidance Zones that can be utilised within the risk-based planning context of the MfE Guidelines (Kerr et al. 2003).

3.1 What is an Active Fault?

Active faults are those faults considered capable of generating strong earthquake shaking and ground surface fault rupture. Ground surface-rupturing earthquakes are typically of magnitude M_w >6.5. An active fault is generally defined within the NZAFD (https://data.gns.cri.nz/af/) as one which has deformed the ground surface within the past 125,000 years (Langridge et al. 2016). This is defined in part for practical reasons as faults which deform marine terraces and alluvial surfaces which formed during the ‘peak Last Interglacial period’ or Marine Isotope Stage (MIS) 5e, or younger (MIS 1–4; e.g. Alloway et al. 2007). These MIS 5e surfaces form a useful datum throughout New Zealand and therefore a pragmatic choice for the definition of activity.

The purpose of this section is to introduce how active faults express themselves, i.e. their behaviour, styles of deformation, activity and geomorphic expression. Active faults are expressed in the landscape as linear traces displacing surficial geologic features which may include hillslopes, alluvial terraces and fans. The age of these displaced features can be used to define how active a fault is. Typically, in New Zealand, alluvial terraces are associated with contemporary river drainages, and therefore they are often <30,000 years old (e.g. Litchfield and Berryman 2005). Hillslopes are mainly formed in bedrock and in New Zealand these surfaces have generally been modified by glacial or cold climate processes during the peak of the Last Glacial period (Barrell et al., 2011). This means that well-defined, linear fault traces that cut across bedrock hillslopes are probably also less than c. 30,000 years old.

Active faults are often defined by a fault scarp. A fault scarp is formed when a fault displaces or deforms a surface and produces an abrupt linear step, which smooths out with erosion over time to form a scarp (Figure 3.1). In some cases, where a fault moves horizontally rather than vertically, surface features such as streams may be deflected, but only a linear trace or furrow may be observed along the fault trace. Traditionally, faults have been mapped from aerial photographs using stereoscopy, i.e. pairs of overlapping aerial photographs that can be used to visualise the ground surface in 3D. The acquisition of airborne LiDAR used to develop Digital Elevation Models (DEM’s) have greatly improved the accuracy to which active fault traces can be mapped (Meigs, 2013; Langridge et al., 2014).

An expanded description of the main styles of active faulting is presented in Appendix 2. This includes a description of strike-slip, reverse and normal dip-slip faults, and also oblique-slip faults where there is both a significant strike-slip and dip-slip component of motion.

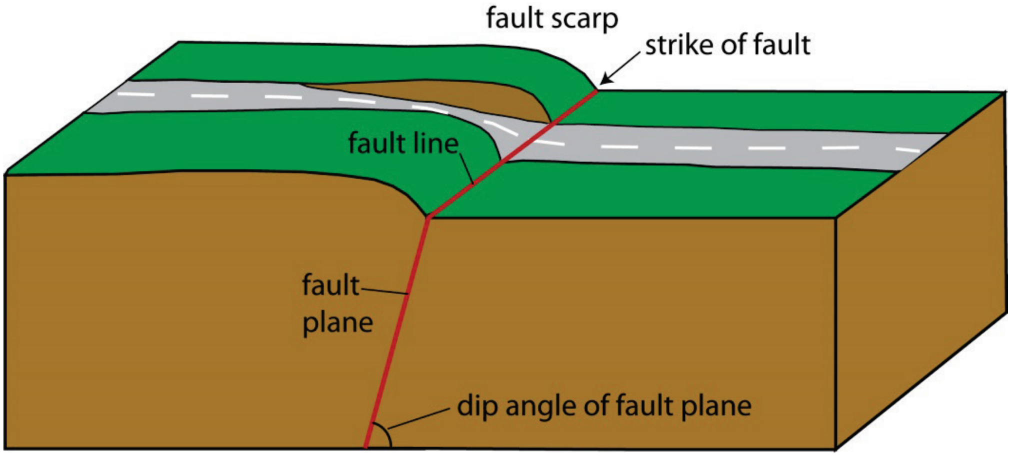


Figure 3.1 Block model of a generic active fault (shown in red).Fault displacement produces a scarp with offset features along the projection of the fault plane at the Earth's surface (fault line or trace).

3.2 What is an Active Fold?

Active folds are mappable, warped parts of the ground-surface landscape. Active folds are commonly found in association with buried active reverse faults, where the upper tip of the reverse fault (see section A2.2) does not extend to the Earth's surface. In such a case, a geomorphic and/or bedrock surface is warped or buckled on the upper (hanging-wall) side of the buried fault tip (Figure 3.2). Folds that form positive relief are termed anticlines and folds that form subsided relief are called synclines. The crest of the raised part of an anticline forms a fold axis, which can sometimes be mapped because, for example, streams will flow away from the axis in either direction down the fold limbs (Figure 3.2; Stevens, 1990; Clement et al., 2017). Anticlines can take on various geomorphic forms, such as broad, gentle, tight, symmetric and asymmetric. Broad, gentle and tight folding refer to the angle between the limbs of the fold, which may also relate to the degree of activity on a structure. Symmetric and asymmetric folding refer to the shape of the fold, where the asymmetry of the fold relative to the axial surface[3] (e.g. one limb being steeper and/or shorter than the other) can provide some information on the dip and dip direction of the buried fault it is related to.

The southern and central parts of the Horizons Region encompass several asymmetric anticlines, that typically deform Late Quaternary fluvial and near-shore sediments (e.g. Jackson et al., 1998; Clement and Fuller, 2018) and form topographic highs or domes. For example, the Pohangina, Himitangi, Shannon and Levin anticlines and the 'Poroutawhao High' (Clement et al. 2017) have been previously mapped and are included as large earthquake sources in the New Zealand National Seismic Hazard Model (NSHM; Stirling et al., 2012).

[3] An axial surface is an imaginary surface that connects the hinge lines in a fold; it is called an axial plane when the surface is planar, connecting many folded beds within a fold.

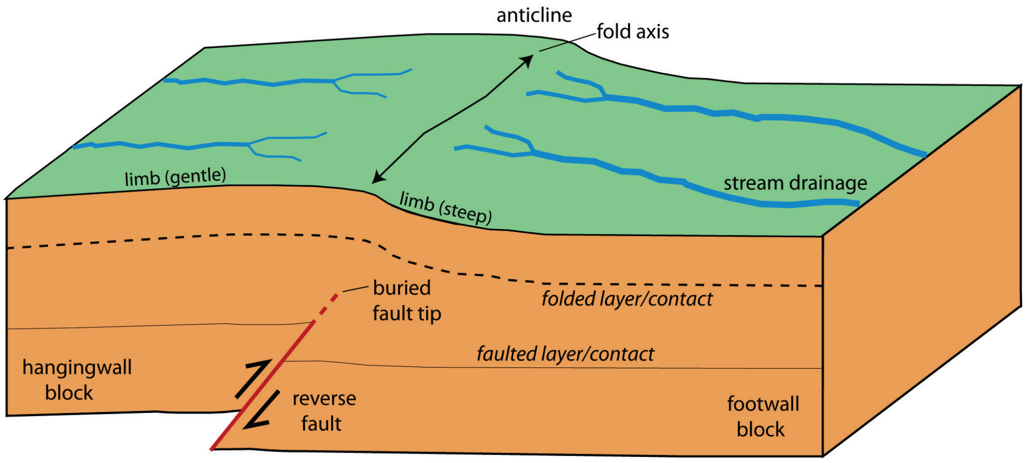


Figure 3.2 Block model of an anticlinal fold that is related to a buried active reverse fault.Motion on the fault has driven upwards the hanging-wall block and folded the ground surface above the fault tip. The fold is asymmetric and defined at the surface by a fold axis and by the stream drainage pattern, where streams drain away from the fold axis. The scale and depth to the fault tip is not specified.

3.3 MfE Guidelines for Development of Land on or Close to Active Faults

In 2003, the Ministry for the Environment (MfE) published guidelines on *"Planning for Development of Land on or Close to Active Faults"* (Kerr et al., 2003, see also King et al., 2003; Van Dissen et al., 2003), i.e. the "MfE Guidelines". The aim of the MfE Guidelines is to assist resource management planners tasked with developing land-use policy and making decisions about development of land on, or near, active faults. The MfE Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas that are subject to fault rupture hazard. The MfE Guidelines are designed primarily for life safety purposes, however, what has increasingly become relevant to councils and landowners is post-event functionality of built structures, i.e. built structures that can still be safely occupied or used after a natural disaster event.

The main elements of the risk-based approach presented by the guidelines are:

1. Fault characterisation relevant to planning for development across fault lines which focuses on: a) accurate location of faults (including "fault complexity", i.e., the distribution and deformation of land around a fault line); b) definition of Fault Avoidance Zones, and; c) classification of faults based on their recurrence interval (i.e. the time interval between large, surface-rupturing earthquakes on the same fault), which is an indicator of the likelihood of a fault rupturing in the near future.
2. The Building Importance Category (BIC), which indicates the acceptable level of risk of different types of buildings within a Fault Avoidance Zone.

For these reasons our report focuses on aspects of accurate fault location, definition of fault complexity and fault recurrence interval and recommendations pertinent to the MfE Guidelines.

Extensive active fault mapping with a view toward developing Fault Avoidance Zones has already been undertaken in other regions of New Zealand (Figure 1.1), including Greater Wellington (e.g., Litchfield and Van Dissen 2014; URS 2006; Van Dissen and Heron 2003; Zachariasen et al. 2000; Begg et al. 2001; Townsend et al. 2002) and Hawke's Bay (e.g. Clark and Ries, 2016; Langridge and Ries 2014, 2015; Langridge et al. 2006; 2011) regions in the North Island, and Canterbury (Barrell 2015; Barrell and Townsend 2012;), West Coast (e.g. Langridge and Ries, 2008) and Marlborough (Langridge and Ries 2008) regions in the South Island.

3.4 Active Fault Recurrence Interval and the MfE Guidelines

Six Recurrence Interval Classes (RI Class) are defined within the MfE Guidelines (Table 3.1). The MfE Guidelines are designed around a hierarchical relationship between recurrence interval and building importance, such that the greater the importance of a structure, with respect to life safety, the longer the recurrence interval needs to be for that building to be permissible. For example, only low occupancy or risk structures, such as farm sheds and fences (e.g. BIC 1 structures), are recommended within the MfE Guidelines as permissible to be built across active faults with average recurrence intervals of surface rupture less than 2000 years. In a “Greenfield” (i.e. undeveloped) setting, more significant structures such as schools, airport terminals, and large hotels (BIC 3 structures) should not be sited across faults with average recurrence intervals shorter than 10,000 years (i.e. RI Class ≤ IV).

Table 3.1 Definition of Recurrence Interval (RI) classes (from Kerr et al. 2003).

RI Class	Average recurrence interval of surface rupture
I	≤2000 years
I	>2000 to ≤3500 years
III	>3500 to ≤5000 years
IV	>5000 to ≤10,000 years
V	>10,000 to ≤20,000 years
VI	>20,000 to ≤125,000 years

3.4.1 Pre-existing Recurrence Interval Data for the Horizons Region

Because of its relevance to the application of the MfE Guidelines, it was deemed important to summarise the current state of knowledge regarding the recurrence intervals of faults in the Horizons Region at the beginning of this project. These are summarised in Table 3.1. These data come from geologic studies (e.g. Jackson et al., 1998; Langridge et al., 2007; Villamor and Berryman, 2006a, b), many of which are from Van Dissen et al. (2003). In many cases, there is little or no geological data related to named or unnamed faults, in which cases estimates are developed based on the amount of landscape deformation that has occurred or from visual comparisons with other faults in the region that have better defined levels of activity or deformation. Overall, the recurrence interval data have large uncertainties, except where fault-specific paleoseismic studies have been undertaken (Van Dissen et al., 2003). In some areas, such as Horowhenua District and Palmerston North City there are few faults that have recurrence interval data (see Chapters 5 and 6), despite some of them being active fault sources in the NSHM (Stirling et al., 2012).

Within the region most of the RI Class I (RI ≤2000 years) faults that occur are in Tararua and Ruapehu districts. These are associated with the NIDFB and Taupo Rift, respectively. Some faults in these two districts have moderate slip rates (e.g. Ruahine, Makuri-Waewaepa and the Raetihi North and South faults) and these fall into RI Class II (>2000 to ≤3500 years). Faults with lower slip rates (e.g. Waitawhiti, Ruataniwha, Leedstown and Nukumaru faults) typically fall into RI Classes III and IV.

The RI Class Confidence is a measure of the quality of the geological data which is used to assess the fault recurrence interval (Table 3.1; Van Dissen et al., 2003). Some faults have detailed slip rate and/or paleoseismic trenching studies that define the RI Class quite well, while other faults recurrence intervals are qualitatively based on landscape and geomorphic inferences. Often when a fault recurrence interval is calculated from geologic data the results may span more than one of the recurrence interval classes, e.g. a fault with a recurrence interval range of 1500–4000 years overlaps RI Classes I, II and III. In such a case the mean recurrence interval may be interpreted as being RI Class II, however, the confidence in that result is diminished because of the relatively poor constraints from geology.

Data in Table 3.2 will be reviewed and updated as better geologic data are gained through future paleoseismic studies. For example, our current data in Table 3.1 contains only two active faults (Northern Ohariu and Otaki Forks faults) with a defined RI Class in Horowhenua or Palmerston North City.

Table 3.2 Fault recurrence interval (RI) data for faults within the Horizons Region* (modified from Van Dissen et al., 2003).

Fault	**District**	**RI Class and range (years)**	**RI Class Confidence**	**Source**
		I (≤2000)		
Alfredton Fault, Wellington Fault, Waipukaka Fault	Tararua		M	1, 2
Mohaka Fault	Tararua, Manawatu		M	1, 2
Dreyers Rock/Kowhai Fault	Tararua		M	1, 2
Waihi Fault	Ruapehu		M	1–3
Snowgrass Fault	Rangitikei, Ruapehu		M	2, 3
Ohakune Fault, Rangipo Fault, Shawcroft Rd Fault, Karioi Fault, National Park Fault, Raurimu Fault	Ruapehu		M	2, 3
		II (>2000 to ≤3500)		
Saunders Rd Fault, Pa Valley Fault, Makuri-Waewaepa Fault, Weber Fault	Tararua		L	1, 2
Ruahine Fault	Tararua, Manawatu		L	1, 2
Hihitahi Fault	Ruapehu		L	1, 2
Raetihi North Fault Raetihi South Fault	Ruapehu		L	1–3
Northern Ohariu Fault	Horowhenua, PNCC		L	1, 2
		III (>3500 to ≤5000)		
Otaki Forks Fault	Horowhenua		L	1, 2
Maunga Fault	Tararua		L	1, 2
Waitawhiti Fault	Tararua		L	1, 2

Fault	District	RI Class and range (years)	RI Class Confidence	Source
Kaweka Fault	Rangitikei		L	1, 2
Ruataniwha Fault	Tararua		L	1, 4
Rangefront Fault Oruawharo Fault	Tararua		L	1, 2, 4
Waipukurau Fault (Zone)	Tararua		L	1, 2, 5
		IV (>5000–≤10,000)		
Mangaoranga Fault	Tararua		L	1, 2
Leedstown Fault	Rangitikei, Manawatu		L	2
Nukumaru Fault	Whanganui		L	1, 2

3.5 Building Importance Category and the MfE Guidelines

Buildings sited within a fault avoidance zone, particularly building crossing active faults, are very likely to be damaged in a fault rupture event. A Building Importance Category (BIC) states the relative importance of assessing the suitability of a building within, or proposed for, a fault avoidance zone (Kerr et al, 2003). The categories in Table 3.3 are modified from the New Zealand Loading Standard classifications and are based on risk levels for building collapse according to building type, use and occupancy. Category one (BIC 1) carries the lowest importance; category the highest importance. Table 3.2 shows a distinction between BIC 2a (e.g. single storey timber-framed dwellings that are common throughout New Zealand) and BIC 2b (which are defined as ‘normal’ structures).

For the MfE Guidelines, a distinction is also made between ‘previously subdivided or developed areas’ and greenfield sites’. Councils can use BIC categories to make decisions about resource consents and to require conditions on buildings within fault avoidance zones (see Appendix 3). Table 3.4 shows the relationship between the fault rupture recurrence interval and BICs in previously subdivided or developed areas, and in greenfield sites (Kerr et al, 2003).

Table 3.3 Building Importance Categories and representative examples. For more detail see Kerr et al. (2003), and King et al. (2003).

Building Importance Category	Description	Examples
1	**Temporary structures** with low hazard to life and other property	• Structures with a floor area of <30m^2 • Farm buildings, fences • Towers in rural situations
2a	**Timber-framed** residential construction	• Timber framed single-story dwellings
2b	**Normal structures** and structures not in other categories	• Timber framed houses with area >300 m^2 • Houses outside the scope of NZS 3604 “Timber Framed Buildings” • Multi-occupancy residential, commercial, and industrial buildings accommodating <5000 people and <10,000 m^2 • Public assembly buildings, theatres and cinemas <1000 m^2 • Car parking buildings
3	**Important structures** that may contain people in crowds or contents of high value to the community or pose risks to people in crowds	• Emergency medical and other emergency facilities not designated as critical post disaster facilities • Airport terminals, principal railway stations, schools • Structures accommodating >5000 people • Public assembly buildings >1000 m^2 • Covered malls >10,000 m^2 • Museums and art galleries >1000 m^2 • Municipal buildings • Grandstands >10,000 people • Service stations • Chemical storage facilities >500m^2
4	**Critical structures** with special post disaster functions	• Major infrastructure facilities • Air traffic control installations • Designated civilian emergency centres, medical emergency facilities, emergency vehicle garages, fire and police stations

Table 3.4 Relationships between Recurrence Interval Class, Average Recurrence Interval of Surface Rupture, and Building Importance Category for Previously Subdivided and Greenfield Sites. From Kerr et al. (2003).

<table>
<tr><th rowspan="2">Recurrence Interval Class</th><th rowspan="2">Average Recurrence Interval of Surface Rupture</th><th colspan="2">Building Importance (BI) Category Limitations (allowable buildings)</th></tr>
<tr><th>Previously subdivided or developed sites</th><th>“Greenfield” sites</th></tr>
<tr><td>I</td><td>≤2000 years</td><td>BI Category 1
temporary buildings only</td><td rowspan="2">BI Category 1
temporary buildings only</td></tr>
<tr><td>II</td><td>>2000 years to
≤3500 years</td><td>BI Category 1& 2a
temporary & residential timber-framed buildings only</td></tr>
<tr><td>III</td><td>>3500 years to
≤5000 years</td><td>BI Category 1, 2a, & 2b
temporary, residential timber-framed & normal structures</td><td>BI Category 1& 2a
temporary & residential timber-framed buildings only</td></tr>
<tr><td>IV</td><td>>5000 years to
≤10,000 years</td><td rowspan="2">BI Category 1, 2a, 2b & 3
temporary, residential timber-framed, normal & important structures (but not critical post-disaster facilities)</td><td>BI Category 1, 2a, & 2b
temporary, residential timber-framed & normal structures</td></tr>
<tr><td>V</td><td>>10,000 years to
≤20,000 years</td><td>BI Category 1, 2a, 2b & 3
temporary, residential timber-framed, normal & important structures (but not critical post-disaster facilities)</td></tr>
<tr><td>VI</td><td>>20,000 years to
≤125,000 years</td><td colspan="2">BI Category 1, 2a, 2b, 3 & 4
critical post-disaster facilities cannot be built across an active fault with a recurrence interval ≤20,000 years</td></tr>
<tr><td colspan="4">Note: Faults with average recurrence intervals >125,000 years are not considered active</td></tr>
</table>

4.0 METHODOLOGY OF FAULT MAPPING

4.1 Data Used for Fault and Fault Avoidance Zone Mapping

Active fault traces have been mapped using a combination of LiDAR DEM and hill-shade models, a national scale (8-m) DEM, and by adopting linework from the NZAFD and QMAP geologic mapping programme. There is a large difference between the locational accuracy of mapped fault traces when comparing LiDAR with either the 8-m DEM, QMAP or NZAFD data. This is a function of the scale with which the fault trace has been mapped and digitised, i.e. LiDAR typically 1: 5,000 to 1: 10,000, and QMAP/NZAFD at 1: 50,000 to 1:250,000 scale.

For current land use planning in regard to building on or adjacent to active faults, particularly in developed and developing areas (e.g. Begg et al., 1994), it is not appropriate to use features 'mapped' at scales of 1: 50,000 (or larger), because their locations are considered too imprecise. During the last decade, several campaigns of airborne LiDAR acquisition have been flown across the southern part of Horizons Region (Figure 4.1). These acquisitions cover parts of the Horowhenua coastal plain, Palmerston North urban area, and the Manawatu and Rangitikei river floodplains. From these data, high quality 1-m DEMs have been developed. The raw data from all acquisitions were supplied to GNS by Horizons in New Zealand Map Grid 1949 projection. These data were re-projected into New Zealand Transverse Mercator 2000 projection and DEMs were interpolated so that they can uniformly produce 1-m DEMs.

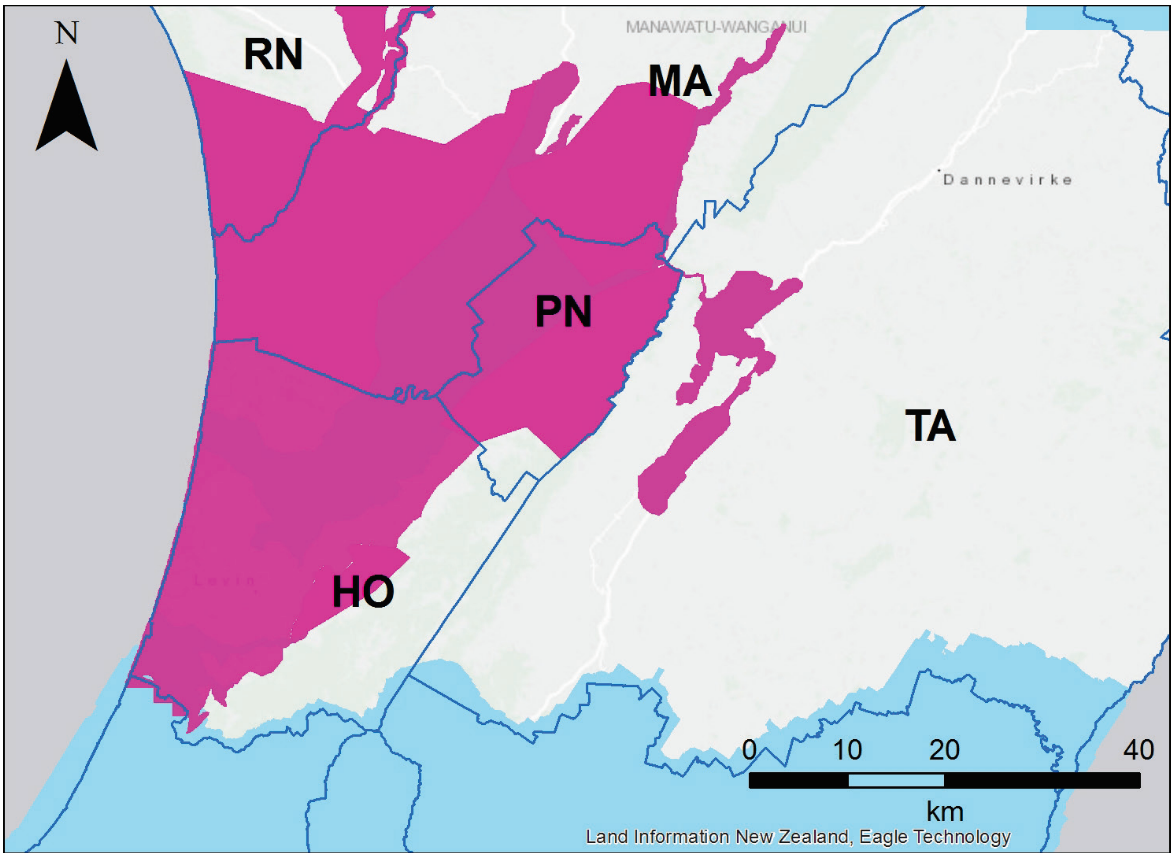


Figure 4.1 Airborne LiDAR coverage across the southern part of the Horizons Region up to 2016 (pink shading). LiDAR coverage across Wellington (GWRC) and Hawkes Bay (HBRC) regions is shown in blue.

Where no LiDAR coverage exists, however, the locations of active faults have been assessed using existing mapping from the Wellington and Wairarapa geologic maps (Begg and Johnston, 2000; Lee and Begg, 2002). In these areas the QMAP linework has been compared with data already in the NZAFD for presence, accuracy, and continuity of fault trace information, and in some cases, has been revised.

4.2 Mapping Fault Lines in a GIS

For this study, the location and attributes of active faults have been assembled in a GIS and recorded in a digital geospatial database (provided as supplementary to this report). The Attributes listed in the GIS Attribute Table are:

Fault_name, **Accuracy, RI_Class, Activity, Fault_complexity**, DOWN_QUAD, Method, DOM_SLIPTYPE, *Deform_width*, *Buffer_dist* and setback. For application of the MfE Guidelines, including developing a FAZ, the most important of these are highlighted in bold. The Accuracy and Fault_complexity is used to define the Deform_width, and Buffer_dist (in italics) which dictate the width of the FAZ. A Data Dictionary defining these attribute terms is contained in Table 4.1.

The digitising of active faults requires expert recognition of tectonically displaced geomorphic landforms and an understanding of the local geology. The most obvious landform feature associated with ground-surface fault rupture is a fault scarp (e.g. Figure 3.1). Photographic examples of fault scarps are included in Chapter 5 of this report. Fault scarps are steps in the land surface that coincide with the locations of faults. They can extend for hundreds of metres in length and are often many metres wide. Therefore, representing a scarp as a line within a GIS is simplistic. In theory, a line within a GIS database has a width of zero and is meant to represent the location where it is estimated the fault would rupture the ground surface. Active faults are therefore more appropriately defined as zones of ground deformation rather than lines. This is because of the location uncertainty of digitising or surveying a line, the lack of knowledge on the exact location of the fault plane (unless the fault plane is exposed in an excavation), and because faults that rupture to the ground surface typically have zones of deformation either side of the main fault plane, as observed for example, in the 2010 rupture of the Greendale Fault (Villamor et al. 2012). This equates to the fault complexity described in Kerr et al. (2003).

In this study we have mapped active faults over much of Horowhenua and Palmerston North City on a LIDAR-derived DEM. Active fault location at the ground surface is mapped as accurate, approximate, or uncertain. *Accurate* fault locations correspond to a clear, sharp fault trace or scarp on the DEM or as observed in the field. In most cases, the fault ‘line’ in the GIS has been drawn near the base of the geomorphic scarp feature, where it is visible. *Approximate* fault locations correspond to places where it not perfectly clear where the fault trace occurs or where the fault forms a broad feature, in which case, it is not perfectly clear where the fault plane (or fault planes) will intercept the ground surface. *Uncertain* fault locations relate to areas where the fault trace has been buried beneath recent deposits (e.g. dune sand or alluvial fan) or eroded away (e.g. by a stream or river). The drawing of an uncertain trace assumes that there is some confidence in the location of the fault trace nearby, i.e., either an accurate or approximate fault location adjacent to it.

No aerial photograph review has been undertaken as part of this study. Therefore, where a LiDAR-derived DEM is not available, such as across parts of the Tararua Ranges, we have typically used fault data from QMAP and the NZAFD. The accuracy to which this data is applicable is to a scale of between 1:50,000 to 1:250,000. In practice, for faults in areas without LiDAR data we have applied an accuracy of ±125 m, which means that a simple “uncertainty” buffer around a fault location derived from QMAP would be 250 m wide.

Table 4.1 GIS attributes applied to active fault data for Horowhenua District and Palmerston North City.

Attribute	Definition
Fault_name	The name given to an active fault
Accuracy	Locational accuracy of the fault trace – linked to the expression of the fault trace and the 'method' used (accurate, approximate, or uncertain)
Activity	Activity of the fault (active or possibly active). Defined by the presence of an active trace across a geological surface that is ≤125,000 years old
DOM_SLIPTYPE	Dominant or primary sense of movement on the fault (reverse, normal, dextral, or sinistral)
DOWN_QUAD	The direction of the down-thrown side of the fault described in terms of compass quadrants
Method	Method used to locate the fault trace (e.g. LiDAR, air photo, or QMAP)
Fault_complexity	The width and distribution of the deformed land around the fault trace (well defined, well defined–extended, uncertain–constrained, uncertain–poorly constrained, or distributed)
Deform_width	Deformation width, i.e. visible deformation width of scarps (i.e. 'fault complexity') in metres – represents zone of the likely location of future intense ground deformation
Buffer_dist	Buffer width, i.e., half of the 'deformation width' in metres
FAZ	The Fault Avoidance Zone, i.e., the sum of the 'deformation width' plus the 20 m 'Margin of safety' setback zone in metres
RI_Class	The average time between surface rupturing events on a fault, grouped into six classifications (RI Class I through VI)

4.3 Fault Complexity

Fault complexity is an important component in the definition of planning consent categories. It is defined within the MfE Guidelines by three terms: 'Well-defined', 'Distributed' and 'Uncertain'. The terms well-defined, distributed and uncertain roughly equate to the width of deformation across which intense ground deformation is likely to occur. The definition of these terms is described in the MfE Guidelines (Kerr et al. 2003). These three terms can be expanded to define whether, for example, an *approximate* fault trace, occurs between two *accurate* fault traces, over across a relatively short distance (200 m) or a greater distance (Table 4.1). For the former, the *approximate* trace could be termed "well-defined–extended" because it is extended over a short distance, or in the latter case, termed "uncertain–constrained". This is because at greater distances from an accurate fault location, the fault trace has the potential to waver or wiggle about where it cannot be mapped at the ground surface.

In this report, fault complexity is equated with line accuracy. We realise that this was not the original intent of the MfE fault complexity terminology. However, these were developed before the widespread acquisition and usage of airborne LiDAR as a tool with which to map active faults. Thus, in this report we often equate 'well-defined' fault complexity with accurate fault locations. The fault complexity term 'distributed' is typically used in this report for approximate fault locations where the scarp is broad and therefore the exact point of fault rupture is unclear, or where a fault splits into two or more fault traces and fault deformation is distributed across a wider area.

The term ‘uncertain’ is used for fault location and covers the fact that the location may be unclear due to subsequent deposition and/or erosion, or whether the feature being mapped is actually of tectonic origin. The corresponding fault complexity can be: uncertain – constrained, if the distance across which the uncertainty occurs is relatively short (<200 m); or, uncertain – poorly constrained, if the distance across which the uncertainty occurs is wide (>200 m); or, there is doubt whether the feature is actually tectonic in origin.

These Fault Complexity terms are applied directly into Resource Consent tables for the MfE Guidelines (e.g. Table A3.1).

Table 4.2 Development of Fault Complexity terms for faults, used in this study for Horizons Region.

Fault location accuracy	Fault complexity	Comment
accurate	Well-defined	associated with a clear, sharp fault feature
approximate	Well-defined–extended	well-defined–extended, if the gap between two accurate traces is < 200 m
“	Distributed	used when the scarp is broad, or the deformation is spread across two or more fault traces
“	Uncertain–constrained	Uncertain–constrained, if the gap between two traces is < 200 m
uncertain	Uncertain–constrained	Uncertain–constrained, if the gap between two traces is < 200 m
“	Uncertain–poorly constrained	Uncertain–poorly constrained, if the gap between two traces is < 200 m; or, there is doubt whether the feature is tectonic in origin

4.4 Constructing Fault Avoidance Zones

Once a fault trace has been identified and mapped, it is assigned GIS attributes including its accuracy, complexity and style of faulting (e.g. strike-slip, reverse), in order to categorise each fault trace to allow for the development of a FAZ.

For this report, the width of Fault Avoidance Zones has been defined by the accuracy and fault complexity attributes in a qualitative fashion, i.e. the width of fault deformation has been assessed on-screen for each trace. In addition, the MfE Guidelines recommend that a *Margin of Safety Buffer* of +20 m be included to each side of (encompassing) the FAZ (Figure 4.2). This buffer is added to acknowledge that there is likely to be “sub-resolution” deformation outside of the geomorphically expressed fault scarp. The total width of each FAZ in this study includes consideration of the fault location and its uncertainty, the fault complexity, with an additional encompassing +20 m width around that, as is recommended in the MfE Guidelines.

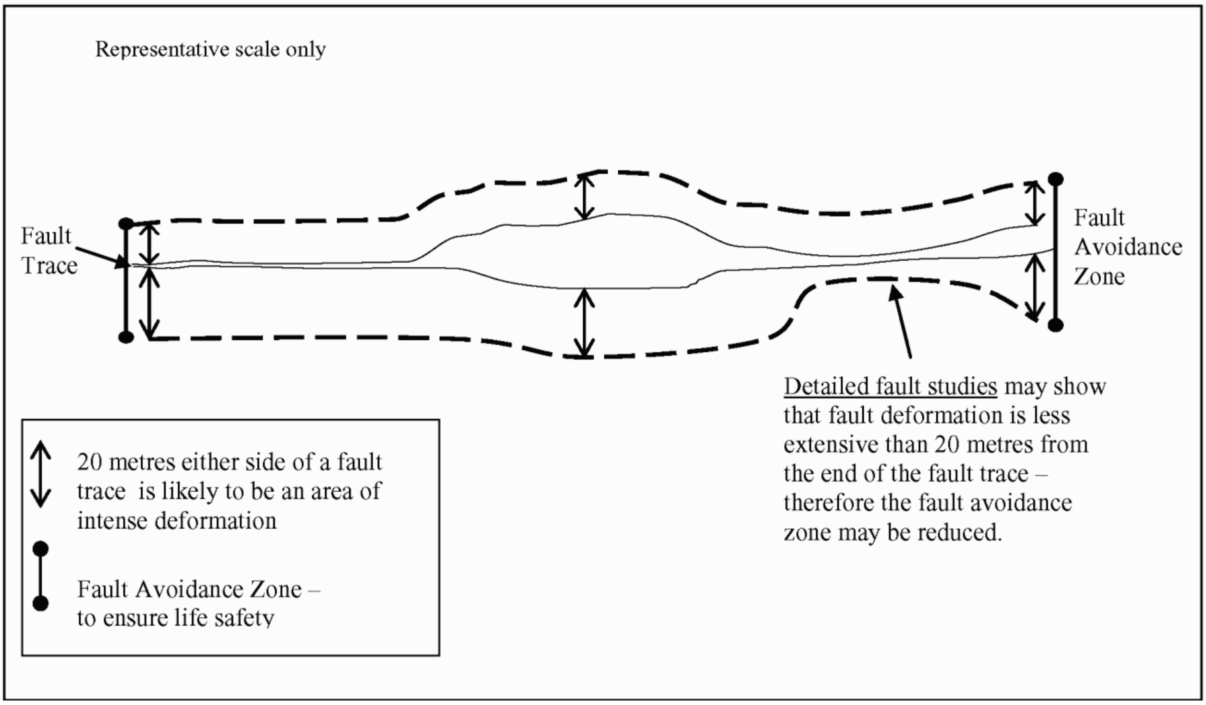


Figure 4.2 A Fault Avoidance Zone (FAZ; heavy dash) and how it may be developed for a district planning map (not drawn to scale), from Kerr et al. (2003). Note the 20 m encompassing buffer as part of the FAZ.

An example Fault Avoidance Zone is shown in Figure 4.2. On the left side of the figure, the fault is accurately mapped and has a '*well-defined'* fault complexity. In the centre, the fault may be mapped approximately and has a *'distributed'* fault complexity (or possibly an '*uncertain – constrained*' fault complexity). On the right side of the figure, the fault is mapped approximately but with a varying degree of confidence. In each case, a 20 m wide 'margin of safety' buffer has been included on each side to develop the full FAZ. As noted in the lower right of Figure 4.2, where detailed fault studies have been undertaken it may be possible to reduce the original mapped width of a given FAZ.

The slip type is relevant to understanding and anticipating the width of deformation in a future rupture. For strike-slip and normal faults we give no preference toward deformation on one side of the fault versus the other. However, for reverse faults, it has been demonstrated that deformation on the hanging-wall block (or uplifted side) is generally over a wider area relative to the footwall side. For example, folding, reverse drag faulting, extension and normal faulting are typical on the upthrown side of historical ruptures of reverse faults and are often recognised in trench exposures (see Figure 4.3). Therefore, in this study the width of the locational accuracy used to develop the FAZ is doubled on the hanging wall side of reverse faults.

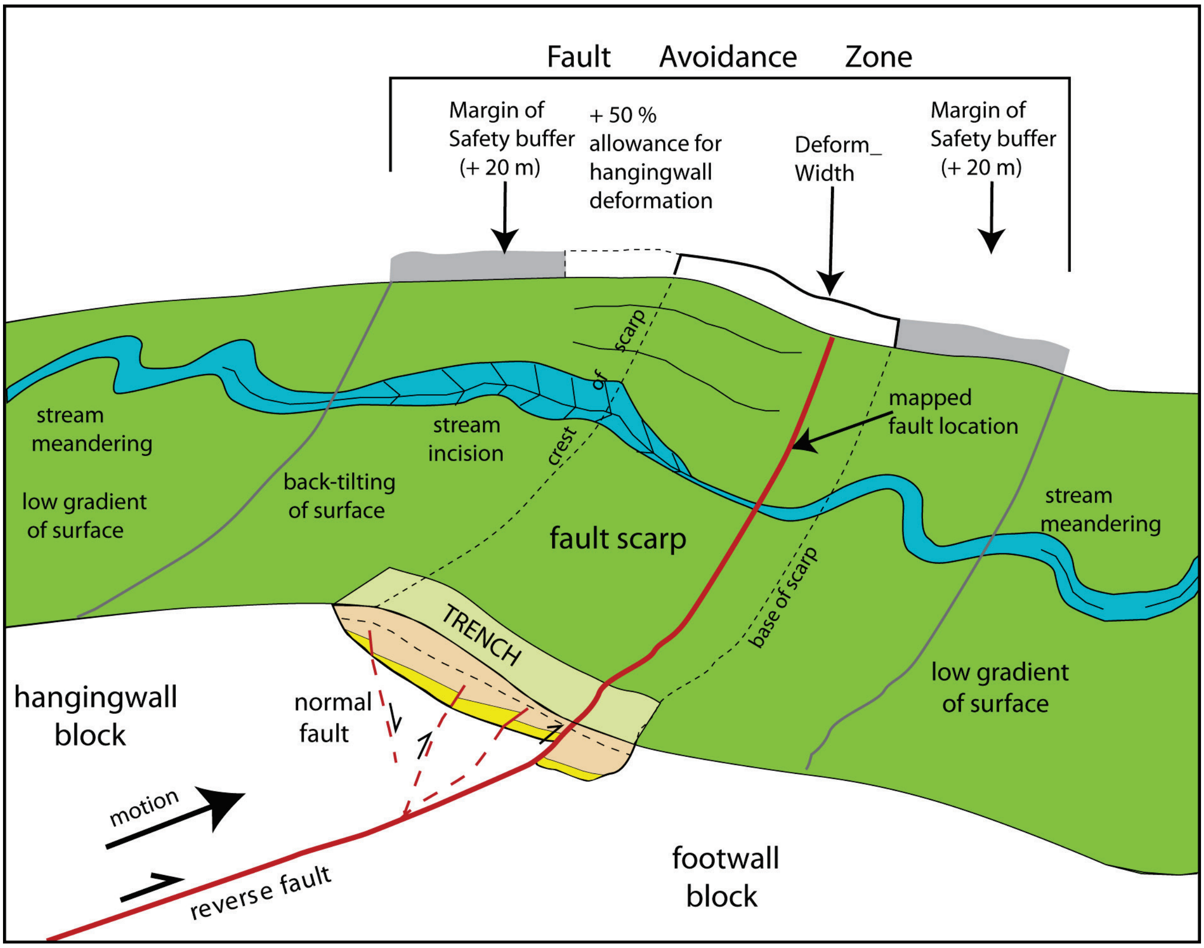


Figure 4.3 Schematic diagram of a dip-slip reverse fault and its scarp. In this case the mapped fault trace (rupture surface; bold red line) is mapped near the base of the scarp. The fault trace itself is 'accurately' mapped and the scarp is 'well-defined' on LiDAR data. The growth of such scarps affects the long-term morphology of streams that cross the structure. The trench shows the evidence for determining surface faulting events (e.g. faulted yellow layer). The complete Fault Avoidance Zone comprises the mapped width of the scarp on LiDAR (Deform_Width), which is extended by 50% on the hanging-wall side of the fault, after which the encompassing 20 m margin of safety buffer is added.

Where there is more than one fault trace making up a distributed or complex zone of faulting, individual Fault Avoidance Zones may overlap. In these cases, the more accurate or higher-activity data (fault location, complexity) should dictate subsequent resource planning decisions. In Horowhenua District, this is particularly evident for closely-spaced reverse faults and where faults splay toward their ends.

4.4.1 Examples of Fault Avoidance Zone Maps

The following section shows examples of Fault Avoidance Zone maps for parts of two active faults described later in the report. These are for parts of the Northern Ohariu Fault (Figure 4.4) and the Poroutawhao Fault (Figure 4.5). The Northern Ohariu Fault is a strike-slip fault, so it has a symmetrical FAZ. The Poroutawhao Fault is a reverse-slip fault, so it shown with an asymmetrical FAZ. Fault line location data has purposely been left off these diagrams to highlight the shape and Fault_complexity designations that are possible. Complete active fault trace and FAZ maps for each fault are shown in Chapters 5 and 6 of this report.

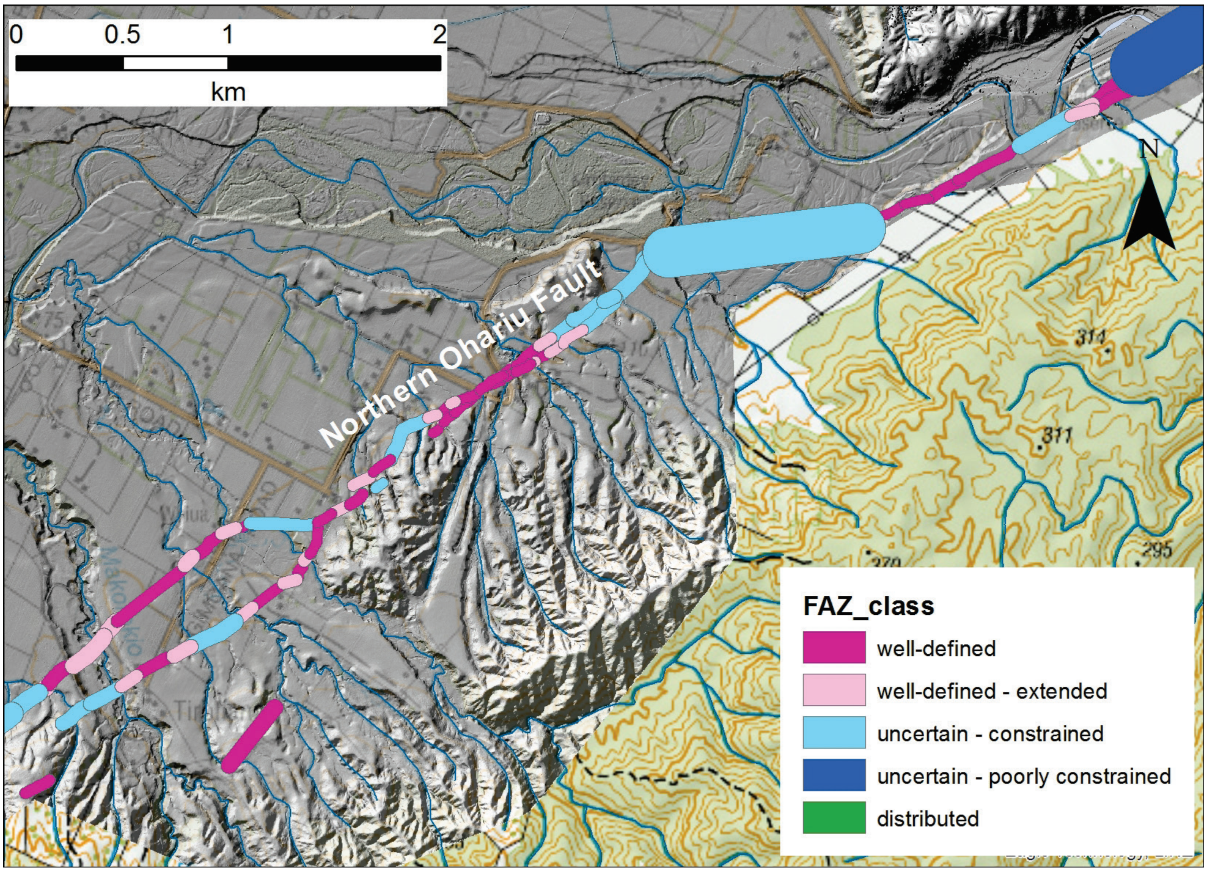


Figure 4.4 Fault Avoidance Zone map for part of the strike-slip Northern Ohariu Fault on the south side of the Ohau River.

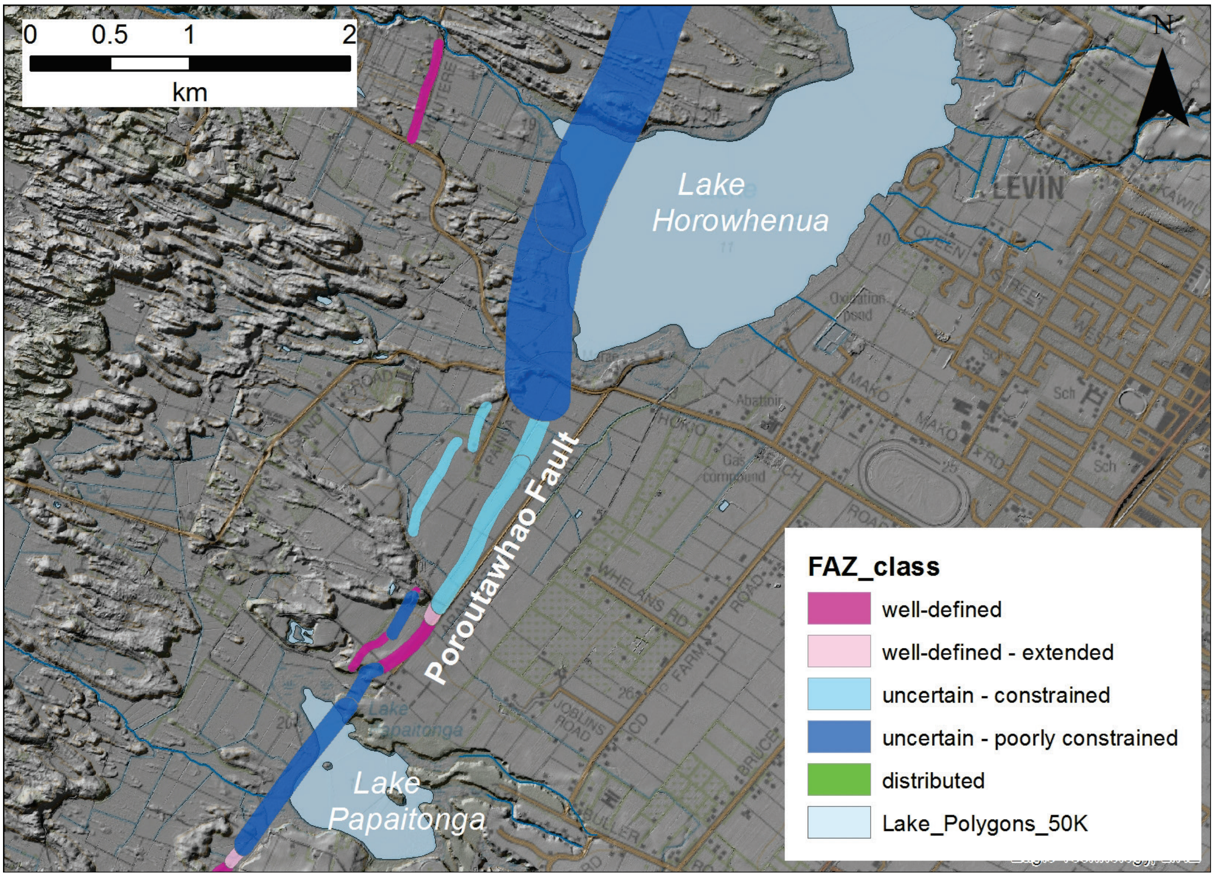


Figure 4.5 Fault Avoidance Zone map for part of the reverse-slip Poroutawhao Fault west of Levin.

4.4.2 Fault Awareness Areas

Fault mapping at between 1:50,000 and 1:250,000 scale is not detailed enough to delineate Fault Avoidance Zones around the faults, nor for directly applying the MfE Guidelines (Kerr et al. 2003) to manage the fault rupture hazard. For faults mapped at 1:50,000 to 1:250,000 scale, a Fault Awareness Area around the fault is recommended (Barrell et al. 2015). In previous fault hazard mapping studies in the Canterbury Region, GNS Science has developed Fault Awareness Areas (FAA) for active faults that have been mapped at a regional-scale (Barrell, et al. 2015). Because the fault location uncertainty is high, or in cases where there is considerable uncertainty about the origin of geomorphic features it is more reasonable to develop a FAA, because it carries a lower level of certainty and therefore risk with it.

In this study, a FAA has been developed for the Otaki Forks Fault (described in section 5.2.3) and for parts of the Northern Ohariu and Tokomaru faults. However, for most other faults, we have either reviewed the QMAP geological data (e.g. Begg and Johnston, 2000), or QMAP data has been superseded by other mapping at a detailed scale. For example, for much of the southern part of the Northern Ohariu Fault in Horowhenua District, we now have airborne LiDAR control that supplements mapping previously undertaken by Van Dissen and Heron (2003). In particular, LiDAR has aided in projecting the known traces of the fault up the Ohau River valley where it is concealed or eroded.

FAAs are developed with a width of ±250 m and do not carry the regulatory levels that are suggested in the MfE Guidelines. In future, if development is proposed for areas with a FAA status, then further fault mapping and/or geologic studies would be required to better define the location of surface faulting and deformation.

4.5 Mapping Active Folds

In this study we have mapped several broad active anticlinal folds by mapping out the axial trace of the fold (see Chapter 5). In such a case, the fold is broad and subdued in character and has no active fault trace associated with it. We have mapped out the axial trace by surface profiling the DEM every 500–1500 m across the folded topography, picking either the highest point on the profile, or the area where the drainage changes direction (as in Figure 3.2).

While folds may be a manifestation of surface deformation related to fault movement, for the purposes of the MfE Guidelines, we do not treat active folds in the same way that we do active faults. It is not practical to develop a Fault Avoidance Zone (or “Fold Avoidance Zone”) for an active fold[4], because it is unclear where the focus of surface deformation will be, and it is likely that the intensity of ground deformation will not be severe enough to pose a life-safety hazard to most buildings (Barrell et al. 2015). It would be impractical to zone and buffer an active fold, because of: (i) the breadth of subtle deformation across a fold; (ii) the lack of focused deformation and its location; and 3) most importantly, the low risk to life safety posed by such broad deformation.

[4] Unless the fold is acutely asymmetric, in which case it may well be defined by a scarp. Barrell et al. (2015) distinguish only monoclinal folds as requiring a FAZ rather than a FAA.

5.0 HOROWHENUA DISTRICT

5.1 Introduction

This study represents the first time that active fault mapping has specifically been collated for the Horowhenua District. With the help of airborne LiDAR-derived topography, it was possible to map out several active faults and folds, some of which were previously unrecognised. The new mapping builds on data from QMAP (Begg and Johnston 2000) and the NZAFD (Langridge et al., 2016) which show the Northern Ohariu and Otaki Forks faults as the only active faults within the district (Figure 1.1). Active (anticlinal) folds originally mapped by QMAP (e.g. Begg and Johnston, 2000) have been re-defined on the basis of their axial traces using airborne LiDAR data (see Section 4.5 of this report).

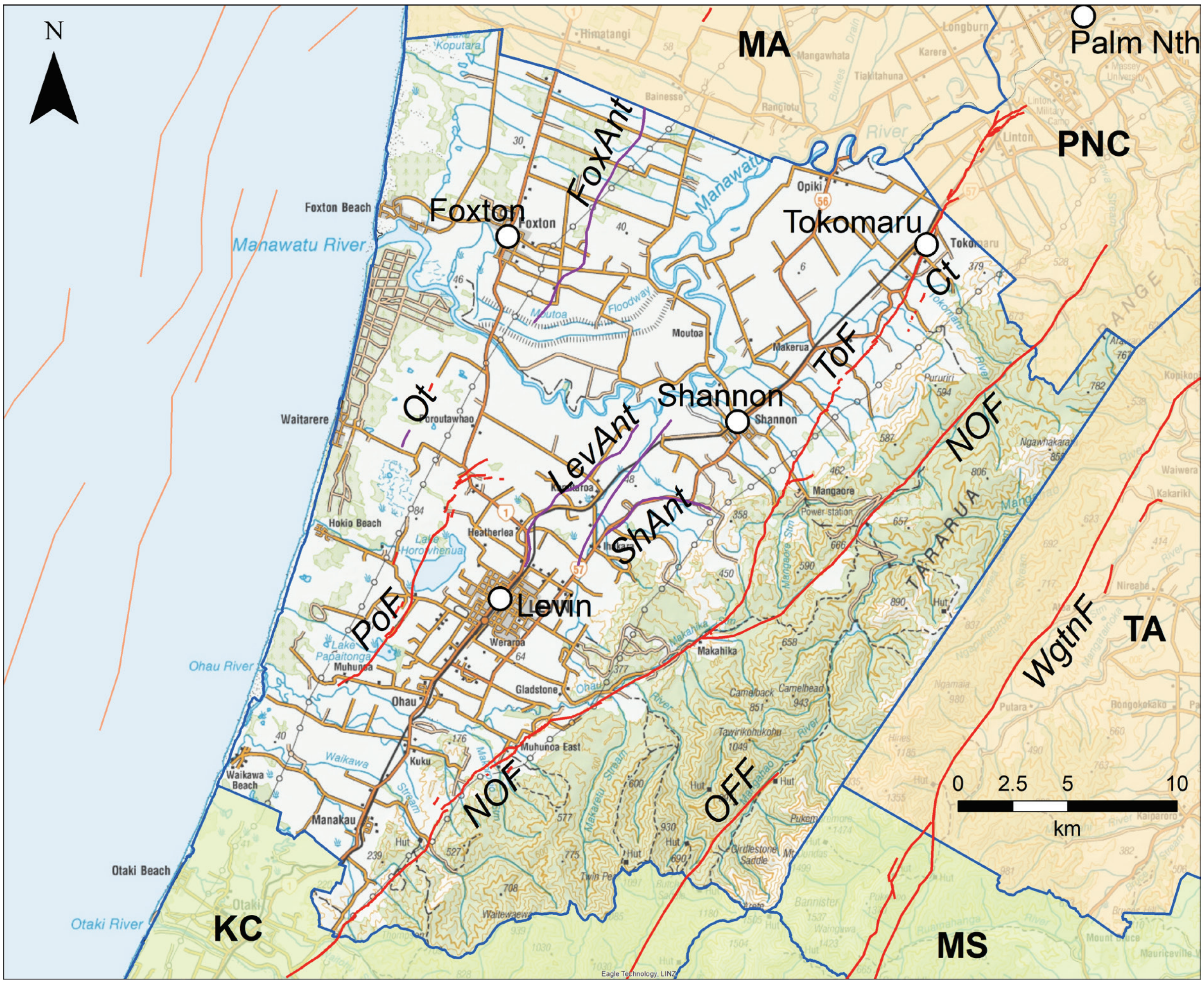


Figure 5.1 New and updated onshore active faults (red) and folds (purple) in the Horowhenua District, as defined in this study. Offshore active faults based on Nodder et al. (2007) are shown as orange lines. Other districts in the Horizons Region are coloured orange, while other districts in other regions are coloured green. See Figure 1.1 for district abbreviations. Fault name abbreviations are: NOF, Northern Ohariu Fault; OFF, Otaki Forks Fault; PoF, Poroutawhao Fault; and ToF, Tokomaru Fault. Smaller traces are abbreviated to: Ot, Oturoa trace (with associated anticline) and Ct, Cluain traces. Fold names are: FoxAnt, Foxton anticline; LevAnt, Levin anticline; and ShAnt, Shannon anticline.

Active faults in the Horowhenua District include the wider NIDFB formed in association with oblique subduction and uplift of the Tararua Ranges, (e.g. the Northern Ohariu and Tokomaru faults) (Beanland, 1995; Litchfield et al., 2014). Between the NIDFB and offshore faults of the Kapiti-Manawatu Fault System are a series of reverse faults and folds occur within the coastal plain, e.g. the Poroutawhao Fault and Oturoa trace/Anticline, the Levin and Foxton anticlines.

Here we describe each of the active faults and folds, in the district with photographs of locations where fault traces and and/or scarps can be identified in the field.

5.2 Active Faults

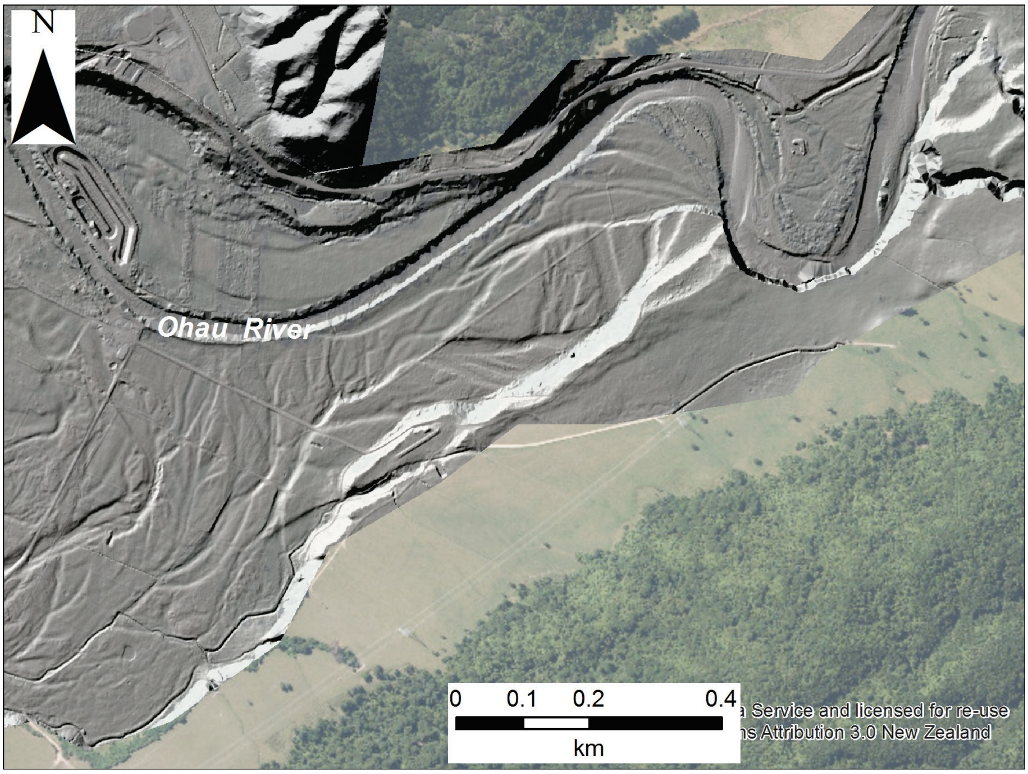
5.2.1 Northern Ohariu Fault

The northeast-striking Northern Ohariu Fault is a right-lateral (dextral) strike-slip fault, and it is the most active and best-known fault in the Horowhenua District (Palmer and Van Dissen, 2002; Van Dissen and Heron, 2004). The Northern Ohariu Fault is mapped from the south in Kāpiti Coast District into Horowhenua District and extends into Palmerston North City (Figure 5.1). Southeast of Manakau, the fault can be identified on Greater Wellington Regional Council (GWRC) LiDAR models and from Waikawa Stream into the Ohau River valley on Horizons LiDAR models. Results from other mapping projects in the region has also been incorporated and reviewed. For example, Van Dissen and Heron (2003) mapped the Northern Ohariu Fault in the southern part of Horowhenua District. In areas not covered by LiDAR, the traces have been adopted from QMAP.

Figure 5.2 shows how active fault traces can be identified from an oblique aerial photo. A similar area is shown in Figure 5.3, where airborne LiDAR data has been acquired in the Ohau River valley. Figure 5.3 demonstrates how LiDAR models can be used to accurately locate fault traces. In areas where the river has eroded away evidence for a fault trace, since the last surface faulting event, the fault's location has been mapped as uncertain. In other areas where the exact location of the fault is unclear, or is broad, the fault has been mapped as approximate.

Figure 5.2 Oblique aerial photograph of the active Northern Ohariu Fault across the Ohau River floodplain near Gladstone. The two arrows highlight the trace of the active Northern Ohariu Fault across river terrace surfaces on the true left side of the river. (Photo: L. Homer, GNS Science). See Figure 5.3 for a wider context.

A



B

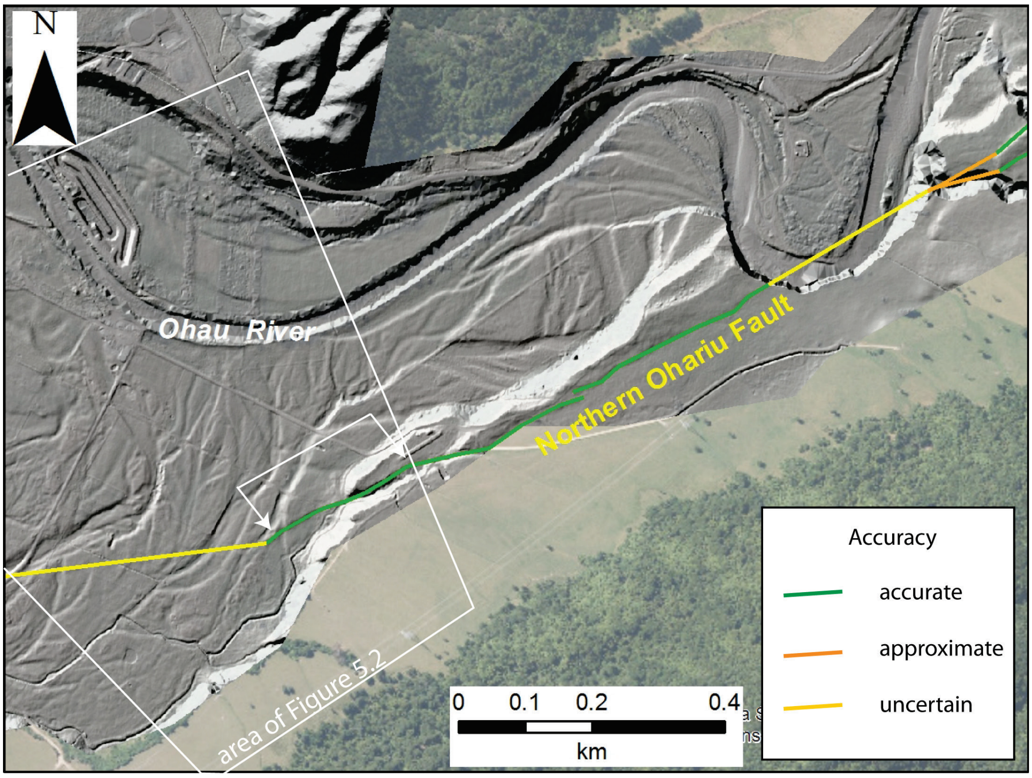


Figure 5.3 A) LiDAR hill-shade image (with a colour orthophoto underlay) of the Ohau River area showing the Northern Ohariu Fault. B) Annotated version of the same image. The area of the photograph in Figure 5.2 is shown, and the double arrow shows the part of the fault shown in Figure 5.2, which is accurately located.

The Recurrence Interval Class (RI Class) of the Northern Ohariu Fault has previously been assigned as RI Class II (Table 3.1), i.e. repeated surface faulting events would be expected every c. 2000–3500 years (Van Dissen et al., 2003). This information comes from a comparison with the Ohariu Fault as observed from geologic studies in the Wellington region (e.g. Litchfield et al., 2003). These authors estimate a lateral slip rate of 1–3 mm/yr, which is similar to the Ohariu Fault in the Wellington region. In addition, fault traces are observed crossing Holocene terraces and some fault displacements observed are of a similar size to those measured on the Ohariu Fault, further south (Palmer and Van Dissen 2002). Without any new specific geologic or paleoseismic data, we infer that the Northern Ohariu Fault should maintain RI Class II status (Table 5.1).

As part of this project we have developed a FAZ for the Northern Ohariu Fault in the Horowhenua District (Figure 5.4). The width of the FAZ depends on the Fault_complexity, deformation width and accuracy of mapping, i.e. whether the fault complexity has been defined as ‘well-defined’, ‘distributed’ or ‘uncertain’.

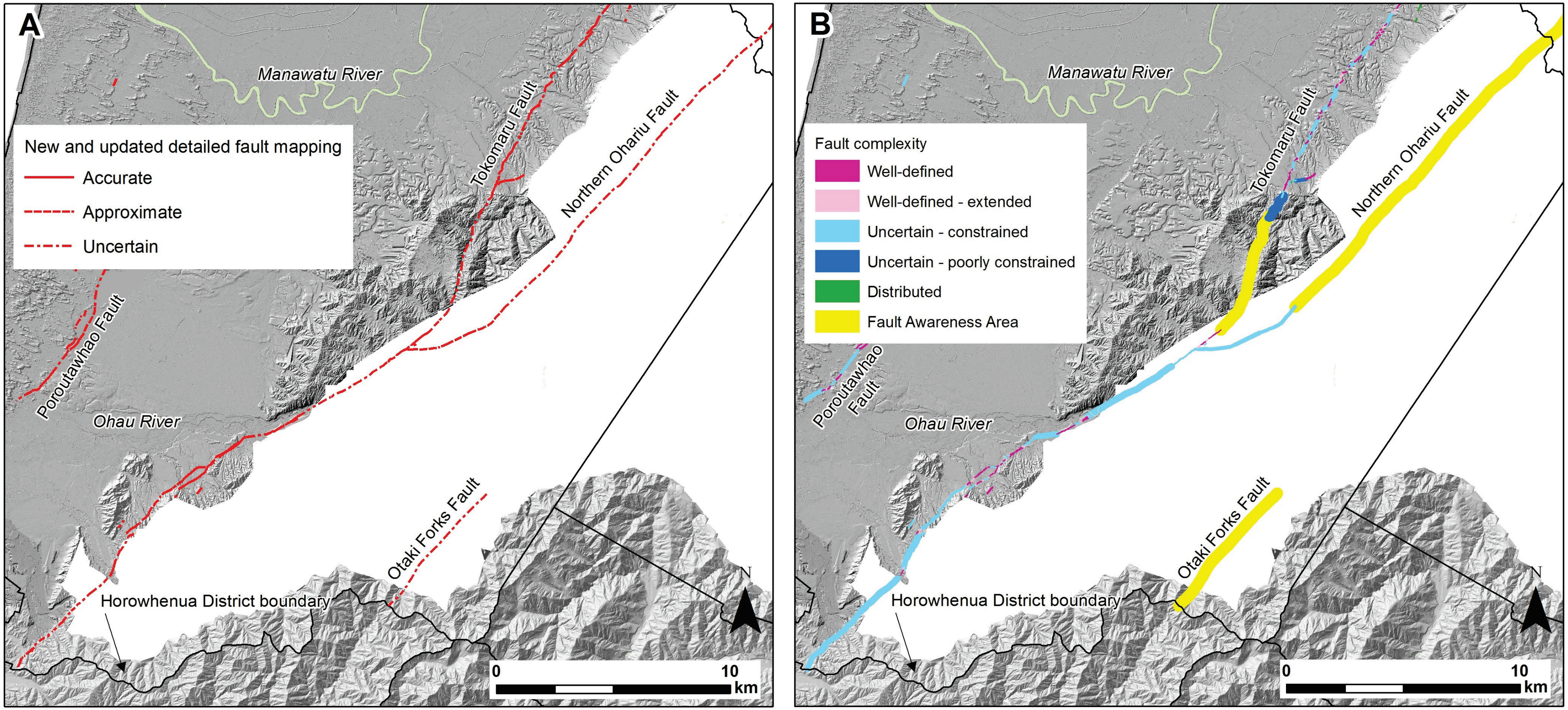


Figure 5.4 Active fault and Fault Avoidance Zone (FAZ) maps for the eastern part of Horowhenua District.A) LiDAR hillshade image showing the location and accuracy of mapping for the Northern Ohariu, Otaki Forks, and Tokomaru faults. B) FAZs and Fault Awareness Areas for the Northern Ohariu Fault, Otaki Forks Fault and Tokomaru Fault.

5.2.2 Tokomaru Fault

The Tokomaru Fault is a recently identified NNE-striking active fault in the Horowhenua District that extends from Makahika Stream to within Palmerston North City (territory), where it was first mapped as an active fault by Beetham et al. (2011). At its southern end the Tokomaru Fault branches away from the Northern Ohariu Fault at Makahika Stream (Figure 5.5). The strike difference between the Northern Ohariu and Tokomaru faults is approx. 12°, (i.e. the Tokomaru Fault strikes c. 12° farther to the north than the Ohariu Fault in that area). Based on this observation of strike, which makes reverse motion a more likely style of fault movement, and the lack of indicators of strike-slip offset along the fault as opposed to simply vertical scarps, we infer that the dominant style of motion on the Tokomaru Fault is reverse slip. However, it still possible that the dominant sense of motion for this fault is in fact dextral strike-slip, like the Northern Ohariu Fault.

The Tokomaru Fault is largely mapped in this study using airborne LiDAR-derived topographic data. At its southern end, the fault is mapped from an 8-m DEM and oblique aerial photographs (Figure 5.5). Over a distance of c. 5 km between Makahika Stream and Mangaore, the Tokomaru Fault is inferred, on the basis of a topographic lineation observed on LiDAR. Because of this inference and the scale of mapping we apply a FAA to this part of the Tokomaru Fault. In the area of the Mangaore village we have mapped a separate, ENE-trending secondary splay of the Tokomaru Fault, over a distance of approx. 1.2 km.

To the north of the Mangaore village, the Tokomaru Fault has been mapped continuously for approx. 15 km toward the NNE all the way to the southern boundary of Palmerston North City. It crosses bedrock hillslopes and late Pleistocene surfaces, e.g. Q5b (71,000–128,000 years), Q3a (24,000–59,000 years) and Q2a (12,000–24,000 years) as defined in Begg and Johnston (2000) (Figure 5.5).

Figure 5.5 Oblique aerial photograph of the Makahika Stream area where the Tokomaru and Northern Ohariu faults diverge. The arrows highlight active traces of the Tokomaru Fault across a hillslope and a terrace (Photo: L Homer, GNS Science.

The Tokomaru Fault is poorly expressed across Holocene (Q1 0–12,000 years) surfaces, south of Mangaharakiekie Stream. From the Tokomaru River northward, active traces and fault scarps are observed across alluvial surfaces, particularly near and within the town of Tokomaru (Figure 5.6). At Tokomaru the fault scarp is approx. 1–1.2 m high across a Q2a surface, and c. 3–4 m in height across a higher alluvial surface (presumably Q3a) upon which most of the village is sited. The Tokomaru Fault continues north into Palmerston North City.

Based on these observations, we suggest the following regarding the activity of the Tokomaru Fault:

1. due to the lack of an active trace, or poor expression of the fault across Holocene alluvium (Q1a), we infer that there have been 0–1 earthquake ruptures on the Tokomaru Fault during the Holocene (the last 11,700 years);
2. there has been at least 1 fault movement since the abandonment of the Q2a surface (since 12,000 years ago or more), producing approx. 1 m of vertical motion.
3. there have been at least 2–3 fault movements since the abandonment of the Q3a surface (since 24,000 years ago or more), producing approx. 3–4 m of vertical motion.

These observations lead us to infer that surface-rupturing earthquakes can occur on the Tokomaru Fault about every 6000–12,000 years on average. Without any new paleoseismic data, we therefore suggest that the Tokomaru Fault be placed in RI Class IV, where surface rupture on a fault would be expected to occur every 5000–10,000 years. While the recurrence of surface rupture events could be >10,000 years, it is more likely that the average recurrence interval is <10,000 years. Based on 1) and 2) above, the vertical slip rate of the Tokomaru Fault is approx. 0.1–0.2 mm/yr[5].

Figure 5.6 Broad scarp of the Tokomaru Fault crossing Tokomaru Street in the village of Tokomaru. The scarp is represented as a rise or bump, with a height of approx. 3–4 m, that cuts obliquely across the road, highlighted by the height of cars at the top and bottom of the scarp. Arrows mark the base of the scarp.

[5] The vertical slip rate does not take into account the dip-slip or any strike-slip component of fault motion.

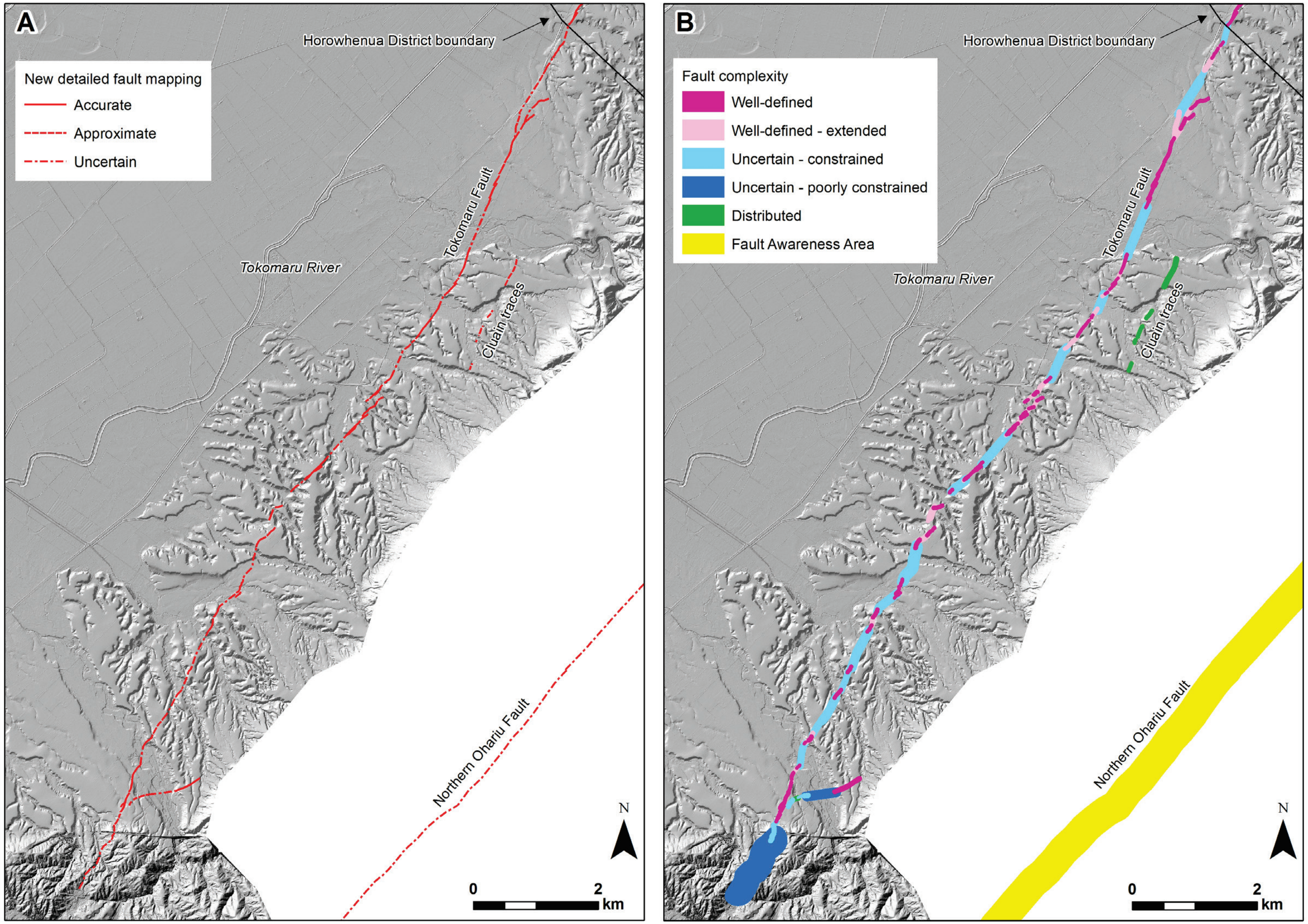


Figure 5.7 Active fault and Fault Avoidance Zone (FAZ) maps for the Tokomaru Fault, Horowhenua District. A) LiDAR hill-shade image showing the location and accuracy of mapping for the Tokomaru Fault and Northern Ohariu Fault and Cluain traces. B) FAZs for the Tokomaru Fault and a Fault Awareness Area (FAA) for the Northern Ohariu Fault.

As part of this project we have developed a FAZ for the Tokomaru Fault (Figure 5.7). The width of the FAZ depends on the accuracy of mapping the fault, i.e. whether the fault has been mapped and attributed as ‘accurate, approximate or uncertain’ in location. A RI Class IV is applied to the entire length of the Tokomaru Fault (Table 5.1).

5.2.3 Otaki Forks Fault

The Otaki Forks Fault is an active fault within the Tararua Range in the southeast of the Horowhenua District (Begg and Johnston, 2000). The Otaki Forks Fault is best known from active traces within the Kāpiti Coast District, where the fault generally follows the steep-sided Otaki River valley. Within the Horowhenua District, the Otaki Forks Fault, as defined by QMAP (Begg and Johnston, 2002), follows the upper Mangahao River valley (Figure 5.8). Begg and Johnston (2000) show it as an active fault in the southern part of the Horowhenua District, but inactive in its northern portion (toward the Tararua District boundary). In this study, due to the lack of airborne LiDAR data across the Tararua Range (aside from the 1 km overlap with GWRC LiDAR), we adopt the active part of the Otaki Forks Fault as mapped by Begg and Johnston (2000).

There is no direct geological data, e.g. slip rate or paleo-earthquake study, to constrain the recurrence interval of faulting on the Otaki Forks Fault. However, Van Dissen et al. (2001) discuss connecting the faulting on the Akatarawa Fault near Wellington, northward onto the Otaki Forks Fault, i.e. there is an inferred structural relationship between large earthquakes on these faults as a system. This concept was adopted into the 2010 NSHM (Stirling et al., 2012) as the AkaOtaki (Akatarawa + Otaki) fault source, for which an average recurrence interval of c. 6800 years is calculated. The Akatarawa Fault is defined as having a maximum recurrence interval of 9000 years (Van Dissen et al. 2001), though these authors qualify that the slip rate may be higher and the recurrence interval lower than stated).

Based on this information, the NZAFD states a RI Class III to the Akatarawa Fault (Van Dissen et al. 2003; Langridge et al. 2016). Therefore, in this case, we infer that the recurrence interval of the Otaki Forks Fault is comparable to the Akatarawa Fault, being RI Class III (>3500 to ≤5000 years) (Table 5.1).

In this study, because the Otaki Forks Fault is defined by QMAP line work only, we have developed a FAA for it, with a buffer width of ±250 m (Figure 5.4). The FAA runs from the boundary with the Kāpiti Coast District to near Mangahao Flats Hut. If future development occurs in this area, then more detailed fault mapping will need to be undertaken at that time.

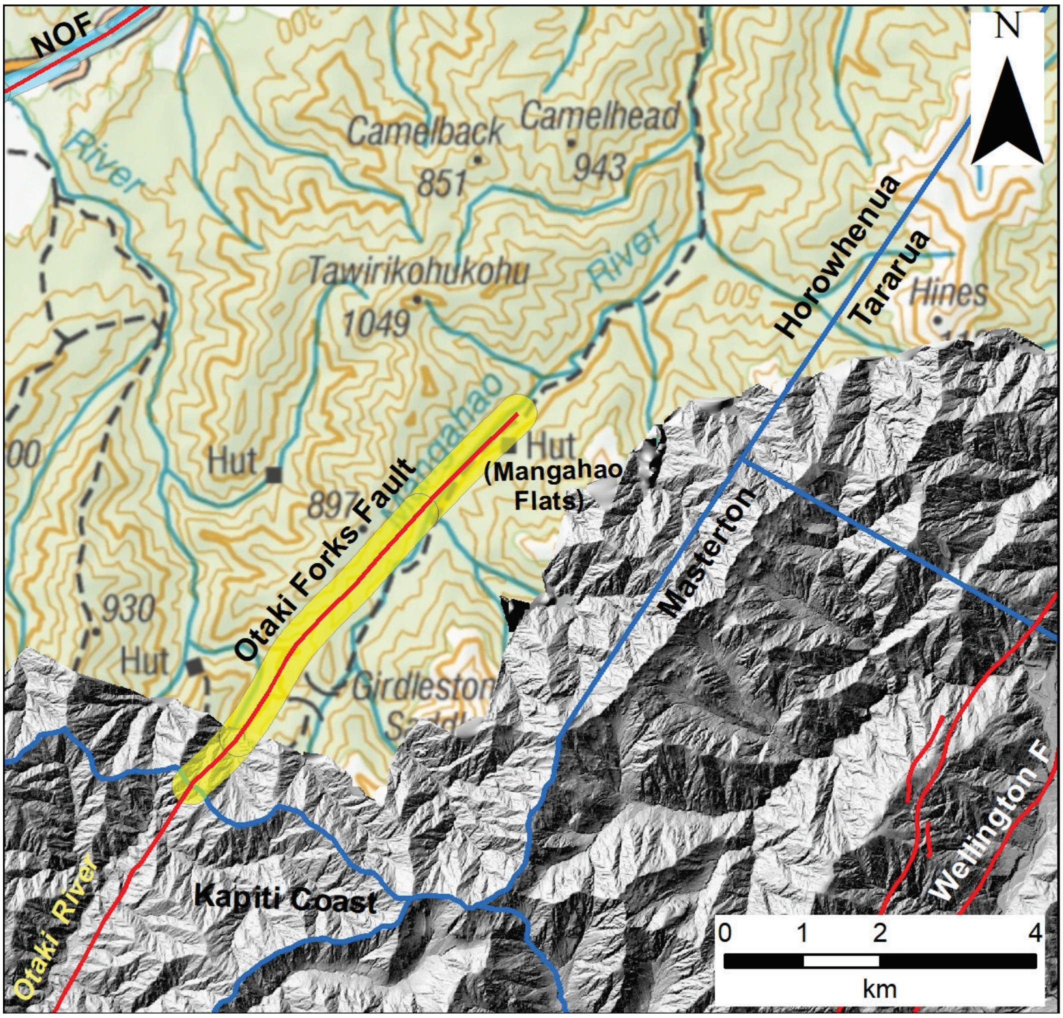


Figure 5.8 Location of the Otaki Forks Fault in the Horowhenua District, generally following the valley of the upper Mangahao River. The GWRC 1-m LiDAR DEM covers the southern edge of the Horizons Region (light grey shading with no topographic map underlay). The yellow shaded buffer is the 500-m-wide FAA defined for the Otaki Forks Fault. NOF, Northern Ohariu Fault.

5.2.4 Poroutawhao Fault

The Poroutawhao Fault is a newly-identified active fault in the western part of Horowhenua District, on the seaward side of Lake Horowhenua (Figure 5.9). The fault is named from the village of Poroutawhao (north of Levin), a raised topographic high recognisable in the local fluvial geomorphology (Clement et al., 2017), and the name of a local seismic fault source in the 2010 NSHM (Stirling et al., 2012). The Poroutawhao Fault is best expressed near Lake Horowhenua where several active fault traces have been mapped from the LiDAR data. The fault is characterised by a series of southeast-facing scarps and fault traces located between Muhunoa and Poroutawhao. These are best expressed to the north and south of Lake Horowhenua (Figure 5.10). The scarp is often expressed as a broad warp in formerly level alluvial surfaces. In several places the fault trace is buried by sand dunes (Figure 5.10). Along with these dunes, the fault, arguably assists in ponding water that drains from the Tararua Ranges, forming lakes Papaitonga and Horowhenua (Figure 5.9). Based on the expression of the fault as a warp, the lack of strike-slip indicators, and by the presence of other folds and reverse faults in the coastal plain of Horowhenua, Manawatu and Rangitikei districts, we infer that the Poroutawhao Fault is a reverse fault.

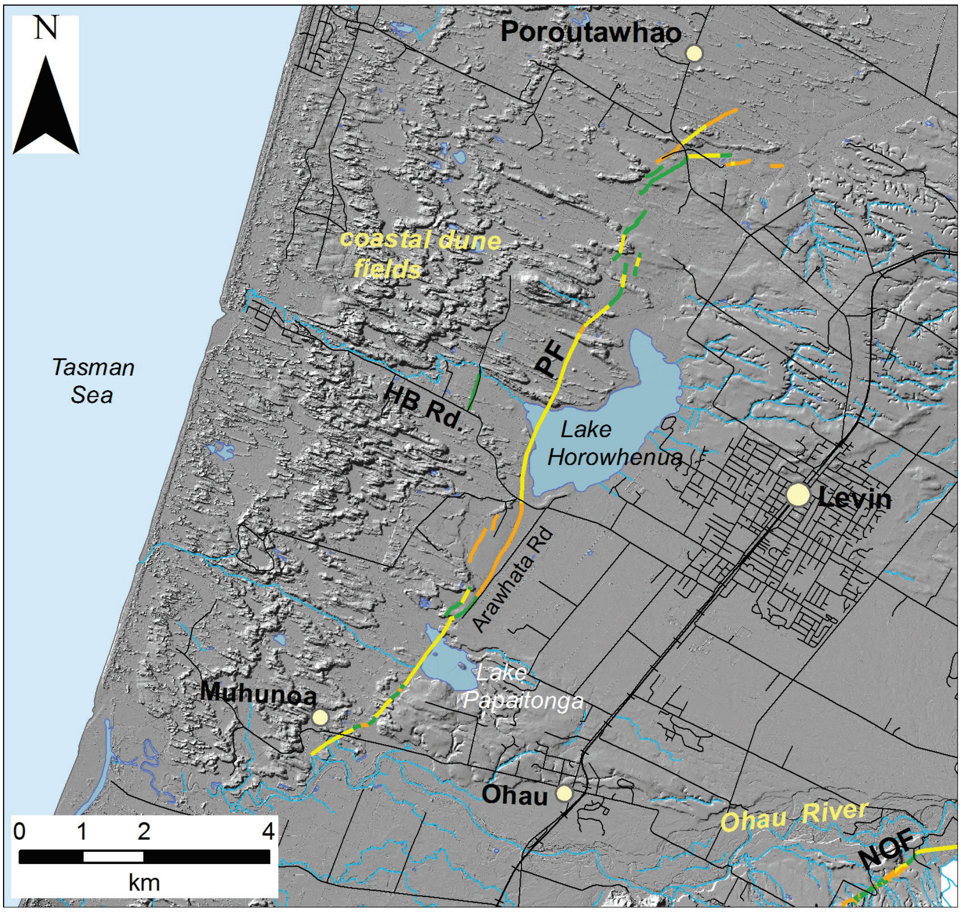


Figure 5.9 Map of active traces along the newly-identified Poroutawhao Fault (PF) near Levin. HB Rd. = Hokio Beach Road.

Figure 5.10 View to the southeast across Lake Horowhenua and Levin (mid-ground) to the Tararua Ranges. Holocene sand dunes create the complex topography in the foreground. Well-mapped traces of the Poroutawhao Fault are marked by black arrows and dashed white lines on either side of the lake. Photo: GNS Science, L. Homer.

We inspected the trace of the Poroutawhao Fault along Arawhata Road, where the broad scarp is typically c. 3.0 ± 0.5 m in height (Figure 5.11). The ages of this surface (or surfaces) on QMAP (Begg and Johnston 2000) along Arawhata Road ranges between Q1a (Holocene alluvium; <11,700 years) and Q5b (Last Interglacial beach deposits (71,000–128,000 yr.), including Q3a and Q2a alluvial units. From our assessment of the LiDAR hill-shade west of the Tararua Ranges from the Ohau River plain to Lake Horowhenua, the geomorphology is consistent with a broad alluvial fan (upon which Levin is built) associated with outwash from the river, which extends to the lake. This surface is probably underlain mostly by Q2a alluvium (12,000–24,000 years), that drapes over older surfaces. Thus, if the faulted surface along much of Arawhata Road is of Q2a age (rather than Q1a as shown by Begg and Johnston, 2000), then a vertical slip rate of 0.1–0.3 mm/yr. can be derived for the Poroutawhao Fault.

Figure 5.11 The trace of the Poroutawhao Fault on Arawhata Road. The fault scarp is marked by parentheses at the edge of the photo and by a white dotted line that marks the width of a 2–2.5 m high fault scarp.

In the vicinity of the Poroutawhao Fault a suite of mappable mid to late Holocene sand dune units occur. Three broad phases of dune building activity have been identified along this coastline: the Foxton phase, from c. 7700–1600 yr. (before present; B.P.); the Motuiti phase from c. 1000–500 yr. B.P., and the Waitarere phase, <500 yr. B.P (Cowie, 1963; Shepherd and Price, 1990; Muckersie and Shepherd, 1995). Another intermediate phase of dune building (c. 2000–1000 yr. B.P. = before present), has been recognised on the basis of dunes with a high abundance of Taupo Pumice (D. Townsend, personal communication, 2018). These units and ages become relevant when discussing the recurrence interval of faulting near the Horowhenua coast.

While the vertical slip rate calculated above gives us an indication of its activity, there is little or no on-fault geological data (e.g. from paleoseismic trenching) that can inform us of the recurrence interval of faulting for the Poroutawhao Fault. We use the following geomorphic evidence to develop a preliminary recurrence interval and RI Class for the Poroutawhao Fault:

1. Based on its height, the fault scarp probably formed from more than 1 surface rupture. If this is the case and the alluvial surface cut by the fault is of Q2a age (12,000–24,000 years), then the recurrence interval could be between 6000 and 12,000 years (or less).

2. A linear, shore-facing scarp occurs 1.4 km west of the trace of the Poroutawhao Fault near Hokio Sand Road. We suggest that this feature is a remnant of the mid-Holocene (c. 7500 yr.) sea-level high-stand (i.e. shoreline) that occurs along many New Zealand coastal areas (Clement et al. 2016). Its prominence in this area suggests that there was a topographic high that existed before the peak of the sea-level high-stand, that resulted in cutting of a coastal cliff, probably related to the fault. This former coastal cliff is as high as the current scarp of the Poroutawhao Fault. It is not clear whether a post-7500 B.P. event has occurred, i.e. whether the Foxton phases sand dunes are faulted, or whether there have been >1 paleo-earthquake ruptures prior to 7500 yr B.P.

In summary, inferences from points 1 and 2 above suggest that the recurrence interval range for surface-rupturing earthquake events on the Poroutawhao Fault fall between c. 5000 and 10,000 years. Therefore, until better data is available, we recommend a preliminary RI Class IV be applied to the Poroutawhao Fault (i.e. RI >5000 to ≤10,000 years) (Table 5.1).

In this project we have developed a FAZ for the Poroutawhao Fault in Horowhenua District (Figure 5.12). The width of the FAZ depends on the accuracy of mapping the fault, i.e. whether the fault has been mapped and attributed as ‘accurate, approximate or uncertain’ in location. A RI Class IV status is applied to the entire length of the Poroutawhao Fault (Table 5.1).

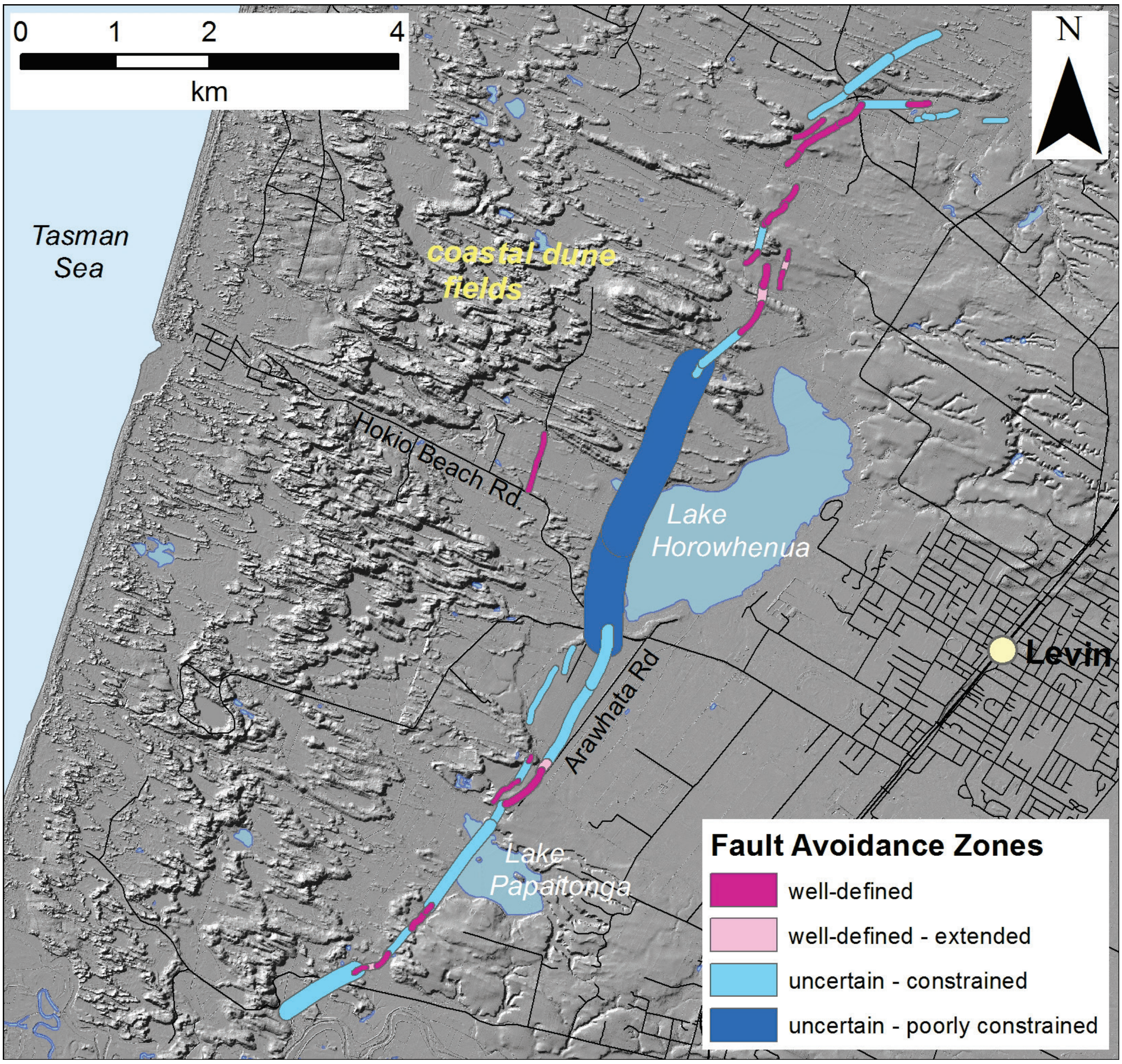


Figure 5.12 Map of Fault Avoidance Zones along the newly-identified Poroutawhao Fault near Levin.

5.2.5 Other Fault Traces

Two other short fault traces have been mapped within the Horowhenua District. These traces are short (<2 km long), discontinuous and do not connect with other known faults. Therefore, these faults remain unnamed at this time. Nevertheless, these traces cut across young geological surfaces, and so are briefly described here.

Just south of Tokomaru, and c. 700 m southeast of the Tokomaru Fault, a series of NNE-trending fault traces can be discontinuously followed over a distance of c. 2 km (Figure 5.7). These traces (‘Cluain traces’ named after Cluain homestead on Albert Road), only occur across Q5b terraces and are typically associated with a c. 2 m high northwest-facing scarp. The ‘Cluain traces’ are too short and too close to the Tokomaru Fault to warrant being given a separate fault name. These traces may rupture with the Tokomaru Fault, however, due to the relatively small amount of surface deformation (2 m) and the antiquity of the displaced deposits (Q5b; 71,000–128,000 yrs.), we suggest that the Cluain trace be considered as a RI Class V fault (i.e. 10,000 < RI ≥ 20,000 yrs.) (Table 5.1).

FAZs have been developed for the Cluain traces (Figure 5.7). The width of the FAZ depends on the accuracy of mapping the fault, i.e. whether the fault has been mapped and attributed as ‘accurate, approximate or uncertain’ in location. A RI Class V status is applied to the entire length of the Cluain traces (Table 5.1).

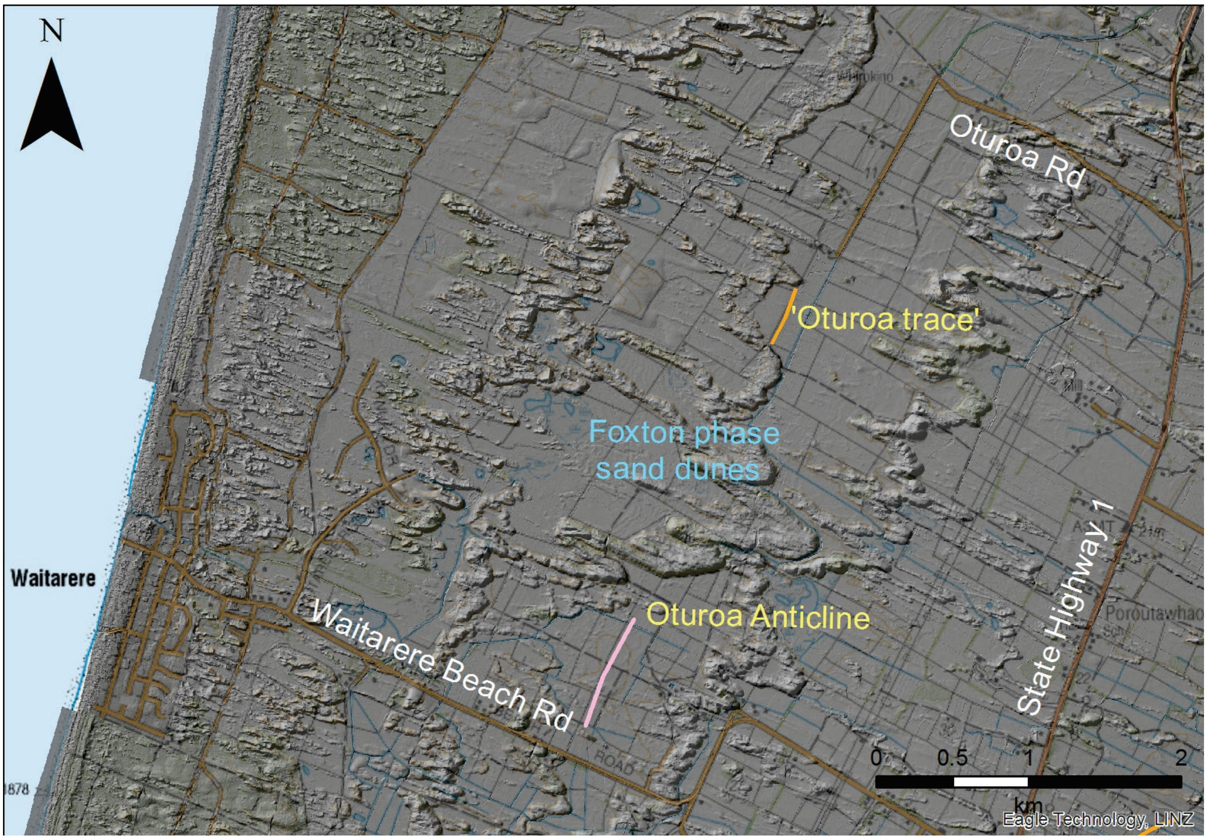


Figure 5.13 Newly mapped locations of the ‘Oturoa trace’ and the axis of the Oturoa Anticline near Waitarere. The coastal landscape and tectonic geomorphology are masked by the landward advance of sand dune ridges, particularly those of the post-7700-year B.P. Foxton sand-dune building phase.

The other short trace is located in sand dune country northeast of Waitarere Beach (Figure 5.13). A single active NNE-trending fault trace can be followed over a distance of c. 0.4 km, near the end of Oturoa Road and c. 3.9 km inland from the coast. This trace (‘Oturoa trace’) is a 2 m high southeast-facing scarp in a flattish area between Foxton phase sand dune ridges.

Just north of Waitarere Beach Road a fold trace has been mapped over a length of c. 750 m. This axial trace is along trend, and to the south of, the Oturoa trace. It is likely that the fault and fold trace are related to the same structure, which is only well-expressed near Oturoa Road, where it is not masked by Foxton phase sand dunes. If so, such an extended structure would be at least 3 km in length. While the Oturoa trace preserves a rather small amount of vertical displacement (2 ± 0.5 m) over a short distance, we suggest that it be considered a RI Class IV fault (i.e. 5,000 to 10,000 years), because it occurs in a similar tectonic regime as the Poroutawhao Fault and the sub-parallel active offshore Kāpiti-Manawatu Fault System (Nodder et al., 2007), and broadly fits the pattern of deformation observed for other on-land faults in Horowhenua District, e.g. the Poroutawhao and Tokomaru faults. In this case, a FAZ has only been developed for the active fault trace near Oturoa Road.

5.3 Active folds

As discussed elsewhere, active folds are an important indicator of active tectonic deformation in the coastal and alluvial areas of the Horowhenua and neighbouring districts. The following paragraphs describe the main active folds within the Horowhenua District and gives an indication of the recurrence interval for deformation events. In this report, FAZs are not developed for active folds because associated deformation is too broadly distributed to be considered a life-safety hazard for buildings.

5.3.1 Oturoa Anticline

The Oturoa Anticline was formerly described in section 5.2.6 above, as part of the ‘Oturoa trace’. A 750 m long fold axis is mapped in association with the Oturoa Anticline, north of Waitarere Beach Road (Figure 5.13). The Oturoa Anticline is defined by a closed 20-m topographic contour, highlighting a local topographic high. We consider the recurrence interval for deformation related to the Oturoa Anticline to be the same as for the Oturoa trace, i.e., RI Class IV (5,000 to 10,000 years).

5.3.2 Foxton Anticline

The Foxton Anticline (Figure 5.1) occurs at the southern end of a zone of folding and contractional faulting which includes the Himitangi Anticline and Mt Stewart-Halcombe Fault in Manawatu District (see Figure A1.1). The Foxton Anticline is a c. 11 km long gentle anticlinal dome extending from the north bank of the Manawatu River (Figure 5.14), northwards to at least the Horowhenua boundary. In the Manawatu District, it is unclear whether the Foxton Anticline is the southern continuation of the Himitangi Anticline or the Mt Stewart-Halcombe Fault (with its own associated fold) (see Jackson et al., 1998), so the name Foxton Anticline is retained for this structure within the Horowhenua District.

We have mapped the axis of the Foxton Anticline using LiDAR data in combination with the upper extents of stream catchments that flow either east or west from the anticlinal axis down the limbs of the fold (e.g. Figure 3.2). The axis that we have mapped is approximate only and cannot be used to accurately assess the location of ground deformation.

Figure 5.14 The broad extent of the gently domed landscape of the Foxton Anticline (light brown area) and its fold axis (black line). The Manawatu River meanders around the topographic high produced by the Foxton Anticline on its way to the sea (Photo: L. Homer, GNS).

Surface profiles on the LiDAR DEM show that the Foxton Anticline has an amplitude (from crest to trough) of 10–15 m across older geomorphic surfaces (probably remnants of Q5b or Q4 surfaces, masked by dune sand) and a 2–6 m amplitude across younger surfaces (probably remnants of Q2a or Q1 surfaces). In general terms, these observations yield vertical rates of growth for the anticline which are between 0.1–0.25 mm/yr. The wavelength of warping associated with the Foxton Anticline spans a width of 5–10 km, meaning that the fold is a subtle feature in the coastal landscape (Figure 5.14). Profiles constructed from the LiDAR DEM indicate that the Foxton Anticline has a steeper eastern limb than the western one, so we infer that the fault associated with it, dips to the northwest. Based on the growth-rate range of this fold, a recurrence interval of >5000 years is suggested for the Foxton Anticline, which is similar to the activity on other active structures in this area. The Foxton Anticline approximates to the southern end of the 'HimitangiAnt' (anticline source) in the 2010 NSHM (Stirling et al. 2012), which has a recurrence interval of c. 6000 years.

5.3.3 Levin Anticline

The Levin Anticline (Figure 5.1, Figure 5.15) is defined by a broad, northeast-trending oval-shaped area of uplifted landscape, north of Levin. The uplifted surface is underlain by deposits mapped as Q5b, representing Last Interglacial marine terrace and beach deposits (Begg and Johnston, 2000; Clement et al., 2017). The southern and northern limits of the Levin Anticline are defined by the extents of the Ohau and Manawatu rivers, respectively, whose courses are partially diverted around the ends of the anticline.

We have mapped the axis of the Levin Anticline using LiDAR data in combination with the upper extents of drainage catchments that flow from the anticlinal axis down across the limbs of the fold to the southeast and northwest (e.g. Figure 3.2). The axis we have mapped (Figure 5.15) is approximate only and cannot be used to assess the location of future subtle ground deformation.

Profiles made using the LiDAR DEM show that the Levin Anticline has an amplitude from crest to trough of 10–15 m across remnants of Q5b surfaces. These observations can be used to generate vertical rates of growth for the anticline of c. 0.1–0.2 mm/yr. The wavelength of warping associated with the Levin Anticline spans a width of 3–4 km. Profiles suggest that the Levin Anticline has a steeper eastern limb than the western one, so we infer that the fault associated with it, dips to the northwest. Based on the growth-rate range of the fold, a recurrence interval of >5000 years is calculated for the Levin Anticline, which is similar to the activity of other active structures in this area. The 'LevinAnt' source (i.e. the fault associated with the Levin Anticline) in the 2010 NSHM (Stirling et al., 2012) has a mean recurrence interval of c. 4900 years.

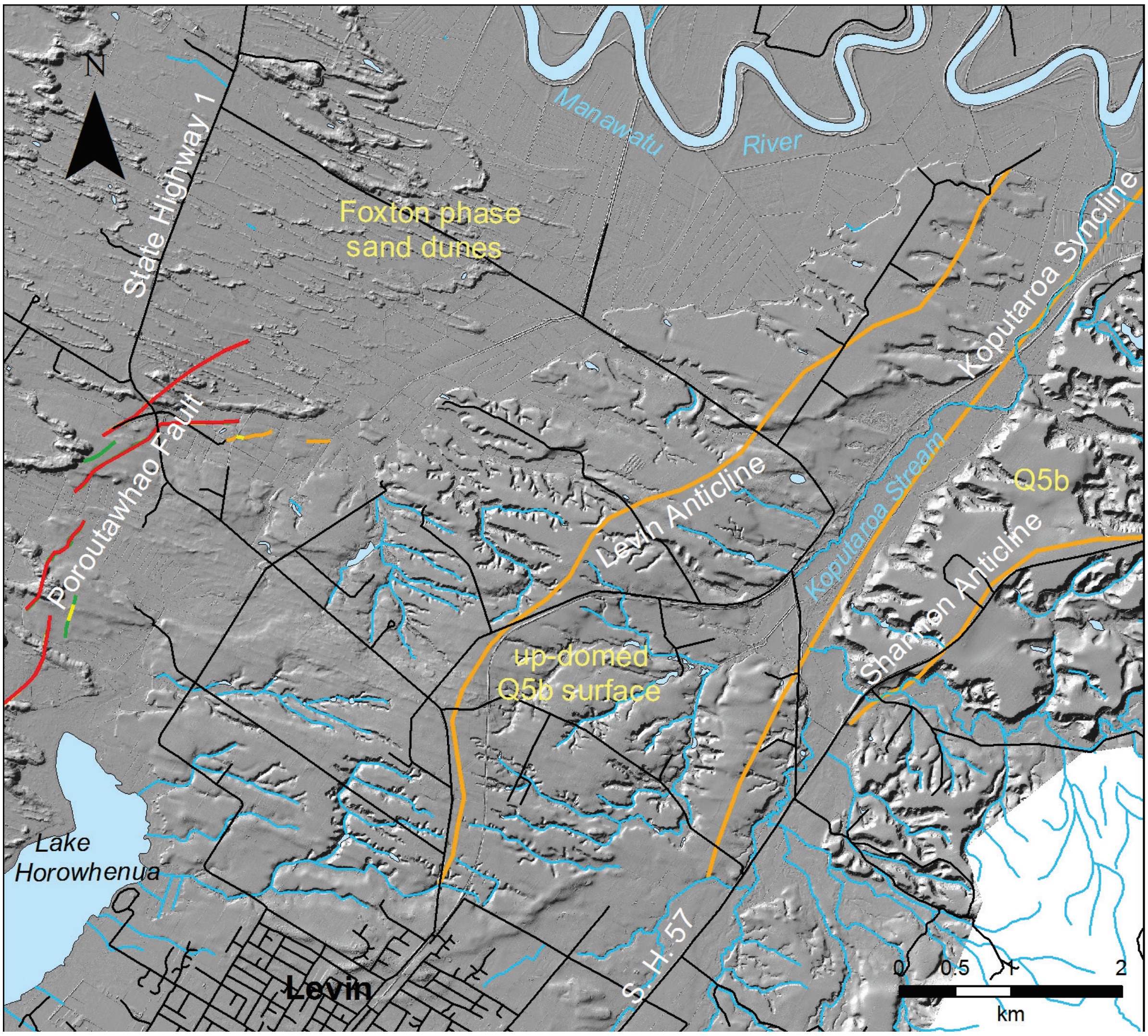


Figure 5.15 Geomorphology of the Levin and Shannon anticlines, northeast of Levin, on a LiDAR hill-shade model. The axial traces of the anticlines are marked by orange lines. Streams drain away from both sides of the axial traces. The anticlines deform Q5b marine/alluvial deposits which are elevated above the younger, incised Holocene landscape (Begg and Johnston, 2000).

5.3.4 Shannon Anticline

The Shannon Anticline forms a topographic high northeast of Levin, and c. 2.6 km east of the Levin Anticline. The Koputaroa Syncline is mapped between these anticlines following the location of Koputaroa Stream, which flows along this natural topographic low (Figure 5.15).

The Shannon Anticline was formerly mapped (Begg and Johnston, 2000) as a c. 5 km long curvilinear fold axis crossing a Q5b surface southwest of Shannon. In this study we have updated the QMAP fold axis location using LiDAR data. The axis mapped is approximate only and cannot be used to assess the location of ground deformation.

The 2010 NSHM (Stirling et al., 2012) shows the 'ShanonnAnt' source (i.e. the fault source related to the Shannon Anticline) as a 15 km long, NE-trending fault source, which is different to its geomorphic expression as mapped in QMAP and in this report. The mean recurrence interval for the 'ShanonnAnt' (anticline source) in the 2010 NSHM is c. 3500 years. We note that this value is rather short, in comparison to the recurrence intervals derived for other nearby folds and faults.

5.4 Summary of Active Faults with FAZs in Horowhenua District

We have defined FAZs for known active faults within the Horowhenua District. We have also updated and developed preliminary recurrence intervals for large earthquakes related to active faults, that can be used in conjunction with the MfE Guidelines. For faults with no information for estimating a recurrence interval from geologic data, or for which there is no evidence of activity, we do not define a FAZ. Similarly, because it is very difficult to estimate the location and amount of co-seismic deformation (tilting, warping) related to folds, we do not provide FAZs for active folds. Table 5.1 below shows new and updated recurrence interval for known active faults in Horowhenua District.

Table 5.1 Fault recurrence interval (RI) information for faults within the Horowhenua District.

Fault	RI Class	RI range (years)	RI Class Confidence	Data source
Northern Ohariu Fault	II	>2000 to ≤3500	M	1, 3
Otaki Forks Fault	III	>3500 to ≤5000	M	2, 3
Tokomaru Fault	IV	>5000 to ≤10,000	M	4
Mangaore Fault	IV	>5000 to ≤10,000	L	4
'Cluain traces'	V	>10,000 to ≤20,000	L	4
Poroutawhao Fault	IV	>5000 to ≤10,000	M	4
'Oturoa trace'	IV	>5000 to ≤10,000	M	4

Notes: RI Class Confidence: M, Medium – uncertainty in average RI embraces a significant proportion (>~25%) of two RI Classes; the mean of the uncertainty range typically determines into which class the fault is placed; L, Low – uncertainty in RI embraces a significant proportion of three or more RI Classes, or there are no fault-specific data (i.e., RI Class is assigned based only on subjective comparison with other faults).

Sources: 1, Van Dissen et al. (2003); 2, Van Dissen et al. (2001); 3, NZAFD (https://data.gns.cri.nz/af/) and Langridge et al. (2016); 4, this study.

6.0 PALMERSTON NORTH CITY

6.1 Introduction

This study represents the first time that active fault mapping has specifically been collated for Palmerston North City (territory). Using airborne LiDAR-derived topography and previous datasets, it was possible to map out active faults and folds (Figure 6.1), some of which were previously unrecognised. The new mapping builds on data from QMAP (Begg and Johnston 2000; Lee and Begg 2002) and the NZAFD (Langridge et al., 2016) which had the Northern Ohariu Fault and Pohangina Anticline/unnamed fault as the only active structures within the district (Figure 1.1). Active (anticlinal) folds originally mapped by QMAP (e.g. Lee and Begg, 2000) have been re-defined on the basis of their axial traces using airborne LiDAR data (see Section 4.5 of this report).

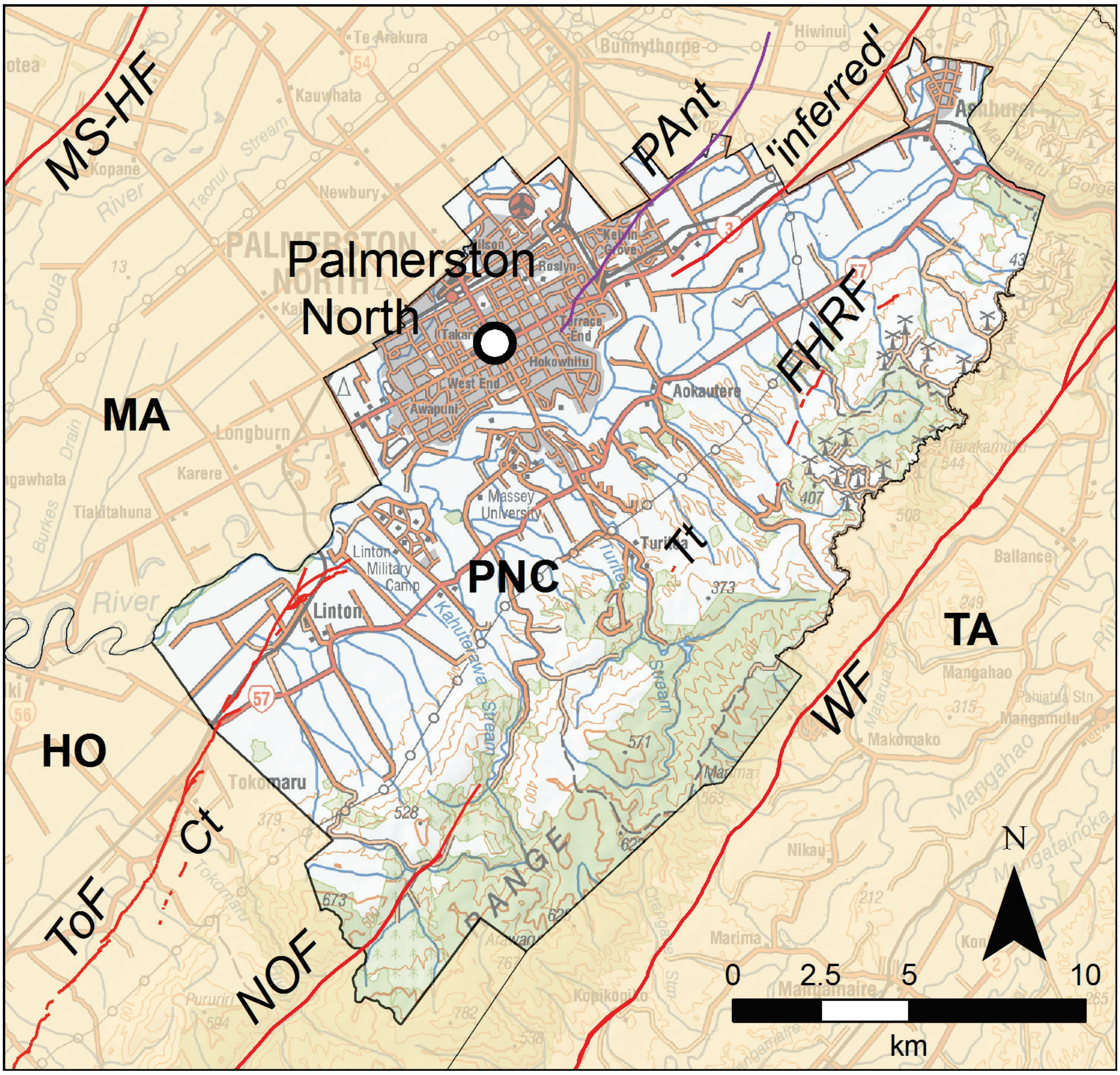


Figure 6.1 New and updated active faults (red) and folds (purple) in Palmerston North City (PNC) and surrounding districts, as defined in this study (for district names see Figure 1.1). Fault name abbreviations are: WF, Wellington Fault; NOF, Northern Ohariu Fault; ToF, Tokomaru Fault; FHRF, Forest Hill Road Fault; and MS-HF, Mt Stewart-Halcomb Fault, and Tt, Turitea and Ct, Cluain traces. Fold name is: PAnt, Pohangina Anticline. The Pohangina Anticline is associated with an unnamed inferred fault, described below.

Active faults within Palmerston North City occur as part of the wider NIDFB formed in association with oblique subduction, (e.g. the Northern Ohariu Fault), and within the fringes of the Tararua Ranges, (e.g. the Tokomaru and Mangaore faults) (Beanland, 1995; Litchfield et al., 2014). The Pohangina Anticline is an active fold that occurs in association with an unnamed, inferred fault. Active faults are also present in the surrounding districts, (e.g. the Wellington and Mt Stewart-Halcombe faults) (Begg and Johnston, 2000), highlighting that active tectonic deformation occurs throughout the region.

Here we describe each of the active faults and folds in the district with photographs and maps of locations where fault traces and/or scarps are identifiable in the field. Further information on some of these faults can be found in the previous chapter on the Horowhenua District.

6.2 Active Faults

6.2.1 Northern Ohariu Fault

Within Palmerston North City, the northeast-striking dextral-slip Northern Ohariu Fault runs from the south in the Horowhenua District via the Kahuterawa Stream basin, across rural and forestry land. The active trace of the Northern Ohariu Fault has been mapped as far north as Kahuterawa Road for the QMAP program (Lee and Begg 2002) (Figure 6.2).

Due to the lack of LiDAR coverage at the edge of the Tararua Range, the Northern Ohariu Fault mapping in this report comes from QMAP and the NZAFD. These data are used to develop a Fault Awareness Area (FAA) for the Northern Ohariu Fault in Palmerston North City. The width of the FAA is 500 m, which reflects the 1: 250,000 scale accuracy of the QMAP data.

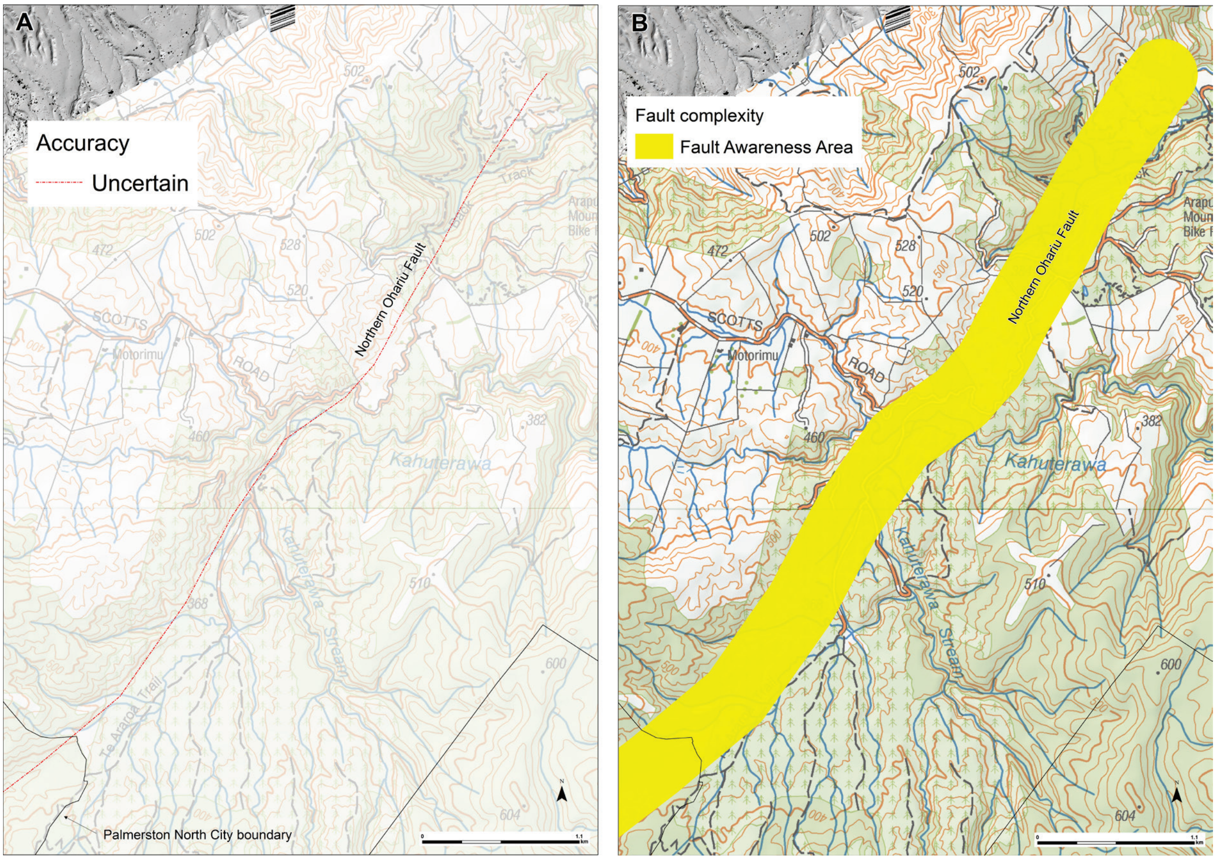


Figure 6.2 Active fault and Fault Awareness Area (FAA) maps for the Northern Ohariu Fault (NOF) in Palmerston North District.A) Map showing the location and accuracy of mapping for the NOF where no airborne LiDAR data exists. B) FAA for the NOF.

The Northern Ohariu Fault has previously been assigned as RI Class II (Table 3.1 and Table 5.1) (Van Dissen et al., 2003), i.e. repeated surface faulting events would be expected every c. 2000–3500 years. This information comes from a comparison with the Ohariu Fault as observed from geologic studies in the Wellington Region (e.g. Litchfield et al., 2003). In addition, fault traces are observed crossing Holocene terraces and some of the fault displacements observed are of a similar size to those measured on the Ohariu Fault, further south (Palmer and Van Dissen 2002). These authors estimate a lateral slip rate of 1–3 mm/yr., which is similar to the Ohariu Fault. Without any new specific geologic or paleoseismic data, we infer that the Northern Ohariu Fault should remain as RI Class II (>2000 to ≤3500 years).

As part of this project we have developed a FAZ for the Northern Ohariu Fault (NOF) in Palmerston North City (Figure 6.2). The width of the FAZ depends on the accuracy of mapping the fault, i.e. whether the fault has been mapped and attributed as 'accurate, approximate or uncertain' in location. A RI Class II status is applied to the entire length of the NOF (Table 6.1).

6.2.2 Tokomaru Fault

The NNE-striking, reverse-slip Tokomaru Fault was first recognised and mapped in the southwestern part of PNC by Beetham et al. (2011). At its southern end in Horowhenua District, the Tokomaru Fault branches away from the Northern Ohariu Fault at Makahika Stream (Figure 5.5). From Tokomaru village, the fault is clearly identifiable on a LiDAR hill-shade model to the PNC boundary. In the southernmost 2 km of PNC, the Tokomaru Fault is coincident with the edge of the LiDAR coverage, so the locations of fault traces are generally mapped as approximate to uncertain. In the field we located active traces of the Tokomaru Fault across Craws and Akers roads near Linton (Figure 6.3). Near Linton the Tokomaru Fault splays into a series of fanning fault traces (referred to as a 'horsetail') (Figure 6.4). Here, the northeast-trending trace of the fault continues to near the Manawatu River, but is not visible on the north side of the river as an active trace. This may be because the river terraces on the south side of the river are more elevated (probably Q2a terraces; 12,000–24,000 yrs. old), and preserve fault scarps, while the terraces on the north side of the river are Holocene in age and are younger than the most recent surface rupturing earthquake.

Figure 6.3 A subtle scarp of the active Tokomaru Fault located across and to the south of Akers Road (marked by arrows). The hills in the distance mark the western edge of the Tararua Ranges.

Recurrence interval data for the Tokomaru Fault comes from geomorphic observations of the fault cross-cutting a series of alluvial terraces near Tokomaru. A discussion of the activity of the Tokomaru Fault appears in Section 5.2.3 of this report. These data led us to infer that surface-rupturing earthquakes can occur on the Tokomaru Fault about every 6000–12,000 years on average. We therefore suggest that the Tokomaru Fault be placed in RI Class IV, where surface rupture on a fault would be expected to occur every >5000 to ≤10,000 years.

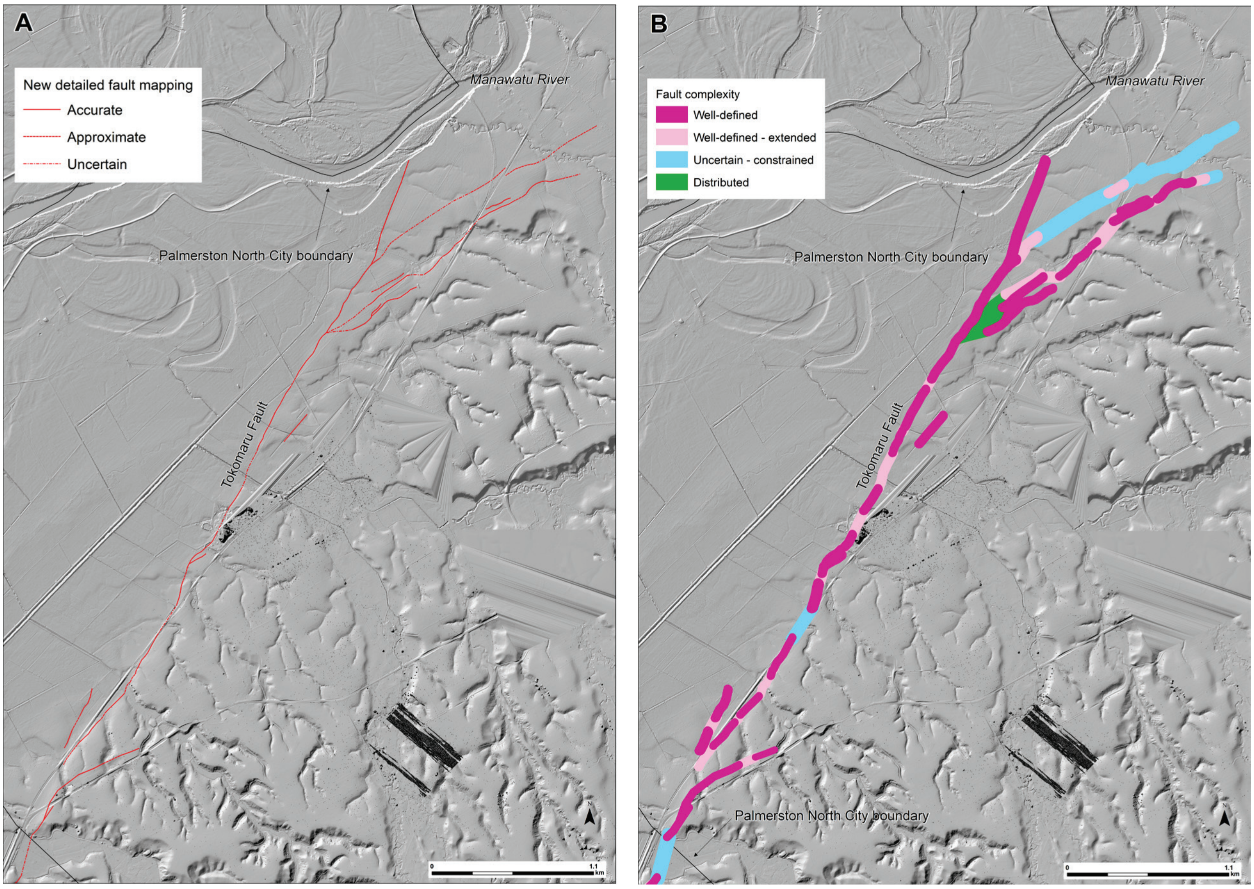


Figure 6.4 Active fault and Fault Avoidance Zone (FAZ) maps for the Tokomaru Fault in Palmerston North District.A) Map showing the location and accuracy of mapping for the Tokomaru Fault where no airborne LiDAR data exists. B) FAZs for the Tokomaru Fault.

As part of this project we have developed a FAZ for the Tokomaru Fault in Palmerston North City (Figure 6.4). The width of the FAZ depends on the accuracy of mapping the fault, i.e. whether the fault has been mapped and attributed as ‘accurate, approximate or uncertain’ in location. A RI Class II status is applied to the entire length of the Tokomaru Fault (Table 6.1).

6.3 Possibly Active Faults and Traces

6.3.1 Forest Hill Road Fault

The Forest Hill Road Fault (Figure 6.5) is a newly recognised fault in the foothills of the Tararua Ranges east of Palmerston North and to the southeast of the Manawatu River. The Forest Hill Road Fault is mapped from LiDAR data as a series of discontinuous linear traces associated with a hillslope break and faceted ridges (to the southeast). The southernmost known traces of the fault occur between Aokautere Road and the Te Rere Hau Wind Farm, where it strikes northeast toward Forest Hill Road. The northernmost known trace occurs to the west of Adams Peak. These traces cut across hill country that is mapped as early Quaternary alluvium (eQa; where 423,000 years to 1.8 million years) based on QMAP geology (Lee et al., 2002). Because the surfaces that are being cut by the Forest Hill Road Fault are quite old, it is entirely possible that this fault has not been active in the last 125,000 years, which is the upper limit for classifying a fault as active in New Zealand (Langridge et al., 2016).

In the case of the Forest Hill Road Fault, while we recognise that a fault exists, it cannot be demonstrably proven to be active. Even if it had been active in the last 125,000 years, it shows little evidence for repeated activity in this time-period, e.g. scarps across late Quaternary units and deposits, or occurrence of Late Quaternary age terrace sequences. We classify the Forest Hill Road Fault as “possibly active” and provide it with a Fault Awareness Area (FAA), because it may be an active fault, and because in future it may be relevant to further define its activity. There are no planning restrictions associated with FAAs.

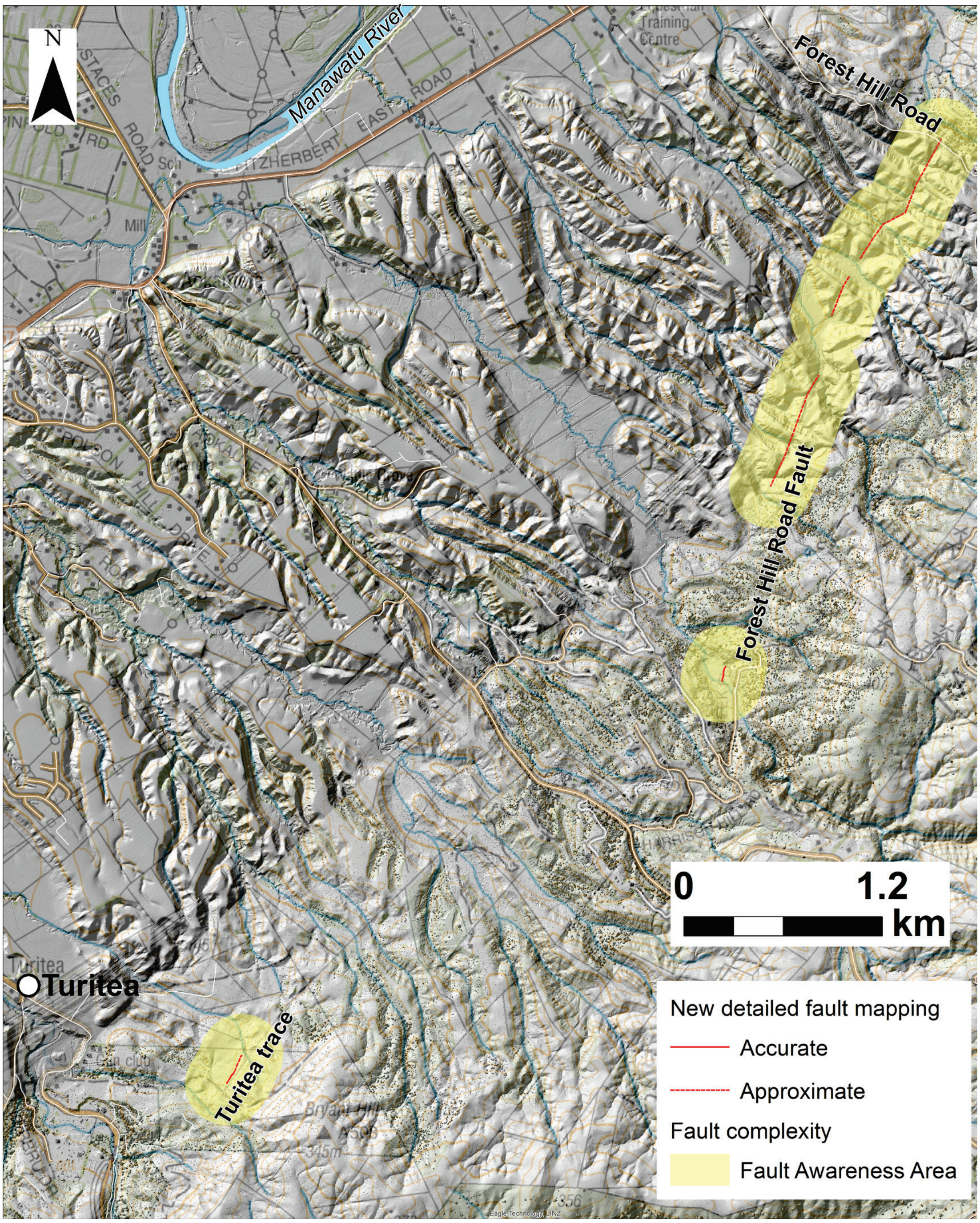


Figure 6.5 Annotated fault trace and Fault Awareness Area map for the Forest Hill Road Fault and ‘Turitea trace’ southeast of Palmerston North.

6.3.2 Turitea Trace

The 'Turitea trace' (Figure 6.5) is a newly recognised fault in the foothills of the Tararua Ranges east of Palmerston North and to the southeast of the Manawatu River. The Turitea trace is a NE-trending trace located 1.4 km southeast of Turitea at the foot of Bryant Hill. The mapped traces there have a total length of c. 200 m. The traces define a short fault of unknown activity. The geological units in this locality are Early Quaternary alluvial deposits of the Mangahao Formation (Lee and Begg 2002).

In the case of the Turitea traces, while we recognise that a fault exists there, it cannot be demonstrably proven to be active. Even if it had been active in the last 125,000 years, it shows no evidence for repeated activity in this time-period, e.g. scarps across late Quaternary units and deposits, or occurrence of Late Quaternary age terrace sequences. We classify the Turitea trace as "possibly active" and provide it with a FAA, because it may be an active fault, and because in future it may be relevant to further define its activity. There are no planning restrictions associated with FAAs.

Both the Turitea trace and the Forest Hill Road Fault are on-strike to the northeast of the Northern Ohariu Fault. It is possible that they are all genetically linked, though the Turitea trace and the Forest Hill Road Fault show no evidence for recent activity.

6.4 Other Faults

6.4.1 Fault Associated with the Pohangina Anticline

An inferred active fault is shown in both the QMAP and the NZAFD datasets (Lee and Begg 2002; Langridge et al. 2016), striking northeast, between Whakarongo in Palmerston North City and the headwaters of the Pohangina River in Manawatu District, running parallel to the Pohangina river valley. This unnamed fault is interpreted to be related to the Pohangina Anticline (Figure 6.6), which is described in greater detail in the next section. In places, the inferred fault trace and anticline axis approach to within 2 km of each other

There are no visible traces on the LiDAR data for this fault, and so we retain the classification as an inferred fault. An inferred fault can be a buried fault – in this case, the inferred fault a buried reverse fault related to the active Pohangina Anticline. At its southern end, the unnamed inferred fault is beneath the Q1a (Holocene; 0–12,000 yr.) alluvium of the Manawatu River. Farther north, the inferred fault is beneath Q2a (latest Pleistocene 12,000–24,000 yr.) and Q3a (late Pleistocene; 24,000–59,000 yr.) alluvium of the Manawatu and Pohangina river systems, and across older Tertiary bedrock farther north of that (Lee et al., 2011).

Neither the location nor the activity of this unnamed inferred fault was confirmed during the course of this study. In addition, even if the location of a buried fault at depth was well-known, it would not be practical to develop a FAZ for such a feature, without the presence of surface geomorphology defining an active fault trace or scarp. For these reasons, we do not develop a FAZ for this unnamed fault in this study, and in future it will be removed from the NZAFD. Should movement occur on this inferred fault at depth it would likely generate damaging levels of earthquake ground shaking, but the ground deformation (i.e., gentle warping and/or tilting) that could result from such fault movement at depth would – in all likelihood – not be severe enough to warrant consideration within the framework of the MfE Guidelines.

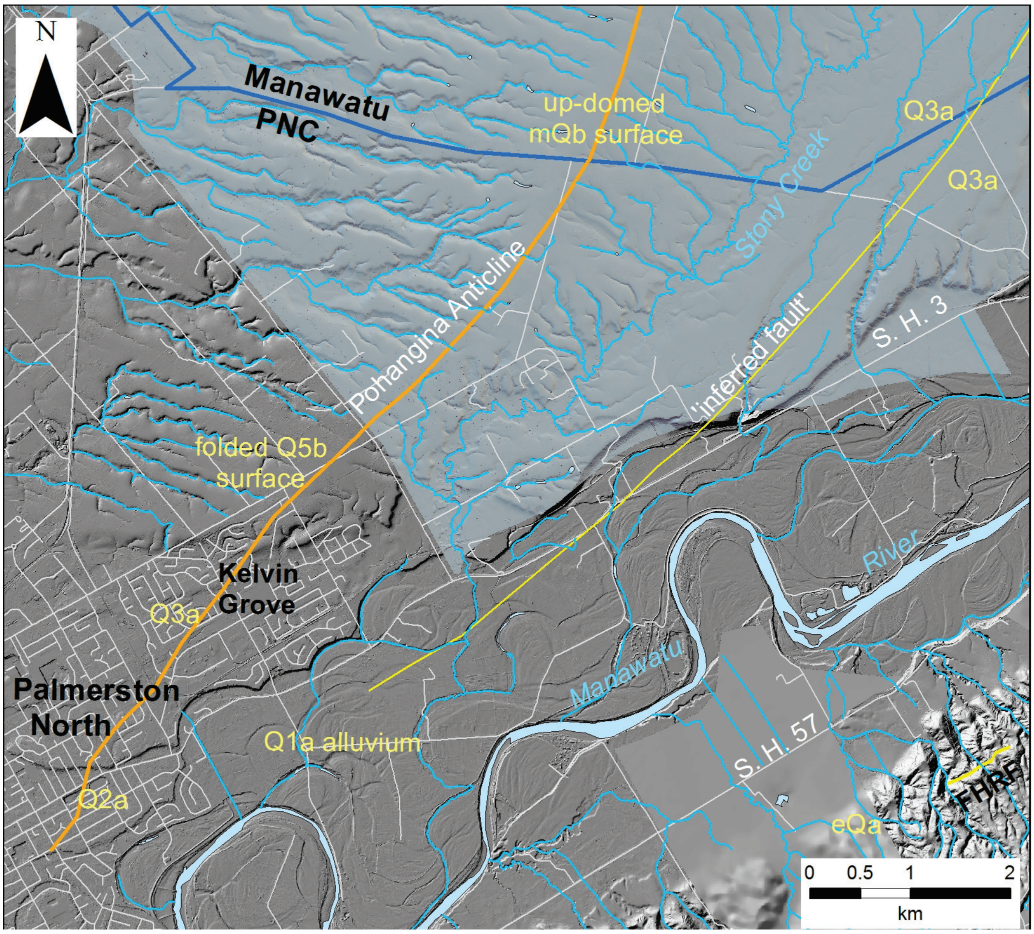


Figure 6.6 A map of the active Pohangina Anticline (axis in orange) and nearby structures in the PNC area. The grey topographic shading is a combination of LiDAR and regional hill-shade models.

6.5 Active Folds

6.5.1 Pohangina Anticline

The Pohangina Anticline (Figure 6.6) is a well-defined, broad northeast-trending active fold that occurs within PNC and the Manawatu District over a distance of at least 35 km (Brackley 1999; Jackson et al., 1998; Lee and Begg, 2000). The Pohangina Anticline deforms mid to late Quaternary alluvial sediments that overlie Tertiary bedrock northeast of Palmerston North (Lee and Begg 2002; Lee et al., 2011). The anticline is asymmetric, with a steeper limb on its eastern flank, from which it is inferred that it is related to a buried fault that dips to the west and would daylight to the east of the anticline if it ruptured to the ground surface.

Within the boundaries of PNC, we have mapped the axis of the Pohangina Anticline (Figure 6.6) using LiDAR data in combination with the upper extents of stream drainage catchments that flow from the anticlinal axis down across the limbs of the fold to the east and west (e.g. Figure 3.2). An important aspect of updating the mapped Pohangina Anticline using LiDAR data was to test whether the anticline could be mapped further south toward the Palmerston North urban area (Figure 6.6). The axis we have mapped is indicative only and cannot be used to assess the location of ground deformation.

North of the Palmerston North urban area, the Pohangina Anticline deforms mid Quaternary (mQb; 186,000–423,000 years) and late Quaternary (Q5b; 71,000–128,000 years) shallow marine sediments (Lee and Begg, 2002). Farther southwest, it folds deposits mapped as Q3a alluvium (24,000–59,000 years). In the north-eastern part of the urban area, in Kelvin Grove, it appears likely that the next youngest surface (Q2a; 12,000–24,000 years) is gently folded (Figure 6.6). There is no clear evidence for tilting or deformation of Holocene alluvial surfaces (Q1a; 0–12,000 years).

These observations are useful because they allow us to characterise the activity and potential recurrence interval of Pohangina Anticline folding events. In general terms, we infer that there have been one or more folding events since the formation and/or abandonment of the Q2a surface. This produces a preliminary recurrence interval range of 6000–24,000 years. This range overlaps RI Classes IV, V and VI. In this case, we place the Pohangina Anticline into RI Class IV, because it has probably had a deformation event post-abandonment of the Q2a surface. The 2010 NSHM estimates a mean recurrence interval for the 'PohanginaAnt' earthquake source of c. 8350 yr. (Stirling et al. 2012).

A preliminary uplift rate can be estimated from the shape of warping across the Q3a surface (24,000–59,000 years) near Roslyn. Assuming that this surface was originally flat, then a profile from the LiDAR data shows that there has been 12–14 m of upward warping of the Q3a surface, which yields vertical rates of growth for the anticline of ≤0.2–0.6 mm/yr. (these values are maximum values assuming that the surfaces had some initial dip to the southwest). This range of uplift rates is consistent with other structures (faults and folds) in the region that have repeated movements every 5000–10,000 years (Van Dissen et al., 2003).

As with other active folds covered in this report, we do not define a FAZ for the Pohangina Anticline.

6.6 Summary of Active Faults with FAZs in Palmerston North City

We have defined FAZs for known active faults within PNC and developed preliminary recurrence interval data for large earthquakes related to active faults, that can be used in conjunction with the MfE Guidelines. For faults with no means of estimating a recurrence interval from geologic data, or for which there is no evidence of activity, we do not define a FAZ. Similarly, because it is very difficult to estimate the location and amount of co-seismic deformation (tilting, warping) related to folds, we do not provide FAZs for active folds. Table 6.1 below shows the updated recurrence interval classifications.

Table 6.1 Fault recurrence interval (RI) data for faults within Palmerston North City (modified from: Van Dissen et al., 2003).

Fault	RI Class	RI (range, years)	RI Class Confidence	Source
Northern Ohariu Fault	II	>2000 to ≤3500	M	1, 2
Tokomaru Fault	IV	>5000 to ≤10,000	M	3
Forest Hill Road Fault	-	(not classified)	-	3
'unnamed' fault'	-	(not classified)	-	2, 3

Notes: RI Class Confidence: M, Medium – uncertainty in average RI embraces a significant proportion (>~25%) of two RI Classes; the mean of the uncertainty range typically determines into which class the fault is placed; L, Low – uncertainty in RI embraces a significant proportion of three or more RI Classes, or there are no fault-specific data (i.e., RI Class is assigned based only on subjective comparison with other faults).

Sources: 1, Van Dissen et al. (2003); 2, NZAFD (https://data.gns.cri.nz/af/) and Langridge et al. (2016); 3, this study.

7.0 SUMMARY

Active fault mapping has been undertaken for Horizons Regional Council covering the districts of Horowhenua and Palmerston North City for the purposes of planning with regards to active faults. A mappable active fault is defined as a geologic fault that has ruptured the ground surface during the last 125,000 years or less. A variety of mapping platforms have been used to map active faults, and where available, airborne LiDAR data has been particularly useful for accurately mapping active faults. Preliminary updated Recurrence Interval Class information has been provided, based largely on inferences from geomorphic relationships along the faults and via comparisons with better studied faults nearby.

In the Horowhenua District, the active faults recognised and mapped are the Northern Ohariu, Otaki Forks, Tokomaru (new) and Poroutawhao (new) faults. Two further active traces have been mapped; these are both too short to be considered separate faults and named. These are the 'Cluain traces' (new) and the 'Oturoa trace' (new). Fault Avoidance Zones have been defined for these active faults according to the Ministry for the Environment's (MfE) guidelines relating to building on or near active faults (Kerr et al., 2003). The Mangaore Fault is identified as a "possibly active" fault, however, because we cannot document an active trace along its length, it is not included as an active fault, nor provided with a Fault Avoidance Zone. Active folds have also been mapped and defined within Horowhenua District as part of this study. These are the Levin, Shannon, Foxton (re-named), and Oturoa (new) anticlines. This study does not present Fault Avoidance Zones for active folds because the location and associated deformation is too broadly distributed to be characterised for fault avoidance purposes. Fault Awareness Areas (FAAs) are developed for parts of some faults in this study. FAAs are designed with a width of ±250 m, but do not carry the regulatory levels that are suggested in the MfE Guidelines. In future, if development is proposed for areas with a FAA status, then further fault mapping and/or geologic studies would be required to better define the location of surface faulting and deformation.

The preliminary recurrence interval (RI) classes defined in this study for the active faults in the Horowhenua District are as follows: Northern Ohariu Fault (RI Class II; >2000 to ≤3500 years), Otaki Forks Fault (RI Class III; >3500 to ≤5000 years), Tokomaru and Poroutawhao faults and 'Oturoa trace' (RI Class IV; >5000 to ≤10,000 years); and the 'Cluain traces' (RI Class V; >10,000 to ≤20,000 years) (Table 5.1).

In Palmerston North City, the active faults recognised and mapped are the Northern Ohariu and Tokomaru faults and Fault Avoidance Zones have been defined for them. Two other faults, the Forest Hill Road fault, and a fault trace (the 'Turitea trace') are identified as "possibly active" faults, but, because we cannot document any traces that are definitively active along their lengths (i.e. proven activity during last 125,000 years), they are not included as active faults, and only Fault Awareness Areas have been developed for them. Another unnamed and inferred fault, which is sub-parallel to the Pohangina Anticline, has no known surface trace; therefore, in this case we do not provide a Fault Avoidance Zone for it either. An active fold (the Pohangina Anticline) has been updated and defined within Palmerston North City as part of this study. We do not present a Fault Avoidance Zone for the Pohangina Anticline because the exact location or amount of deformation related to it cannot be easily described for folds.

The preliminary MfE RI Classes defined in this study for the active faults in Palmerston North City are as follows: Northern Ohariu Fault (RI Class II; >2000 to ≤3500 years) and Tokomaru, Fault (RI Class IV; >5000 to ≤10,000 years) (Table 5.1).

8.0 RECOMMENDATIONS

We recommend that the Fault Avoidance Zones (FAZ) developed for the Horowhenua District and Palmerston North City during this study and the RI Class information provided in this report for those faults, along with the MfE Guidelines (Kerr et al., 2003), be adopted in future planning decisions regarding development of land on or close to active faults. For use with the MfE Guidelines, these then need to be considered for individual planning decisions based on the status of the land (Greenfield vs. Already Developed/Subdivided) and the Building Importance Category intended for the site (see Tables in Appendix 3). Fault Awareness Areas, developed for parts of some faults indicated here, carry no guidelines related to restricting planning decisions.

We recommend that the MfE Guidelines be treated as a standard reference when considering resource consent applications in these districts. In addition, we recommend that GIS data for FAZs be provided on LIM reports so that buyers and sellers of land are aware that a natural hazard exists there. This GIS data can be used at an individual property specific scale.

A caveat to this work is that much of the effort put into developing recurrence interval values for these faults is preliminary. We recommend that a planned approach is developed between GNS Science, Horizons and funding agencies to attain better geologic constraints on the slip rate, recurrence interval and/or timing of past surface-rupturing earthquakes on some of the active faults described in this report, for example, the Poroutawhao and Tokomaru faults.

We recommend that the methodology we have developed for mapping active faults and developing FAZs that are compatible with and facilitate the utilisation of the MfE Guidelines be continued for the other districts in Horizons region. A straightforward approach would be to continue this work in the neighbouring districts of Manawatu and Rangitikei, and to later address Whanganui, Ruapehu and Tararua districts.

9.0 ACKNOWLEDGMENTS

We wish to thank Horizons Regional Council for adopting this work as part of its natural hazards program and for providing airborne LiDAR data to GNS Science as part of the project. We wish to thank Dr. Dougal Townsend, Russ Van Dissen, and Dr. Nicola Litchfield for reviewing this report. David McCorkindale (Horowhenua D.C.) provided additional review comments. Some fault mapping was provided by Dr. Dougal Townsend.

10.0 REFERENCES

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APPENDICES

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APPENDIX 1 STYLES OF FAULTING IN THE DISTRICTS OF HORIZONS REGION

The following is a brief introduction to the tectonics and active faulting across the Horizons Region. The Tararua District spans the fore-arc region of the HSM to the crest of the axial ranges (Figure 1.1 and Figure 2.2). The district is characterised by tectonic deformation dominated by strike- slip, oblique-slip and reverse faulting. Onshore, the Tararua District hosts the greatest amount of tectonic strain, measured in terms of fault slip rate, for any district within the region (Litchfield et al. 2014). The following are a list of the most active known faults in the district: Alfredton, Saunders Road, Pa Valley, Waipukaka, Makuri-Waewaepa, Waitawhiti, Pahiatua, Ruataniwha, Woodville, Mohaka and Wellington faults (Figure 1.1 and Figure 2.2).

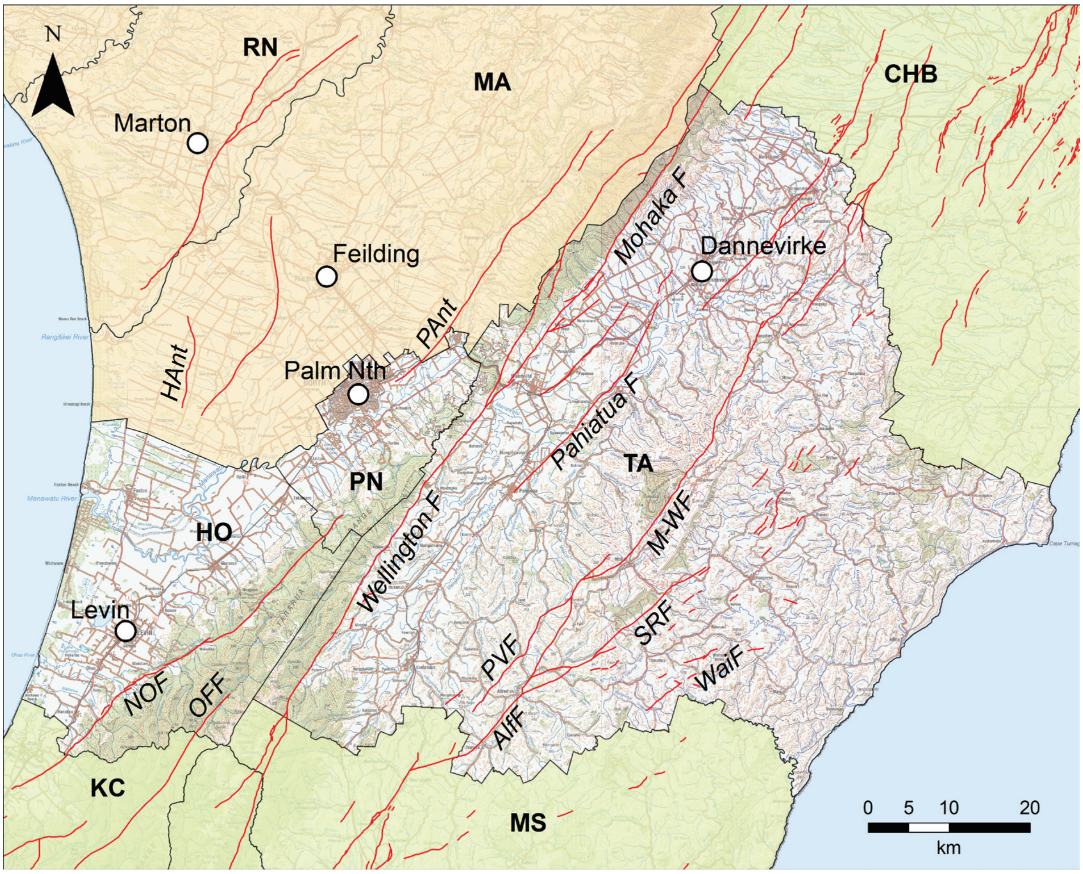

Figure A1.1 Active fault and fold map for the southern Horizons Region spanning Tararua, Horowhenua and Palmerston North districts study (fault location data comes from NZAFD; https://data.gns.cri.nz/af/ prior to this study). For district names see Figure 1.1; also KC, Kapiti Coast, MS, Masterton, CHB, Central Hawke's Bay districts. Fault and fold names are abbreviated to: AlfF, Alfredton Fault, WaiF, Waitawhiti Fault; PVF, Pa Valley Fault, SRF, Saunders Road Fault; NOF, Northern Ohariu Fault; and OFF, Otaki Forks Fault, PAnt, Pohangina anticline and HAnt, Himitangi anticline.

The Palmerston North City[6] and Manawatu districts border the Tararua District at the crest of the axial ranges. These districts span from the axial ranges to the Wanganui Basin (Figure 1.1 and Figure 2.2). The main styles of faulting in these districts are strike-slip and reverse faults and associated folds. Major active structures in Manawatu District include the Ruahine and Mt Stewart-Halcomb faults and the Pohangina Anticline (Figure 1.1).

[6] Horowhenua and Palmerston North City are expanded on in chapters 5 and 6.

The Rangitikei and Whanganui districts span most of the back-arc region of the HSM and cover the northern uplifted portion of the Wanganui Basin. There are only a few named active faults in these districts, including the Leedstown, Putorino, Snowgrass and Nukumaru faults (Figure 1.1). The two major styles of active fault movement in this area are reverse and normal.

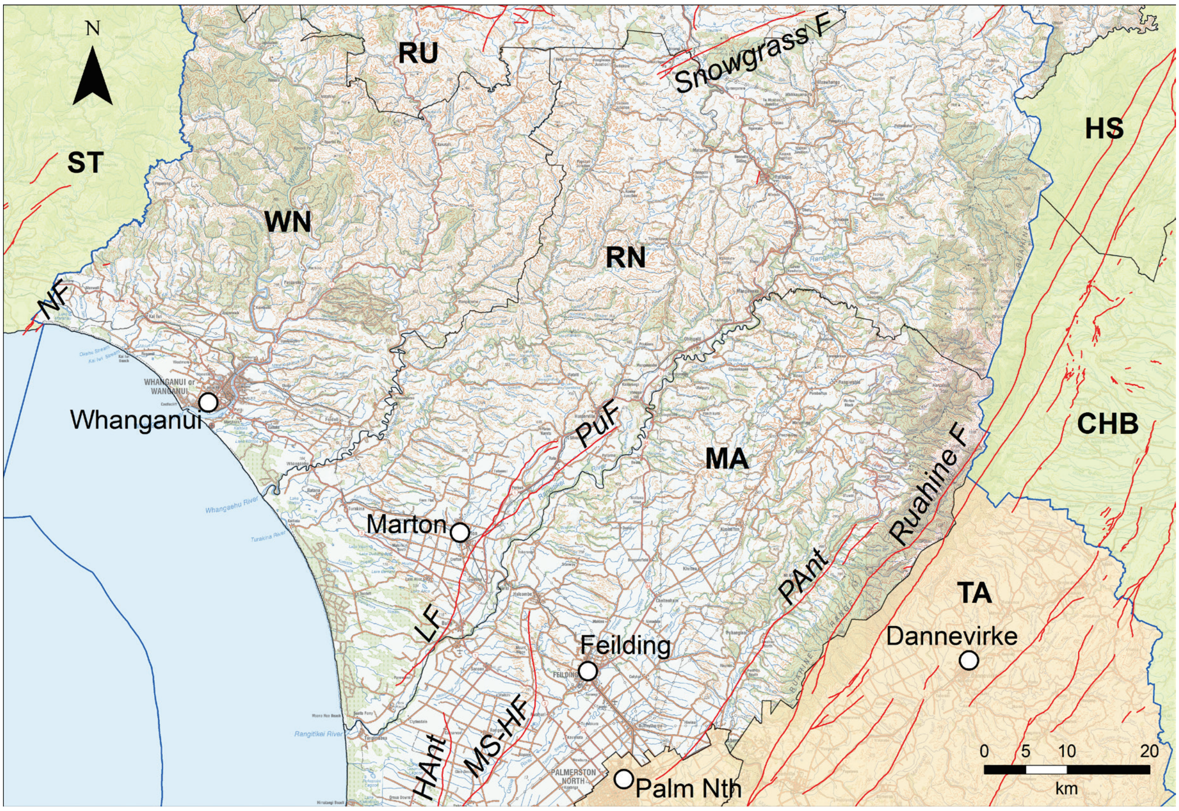

Figure A1.2 Location of active faults and folds in the central part of the Horizons Region spanning most of the Manawatu (MA), Whanganui (WN) and Rangitikei (RN) districts (fault location data comes from the NZAFD; https://data.gns.cri.nz/af/ prior to this study). For district names see Figure 1.1; also, ST, South Taranaki, HS, Hastings; and CHB, Central Hawke's Bay districts. Fault and fold names are abbreviated to: MS-HF, Mt Stewart-Halcomb Fault, LF, Leedstown Fault; PuF, Putorino Fault, and NF, Nukumaru Fault, PAnt, Pohangina anticline and HAnt, Himitangi anticline.

In the northern part of Horizons region, Ruapehu District overlaps the southern end of the Taupo Volcanic Zone (TVZ). Active faulting within the TVZ is related to extension and normal faulting within the Taupo Rift (Figure A1.3; Villamor and Berryman, 2006b). There are many named active normal faults in Ruapehu District, including the: Ohakune, Karioi, Snowgrass, Rangipo, Moawhango, Wahianoa, Raetihi (North and South), Raurimu, National Park and Waihi faults (Villamor and Berryman, 2006a).

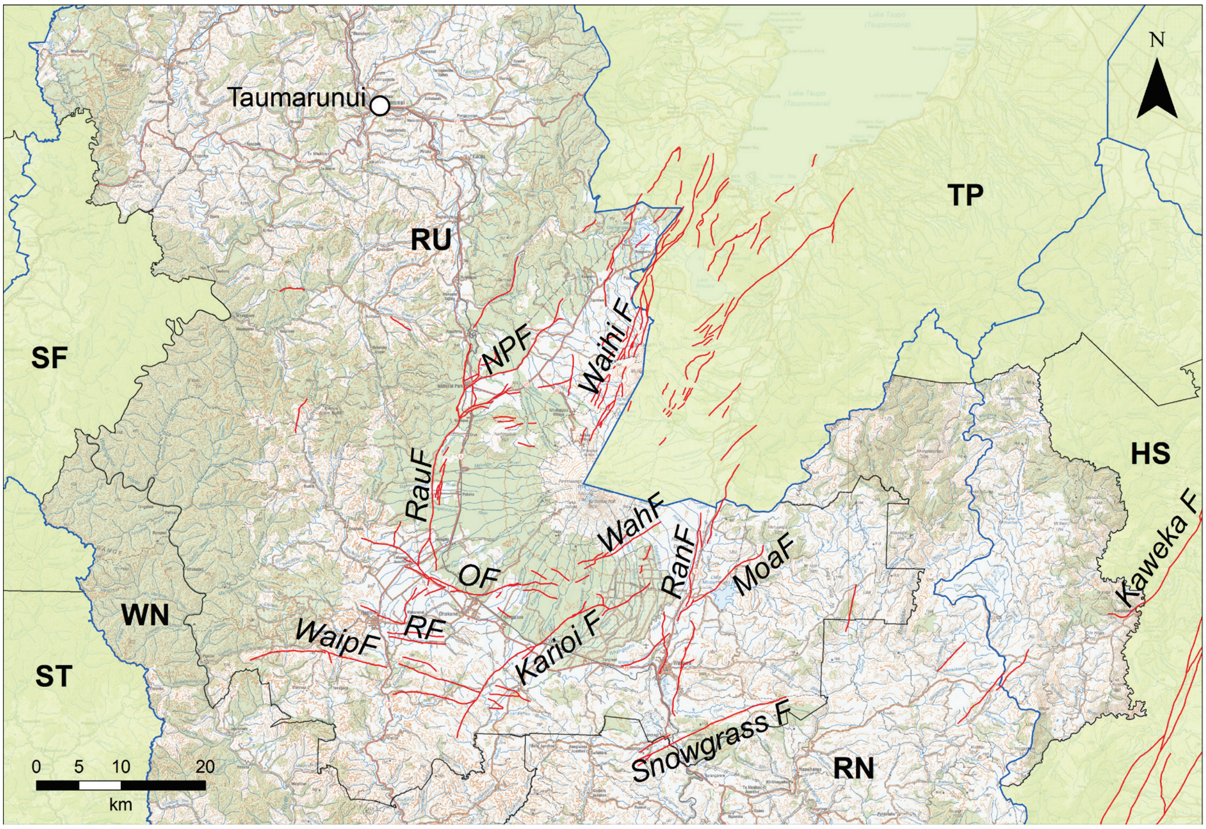

Figure A1.3 Location of active faults and folds in the northern part of the Horizons Region spanning most of Ruapehu (RU) District and surrounding areas (data from the NZAFD; https://data.gns.cri.nz/af/ prior to this study). For district names see Figure 1.1; also, ST, South Taranaki, SF, Stratford; TP, Taupo; HS, and Hastings districts. Fault names are abbreviated to: WaipF, Waipuna Fault; RF, Raetihi Fault; OF, Ohakune Fault, RauF, Raurimu Fault; NPF, National Park Fault; WahF, Wahianoa Fault; RanF, Rangipo Fault; and MoaF, Moawhango Fault.

APPENDIX 2 STYLES OF FAULT MOVEMENT

Faults can be categorised as: strike-slip faults, where the dominant style (sense) of motion is horizontal, and dip-slip faults, where the dominant sense of motion is vertical and occurs up or down the dip plane of the fault, and oblique-slip faults, where there is both a dip-slip and strike-slip component of motion. Dip-slip faults can be divided into reverse and normal faults. Active anticlinal folds typically form in relation to reverse faults.

A2.1 Strike-Slip Faults

Strike-slip refers to a style of faulting where the dominant sense of motion is horizontal, and therefore slip occurs along the strike of the fault. Strike-slip faults are defined as either right-lateral (dextral), where the motion on the opposite side of the fault is to the right (Figure A2.1), or, left-lateral (sinistral) where the opposite side of the fault moves to the left.

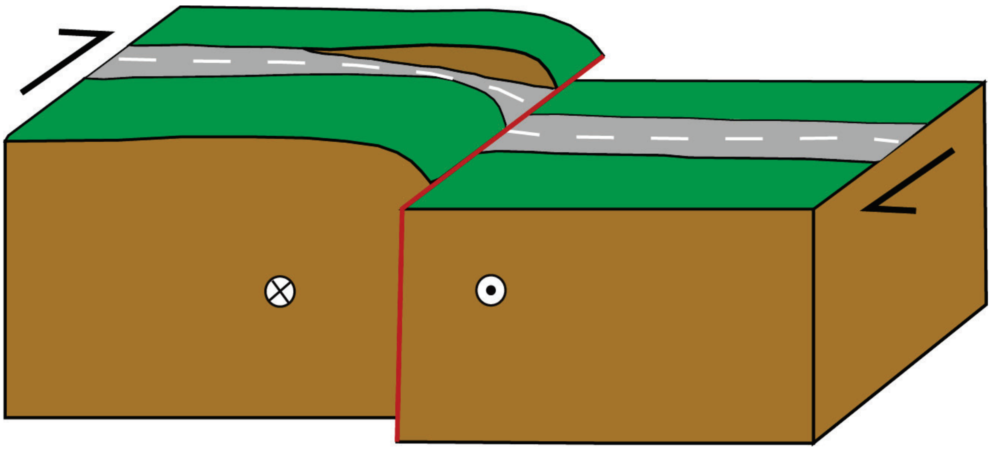

Figure A2.1 Block model of a strike-slip fault (red line).This is a right-lateral (dextral) fault, as shown by the black arrows and by the sense of movement across the two blocks and a separation towards the right across the road. A small amount of vertical movement is also implied by the mappable fault trace and scarp. Symbols on the front of the blocks indicate movement away (circle with cross) and movement toward (circle with dot) the viewer.

Most strike-slip faults in New Zealand, such as the Alpine, Hope, Wairarapa and Wellington faults, have a right-lateral sense of movement (Langridge et al., 2016). In Horizons Region, right-lateral strike-slip faults predominate within and on the boundaries of the North Island axial ranges (i.e. Tararua and Ruahine ranges), and include the Wellington, Mohaka and Ruahine faults (Figure A1.3). Some important active left-lateral strike-slip faults in New Zealand include the Papatea Fault in Kaikōura, which ruptured in the 2016 Kaikōura earthquake, and the Mangataura Fault, located east of the Mohaka Fault in inland Hawke's Bay (Langridge and Ries, 2014; Langridge et al., 2018).

A2.2 Reverse Faults

Reverse faults form under compression and are characterised by vertical motion of the hanging-wall block up and over the footwall block (Figure A2.2). Reverse faults typically create topography ranging from the scale of a fault scarp, which can be mapped, to a mountain range, e.g. the Seaward Kaikōura Range (Van Dissen and Yeats, 1991).

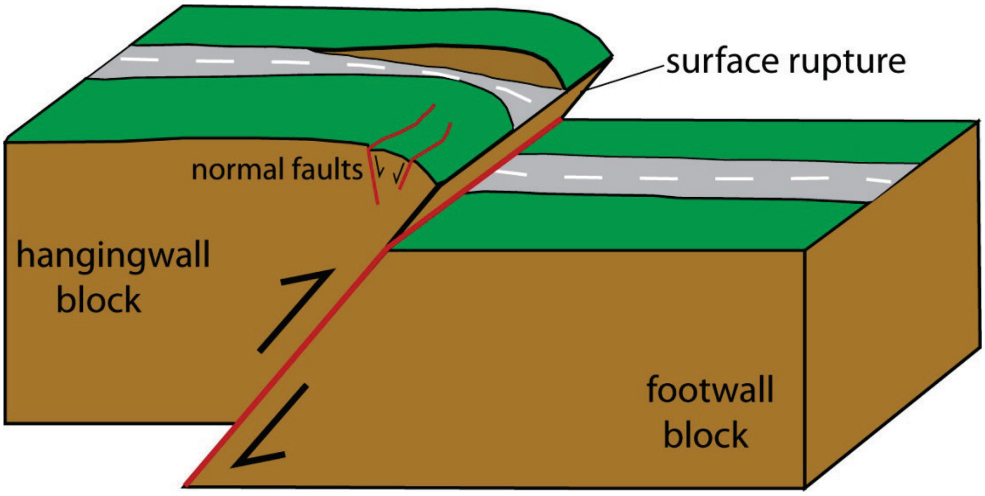

Figure A2.2 Block model of a reverse dip-slip fault that has recently ruptured. Relative movement between the blocks is vertical and along the dip direction of the fault plane. In this case, the hanging-wall block has been pushed up and over the footwall block. Folding (bending) and normal faulting are common features of deformation in the hanging-wall block of reverse faults.

Reverse faulting predominates within the southern and central part of The Horizons region and is often inferred (in cases when no faulting is evident at the surface) through association with active folds (described below). Examples of these include the Leedstown and Putorino faults and the Himitangi and Pohangina anticlines (Figure A1.2). A common feature of the tectonics in the Horizons Region are these sub-parallel, typically east-directed sheets of reverse and thrust[7] faults that occur in the upper crust above the plate boundary, i.e. the thin upper sliver of the Australian plate overlying the Hikurangi subduction zone in the eastern North Island (Cashman et al., 1992; Kelsey et al., 1995). Reverse faults have also been mapped off the east coast of the North Island by NIWA (e.g. Barnes et al., 2002).

A2.3 Normal Faults

Normal faults are dip-slip faults that form under conditions of extension and are characterised by downward motion of the hanging-wall block relative to the footwall block along the dip direction (Figure A2.3).

Normal faulting and extension are important processes, particularly in Ruapehu District, at the southern end of the Taupo Volcanic Zone (TVZ), or Taupo Rift (Villamor and Berryman, 2006a, b). The mechanisms for this extension here are probably related to a combination of: magma injection into, and inflation of, the crust within the TVZ; gravitational collapse of the crust in the central North Island; and oblique plate boundary extension related to translation of the eastern North Island (Beanland and Haines, 1998; Wallace et al., 2004).

7 A thrust fault is a reverse fault with a low angle of dip, typically ≤40 degrees in the near surface.

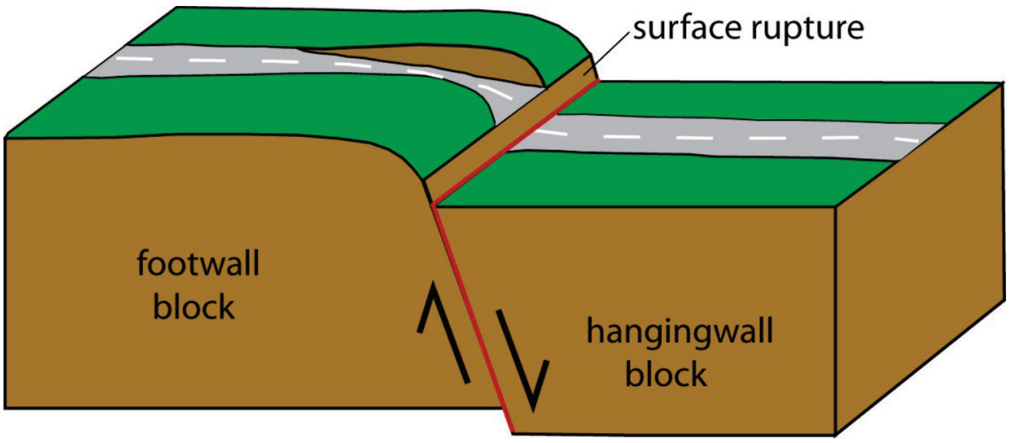

Figure A2.3 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

A2.4 Oblique-Slip Faults

In the NZAFD, both the dominant and subordinate (or secondary) sense of fault movement are usually described, e.g. reverse dextral or sinistral normal (in these cases the first descriptor is an adjective). This is useful in New Zealand because of the oblique-compressional (transpressional) tectonics of the Australia-Pacific plate boundary. Faults will typically have a dominant sense; however, in some cases, active faults also have a significant subordinate sense and can be termed oblique-slip faults (Figure A2.4). A good example is the sinistral reverse Papatea Fault, which ruptured in the 2016 Kaikōura earthquake (Langridge et al., 2018; Litchfield et al., 2018), where several meters of sinistral slip was exceeded by the reverse component of fault motion. Some of the faults described on the west side of the Tararua Range in Horowhenua District are probably oblique-slip faults, having a combination of dextral strike-slip and reverse faulting styles (e.g. Tokomaru and Mangaore faults, see Chapter 5).

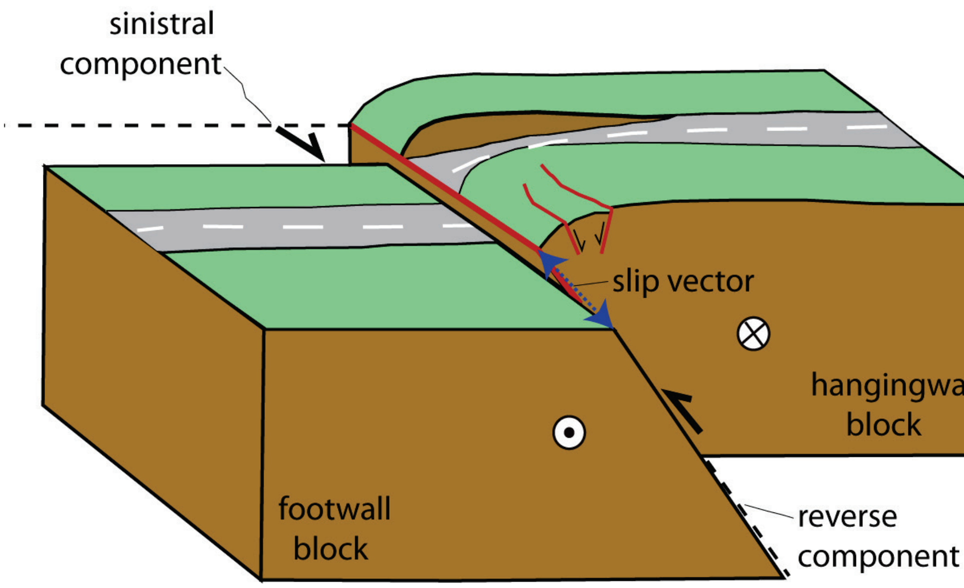

Figure A2.4 Block model of an oblique slip fault. In this case the fault is sinistral reverse. The relative movement of the blocks is both vertical (in the dip direction of the fault plane), and strike-slip (in the direction of the strike of the fault), as shown by the oblique blue arrow. Symbols on the front of the blocks indicate movement away (circle with cross) and movement toward (circle with dot) the viewer.

APPENDIX 3 EXAMPLES OF THE APPLICATION OF FAULT AVOIDANCE ZONES

The following section provide hypothetical examples of how the MfE Guidelines could be used to inform planning decisions and includes tables taken from Kerr et al. (2003) for RI Classes II, IV and V active faults within Horowhenua District and Palmerston North City.

A3.1 RI Class II Fault and a BIC 2a Structure

In this example, a rural family that lives at Gladstone Reserve in the Ohau River valley wants to build a new guest house (BIC 2a structure) within a Fault Avoidance Zone along the Northern Ohariu Fault (a RI Class II fault). At their 'Greenfield' site the fault is 'well-defined' because of LiDAR coverage and the Resource Consent Category recommended by the MfE Guidelines would be '*Non-Complying*' (Table A3.1).

Table A3.1 Examples, based on the MfE Guidelines, of Resource Consent Categories for both developed and/or Already Subdivided sites, and Greenfield sites along RI Class II faults.Categories account for various combinations of Building Importance Category and Fault Complexity.

Example Resource Consent Categories for Class II faults (RI >2000 to ≤3500 years): e.g. Northern Ohariu Fault (in Horowhenua and Palmerston North City)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	*Discretionary*	*Non-Complying*	Non-Complying
Uncertain	Permitted	Permitted	*Discretionary*	*Non-Complying*	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

Notes

* Indicates that the Resource Consent Category is permitted but could be Controlled or Discretionary given that the fault location is well defined.

Italics: The use of italics indicates that the Resource Consent Category – activity status of these categories is more flexible. For example, where Discretionary is indicated, Controlled may be considered more suitable by the Council, or vice versa.

In a situation where the amount of available land for a building site is limited, a developer or may, with prior Council approval of concept, undertake further geological studies or surveying to better document the location of the fault and therefore the likely zone of fault deformation. These fault studies (see Figure 4.2) could include detailed mapping of fault traces and scarps, trench excavation of the fault to locate deformation (or constrain undeformed ground), and surveying the fault to provide better locational accuracy. In addition, in a case where the recurrence interval is poorly constrained, it may be advantageous to undertake paleoseismic studies that can better constrain the timing of past events. Such studies would require excavation and geologic dating of deposits with a view toward dating earthquakes, or alternatively, using the slip rate to define the recurrence interval. With a better estimate of the recurrence interval, more appropriate decisions regarding the BIC can be made.

A3.2 RI Class IV Fault and a Housing Development with BIC 2a/2b Structures

In this case, a developer wants to create a lifestyle housing block west of Levin, just south of Lake Horowhenua along Arawhata Road (Figure 5.9). Some of the Greenfield sites will have BIC 2a structures and some are planned to have BIC 2b structures. Some of these sites are located within Fault Avoidance Zones for the Poroutawhao Fault, which is a RI Class IV fault (RI >5000 to ≤10,000 years). All of the traces are mapped as ‘approximate’ from LiDAR and the FAZs have a ‘uncertain–constrained’ fault complexity attribution. For both BIC 2a and 2b house structures near these faults, the Resource Consent Category recommended by the MfE Guidelines is Permitted (Table A3.2). Horowhenua District Council has some flexibility about how it can define its planning and consent outcomes in such a case.

Table A3.2 Examples, based on the MfE Guidelines, of Resource Consent Category for both developed and/or already subdivided sites, and Greenfield sites along RI Class IV faults.Categories account for various combinations of Building Importance Category and Fault Complexity.

Example Resource Consent Categories for Class IV faults (>5000 to ≤10,000 years) e.g., Otaki Forks, Tokomaru, and Poroutawhao faults; Oturoa trace (Horowhenua); and Tokomaru Fault (Palmerston North City)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain	Permitted	Permitted	Permitted	Permitted	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	Permitted*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
Uncertain	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying

Notes

* Indicates that the Resource Consent Category is permitted but could be Controlled or Discretionary given that the fault location is well defined.

Italics: The use of italics indicates that the Resource Consent Category – activity status of these categories is more flexible. For example, where Discretionary is indicated, Controlled may be considered more suitable by the Council, or vice versa.

A3.3 RI Class IV Fault and a School Relocation

In this example, the Ministry of Education and the village of Linton (within Palmerston North City), are considering relocating the Linton Primary School away from the current site which is close to overhead power lines and a noisy railway. They have selected a site 1 km to the northwest along Akers Road (Figure 6.2). However, as have been identified in this report, there are several active fault traces and a FAZ defined for the Tokomaru Fault in this area. The school buildings represent BIC Class 3 (important) structures. For this Greenfield site, a school location would represent as recommended by the MfE Guidelines, a '*Non-Complying'* activity where the RI Class IV Tokomaru Fault is 'well-defined', and a '*Discretionary'* activity where the fault has a distributed character or an uncertain fault complexity (Table A3.2).

A3.4 RI Class V Fault and a proposed BIC 2b House

In this example, a family wish to build a two-storey wooden-framed house (BIC 2b) within a FAZ relating to the 'Cluain traces' in north-eastern part of Horowhenua District. The fault complexity defined for the Cluain traces is Distributed, because the scarps mapped have a broad character. The Council has asked the family to set back outside of the FAZ.

In the case of a RI Class V fault (RI >10,000 to ≤20,000 years), such as those that are part of the 'Cluain traces' the only activities that are not defined as 'Permitted' or 'Permitted*' are for buildings of BIC Class 4 (Table A3.3). This recognises that the likelihood of a ground-surface rupturing event occurring on a RI Class V fault is very low (though still exists). While it would be deemed prudent to set back from the FAZ, there should in fact be no requirement in this case for the family to set back from the FAZ because the risk of a fault with this activity causing surface rupture is relatively low.

Table A3.3 Examples, based on the MfE Guidelines, of Resource Consent Category for both developed and/or already subdivided sites, and Greenfield sites along RI Class V faults.Categories account for various combinations of Building Importance Category and Fault Complexity.

Example Resource Consent Categories for the 'Cluain traces' (Horowhenua): Fault Recurrence Interval Class V (>10,000 to ≤20,000 years)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain	Permitted	Permitted	Permitted	Permitted	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain	Permitted	Permitted	Permitted	Permitted	Non-Complying

Notes

* Indicates that the Resource Consent Category is permitted but could be Controlled or Discretionary given that the fault location is well defined.

Italics: The use of italics indicates that the Resource Consent Category – activity status of these categories is more flexible. For example, where Discretionary is indicated, Controlled may be considered more suitable by the Council, or vice versa.