Active fault mapping and fault avoidance and awareness zones for the Whanganui District

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DISCLAIMER

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EXECUTIVE SUMMARY

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

New active fault mapping and Fault Avoidance Zones (FAZs) are presented here for the Whanganui District. There are a small number of discontinuous active faults 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 in detail to develop 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 (BIC) of the structure(s) that may be impacted by fault rupture ground deformation. Fault Awareness Areas (FAAs) have been developed for areas where the resolution (scale) of mapping is not refined enough to permit the more detailed mapping of FAZs, where it has not been established that the mapped feature is of a tectonic (faulting) origin or where it has not been possible to estimate a recurrence interval for a fault.

Active fault trace mapping was undertaken in the Whanganui District using hillshade models developed from airborne Light Detection and Ranging (LiDAR) data and a Horizons-wide Digital Surface Model (DSM), from the review of mapping in GNS Science geological and active fault datasets and from digital orthophotograph mosaics. Fault mapping was undertaken at scales between c. 1:5000 and 1:10,000, where LiDAR data are available. Active faults have been mapped in a Geographic Information System (GIS), and locations of traces are 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 and parameterisation of FAZs.

In the Whanganui District, there is only one previously known active fault: the Nukumaru Fault.[1] The Nukumaru Fault has been remapped as part of this study. The remainder of fault features identified in the Whanganui District are classified as 'possible' active faults, due mainly to their discontinuous nature.

This study has developed new and updated recurrence interval (RI) Class information for the Nukumaru Fault. The low slip rate of the fault results in a long recurrence interval (19,500 to 25,600 years), placing it within RI Class V with a low level of confidence. FAZs have been defined for two active traces of the fault in accordance with the MfE Guidelines.

There is currently no information to constrain the recurrence interval of the other mapped features. FAAs have been developed for these 'possible' active faults, and no RI Class is assigned. FAAs are distinct from FAZs and carry no requirements related to the MfE Guidelines.

We recommend that the active fault mapping and FAZs developed for the Whanganui District in 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 (i.e. well-defined,

1 The Nukumaru Fault is a zone comprising a series of overlapping, discontinuous fault traces, which we refer to as simply the Nukumaru Fault.

well-defined extended, distributed, uncertain constrained and uncertain poorly constrained) and according to recurrence interval class. As outlined in the MfE Guidelines, this information, when combined with land-use status (i.e. 'Greenfield' site or 'Already Developed/Subdivided' site) and intended or existing 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, a series 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 BIC are included in the Appendices.

We recommend that the MfE Guidelines be treated as a standard reference when considering resource consent applications in the Whanganui District. In addition, we recommend that GIS data for FAZs, which can be used at an individual property-specific scale, be provided on Land Information Memorandum (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.

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1.0 INTRODUCTION

1.1 Preamble

Southern North Island lies above the boundary between the Australian and Pacific tectonic plates (Figure 1.1 inset and Figure 2.1). 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; Figure 1.1) 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 Taupō Rift (Beanland and Haines 1998; Villamor and Berryman 2006b). The Horizons Region is crossed by numerous active crustal faults (and folds) that have ruptured and deformed the ground. These faults include the Wellington, Ruahine, Mohaka, Leedstown, Mt Stewart-Halcombe, 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. Van Dissen et al. 2003; Schermer et al. 2004; Langridge et al. 2006).

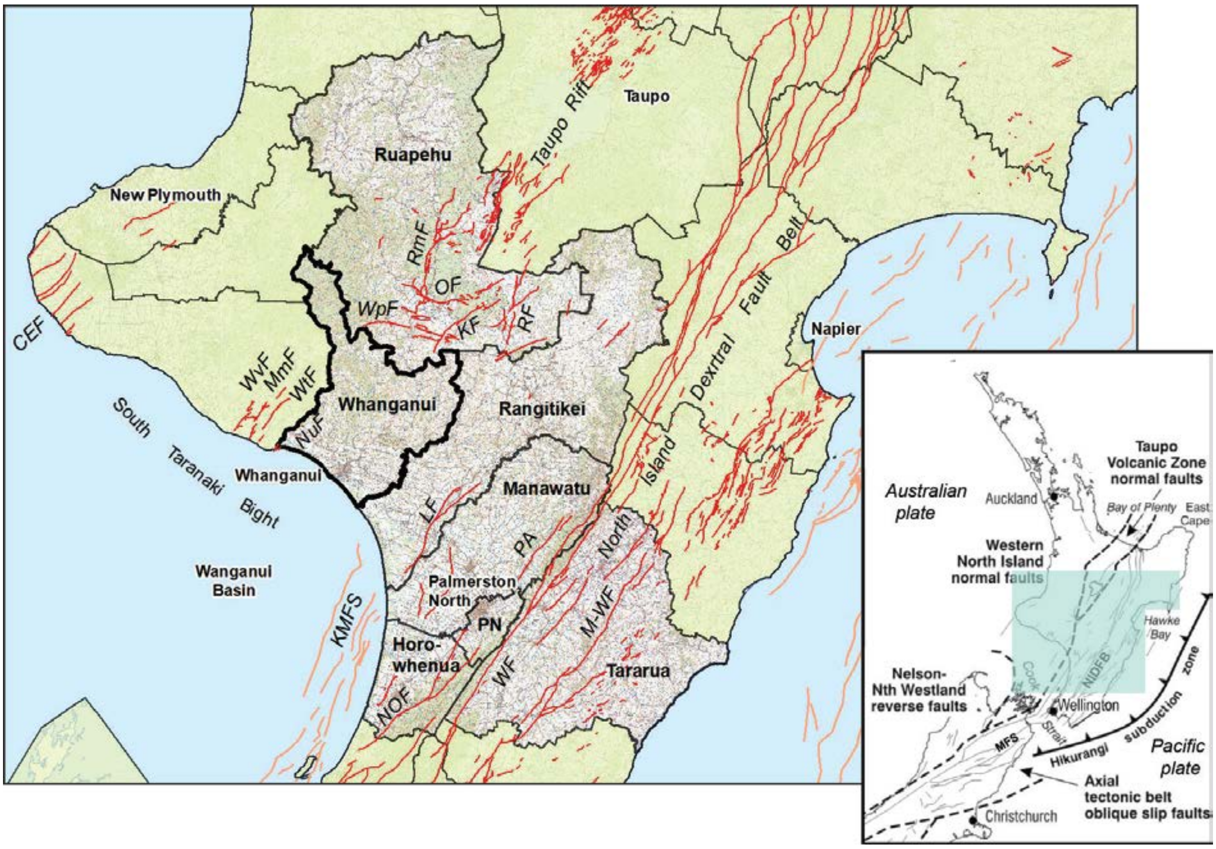

Figure 1.1 The area administered by Horizons Regional Council (unshaded), showing its various districts. PN = Palmerston North. Onshore active faults (red) within the lower North Island area sourced from the New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al. 2016) as they appeared prior to this study. Fault names in italics are: CE = Cape Egmont Fault (zone); RmF = Raurimu Fault; OF = Ohakune Fault; WpF = Waipuna Fault; KF = Karioi Fault; RF = Rangipo (Desert Road) Fault; WvF = Waverley Fault; MmF = Moumahaki Fault; WtF = Waitotara Fault; NuF = Nukumaru Fault; LF = Leedstown Fault; M-WF = Makuri-Waewaepa Fault; NOF = Northern Ohariu Fault and WF = Wellington Fault. KMFS = Kāpiti-Manawatū Fault System. Inset: Active tectonic map of central New Zealand with seismo-tectonic regions. NIDFB = North Island Dextral Fault Belt; MFS = Marlborough Fault System. Inset: 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 is to be expected, and loss of life may occur where buildings (or 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 1987 Edgecumbe, 2010 Darfield and 2016 Kaikōura earthquakes provide examples of the types of impacts to engineered structures caused by ground-surface fault rupture (e.g. Beanland et al. 1989; Van Dissen et al. 2011, 2019).

1.2 Scope of Work

GNS Science (GNS) has been contracted by the Horizons Regional Council ('Horizons') to conduct a region-wide active fault mapping and fault avoidance zone programme to improve understanding of the effects of, and mitigation design for, hazards resulting from surface fault rupture deformation associated with large earthquakes. The fault mapping is being undertaken in a style that facilitates application of the Ministry for the Environment's guidelines regarding 'Planning for Development of Land on or Close to Active Faults' (Kerr et al. 2003; hereafter called the MfE Guidelines). It also builds upon previous active fault studies in the region (e.g. Jackson et al. 1998; Schermer et al. 2004; Litchfield et al. 2014), and new or updated information will be included in the New Zealand Active Faults Database (NZAFD; https://data.gns.cri.nz/af/). The Horizons fault mapping and fault avoidance programme began in the two southernmost districts of the Horizons Region: the Horowhenua District and Palmerston North City (Phase 1; Langridge and Morgenstern 2018). Phase 2 continued the work into the Manawatū District (Phase 2a; Langridge and Morgenstern 2019) and the Rangitikei District (Phase 2b; Langridge and Morgenstern 2020) and is extended here to the Whanganui District (Phase 3a).

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, supplied by the Horizons Regional Council. In addition, we worked with Horizons to construct a region-wide 1-m-resolution Digital Surface Model (DSM) from aerial imagery in order to develop a digital topographic dataset across the whole district.

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 the Rangitikei District – the scope of work is as follows:

- Provide a review on active tectonics, seismicity and faulting in the Horizons Region.
- Where airborne LiDAR-derived topographic data exist, map and attribute active fault traces at 1:10,000 or better. This effort has been facilitated by the acquisition of several airborne LiDAR datasets funded by Horizons Regional Council and provided to GNS.
- Use a 1-m DSM of the Horizons Region to improve the mapping of active fault traces where LiDAR data do not exist.
- Incorporate active fault line work and attributes from other mapping studies, such as 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; Langridge et al. 2016).

- Develop Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs) based on the updated fault line data described above. The goal is to provide Horizons Regional Council with up-to-date geospatial datasets that are valid for planning purposes and which are wholly compatible with application of the MfE Guidelines.
- Map active folds to better locate and characterise their tectonic activity.[2]
- Provide an update on active fault recurrence interval data for the Whanganui District, 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 the Horizons Regional Council and the Whanganui District planning staff.

Section 2 of this report describes the tectonic and seismic character across the Horizons Region, including a record of historical earthquakes.

Section 3 introduces the fundamental elements of the MfE Guidelines. It includes an introduction to what active faults and folds are and why they should be mapped for hazard purposes, outlining the history of recent active fault mapping in neighbouring districts.

Section 4 describes the methodologies used for fault and fold mapping; how 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.

Section 5 describes the results and implications for active faults and ‘possible’ active faults within the Whanganui District and, where possible, provides new or updated recurrence interval information and FAZs for those faults that are considered active. FAAs are developed for the possible active faults.

Section 6 provides a summary of the results of this work, and Section 7 contains recommendations for implementing this work in future planning decisions.

Appendix 1 to this report provides a background to various styles of faulting throughout the Horizons Region, with descriptions of different types of geologic faults.

The report is accompanied by digital geospatial Geographic Information System (GIS) datasets, including active fault mapping (lines), and FAZs and FAAs (polygons). These should facilitate the direct incorporation of FAZs 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 It is not plausible to create avoidance zones for active folds; however, better characterisation is useful and may provide relevant information on the possible tectonic relationships between active faults and active folds.

2.0 THE HORIZONS REGION

2.1 Physiographic Setting

The Horizons Region includes seven Territorial Authorities that span an area encompassing many diverse and varied landscape types across central to southern North Island (Figure 1.1). In the north, the region includes the southern part of the extensional Taupō Rift and Taupō Volcanic Zone (Villamor and Berryman 2006a, b) in the Ruapehu District. In south-western North Island, large rivers drain from the elevated central and south-western parts of the island across a broad coastal plain (e.g. Whanganui, Rangitikei and Manawatū Districts). These lowland settings extend and taper into the southern part of the Horizons Region, covering Horowhenua District and Palmerston North City. In the southeast, Tararua District covers an area from the northern Tararua and southern Ruahine ranges to the east coast of the North Island.

The primary hazards from earthquakes include seismic shaking (ground motion), ground-surface fault rupture, uplift, liquefaction, earth movement (e.g. rock fall and landslides), subsidence and tsunami. Following from Langridge and Morgenstern (2020), this report focuses on active fault mapping in the Whanganui District and deals with the hazards relating to ground-surface fault rupture deformation, including surface faulting and folding. This report also focuses on the 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.

2.2 Tectonic Setting

The southern part of the North Island overlies the Australian-Pacific plate boundary which, at the location of the Horizons Region, forms part of the Hikurangi Subduction Margin. Figure 2.1 shows a stylised cross-section of the region from approximately Waverley to Cape Turnagain. The Hikurangi Subduction Margin comprises a subduction interface (the fault between the down-going Pacific Plate and the overlying Australian Plate); a forearc characterised by reverse, oblique and strike-slip faulting; a central zone characterised by strike-slip, oblique and reverse faulting forming the axial ranges; a volcanic arc characterised by normal faulting (not indicated in the figure); and a back-arc region characterised by reverse faulting and folding (Berryman and Beanland 1991; Wallace et al. 2004; Nicol et al. 2007). Thus, a diverse range of active tectonic deformation[3] is reflected in the broad area covered by the Horizons Region.

The largest fault in the region is the Hikurangi subduction interface, which represents the surface between the Pacific and Australian plates beneath the North Island (Figure 2.1). The plate interface is considered capable of generating a 'great' earthquake (M_W >8) and possibly a megaquake (M_W >9; Wallace et al. 2009; Stirling et al. 2012). In such a scenario, rupture of the Hikurangi subduction interface (i.e., as a gently dipping thrust fault plane) would propagate to the seafloor off the east coast of Tararua District (Figure 2.1) and a significant tsunami impacting the east coast and beyond could be generated. In addition, a magnitude M_W 8–9 earthquake on the plate interface would generate severe ground shaking throughout much of central New Zealand and beyond.

3 Descriptions and diagrams of these types and styles of faulting are described in Appendix 1.

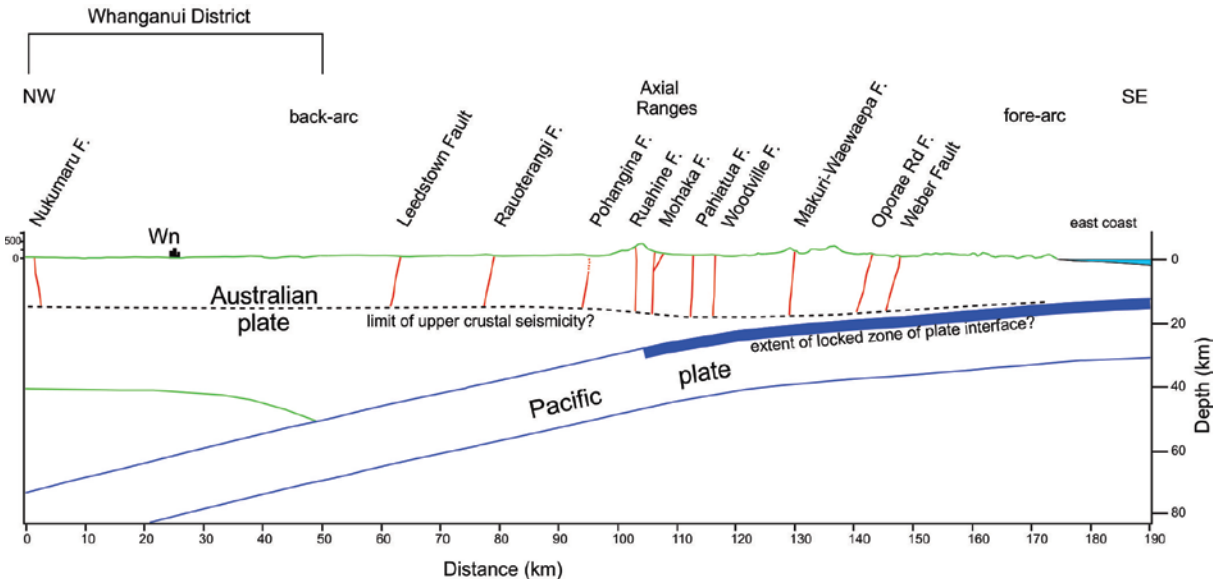

Figure 2.1 Simplified cross-section of southern North Island from west of Whanganui (Wn) to offshore of Cape Turnagain in the east, showing the tectonic features that are relevant to the Horizons Region. The cross-section intersects several active upper crustal faults and includes the Hikurangi Subduction Margin or Zone. Modified from Langridge and Morgenstern (2020).

In the Whanganui District, the regional geological pattern is one of gently south- or southwest-dipping sedimentary rocks, tilted as a result of uplift in the central North Island and subsidence offshore to the southwest in the Wanganui Basin (Kamp et al. 2004; Pulford and Stern 2004; Townsend et al. 2008; Lee et al. 2011; Nicol et al. 2011). As these relatively soft Plio-Pleistocene rocks have been uplifted and tilted to the southwest, erosion and transport of sediment from inland has approximately kept pace with subsidence and deposition offshore throughout the last c. 4 million years to form a >4000-m-thick pile of sedimentary strata (Fleming 1953; Kamp et al. 2004; Townsend et al. 2008).

The South Taranaki-Whanganui area is renowned for its well-preserved flights of marine terraces (raised beaches), formed by sea-level fluctuations over hundreds of thousands of years and preserved by steady regional uplift. Marine terrace formation and preservation is favoured during times of high sea-level during interglacial periods, whereas the cutting of terraces and deposition of beach sediments preferentially occurs at the peaks of highest sea level during the various stages. The Marine Isotope Stage (MIS) 17 (~690,000–660,000 years ago) Marorau Marine Terrace (Pillans 1990a) is the oldest mapped terrace that is preserved (Townsend et al. 2008), but remnants of even older marine surfaces may exist inland. Successively younger marine terraces (MIS 15, 13, 11, 9, 7 and 5) are preserved at ever-decreasing elevations towards the coast, with the youngest (modern) high-stand currently forming the cliffs just inland from modern beaches (MIS 1).

The paleo-shorelines are marked by topographic steps that separate older and younger terraces, and are generally gently curved and parallel with the modern coastline along the South Taranaki Bight (Figure 1.1). However, in the west of the Whanganui District, the risers display local complexity in association with the Nukumaru Fault. This suggests that these geomorphic features have been affected by local tectonics, either through uplift and folding of the terraces and risers themselves, or that the erosion-resistant Nukumaru Limestone, which has been deformed and exposed within this long-lived fault zone (Fleming 1953), has influenced the coastal dynamics and formation of the contemporaneous coastlines (e.g. Nukumaru Limestone is exposed along the protruding headland at Waiinu Beach, just west of Whanganui District; Figure 2.2).

Figure 2.2 The well-preserved marine terraces and coastal cliffs near Kai-Iwi, north of Whanganui City, exemplify the district's coastline. The jutting headland exposes Pleistocene-aged Nukumaru Limestone (Fleming 1953), which has been faulted and possibly folded by the Nukumaru Fault. Holocene sand dunes (e.g. at centre) form lumpy deposits on many of the terraces, making identification of active faults difficult. Photo: D Townsend / GNS. D02_1473.

Gravitational failures or landslides are widespread throughout the Whanganui District. Many of the larger landslides are shown on geological maps (e.g. Townsend et al. 2008; Heron 2018), but most of the smaller ones (as well as a few of the larger ones) are not depicted. Triggering of movement is commonly caused by high pore-water pressures resulting from intense or long-duration rainfall, or by ground accelerations caused by earthquake shaking.

Larger, deep-seated failures occur mainly in the Plio-Pleistocene mudstone-sandstone rocks. These landslides are typically rotational or translational in style (e.g. Hungr et al. 2014), involving a slide or slip plane, which is commonly a thin, weathered layer of volcanic ash (Massey 2010) at depth on which a volume of rock moves under gravity. As a landslide moves, individual blocks within the mass are transported and rotated by different amounts, breaking up into smaller blocks, eventually coming to a rest and usually resulting in a lumpy or hummocky deposit (Figure 2.3). Quaternary terrace deposits are more susceptible to smaller toppling failures at their edges, usually caused by removal of supporting material as streams and rivers undercut the terraces. Another form of landsliding common to the area is caused by intense rainfall, resulting in water-saturated mixtures of eroded rock known as debris flows and debris floods.

These forms of erosion can rapidly alter the landscape, often removing or burying evidence of faulting activity, especially in areas underlain by young, soft bedrock such as most of the Whanganui District. Additionally, landslide scarps may have the appearance of tectonic fault features, so extra care must be taken with interpretations of features in terrain that is susceptible to landsliding (e.g. Figure 2.3).

Figure 2.3 Landsliding in the hill country of inland Whanganui District has formed characteristic lumpy topography. Extra care must be taken in such areas to distinguish gravitational (landslides) from tectonic (faulting) landscape features. The road shown is Fields Track, just east of the Whanganui River, and the view direction is to the northeast. Photo: D Townsend / GNS. D02_1628.

2.3 Regional and Historical Seismicity

The Horizons Region has a well-documented record of historical (post-1840 AD) earthquakes that have been both damaging and destructive. Figure 2.4 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, in some cases, 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.

From 1840 to 1870, three significant large earthquakes impacted the region. In July 1843, a M_W ~7.6 earthquake, formerly the 'Wanganui earthquake', occurred. It was so called because of the significant damage it caused in Whanganui (Downes 1995). A more recent historical earthquake compilation that includes shaking intensity reports from further afield (Downes and Dowrick 2014), 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.

The M_W ~8.2 Wairarapa earthquake occurred on January 23, 1855, and is the largest historical earthquake to have occurred in New Zealand. Surface rupture occurred on the Wairarapa and Alfredton faults (Schermer et al. 2004), the latter of which is located within the Tararua District. Shaking intensities of Modified Mercalli Intensity (MMI)8–9 were experienced at Paiaka, south of the Manawatū River, and MMI 7 at Whanganui (Downes and Dowrick 2014). The 1855 quake followed the M ~7.5 1848 Marlborough earthquake, which caused similar levels of strong shaking in Horowhenua, Manawatū and Whanganui (Downes and Dowrick 2014; Grapes et al. 1998).

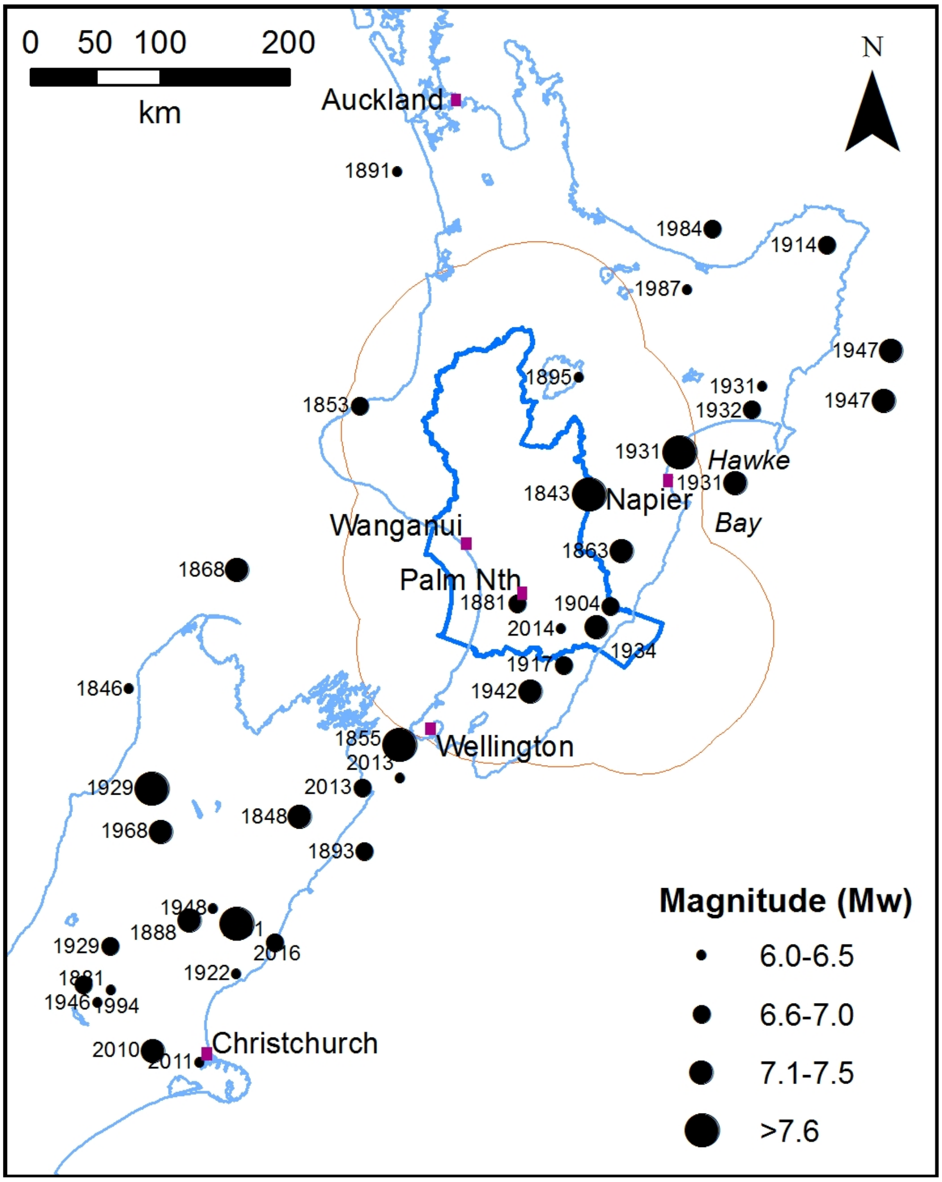

Figure 2.4 Epicentres of significant shallow (<30 km depth) earthquakes in central New Zealand that have occurred from 1840–2016. Highlighted in dark blue is the Horizons Region, and the orange line is an area that extends a further 75 km around the region to consider impacts from nearby earthquakes. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

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

In June 1881, a M_W ~6.7 earthquake occurred, with an epicentre located 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)[4] were most strongly felt on North Island's east coast (in the Tararua District) near Cape Turnagain. Reported maximum shaking intensities decreased in all directions from this area but ranged from MMI 5–7 across much of the Horizons Region.

4 A description of the New Zealand Modified Mercalli Intensity scale of Dowrick (1996) can be viewed at https://www.geonet.org.nz/earthquake/mmi

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 the Horizons Region in this event.

During the second quarter of the 20th century, Hawke's Bay and surrounding regions were rocked by several large earthquakes, including the February 3, 1931 M_W 7.6 Hawke's Bay earthquake (also known as the Napier earthquake) which killed 256 people and destroyed the settlements of Napier and Hastings. Earthquake 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 on February 13, 1931, and the 1932 M_W 6.9 Wairoa earthquake (Figure 2.4).

The 1934 M_W 7.4 Pahiatua (Horoeka) earthquake caused ground surface rupture on faults in the Tararua District. Geologic studies show that this earthquake caused surface rupture on the Waipukaka Fault, which has had at least two other Holocene surface-rupturing earthquakes (Schermer et al. 2004). The earthquake in 1934 caused extensive damage from 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, earthquakes shook the lower North Island on June 24 and August 2. They were large and shallow, with the epicentres located close together and east of Masterton in the Wairarapa area. The June earthquake is sometimes referred to as the 'Masterton earthquake', but both caused damage over a wide area, from Dannevirke and Eketahuna to Wellington, Whanganui and Ōtaki. There was one death in Wellington relating to the June 24 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 (Figures 2.4 and 2.5). This event occurred at a depth of c. 34 km and was felt strongly across the country, from Auckland to Dunedin, with more than 9000 felt 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 2.4, Figure 2.5 shows the seismicity of the Horizons Region over a five-year period from 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 broadly related to the Hikurangi Subduction Zone and local earthquake swarms, including a long-lived swarm offshore from Whanganui City.

There are no known historic earthquakes of M_w >6 that have occurred within the boundaries of the Whanganui District (Figure 2.4), and the district typically has a relatively low level of background seismicity (Figure 2.5).

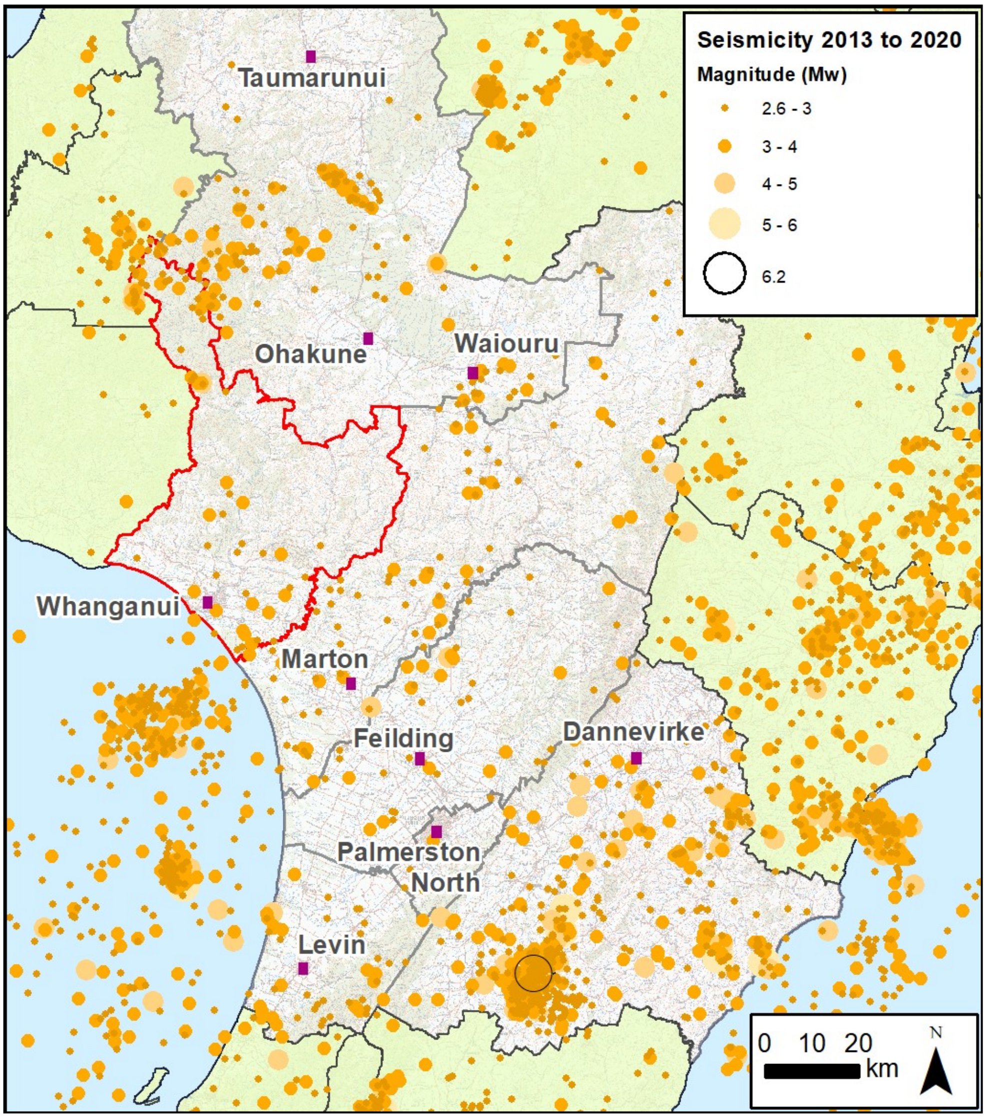

Figure 2.5 Epicentral locations of shallow (<40 km) earthquakes of Mw >2.6 that occurred between August 2013 and mid-June 2020 within, or close to, the Horizons Region. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue). The largest event is the 2014 M_w 6.2 Eketahuna earthquake. The cluster offshore from Whanganui City is an ongoing earthquake 'swarm' associated with fluids in the lower crust that have been driven off the Pacific Plate as it subducts under the Australian Plate beneath the North Island (Reyners et al. 2007) formation of the Wanganui Basin. The cluster of points in the northern Whanganui to central Ruapehu districts (northwest of Ohakune) also represents an ongoing series of events that occur along a line roughly between Mt Ruapehu and Mt Taranaki (the 'Taranaki-Ruapehu Line'), which represents a major change in the geophysical properties of the Earth's crust from ~25-km-thick crust to north to ~32-km-thick crust to south (Salmon et al. 2011; Dimech et al. 2017).

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 limited use for planning purposes. Phases 1 and 2 of the Horizons Region active fault mapping programme were undertaken across Horowhenua, Manawatū and Rangitikei districts and Palmerston North City to refine active fault locations and to produce FAZs that can be utilised within the risk-based planning context of the MfE Guidelines (Kerr et al. 2003; Langridge and Morgenstern 2018, 2019, 2020). These projects drew on the significant extent of available airborne LiDAR data coverage there. This project (Phase 3) relies heavily on the Horizons Regional 1-m-resolution DSM (developed from aerial photographs), as the airborne LiDAR data coverage for Whanganui District is patchy and currently consists of two surveys that mainly cover the city and parts of the surrounding coastal plain.

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 Mw >6.5[5]. An active fault is generally defined within the NZAFD and herein as one that has deformed the ground surface within the past 125,000 years (Langridge et al. 2016). This is defined in part for practical reasons, for mapped faults that deform marine terraces and alluvial surfaces that 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 much of New Zealand and therefore are a pragmatic choice for the definition of activity. One exception to this classification is within the Taupō Rift (part of which is within Ruapehu District), where active faults are defined as those with evidence of activity within the last 25,000 years (Langridge et al. 2016; Villamor et al. 2017). Another exception is within low strain areas far away from the main plate boundary faults. In such areas, faults may have very long recurrence intervals, or they may rupture episodically, switching between active and dormant periods. In those areas, an active fault is sometimes defined as a "fault that shows evidence of surface rupture or ground deformation during the current tectonic regime" (Villamor et al. 2018).

The purpose of this section is to introduce how active faults express themselves in the landscape, i.e. their behaviour, styles of deformation, activity and geomorphic expression. Active faults are typically expressed in the landscape as linear traces that displace ('offset') surficial geomorphic features including 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 commonly formed in bedrock and have a thin colluvial (slop-wash) cover. 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.

5 Surface rupture can also occur during smaller earthquakes, when the earthquake epicentre is relatively close to the Earth's surface.

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 may smooth out over time due to erosion (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 subtle linear trace may be preserved 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 data used to develop Digital Elevation Models (DEMs) has 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 1. This includes a description of strike-slip, reverse and normal dip-slip faults, and oblique-slip faults where there is both a significant strike-slip and dip-slip component of motion. All faults and 'possible' faults in the Whanganui District are interpreted to be normal faults.

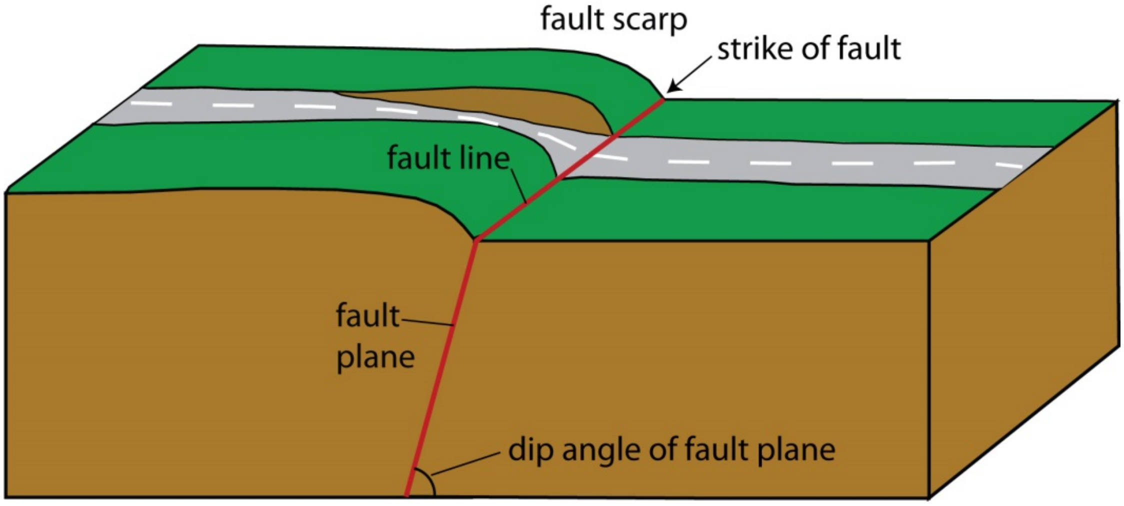

Figure 3.1 Block model of a generic active fault (shown in red). Fault displacement produces a scarp with offset features along the projection of the fault plane at the Earth's surface (fault line or trace).

3.2 What is an Active Fold?

Active folds exist where parts of the Earth's crust are being warped or folded and are usually evident in the landscape (e.g. Figure 3.2). Folds that form positive (high or convex) relief are termed anticlines (limbs dip away from the axis and each other) and folds that form negative (low or concave) relief are called synclines (limbs dip towards the axis and each other).

Active anticlines are commonly found in association with buried active reverse faults, where the upper tip of the fault (see Section A1.2) does not extend to the Earth's surface. In such a case, the ground is warped or buckled on the raised (hanging-wall) side of the buried fault (Figure 3.2). The raised part of the anticline forms a ridge on or near the fold axis, which can sometimes be mapped in the landscape because it forms high topography, and streams will flow away from the ridge in either direction down the fold limbs (Stevens 1990; Clement et al. 2017; Langridge and Morgenstern 2020). Such folds are typically asymmetrical (e.g. with an inclined axial plane and one limb being shorter and steeper than the other), and the asymmetry can provide information about the dip and dip direction of the buried fault (e.g. Figure 3.2). The syncline associated with these structures is typically less evident because it is not as well-formed initially and commonly becomes buried with younger sediment.

The southern and central parts of the Horizons Region host several asymmetric anticlines that typically deform late Quaternary fluvial and near-shore sedimentary strata (e.g. Te Punga 1957; Jackson et al. 1998; Clement and Fuller 2018; Langridge and Morgenstern 2020) and form topographic highs or domes. For example, across the Horowhenua, Manawatū and Rangitikei districts, the Pohangina, Himatangi, Shannon, Levin and Marton anticlines and the 'Poroutawhao High' (Begg and Johnston 2000; Clement et al. 2017) were previously recognised and were reviewed by Langridge and Morgenstern (2018, 2019, 2020). Where such folds are actively deforming late Quaternary surfaces, they can be considered to be underlain by active reverse faults (Figure 3.2), which are capable of generating moderate to large earthquakes and as such have been included in the New Zealand National Seismic Hazard Model (NSHM), e.g. the Poroutawhao active fault earthquake source of Stirling et al. (2012). However, we did not map any active folds in the Whanganui District as a part of this study.

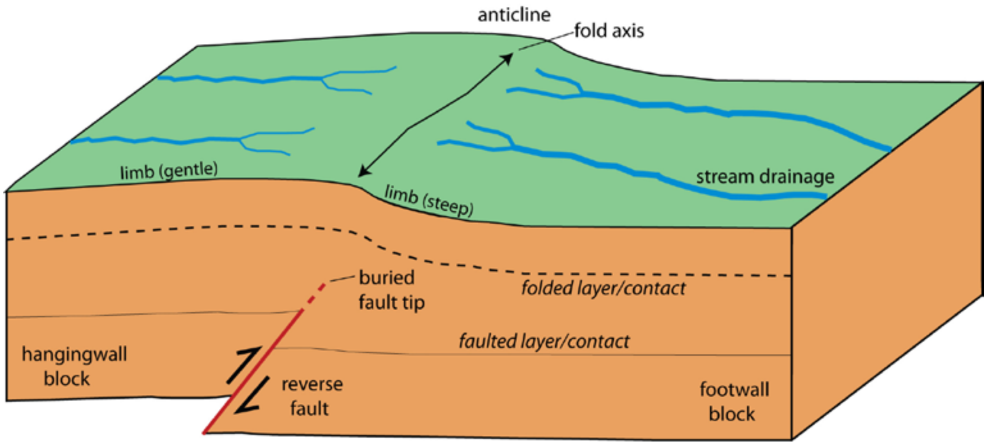

Figure 3.2 Block model of an anticlinal fold that is related to a buried active reverse fault. Motion on the fault has driven the hanging-wall block upwards and folded the ground surface above the fault tip. The fold is asymmetric and defined at the surface by a fold axis and by the stream drainage pattern, where streams drain away from the anticlinal fold axis. The scale and depth to the fault tip is schematic only and implies no spatial relationships.

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 become increasingly relevant to councils and landowners is post-event functionality of built structures, i.e. built structures that can be readily repaired and safely occupied or used after a natural disaster event.

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

1. Fault characterisation relevant to planning for development across fault lines that 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 FAZs; 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 FAZ.

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

Phases 1 through 2b of the Horizons active fault mapping programme build on an extensive history of recent fault mapping undertaken with a view toward developing FAZs in other regions of New Zealand. These studies have been, for example, in Greater Wellington (e.g. Litchfield and Van Dissen 2014; URS Corporation 2006; Van Dissen and Heron 2003; Zachariasen et al. 2000; Begg et al. 2001; Townsend et al. 2002), Bay of Plenty (Villamor et al. 2010) and Hawke's Bay (e.g. Clark and Ries 2016; Langridge and Ries 2014, 2015; Langridge et al. 2006, 2011) in the North Island; and Canterbury (Barrell and Townsend 2012; Barrell 2015), West Coast (e.g. Langridge and Ries 2010) and Marlborough (Langridge and Ries 2016; Litchfield et al. 2019) in the South Island.

3.4 Active Fault Recurrence Interval and the MfE Guidelines

Six recurrence interval (RI) classes, each of which define a distinct range of time, are defined within the MfE Guidelines (Table 3.1; Kerr et al. 2003). 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 low-risk structures, such as farm sheds (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 (i.e. RI Class I). 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 classes (from Kerr et al. 2003).

RI Class	Average Recurrence Interval of Surface Rupture
I	≤2000 years
II	>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

For phases 1–2 of the Horizons active fault mapping programme, the state of knowledge regarding the recurrence intervals of faults in the region and preliminary recurrence interval classes for all faults in the Horowhenua, Palmerston North, Manawatū and Rangitikei districts were summarised by Langridge and Morgenstern (2018, 2019, 2020).

Based on current data, the Horizons Region contains active faults in RI Classes I–V (Van Dissen et al. 2003; Langridge and Morgenstern 2018, 2019, 2020). Most of the RI Class I (RI ≤2000 years) faults occur in the Tararua and Ruapehu districts, where the most active seismo-tectonic belts exist, e.g. the NIDFB and Taupō Rift, respectively (Figure 1.1). RI Class II faults (>2000 to ≤3500 years) occur within the Tararua, Manawatū, Horowhenua and Ruapehu districts. These faults typically have moderate slip rates (e.g. Ruahine, Makuri-Waewaepa, Raetihi North and Raetihi South faults). Faults with lower slip rates typically have longer recurrence intervals and fall into RI Class III (>3500 to ≤5000 years), e.g. Waitawhiti and Kaweka faults, and RI Class IV (>5000 to ≤10,000 years), e.g. Leedstown and Nukumaru faults.

In the Whanganui District, there are few faults that have published recurrence interval data (see Section 5), despite some of them being documented as active fault earthquake sources in the New Zealand National Seismic Hazard Model (NSHM) (Stirling et al. 2012) and as simplified fault zones in the active fault model of Litchfield et al. (2014).

The RI Class Confidence is a measure of the quality of the geological data which are 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, whereas for other faults, recurrence intervals are qualitatively based on observations of landscape or geomorphic deformation. 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 used to assign a RI Class of II; however, the confidence in that assignment is medium or low because the actual recurrence interval range spans three RI Classes.

3.4.2 RI Class Categories for the Whanganui District

Prior to this study, the only fault in the Whanganui District with an RI Class applied to it was the Nukumaru Fault. In this report, we review and revise the RI Class for the Nukumaru Fault through a new estimation of the slip rate based on topographic profiling using the LiDAR and DSM data, combined with estimates of single event displacement (Section 5.1.1).

For the remaining faults mapped in this study, there is no information to constrain the recurrence interval. For example, none are included in the 2010 version of the NSHM. For these ‘possible’ active faults we define FAAs (Section 4.4.1) rather than FAZs and do not assign a RI Class.

3.5 Building Importance Category and the MfE Guidelines

Buildings sited across active faults are very likely to be damaged in a ground-surface-rupturing earthquake. A BIC states the relative importance of assessing the suitability of a building within, or proposed for, a FAZ (Kerr et al. 2003). The BICs listed in Table 3.2 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 four (BIC 4) the highest importance.

Table 3.2 Building importance categories (BIC) and representative examples. For more detail see Kerr et al. (2003) and King et al. (2003).

BIC	Description	Examples
1	**Temporary structures** with low hazard to life and other property	• Structures with a floor area of <30 m^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 an 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

In the MfE Guidelines, a distinction is made between single-storey timber-framed dwellings (that are common throughout New Zealand) and other ‘normal’ structures (BIC 2b). A distinction is also made between ‘previously subdivided or developed areas’ and ‘Greenfield’ sites. Councils can use BICs to make decisions about resource consents and to require conditions on buildings within FAZs (see Appendix 2). Table 3.3 shows the relationship between the fault rupture recurrence interval and BICs in both previously subdivided or developed areas and Greenfield sites (Kerr et al. 2003).

Table 3.3 Relationships between RI Class, average recurrence interval of surface rupture, and Building Importance Category for previously subdivided or developed and Greenfield sites. From Kerr et al. (2003).

Recurrence Interval Class	Average Recurrence Interval of Surface Rupture	BIC Limitations (Allowable Buildings)	
		Previously Subdivided or Developed Sites	‘Greenfield’ Sites
I	≤2000 years	**BIC 1** Temporary buildings only	**BIC 1** Temporary buildings only
II	>2000 years to ≤3500 years	**BIC 1 and 2a** Temporary and residential timber-framed buildings only	
III	>3500 years to ≤5000 years	**BIC 1, 2a and 2b** Temporary, residential timber-framed and normal structures	**BIC 1 and 2a** Temporary and residential timber-framed buildings only
IV	>5000 years to ≤10,000 years	**BIC 1, 2a, 2b and 3** Temporary, residential timber-framed, normal and important structures (but not critical post-disaster facilities)	**BIC 1, 2a and 2b** Temporary, residential timber-framed and normal structures
V	>10,000 years to ≤20,000 years		**BIC 1, 2a, 2b and 3** Temporary, residential timber-framed, normal and important structures (but not critical post-disaster facilities)
VI	>20,000 years to ≤125,000 years	**BIC 1, 2a, 2b, 3 and 4** Critical post-disaster facilities cannot be built across an active fault with a recurrence interval ≤2000 years	

Note: Faults with average recurrence intervals >125,000 years are not considered active.

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 hillshade models, and a regional-scale 1-m-resolution DSM (Figure 4.1). Data from two LiDAR survey acquisitions with 1-m-resolution were supplied by Horizons Regional Council. Mapping using LiDAR data is typically undertaken at scales of 1:5000 to 1:10,000. Mapping undertaken for the GNS Science-led ‘QMAP’ geological programme and for much of the NZAFD is rendered at scales of 1:50,000 for portrayal at 1:250,000. GIS linework from the NZAFD and QMAP (Langridge et al. 2016; Heron 2018) were reviewed alongside our mapping.

For current land-use planning with respect to building on or adjacent to active faults, particularly in developed and developing areas, 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 the Horizons Region. These acquisitions cover parts of the Manawatū, Pohangina and Rangitikei river floodplains and the coastline (Figure 4.1). The raw data from many of these acquisitions were supplied to GNS Science by Horizons Regional Council for use in this project. From these data, high quality 1-m-resolution DEMs and hillshade models have been developed.

In areas where no LiDAR coverage exists, a 1-m-resolution DSM was developed by Horizons Regional Council from aerial orthophotographs for Phase 2 of this project (Langridge and Morgenstern 2019, 2020). Unlike the DEM developed from the LiDAR data, the DSM does not filter out vegetation or buildings, so there is less precision in the fault mapping in those areas. However, the DSM allows for higher-resolution mapping than the national-scale 8-m-resolution DEM and hillshade model that are otherwise the best available elevation models.

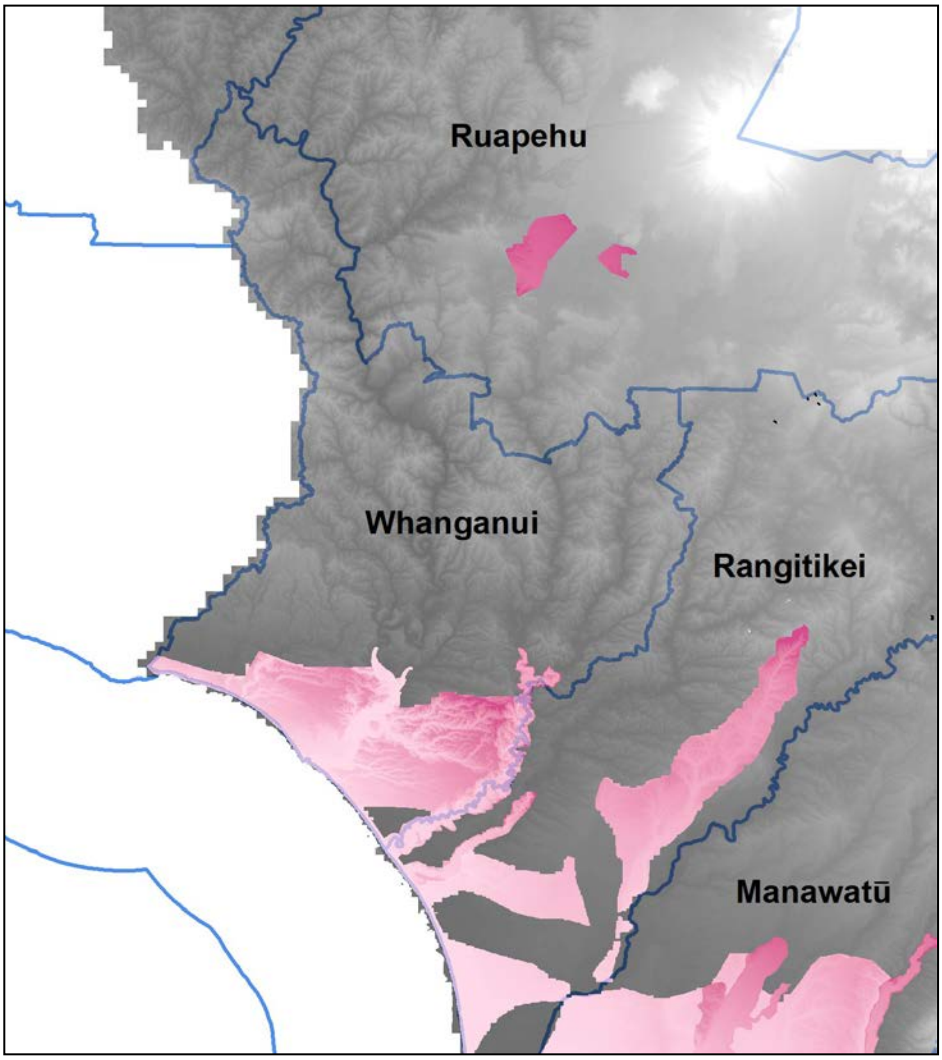

Figure 4.1 Digital topographic coverage across the western part of the Horizons Region used in this project. Airborne LiDAR is shown by pink shading and a regional 1-m-resolution DSM is shown with grey shading. Blue lines show territorial authority boundaries (named).

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 (see Table 4.1) are:

Fault_name, **Accuracy,** Tect_origin, **RI_Class, Activity, Fault_comp**, DOWN_QUAD, Method, DOM_SLIPTYPE, SUB_SLIPTYPE, *Deform_wid*, *Buffer_dis* and FAZ.

For application of the MfE Guidelines, including development of a FAZ, the most important of these are highlighted in bold. The Accuracy and Fault_comp attribute fields are used to define the Deform_wid field, and Buffer_dis (in italics) dictates the width of the FAZ. A brief glossary defining these attribute terms is presented in Table 4.1. The assignation of attributes to the GIS linework is as important as drawing the lines themselves.

The mapping of active faults requires expert recognition of tectonically displaced geomorphic landforms and a good 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 Section 5 of this report. Fault scarps are linear steps (risers) in the land surface that coincide with the locations of faults where they have broken through to the ground surface. Individual scarps and traces can extend for hundreds of metres in length and are often many metres to tens of metres wide. Therefore, representing a scarp as a line within a GIS requires simplification. In theory, a line within a GIS database has a width of zero and is meant to represent the exact location where 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: (1) the location uncertainty of digitising or surveying a line, (2) the lack of knowledge on the exact location of the fault plane (unless the fault plane is exposed in an excavation) and (3) 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 is embodied in the fault complexity term described in Kerr et al. (2003).

In the GIS database provided, the fault locations at the ground surface are mapped as accurate, approximate or uncertain. Faults that are attributed as ‘accurate’ correspond to a clear, sharp 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. Faults attributed as ‘approximate’ correspond to places where it is less certain where the fault trace occurs or where the fault forms a broad feature, in which case, it is less clear where the fault plane (or fault planes) will intercept the ground surface. Faults attributed with ‘uncertain’ locations relate to where the fault trace has been buried beneath Holocene deposits (e.g. dune sand or alluvial fan) or eroded away (e.g. by a stream or river) or is simply poorly expressed on the Earth’s surface. The inclusion of an uncertain trace assumes that there is some confidence in the location of the fault from nearby, i.e. typically either an accurate or approximate trace nearby.

The same terms (‘accurate’, ‘approximate’ and ‘uncertain’) are applied to mapping on the DSM. Despite the LiDAR DEM and the DSM both having a 1-m pixel resolution, features that are obvious on the DEM are somewhat less sharp or easily locatable on the 1-m DSM (in comparison) due to vegetation cover (trees, scrub) or buildings. The diminished level of precision attainable from the DSM, and hence greater uncertainty in accurately locating the faults on the model, is reflected in the generally wider FAZs constructed for areas without LiDAR data.

Table 4.1 Active fault data GIS attributes for the Whanganui District.

Attribute	Definition
Fault_name	The name given to an active fault (or possible active fault).
Accuracy	Locational accuracy of the fault trace – linked to the expression of the fault trace and the 'method' used e.g., accurate, approximate or uncertain.
Tect_origin	The confidence with which we can be certain that the feature mapped has a tectonic origin, as opposed to erosional or gravitational. The Tect_origin terms are 'definite', 'likely' and 'possible'.
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 or deposits of that age that are faulted.
Fault_comp	The fault complexity term that is derived from the accuracy and expression of the surface faulting. The Fault_comp terms are 'well-defined', 'well-defined extended', 'distributed', 'uncertain constrained' and 'uncertain poorly-constrained'.
DOM_SLIPTYPE	The dominant or primary sense of movement (slip) on a fault (reverse, normal, dextral, or sinistral).
SUB_SLIPTYPE	The subordinate or secondary sense of movement (slip) on a 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 and draw the fault trace (e.g. LiDAR, regional 1-m DSM, comparison with NZAFD or QMAP).
Deform_wid	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_dis	The buffer width or distance, i.e. half of the 'deformation width' in metres. However, in the case of reverse faults, the Buffer_dis is doubled on the hanging-wall side of the fault.
RI_Class	The average time between surface-rupturing events on a fault, grouped into six classifications (RI Class I–VI).

In some cases, it is not clear whether a mapped feature is of tectonic origin. For example, eroded edges of a range-front or a terrace edge could be linear and parallel to a known or suspected fault. Other linear scarp features could be related to gravitational processes or landsliding. In either case, there may be uncertainty whether what is mapped is of tectonic (faulting) origin. Therefore, we have included a GIS field called ‘Tect_origin’, which has descriptors of ‘definite’, ‘likely’ and ‘possible’, with decreasing levels of certainty about a feature’s tectonic origin.

A decision was also required as to whether the mapped feature or fault is active. In most cases, features that are mapped as definite or likely tectonic origin were attributed as ‘active’ faults (see Table 4.1), whereas features mapped as possible active faults were attributed as ‘possibly active’. Thus, for this report, there is a strong interdependence between the Tect_origin and Activity attributes.

Added complications to fault mapping may arise from sand dunes masking the terrace surfaces or erosion of terraces by local streams and rivers. Farther inland, the mapping of fault traces is hampered by the predominance of easily erodible young mudstone rock, meaning that fault scarps are readily modified (buried or removed) by landslides. Dense forest cover is another factor hampering the mapping of fault traces where the DSM is the only available digital model, as trees and other vegetation appear as ‘noise’ and may obscure fault traces. This is particularly an issue for inland parts of Whanganui District.

4.3 Fault Complexity

Fault complexity is an important parameter in the MfE Guidelines and is defined by three terms: ‘well-defined’, ‘distributed’ and ‘uncertain’. The terms ‘well-defined’ and ‘distributed’ roughly relate to the width of deformation across which intense ground deformation is likely to occur. These terms are described in the MfE Guidelines (Kerr et al. 2003). The three terms can be expanded to define whether, for example, an ‘approximate’ fault trace links together two ‘accurate’ fault traces across a relatively short distance (200 m) or a greater distance (Table 4.2). 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 due mainly to natural irregularity in the fault plane, so that with greater along-strike distance from the last known location there is the potential for the fault to deviate from its projected (inferred) location.

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, the MfE Guidelines terms were developed before the widespread acquisition and usage of airborne LiDAR or DSMs as a tool with which to map active faults. Thus, in this report, we often equate ‘well-defined’ fault complexity with accurately mapped faults. The fault complexity term ‘distributed’ is typically used in this report for approximate fault locations where the scarp is broad and therefore the exact line of fault rupture is unclear, or where a fault splits into two or more sub-parallel traces and fault deformation is distributed across a wider area.

The term ‘uncertain’ is used for fault location accuracy where the location may be unclear due to deposition and/or erosion since the most recent fault movement, burying or removing the trace. 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). These fault complexity terms link directly into Resource Consent Category tables for the MfE Guidelines.

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	If the constraint 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	If the constraint between two mapped traces is <200 m
Uncertain	Uncertain constrained	If the constraint between two mapped traces is <200 m
	Uncertain poorly constrained	If the constraint between two mapped traces is >200 m

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 FAZs 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. The MfE Guidelines recommend that an additional 'margin of safety' buffer of +20 m be included on 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. Thus, 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.

An example of a FAZ 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 width of a given FAZ, i.e. the certainty of fault deformation is better understood.

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) generally occurs over a wider area relative to the footwall (Kelson et al. 2001). For example, reverse faulting, drag folding and extension are typical on the up-thrown side of historical ruptures of reverse faults and are often recognised in trench exposures (see Figure 4.3). Thus, in this study, the width of the locational accuracy used to construct the FAZ is doubled on the hanging-wall side of reverse faults. All of the faults mapped onshore in the Whanganui District to date are classified as normal and so have symmetrical FAZs or FAAs.

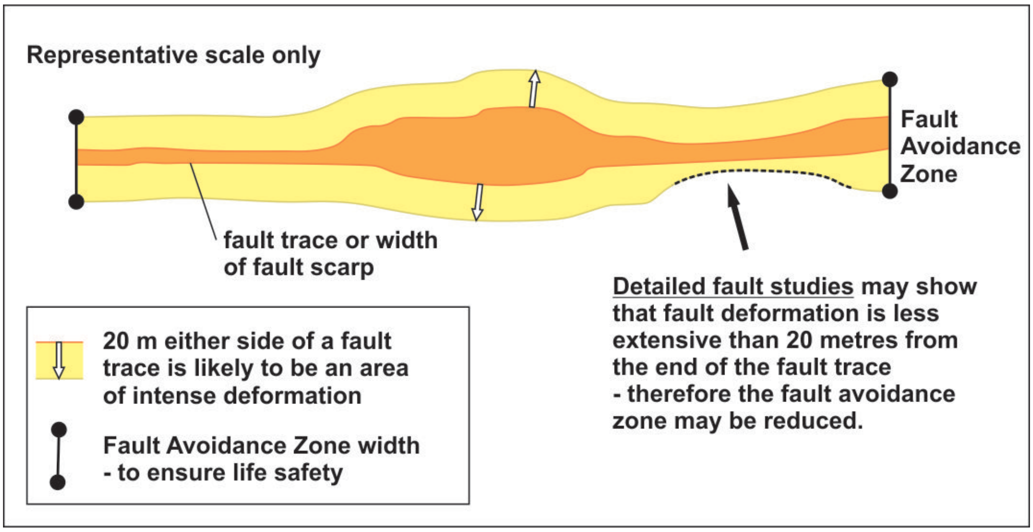

Figure 4.2 A fault avoidance zone (yellow), encompassing the fault scarp or zone (as shown in orange) for a stretch of hypothetical fault, and how it may be developed for a district-planning map. After Langridge and Morgenstern (2020).

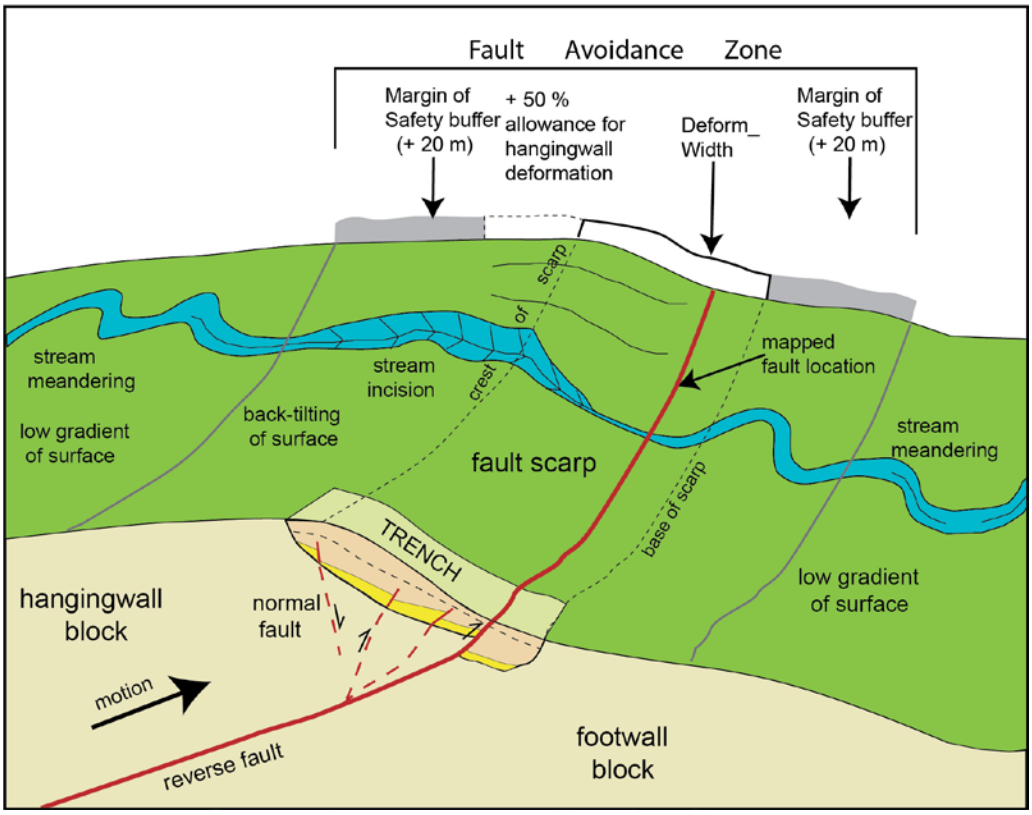

Figure 4.3 Schematic cross-section of a dip-slip reverse fault and its scarp (after Langridge and Morgenstern 2020). In this case, the mapped fault trace (and rupture plane; bold red line) is mapped near the base of the scarp. The fault trace itself is 'accurately' mapped and the scarp is 'well-defined' on LiDAR data. The growth of such scarps affects the long-term morphology of streams that cross the structure. The trench displays evidence for recurrence interval information. The complete Fault Avoidance Zone comprises the mapped width of the scarp on LiDAR (Deform_Wid = 2 x buffer_dis), which is extended by an extra 'buffer_dis' on the hanging-wall side of the fault, after which the +20-m margin of safety buffer is added. Figure from Langridge and Morgenstern (2020).

Where there is more than one fault trace making up a distributed or wide zone of faulting, individual FAZs may overlap. In these cases, the more accurate or higher-activity data (fault location, complexity) should dictate subsequent resource-planning decisions.

Included below is an example of the FAZs and FAAs developed for the Nukumaru Fault in the western Whanganui District (Figure 4.4).

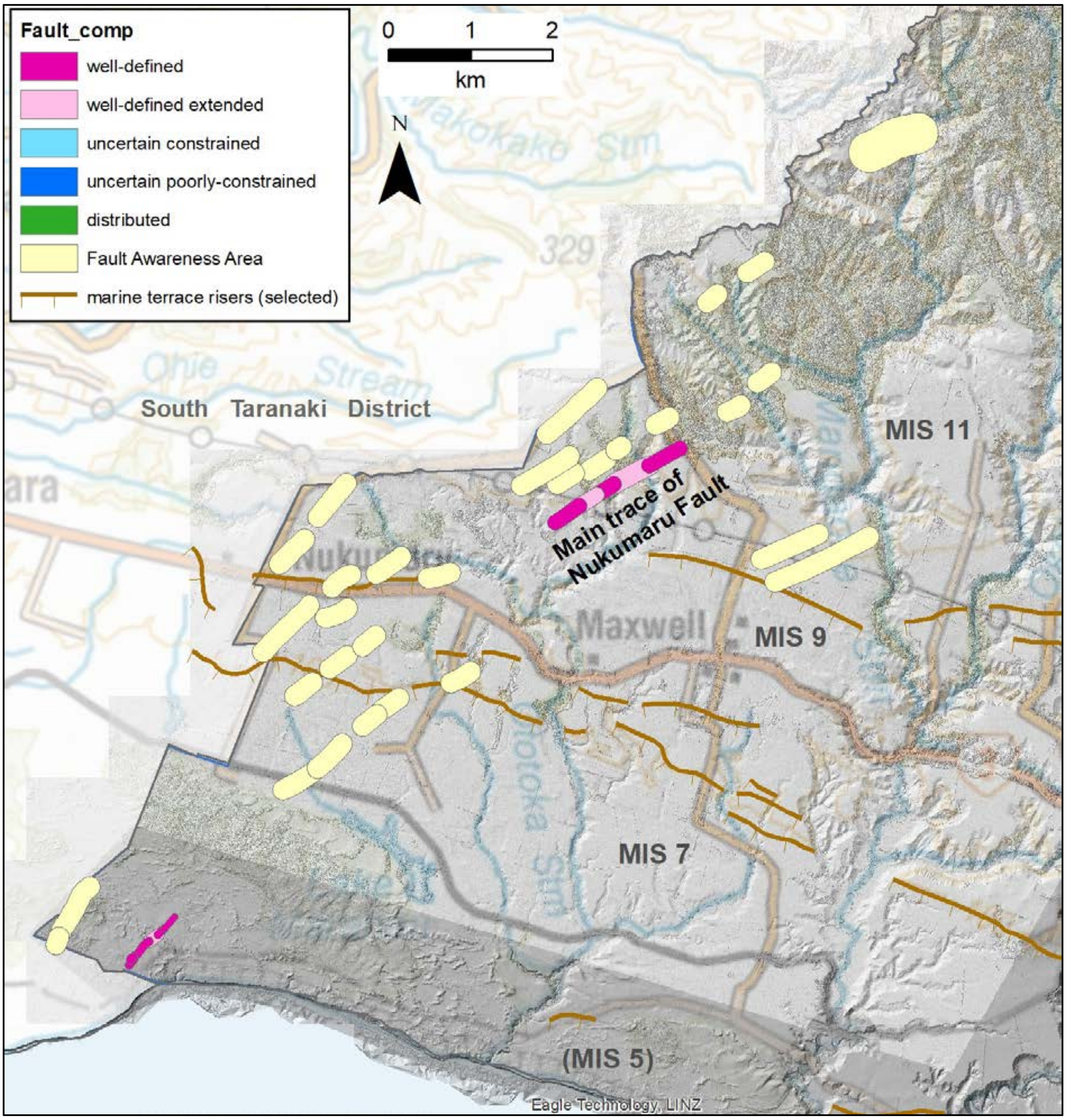

Figure 4.4 Example of FAZs and FAAs developed for the Nukumaru Fault in the south-western Whanganui District. See Figure 5.1 for location. Marine terrace risers (steps approximating old shorelines) have been mapped using the DSM and differ from those in Pillans (1990a) and Heron (2018).

4.4.1 Fault Awareness Areas

Faults mapped at 1:50,000 or those faults rendered at 1:250,000 scale are not detailed enough to delineate FAZs around the faults, nor for directly applying the MfE Guidelines (Kerr et al. 2003) to mitigate the fault rupture hazard. For faults mapped or depicted between 1:50,000 and 1:250,000 scale, a Fault Awareness Area (FAA) around the fault is recommended (Barrell 2015; Barrell et al. 2015). The purpose of a FAA is to highlight that there may be a tectonic feature (fault) within that area. In previous fault-related hazard mapping studies in the Canterbury Region, GNS Science has developed FAAs for active faults that have been mapped at a regional scale (Barrell et al. 2015). This is useful in cases where the fault location uncertainty is high, or in cases where there is considerable uncertainty about the origin of geomorphic features, i.e. it is more reasonable to develop a FAA than a FAZ for such features because a mapped feature may have less certainty whether or not it is tectonic, and therefore the level of hazard associated with it is less certain. As such, FAAs highlight the need to undertake further work to test whether a mapped feature is related to tectonic (fault) deformation.

Where a feature is well-defined, FAAs are developed with a width of ±125 m (i.e. total width 250 m; Figure 4.4); where features are less well-defined, they are given a width of ±250 m (i.e. total width 500 m). FAAs 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 and/or nature of surface faulting and deformation. In this present study, FAAs have been developed for parts of the Nukumaru Fault that do not have FAZs and all other ‘possible’ faults. These FAAs are given buffer widths of ±125 m where features are well-defined on the marine terrace surfaces and/or mapped from LiDAR data and ±250 m for all other possible faults that are mapped using the 1-m DSM.

4.5 Active Folds

Active folding is commonly part of the manifestation of active reverse faults, some of which penetrate to the Earth’s surface and have a fault scarp and some of which are blind or have a fault tip that is buried beneath the Earth’s surface (Figure 3.2). In general, the closer the buried fault tip is to the ground surface, the narrower the zone of associated deformation at the surface will be. A reverse fault-fold combination will form an anticline on the up-thrown side of the fault, with amplitude of the ridge or crest being a measure of the combined deformation. Folding may also occur in association with normal faulting, where the hanging-wall fault block collapses over the fault plane due to extension in the fault zone. Active folds have been identified in other districts in the Horizons Region, but we have not identified any active folds within the Whanganui District. There is therefore no further discussion of active folds in this report.

5.0 ACTIVE FAULTS OF THE WHANGANUI DISTRICT

This study represents the first time that active fault mapping has specifically been collated for the Whanganui District (Figure 5.1). With the help of an airborne LiDAR-derived DEM and a regional 1-m-resolution DSM, it has become possible to map active faults and to identify some 'possible' active faults. The new mapping builds on data from QMAP (Begg and Johnston 2000; Townsend et al. 2008; Lee et al. 2011; Heron 2018) and the NZAFD (Langridge et al. 2016), which identified the Nukumaru Fault as the only known active fault within the district. All other features identified in this study are classified as 'possible' active faults.

Large parts of the central and northern Whanganui District are devoid of known or mapped active fault traces. This area is underlain by latest Neogene and Quaternary rock (predominantly mudstone, but including sandstone, limestone and minor volcaniclastics), and its associated dissected hill country geomorphology (Townsend et al. 2008) makes mapping active faults difficult. This is hampered further by the lack of LiDAR survey data in densely vegetated areas.

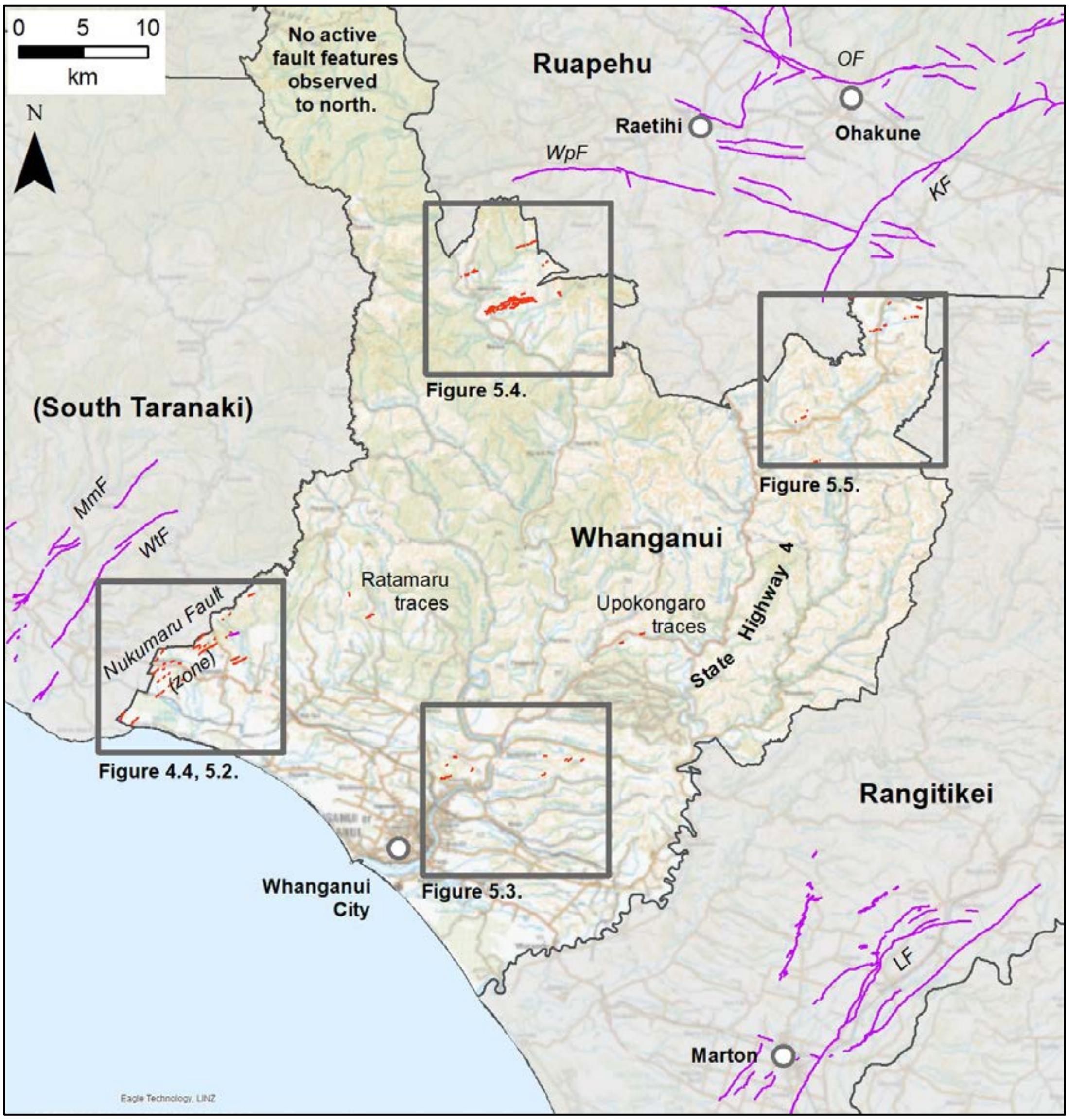

Figure 5.1 New and updated onshore active faults and possible active faults (red) for Whanganui District as defined in this study. Active faults outside the district are shown by purple lines. Fault name abbreviations are as in Figure 1.1. Boxes show the areas of detailed maps in Sections 4 and 5.

Below, we describe the active faults and 'possible' active faults within the district, generally from southwest to northeast. Active faults, as defined in this study, are those for which FAZs have been designed. The only 'definite' or 'likely' active faults mapped (i.e. having evidence for movement or repeated movements during the last 125,000 years [Langridge et al. 2016]) are two strands of the Nukumaru Fault. All other features are designated as 'possible' active faults, which are grouped by area and described below. FAAs have been constructed for these features.

5.1 Active Faults

5.1.1 Nukumaru Fault

The main tectonically active area within the Whanganui District is the far southwest and, specifically, the Nukumaru Fault. Active faults and 'possible' active faults (see Section 5.2.1) cutting across late Quaternary marine terraces make up the fault zone. The zone is up to ~3 km in width and extends beyond the Whanganui District boundary into the South Taranaki District (Figure 5.2). Fault traces are all NW–SE-striking; some extend toward the coast, albeit mantled by Holocene sand dunes, and possibly offshore (Pillans 1990a,b; Townsend et al. 2008). The faults may also extend inland, but erosion of the marine terraces and soft mudstone bedrock there has not favoured preservation of morphological scarps. Exposures of some of the faults show that they have a normal sense of movement (slip type), and they are tentatively interpreted as secondary (flexural or bending-moment) faults, associated with folding (Pillans 1990b).

Prior to this study, the only active faults within the Whanganui District were two traces within this zone (Figures 5.1 and 5.2). One of these traces was mapped as an ~800-m-long line crossing an eroded MIS 11 (c. 420,000–360,000 years old) marine terrace about 3.3 km north of Maxwell. However, this feature is not evident on the Horizons Regional 1-m-resolution DSM. Although unlikely, it is possible that this previously-mapped 'trace' is not apparent in the DSM because it is obscured by pasture/crops growing on the terrace. This previously-mapped feature lines up with other newly mapped 'possible active faults' in the zone, and also the redefined 'main' trace (see below). However, as it is not visible on the DSM, we have removed it from the GIS and transferred the active status to the main trace of the Nukumaru Fault.

The only other previously mapped active fault is near the south-western edge of the Whanganui District. In previous maps (Heron 2018, NZAFD) the expression of this fault is classified as 'unknown'. There is a hint of a structure in this location on aerial photo mosaics, but it occurs right on the edge of the LiDAR data coverage and the area is now covered in pine forest, so the DSM is too noisy to verify any structure there. We have left this trace in the GIS for now, but with no RI value attached.

The largest scarp of the Nukumaru Fault is well expressed and ~15 m high where it crosses MIS 11 marine terrace (the 'main' trace; Figure 5.2). However, its extension to the southwest across younger terraces, as suggested by Pillans (1990b), is not evident from the DSM or LiDAR data. This fault was conservatively assessed by Townsend et al. (2008, and thereafter Heron 2018) as an inactive fault. This is because the QMAP definition of an 'active' fault is one that has demonstrable displacement in the last 125,000 years or has sustained multiple displacements in the last 500,000 years. On reassessment and, given that the scarp height of ~15 m probably reflects multiple displacements of the MIS 11 marine terrace, it is reasonable to redefine this as an active fault. The Whanganui District is also a low strain area far away from the main plate boundary faults and so it also fits the criteria of a "fault that shows evidence of surface rupture or ground deformation during the current tectonic regime" (Villamor et al. 2018). See below for RI information pertaining to this trace.

A previously unrecognised ~800-m-long scarp near the coast apparently displaces the MIS 5 marine terrace. This scarp is mantled by sand dunes but still has clear surface form in places. There is the possibility that this fault is much older: the erosion-resistant Nukumaru Limestone crops out in this area (Fleming 1953) and, if this fault represents an old (Pleistocene) fault that vertically displaced the Nukumaru Limestone, differential erosion may be resolving the height difference in the limestone beds, producing a step that looks like a Quaternary fault scarp.

The only two Fault Avoidance Zones constructed for this report are for strands of the Nukumaru Fault. These are for the largest 'main' trace and also the newly mapped trace near the coast (see Figures 4.4 and 5.2).

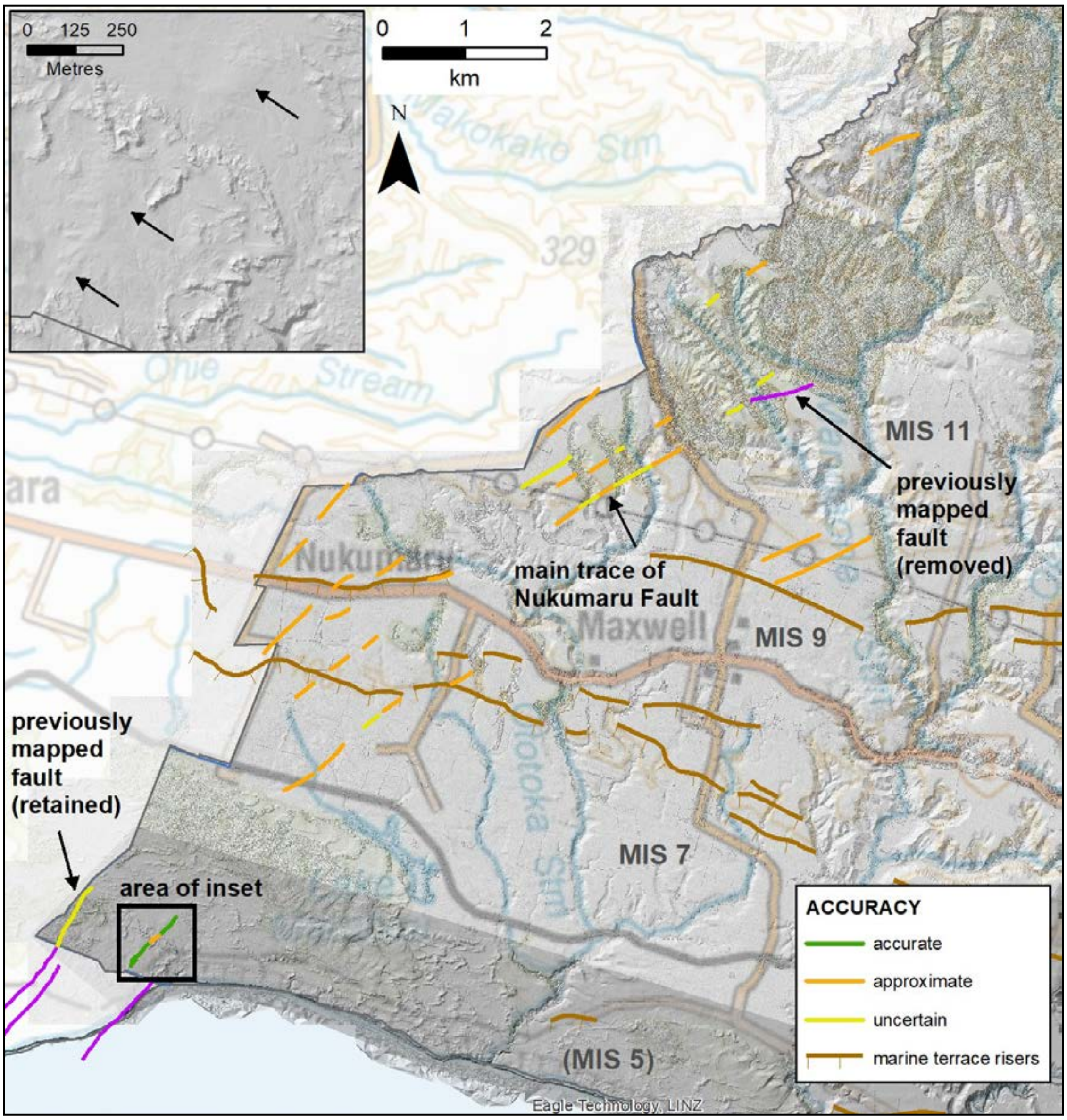

Figure 5.2 Active traces (coloured by accuracy) of the Nukumaru Fault, in south-western Whanganui District. The purple lines include previously mapped faults (from the NZAFD and Heron 2018) that are either outside the district or that we cannot verify. FAZs and FAAs are shown in Figure 4.4. The inset map shows the newly recognised trace (arrowed) near the coast, as is visible on the LiDAR hillshade map (darker grey on main figure). The marine terrace risers (steps approximating old shorelines) have been mapped from the DSM and their locations differ from those shown in Pillans (1990a) and Heron (2018).

The main trace is well-defined across the MIS 11 marine terrace (Figure 4.4). Tributaries of Ototoka Stream form deep gullies eroded into the marine terraces in this area, two of which intersect the mapped fault trace. There is no evidence from the DSM of a fault scarp crossing these gullies (which are partly obscured by vegetation), but two short segments (with Fault_comp of 'well-defined extended') have been added to link the well-defined traces that have been mapped on the terrace. The FAZ has a width of ±75 m for the 'definite' fault segments and for one of the 'likely' segments, and ±125 m for the longer 'likely' segment. With the additional +20 m for the setback area, as recommended in the MfE Guidelines, this results in a FAZ 190–290 m wide.

A previously unidentified fault near the coast is mapped from the narrow strip of LiDAR data available (Figure 5.2; see inset). This trace is ~800 m long, is sharply defined and is approximately within the area labelled 'Nukumaru Fault Zone' on the late Quaternary marine terrace map of Pillans (1990a), which shows other active faults but nothing in this location. The traces are mapped as 'accurate' or 'approximate' and Fault_comp is either well-defined or well-defined extended. The FAZ developed for this feature varies in width between 80 and ±150 m, depending on the mapped accuracy and width of the scarp (Figure 4.4). The widest part of the zone accounts for a ~30-m-long segment that is concealed beneath sand dunes ('well-defined extended').

A recurrence interval (RI) of faulting has been calculated for the main trace of the Nukumaru Fault using estimates of single event displacement and a revised slip rate (Table 5.1). The slip rate has been determined using profiles of the DSM in ArcGIS to measure the vertical displacement of the surface in metres across the mapped trace. These vertical displacements are converted to dip-slip displacements on the fault plane, assuming that all faults in this area are steeply-dipping (70 ±10°) normal faults (e.g. Pillans 1990b; Stirling et al. 2012). Dividing the dip displacement (in metres) by the ages of the terraces (in thousands of years) (Pillans 1990; Heron 2018), these dip-slip displacements are converted to average dip-slip rates (SR) in metres/thousand years (or mm/year).

Pillans (1990a, b) calculated a slip rate for the Nukumaru Fault of 0.07 mm/yr for the last 2.2 million years, or an average of 0.08 mm/yr over the last 500,000 years (Table 5.1). Displacements were measured on the wave-cut platforms of marine terraces (rather than the terrace surfaces as used here), but there is not enough information to repeat or verify his surveying. Some repeat measurements were attempted, but the figures we obtained for scarp heights were about half of the displacement values presented in Pillans (1990a, b) (Table 5.1). The method used here also differs in that we are measuring displacements from terrace surfaces, which will include cover beds overlying the wave-cut platforms. However, it is likely that the thicknesses of cover will be the same on both sides of the fault (i.e. on the same terrace); therefore, the scarps measured here should be representative of the vertical component of fault displacement. We acknowledge that the slip rate for the Nukumaru Fault could be as high as that presented by Pillans (1990a, b), but this is probably an upper limit.

The RI calculation requires information about the single event displacement (SED), or the amount of fault displacement that may occur in any one surface-rupturing event. Given the paucity of data on active faults in the Whanganui District, we have assumed conservative SEDs of 1–2 m (dip-slip) based on studies of other normal faults, for example, the nearby Waverley Fault Zone in the South Taranaki District (Townsend 1998) and further afield on the Taranaki Peninsula (Townsend et al. 2010). The calculated RI ranges from 19,500 to 59,500 years, which spans the upper end of RI Class V and lower end of RI Class VI. This has a low confidence due to poor precision of dating of terraces, the complexity of multiple fault scarps within the fault zone and the uncertainty in the SED range.

If the SEDs are smaller than the 1–2 m used here in calculations, then RIs could be shorter (lower, or more active), as the faults would need to rupture more frequently in order to accumulate the observed displacement. We provide some simple sensitivity analysis of the SED parameter by halving and doubling the value (Scenarios A and B in Table 5.1, respectively) to give an indication of the effects of using different SED values on our RI calculations. Under Scenario A (halving the SED), the RI range is 9700 to 29,750 years; under Scenario B (doubling the SED), the range is 39,100 to 119,000 years.

Table 5.1 Displacements, ages of terraces, and calculated dip-slip rates for the Nukumaru Fault*. Single event displacement (SED) is 1–2 m, except for scenarios A and B. Indicative recurrence intervals and RI Classes are given.

Nukumaru Fault	Scarp Height (m)	Terrace and Age (Thousands of Years)	Dip-Slip Rate (mm/year)	SED (m)	RI (Years)	RI Class
This study*	14–16*	Rangitatau/Ararata 423–361	0.03–0.05	1–2	19,500 to 59,500	V–VI
Scenario A*	-	-	-	0.5–1	9700 to 29,750	IV–VI
Scenario B*	-	-	-	2–4	39,100 to 119,000	VI
Pillans (1990a, b)	30**	Rangitatau 450	0.07–0.08	1–2	13,000 to 29,550	V–VI
	30**	Ararata 400	0.07–0.08	1–2	11,500 to 26,300	V–VI

*Main trace of Nukumaru Fault only. Terrace names are from Pillans (1990a) and ages are from Heron (2018). Scenarios A and B show the effects of halving and doubling the SED to give an indication of the sensitivity of this parameter; no other parameters from the first row were changed.

**Pillans (1990a, b) calculations use heights of wave-cut platform to estimate fault vertical displacement, approximately twice the value that we measure for this fault from the DSM. The RI values presented here use the same 1–2 m SED values as our calculations, but we cannot verify the published displacement values.

5.1.1.1 Some Caveats

As mapped, the Nukumaru Fault includes several overlapping traces that probably connect at depth. This has implications for the activity of the zone as a whole, which may be higher than interpreted here. This is because the presented RI is calculated from only one strand (admittedly, probably the most active one, or at least that which has the largest scarp) of the whole zone. Strain may be distributed across different splays of the zone and not every splay might rupture in every faulting event, as observed for the many distributed faults that ruptured to the surface during the 2016 Kaikōura earthquake (e.g. Litchfield et al. 2018). Thus, there may be other splays of the Nukumaru Fault that carry a low slip-rate, but without more specific or detailed study to determine the tectonic origin and/or slip-rates of those mapped features, we are hesitant to apply any RIs to these possible fault traces.

Fault-plane dip is another factor that could affect the SED value and therefore the calculated RIs. If the fault dips significantly less than the 70° assumed here, then slip rates would need to be higher in order to achieve the observed vertical displacements and thus, assuming the same 1–2 m SED as above, RIs would be shorter than presented here. The mapped fault traces are generally very straight, even where intersecting variable topography of ridges and valleys, indicating that their planes are probably quite steep. Nevertheless, we have included a range of dip values (±10°) in our calculations to account for some of this uncertainty.

5.1.1.2 Nukumaru Fault RI Class Summary

Taking into account all of the uncertainties discussed above, we tentatively place the Nukumaru Fault into RI Class V (>10,000 to ≤20,000 years) with a low level of confidence (Table 5.2).

Table 5.2 Recurrence interval data for the Nukumaru Fault updated from this study.

Fault	District	RI Class Confidence^
RI Class V Faults (>10,000 to ≤20,000 Years)		
Nukumaru Fault	Whanganui	L

^RI Class Confidence: L, Low – uncertainty in recurrence interval 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 comparison with other faults).

5.2 Possible Active Faults

Some faults or fault-like features are evident in the landscape but have a significant amount of uncertainty as to whether they are active tectonic structures. The uncertainty arises mainly because: (i) they may be scarps that have a fluvial origin, e.g. old riverbanks; (ii) they may be scarps that have a gravitational origin, e.g. ridge rents, landslide head scarps, etc.; or (iii) they may be a geologic lineament related to a hard bedrock unit, i.e. a bedding strike ridge. These features are mapped as ‘possible’ active faults and are treated differently from active faults in this report. In general, these features require more work or evidence to classify them as active faults. For planning purposes, in this study they are identified by linework and developed into FAAs, i.e. they are areas where an active fault may exist, though more work is required to determine their origin and/or activity. This work could include geophysical studies that define the subterranean structure, ground mapping and/or surveying, or paleoseismic studies, e.g. trenching the feature.

All mapped features outside the Nukumaru Fault, and some within it, fall into this category, as outlined below.

5.2.1 Nukumaru Fault

As well as the ‘definite’ and ‘likely’ faults mapped as part of the Nukumaru Fault (see Section 5.1.1), other ‘possible’ active faults have been mapped as far as ~14 km inland into the dissected hill country (Figure 5.2). FAAs were developed by buffering the mapped possible faults according to the level of Accuracy, Activity, Tect_origin and Method (e.g. Figure 4.4).

Well-expressed scarps mapped from the DSM or LiDAR DEM (where available), and those that cross the marine terrace surfaces, can be located with relative precision. The FAAs developed for these possible active faults are 250 m wide. Moderately expressed possible faults in the hill country away from the terraces are mapped from the DSM with less precision, and, accordingly, their FAAs are 500 m wide.

5.2.2 North Whanganui Area

Several short steps or scarp were noted on the LiDAR DTM crossing the MIS 9 marine terrace (including Brunswick and Braemore terraces; Pillans 1990a) and MIS 6 alluvial terrace (Heron 2018) just north of Whanganui City (Figure 5.3). These are mapped as ‘possible’ active faults due to their orientations approximately parallel with the regional trend of other tectonic structures and approximately perpendicular to the marine terrace risers in this area. However, it is also possible that they are the edges of local fluvial channels (streambanks) that were cut prior to incision of the Whanganui River (and other local streams) into the terraces. Additionally, they could be incipient scarps related to gravitational collapse/ landslides, of which there are many in this area with the same general orientation.

Due to their relatively well-expressed scarps and the LiDAR coverage of this area, the FAAs developed for these possible active faults are 250 m wide.

5.2.3 East Whanganui Area

Several short steps or scarps were noted on the LiDAR DTM and regional 1-m-resolution DSM on the MIS 11 (Rangitatau; Pillans 1990a) marine terrace east of Whanganui City (Figure 5.3). These features are mapped as ‘possible’ active faults due to their orientations being approximately parallel with the regional trend of other tectonic structures. As for the North Whanganui scarps (see above), we cannot rule out the possibility of these features being related to local fluvial channels (streambanks) or to gravitational collapse/landslide scarps.

Because these mapped features cross marine terrace surfaces, they can be mapped with relative precision; thus, the FAAs developed for them are 250 m wide.

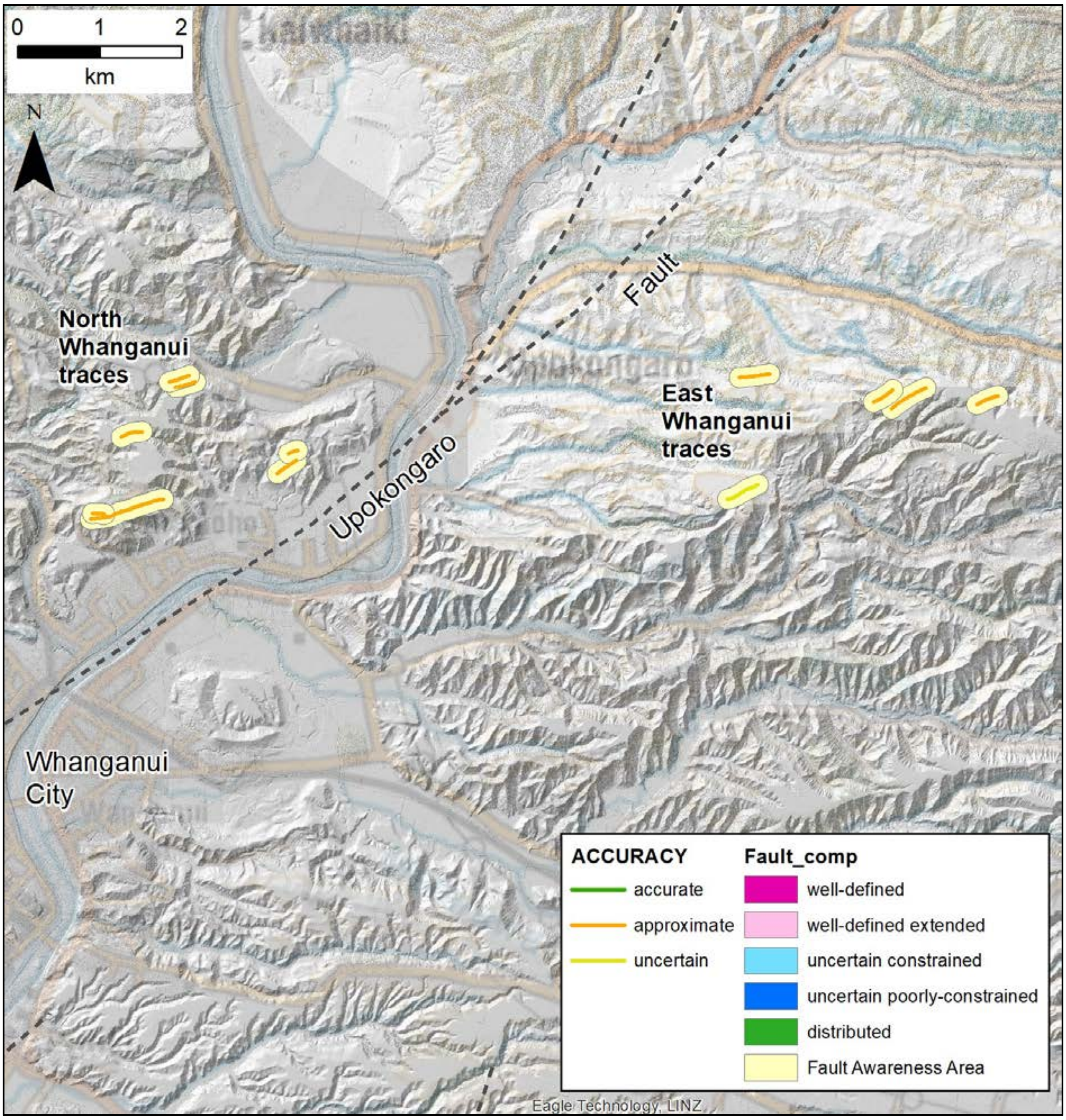

Figure 5.3 Possible active faults mapped on marine terraces north and east of Whanganui City. The generally flat ground and LiDAR coverage in this area allow for a relatively high precision of mapping. Scarps are parallel to the general orientations of streams and may be related to fluvial incision. The position of the Upokongaro Fault (inactive) is also shown (Fleming 1953; Heron 2018).

5.2.4 Ratamaru Area

Two short traces are mapped in the hill country ~10 km NE of Kai-Iwi (named after a nearby airstrip; Figure 5.1). These apparently cut MIS 15 and MIS 17 marine terrace remnants (Pillans 1990a; Townsend et al. 2008). They are perpendicular to each other and their interrelationship and origin is unclear; they could be related to landslides/gravitational collapses. They are included here as ‘possible’ active faults and the FAAs developed for them are 500 m wide.

5.2.5 Upokongaro Area

Two short traces are mapped in the upper Upokongaro / Haupari Stream to Makuao Stream area, near State Highway 4 (Figure 5.1). These traces are sharp (well-expressed) and, accordingly, the FAAs for these possible active faults are 250 m wide. The 1300 m along-strike gap between the traces is occupied by hummocky ground (mapped as a landslide; Townsend et al. 2008), so the traces might be part of one continuous feature that is partly buried by landslide debris. If this is the case, then the (buried) feature probably crosses State Highway 4 at NZTM ~1791250E, 5593600N.

The Upokongaro Fault was mapped in this area by Fleming (1953) but with no indication that it is an active fault. The Upokongaro Fault is downthrown to the east and vertically displaces the c.2.4 million-year-old Hautawa Shellbed by 25 m (Fleming 1953). Pillans (1990b) suggested that displacement of the marine terraces across the Upokongaro Fault is “unlikely to exceed 10 m”.

5.2.6 Morikau Area

Several overlapping traces are mapped near the crest of the ridge between Whataumu and Mangoihe streams, near Ranana on the east bank of Whanganui River (Figure 5.4). There is an obvious landslide in this area, within which many of these traces are mapped. We cannot rule out the possibility that these scarps are due to movement of the landslide (i.e. a planar or translational slide parallel to bedding; Hungr et al. 2014). However, they are included here as ‘possible’ faults because they are very fresh, linear traces that are parallel with the regional structural trend. There are three short traces along strike, ~1.5 km to the east, which are not mapped within a landslide and appear to be contiguous (on trend) with the main group of traces. Individually, these well-defined features have FAAs that are 250 m wide but, because there are many parallel scarps forming the main group, the FAA buffers overlap to form an ~800-m-wide, ~4-km-long zone (Figure 5.4). If the three traces to the east are included, these features define a discontinuous zone of well-defined scarps that is >6 km long.

Two more short scarps are mapped in the Mangoihe Stream valley near the confluence with Matihope Stream. These traces are well expressed and, accordingly, the FAAs for these possible active faults are 250 m wide.

5.2.7 Otaranoho Area

Several overlapping traces are mapped across gently sloping ground on the north side of Mangoihe Stream, crossing Otaranoho Road at their eastern end (Figure 5.4). There is another group of traces ~3.4 km to the east along strike. The area between the two sets of traces is heavily vegetated and difficult to interpret from the DSM. The scarps are broad or subtle and face to the south, down the regional bedding dip. Thus, they might also be related to a large landslide like the Morikau traces (see above). However, since they are parallel with the regional structural trend, we classify them as possible active faults. Their orientation is also consistent with the active Waipuna Fault (Villamor et al. 2006; Townsend et al. 2008; Langridge et al. 2016), about 5 km to the north in the Ruapehu District (see Figure 5.1), as well as other potentially active faults ~10 km to the east, also in Ruapehu District. We have constructed 500-m-wide FAAs for these possible active faults.

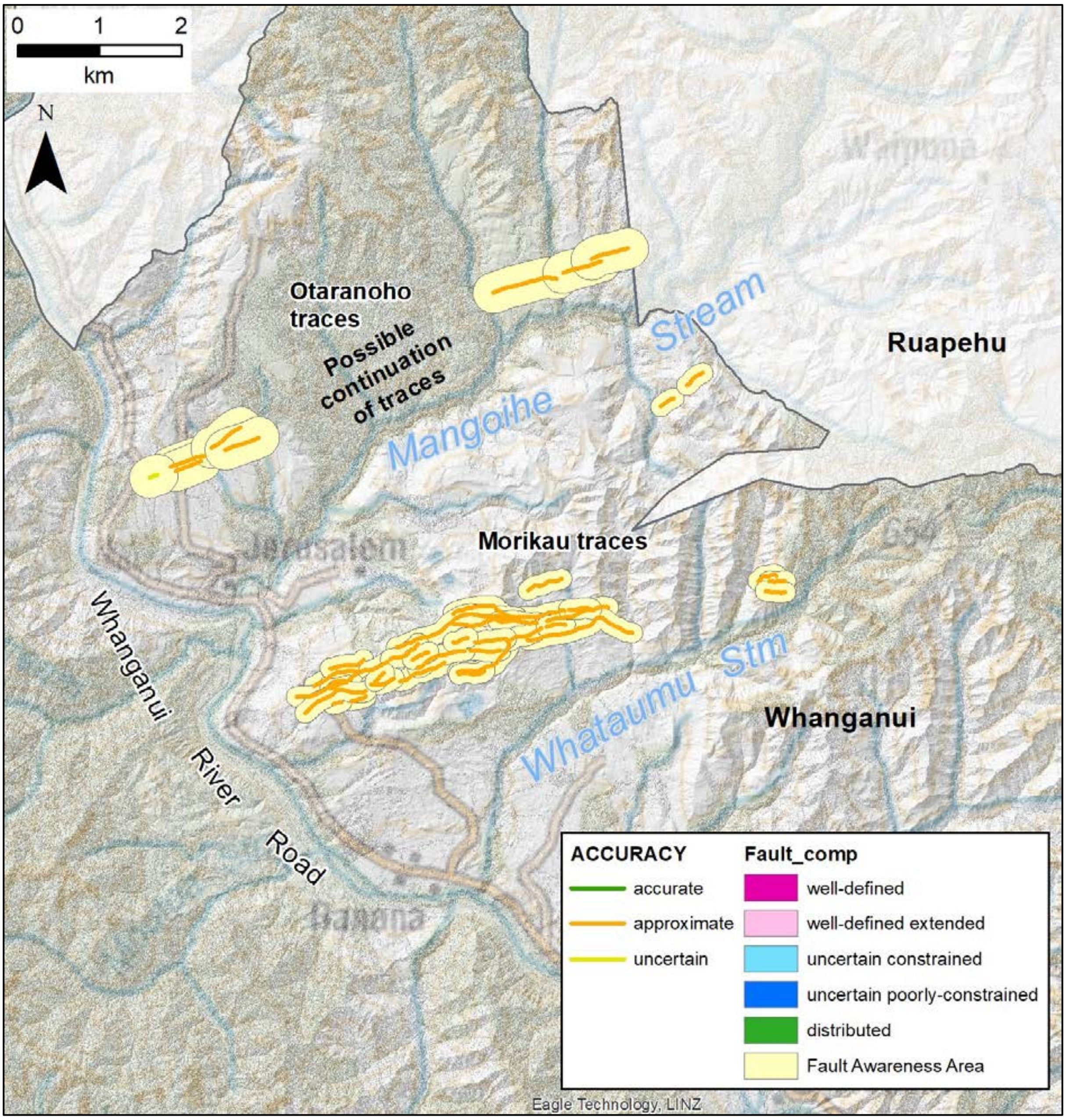

Figure 5.4 Traces and FAAs mapped in the Jerusalem-Ranana area, near the Whanganui River. A series of well-defined scarps on the ridge between Whataumu and Mangoihe stream form a 6-km-long, 800-m-wide zone of deformation. Other possible faults north of Mangoihe Stream are less distinct.

5.2.8 Te Hue Area

Three discontinuous traces are mapped on the ridge between the Mangawhero and Whangaehu rivers, about 2.7 km south of Fields Track (Figure 5.5). Together, they form a ~1.6-km-long zone of subtle scarps. We cannot rule out the possibility that these features are related to landsliding/gravitational collapse, of which there are many in this area. However, due to their orientation parallel with the regional structural trend, we classify these features as possible active faults with FAAs that are 500 m wide.

5.2.9 Ahurangi Area

A series of uphill-facing scarps are mapped on the south side of Ahurangi Stream valley, just north of Fields Track (Figure 5.5). The scarps face uphill (southeast) and are approximately parallel to the contours, forming a ~10-m-wide bench on the hillside. Given that these features are linear and only visible on one side of the ridge, it is difficult to determine whether they are dipping steeply (could be a fault) or gently (could be a sediment layer). There are variably cemented shell beds in the locally-outcropping Paparangi Group (Townsend et al. 2008) that could form such features in the landscape. However, no other similar features were noted in this area, as would be expected if they were related to bedding, which would most likely form (originally) continuous sheets several kilometres wide.

The features are well-expressed and included here as 'possible' active faults until more assessment is undertaken. The FAAs for these possible active faults are 250 m wide.

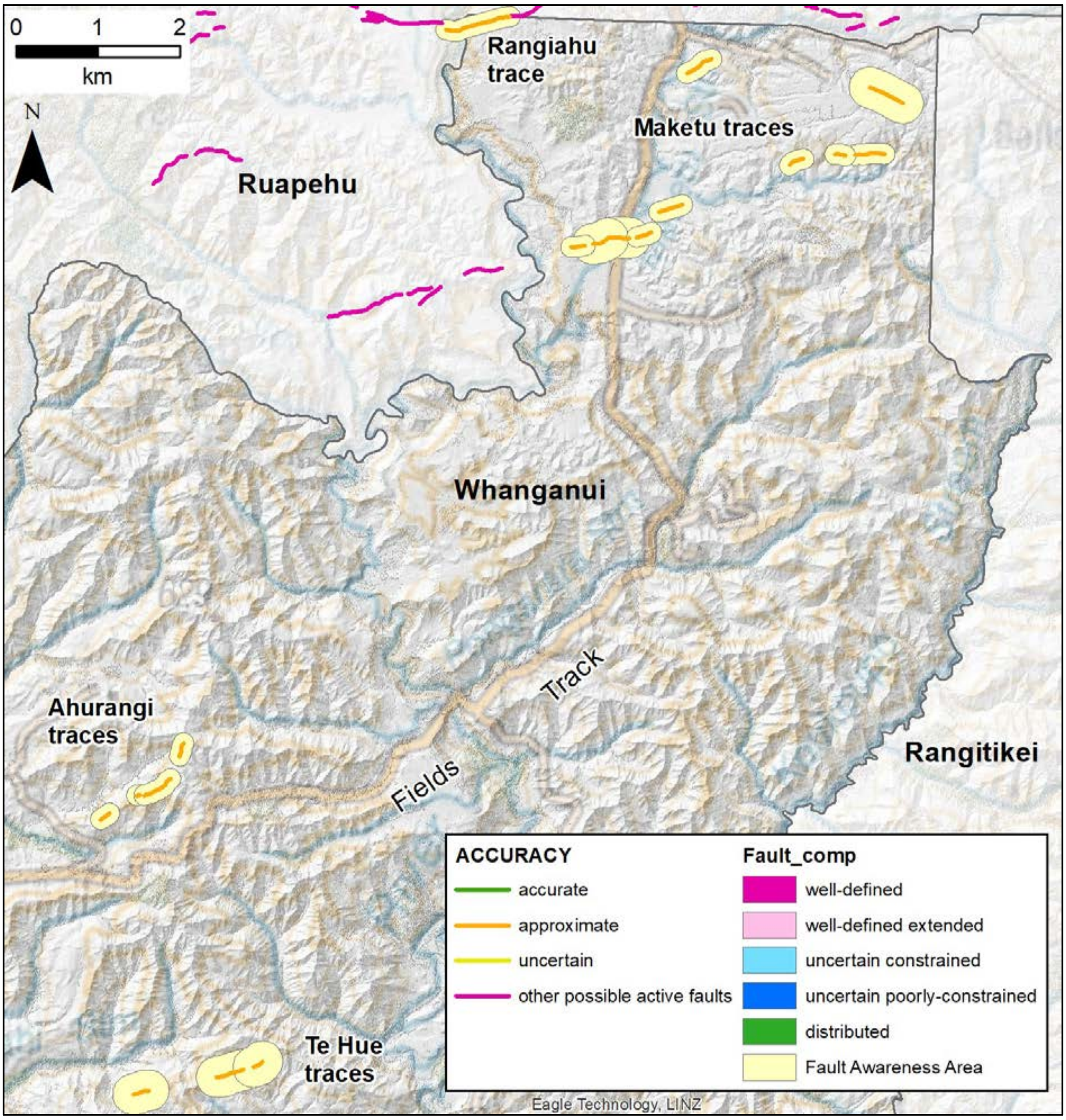

Figure 5.5 Traces and FAAs mapped in the north-eastern Whanganui District. Other possible active faults mapped from the DSM in the Ruapehu District (magenta lines) are presented to show the continuity of some of these features.

5.2.10 Maketu Area

Several short traces are mapped in the Maketu Stream valley and surrounding hills (Figure 5.5). They are approximately parallel with the regional east–west structural trend. One of these features crosses the Whangaehu Valley Road at NZTM 1809960E, 5617240N and possibly continues west into the Ruapehu District. Some traces are well-expressed and some are moderately expressed; thus, the FAAs for these possible active faults vary between 250 and 500 m wide, respectively.

5.2.11 Rangiahu Area

A scarp is mapped across a northern corner of the Whanganui District adjacent to the Whangaehu River (Figure 5.5). There is an obvious young landslide just to the south of the scarp, which probably forms part of the landslide head (or lateral) scarp. However, this scarp continues to the east into the much hillier country just to the north of the Whanganui District (Ruapehu District) as an eroded scarp. Given the rounded nature of this scarp, it may represent an inactive fault defined by eroded dip-slopes (= resistant bedding planes) in the Tangahoe Mudstone (Townsend et al. 2008) rather than displacement of younger topographic features. The recent landslide may be utilising the ‘old’ fault as a structural weakness.

This scarp appears to continue to the west across the Whangaehu River and into the Ruapehu District, where well-defined active fault traces can be seen displacing fluvial terraces within the Rangiahu valley. All these traces (possible active faults) are approximately parallel with the east–west regional structural trend, including the Waipuna-Raetihi-Ohakune fault sets (Figure 5.1; Villamor and Berryman 2006 a, b). A 250-m-wide FAA has been constructed for the well-expressed part of the trace that we map within the Whanganui District.

6.0 APPLICATION OF FAULT AVOIDANCE ZONES FOR THE NUKUMARU FAULT

Tables 6.1 and 6.2 outline how the information from this report can be applied for planning in terms of resource consent categories for the Nukumaru Fault. The tables present examples of relationships between Resource Consent Category, Building Importance Category, fault Recurrence Interval Class and Fault Complexity for both previously developed and Greenfield sites along the Nukumaru Fault. These examples are modified from the MfE guidelines based on recommendations made for a similar fault mapping study for the Kāpiti Coast District Council (Van Dissen and Heron 2003).

Table 6.1 Example of relationships between Resource Consent Category, Building Importance Category, fault Recurrence Interval Class and Fault Complexity for developed and/or already subdivided sites for the Nukumaru Fault. Based on the MfE Guidelines (for more detail, see Kerr et al. 2003).

Developed and/or Already Subdivided Sites					
Nukumaru Fault (Based on Fault Recurrence Interval Class V, >10,000 years to ≤20,000 Years)					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed, and Uncertain – constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain – poorly constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying

* Indicates that the Resource Consent Category is permitted but could be controlled or discretionary, given that the fault location is well-defined.

Table 6.2 Example of relationships between Resource Consent Category, Building Importance Category, fault Recurrence Interval Class and Fault Complexity for Greenfield sites for the Nukumaru Fault. Based on the MfE Guidelines (for more detail, see Kerr et al. 2003).

Greenfield Sites					
Nukumaru Fault (Based on Fault Recurrence Interval Class V, >10,000 years to ≤20,000 Years)					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed, and Uncertain – constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain – poorly constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying

* Indicates that the Resource Consent Category is permitted but could be controlled or discretionary given that the fault location is well-defined.

7.0 CONCLUSIONS

Active fault mapping has been undertaken for Horizons Regional Council, covering the Whanganui District for the purposes of planning with regards to active faults. Active faults are those faults considered capable of generating strong earthquake shaking and ground-surface fault rupture. A variety of mapping platforms and techniques have been useful for characterising the location and activity of active faults within the district, including airborne LiDAR data and a regional 1-m-resolution DSM. A preliminary recurrence interval class has been provided for the main trace of the Nukumaru Fault, based on the height of the scarp as measured from the DSM, the age of the terrace(s) from previous geological mapping and fault slip information from comparisons with better-studied faults nearby, including some in the South Taranaki District. The preliminary RI Class defined in this study for the Nukumaru Fault is RI Class V ($>$10,000 years to $\leq$20,000 years). This carries a low level of confidence due mainly to the poor preservation of geological surfaces from which we can calculate slip rates and single event displacements.

Other ‘possible’ active faults are mapped in various locations throughout the district and are described by area. These include several short scarp-like features crossing the marine terraces to the north and east of Whanganui City and other possible active faults mapped in the dissected hill country inland. Some of these features could possibly be related to cutting of stream and river channels and some could be related to landslides. No active folds were identified within the Whanganui District.

There is not enough geological information to assign slip rates or recurrence intervals to these features. Therefore, FAZs and RI classes have not been defined for them. FAAs have been designed for these features, which recognises that they are possibly active faults, but their tectonic origin and level of activity is unknown. Depending on the nature of the mapped feature, FAAs have total widths of either 250 or 500 m. FAAs do not carry the regulatory levels that relate to the MfE Guidelines for their FAZ counterparts. 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 presence and location of surface faulting and deformation.

The outcomes of fault mapping, and FAZ and FAA development, are in keeping with the goals of the ‘MfE Guidelines’ (Kerr et al. 2003), and the accompanying GIS products developed in this study can be used at detailed scales for planning purposes according to those guidelines.

8.0 RECOMMENDATIONS

We recommend that the FAZs and FAAs developed for the Whanganui District 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 versus Already Developed/Subdivided) and the BIC intended for the site (see Tables 6.1 and 6.2). FAAs developed for some faults, or parts of a fault, in this study carry no guidelines related to restrictive planning decisions. In future, more work needs to be undertaken to characterise the origin and activity of such features.

We recommend that the MfE Guidelines be treated as a standard reference when considering resource consent applications throughout the district. In addition, we recommend that GIS data for FAZs be provided on Land Information Memorandum (LIM) reports, so that buyers and sellers of land are aware that a natural hazard exists there or nearby. This GIS data for faults and FAZs can be used at an individual property-specific scale.

A caveat to this work is that much of the effort put into developing RI Classes for these faults is preliminary. We recommend that a planned approach is developed between GNS Science, Horizons Regional Council and funding agencies to attain better geologic constraints on the slip rate, recurrence interval and/or timing of past surface-rupturing earthquakes that occurred on the Nukumaru Fault. Better mapping of the marine terraces and risers, and better dating of them, would help to define geological constraints for features mapped within the zone.

Additional effort should be directed to the many ‘possible’ active faults identified as a part of this study to determine their tectonic origin and/or their activity. This would best be done when more LiDAR data become available.

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APPENDICES

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APPENDIX 1 STYLES OF FAULT MOVEMENT

Faults can be categorised as strike-slip faults, where the dominant style (sense) of motion is horizontal; 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.

A1.1 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 A1.1), or left-lateral (sinistral) where the opposite side of the fault moves to the left.

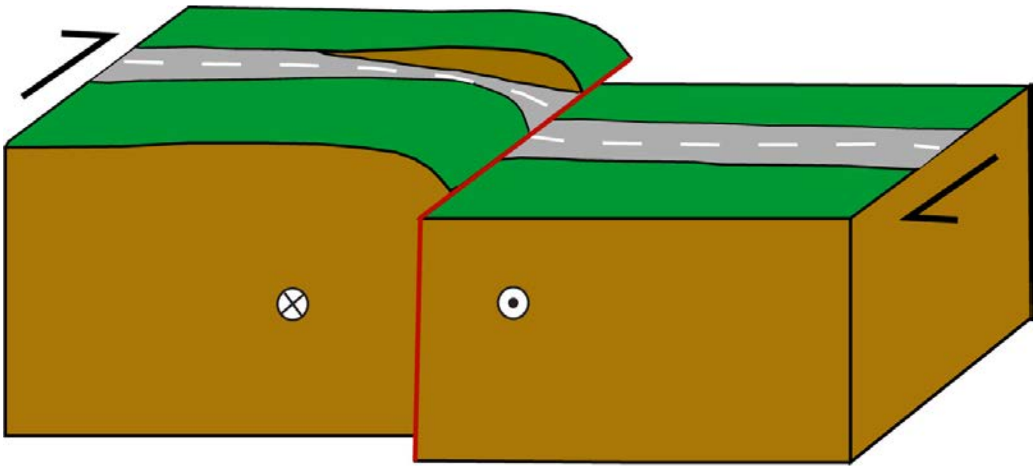

Figure A1.1 Block model of a strike-slip fault (red line). This is a right-lateral (dextral) fault, as shown by the black arrows and by the sense of movement across the two blocks and a separation towards the right across the road. A small amount of vertical movement is also implied by the mappable fault 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 the 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, Northern Ohariu and Ruahine faults (Figure 1.1). Some important active left-lateral strike-slip faults in New Zealand include the Papatea Fault, 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).

A1.2 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 A1.2). 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).

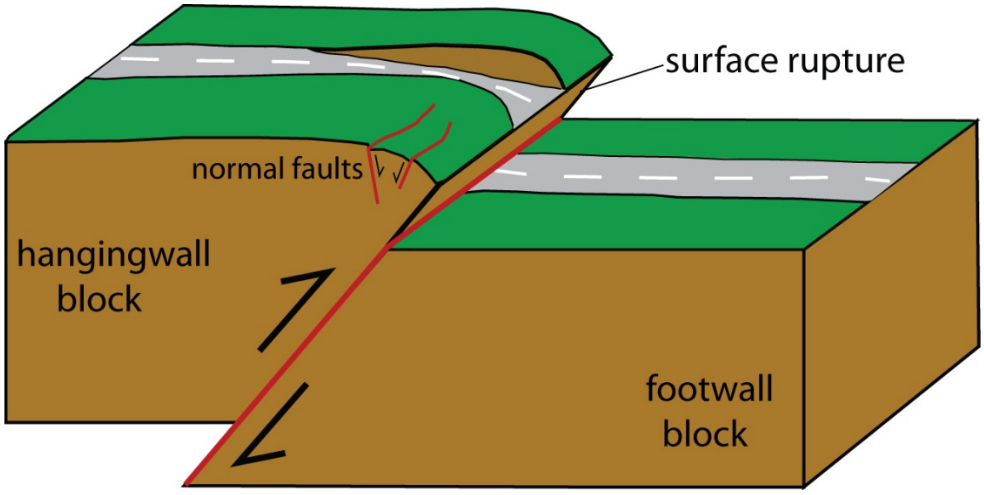

Figure A1.2 Block model of a reverse dip-slip fault that has recently ruptured. Relative movement between the blocks is vertical and along the dip direction of the fault plane. In this case, the hanging-wall block has been pushed up and over the footwall block. Folding (bending) and normal faulting are 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. Examples of these include the Leedstown, Himatangi and Rauoterangi faults and the Pohangina and Marton anticlines (Langridge and Morgenstern 2018, 2019, 2020). A common feature of the tectonics in the Horizons Region are these sub-parallel, typically east-directed sheets of reverse and thrust[6] faults that occur in the upper crust above the plate interface, i.e. within the upper plate overlying the Hikurangi subduction zone in the eastern North Island (Cashman et al. 1992; Kelsey et al. 1995). Active reverse faults have also been mapped off the west coast of the North Island (e.g. Nodder et al. 2007).

A1.3 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 A1.3). All onshore active faults and possible active faults in the Whanganui District are interpreted to be of this type.

Normal faulting and extension are important processes, particularly in the Ruapehu District at the southern end of the Taupō Volcanic Zone (TVZ) or Taupō Rift (Villamor and Berryman 2006a, b). The mechanisms for extension there 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).

Bending-moment normal faults appear to be a common feature in the hanging-wall block of the Leedstown Fault in the Rangitikei District. In this case, compressional tectonics drives reverse motion on the Leedstown Fault and bending of the hanging-wall side of the fault block. The result of bending is an anticlinal fold, and in some cases bending-moment normal faults will also form in this setting as the bending/warping results in extension in the top of the anticline (Figure A1.2), for example, within the Marton Fault Zone (Langridge and Morgenstern 2020).

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

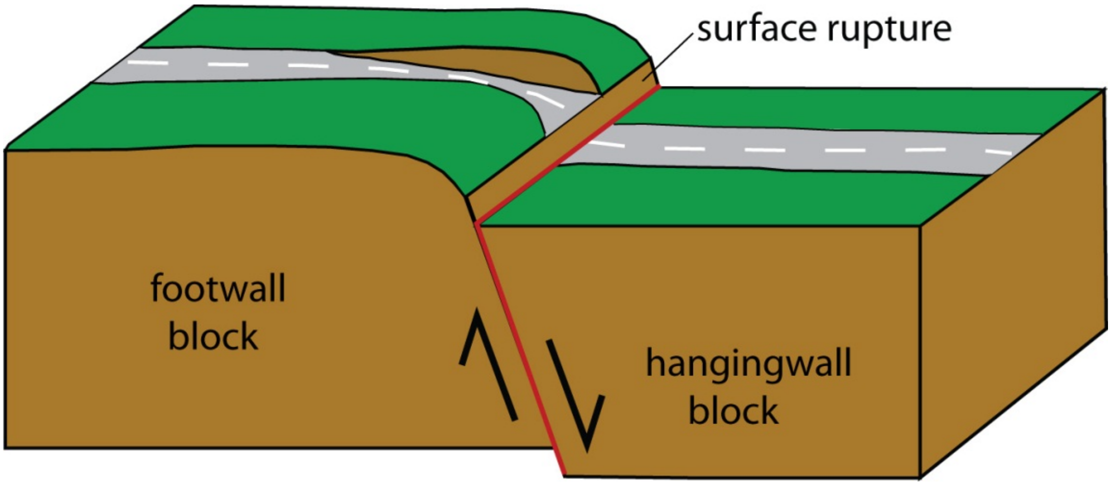

Figure A1.3 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

A1.4 Oblique-Slip Faults

In the New Zealand Active Faults Database (NZAFD; Langridge et al. 2016), 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 Australian-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 A1.4). 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 metres of sinistral slip was exceeded by the reverse component of fault motion.

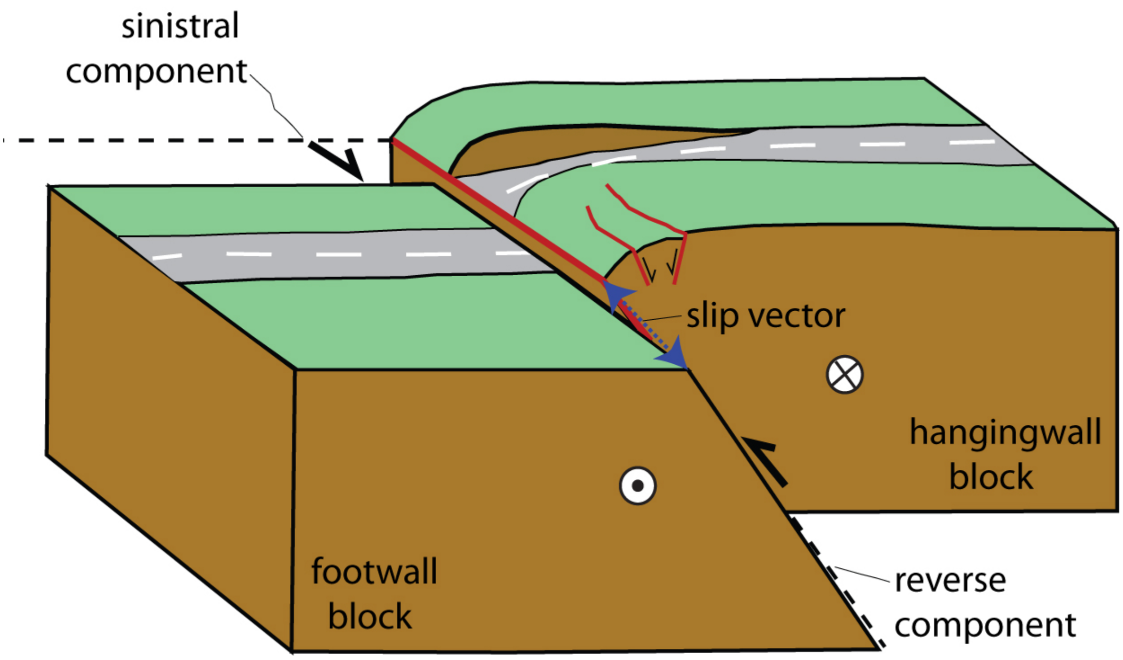

Figure A1.4 Block model of an oblique-slip fault. In this case, the fault is reverse sinistral. The relative movement of the blocks is both vertical (in the dip direction of the fault plane) and strike-slip (in the direction of the strike of the fault), as shown by the oblique blue arrow. Symbols on the front of the blocks indicate movement away (circle with cross) and movement toward (circle with dot) the viewer.

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