Active Fault Mapping and Fault Avoidance Zones for the Rangitikei District

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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 straddles the active Australian-Pacific plate boundary in the southern North Island and has a history of large earthquakes and many known active faults.

New active fault mapping and Fault Avoidance Zones (FAZs) are presented here for the Rangitikei District. The district is traversed by active faults (and associated active folds) that pose a surface rupture (or ground deformation) hazard to buildings and infrastructure. Following the Ministry for the Environment's (MfE) Guidelines – 'Planning for Development of Land on or Close to Active Faults' (Kerr et al. 2003; the 'MfE Guidelines') – fault traces have been mapped 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 Rangitikei 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 is available. Active faults have been mapped in a Geographic Information System (GIS) with traces that 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 Rangitikei District, there are several previously known active faults that have been re-mapped, including the Leedstown Fault, Putorino Fault, Kaweka Fault, Taihape Fault, Snowgrass Fault and the newly named Mangaohane Fault[1]. This study recognises a suite of active normal faults and fault zones associated with the reverse-slip Leedstown and Putorino faults, called here the Jeffersons Line Fault, Marton Fault Zone (MFZ), Galpins Road Fault Zone (GRFZ) and Mt Curl Road Fault Zone (MCRFZ). Several other active faults have been named and mapped in the north-eastern part of the district, including the Mt Maire fault, Swinburne Bush fault, Erewhon fault, Timahanga fault, Dirty Spur fault and Taumataomekura fault.

This study has developed new and updated recurrence interval (RI) class information for many of the active faults in the Rangitikei District described above. The most active faults in the district are the RI Class II Snowgrass Fault (i.e. RI >2000 to ≤3500 years) and the RI Class III Kaweka Fault and Mangaohane Fault (i.e. RI >3500 to ≤5000 years). The Leedstown Fault retains a RI Class IV status (i.e. RI >5000 to ≤10,000 years) along with the Putorino Fault. The RI Class of the other faults and fault zones (Jeffersons Line Fault and MFZ, GRFZ and

[1] Upper case 'Fault' is used in this report to denote previously known faults or those that are recognised as 'definitely or likely' active faults; lower case 'fault' is used to denote features that are new or are 'possibly active' faults.

MCRFZ) have also been designated as RI Class IV because of their close association with the Leedstown and Putorino faults. The Dirty Spur and Taumataomekura faults had previously been assigned a RI Class IV status based on their expression in the Manawatū District. FAZs have been defined for these active faults according to the MfE Guidelines.

The RI Class of most other faults (Taihape Fault and the Mt Maire, Swinburne Bush, Erewhon and Timahanga faults) is poorly known at this time. FAAs have been developed for 'possibly active' faults and for parts of faults that have been mapped at small scales between 1:50,000 and 1:250,000. FAAs are distinct from FAZs and carry no requirements related to the MfE Guidelines. This study also recognises two active folds (defined by their fold axes) within the Rangitikei District: the Marton and Utiku anticlines. Avoidance zones are not developed for active folds because fold axes are not typically associated with life-safety-threatening ground deformation.

We recommend that the active fault mapping and FAZs developed for the Rangitikei 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, 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 Rangitikei 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.

1.0 INTRODUCTION

1.1 Preamble

The southern North Island straddles 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 surface in the past. These faults include the Wellington, Ruahine, 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. Langridge et al. 2006; Schermer et al. 2004;Van Dissen et al. 2003).

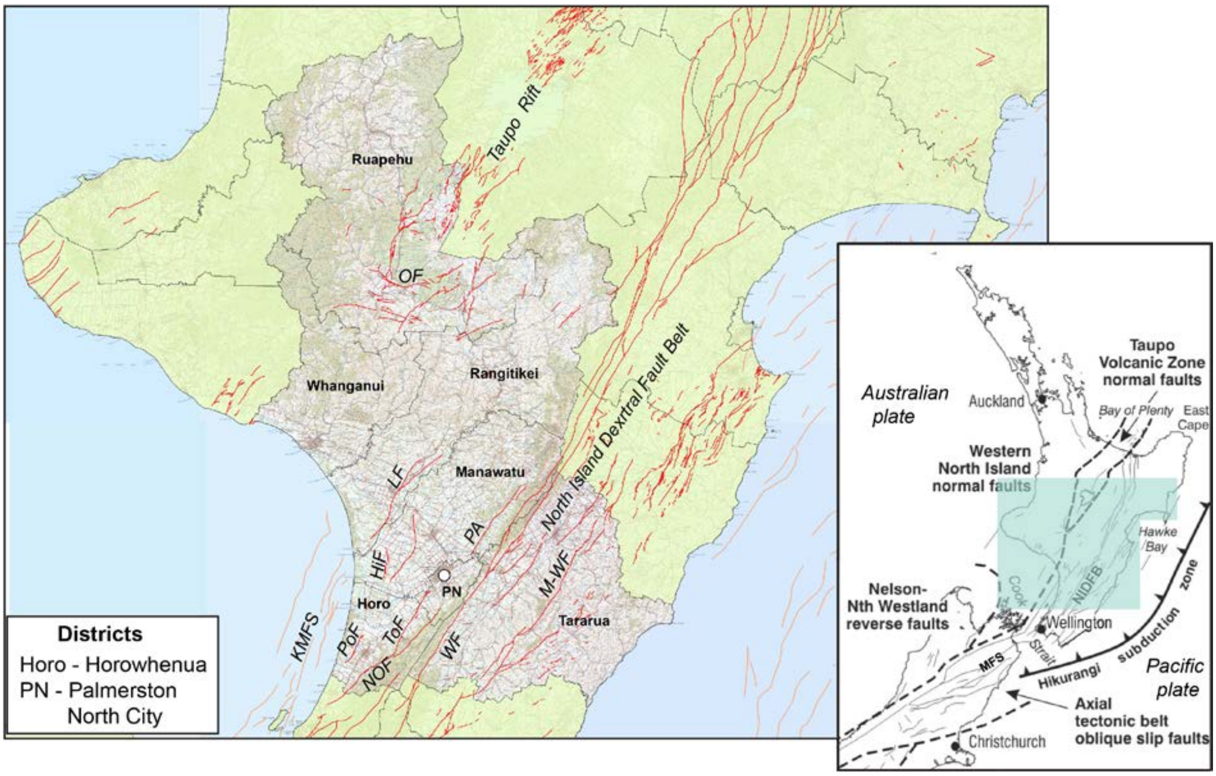

Figure 1.1 The area administered by Horizons Regional Council, showing its various districts. Onshore active faults (red) within the lower North Island area sourced from the New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al. 2016) as they appeared prior to this study. Fault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

Ground surface rupture of an active fault will result in a zone of intense ground deformation as opposite sides of the fault move past or over each other during an earthquake. Property damage can be expected, and loss of life may occur where buildings (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) have been contracted by the Horizons Regional Council to conduct a region-wide active fault mapping and fault avoidance zone programme in order 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, 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 is extended here to the Rangitikei District (Phase 2b).

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 Reginal Council. In addition, we worked with Horizons to construct a region-wide 1-m 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 exists, map and attribute active fault traces at 1:10,000 scale or better. This effort has been facilitated by the acquisition of several airborne LiDAR datasets funded by Horizons Regional Council and provided to GNS.
- Use a 1-m DSM of the Horizons Region in order to improve the mapping of active fault traces where LiDAR data does 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 in order to better locate and characterise their tectonic activity[2].
- Undertake a limited field review of active fault and fold features to attempt to better characterise recurrence interval information for active faults identified in the district.
- Provide an update on active fault recurrence interval data for the Rangitikei 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 Rangitikei 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 also 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 regions. Section 3 concludes with a summary of previously known active fault recurrence interval information for the Horizons Region as relevant to the MfE Guidelines (Kerr et al. 2003).

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, ‘possibly active’ faults and folds within the Rangitikei District and, where possible, provides new or updated recurrence interval information and FAZs for those faults that are considered active.

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. Appendix 2 provides some examples – using faults within the Rangitikei District – to assist planners in making resource consent decisions regarding the FAZs there.

The report is accompanied by digital geospatial (GIS) data, including active fault mapping and FAZs (polygons), as well as data on locations of fold axes. 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 different landscape types across the central to southern North Island (Figure 2.1). The physiography of the region is diverse and varied. In the north, the region includes the southern part of the extensional Taupō Rift and Volcanic Zone (Villamor and Berryman 2006a, b) in the Ruapehu District. In the 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 elevated Tararua 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. This report focuses on active fault mapping in the Rangitikei 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 lower North Island straddles 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). Thus, a diverse range of active tectonic deformation[3] is reflected in the broad area covered by the Horizons Region.

Technically, the largest fault in the region is the Hikurangi subduction interface (dark blue bold line in Figure 2.1), where the Pacific Plate subducts to the northwest under the Australian Plate, beneath the North Island. The plate interface is considered capable of generating a 'great' earthquake (M_W >8) and possibly a megaquake (M_W >9). 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.

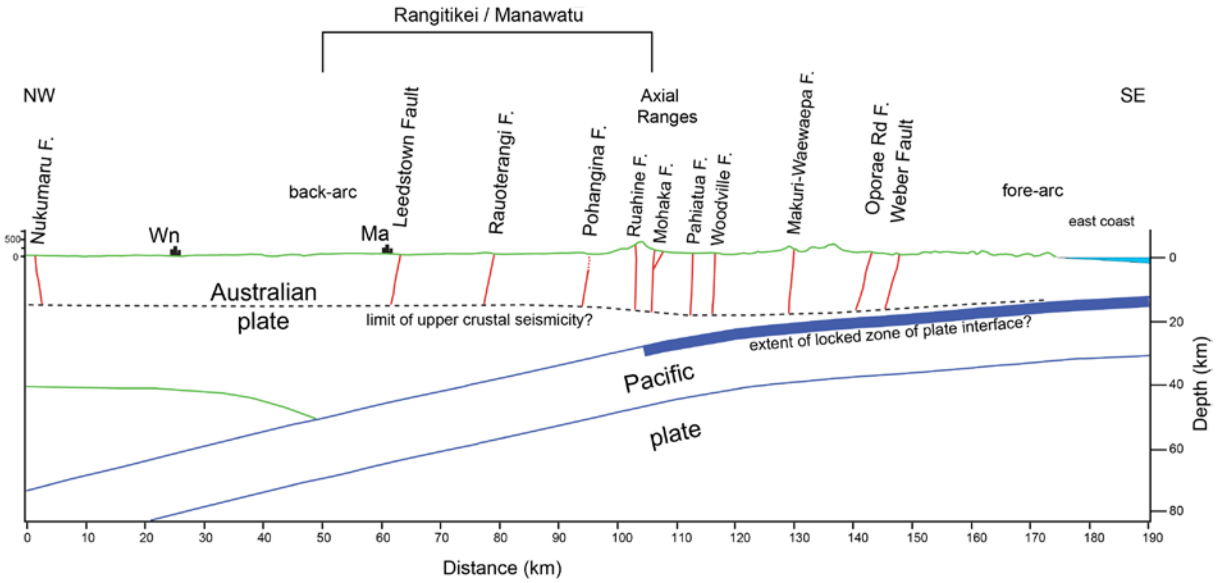

Figure 2.1 Simplified cross-section of the lower North Island from west of Whanganui (Wn) to offshore of Cape Turnagain in the east, showing the tectonic features that are relevant to the Horizons Region. The cross-section intersects several active upper crustal faults and includes the Hikurangi Subduction Margin or Zone. Rangitikei and Manawatū districts broadly span the area between the Axial Ranges and back-arc. Marton (Ma) is also indicated.

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 2.2 shows the epicentres of shallow (<30 km depth) historical earthquakes with magnitude M_W >6 throughout central New Zealand. These represent significant earthquakes that caused shaking damage and, 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 heavy 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. In the 1855 Wairarapa earthquake, 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 after 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).

In February 1863, the M_W ~7.5 Waipukurau earthquake occurred and is believed to have originated on a reverse fault in the vicinity of Waipukurau, 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 the 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.

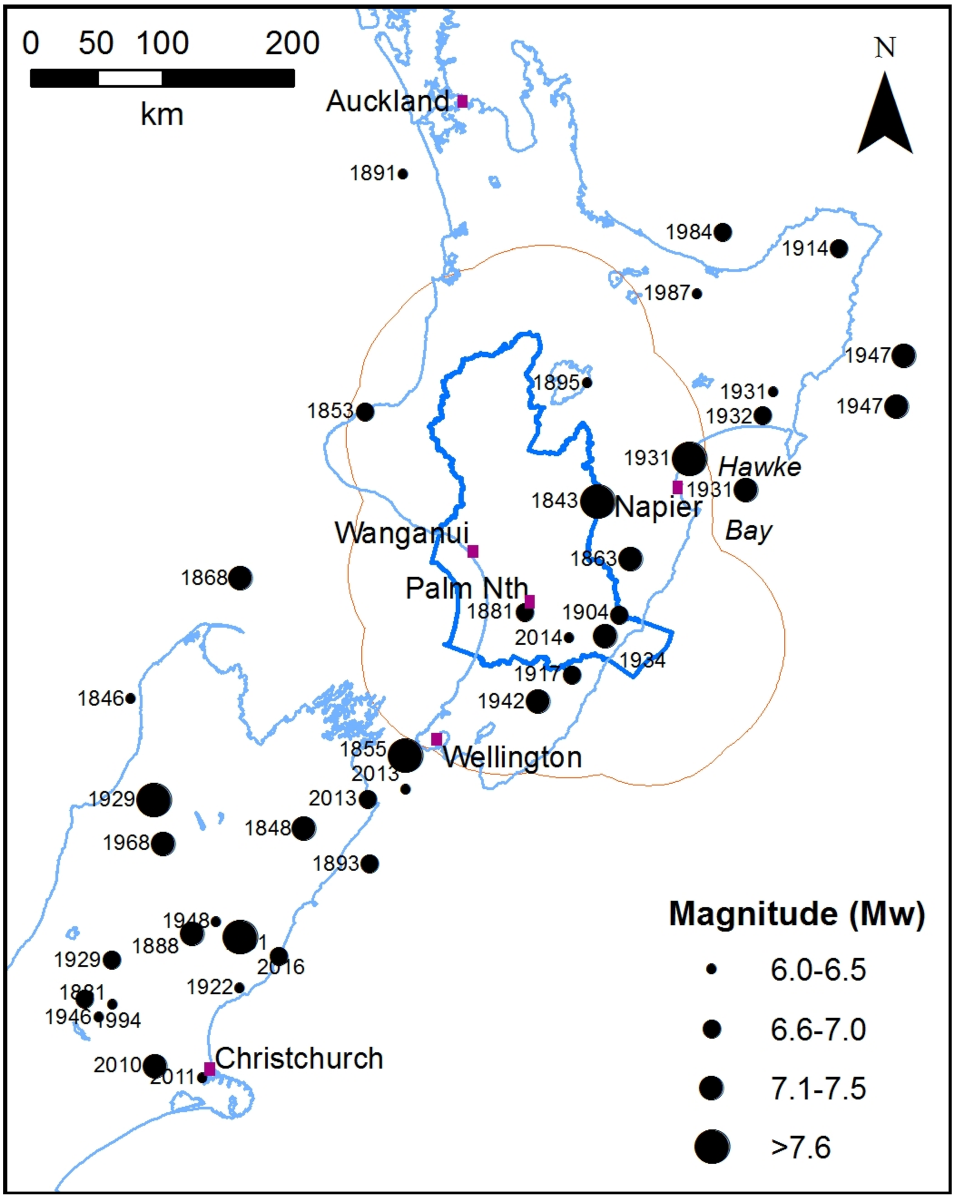

Figure 2.2 Epicentres of significant shallow (<30 km depth) earthquakes in central New Zealand that have occurred from 1840–2016. Highlighted in dark blue is the Horizons Region, and the orange line is an area that extends a further 75 km around the region to consider impacts from nearby earthquakes. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

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.

[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

During the second quarter of the 20th century, Hawke's Bay and surrounding regions were rocked by a number of 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 cities of Napier and Hastings. During this event, felt intensities of 'damaging' to 'very damaging' (MMI 6–7) were reported across the Horizons Region. The Hawke's Bay earthquake was followed by a damaging aftershock on February 13, 1931, and the 1932 M_W 6.9 Wairoa earthquake (Figure 2.2).

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 the northern Wairarapa to Hawke's Bay, particularly between Porangahau and Castlepoint. The worst damage was noted in Pahiatua, the largest town near the earthquake epicentre. There were no deaths caused by this earthquake, although one person required hospitalisation.

In 1942, 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 2.2 and 2.3). This event occurred at a depth of c. 34 km and was felt strongly across the country, from Auckland to Dunedin, with more than 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 2.2, Figure 2.3 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 of the Whangaehu River.

There are no known historic earthquakes of M_w >6 that have occurred within the boundaries of the Rangitikei District (Figure 2.2), and the district typically has a relatively low level of background seismicity (Figure 2.3).

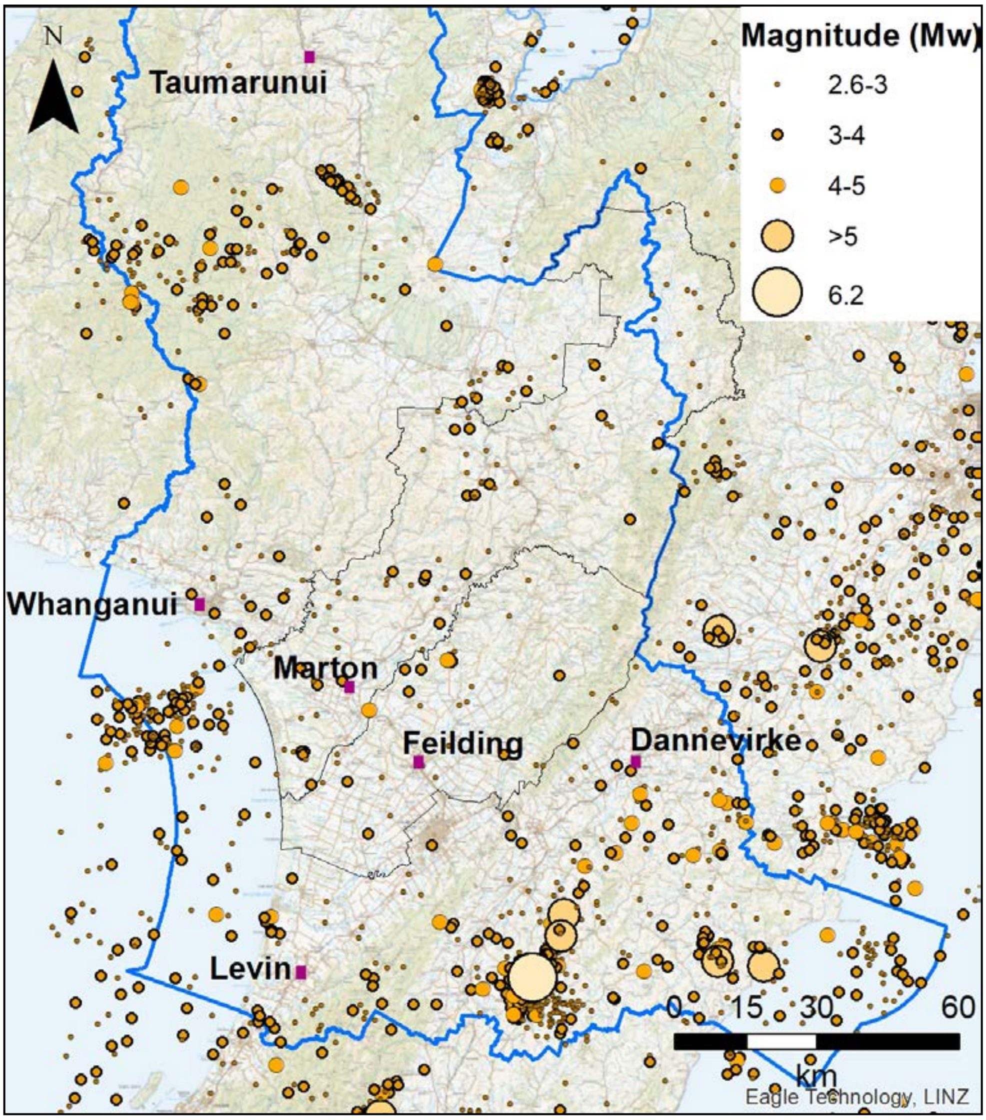

Figure 2.3 Epicentral locations of shall (<40 km) earthquakes of Mw >2.6 that occurred over five years between August 2013–18 within, or close to, the Horizons Region (marked in dark blue). Earthquakes are colour-coded in magnitude bands. The largest event is the 2014 M_w 6.2 Eketahuna earthquake. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

3.0 ACTIVE FAULTS AND THE MFE GUIDELINES

The Horizons Region has a large number of active faults, which have previously been mapped mostly at scales of >1:10,000 (1:250,000 [see Heron 2018] or 1:50,000 [Langridge et al. 2016] – NZAFD; http://data.gns.cri.nz/af/) (Figure 1.1). The locations of active faults mapped at scales of >1:10,000 have significant locational uncertainty and accordingly have limited use for planning purposes. Phases 1 and 2a of the Horizons Region active fault mapping programme were undertaken across Horowhenua and Manawatū 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). These projects drew on the significant extent of available airborne LiDAR coverage there. For this project (Phase 2b), there is also good LiDAR coverage across the south-eastern part of the Rangitikei District that facilitates detailed mapping of active fault features.

3.1 What is an Active Fault?

Active faults are those faults considered capable of generating strong earthquake shaking and ground-surface fault rupture. Ground-surface-rupturing earthquakes are typically of magnitude M_w >6.5[5]. An active fault is generally defined within the NZAFD and here 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. The only 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).

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 displacing surficial geomorphic features, which may include hillslopes, alluvial terraces and fans. The age of these displaced features can be used to define how active a fault is. Typically, in New Zealand, alluvial terraces are associated with contemporary river drainages, 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.

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 used to develop

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

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.

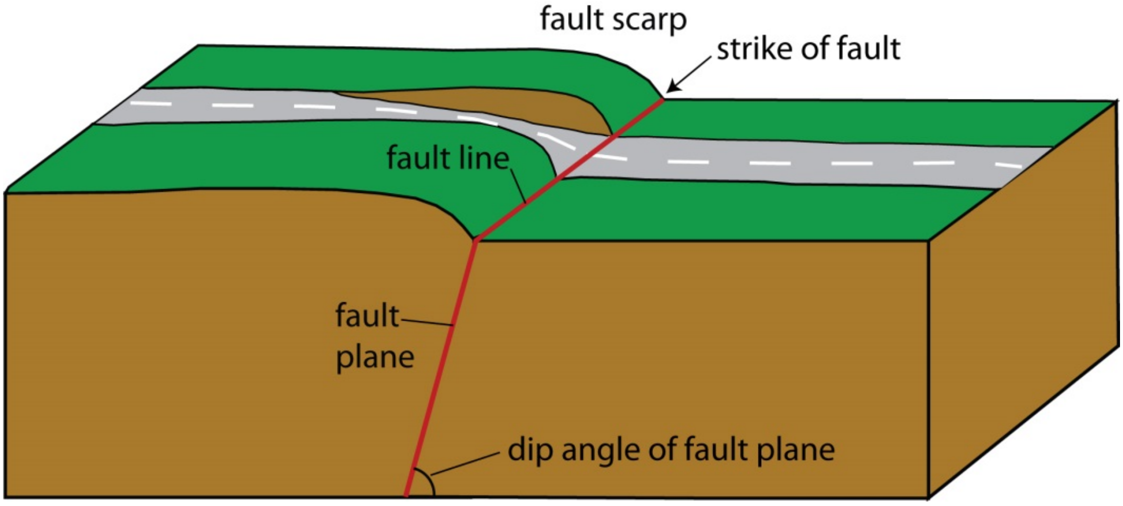

Figure 3.1 Block model of a generic active fault (shown in red). Fault displacement produces a scarp with offset features along the projection of the fault plane at the Earth's surface (fault line or trace).

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. A fold axis is an imaginary line which connects the most tightly-folded part of the structure within a particular geological stratum (or geomorphic surface). In three dimensions, the axis can be connected through the folded geological layers to define the axial plane (or axial surface). The fold limbs are straighter and lie to either side of the axis (Figure 3.2). Folds that form positive (or high) relief are termed anticlines (limbs dip away from the axis and each other) and folds that form negative (or low) relief are called synclines (limbs dip towards the axis and each other). Folds can take on various forms, such as broad, gentle, tight, symmetrical and asymmetrical. Broad, gentle and tight folding refer to the angle between the limbs of the fold, which may also relate to the degree of activity on a structure and/or its age. Symmetrical folds have limbs of equal length and angle relative to the axial plane, whereas asymmetrical folds have one longer limb and one shorter limb (e.g. Figure 3.2).

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). 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 sediments (e.g. Te Punga 1957; Jackson et al. 1998; Clement and Fuller 2018) and form topographic highs or domes. For example, across the Horowhenua and Manawatū Districts, the Pohangina, Himatangi, Shannon and Levin 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). 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).

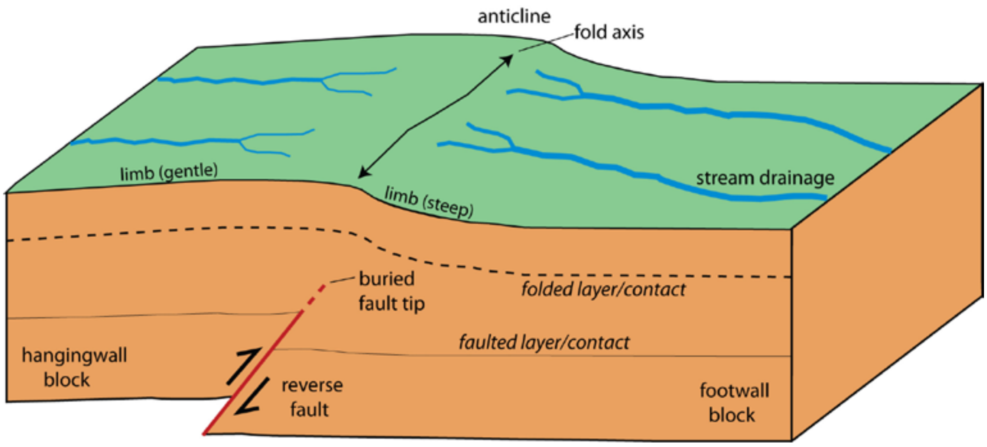

Figure 3.2 Block model of an anticlinal fold that is related to a buried active reverse fault. Motion on the fault has driven the hanging-wall block upwards and folded the ground surface above the fault tip. The fold is asymmetric and defined at the surface by a fold axis and by the stream drainage pattern,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

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

In 2003, the Ministry for the Environment (MfE) published guidelines on 'Planning for Development of Land on or Close to Active Faults' (Kerr et al. 2003, see also King et al. 2003; Van Dissen et al. 2003), i.e. the 'MfE Guidelines'. The aim of the MfE Guidelines is to assist resource management planners tasked with developing land-use policy and making decisions about development of land on, or near, active faults. The MfE Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas that are subject to fault rupture hazard. The MfE Guidelines are designed primarily for life safety purposes; however, what has 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), the 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), the West Coast (e.g. Langridge and Ries 2010) and Marlborough (Langridge and Ries 2016) 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 Phase 1 of the Horizons active fault mapping programme, Langridge and Morgenstern (2018) summarised the current state of knowledge regarding the recurrence intervals of faults in the region and defined preliminary recurrence interval classes for all faults in the Horowhenua and Palmerston North districts (Table 3.2). These data come from (a) geologic studies (e.g. Jackson et al. 1998; Langridge et al. 2007; Villamor and Berryman 2006b; and summarised by Van Dissen et al. 2003) and (b) estimates based on determinations from geomorphology. Often, there is little or no available geological data for active faults, therefore estimates are developed based on the amount of associated landscape deformation or from geologic comparisons with other faults in the region that have better-defined levels of activity.

Overall, the recurrence interval data have large uncertainties, except where fault-specific paleoseismic studies have been undertaken (Van Dissen et al. 2003). In the Rangitikei 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 NSHM (Stirling et al. 2012) and as simplified fault zones in the active fault model of Litchfield et al. (2014).

Table 3.2 Fault recurrence interval data for faults within the Horizons Region through Phases 1 to 2a of this programme* (modified from Langridge and Morgenstern 2018, 2019). Faults with previously established RI Classes in the Rangitikei District are shown in italics (see Langridge et al. 2016).

Fault	District	RI Class Confidence^	Source Number
RI Class I Faults (≤2000 Years)			
Mohaka Fault	Tararua, Manawatū	M	1, 2
Snowgrass Fault	Rangitikei, Ruapehu	M	1, 2
RI Class II Faults (>2000 to ≤3500 Years)			
Ruahine Fault	Tararua, Manawatū	L	1, 2, 4
Northern Ohariu Fault	Horowhenua, PNC	L	1–3
RI Class III Faults (>3500 to ≤5000 Years)			
Otaki Forks Fault	Horowhenua	L	1–3
Kaweka Fault	Rangitikei	L	1, 2
RI Class IV Faults (>5000 to ≤10,000 Years)			
Tokomaru Fault	Horowhenua, PNC	M	3
Poroutawhao Fault, Oturoa trace	Horowhenua	M	3
Himatangi Fault, Mt Stewart-Halcombe Fault, Rauoterangi Fault	Manawatū	L	4
Traverse fault, Howlett Creek fault, Rauoterangi Fault	Manawatū	L	4
Leedstown Fault	Rangitikei, Manawatū	L	1, 2
Taumataomekura fault, Dirty Spur fault	Rangitikei, Manawatū	L	4
Nukumaru Fault	Whanganui	L	1, 2
RI Class V Faults (>10,000 to ≤20,000 Years)			
Cluain trace	Horowhenua	M	3

* This table summarises data available prior to this study. PNC, Palmerston North City. ^RI Class Confidence: M, Medium – uncertainty in average recurrence interval embraces a significant proportion (>~25%) of two RI Classes. The mean of the uncertainty range typically determines into which class the fault is placed; L, Low – uncertainty in 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).

Sources: 1, Van Dissen et al. (2003); 2, NZAFD (https://data.gns.cri.nz/af/); 3, Langridge and Morgenstern (2018); 4, Langridge and Morgenstern (2019).

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). Most of the RI Class I (RI ≤2000 years) faults occur in the Tararua and Ruapehu Districts, where the most active seismotectonic 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.

The RI Class Confidence is a measure of the quality of the geological data which is used to assess the fault recurrence interval (Table 3.1; Van Dissen et al. 2003). Some faults have detailed slip rate and/or paleoseismic trenching studies that define the RI Class quite well, while 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. The values in Table 3.2 will be reviewed and updated as better geologic data are gained through future paleoseismic studies (see Table 5.1).

3.4.2 Derivation of Preliminary RI Class Categories for the Rangitikei District

An important part of utilising the MfE Guidelines is to be able to apply RI Class information to active faults in a given territory. Prior to this study, only three faults in the Rangitikei District had RI Classes applied to them; these being the strike-slip Kaweka Fault, normal Snowgrass Fault and the reverse-slip Leedstown Fault (Van Dissen et al. 2003; Langridge et al. 2016). In this report, several of the active faults and fault traces identified have a new and preliminary RI Class developed for them. This is typically achieved through an estimation of the slip rate, based on topographic profiling using the LiDAR and DSMs.

Derivation of slip rate for many of the faults in the Rangitikei District is possible because they are predominantly dip-slip (reverse and normal) faults, where the deformation is resolved in a dominantly vertical sense of motion that can be characterised using LiDAR and/or DSMs in a GIS. Figure 3.3 shows an example of how the vertical and reverse slip rates were derived for the active Rauoterangi Fault in the Manawatū District (Langridge and Morgenstern 2019). This methodology was also applied to dip-slip faults in the Rangitikei District.

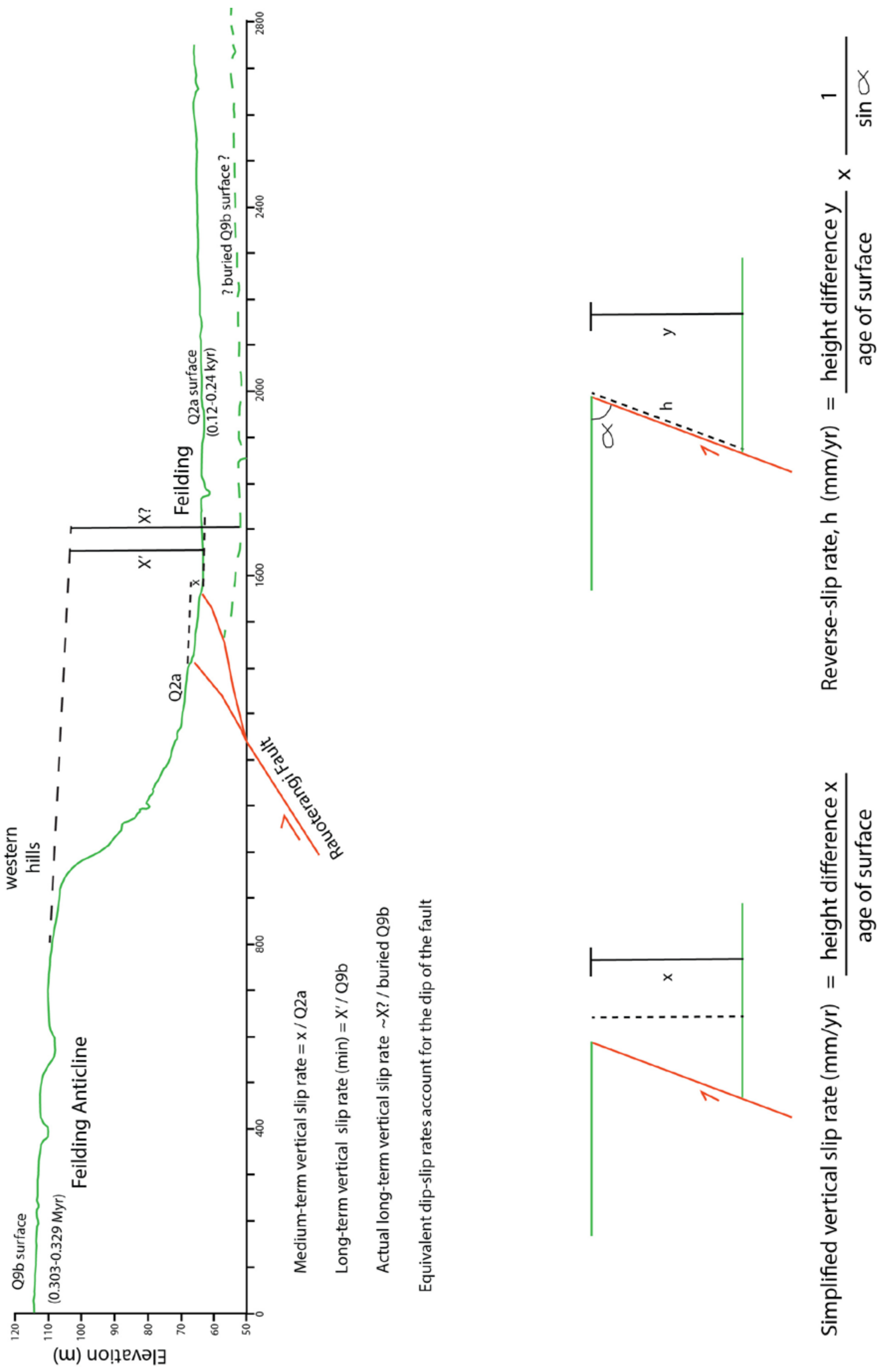

Figure 3.3 Cross-section spanning the western hills and town of Feilding in the Manawatū District, showing how vertical and dip-slip rates are calculated for faults, using the Rauoterangi Fault as an example. Fault scarp heights (x) across a Q2a river terrace define medium-term vertical slip rates, while offset of the older Q9b surface (X' or X?) defines a long-term vertical slip rate. Ages of surfaces from Heron (2018).

Slip rates applied to fault sources in the NSHM (Stirling et al. 2012) can be used to assign a preliminary RI Class to faults that have little geologic or paleoseismic data, such as many of the faults within the Rangitikei District. For example, most fault sources with a slip rate of ≥1.5 mm/yr (1.5 m/1000 yr) in the NSHM fall into RI Class I, with an average recurrence interval of ≤2000 years. Similarly, most faults with a slip rate range of <0.1 mm/yr (<1 m/10,000 yr) fall into RI Class V or even RI Class VI. There are many exceptions to the ranges displayed in Table 3.3 due to the nature of the parametric equations used in the NSHM and how some faults have been segmented (based on their length) or used as shared-source scenarios, e.g. the Alpine Fault sources. Therefore, there are cases where fault sources with relatively high slip rates have a predicted longer recurrence interval and other cases where fault sources with lower slip rates have a shorter recurrence interval (RI Class). In general, it is reasonable to expect that this uncertainty represents the equivalent of ±1 RI Class. For example, the Putorino Fault (which is assigned an RI Class of IV in this report), may have a shorter average recurrence interval (RI Class III) or longer average recurrence interval (RI Class V) than expressed by our preliminary determinations. In many cases, it would take new geologic or paleoseismic studies to refine these preliminary assessments.

Table 3.3 Broad relationship between RI Class and slip rate for active fault earthquake sources in the NSHM (Stirling et al. 2012).

RI Class	Average RI (Years)	Slip Rate* (mm/yr)	Typical RI Class (and Range)
I	≤2000	≥1.5	I (I–II)
II	>2000 to ≤3500	0.6–1.5	II (I–III)
III	>3500 to ≤5000	0.3–0.6	III (II–IV)
IV	>5000 to ≤10,000	0.1–0.3	IV (III–V)
V	>10,000 to ≤20,000	≤0.1	V (IV–VI)

* Broad ranges and cut-offs of slip rate relative to average recurrence intervals.

3.5 Building Importance Category and the MfE Guidelines

Buildings sited across active faults are very likely to be damaged in a fault rupture event. 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 3.4 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 3.4 Building importance categories 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 3.5 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 3.5 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 DSM (Figure 4.1). Several small airborne LiDAR acquisitions with a 1-m resolution were supplied by Horizons Regional Council. Mapping on LiDAR is typically undertaken at scales of 1:5000 to 1:10,000. Mapping undertaken for the QMAP geological programme and for much of the NZAFD is rendered at scales of 1:50,000 to 1:250,000. GIS linework from the NZAFD and QMAP were also reviewed alongside our mapping (Heron 2018; Langridge et al. 2016).

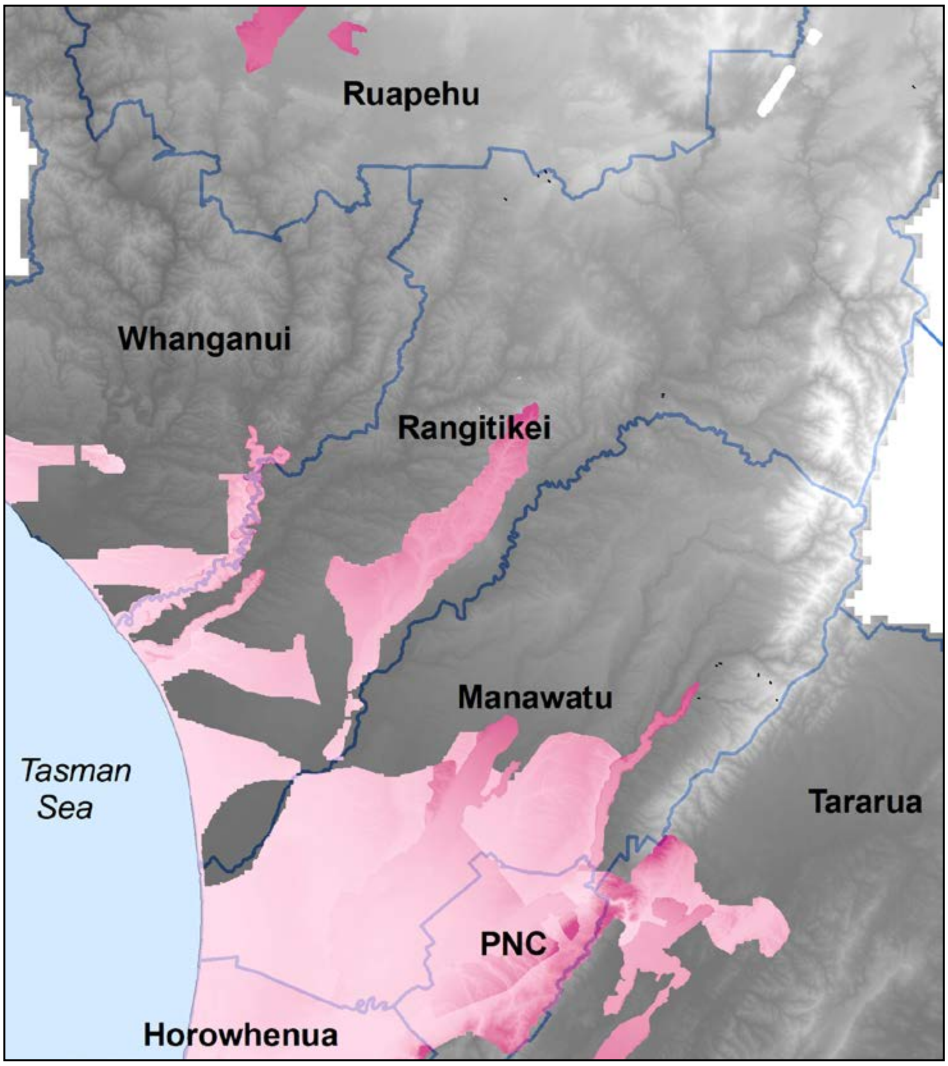

Figure 4.1 Digital topographic coverage across the central part of the Horizons Region used in this project. Airborne LiDAR is shown by pink shading and a regional 1-m DSM is shown with grey shading.

For current land-use planning in regard 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 DEMs and hillshade models have been developed.

In areas where no LiDAR coverage exists, a 1-m DSM was developed by Horizons Regional Council from aerial orthophotographs for Phase 2 (Langridge and Morgenstern 2019). 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 1-m DSM allows for higher-resolution mapping than the national-scale 8-m DEM and hillshade model that are otherwise the best available elevation models.

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 is used to define the Deform_wid, 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 the location uncertainty of digitising or surveying a line; the lack of knowledge on the exact location of the fault plane (unless the fault plane is exposed in an excavation); and because faults that rupture to the ground surface typically have zones of deformation either side of the main fault plane, as observed, for example, in the 2010 rupture of the Greendale Fault (Villamor et al. 2012). This 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 recent 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 1-m DSM. Despite the fact that the LiDAR DEM and the DSM both have 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 wider FAZs constructed for areas without LiDAR data.

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

Attribute	Definition
Fault_name	The name given to an active fault.
Accuracy	Locational accuracy of the fault trace – linked to the expression of the fault trace and the ‘method’ used 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, 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.
FAZ	The Fault Avoidance Zone, i.e. the sum of the ‘deformation width’ plus the 20 m ‘margin of safety’ setback zone in metres (see Kerr et al. 2003).
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 the feature mapped 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. In another case, linear features in the ranges could be related to gravitational processes, known as ridge renting in New Zealand, or even landsliding. In either case, there may be uncertainty whether what is mapped is actually of tectonic (faulting) origin. Therefore, we have included a GIS field called ‘Tect_origin’, which has descriptors of ‘definite’, i.e. definitely of tectonic origin, ‘likely’, or ‘possible’. Similarly, a decision was required as to whether the feature or fault mapped was active. In most cases, features that were of definite or likely tectonic origin were attributed as ‘active’ fault features (see Table 4.1), whereas features of possible tectonic origin were attributed as ‘possibly active’ faults.

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 equate to the width of deformation across which intense ground deformation is likely to occur. The definition of these terms is described in the MfE Guidelines (Kerr et al. 2003). These three terms can be expanded to define whether, for example, an ‘approximate’ fault trace 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 as a tool with which to map active faults. Thus, in this report we often equate ‘well-defined’ fault complexity with accurate fault locations. The fault complexity term ‘distributed’ is typically used in this report for approximate fault locations where the scarp is broad and therefore the exact 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 and covers the fact that the location may be unclear due to subsequent deposition and/or erosion since the most recent fault movement. 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 (e.g. Table A2.1).

Table 4.2 Development of fault complexity terms for faults, used in this study for Horizons Region.

Fault Location Accuracy	Fault Complexity	Comment
Accurate	Well-defined	Associated with a clear, sharp fault feature
Approximate	Well-defined extended	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.

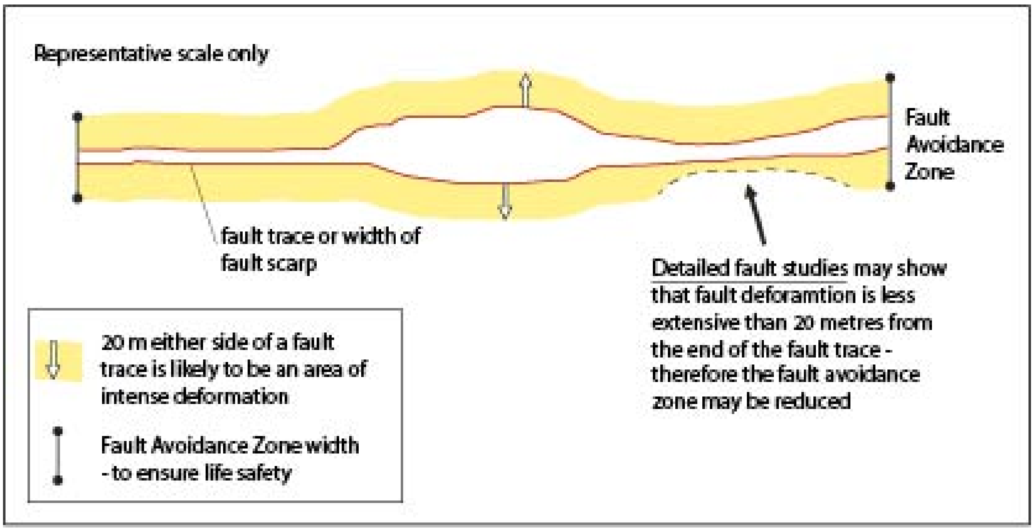

Figure 4.2 A fault avoidance zone (encompassing fault zone and orange bars) for a stretch of a fault, and how it may be developed for a district-planning map (modified from Kerr et al. 2003).

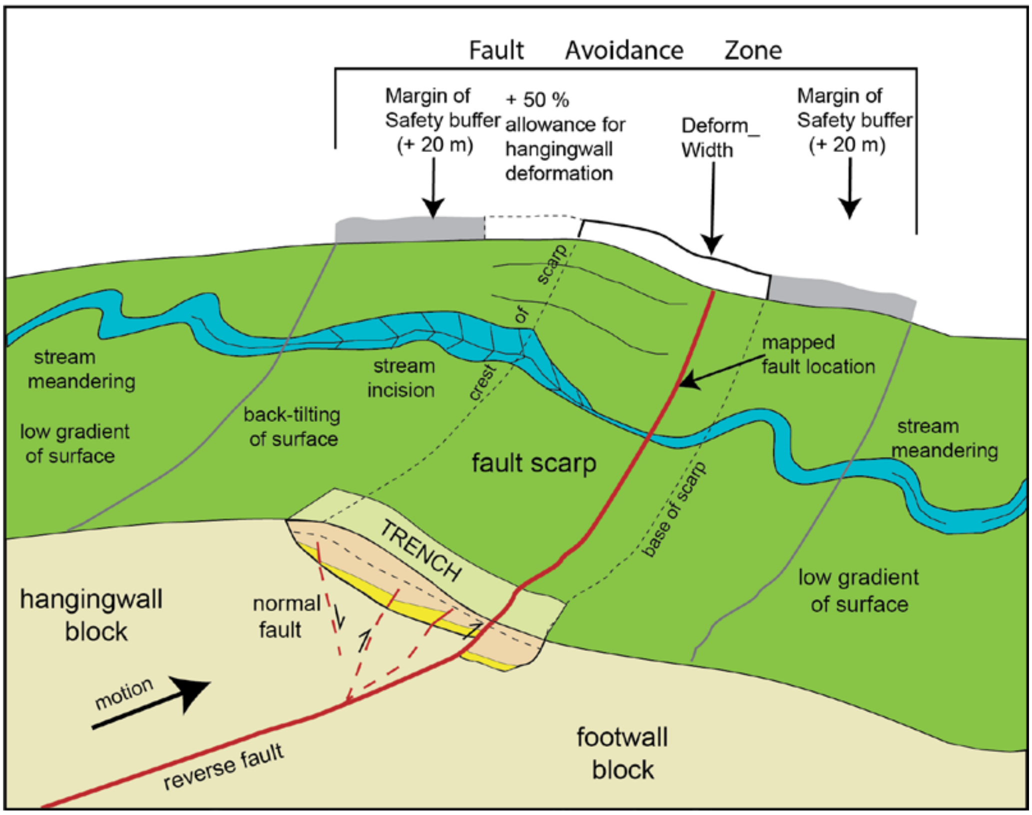

Figure 4.3 Schematic cross-section of a dip-slip reverse fault and its scarp. In this case, the mapped fault trace (and rupture plane; bold red line) is mapped near the base of the scarp. The fault trace itself is ‘accurately’ mapped and the scarp is ‘well-defined’ on LiDAR data. The growth of such scarps 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.

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. In the Rangitikei District, this is particularly evident for closely-spaced reverse faults and where faults splay toward their ends. Figure 4.4 illustrates an example of a FAZ map for a part of the active reverse-slip Leedstown Fault near Marton.

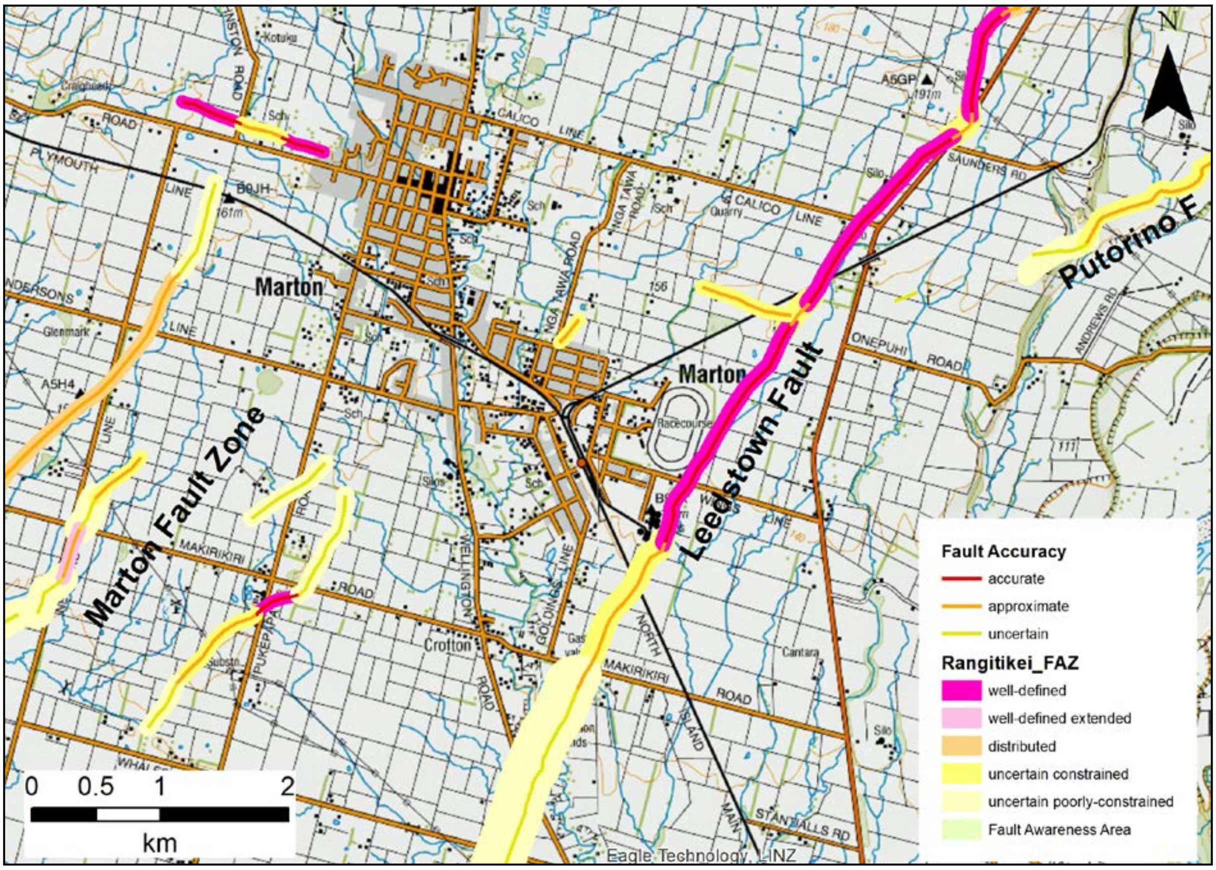

Figure 4.4 Fault avoidance zone map for the Marton area. Marton lies on the hanging-wall (up-thrown) side of the reverse-slip Leedstown Fault.

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 at 1:50,000 to 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 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 an FAZ for such areas because it carries a lower level of certainty and therefore likelihood of hazard associated with it. FAAs also highlight the need to undertake further work to test whether a mapped feature is related to tectonic (fault) deformation.

FAAs are developed with a width of ±250 m and do not carry the regulatory levels that are suggested in the MfE Guidelines. In future, if development is proposed for areas with a FAA status, then further fault mapping and/or geologic studies would be required to better define the location and/or nature of surface faulting and deformation. In this study, FAAs have been developed for the Erewhon fault (Figure 4.5) where we have mapped the fault traces using the 1-m DSM.

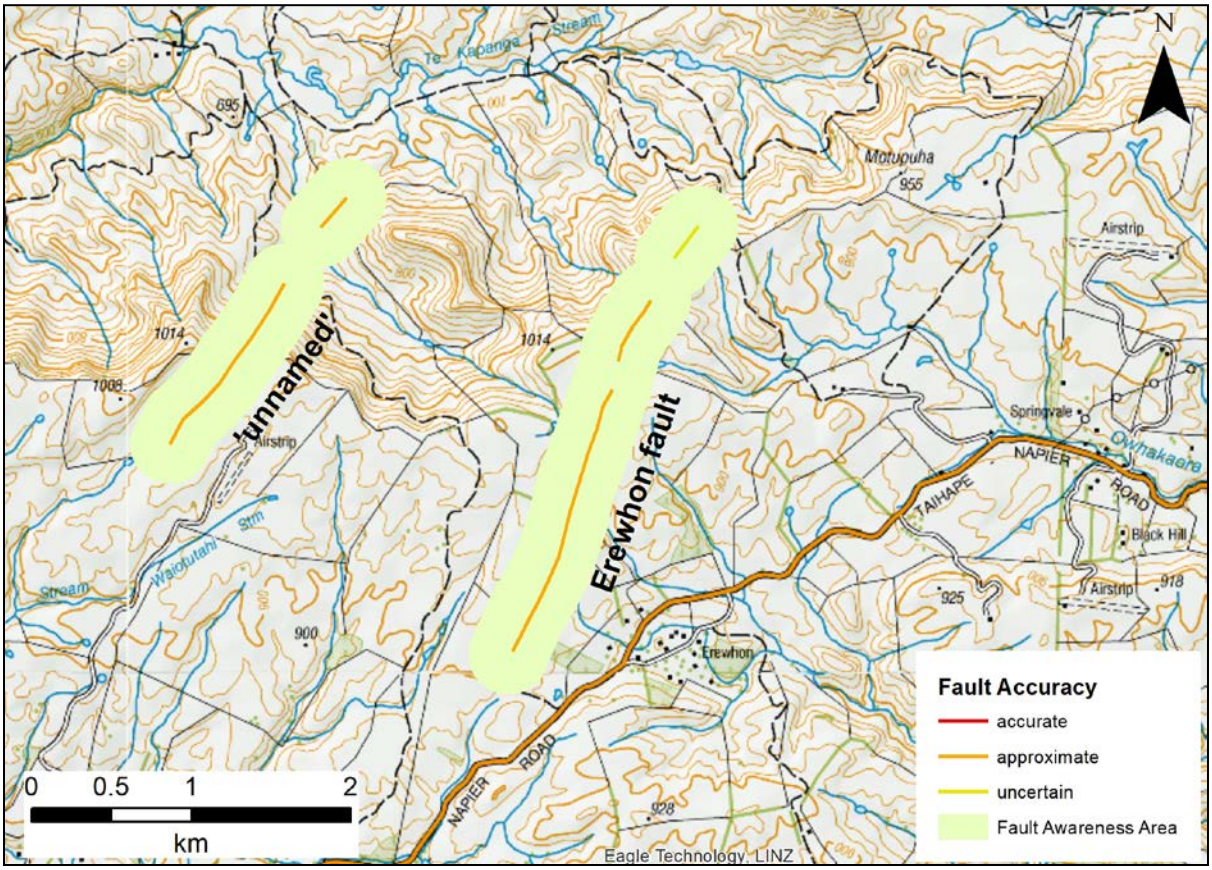

Figure 4.5 Examples of fault awareness areas for the Erewhon fault and an unnamed fault within the northern part of the Rangitikei District.

4.5 Mapping 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. In this study, we have focused on the two active anticlines identified in the Rangitikei District: the Marton Anticline and the Utiku Anticline (see Section 5.3).

While folds may be a manifestation of surface deformation related to fault movement, for the purposes of the MfE Guidelines, we do not treat active folds in the same way that we do active faults. It is not practical to develop a FAZ (or 'Fold' Avoidance Zone) for an active fold[6] because it is unclear where the focus of surface deformation will be, and it is likely that the intensity of ground deformation will not be severe enough to pose a life-safety hazard to most buildings (Barrell et al. 2015). It would be impractical to zone and buffer an active fold because of: (i) the substantial breadth of subtle deformation across a fold, (ii) the lack of focused (high-intensity) ground deformation and its location and (iii), most importantly, the low risk to life safety posed by such broad deformation.

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

5.0 ACTIVE FAULTS AND FOLDS OF RANGITIKEI DISTRICT

This study represents the first time that active fault mapping has specifically been collated for the Rangitikei District (Figure 5.1). With the help of an airborne LiDAR-derived DEM and a regional 1-m DSM, it was possible to map several active faults, as well as active folds, and to identify some ‘possibly active’ faults. The new mapping builds on data from QMAP (Heron 2018; Begg and Johnston 2000; Townsend et al. 2008; Lee et al. 2011) and the NZAFD (Langridge et al. 2016), which identified the Leedstown, Putorino, Taihape, Snowgrass and Kaweka faults as the only named active faults within the district. The locations of active (anticlinal) fold axes originally mapped by QMAP (e.g. Heron 2018) have been refined using airborne LiDAR and DSM datasets.

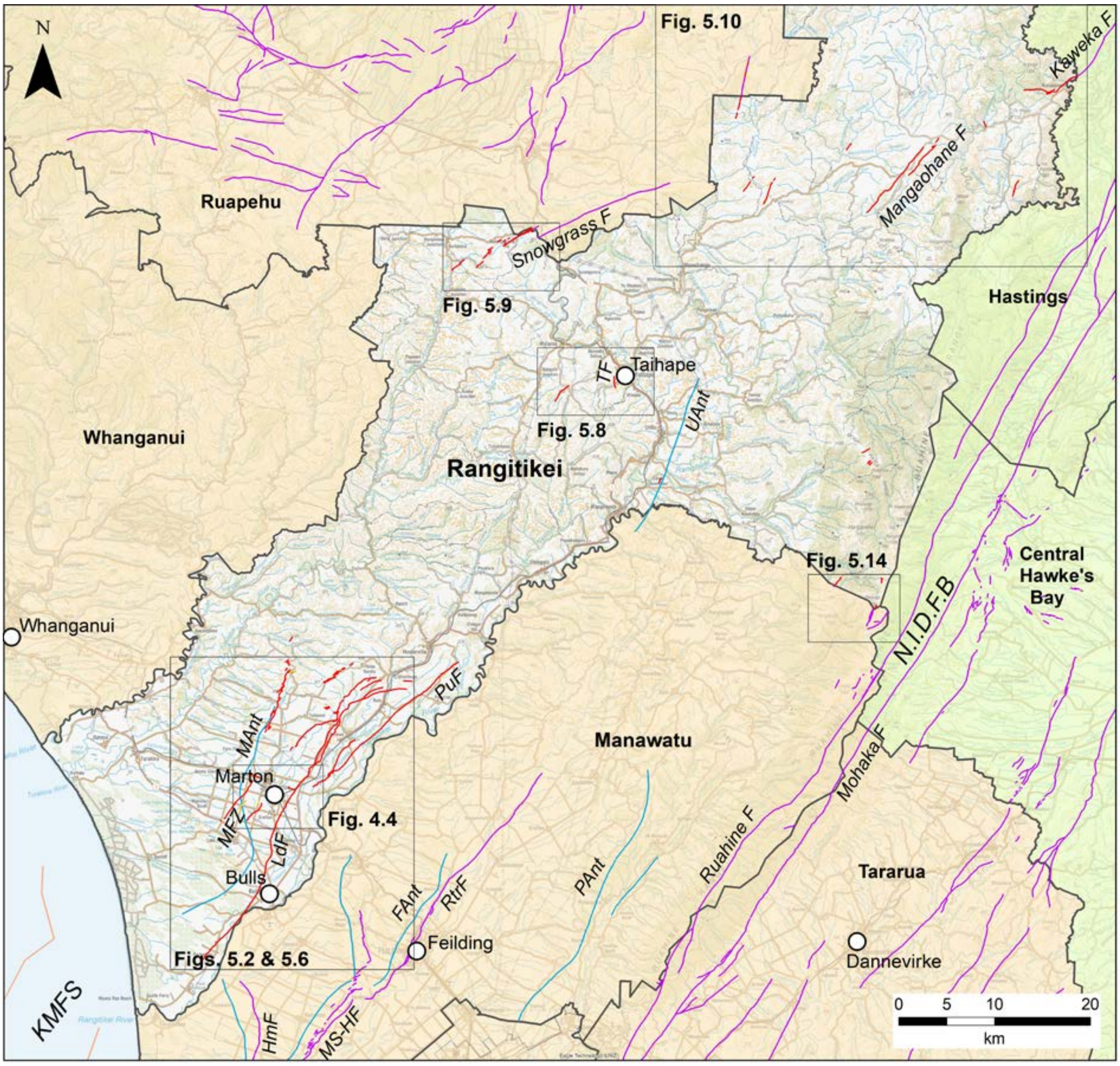

Figure 5.1 New and updated onshore active faults (red) and folds (blue) in the Rangitikei District, as defined in this study. Active faults outside of Rangitikei are shown by purple lines. Offshore active faults (orange lines) of the Kāpiti-Manawatū Fault System (KMFS) are from Nodder et al. (2007). Other districts in the Horizons Region are shaded orange. Fault name abbreviations are: LdF, Leedstown Fault; MFZ, Marton Fault Zone; PuF, Putorino Fault; TF, Taihape Fault; HmF, Himatangi Fault; MS-HF, Mt Stewart-Halcombe Fault; and RtrF, Rauoterangi Fault. Fold names are: MAnt, Marton; FAnt, Feilding; UAnt, Utiku; PAnt, Pohangina anticlines. Boxes show the areas of detailed maps in Sections 4 and 5. NIDFB refers to the North Island Dextral Fault Belt.

Active faults in the Rangitikei District (Figure 5.1) are found in association with the north-eastern onshore part of the Kāpiti-Manawatū Fault System (KMFS), e.g. the Leedstown and Putorino faults (Figure 1.1; Nodder et al. 2007; Litchfield et al. 2014); the western edge of the NIDFB, e.g. the Kaweka and Mangaohane faults (Beanland and Haines 1998); and the southern edge of the Taupō Rift, e.g. the Snowgrass Fault (Villamor and Berryman 2006b). Large parts of the central and northern Rangitikei District are devoid of known or mapped active fault traces. Much of this area is underlain by predominantly Tertiary mudstone rock and its associated dissected hill country geomorphology (Townsend et al. 2008), which makes mapping of active faults difficult.

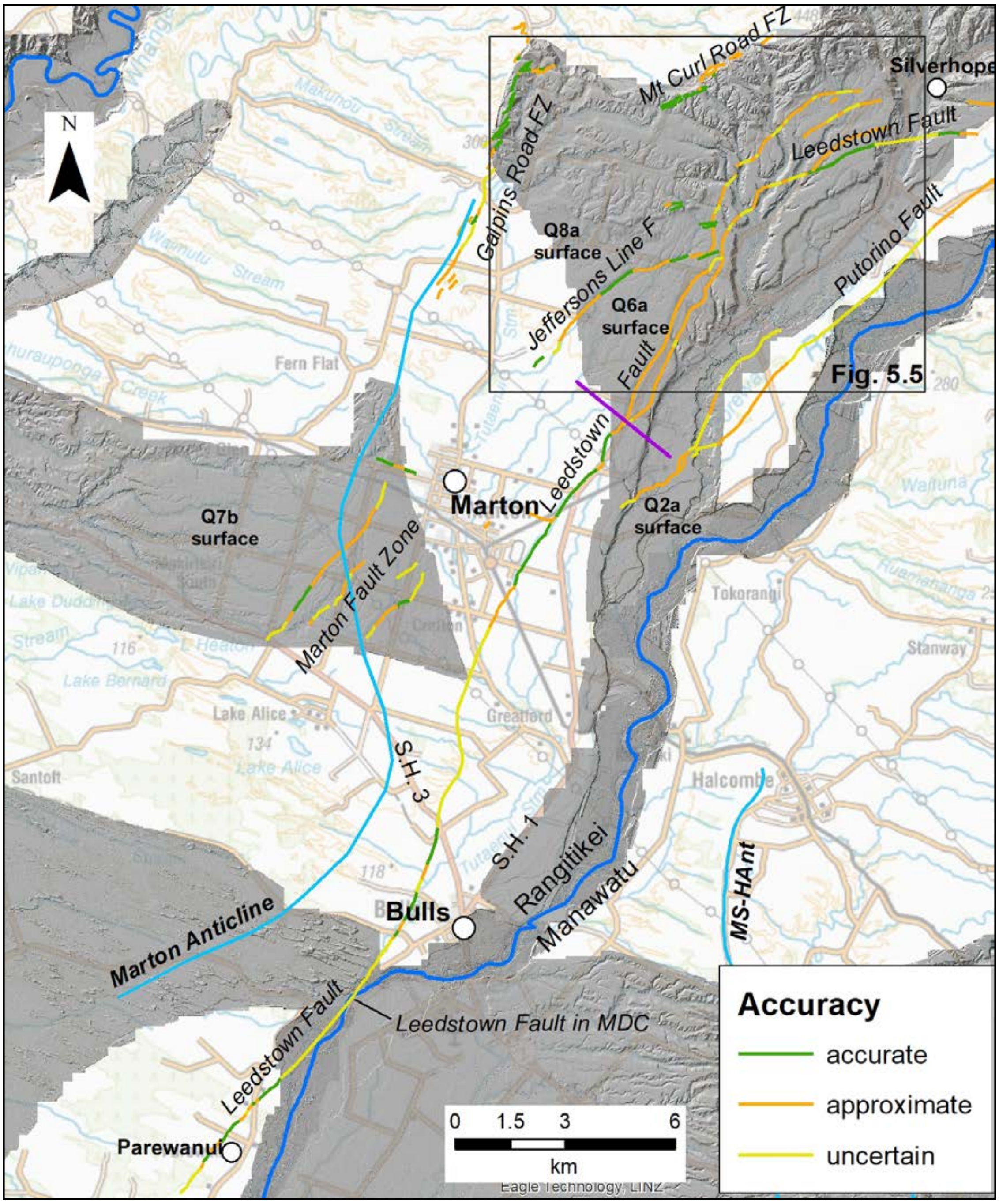

Figure 5.2 Active faults (coloured by accuracy) and folds (blue) mapped in the south-western part of Rangitikei District, displayed on LiDAR hillshade models in the area. Collectively, these faults form a 'family' of faults focused around the reverse-slip Leedstown and Putorino faults and the Marton Anticline. The character of the Leedstown Fault changes to the northeast of Marton (marked by purple line), where faulting has a dominantly normal style of motion to the northeast. MDC = Manawatū District Council.

Here we describe each of the active faults, 'possibly active' faults and folds from southwest to northeast through the district with photographs of locations where fault traces and and/or scarps can be identified in the field. Throughout this section, the use of upper case 'Fault' denotes previously known faults or those that are recognised as 'definitely or likely' to be active (having evidence for movement or repeated movements during the last 125,000 years; Langridge et al. 2016), while the use of lower case 'fault' is used to denote features that are newly recognised / minor active faults, or are denoted as 'possibly active' faults. Active faults, as defined in this study, are those for which FAZs are typically designed.

5.1 Active Faults

5.1.1 Leedstown Fault

Our analysis of active faulting in the south-western part of the Rangitikei District (Figure 5.2) indicates that the faults in this area, including the Leedstown, Putorino and Jeffersons Line faults, and the Marton, Galpins Road and Mt Curl Road fault zones, can be considered as belonging to a family of faults that we refer to as the Leedstown Fault System. The system spans a length of at least 42 km and a width of up to c. 11 km and is broadly associated with the active Marton Anticline. The dominant fault in this system is the reverse-slip Leedstown Fault, which was formerly defined as being a RI Class IV fault (Van Dissen et al. 2003; Langridge et al. 2016).

In this study, the Leedstown Fault is mapped as a c. 38-km-long structure from near Parewanui in the southwest (Figures 5.2 and 5.3) to near Silverhope in the northeast, using LiDAR data that covers much of its length. In the southwest toward the coast, the Leedstown Fault appears in QMAP regional geology (Townsend et al. 2008) as a concealed active fault beneath Q1a (alluvium) and Q1d (dune) deposits and, in part, as an approximate active fault along the boundary between Q2a and Q1a (alluvium) related to the Rangitikei River system (Townsend et al. 2008). In this study we recognise (with the help of LiDAR) accurate and approximate fault traces along the boundary between Q2a and Q1a near Parewanui and towards Bulls. These traces are linked together with uncertain traces, where the location is not well known.

The Rangitikei River valley broadly follows the path of the Leedstown Fault, which has a curvate surface geometry. Marton is on the uplifted (hanging-wall) side of the fault and Bulls is on the down-thrown (footwall) side. Part of the Leedstown Fault encroaches into the Manawatū District River valley (see Langridge and Morgenstern 2019). Northeast of Marton, the Leedstown Fault splits into two or more distinct traces that, towards the northeast, curve to become east-west striking near Silverhope (Figure 5.2). These faults display down to the southeast motion; therefore, we consider that the northern end of the Leedstown Fault consists of faults with a normal sense of motion.

Figure 5.3 Active trace of the Leedstown Fault (raised surface in distance), near its south-western end. Photo taken from Dalrymple Road. This subtle trace forms a linear 2–3-m-high riser in the road and to either side of it.

Along the southern part of the fault, scarp heights are c. 3 m where Holocene dune deposits (<12,000 years) could be mantling an older scarp, or 3–4 m in height where they form the boundary between Q2a (12,000–24,000 years) and Q1a sediments (Figure 5.3). In these cases, we assume that the scarps have formed since Q2a time, i.e. since c. 12,000–24,000 years, which yields vertical slip rates for these scarps of c. 0.13–0.33 mm/yr. These vertical slip rates convert to reverse-slip rates of c. 0.14–0.43 mm/yr (using a dip range of 50–70° W).

In the central part of the fault near Marton (Figure 5.4), the fault offsets Q6a surfaces (alluvium; 128,000–186,000 years). The maximum scarp height across the Q6a surface is c.17–19 m (and has the form of a broad scarp). These ages and heights yield a vertical slip rate of c. 0.09–0.15 mm/yr. However, in some places the scarp height is only 7–8 m. In these areas, it is possible that the Q6a surface has been re-occupied by an alluvial floodplain since it was first displaced by the fault. If, for example, the surface was occupied during the Q3 or Q2 time (i.e. depositing Q3a or Q2a alluvium), then vertical slip rates could be as high as 0.3 mm/yr. We therefore suggest a rate of c. 0.1–0.3 mm/yr for the central part of the Leedstown Fault. These vertical slip rates convert to reverse-slip rates of c. 0.11–0.39 mm/yr (using a dip range of 50–70° W).

Figure 5.4 Fault scarp of the Leedstown Fault (shown between white arrows) in its central part north of Marton. Photo taken from Calico Line adjacent to State Highway 1. The scarp here is c. 8 m high across a Q6a alluvial terrace surface.

Summed vertical deformation across the two major northern strands ranges from c. 9–13 m, measured across the mapped Q6a surface (Townsend et al. 2008). From these scarp heights, we calculate vertical slip rates of 0.05–0.1 mm/yr. These two curved fault traces appear to accommodate extension (i.e. they act as normal faults) and thus may not represent the same style or rate of deformation as seen on the southern and central parts of the Leedstown Fault (Figure 5.5). The reasons for this change in style may be due to the reverse component of motion being transferred onto the Putorino Fault, which is discussed below.

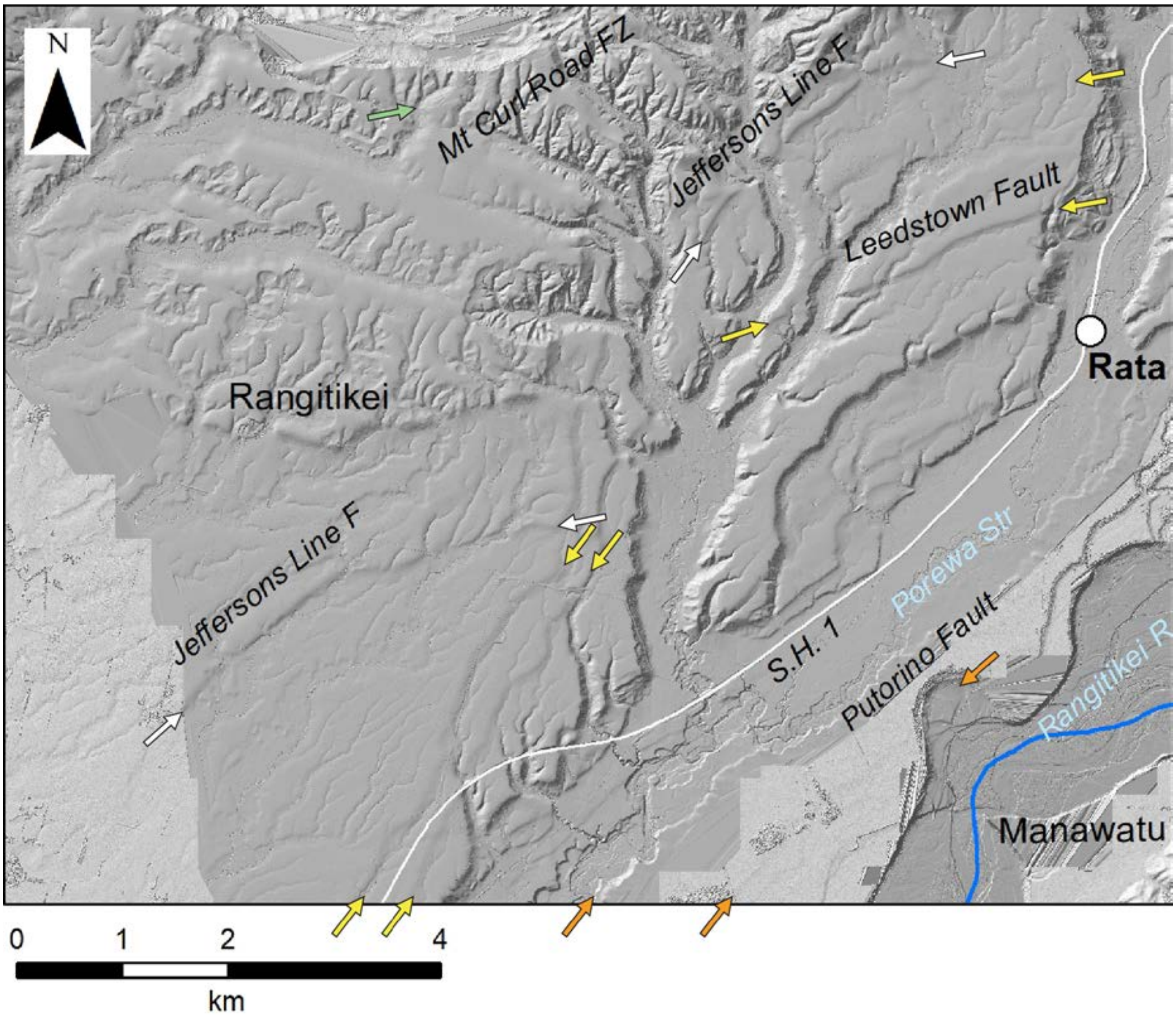

Figure 5.5 Uninterpreted LiDAR (dark grey) and DSM hillshade map of the north-eastern end of the 'Leedstown Fault System'. Coloured arrows point to the ends of mapped active fault traces along the Putorino Fault (orange), Leedstown Fault (yellow), Jeffersons Line Fault (white) and Mt Curl Fault Zone (green).

In summary, profiling of fault scarps and vertical deformation yields vertical slip rates along the Leedstown Fault of typically 0.1–0.3 mm/yr (equivalent to 1–3 m every 10,000 years). These vertical slip rates convert to reverse-slip rates of c. 0.1–0.4 mm/yr (using a dip range of 50–70° W). From these rates, we make a comparison to earthquake fault sources within the NSHM (Table 3.3) and suggest that the Leedstown Fault could experience a large surface-rupturing earthquake every 5000–10,000 years (i.e. RI Class IV).

FAZ developed for the Leedstown Fault range in width from 130 m for an accurate: well-defined FAZ to 160 m width for an approximate: distributed FAZ and to 415 m for an uncertain: uncertain poorly constrained FAZ (see Figure 5.6).

5.1.2 Putorino Fault

The 20-km-long northeast-striking Putorino Fault is an active reverse fault in the south-eastern part of Rangitikei District (Figures 5.2 and 5.5). In this study, we have reviewed active fault and geologic data in the area of the Putorino Fault, including linework for the Rangitikei and Rangatira faults, mapped as sub-parallel to the Putorino Fault in QMAP geology (Heron 2018). The Putorino Fault appears in QMAP regional geology and the NZAFD as a discontinuous active reverse fault (Townsend et al. 2008; Langridge et al. 2016).

The linework presented in the GIS and in maps here represents a significant update to previous interpretations. The new mapping, based on LiDAR and the regional 1-m DSM, shows the fault traces are consistently c. 500 m to the southeast of the previous mapped position of the fault. The Putorino Fault is mapped mainly with an approximate or uncertain accuracy along its length. No active fault traces have been recognised along either the Rangitikei or Rangatira faults in this area, corroborating their previously mapped status as inactive structures (Heron 2018; Townsend et al. 2008).

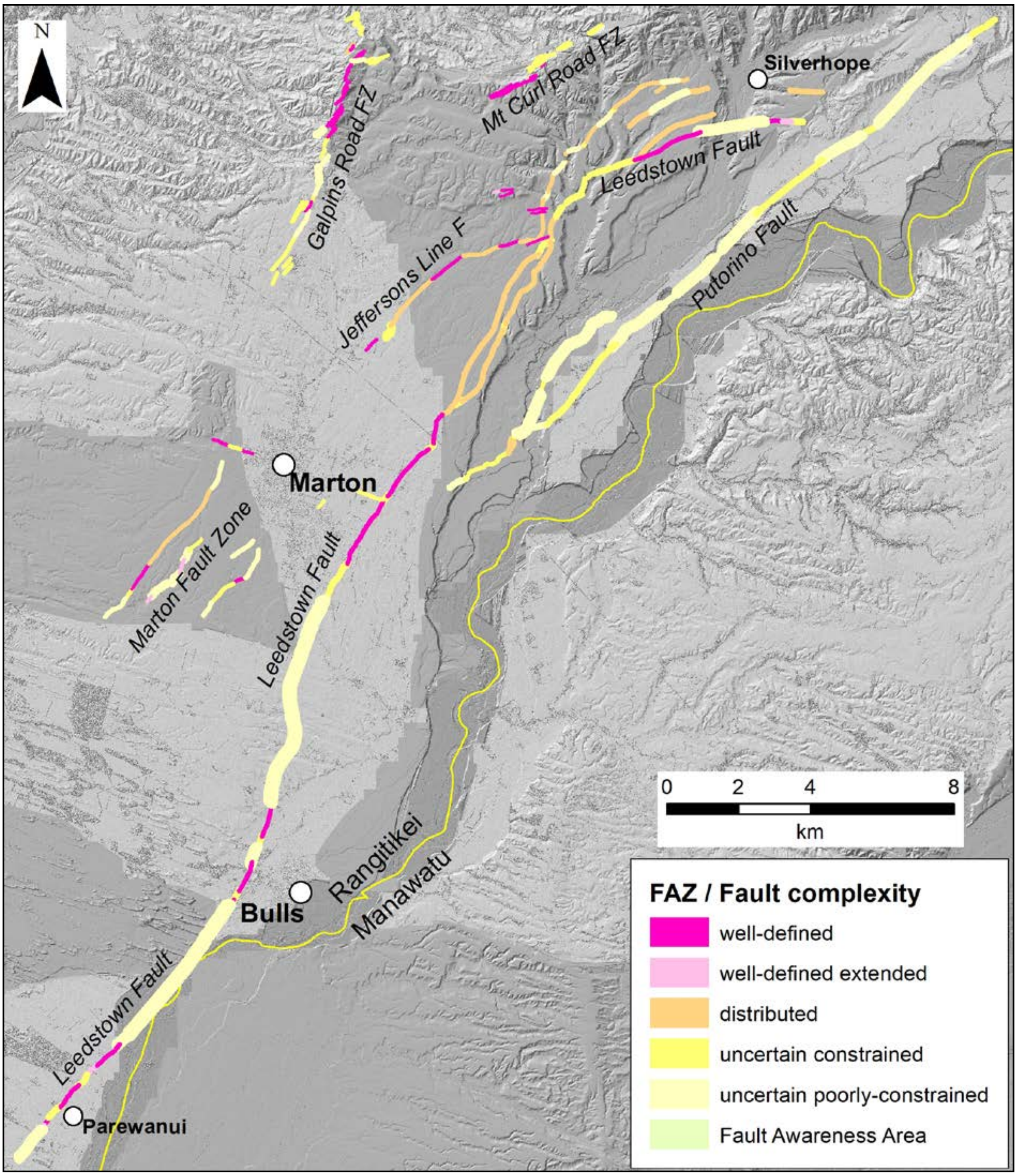

Figure 5.6 Fault avoidance zone map for faults in the south-western part of Rangitikei District, displayed on LiDAR (dark grey) and DSM hillshade models. Fault avoidance zones are based on fault mapping accuracy and fault complexity terms.

The Putorino Fault is possibly a branch or splay of the Leedstown Fault; however, we are not able to map it in this fashion (as joining into the Leedstown Fault) at the ground surface. In the southwest, the Putorino Fault steps and splays away from the Leedstown Fault east of Marton around Porewa Stream (Figures 5.5 and 5.6). A northern splay of the Putorino Fault is mapped along the southern side of Porewa Stream valley, following the former mapped trace of the Putorino Fault to the northeast for c. 3 km, after which it cannot be traced. While it is possible that this northern splay continues along Porewa Stream (i.e. beneath young sediments), we have not mapped it farther to the northeast.

Near its south-western end, the Putorino Fault exhibits southeast-facing scarps with a height of c. 7 m (separating terrace Q3a from Q2a) and c. 2.5 m across a terrace mapped as Q2a (i.e. 12,000–24,000 years). Part of the reason for a high (7 m) scarp may be due to the juxtaposition of Q3a and Q2a terraces, i.e. this could be a combination of both a fluvial riser and fault scarp. Nevertheless, based on cross-sectional profiling using DEMs, vertical slip rates of c. 0.21–0.29 mm/yr can be derived from these scarps. These vertical slip rates are comparable to those derived for the Leedstown Fault, described above. These values are consistent with a component of the reverse motion being partitioned from the Leedstown onto the Putorino Fault. The vertical slip rates presented here for the Putorino Fault convert to reverse-slip rates of c. 0.22–0.38 mm/yr (using a dip range of 50–70°W).

In the central part of the mapped Putorino Fault, a 7-m-high riser separates the mapped Q3a and Q2a terraces (Figure 5.5). We attribute this long straight riser to the location of the Putorino Fault, arguing that, in comparison, the riser between Q2a and Q1a is curved with distinct bow-shaped erosional cuts (as opposed to being straight like the mapped Q3a–Q2a riser). The main (southern) trace of the Putorino Fault continues to the northeast across alluvial terraces (Q3a, Q2a) separating Porewa Stream from the Rangitikei River. In this area there is a 3–4-m-high southeast-facing scarp across a Q3a alluvial surface (Townsend et al. 2008). Using the young end of the age range for Q3a (24,000–59,000 years) corresponds to vertical slip rates of 0.13–0.17 mm/yr. These vertical slip rates convert to reverse-slip rates of c. 0.14–0.22 mm/yr (using a dip range of 50–70°W).

Close to the northeast end of its mapped extent, the Putorino Fault climbs onto a higher surface, mapped as Q6a (alluvium; 128,000–186,000 years). This trace is associated with a scarp of c. 25–29 m height. If the younger end of this age range is used to define rates, these scarps would be associated with vertical slip rates of 0.2–0.23 mm/yr on the Putorino Fault. These rates convert to reverse-slip rates of c. 0.21–0.3 mm/yr (using a dip range of 50–70°W).

Based on this set of slip rate observations and calculations along its length (i.e. reverse-slip rates of 0.2–0.4 mm/yr), we apply a provisional RI Class IV (>5000 to ≤10,000 years) to the Putorino Fault by a comparison to fault slip rates and recurrence intervals in the NSHM (Table 3.3). RI Class designation for the Putorino Fault is consistent with estimates for the Leedstown Fault, which has a similar style of surface deformation and tectonic relationship.

FAZs developed for the Putorino Fault range from 130 m width for an approximate: uncertain constrained FAZ to 340 m for an uncertain: uncertain poorly constrained FAZ (Figure 5.6).

5.1.3 Marton Fault Zone (New)

The mainly NNE-striking Marton Fault Zone (MFZ) describes a discontinuous zone of extension (normal faulting) that occurs predominantly to the southwest of Marton. The MFZ is up to c. 6 km long and typically up to 2 km wide (Figures 5.2 and 5.6). The MFZ is parallel to, and c. 2–4 km northwest of, the Leedstown Fault. Fault traces of the MFZ were not recognised as faults prior to this study but are apparent on the LiDAR hillshade model. Southeast of Marton, there are at least three parallel, mappable fault traces that form a graben, with channel drainages following the NNE grain flowing toward the SSW. The MFZ has not been mapped within the built-up part of Marton township. This is in part due to: (i) the subtle nature of the faulting in the MFZ, (ii) the lack of LiDAR coverage across Marton and (iii) the presence of the network of channels related to the Tutaenui Stream catchment. However, this does not discount the possible presence of faulting through this area.

An unusual characteristic of the MFZ is that it is obliquely transected by the axis of the Marton Anticline (Figure 5.2), which is NNW-trending in that area. The simplest explanation for this faulting is that it occurs as bending-moment normal faulting in the hanging-wall of the reverse-slip Leedstown Fault and across the crest of the Marton Anticline. This would not be considered as ‘seismogenic faulting’, i.e. faulting that occurs from an earthquake source at depth and ruptures a fault plane, but rather as secondary, near-surface faulting related to tectonic movement of the Leedstown Fault and Marton Anticline. Nevertheless, the faults of the MFZ still pose a surface faulting (deformation) hazard, as they could rupture in conjunction with the Leedstown Fault or other nearby faults.

Fault scarps along the MFZ vary from 1 to 5 m high along the zone of faulting formed across either a Q6a alluvial surface or Q7b marine surface. Using the age bracket of Q6a (alluvium; 128,000–186,000 years), we estimate a fault slip rate of ≤0.04 mm/yr. This very low slip rate would suggest that the MFZ could be placed into RI Class V, i.e. the recurrence interval is >10,000 years and ≤20,000 years. However, in this case, we consider that the MFZ is likely to rupture in conjunction with the Leedstown Fault and therefore should be considered as being RI Class IV (>5000 to ≤10,000 years). However, the very low slip rates recorded for the MFZ could equate with small (<1 m) single-event displacements (or longer repeat times compared to the Leedstown Fault), and these could be considerations made for future planning decisions.

FAZ developed for the Marton Fault Zone range in width from 100 m for an accurate: well-defined FAZ to 240 m width for an uncertain: uncertain poorly constrained FAZ (Figure 4.4). Because the MFZ is a zone of normal faulting, the FAZ buffers are symmetrical in their dimensions.

5.1.4 Jeffersons Line Fault (New)

The Jeffersons Line Fault is c. 12.6 km long and occurs immediately to the northwest of the Leedstown Fault (Figure 5.6). The fault is named after Jeffersons Line, a road north of Marton. The Jeffersons Line Fault has a sinuous surface geometry but generally follows the grain of active faulting (and alluviation) in the area. We have interpreted the Jeffersons Line Fault as being related to active normal faulting that occurs in the hanging-wall of the Leedstown Fault. However, we cannot be absolutely certain that some of the features assigned to this fault are not alluvial in origin and, in these cases, they are assigned the term ‘likely’ for Tect_origin.

In the southwest, the Jeffersons Line Fault is arcuate and follows the mapped riser that separates a Q8a (245,000–303,000 years) alluvial surface from a Q6a (128,000–186,000 years) alluvial surface. In this case, this riser could be interpreted as merely an alluvial riser; however, we interpret it as a fault scarp as it is parallel to the regional structure, e.g. the Leedstown Fault. In the northwest, the fault trace is also arcuate and is sub-parallel to arcuate traces related to the north-eastern end of the Leedstown Fault and perpendicular to a major (unnamed) stream system that drains from the north (Figure 5.5). In this case, the scarp cuts across a terrace mapped as being capped by Q6a alluvium (Heron 2018; Townsend et al. 2008). This scarp is 7–20 m high across the Q6a terrace surface. Using this scarp, we calculate a vertical slip rate of 0.04–0.16 mm/yr, or up to 1.6 m of vertical deformation every 10,000 years. We conservatively place the Jeffersons Line Fault into RI Class IV (>5000 to ≤10,000 years), due to its length and proximity to the Leedstown Fault and its similar geomorphic setting to other faults in the south-western part of the Rangitikei District.

FAZ developed for the Jeffersons Line Fault typically range in width from 100 m for an accurate: well-defined FAZ, to 240 m for an uncertain: uncertain constrained FAZ. Because the Jeffersons Line Fault is interpreted as a zone of normal faulting, the FAZ buffers are symmetrical in their dimensions.

5.1.5 Galpins Road Fault Zone (New)

In the northern part of the 'Leedstown Fault System' the Galpins Road Fault Zone (GRFZ) and Mt Curl Road Fault Zone (Section 5.1.6) are mapped and interpreted as zones of active normal faulting (Figures 5.2 and 5.7). The presence of normal faulting in this area is not well understood, but probably relates to the proximity of these zones of faulting to the Marton Anticline and Leedstown Fault, respectively.

The GRFZ is a 4–6.6-km-long zone of discontinuous NNE-striking active normal faulting mapped to the north of Marton Reservoir and adjacent to Galpins Road (Figure 5.7). The GRFZ projects to the north of the mapped axis of the Marton Anticline as a zone of left stepping normal fault traces. In this case, as with the Marton Fault Zone (MFZ), the faulting may in fact be shallow and related to the broader structure of the Marton Anticline and the 'Leedstown Fault System' (as opposed to being discreet seismogenic faulting on the GRFZ).

This zone of faulting was formerly mapped as an inactive fault (the Galpin Fault; Heron 2018) but recognised within the NSHM as the 'Galpin' earthquake fault source (Stirling et al. 2012). The Galpin source is characterised as a normal fault with a calculated magnitude of M_w 6.3 and an average recurrence interval of 13,600 years (Stirling et al. 2012). It is difficult to characterise the frequency of faulting along this zone from the surface geology. However, the fault traces relating to the GRFZ cut across hillslopes that have probably been in a state of equilibrium (form) throughout the Holocene period. In other words, the active traces have formed during the last 11,700 years or so.

Because the GRFZ is broadly correlated with the 'Leedstown Fault System', we assign it a preliminary RI Class of IV (RI >5,000 to ≤10,000 years). The tectonic imprint of the GRFZ is less well-expressed compared to the Leedstown, Jefferson Line and Putorino faults, which may be a reflection of the style of faulting or a diminishing expression of active tectonism in central Rangitikei District. As described for the MFZ, the weaker expression could equate with smaller (<1 m) single-event displacements, and this could be a consideration made for future planning decisions.

FAZs developed for the GRFZ typically range in width from 100 m for an accurate: well-defined FAZ to 160 m for an uncertain: uncertain poorly constrained FAZ. Because the Jeffersons Line Fault is interpreted as a zone of normal faulting, the FAZ buffers are symmetrical in their dimensions.

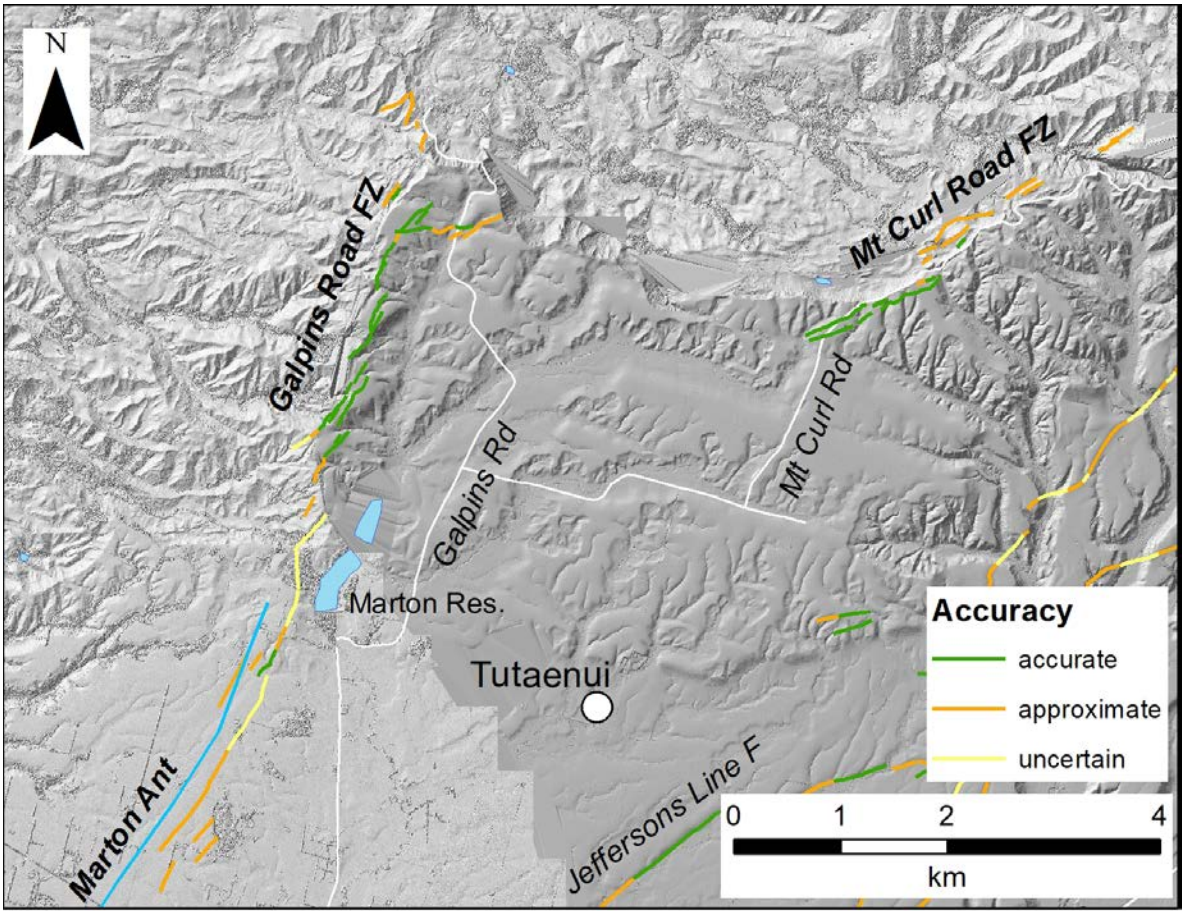

Figure 5.7 Active fault trace maps for the Galpins Road Fault Zone and Mt Curl Road Fault Zone, displayed on LiDAR (dark grey) and DSM hillshade models. The northern end of the Marton Anticline axis is shown in blue at lower left.

5.1.6 Mt Curl Road Fault Zone (New)

The Mt Curl Road Fault Zone (MCRFZ) is a 3.6-km-long zone of discontinuous, northeast-striking active normal faulting mapped to the east of the GRFZ (Figure 5.7). The MCRFZ is also located parallel to, and c. 2.3 km northwest of the Jeffersons Line Fault (and 4 km to the northwest of the northern part of the Leedstown Fault). We infer that the MCRFZ is part of the 'Leedstown Fault System' (see above) and occurs as a zone of passive (i.e. non-seismogenic) extension in the hanging-wall of this fault system, in response to active reverse faulting. Nevertheless, the MCRFZ represents active ground surface deformation, so is still included in this report for the purposes of planning and application of the MfE Guidelines.

Because the MCRFZ is broadly correlated with the 'Leedstown Fault System', we assign it a preliminary RI Class of IV (RI >5,000 to ≤10,000 years). Like the GRFZ, the tectonic imprint of the MCRFZ is typically poorly expressed compared to the Leedstown, Jefferson Line and Putorino faults, which means that it could equate with smaller (<1 m) single-event displacements, and this could be a consideration made for future planning decisions.

FAZ developed for the MCRFZ typically range in width from 100 m for an accurate: well-defined FAZ to 140 m for an approximate: uncertain constrained FAZ. Because the MCRFZ is interpreted as a zone of normal faulting, the FAZ buffers are symmetrical in their dimensions.

5.1.7 Taihape Fault

The Taihape Fault is an active NNW-striking normal fault located immediately west of Taihape township (Figure 5.8). It was formerly mapped as a 1.5-km-long active fault in central Rangitikei District (Langridge et al. 2016; Lee et al. 2011). The mapped trace of the Taihape Fault is short and isolated, occurring about halfway between the 'Leedstown Fault System' and the southern end of the Taupō Rift, where normal faulting predominates (Villamor and Berryman 2006b). In this study, we re-mapped the Taihape Fault as a 1.2-km-long fault using the 1-m DSM (confirmed with the help of CI Massey, GNS Science) to the north and south of Otaihape Stream, west of the town. The mapped fault trace occurs across farmland, c. 100–200 m west of the main head scarp of the active Taihape landslide (e.g. Massey 2010).

There is no geological data available at this time with which to derive a precise recurrence interval class for the Taihape Fault. The NSHM (Stirling et al. 2012) identifies the 'Taihape' active fault earthquake source as a 10-km-long normal fault source, capable of generating a M_w 6.1 earthquake, with c. 0.4 m surface displacement, on average every 3900 years. The traces of the Taihape Fault cut across hillslopes that have probably been in a state of equilibrium (form) throughout the Holocene period (the last 11,700 years or so). We suggest a preliminary RI Class IV (>5000 to ≤10,000 years) for the Taihape Fault, which implies that there has been at least one fault movement during the Holocene.

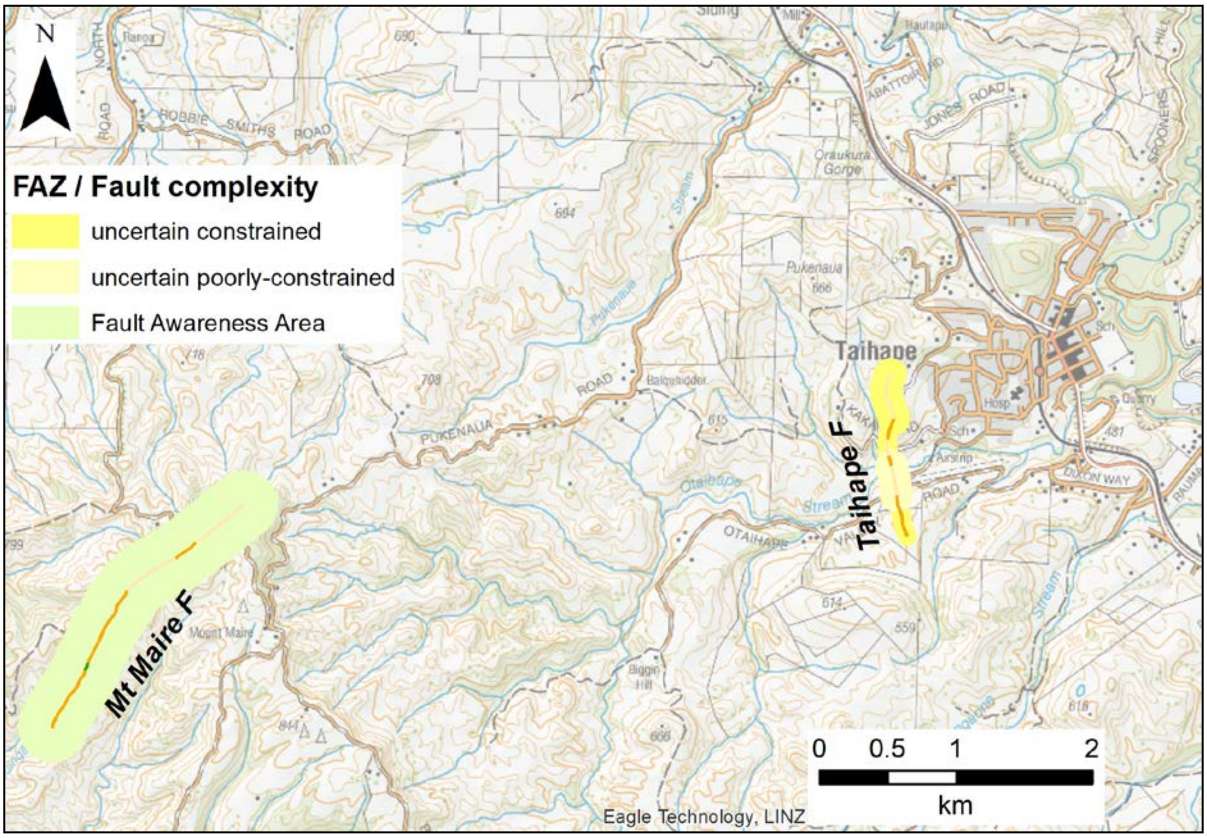

Figure 5.8 Active fault trace and fault avoidance zone buffer maps for the Mt Maire fault and Taihape Fault.

FAZs developed for the Taihape Fault typically range in width from 140 m for an approximate: uncertain constrained FAZ to 240 m for an uncertain: uncertain poorly constrained FAZ. Because the Taihape Fault is interpreted as a zone of normal faulting, the FAZ buffers are symmetrical in their dimensions.

As part of this study, we reviewed an active trace shown in the high resolution GNS active faults dataset (called AF.Traces). This trace is c. 3 km southeast of the Taihape Fault and forms part of the Rangitikei Fault on geological maps (Heron 2018; Lee et al. 2011). As part of this study, we found little evidence from the 1-m DSM to suggest that this is an active fault trace.

5.1.8 Mt Maire Fault (New)

The Mt Maire fault is interpreted to be an active northeast-striking normal fault, located c. 6 km west of Taihape township (Figure 5.8). It was formerly mapped as a 1.25-km-long active fault trace in central Rangitikei District, identified in the high-resolution GNS Active faults dataset (AF.Traces) as the Mataroa Fault. Like the Taihape Fault, the Mt Maire fault is a short, isolated fault that occurs about halfway between the 'Leedstown Fault System' and the southern end of the Taupō Rift. In this study, we re-mapped the Mt Maire fault as a 2.2-km-long fault using the 1-m DSM. Fault traces cut across mid to late Pliocene bedrock hill country near Mt Maire (Heron 2018).

In this study, we prefer the name 'Mt Maire fault' to 'Mataroa Fault' because of its proximity to Mt Maire (0.6 versus 4.6 km). The name 'Mataroa' is also given to an active fault earthquake source in the NSHM, representing a similar earthquake source to the 'Taihape' source described above. The 10-km-long Mataroa active fault earthquake source is considerably longer than the mapped trace of the Mt Maire fault.

There is sparse geological information with which to determine a recurrence interval for the Mt Maire fault. In this case, we define the Mt Maire fault with a FAA because there is not an easy means to derive a recurrence interval for it.

5.1.9 Snowgrass Fault

The ENE-striking Snowgrass Fault is an active normal fault in the northern part of Rangitikei District and continues into the southern part of Ruapehu District. The Snowgrass Fault occurs immediately south of the Taupō Rift and is broadly associated with this volcanic rift (Villamor and Berryman 2006b). Based on its designation as a RI Class I fault by Van Dissen et al. (2003), the Snowgrass Fault could be considered the most active fault in the district, i.e. repeating ground-surface-rupturing earthquakes every 2000 years or less. In this study, we mapped the Snowgrass Fault as a zone of faulting with active traces and 'possibly active' traces, spanning a zone ranging in width between 1.2 and 4 km in width.

As part of this study, we reviewed active fault data for the Snowgrass Fault from QMAP, the NZAFD and from the high-resolution GNS active faults dataset (AF.Traces), and remapped fault traces using the 1-m DSM (Figure 5.9). For the latter, we also used insights into the broader context of the Snowgrass Fault by viewing it on-screen within Ruapehu District. The mapping review highlights that the Snowgrass Fault is a complex zone of normal faulting. Some of the active and 'possibly active' traces defined in the GIS appear as sharp geomorphic lineaments where the Tertiary bedrock platform, comprising Matemateaonga Formation, has been dissected.

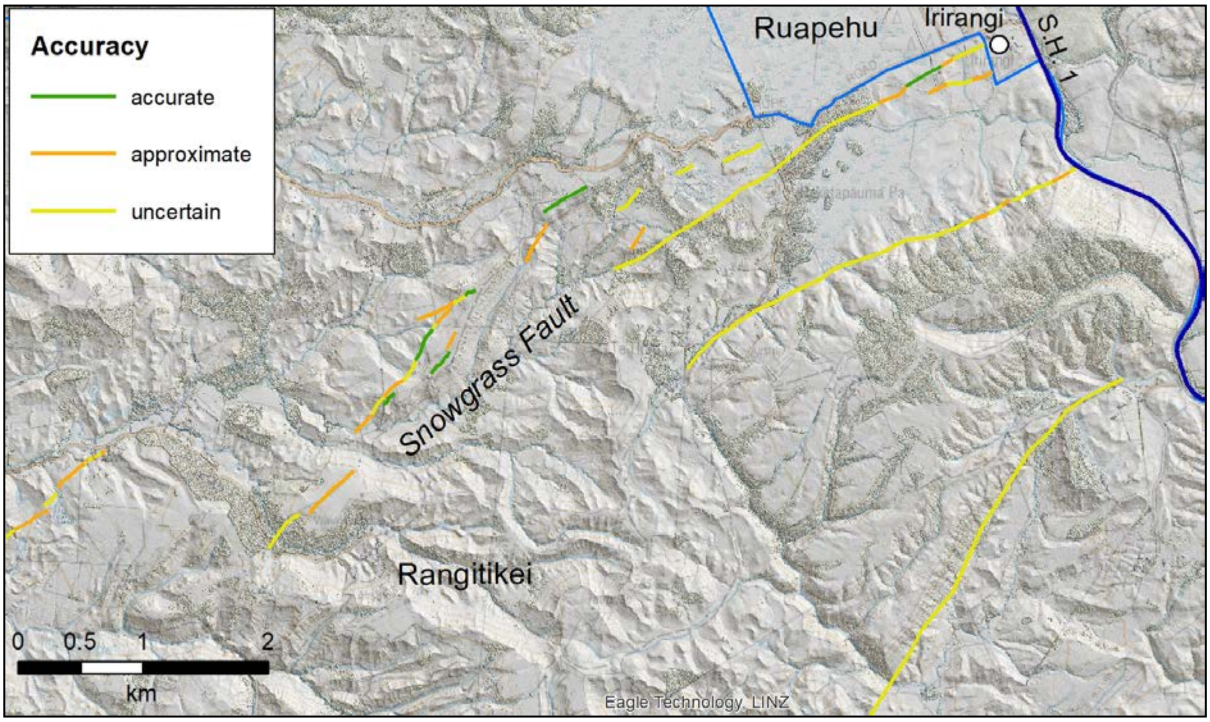

Figure 5.9 Active fault traces of the Snowgrass Fault mapped in northern Rangitikei District near Irirangi. Fault traces are either mapped as accurate (green), approximate (orange) or uncertain (yellow).

In the north, the Snowgrass Fault is mapped from Irirangi on State Highway 1 toward the WSW for a distance of c. 9.4 km to Turakina Valley Road (Figure 5.9). We mapped the Snowgrass Fault on the 1-m DSM as a right-stepping zone of discontinuous active faulting with both north- and south-facing normal fault scarps along its length. We have mapped the traces as accurate, approximate or uncertain and, in many cases, we cannot always connect the mapped traces along-strike on the ground surface. The fault is exposed in a road cutting on State Highway 1 near Irirangi (Figure 5.10). About 1.2 km south of Irirangi, a second major strand of the Snowgrass Fault projects towards State Highway 1. West of the highway, we mapped traces of this fault strand as ‘active’, or as ‘possibly active’ because, even though there is a scarp, the age of the landscape is poorly known. Similarly, c. 2 km further south, another NE-trending lineament has been mapped as a ‘possibly active’ fault, based on the dissection of the bedrock plateau there (Figure 5.9).

The Snowgrass Fault has formerly been designated as a RI Class I fault (Van Dissen et al. 2003; Langridge et al. 2016). Villamor and Berryman (2006b) estimate a slip rate range of 0.4–0.7 mm/yr from scarp heights along the fault (Figure 5.10). Using the magnitude-length regression equation for normal faults of the Taupō Rift (in Van Dissen et al. 2003), we derive a more conservative estimate for the Snowgrass Fault recurrence interval, i.e. RI Class II (or possibly III). In this case, we infer that the recurrence interval is RI Class II (>2000 to ≤3500 years) rather than RI Class I, based on unpublished geological insights (P Villamor, pers. comm. 2019) that compare it to the activity observed on faults which are part of the southern Taupō Rift (Villamor and Berryman 2006a, b).

Figure 5.10 Exposure of the active Snowgrass Fault in State Highway 1 roadcut near Irirangi, identified by white arrows. The fault forms the sharp break between light grey Tertiary rocks and orange-brown Late Quaternary lahars and tephra deposits, mostly from Mt Ruapehu. The scarp, highlighted by the fence line, is c. 5 m high.

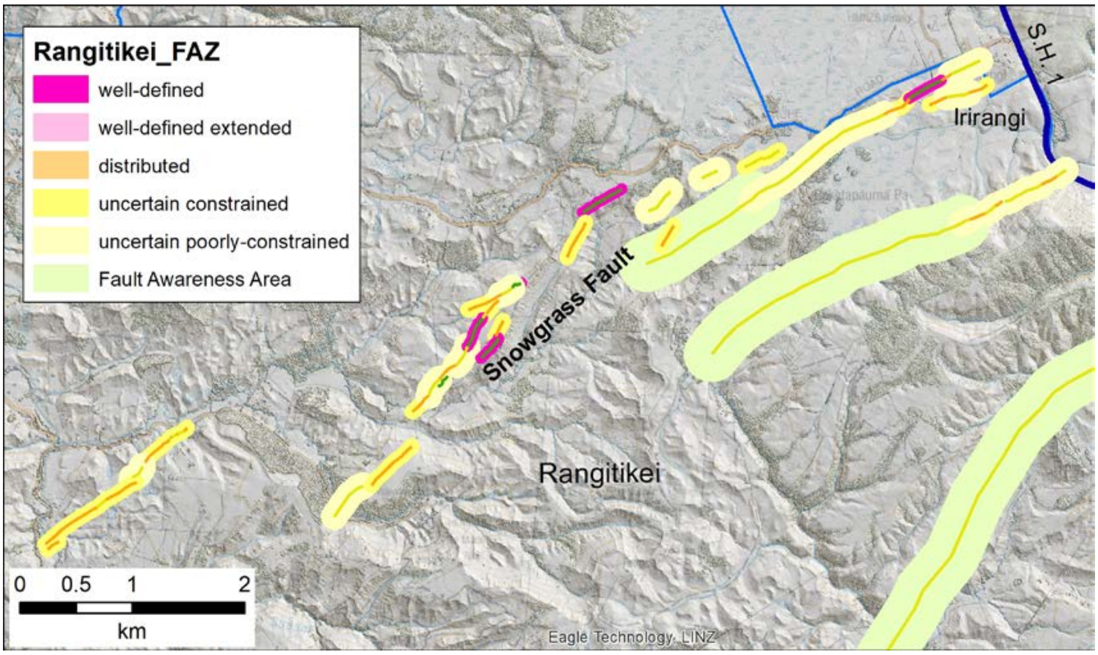

Figure 5.11 Fault avoidance zone map for faults in the south-western part of Rangitikei District, displayed on the DSM hillshade model. FAZs are based on fault mapping accuracy and fault complexity terms. Fault awareness areas (light green) have been applied where the fault location and/or certainty of the feature is unclear.

We developed both FAZs and FAAs for the Snowgrass Fault (Figure 5.11). FAZs for the Snowgrass Fault range in width from 100 m for an accurate: well-defined FAZ to 240 m for an uncertain: uncertain poorly constrained FAZ. FAZ are symmetrical in form because the Snowgrass Fault has a normal style of faulting (Figure 5.10). FAAs developed for the fault have a width of 500 m. FAAs reflect the fact that we are not certain of whether all of the mapped traces are active faults.

5.1.10 Mangaohane Fault (New)

The northeast-striking Mangaohane Fault is one of several short active faults that have been identified in the north-eastern part of the Rangitikei District (Figure 5.12). These faults, including the Kaweka Fault and the newly named Swinburne Bush and Timahanga faults, occur in the area between the Taupō Rift and the NIDFB (Villamor and Berryman 2006b).

The Mangaohane Fault, named after Mangaohane Stream, comprises two sub-parallel mapped fault strands that extend over a length of c. 10.6 km near the Taihape-Napier Road (Gentle Annie Highway). The Mangaohane Fault was formerly recognised as an active fault on QMAP geological maps and in the NZAFD, but was not given a name (Lee et al. 2011; Langridge et al. 2016). The Mangaohane Fault is arguably a splay of the Rauoterangi Fault, which is a major bedrock fault in the southern North Island (Heron 2018; Lee et al. 2011) with demonstrable activity in the Manawatū District (Langridge and Morgenstern 2019).

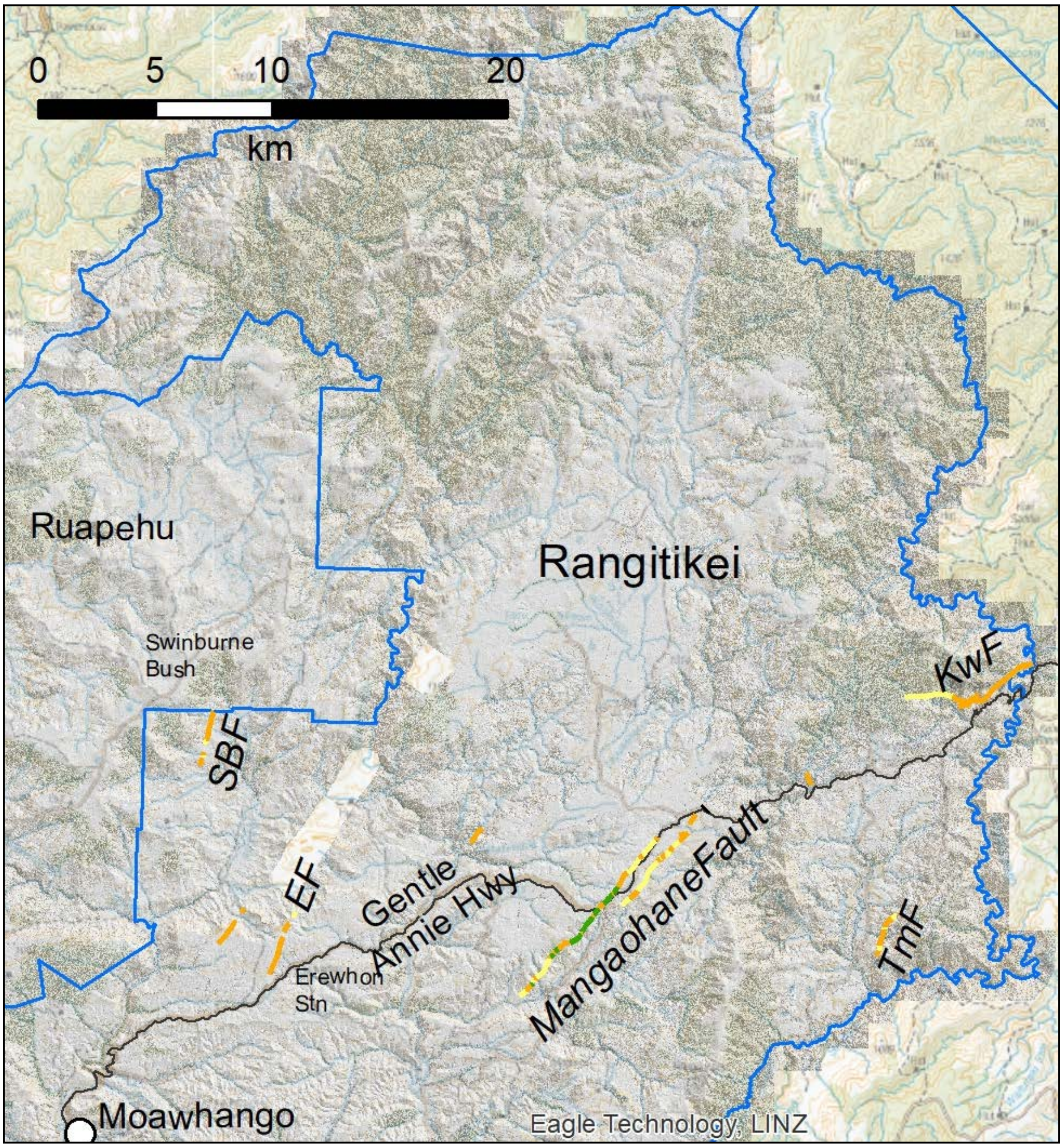

Figure 5.12 Active faults mapped in the north-eastern part of the Rangitikei District. Abbreviations for named faults: EF = Erewhon fault; KwF, Kaweka Fault; SBF, Swinburne Bush fault; TmF, Timahanga fault. There are no known active faults in the district north of those mapped here.

The Mangaohane Fault has a continuous accurate to approximate rupture trace mapped over a distance of at least 5 km along the south-eastern edge of an unnamed plateau formed in Early Pliocene Matemateaonga Formation (Figure 5.13). Near (and across) the Gentle Annie Highway, the Mangaohane Fault has a linear trace with a sharp 2–3-m-high scarp and a down-to-the-southeast sense of movement. It is inferred to be a 'high-angle' active fault (Lee et al. 2011). The style of faulting (normal, reverse or strike-slip) on the Mangaohane Fault is not well understood. It is possible that the Mangaohane Fault has a significant strike-slip or oblique-slip character due to its proximity to the NIDFB.

While it is not possible to determine the style of faulting, it is possible to consider a vertical slip rate range from the fault scarp. We infer that the scarp crossing the bedrock plateau has formed during or since the end of the last cold climate stage (i.e. 12,000–24,000 years). If this is a reasonable assumption, then a slip rate of 0.08–0.25 mm/yr is calculated. No further geological or paleoseismological data is known for the Mangaohane Fault.

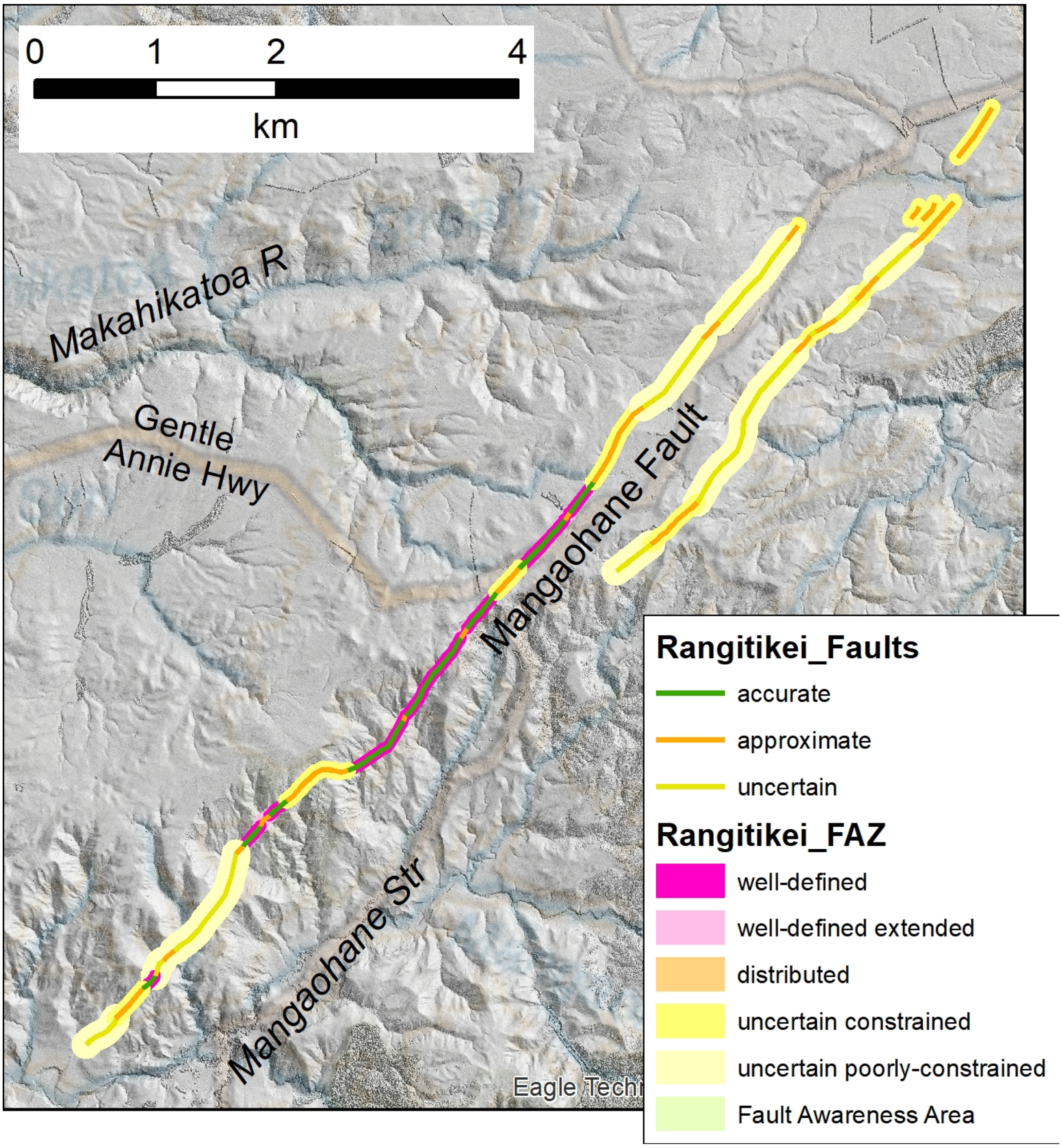

Figure 5.13 Active fault traces and fault avoidance zones for the Mangaohane Fault in the north-eastern Rangitikei District.

In the NSHM (Stirling et al. 2012), there is no active fault earthquake source that strictly acknowledges the role of the Mangaohane Fault. Instead, seismic potential is characterised by a feature (the Kaweka ‘earthquake fault source’) that links the Snowgrass Fault with the Kaweka Fault (Section 5.1.11). The Kaweka Fault, and Kaweka ‘earthquake fault source’, have been previously assigned an RI Class III (>3500 to ≤5000 years) and an average RI of c. 4039 years in the NZAFD and NSHM, respectively (Van Dissen et al. 2003; Langridge et al. 2016; Stirling et al. 2012).

It may be reasonable, in this case – with a lack of any further geological data – to conservatively place the Mangaohane Fault in RI Class III (>3500 to ≤5000 years), reflecting an important active tectonic link between the NIDFB and the Taupō Rift. Future reviews of the NSHM may consider the role of the Mangaohane Fault with the Kaweka and Rauoterangi faults as a distinct active fault earthquake source.

FAZs developed for the Mangaohane Fault range in width from 100 m for an accurate: well-defined FAZ to 240 m for an uncertain: uncertain poorly constrained FAZ. FAZs for the Mangaohane Fault are symmetrical in form because we do not know its style of faulting (Figure 5.13).

5.1.11 Kaweka Fault

The Kaweka Fault is an active fault associated with the Kaweka Range in the Rangitikei and Hastings Districts (Litchfield et al. 2014; Langridge et al. 2016). The fault has a mapped length of at least 26 km across both districts (Figure 5.1). In the Rangitikei District, the ENE-striking fault is mapped over a length of c. 6 km to the north of the Napier-Taihape Road, in remote country near Kuripapango (Figure 5.14). The style of faulting on the Kaweka Fault is not well known, but it assumed to accommodate both dextral strike-slip (dominant), with a rate of 1 ± 0.5 mm/yr, and normal motion, resulting in uplift of the Kaweka Range.

The Kaweka Fault has been designated as a RI Class III fault, i.e. RI from >3500 to ≤5000 years (Van Dissen et al. 2003). The slip rate shown above is more typical of a RI Class II fault in New Zealand (Table 3.1). However, with no new data available, this is the range that we use to define the RI Class for the Kaweka Fault in this study.

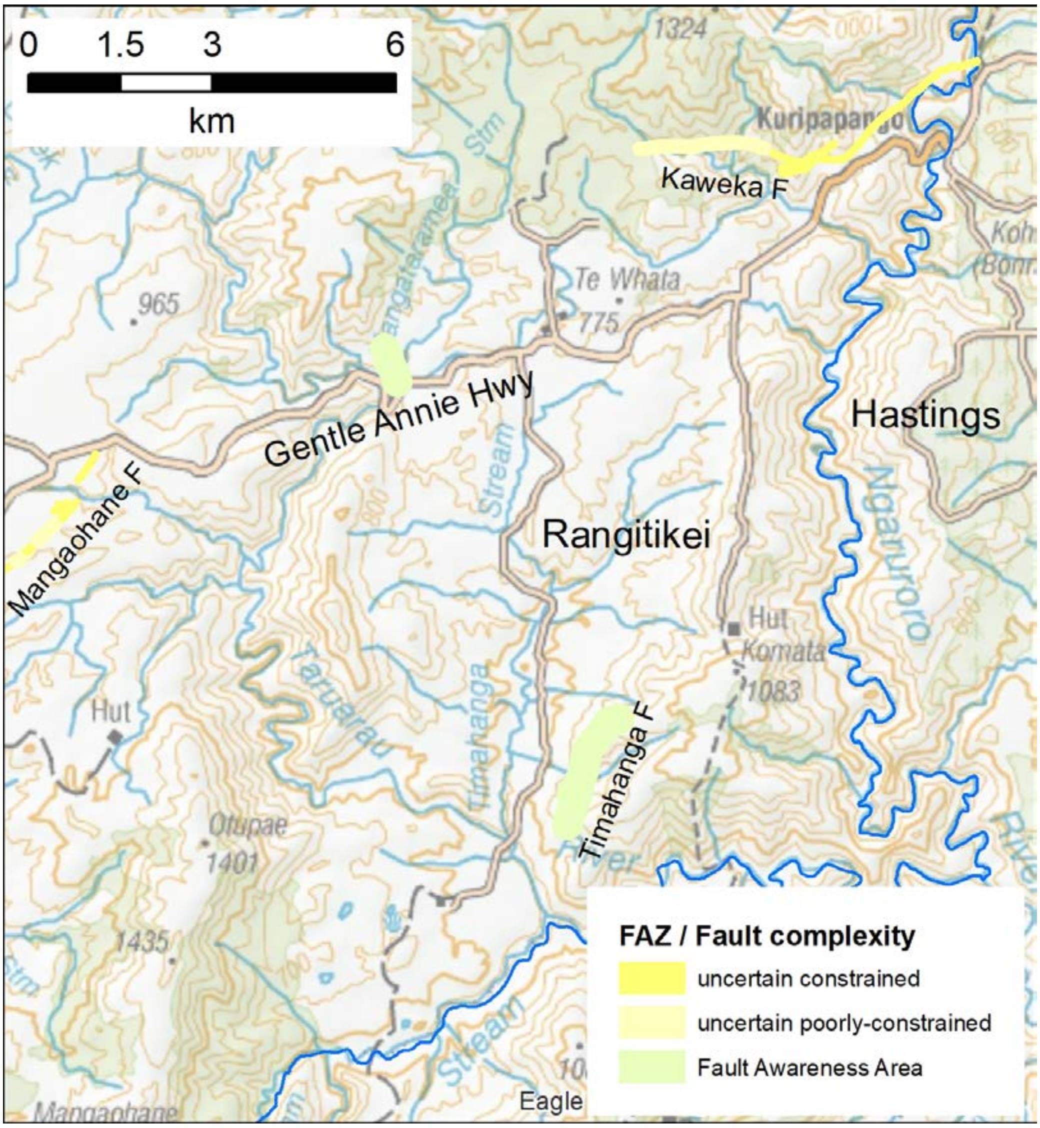

Figure 5.14 Fault avoidance zone buffers for the Kaweka and Timahanga faults and part of the Mangaohane Fault in the north-eastern part of Rangitikei District. A fault awareness area is provided for an unnamed fault trace along the Napier–Taihape (Gentle Annie) Road.

FAZs developed for the Kaweka Fault range in width from 140 m for an approximate: uncertain constrained FAZ to 240 m for an uncertain: uncertain poorly constrained FAZ (Figure 5.14).

5.1.12 Other Faults

This section describes all other minor named and unnamed active faults in the Rangitikei District. Named faults and traces (c.f. unnamed faults) typically have a mappable length of 2 km or more and are named from a nearby geographical feature.

The Swinburne Bush fault (new) is a short (2.4-km-long) NNE-striking active fault mapped on the 1-m DSM at the northern boundary of the Rangitikei District (Figure 5.12). The fault probably continues into the Ruapehu District and may have a total length of c. 5.5 km.

The active trace of the Swinburne Bush fault was formerly recognised on QMAP geological maps and as an unnamed active trace in the NZAFD (Lee et al. 2011; Langridge et al. 2016). QMAP recognises the fault as having a normal dip-slip sense of movement (Heron 2018). Mappable traces take the form of a normal fault with an uphill-facing, down-to-the-west sense of movement at the east edge of the Three Kings Range. There is no geological information with which to define the recurrence interval of the Swinburne Bush fault. Therefore, in this study a FAA is applied to it, which recognises the presence of the fault and the need to discern more about its activity in future.

The Erewhon fault (new) is an active NNE-striking fault recognised to the west of the Mangaohane Fault near the Napier–Taihape Road at Erewhon Station (Figure 5.12). The mapped length of the fault in this study is at least c. 2.3 km. Mappable traces take the form of a normal fault with east-facing scarps across Matemateaonga Formation bedrock. There is no geological information with which to define the recurrence interval of the Erewhon fault. Therefore, in this study a FAA is applied to it, which recognises the presence of the fault and the need to discern more about its activity in future.

The Timahanga fault (new) is an active NNE-striking fault identified to the east of the Mangaohane Fault within the Ruahine Ranges in the Timahanga Stream catchment (Figure 5.14). The mapped length of the fault in this study is c. 2 km. Mappable traces take the form of a normal fault with an uphill-facing, down-to-the-east sense of movement at the west edge of the Kaikomata Range. There is no geological information with which to define the recurrence interval of the Timahanga fault. Therefore, in this study a FAA is applied to it, which recognises the presence of the fault and the need to discern more about its activity in future.

The Dirty Spur fault is an active northeast-striking fault recognised at the south-eastern edge of Rangitikei District and named after Dirty Spur (Figure 5.15; Langridge and Morgenstern 2019). The mapped length of the fault is c. 1.2 km with a down-to-the-northwest sense of movement. Mappable traces take the form of a normal fault (or a ridge rent) located near Pourangaki hill. Langridge and Morgenstern (2019) provided a preliminary RI Class IV for the Dirty Spur fault (>5000 to ≤10,000 years) based on its proximity to the Ruahine Fault and because it has mappable fault traces across alpine ridgelines in the Ruahine Range. FAZs developed for the Dirty Spur fault range in width from 100 m for an accurate: well-defined FAZ to 240 m for an uncertain: uncertain constrained FAZ (Figure 5.15).

The Taumataomekura fault is an active NNE-striking fault recognised at the eastern edge of Rangitikei District and named after a peak at the Manawatū-Rangitikei district boundary (Figure 5.15; Langridge and Morgenstern 2019). The mapped length of the fault is c. 2.4 km, which is mostly identified within the Manawatū District. Mappable traces take the form of a dextral (to normal) fault or fault zone cutting across steep hillslopes in the Ruahine Range. Langridge and Morgenstern (2019) provided a preliminary RI Class IV for the Taumataomekura fault (>5000 to ≤10,000 years) based on its proximity to the Ruahine Fault and because it has mappable fault traces across alpine ridgelines in the Ruahine Range.

FAZs developed for the Taumataomekura fault range in width from 100 m for an accurate: well-defined FAZ to 240 m for an uncertain: uncertain poorly constrained FAZ (Figure 5.15).

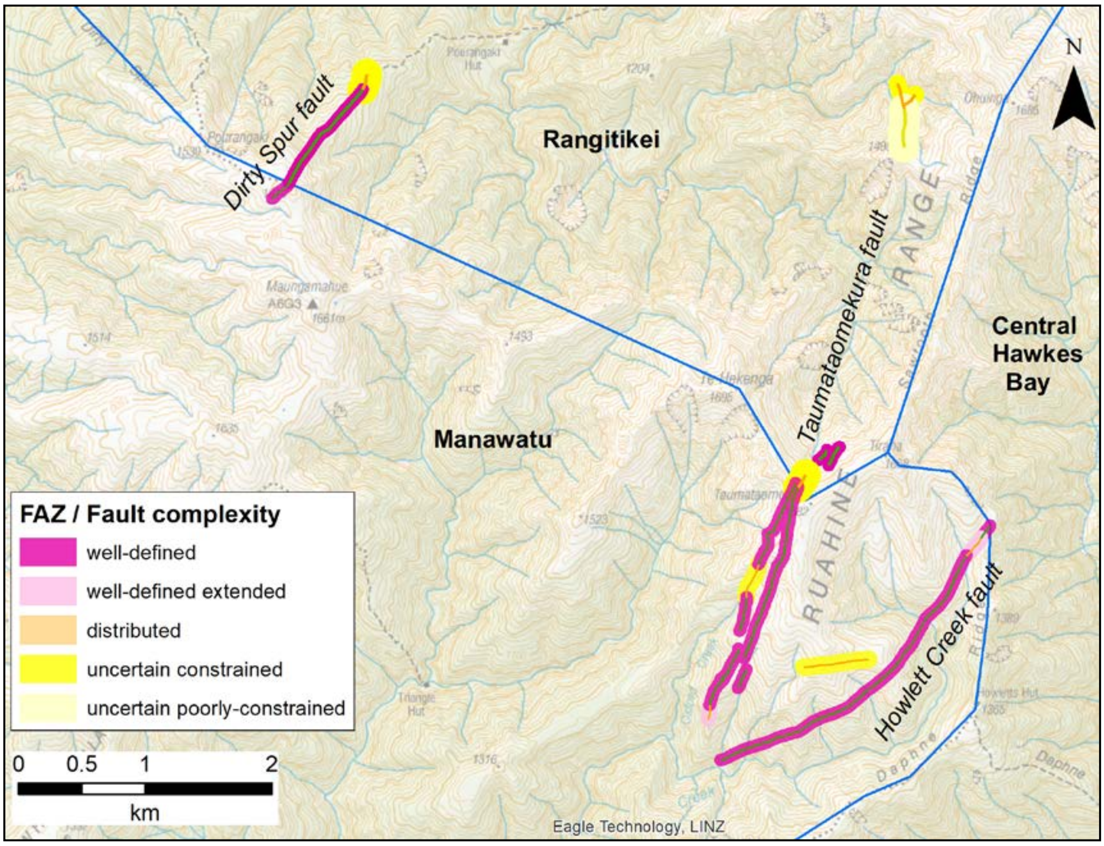

Figure 5.15 Active fault traces (and fault avoidance zones) mapped in the eastern boundary area between the Rangitikei and the Manawatū districts in the Ruahine Ranges area.

There are other unnamed active fault traces identified and mapped within the wider part of the north-eastern Rangitikei District (Figure 5.1). These traces are short (<2 km long), discontinuous and do not connect with other known faults. These all have no known recurrence interval information. We treat these faults in the same way as we have the Swinburne Bush, Erewhon and Timahanga faults, which is to apply a FAA to them. This recognises the presence of active fault traces and the need to discern more about their activity in future. In addition, we have reviewed active fault traces shown across the district in the NZAFD (Langridge et al. 2016) and in the high-resolution GNS active faults dataset (AF.Traces). In some cases, we have adjusted the mapped trace based on viewing the 1-m DSM and, in other cases, we have failed to find reasonable evidence for an active fault trace using the 1-m DSM, in which case those traces are not included here.

5.2 Possibly 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; (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 are mapped as 'possibly 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. Therefore, these possibly active faults will not be included in the online NZAFD at this time. 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 prove 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.

Only four ‘possibly active’ fault traces have been mapped as part of this study. These all occur in the northern part of the Rangitikei District. Two traces were mapped c. 2.2 km west of the Erewhon fault (Figure 5.12). Another trace was mapped between the Mangaohane Fault and the Kaweka Fault (Figure 5.14). A fourth possibly active fault trace is located c. 250 m from the mapped axial trace of the Utiku Anticline in the Kaiwhata River valley (Figure 5.1).

5.3 Active Folds

Active folds are an important indicator of active tectonic deformation and can be mapped where suitable geological surfaces exist. The following paragraphs describe the active Marton and Utiku anticlines within the Rangitikei District (Figures 5.1 and 5.2). No other active folds have been defined on QMAP geological maps for the Rangitikei District (Townsend et al. 2008). In this report, FAZs are not developed for active folds because associated deformation is too broadly distributed to be considered a life-safety hazard for buildings.

5.3.1 Marton Anticline

The Marton Anticline was defined by Te Punga (1957) as one of the active anticlines of the southern North Island. The Marton Anticline is a broad subdued fold, shown by a sinuous fold axis on QMAP geological maps (Heron 2018; Townsend et al. 2008). The NSHM shows the anticline (MartonAnt) as an active fault earthquake source extending from the Rangitikei District coast to the Marton area (Jackson et al. 1998; Stirling et al. 2012).

In this study, we have remapped the axial trace of the Marton Anticline using the LiDAR and 1-m DSM to profile deformed surfaces related to the anticline (Figure 5.2). We have profiled the DEMs and DSM every 500–1500 m along the axis, picking either the highest point on the profile or the area where the drainage changes direction, which we take to represent the axis of the fold.

While sinuous, the c. 26.5-km-long axial trace broadly follows the shape of the surface traces of the NNE-striking Leedstown Fault, especially in the southwest. From this, we infer that the Marton Anticline and Leedstown Fault are related, i.e. the Marton Anticline is an expression of the east-verging faulting on the west-dipping, reverse-slip Leedstown Fault. Between Lake Alice and Marton, the axis of the anticline bends to the north and around to the west of Marton. The northern end of the anticline is on-trend with the GRFZ, which is identified in this report as an active zone of extension and is possibly also related to activity on the Leedstown Fault. In Section 5.1 of this report, we describe how other mapped zones of faulting may also be related to a wider ‘Leedstown Fault System’ (or family of faults) that includes compressional tectonic features, e.g. the Leedstown and Putorino faults and the Marton Anticline and extensional features. e.g. the Marton Fault Zone, Jeffersons Line Fault and Mt Curl Road Fault Zone.

The NSHM shows MartonAnt as a 25-km-long buried active fault earthquake source with an inferred slip rate of 0.2 mm/yr and a calculated magnitude Mw 6.8 and recurrence interval of c. 8700 yr. In comparison, the Leedstown Fault (and similarly other nearby faults) has been defined in this report with a RI Class IV, based on vertical slip rates of 0.1–0.25 mm/yr. Future iterations of the NSHM could therefore treat the Leedstown Fault as an active fault earthquake source (as opposed to using MartonAnt).

5.3.2 Utiku Anticline

The Utiku Anticline (Figure 5.1) is shown as an active fold on QMAP geological maps (Heron 2018; Lee et al. 2011). The Utiku Anticline is mapped as a c. 17.5-km-long anticlinal fold axis in the northern Manawatū District from near Mangaweka to east of Taihape in the Rangitikei District and is broadly associated with large landslide complexes formed in Pliocene Tangahoe Mudstone (Lee et al. 2011). Active deformation related to the Utiku Anticline is not easy to characterise due to the relief created by the rivers and bedrock across this part of the Rangitikei District. Therefore, in this study we have not revised the mapped axial trace of the Utiku Anticline shown by Lee et al. (2011), which is based mainly on bedrock structural measurements. A single, short fault trace has been recognised north of Kawhatau Valley Rd on the DSM (Figure 5.16). The Utiku Anticline is mapped c. 3 km west of the Rauoterangi Fault, a major bedrock fault in the southern North Island (Langridge and Morgenstern 2019). The Utiku Anticline is not an active fault earthquake source in the NSHM (Stirling et al. 2012) and has no known parameters with which to define its activity. In future, the activity of this structure should be reviewed more carefully.

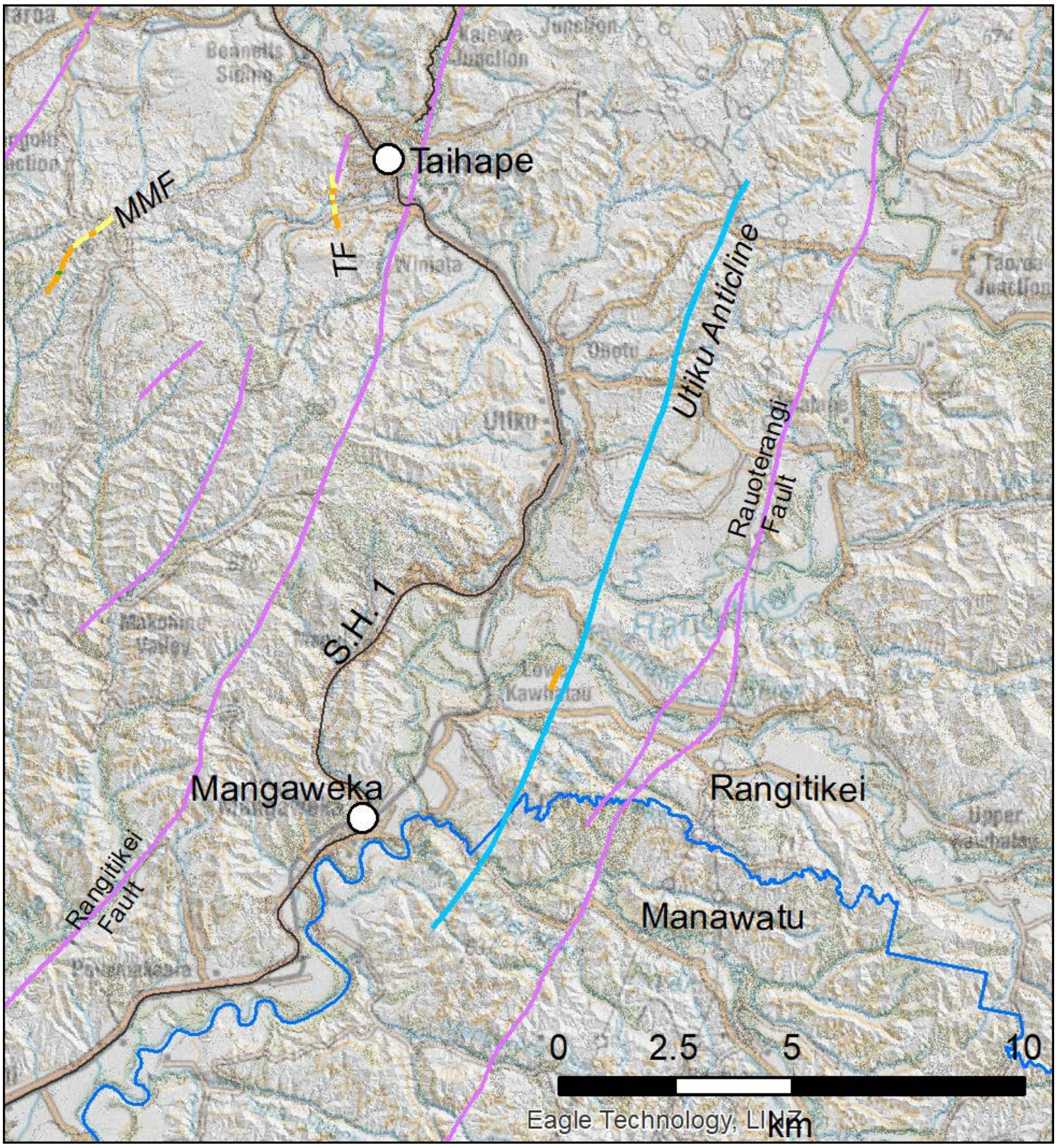

Figure 5.16 Faults and folds of the Utiku area, highlighting the mapped axial trace of the active Utiku Anticline (blue) and bedrock faults from QMAP (purple; Lee et al. 2011). Active faults mapped in this study including the Taihape (TF) and Mt Maire (MMF) faults are shown by orange and yellow linework.

5.4 Summary of Active Faults with Fault Avoidance Zones in Rangitikei District

Table 5.1 summarises the recurrence interval data that we have defined for active faults in the Rangitikei District. For those that are active, and have also been assigned an RI Class, we have defined FAZs. For those with no information for estimating a recurrence interval from geologic data, or for which there is ambiguous evidence of activity, we do not define a FAZ or RI Class (see Section 5.2). In addition, because co-seismic deformation associated with folding is broadly distributed (i.e. low strain, as opposed to co-seismic surface rupture deformation from faulting) and does not typically pose a collapse hazard for engineered structures, we do not provide FAZs or recurrence interval information for active folds.

Table 5.1 Fault recurrence interval information for faults within the Rangitikei District.

Fault	RI Class	RI Range (Years)	RI Class Confidence	Data Source
Snowgrass Fault	II	>2000 to ≤3500	M	1, 7
Kaweka Fault	III	>3500 to ≤5000	M	2–4
Mangaohane Fault	III	>3500 to ≤5000	M	4, 5, 7
Leedstown Fault	IV	>5000 to ≤10,000	M	2–4
Putorino Fault	IV	>5000 to ≤10,000	M	4, 6
Marton Fault Zone	IV	>5000 to ≤10,000	L	7
Jeffersons Line Fault	IV	>5000 to ≤10,000	M	7
Galpins Rd and Mt Curl Fault Zones	IV	>5000 to ≤10,000	M	5, 7
Taihape Fault	IV	>5000 to ≤10,000	M	4, 7
Dirty Spur fault	IV	>5000 to ≤10,000	M	6
Taumataomekura fault	IV	>5000 to ≤10,000	M	6
Mt Maire fault	-	-	L	5, 7
Swinburne Bush, Erewhon and Timahanga faults	-	-	L	7
Unnamed faults*	-	>5000 to ≤10,000	L	7

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

Sources: 1, Villamor and Berryman (2006a); 2, Van Dissen et al. (2003); 3, Litchfield et al. (2014); 4, NZAFD (https://data.gns.cri.nz/af/) and Langridge et al. (2016); 5, Stirling et al. (2012); 6, Langridge and Morgenstern (2019); 7, this study.

Table 5.1 shows new and updated recurrence interval data for known active faults in the Rangitikei District. Recurrence interval data for many of these faults (particularly the RI Class IV faults) should be considered preliminary, as they are based on landscape-derived slip rate estimates and on comparison to other faults that have a similar expression in the landscape. In the future, geologic studies, including paleoseismic trenching, could be undertaken to improve estimates of recurrence intervals and RI Classes shown here.

6.0 CONCLUSIONS

Active fault mapping has been undertaken for Horizons Regional Council covering the Rangitikei District for the purposes of planning with regards to active faults. A mappable active fault is defined as a geologic fault that has ruptured the ground surface during the last 125,000 years or less. A variety of mapping platforms 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 DSM. Preliminary recurrence interval class information has been provided for several faults, based largely on inferences from geomorphic relationships along the faults and through comparisons with better-studied faults nearby.

In the Rangitikei District, the active faults and fault zones mapped include the Leedstown Fault, Putorino Fault, Jeffersons Line Fault, Marton Fault Zone, Galpins Road Fault Zone, Mt Curl Road Fault Zone, Taihape Fault, Snowgrass Fault, Kaweka Fault and Mangaohane Fault. Several other short active faults – Mt Maire fault, Erewhon fault, Swinburne Bush fault, Timahanga fault, Dirty Spur fault and Taumataomekura fault – are also recognised and mapped. The report also identifies several short unnamed active fault traces.

The preliminary RI Classes defined in this study for the active faults in the Rangitikei District are as follows: Snowgrass Fault (RI Class II; >2000 to ≤3500 years); Kaweka and Mangaohane faults (RI Class III; >3500 to ≤5000 years); all other active faults described here, i.e. the Leedstown, Putorino, Jeffersons Line, Dirty Spur, Taumataomekura and Taihape faults, and the Marton, Galpins Road and Mt Curl Road fault zones, have been assigned a RI Class IV status (RI >5000 to ≤10,000 years). In future, if development is proposed for FAZ areas, then further fault mapping and/or geologic studies could be required to better define the location and RI Class of active faults.

For many of the short and/or unnamed active faults, e.g. the Mt Maire, Erewhon, Swinburne Bush and Timahanga faults, there is not enough geologic data with which to define a recurrence interval class. Therefore, in these cases, FAZ and RI Class have not been defined for them. FAAs have been designed for these features, which recognises that they are probably active, but their level of activity is unknown. FAAs have a total width of 500 m, but 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.

Several RI Class IV active faults and fault zones occur in the vicinity of Marton township and FAZs have been developed for these faults. Appendix 2 provides some examples to assist planners in making resource consent decisions regarding the FAZs in the Marton area.

Two active folds have also been defined within Rangitikei District as part of this study. These are the Marton Anticline and Utiku Anticline. This study does not present FAZs or RI Class information for active folds because the location and associated deformation is anticipated to be too distributed to warrant characterisation for fault avoidance purposes.

The outcomes of fault mapping and FAZ 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.

7.0 RECOMMENDATIONS

We recommend that the FAZs and FAAs developed for the Rangitikei 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 vs. Already Developed/Subdivided) and the BIC intended for the site (see Table A2.1). 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 on some of the active faults described in this report, for example, the Leedstown Fault and related faults in the Marton area.

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9.0 REFERENCES

Alloway BV, Lowe DJ, Barrell DJA, Newnham RM, Almond PC, Augustinus PC, Bertler NAN, Carter L, Litchfield NJ, McGlone MS, et al. 2007. Towards a climate event stratigraphy for New Zealand over the past 30 000 years (NZ-INTIMATE project). *Journal of Quaternary Science*. 22(1):9–35. doi:10.1002/jqs.1079.

Barrell DJA. 2015. General distribution and characteristics of active faults and folds in the Kaikoura District, North Canterbury. Dunedin (NZ): GNS Science. 59 p. Consultancy Report 2014/210. Prepared for: Environment Canterbury.

Barrell DJA, Andersen BG, Denton GH. 2011. Glacial geomorphology of the central South Island, New Zealand. Lower Hutt (NZ): GNS Science. 81 p. + map (5 sheets) + legend (1 sheet). (GNS Science monograph; 27).

Barrell DJA, Jack H, Gadsby M. 2015. Guidelines for using regional-scale earthquake fault information in Canterbury. Dunedin (NZ): GNS Science. 30 p. Consultancy Report 2014/211. Prepared for: Canterbury Regional Council (Environment Canterbury).

Barrell DJA, Townsend DB. 2012. General distribution and characteristics of active faults and folds in the Hurunui District, North Canterbury. Dunedin (NZ): GNS Science. 30 p. + 1 CD. Consultancy Report 2012/113. Prepared for: Environment Canterbury.

Beanland S, Berryman KR, Blick GH. 1989. Geological investigations of the 1987 Edgecumbe earthquake, New Zealand. *New Zealand Journal of Geology and Geophysics*. 32(1):73–91. doi:10.1080/00288306.1989.10421390.

Beanland S, Haines J. 1998. The kinematics of active deformation in the North Island, New Zealand, determined from geological strain rates. *New Zealand Journal of Geology and Geophysics*. 41(4):311–323. doi:10.1080/00288306.1998.9514813.

Begg JG, Johnston MR. 2000. Geology of the Wellington area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 64 p. + 1 sheet, scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 10).

Begg JG, Villamor P, Zachariasen J, Litchfield NJ. 2001. Paleoseismic assessment of the active Masterton and Carterton faults, Wairarapa. Lower Hutt (NZ). Institute of Geological & Nuclear Sciences Limited. 32 p. Consultancy Report 2001/70. Prepared for: Wairarapa Engineering Lifelines Association.

Berryman K, Beanland S. 1991. Variation in fault behaviour in different tectonic provinces of New Zealand. *Journal of Structural Geology*. 13(2):177–189. doi:10.1016/0191-8141(91)90065-Q.

Cashman S, Kelsey H, Erdman C, Cutten H, Berryman K. 1992. Strain partitioning between structural domains in the forearc of the Hikurangi Subduction Zone, New Zealand. *Tectonics*. 11(2):242–257. doi:10.1029/91TC02363.

Clark KJ, Ries WF. 2016. Mapping of active faults and fault avoidance zones for Wairoa District: 2016 update. Lower Hutt (NZ): GNS Science. 35 p. + 1 DVD. Consultancy Report 2016/133. Prepared for: Hawke's Bay Regional Council.

Clement A, Fuller I. 2018. Influence of system controls on the Late Quaternary geomorphic evolution of a rapidly-infilled incised-valley system: the lower Manawatu valley, North Island New Zealand. *Geomorphology*. 303:13–29. doi:10.1016/j.geomorph.2017.11.016.

Clement A, Fuller I, Sloss C. 2017. Facies architecture, morphostratigraphy, and sedimentary evolution of a rapidly-infilled Holocene incised-valley estuary: the lower Manawatu valley, North Island New Zealand. *Marine Geology*. 390:214–233. doi:10.1016/j.margeo.2017.06.011.

Cowie JD. 1963. Dune-building phases in the Manawatu district, New Zealand. *New Zealand Journal of Geology and Geophysics*. 6(2):268–280. doi:10.1080/00288306.1963.10420083.

Downes GL. 1995. Atlas of isoseismal maps of New Zealand earthquakes. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 304 p. (Institute of Geological & Nuclear Sciences monograph; 11).

Downes GL, Dowrick DJ. 2014. Atlas of isoseismal maps of New Zealand earthquakes: 1843–2003. 2nd ed. (revised). Lower Hutt (NZ): GNS Science. 1 DVD. (GNS Science monograph; 25).

Dowrick DJ. 1996. The Modified Mercalli earthquake intensity scale. *Bulletin of the New Zealand Society for Earthquake Engineering*. 29(2):92–106. doi:10.5459/bnzsee.29.2.92-106.

Grapes R, Little T, Downes G. 1998. Rupturing of the Awatere Fault during the 1848 October 16 Marlborough earthquake, New Zealand: historical and present day evidence. *New Zealand Journal of Geology and Geophysics*. 41(4):387–399. doi:10.1080/00288306.1998.9514818.

Grouden P. 1966. Early New Zealand earthquakes. Wellington (NZ): Seismological Observatory.

Heron DW, custodian. 2018. Geological map of New Zealand [map]. 2nd ed. Lower Hutt (NZ): GNS Science. 1 CD, scale 1:250,000. (GNS Science 1:250,000 geological map; 1).

Hull AG. 1990. Tectonics of the 1931 Hawke's Bay earthquake. *New Zealand Journal of Geology and Geophysics*. 33(2):309–320. doi:10.1080/00288306.1990.10425689.

Jackson J, van Dissen R, Berryman K. 1998. Tilting of active folds and faults in the Manawatu region, New Zealand: evidence from surface drainage patterns. *New Zealand Journal of Geology and Geophysics*. 41(4):377–385. doi:10.1080/00288306.1998.9514817.

Kelsey HM, Cashman SM, Beanland S, Berryman KR. 1995. Structural evolution along the inner forearc of the obliquely convergent Hikurangi margin, New Zealand. *Tectonics*. 14(1):1–18. doi:10.1029/94TC01506.

Kelson KI, Kang K-H, Page WD, Lee C-T, Cluff LS. 2001. Representative styles of deformation along the Chelungpu Fault from the 1999 Chi-Chi (Taiwan) Earthquake: geomorphic characteristics and responses of man-made structures. *Bulletin of the Seismological Society of America*. 91(5):930–952. doi:10.1785/0120000741.

Kerr J, Nathan S, Van Dissen RJ, Webb P, Brunsdon D, King AB. 2003. Planning for development of land on or close to active faults: a guideline to assist resource management planners in New Zealand. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 71 p. Client Report 2002/124. Prepared for: Ministry for the Environment.

King AB, Brunsdon DR, Shephard RB, Kerr JE, Van Dissen RJ. 2003. Building adjacent to active faults: a risk-based approach. In: *Proceedings of the 2003 Pacific Conference on Earthquake Engineering*. 2003 Feb 13–15; Christchurch, New Zealand. Wellington (NZ): New Zealand Society for Earthquake Engineering. 8 p. Paper 158.

Langridge RM, Berryman KR, Van Dissen RJ. 2007. Late Holocene paleoseismicity of the Pahiatua section of the Wellington Fault, New Zealand. *New Zealand Journal of Geology and Geophysics*. 50(3):205–226. doi:10.1080/00288300709509832.

Langridge RM, Morgenstern R. 2018. Active fault mapping and fault avoidance zones for Horowhenua District and Palmerston North City. Lower Hutt (NZ). GNS Science. 72 p. Consultancy Report 2018/75. Prepared for: Horizons Regional Council.

Langridge RM, Morgenstern R. 2019. Active fault mapping and fault avoidance zones for the Manawatū District. Lower Hutt (NZ): GNS Science. 69 p. Consultancy Report 2019/123. Prepared for: Horizons Regional Council.

Langridge RM, Ries W. 2010. Mapping and fault rupture avoidance zonation for the Alpine Fault in the West Coast region. Lower Hutt (NZ): GNS Science. 40 p. + 1 CD. Consultancy Report 2009/18. Prepared for: West Coast Regional Council.

Langridge RM, Ries WF. 2014. Active fault mapping and fault avoidance zones for Central Hawke’s Bay District: 2013 update. Lower Hutt (NZ): GNS Science. 50 p. + 1 CD. Consultancy Report 2013/151. Prepared for: Hawke's Bay Regional Council.

Langridge RM, Ries WF. 2015. Active fault mapping and fault avoidance zones for Hastings District and environs. Lower Hutt (NZ): GNS Science. 50 p. + 1 DVD. Consultancy Report 2015/112. Prepared for: Hawke's Bay Regional Council.

Langridge RM, Ries WF. 2016. Active fault mapping and fault avoidance zone for the Wairau Fault, Marlborough District. Lower Hutt (NZ): GNS Science 49 p. + 1 DVD. Consultancy Report 2016/25. Prepared for: Marlborough District Council.

Langridge RM, Ries WF, Farrier T, Barth NC, Khajavi N, De Pascale GP. 2014. Developing sub 5-m LiDAR DEMs for forested sections of the Alpine and Hope faults, South Island, New Zealand: implications for structural interpretations. *Journal of Structural Geology*. 64:53–66. doi:10.1016/j.jsg.2013.11.007.

Langridge RM, Ries WF, Litchfield NJ, Villamor P, Van Dissen RJ, Barrell DJA, Rattenbury MS, Heron DW, Haubrock S, Townsend DB, et al. 2016. The New Zealand Active Faults Database. *New Zealand Journal of Geology and Geophysics*. 59(1):86–96. doi:10.1080/00288306.2015.1112818.

Langridge R, Rowland J, Villamor P, Mountjoy J, Townsend D, Nissen E, Madugo C, Ries W, Gasston C, Canva A, et al. 2018. Coseismic rupture and preliminary slip estimates for the Papatea Fault and its role in the 2016 Mw 7.8 Kaikōura, New Zealand, earthquake. *Bulletin of the Seismological Society of America*. 108(3B):1596–1622. doi:10.1785/0120170336.

Langridge RM, Villamor P, Basili R. 2006. Earthquake fault trace survey: Central Hawke's Bay District. Lower Hutt (NZ): GNS Science. 31 p. Consultancy Report 2006/98. Prepared for: Hawke's Bay Regional Council.

Langridge RM, Zajac A, Ries W. 2011. Fault avoidance zone mapping for Wairoa District, Napier City and surrounds. Lower Hutt (NZ): GNS Science. 35 p. + 1 CD. Consultancy Report 2010/105. Prepared for: Hawke’s Bay Regional Council.

Lee JM, Bland KJ, Townsend DB, Kamp PJJ, compilers. 2011. Geology of the Hawke's Bay area [map]. Lower Hutt (NZ): GNS Science. 93 p. + 1 folded map, scale 1:250,000. (GNS Science 1:250,000 geological map; 8).

Litchfield N, Berryman K. 2005. Correlation of fluvial terraces within the Hikurangi Margin, New Zealand: implications for climate and baselevel controls. *Geomorphology*. 68(3–4):291–313. doi:10.1016/j.geomorph.2004.12.001.

Litchfield NJ, Van Dissen RJ. 2014. Porirua district fault trace study. Lower Hutt (NZ): GNS Science. 53 p. Consultancy Report 2014/213. Prepared for: Greater Wellington Regional Council; Porirua Council.

Litchfield NJ, Van Dissen R, Sutherland R, Barnes PM, Cox SC, Norris R, Beavan RJ, Langridge R, Villamor P, Berryman K, et al. 2014. A model of active faulting in New Zealand. *New Zealand Journal of Geology and Geophysics*. 57(1):32–56. doi:10.1080/00288306.2013.854256.

Massey CI. 2010. The dynamics of reactivated landslides: Utiku and Taihape, North Island, New Zealand [PhD Thesis]. Durham University. 338 p.

Meigs A. 2013. Active tectonics and the LiDAR revolution. *Lithosphere*. 5:226–229. doi:10.1130/RF.L004.1.

Milne JGD. 1973. Maps and sections of river terraces in the Rangitikei Basin, North Island, New Zealand. Wellington (NZ): Department of Scientific and Industrial Research. 4 sheets. (NZ Soil Survey report; 4).

Nodder S, Lamarche G, Proust J-N, Stirling M. 2007. Characterizing earthquake recurrence parameters for offshore faults in the low-strain, compressional Kapiti-Manawatu Fault System, New Zealand. *Journal of Geophysical Research: Solid Earth*. 112(B12):B12102. doi:10.1029/2007JB005019.

Schermer ER, Van Dissen R, Berryman KR, Kelsey HM, Cashman SM. 2004. Active faults, paleoseismology, and historical fault rupture in northern Wairarapa, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*. 47(1):101–122. doi:10.1080/00288306.2004.9515040.

Stevens GR. 1990. Rugged landscape: the geology of central New Zealand, including Wellington, Wairarapa, Manawatu, and the Marlborough Sounds. Wellington (NZ): Department of Scientific and Industrial Research. 286 p. (DSIR information series; 169).

Stirling M, McVerry G, Gerstenberger M, Litchfield N, Dissen R, Berryman K, Barnes P, Wallace L, Villamor P, Langridge R, et al. 2012. National Seismic Hazard Model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America*. 102(4):1514–1542. doi:10.1785/0120110170.

Stirling M, Wesnousky S, Berryman K. 1998. Probabilistic seismic hazard analysis of New Zealand. *New Zealand Journal of Geology and Geophysics*. 41(4):355–375. doi:10.1080/00288306.1998.9514816.

Te Punga MT. 1957. Live anticlines in western Wellington. *New Zealand Journal of Science and Technology*. B38:433–446.

Townsend DB, Begg JG, Villamor P, Lukovic B. 2002. Late Quaternary displacement of the Mokonui Fault, Wairarapa, New Zealand: a preliminary assessment of earthquake generating potential. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 30 p. + 2 maps. Client Report 2002/58. Prepared for: Wairarapa Engineering Lifelines Association.

Townsend D, Nicol A, Mouslopoulou V, Begg JG, Beetham RD, Clark D, Giba M, Heron D, Lukovic B, McPherson A, et al. 2010. Palaeoearthquake histories across a normal fault system in the southwest Taranaki Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics*. 53(4):375–394. doi:10.1080/00288306.2010.526547.

Townsend DB, Vonk A, Kamp PJJ, compilers. 2008. Geology of the Taranaki area [map]. Lower Hutt (NZ): GNS Science. 77 p. + 1 folded map, scale 1:250,000. (GNS Science 1:250,000 geological map; 7).

URS Corporation. 2006. Wairarapa fault areas. San Francisco (CA): URS Corporation. https://mapping1.gw.govt.nz/arcgis/rest/services/Hazards/Earthquake_Related_Hazards/MapServer/13.

Van Dissen RJ, Barrell DJA, Litchfield NJ, Villamor P, Quigley M, King AB, Furlong K, Begg JG, Townsend DB, Mackenzie H, et al. 2011. Surface rupture displacement on the Greendale Fault during the M_w 7.1 Darfield (Canterbury) earthquake, New Zealand, and its impact on man-made structures. In: *Ninth Pacific Conference on Earthquake Engineering: building an earthquake resilient society, April 14–16, 2011, University of Auckland, Auckland, New Zealand*. Auckland (NZ): 9PCEE. 8 p. Paper 186.

Van Dissen RJ, Berryman KR, Webb TH, Stirling MW, Villamor P, Wood PR, Nathan S, Nicol A, Begg JG, Barrell DJA, et al. 2003. An interim classification of New Zealand's active faults for the mitigation of surface rupture hazard. In: *Proceedings of the 2003 Pacific Conference on Earthquake Engineering*. 2003 Feb 13–15; Christchurch, New Zealand. Wellington (NZ): New Zealand Society for Earthquake Engineering. 8 p. Paper 155.

Van Dissen RJ, Heron DW. 2003. Earthquake Fault Trace Survey, Kapiti Coast District. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 45 p. Client Report 2003/77. Prepared for: Kāpiti Coast District Council.

Van Dissen RJ, Heron DW, Hinton S, Guerin A. 2004. Mapping active faults and mitigating surface rupture hazard in the Kapiti Coast District, New Zealand. In: Gregory G, editor. *Getting the message across and moving ahead: New Zealand Society for Earthquake Engineering Conference*. 2004 Mar 19–21, 2004; Rotorua (NZ). Wellington (NZ): New Zealand Society for Earthquake Engineering. 9 p. Paper 21.

Van Dissen RJ, Stahl T, King A, Pettinga J, R., Fenton C, Little TA, Litchfield NJ, Stirling MW, Langridge RM, Nicol A, et al. 2019. Impacts of surface fault rupture on residential structures during the 2016 Mw 7.8 Kaikōura earthquake, New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering*. 52(1):1–22. doi:10.5459/bnzsee.52.1.1-22.

Van Dissen R, Yeats RS. 1991. Hope fault, Jordan thrust, and uplift of the Seaward Kaikoura Range, New Zealand. *Geology*. 19(4):393–396. doi:10.1130/0091-7613(1991)019<0393:HFJTAU>2.3.CO;2.

Villamor P, Berryman KR. 2006a. Evolution of the southern termination of the Taupo Rift, New Zealand. *New Zealand Journal of Geology and Geophysics*. 49(1):23–37. doi:10.1080/00288306.2006.9515145.

Villamor P, Berryman KR. 2006b. Late Quaternary geometry and kinematics of faults at the southern termination of the Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics*. 49(1):1–21. doi:10.1080/00288306.2006.9515144.

Villamor P, Berryman KR, Ellis SM, Schreurs G, Wallace LM, Leonard GS, Langridge RM, Ries WF. 2017. Rapid evolution of subduction-related continental intraarc rifts: the Taupo Rift, New Zealand. *Tectonics*. 36(10):2250–2272. doi:10.1002/2017tc004715.

Villamor P, Litchfield NJ, Barrell DJA, van Dissen RJ, Hornblow S, Quigley M, Levick S, Ries W, Duffy B, Begg JG, et al. 2012. Map of the 2010 Greendale Fault surface rupture, Canterbury, New Zealand: application to land use planning. *New Zealand Journal of Geology and Geophysics*. 55(3):223–230. doi:10.1080/00288306.2012.680473.

Villamor P, Ries W, Zajac A. 2010. Rotorua District Council hazard studies: active fault hazards. Lower Hutt (NZ): GNS Science. 28 p. Consultancy Report 2010/182. Prepared for: Rotorua District Council.

Wallace LM, Beavan J, McCaffrey R, Darby D. 2004. Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. *Journal of Geophysical Research: Solid Earth*. 109(B12):B12406. doi:10.1029/2004JB003241.

Zachariasen J, Villamor P, Lee JM, Lukovic B, Begg JG. 2000. Late Quaternary faulting of the Masterton and Carterton faults, Wairarapa, New Zealand. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 36 p. Client Report 2000/71. Prepared for: Wairarapa Engineering Lifelines Association.

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.

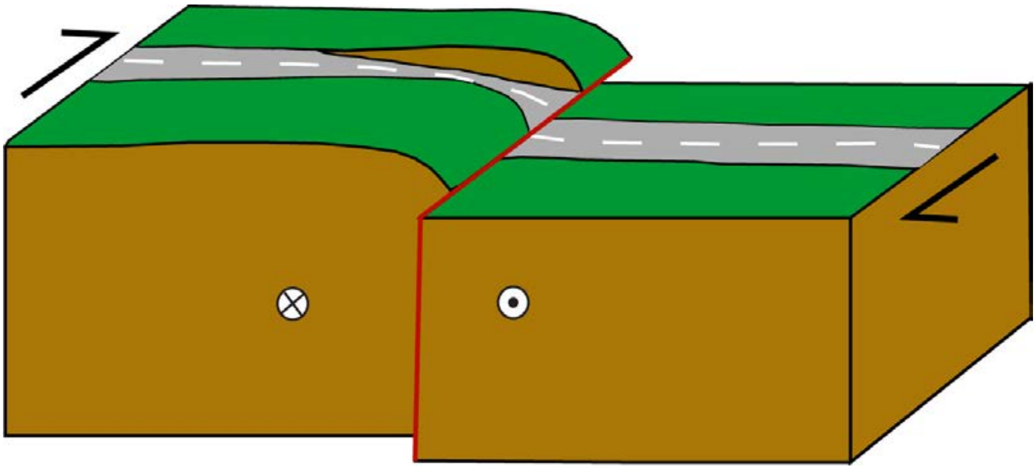

Figure A1.1 Block model of a strike-slip fault (red line). This is a right-lateral (dextral) fault, as shown by the black arrows and by the sense of movement across the two blocks and a separation towards the right across the road. A small amount of vertical movement is also implied by the mappable fault 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, Kaweka and Ruahine faults (Figure 1.1). Some important active left-lateral strike-slip faults in New Zealand include the Papatea Fault in Kaikōura, which ruptured in the 2016 Kaikōura earthquake, and the Mangataura Fault, located east of the Mohaka Fault in inland Hawke's Bay (Langridge and Ries 2014; Langridge et al. 2018).

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).

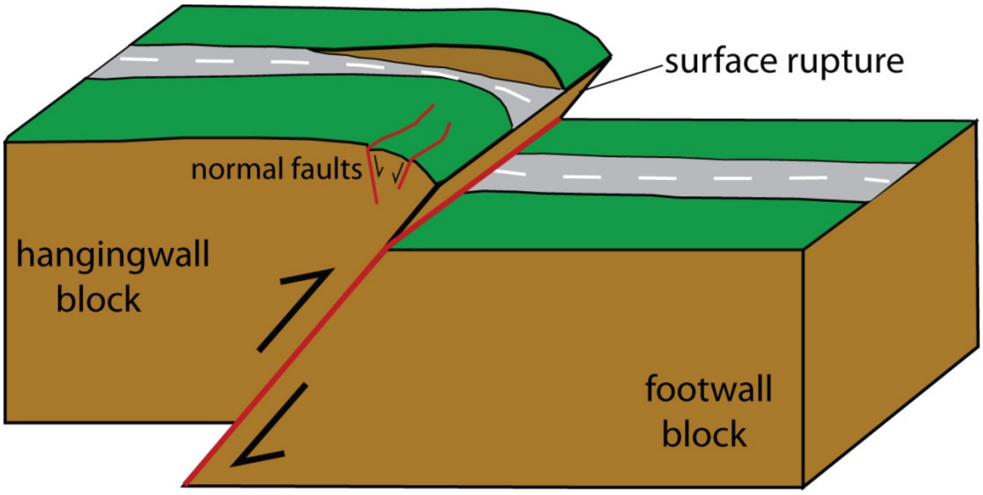

Figure A1.2 Block model of a reverse dip-slip fault that has recently ruptured. Relative movement between the blocks is vertical and along the dip direction of the fault plane. In this case, the hanging-wall block has been pushed up and over the footwall block. Folding (bending) and normal faulting are 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 (described below). Examples of these include the Leedstown, Himatangi and Rauoterangi faults and the Pohangina Anticline (Figure 5.1). A common feature of the tectonics in the Horizons Region are these sub-parallel, typically east-directed sheets of reverse and thrust[7] faults that occur in the upper crust above the plate interface, i.e. within the thin upper sliver of the Australian Plate overlying the Hikurangi subduction zone in the eastern North Island (Cashman et al. 1992; Kelsey et al. 1995). Reverse faults have also been mapped off the west coast of the North Island by NIWA (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).

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 this extension here are probably related to a combination of magma injection into, and inflation of, the crust within the TVZ; gravitational collapse of the crust in the central North Island; and oblique plate boundary extension related to translation of the eastern North Island (Beanland and Haines 1998; Wallace et al. 2004).

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, the Marton Fault Zone (Section 5.1.3).

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

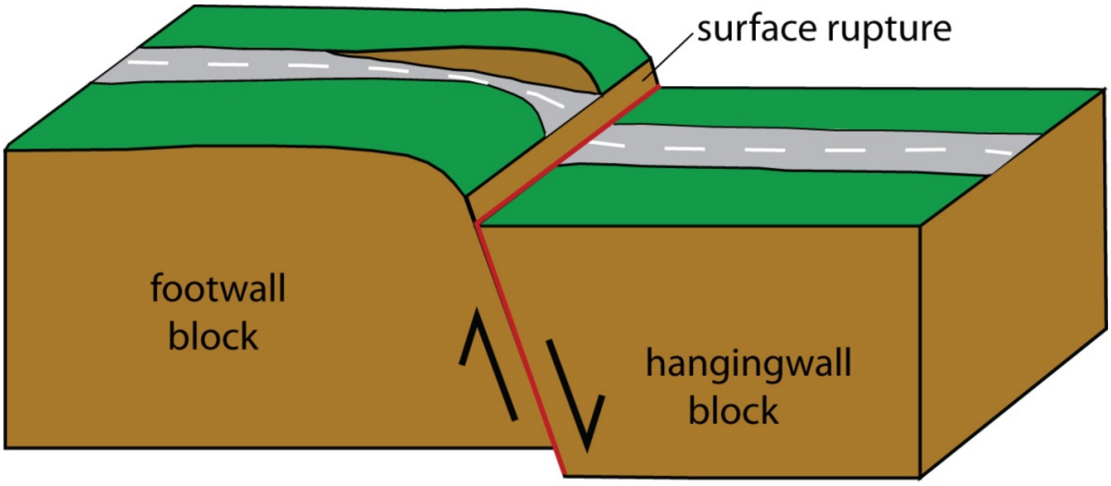

Figure A1.3 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

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 meters of sinistral slip was exceeded by the reverse component of fault motion.

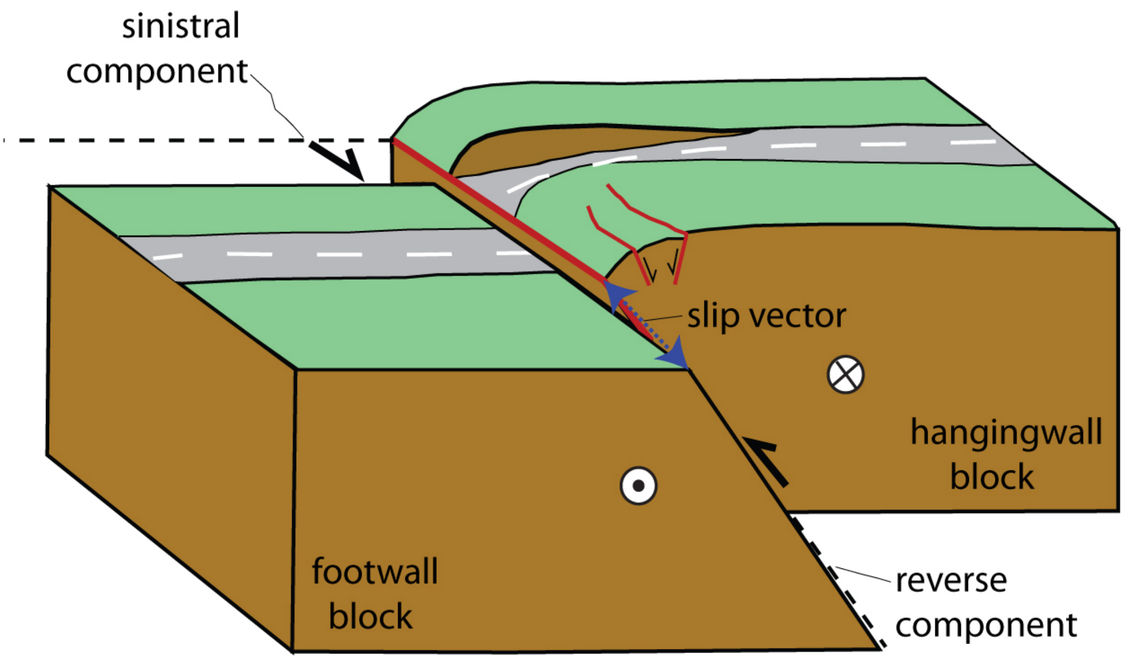

Figure A1.4 Block model of an oblique-slip fault. In this case, the fault is sinistral reverse. The relative movement of the blocks is both vertical (in the dip direction of the fault plane) and strike-slip (in the direction of the strike of the fault), as shown by the oblique blue arrow. Symbols on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

APPENDIX 2 APPLICATION OF FAULT AVOIDANCE ZONES IN THE RANGITIKEI DISTRICT – EXAMPLES

The following section provides hypothetical examples of how the MfE Guidelines could be used to inform planning decisions and includes tables taken from Kerr et al. (2003) for the RI Class IV faults of the 'Leedstown Fault System' near Marton. This area is highlighted because it is likely that many of the future planning decisions will concern surface fault rupture hazard in this most-developed part of the district. Because the MfE Guidelines are risk-based, the designated RI Class is relevant to the future outcomes of resource consent applications. An additional example for a RI Class II fault is also provided.

A2.1 RI Class IV Fault and a Housing Development with BIC 2a/2b Structures

In this case, a developer wants to create a lifestyle housing block on the south edge of Marton in the Makirikiri Road area, straddling the Leedstown Fault (Figure 4.4). Some of these Greenfield sites will have BIC 2a structures and some are planned to have BIC 2b structures. Some of these sites are located within Fault Avoidance Zones (FAZs) for the Leedstown Fault. All of the traces are mapped as 'approximate' from LiDAR and the FAZs have an 'uncertain constrained' fault complexity attribute. For both BIC 2a and 2b house structures near these faults, the Resource Consent Category recommended by the MfE Guidelines is Permitted (Table A2.1).

Even though the recommended Resource Consent Category is Permitted, the Rangitikei District Council may wish to retain some flexibility about how it can exercise its planning and consent outcomes in such a case. For example, it may be possible to work with the developer to help site houses outside (or toward the outer edges) of FAZs. A further alternative could be to undertake further surveying or fault trenching to better locate the fault or areas of most intense ground deformation, which could be avoided. In addition, further clarity of the life safety hazard could be attained by undertaking paleoseismic studies to better define the RI Class of the Leedstown Fault.

A2.2 Renovations to a Home on Wings Line

A family wish to extend their house on Wings Line by adding an extra bedroom to the house, which straddles the FAZ for the Leedstown Fault (Figure 4.4). The fault is mapped as 'accurate' from LiDAR, and the FAZs have a 'well-defined' fault complexity attribute. The site is 'Already Developed', and the owners have existing land-use rights under the Resource Management Act. For the BIC 2a structure in question, the Resource Consent Category recommended by the MfE Guidelines is 'Permitted*' (Table A2.1). In this case, the Resource Consent Category is permitted but could be 'Controlled' or 'Discretionary', given that the fault location is well-defined. Again, the Rangitikei District Council may wish to retain some flexibility about how it can exercise its planning and consent outcomes in such a case, because the life safety risk with regards to a low BIC structure built on a RI Class IV fault is moderately low.

A2.3 A School in Feilding Straddles a Fault Avoidance Zone

Buildings within the Huntley School in Marton fall within an a 120-m-wide 'uncertain constrained' FAZ considered part of the Marton Fault Zone (MFZ; Figure 4.4). An E-W-striking 'approximate' fault trace is mapped through the school grounds from a LiDAR DEM and relate to a broad 2–4-m-high step across the school property. The school buildings probably represent BIC Class 2b (normal) structures on a developed site (see Table A2.1). While the activity is permitted, the School Board and the Rangitikei District Council may need to work together to assess the risk to the buildings and their occupancy at this school.

Table A2.1 Examples, based on the MfE Guidelines, of Resource Consent Category for both Developed and/or Already Subdivided sites and Greenfield sites along RI Class IV faults. Resource Consent categories account for various combinations of Building Importance Category and Fault Complexity.

Example Resource Consent Categories for Class IV Faults (>5000 to ≤10,000 Years) e.g. Rauoterangi, Himatangi and Mt Stewart-Halcombe Faults (Rangitikei)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	Permitted*	Permitted*	Permitted*	Non-complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-complying
Uncertain	Permitted	Permitted	Permitted	Permitted	Non-complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	Permitted*	Permitted*	*Non-complying*	Non-complying
Distributed	Permitted	Permitted	Permitted	*Discretionary*	Non-complying
Uncertain	Permitted	Permitted	Permitted	*Discretionary*	Non-complying

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

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

This may be a case where it is important to better constrain the RI Class and/or the single-event displacement of the fault within the MFZ, as these may impact on future decisions regarding this site (upkeep, renovation of classrooms) or sites that have BIC 3 (important) buildings on them or planned for them. Paleoseismic studies that include geologic dating may be required to improve the science behind the designation of RI Class IV for the MFZ.

A2.4 Consent for a Hunting Lodge along the Napier–Taihape Road

In this example, a large BIC 2b hunting lodge is proposed to develop an eco-tourism business at Erewhon Station (Figure 4.5). The piece of land falls across a Fault Awareness Area (FAA) for the Erewhon fault, northeast of the station. This fault is probably active, but there is no known geological or fault rupture recurrence interval data from which to define its activity, therefore a FAA has been defined for it. Development within a FAA is less stringent than for FAZs (Barrell et al. 2015). In the case of a larger development or subdivision, the council may deem it important to learn more about this fault feature. Further studies, such as geophysical or geological survey, could be undertaken to determine whether the feature mapped and assigned an FAA is an active fault trace or not. In addition, to further clarify its activity, paleoseismic studies of the Erewhon Fault could be undertaken to define a RI Class for this fault.

A2.5 RI Class II Fault and a BIC 2a Structure

In this example, a rural family that lives near Irirangi in the north of the Rangitikei District wants to build a farm-stay house (BIC 2a structure) within a FAZ along the Snowgrass Fault. In this study, the Snowgrass Fault has been designated as a RI Class II fault (Figure 5.11). At their

'Greenfield' site, the fault is 'well-defined' from mapping on the regional digital surface model. In this case, the Resource Consent Category recommended by the MfE Guidelines would be '*Non-complying*' (Table A2.2), i.e. it carries a higher life safety risk than other examples discussed above.

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

Table A2.2 Examples, based on the MfE Guidelines, of Resource Consent Categories for both Developed and/or Already Subdivided sites and Greenfield sites along RI Class II faults. Resource Consent categories account for various combinations of Building Importance Category and Fault Complexity.

Example Resource Consent Categories for Class II faults (RI >2000 to ≤3500 years) e.g. Ruahine Fault (Rangitikei)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	Permitted*	*Non-complying*	*Non-complying*	Non-complying
Distributed	Permitted	Permitted	*Discretionary*	*Non-complying*	Non-complying
Uncertain	Permitted	Permitted	*Discretionary*	*Non-complying*	Non-complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	*Non-complying*	*Non-complying*	*Non-complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-complying*	*Non-complying*	Non-complying
Uncertain	Permitted	*Discretionary*	*Non-complying*	*Non-complying*	Non-complying

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

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

In many cases, a sensible planning option could be to investigate altering the plans and shifting the house site outside of the FAZ, or to an area nearby that has an Approximate or Uncertain fault location, where the consent category is '*Discretionary*', rather than '*Non-complying*'.

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