Active Fault Mapping and Fault Avoidance Zones for the Manawatū District

RM Langridge R Morgenstern

GNS Science Consultancy Report 2019/123
December 2020 – Revised

DISCLAIMER

Use of Data:

Date that GNS Science can use associated data: December 2020

BIBLIOGRAPHIC REFERENCE

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. Revised December 2020.

CONTENTS

EXECUTIVE SUMMARY V

1.0 INTRODUCTION 1

1.1 Scope of Work 2

2.0 HORIZONS REGION 4

2.1 Tectonic Setting 4

2.2 Regional and Historical Seismicity 5

3.0 ACTIVE FAULTS AND THE MFE GUIDELINES 9

3.1 What is an Active Fault? 9

3.2 What is an Active Fold? 10

3.3 MfE Guidelines for Development of Land on or Close to Active Faults 11

3.4 Active Fault Recurrence Interval and the MfE Guidelines 12

3.4.1 Pre-Existing Recurrence Interval Data for the Horizons Region 12

3.4.2 Derivation of Preliminary RI Class Categories for the Manawatū District 14

3.5 Building Importance Category and the MfE Guidelines 17

4.0 METHODOLOGY OF FAULT MAPPING 19

4.1 Data Used for Fault and Fault Avoidance Zone Mapping 19

4.2 Mapping Fault Lines in a GIS 20

4.3 Fault Complexity 22

4.4 Constructing Fault Avoidance Zones (FAZs) 23

4.4.1 Fault Awareness Areas 25

4.5 Mapping Active Folds 26

5.0 FAULTS AND FOLDS OF MANAWATŪ DISTRICT 28

5.1 Active Faults 29

5.1.1 Himatangi Fault (and Himatangi Anticline) 30

5.1.2 Mt Stewart-Halcombe Fault (and Mt Stewart-Halcombe Anticline) 31

5.1.3 Rauoterangi Fault (and Feilding Anticline) 33

5.1.4 Ruahine Fault 37

5.1.5 Mohaka Fault 38

5.1.6 Leedstown Fault 39

5.1.7 Other Active Faults 40

5.2 Possibly Active Faults 42

5.2.1 Ohakea fault 42

5.2.2 Taonui fault 42

5.2.3 Raukawa Fault 44

5.2.4 Pohangina fault (and Pohangina Anticline) 45

5.2.5 Komako fault 48

5.3 Active Folds 48

5.4 Summary of Active Faults with FAZs in Manawatū District 50

6.0 SUMMARY 51

7.0 RECOMMENDATIONS 52

8.0 ACKNOWLEDGEMENTS 53

9.0 REFERENCES 53

FIGURES

Figure 1.1 The area administered by Horizons Regional Council, showing its various districts. 1

Figure 2.1 Simplified tectonic cross-section of the lower North Island in the Horizons Region from offshore of Akitio in the east to near Whanganui (WN) in the west 5

Figure 2.2 Epicentres of significant shallow (<30 km depth) earthquakes in central New Zealand that have occurred since 1843. 6

Figure 2.3 Epicentral locations of shallow (<40 km) earthquakes of M_w >2.6 that occurred over five years between August 2013 and 2018 within, or close to, the Horizons Region 8

Figure 3.1 Block model of a generic active fault 10

Figure 3.2 Block model of an anticlinal fold that is related to a buried active reverse fault. 11

Figure 3.3 Cross-section spanning the western hills and town of Feilding showing how vertical and dip-slip rates are calculated for faults, using the Rauoterangi Fault as an example. 15

Figure 4.1 Digital topographic coverage across the central part of the Horizons Region used in this project. 19

Figure 4.2 A Fault Avoidance Zone (FAZ; heavy dash) and how it may be developed for a district planning map (not drawn to scale), from Kerr et al. (2003). 24

Figure 4.3 Schematic diagram of a dip-slip reverse fault and its scarp 24

Figure 4.4 Fault Avoidance Zone map for part of the reverse-slip Mt Stewart-Halcombe Fault near Rongotea. 25

Figure 4.5 Fault Awareness Areas and FAZ map for the southern part of the Ruahine Fault in the Manawatū District. 26

Figure 5.1 New and updated onshore active faults (red) and folds (blue) in the Manawatū District, as defined in this study. 28

Figure 5.2 Fault mapping (defined in this study) for three active (or ‘possibly active’) faults in the southwestern part of the Manawatū District, highlighting fault accuracy designations. 29

Figure 5.3 Active traces and fault avoidance zones developed for the Himatangi Fault. 30

Figure 5.4 East-facing scarp of the Himatangi Fault along Kaimatarau Rd, delineated by white arrows. 31

Figure 5.5 Maps of active (and likely active) faults and fault avoidance zones (FAZ) for the NNE- and north-striking Mt Stewart-Halcombe Fault and Rauoterangi Fault 32

Figure 5.6 The southeast-facing scarp of the Mt Stewart-Halcombe Fault along Taipo Rd 33

Figure 5.7 Identification of the active NNE-striking Rauoterangi Fault (RtrF) proximal to Feilding township. 34

Figure 5.8 A well-defined active trace of the Rauoterangi Fault forming a fault scarp (between arrows) at the end of Coronation Street in suburban Feilding. 35

Figure 5.9 The east-dipping, uplifted Q9b marine surface forming the top of the western hills of Feilding 35

Figure 5.10 Fault Avoidance Zone (FAZ) and Fault Awareness Area (FAA) map for the Rauoterangi Fault in suburban Feilding 37

Figure 5.11 Fault Avoidance Zone and Fault Awareness Area map for the northern part of the Ruahine Fault, Mohaka Fault and Traverse fault (Tf) in the Manawatū District. 38

Figure 5.12 Oblique aerial photograph of the active trace of the Mohaka Fault 39

Figure 5.13 Fault linework (black) and FAZs for the active Leedstown Fault in the Manawatū District, and a Fault Awareness Area for the 'possibly active' Ohakea fault. 40
Figure 5.14 Active fault traces mapped (and FAZs) in the north-eastern corner of the Manawatū District and in the south-eastern corner of the Rangitikei District in the Ruahine Ranges area....................41
Figure 5.15 Location of the NE-striking Taonui fault (new) to the southeast of Feilding marked by white arrows on an uninterpreted LiDAR hill-shade image. 43
Figure 5.16 Mapped locations of the 'possibly active' Raukawa Fault near Manawatū Gorge. 44
Figure 5.17 Possible fault traces and folds of the Pohangina Valley area. Fault Awareness Areas and FAZs at Awahou North are also shown. 46
Figure 5.18 View to the west of a scarp across Grove Road 47
Figure 5.19 Active fault traces mapped, and FAZs and FAAs constructed for faults in the upper Pohangina Valley and Ruahine Range areas of the Manawatū District. 47
Figure 5.20 Axial traces of active anticlinal folds (light blue) in the southern part of Horizons Region, as defined in this study. 49

TABLES

Table 3.1 Definition of Recurrence Interval classes 12
Table 3.2 Fault recurrence interval data for faults within the Horizons Region 13
Table 3.3 Broad relationship between RI Class and slip rate for active fault earthquake sources in the New Zealand national seismic hazard model 16
Table 3.4 Building Importance Categories and representative examples. 17
Table 3.5 Relationships between Recurrence Interval Class, Average Recurrence Interval of Surface Rupture, and Building Importance Category for Previously Subdivided and Greenfield Sites. ...18
Table 4.1 Active fault data GIS attributes for the Manawatū District. 21
Table 4.2 Development of fault complexity terms for faults, used in this study for Horizons Region. 23
Table 5.1 Fault recurrence interval information for faults within the Manawatū District. 50

APPENDICES

APPENDIX 1 STYLES OF FAULT MOVEMENT 61
A1.1 Strike-Slip Faults 61
A1.2 Reverse Faults 61
A1.3 Normal Faults 62
A1.4 Oblique-Slip Faults 63
APPENDIX 2 THE RAUOTEANGI FAULT IN FEILDING 64
A2.1 Examples of the Application of FAZs in Feilding 66
A2.1.1 RI Class IV Fault and a Housing Development with BIC 2a/2b Structures..... 66
A2.1.2 Renovations to a Home in Coronation Street 66
A2.1.3 A School in Feilding Straddles a FAZ 66
A2.1.4 Consent for a Large House Along the Western Hills 67
APPENDIX 3 ANOTHER EXAMPLE OF THE APPLICATION OF A FAZ 68
A3.1 RI Class II Fault and a BIC 2a Structure 68

APPENDIX FIGURES

Figure A1.1 Block model of a strike-slip fault 61
Figure A1.2 Block model of a reverse dip-slip fault that has recently ruptured. 62
Figure A1.3 Block model of a normal dip-slip fault. 63
Figure A1.4 Block model of an oblique slip fault. In this case the fault is sinistral reverse. 63
Figure A2.1 Map view of FAZs and FAAs for the Rauoterangi Fault in the Fielding area. 64
Figure A2.2 Cross-sectional view of the range front with FAZs and FAA for the Rauoterangi Fault in the Feilding area. 65

APPENDIX TABLES

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. 67
Table A3.1 Examples, based on the MfE Guidelines, of Resource Consent Categories for both Developed and/or Already Subdivided sites, and Greenfield sites along RI Class II faults. 68

EXECUTIVE SUMMARY

GNS Science has been contracted by the Horizons Regional Council ('Horizons') 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 are presented here for the Manawatū 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 to develop Fault Avoidance Zones (FAZs) that buffer the active faults at a scale that is suitable for district planning use. In terms of life safety, the 'MfE Guidelines' focus on: (i) the location and complexity of faulting; (ii) the characterisation of recurrence interval of surface faulting; and (iii) the building importance category of the structure(s) that may be impacted by fault rupture ground deformation. Fault Awareness Areas (FAAs) have been developed for areas where the resolution (scale) of mapping is not refined enough to permit the more detailed mapping of Fault Avoidance Zones, or where it has not been established that the mapped feature is of a tectonic (faulting) origin.

Active fault trace mapping was undertaken in the Manawatū District using hill-shade models developed from airborne Light Detection and Ranging (LiDAR) data and from review of active fault mapping from GNS Science geological and active fault datasets, a Horizons-wide Digital Surface Model (DSM) and orthophotographs. Fault mapping was undertaken at scales between c. 1:5000 and 1:10,000 where LiDAR data is available. Active faults have been mapped in a Geographic Information System (GIS) with traces being attributed as accurate, approximate, or uncertain. These terms are used to help characterise the fault complexity, i.e. how the fault deformation is expressed at the Earth's surface. Fault complexity can vary from well-defined to distributed or uncertain. The accuracy and complexity terms are further used to define the width and parameterisation of FAZs.

In the Manawatū District, there are several previously known active faults that have been re-mapped: the Mohaka Fault, Ruahine Fault, Leedstown Fault and Mt Stewart-Halcombe Fault[1]. This study has also identified and/or named new active reverse faults: the Himatangi Fault, Rauoterangi Fault, Pohangina fault, and Komako fault. Traces along the Raukawa Fault and Taonui fault are defined as possibly active faults due to a lack of certainty of activity. Several other short, active fault traces have also been identified (Traverse, Howlett Creek, Dirty Spur and Taumataomekura faults).

In the Manawatū District existing Recurrence Interval (RI) Class information is only available for the strike-slip Mohaka (RI Class I; ≤2000 years), Ruahine (RI Class II; >2000 to ≤3500 years) and Leedstown (RI Class IV; >5000 to ≤10,000 years) faults. The RI Class of most other faults is poorly known at this time. However, based on their topographic expression and a comparison to other faults in the region we assess several of the other active faults described here as being RI Class IV (>5000 to ≤10,000 years), i.e. the Mt Stewart-Halcombe Fault, Himatangi Fault, Rauoterangi Fault and the Pohangina, Komako, Traverse, Howlett Creek,

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.

Dirty Spur and Taumataomekura faults. FAZs have been defined for these active faults according to the MfE Guidelines. 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 (e.g. Raukawa Fault, Taonui fault and parts of the Pohangina fault and Rauoterangi Fault). FAAs are distinct from FAZs and carry no requirements related to the MfE Guidelines.

The axes of active folds have also been re-mapped for the Himatangi, Mt Stewart-Halcombe, Feilding, Utiku and Pohangina anticlines. This study does not present avoidance zones for active folds because fold axes are not typically associated with life-safety threatening ground deformation.

We recommend that the active fault mapping and FAZs developed for the Manawatū 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 Building Importance Category (BIC), provides a risk-based rationale for making land use planning decisions pertaining to the development of land close to, or on, active faults. To assist planners 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.

We recommend that the MfE Guidelines be treated as a standard reference when considering resource consent applications in the Manawatū 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

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 2.1) 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 1995; Villamor and Berryman 2006a). The Horizons Region is crossed by numerous active crustal faults (and folds) that have ruptured and deformed the ground surface in the past. These faults include the Wellington, 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).

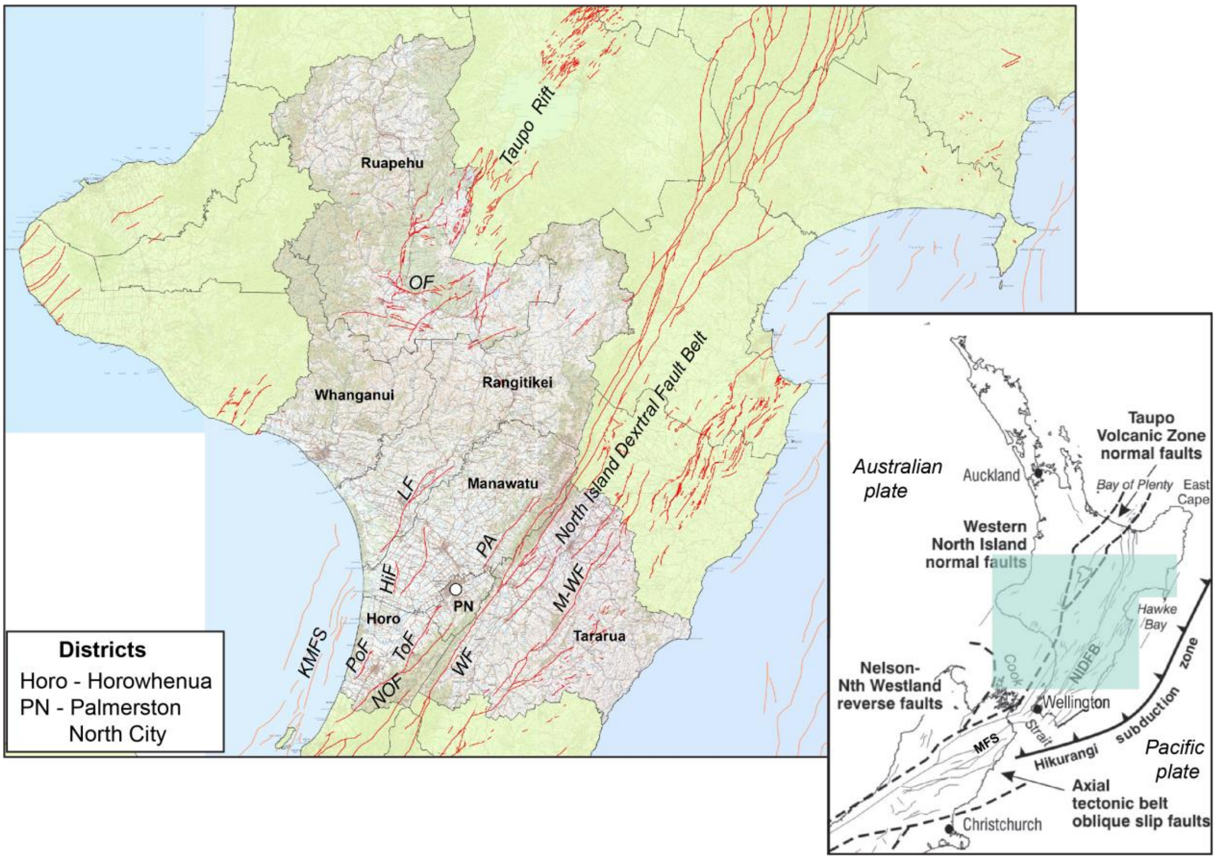

Figure 1.1 The area administered by Horizons Regional Council, showing its various districts. Onshore active faults (red) within the lower North Island area sourced from the New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al. 2016) as they appeared prior to this study. Fault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

Ground surface rupture of an active fault will result in a zone of intense ground deformation as opposite sides of the fault move past or over each other during an earthquake. Property damage can be expected, and loss of life may occur where buildings, and other structures, have been constructed across, or in the immediate vicinity of, the rupturing fault. In addition to the effects of strong ground motions, the 1931 Hawke's Bay, 1987 Edgecumbe, 2010 Darfield and 2016 Kaikōura earthquakes provide examples of the types of impacts to engineered structures caused by ground-surface fault rupture (e.g. Hull 1990; Beanland et al. 1989; Van Dissen et al. 2011, 2019).

1.1 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 understandings 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*' (hereafter called the 'MfE Guidelines'; Kerr et al. 2003). It also builds upon previous active fault studies in the region and the New Zealand Active Faults Database (NZAFD; https://data.gns.cri.nz/af/) coverage to date. The Horizons fault mapping and fault avoidance program began in the two southernmost districts within Horizons Region: Horowhenua District and Palmerston North City (Phase 1; Langridge and Morgenstern 2019) and is extended here to the Manawatū District (Phase 2a).

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, 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 Manawatū 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 and provided to GNS.
- Build a 1-m Digital Surface Model of the Horizons Region in order to improve the mapping of active traces, where LiDAR does not exist.
- Incorporate active fault line work and attributes from other mapping studies, such as Begg and Johnston (2000); (i.e. part of the QMAP Geological Map of New Zealand Project; Heron 2018), previous GNS reports, and review data within the NZAFD (1:50,000 to 1:250,000 scale).

- 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 with up-to-date geospatial datasets that are valid for planning purposes and wholly compatible with application of the MfE Guidelines.
- Map active folds in order to better locate and characterise their tectonic activity[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 Manawatū 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 Manawatū District planning staff.

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

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

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

Chapter 5 describes the results and implications for active faults, 'possibly active' faults and folds within the Manawatū District and provides updated recurrence intervals for each of the active faults.

Chapter 6 provides a summary of the results of this work, and Chapter 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 a focus toward Feilding and the newly mapped Rauoterangi Fault and provides some examples to assist planners in making resource consent decisions regarding the FAZs there. Appendix 3 provides an additional example of how the MfE Guidelines consent tables could be applied to an RI Class II fault in the Manawatū District.

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.

2.0 HORIZONS REGION

The Horizons Region includes seven Territorial Authorities that span an area encompassing many different landscape types across the central to southern North Island (Figure 2.1). The physiography of the region is diverse and varied. In the north, the region borders onto the extensional Taupō Rift and Volcanic Zone (Villamor and Berryman 2006a, b) in the Ruapehu District. In the southwestern North Island, large rivers drain from the elevated central and southwestern parts of the island across a broad coastal plain (e.g. Whanganui, Rangitikei, and Manawatū districts). These settings extend and taper into the southern part of the Horizons Region, covering Horowhenua District and Palmerston North City. Lastly, in the southeast, Tararua District covers an area from the elevated Tararua Ranges to the east coast of the North Island.

The primary 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 Manawatū District and deals with the hazards relating to ground surface fault rupture deformation, including surface faulting and folding. This report also focuses on the effects/impacts of surface fault rupture on the built environment, specifically in terms of planning for, and mitigating against, the impacts of surface fault rupture hazard. To augment this discussion of earthquake hazard, we also present a compilation of large historical earthquakes in these districts.

2.1 Tectonic Setting

The lower North Island straddles the Australian-Pacific plate boundary which, at the location of the Horizons Region, forms part of the Hikurangi Subduction Margin (HSM). Figure 2.1 shows a plate boundary cross-section of the region. The HSM 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; axial ranges characterised by strike-slip, oblique and reverse faulting; a volcanic arc characterised by normal faulting (not indicated in figure); and a back-arc region characterised by reverse faulting and folding (Berryman and Beanland 1991; Little et al. 2009). Thus, a diverse suite of active tectonic styles of faulting and deformation[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 on 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, surface rupture of the Hikurangi subduction interface (i.e. as a gently dipping thrust fault) would occur at the seafloor off the east coast of Tararua District (Figure 2.1) and a significant tsunami would be generated that would impact the east coast. In addition, a magnitude M_W 8–9 earthquake on the 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.

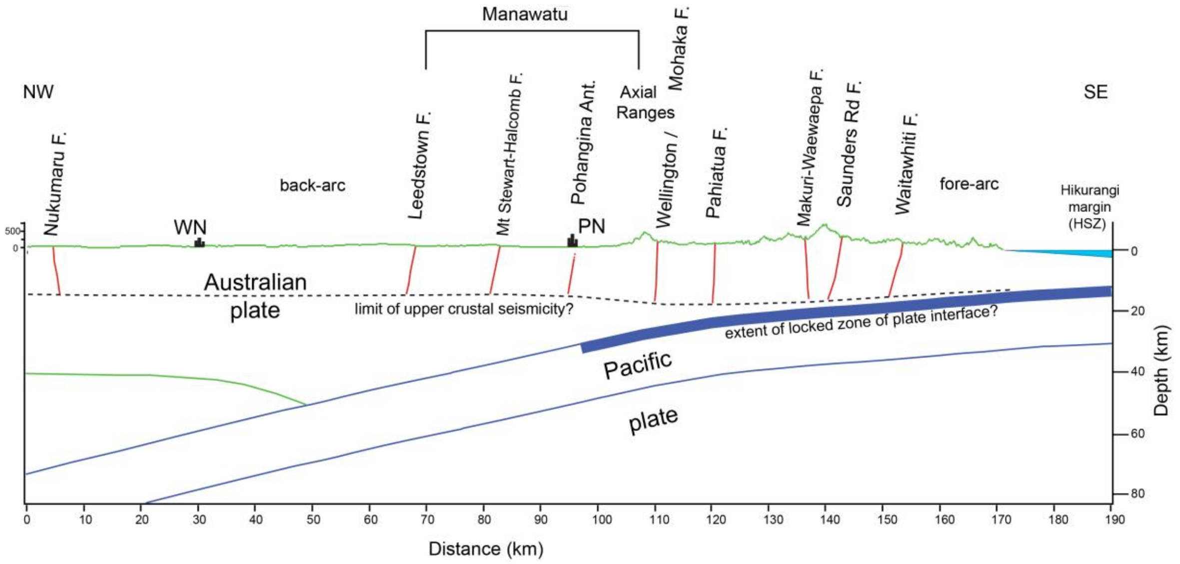

Figure 2.1 Simplified tectonic cross-section of the lower North Island in the Horizons Region from offshore of Akitio in the east to near Whanganui (WN) in the west The cross-section intercepts several active upper crustal faults and includes the Hikurangi Subduction Margin or Zone (HSZ). The Manawatū District broadly spans the area between the Axial Ranges and back-arc. Palmerston North (PN) is also indicated. Ant, anticline; F, fault.

2.2 Regional and Historical Seismicity

The Horizons Region has a well-documented record of historical (post-1840 AD) earthquakes that have been both damaging and destructive. Figure 2.1 shows the epicentres of shallow (<30 km depth) historical earthquakes with magnitude M_w >6 throughout central New Zealand. These represent significant earthquakes that caused shaking damage and for a subset of these events, ground surface-rupturing earthquakes. The Horizons Region boundary is shown in dark blue to highlight large earthquakes that have occurred within or close to the region.

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

The M_W ~8.2 Wairarapa Earthquake occurred on January 23rd, 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 MMI 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). The 1863 earthquake produced strong ground motions across the region, particularly in the Tararua District.

In June 1881 a magnitude 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) were most strongly felt on the eastern coast of the Tararua District near Cape Turnagain. Shaking intensities decreased in all directions from this area but ranged from MMI 5–7 across much of the Horizons Region.

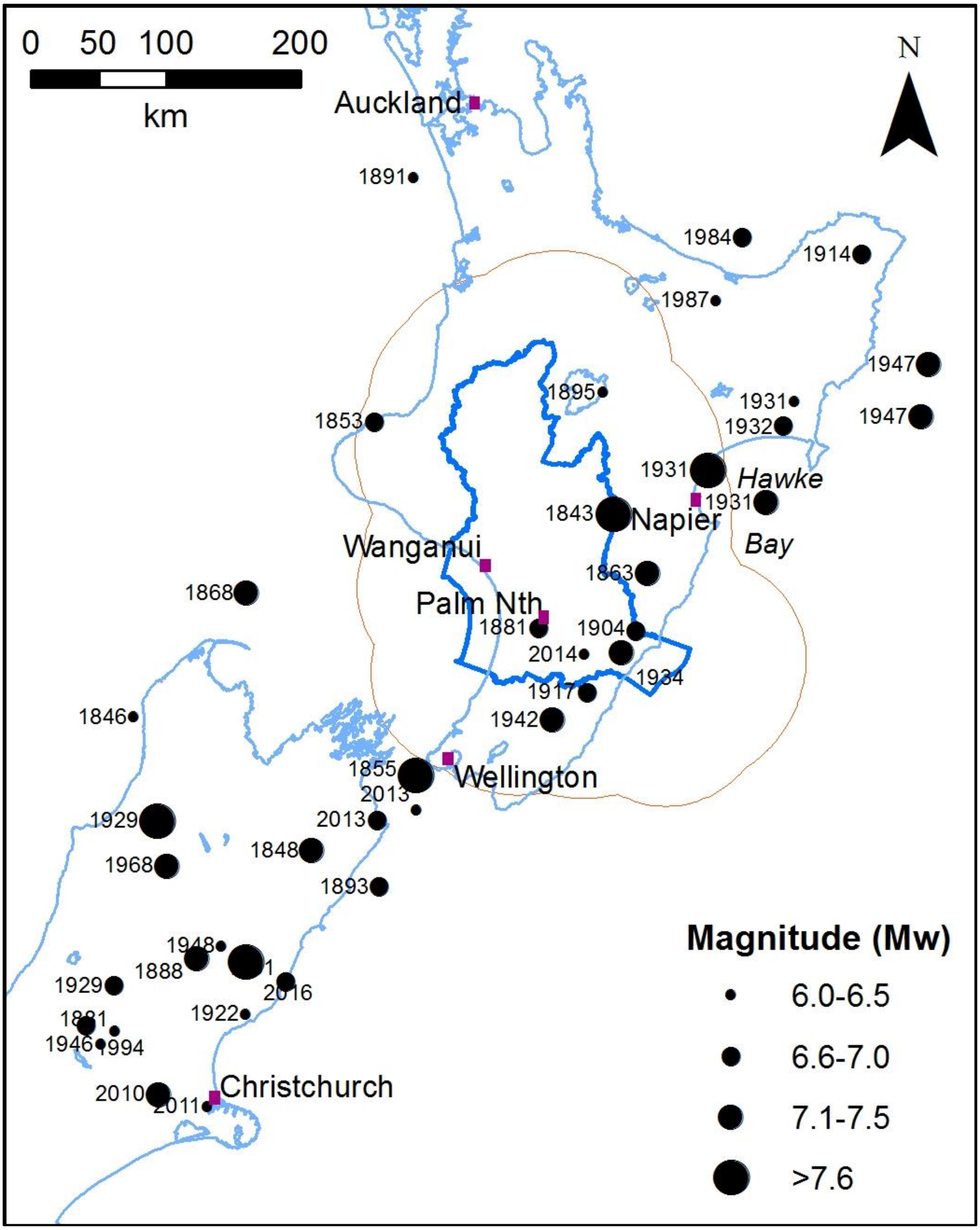

Figure 2.2 Epicentres of significant shallow (<30 km depth) earthquakes in central New Zealand that have occurred since 1843. Highlighted in dark blue is the Horizons Region and the red line is an area that extends a further 75 km around the region to consider impacts from earthquakes outside of the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

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

During the first half of the 20th century, Hawke's Bay and surrounding regions were rocked by a number of large earthquakes, including the 1931 M_W 7.6 Hawke's Bay earthquake (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 in 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 had at least two other Holocene surface rupturing earthquake events (Schermer et al. 2004). The earthquake caused extensive damage from the northern Wairarapa to Hawke's Bay, particularly between Porangahau and Castlepoint. The worst damage was noted in Pahiatua, the largest town near the earthquake epicentre. There were no deaths caused by this earthquake, although one person required hospitalisation.

In 1942, two earthquakes shook the lower North Island on 24 June and 2 August. They were large and shallow with the epicentres located close together east of Masterton in the Wairarapa area. The June earthquake 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 24 June earthquake (Downes 1995; Schermer et al. 2004).

The largest earthquake to occur within the Horizons Region this century was the 2014 M_W 6.2 Eketahuna earthquake (Figure 2.2 and Figure 2.3). This event occurred at a depth of c. 34 km and was felt strongly across the country, from Auckland to Dunedin, with more than 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 related to the HSM 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 Manawatū District (Figure 2.2) and the district typically has a relatively low level of background seismicity (Figure 2.3).

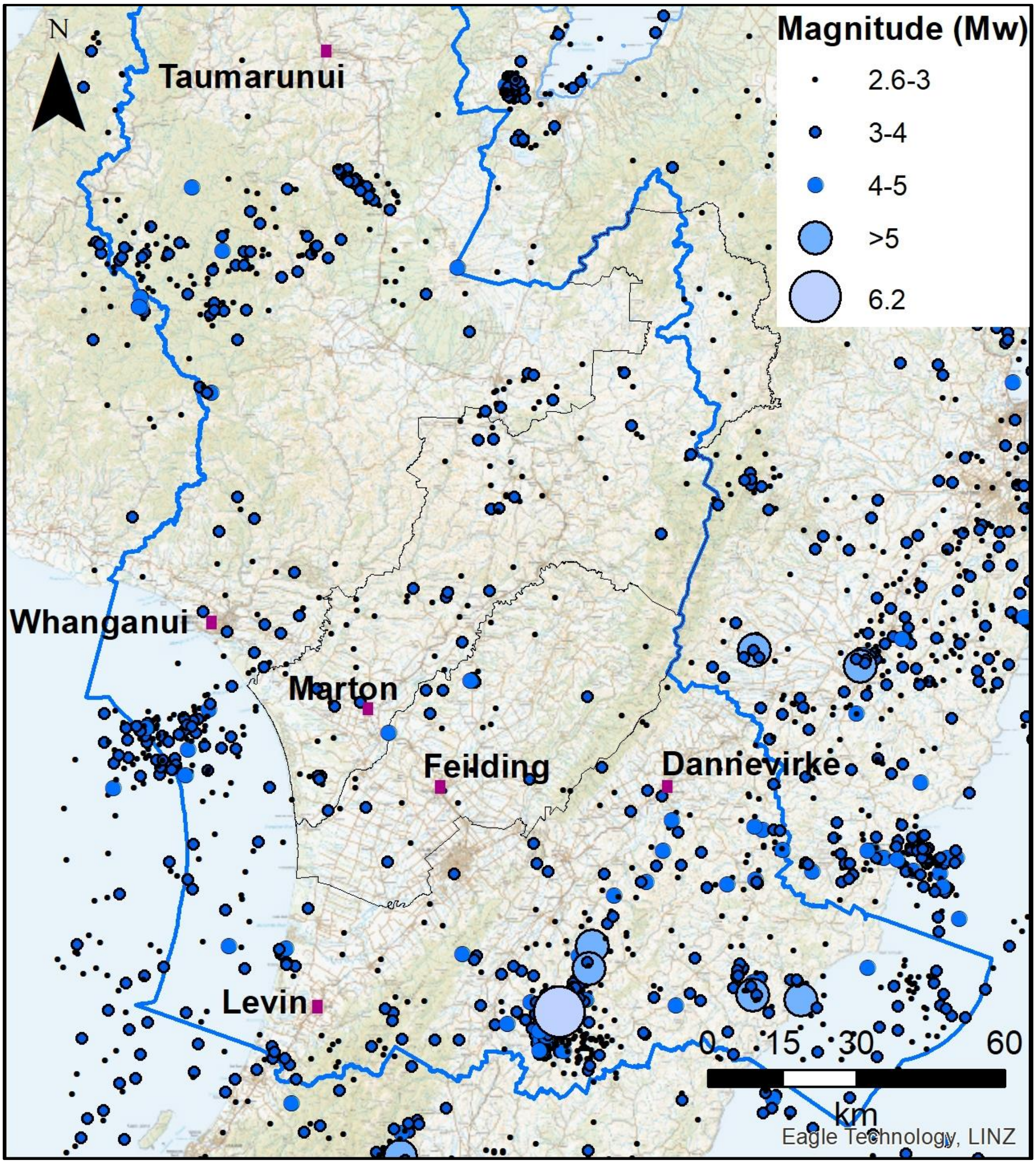

Figure 2.3 Epicentral locations of shallow (<40 km) earthquakes of M_w >2.6 that occurred over five years between August 2013 and 2018 within, or close to, the Horizons Region (marked in dark blue). Earthquakes are colour coded in magnitude bands. The largest event is the 2014 M_w 6.2 Eketahuna earthquake. 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 3.1). The locations of active faults mapped at scales of >1:10,000 have significant locational uncertainty and accordingly have limited use for planning purposes. Phase 1 of the Horizons Region active fault mapping program was undertaken across Horowhenua District and Palmerston North City in order to refine active fault locations and to produce Fault Avoidance Zones that can be utilised within the risk-based planning context of the MfE Guidelines (Kerr et al. 2003; Langridge and Morgenstern 2019). That project drew on the significant amounts of airborne LiDAR across those areas. For this project (Phase 2a), there is good LiDAR coverage across the southern half of the Manawatū 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[4]. An active fault is generally defined within the NZAFD (https://data.gns.cri.nz/af/) 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 which formed during the 'peak Last Interglacial period' or Marine Isotope Stage (MIS) 5e, or younger (MIS 1–4; e.g. Alloway et al. 2007). These MIS 5e surfaces form a useful datum throughout New Zealand and therefore a pragmatic choice for the definition of activity. The only exception to this classification is within the Taupō Rift (which is in part 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 expressed in the landscape as linear traces displacing surficial geologic features which may include hillslopes, alluvial terraces and fans. The age of these displaced features can be used to define how active a fault is. Typically, in New Zealand, alluvial terraces are associated with contemporary river drainages, and therefore they are often <30,000 years old (e.g. Litchfield and Berryman 2005). Hillslopes are mainly formed in bedrock and in New Zealand these surfaces have generally been modified by glacial or cold climate processes during the peak of the Last Glacial period (Barrell et al. 2011). This means that well-defined, linear fault traces that cut across bedrock hillslopes are probably also less than c. 30,000 years old.

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

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

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.

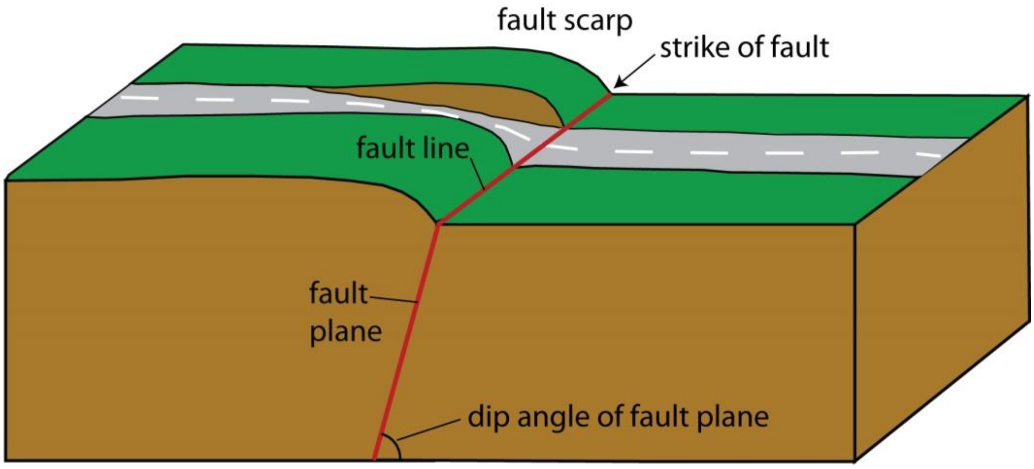

Figure 3.1 Block model of a generic active fault (shown in red). Fault displacement produces a scarp with offset features along the projection of the fault plane at the Earth's surface (fault line or trace).

3.2 What is an Active Fold?

Active folds are mappable, warped parts of the ground-surface landscape. Active folds are commonly found in association with buried active reverse faults, where the upper tip of the reverse fault (see Section A1.2) does not extend to the Earth's surface. In such a case, a geomorphic and/or bedrock surface is warped or buckled on the upper (hanging-wall) side of the buried fault tip (Figure 3.2). Folds that form positive relief are termed anticlines and folds that form subsided relief are called synclines. The crest of the raised part of an anticline forms a fold axis, which can sometimes be mapped because, for example, streams will flow away from the axis in either direction down the fold limbs (Figure 3.2; Stevens 1990; Clement et al. 2017). This attests to the long-lived nature of these structures. Anticlines can take on various geomorphic forms, such as broad, gentle, tight, symmetric and asymmetric. Broad, gentle and tight folding refer to the angle between the limbs of the fold, which may also relate to the degree of activity on a structure. Symmetric and asymmetric folds refer to the shape of the fold, where the asymmetry of the fold relative to the axial surface[5] (e.g. one limb being steeper and/or shorter than the other) can provide some information on the dip and dip direction of the buried fault it is related to.

The southern and central parts of the Horizons Region 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 Palmerston North districts the Pohangina, Foxton-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 (2019). Where folds are actively deforming Late Quaternary surfaces they can be considered to be underlain by active reverse faults (Figure 3.2) 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).

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

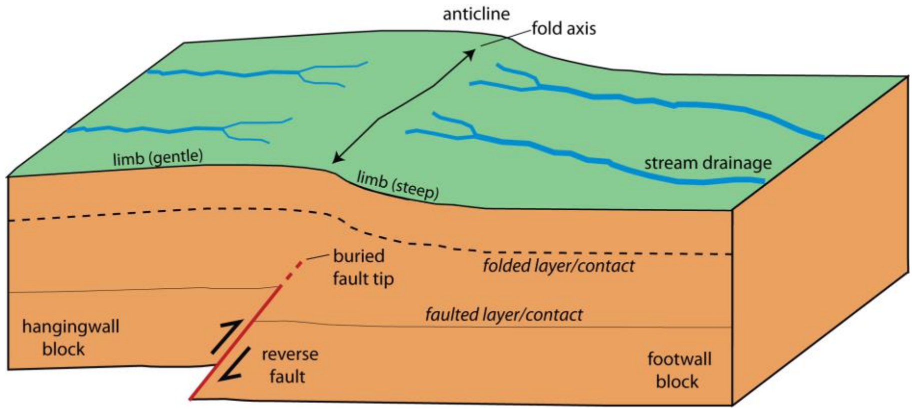

Figure 3.2 Block model of an anticlinal fold that is related to a buried active reverse fault.Motion on the fault has driven upwards the hanging-wall block and folded the ground surface above the fault tip. The fold is asymmetric and defined at the surface by a fold axis and by the stream drainage pattern,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

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

In 2003, the Ministry for the Environment (MfE) published guidelines on *'Planning for Development of Land on or Close to Active Faults*' (Kerr et al. 2003, see also King et al. 2003; Van Dissen et al. 2003), i.e. the 'MfE Guidelines'. The aim of the MfE Guidelines is to assist resource management planners tasked with developing land-use policy and making decisions about development of land on, or near, active faults. The MfE Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas that are subject to fault rupture hazard. The MfE Guidelines are designed primarily for life safety purposes; however, what has increasingly become relevant to councils and landowners is post-event functionality of built structures, i.e. built structures that can 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 which focuses on: (a) accurate location of faults (including 'fault complexity', i.e. the distribution and deformation of land around a fault line); (b) definition of Fault Avoidance Zones, and; (c) classification of faults based on their recurrence interval (i.e. the time interval between large, surface-rupturing earthquakes on the same fault), which is an indicator of the likelihood of a fault rupturing in the near future.
2. The Building Importance Category (BIC), which indicates the acceptable level of risk of different types of buildings within a Fault Avoidance Zone.

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

Aside from Phase 1 of the Horizons active fault mapping program (Langridge and Morgenstern 2019), there has been extensive active fault mapping with a view toward developing Fault Avoidance Zones in other regions of New Zealand. These studies have been, for example, in Greater Wellington (e.g. Litchfield and Van Dissen 2014; URS 2006; Van Dissen and Heron 2003; Zachariasen et al. 2000; Begg et al. 2001; Townsend et al. 2002) and Hawke's Bay (e.g. Clark and Ries 2016; Langridge and Ries 2014, 2015; Langridge et al. 2006, 2011) in the North Island, and Canterbury (Barrell 2015; Barrell and Townsend 2012), West Coast (e.g. Langridge and Ries 2008) and Marlborough (Langridge and Ries 2008) in the South Island.

3.4 Active Fault Recurrence Interval and the MfE Guidelines

Six Recurrence Interval Classes (RI Class), 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 (RI) 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 program Langridge and Morgenstern (2019) 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 2006a; and summarised by Van Dissen et al. 2003); and (b) estimates based on determinations from geomorphology. In many cases, there is little, or no geological data related to named or unnamed faults, in which cases estimates are developed based on the amount of landscape deformation occurred or from geologic comparisons with other faults in the region that have better defined levels of activity or deformation.

These data come from: (a) geologic studies (e.g. Jackson et al. 1998; Langridge et al. 2007; Villamor and Berryman 2006a; and summarised by Van Dissen et al. 2003); and (b) estimates based on determinations from geomorphology. In many cases, there is little, or no geological data related to named or unnamed faults, in which cases estimates are developed based on the amount of observed landscape deformation or from geologic comparisons with other faults in the region that have better defined levels of activity or deformation.

Table 3.2 Fault recurrence interval (RI) data for faults within the Horizons Region* (modified from Langridge and Morgenstern 2019). Faults with established RI Classes in the Manawatū District are shown in italics.

Fault	District	RI Class Confidence^	Source#
RI Class I Faults (≤2000 Years)			
Alfredton Fault, Wellington Fault, Waipukaka Fault	Tararua	M	1, 2
Mohaka Fault	Tararua, Manawatū	M	1, 2
Dreyers Rock/Kowhai Fault	Tararua	M	1, 2
Waihi Fault	Ruapehu	M	1–3
Snowgrass Fault	Rangitikei, Ruapehu	M	2, 3
Ohakune Fault, Rangipo Fault, Shawcroft Rd Fault, Karioi Fault, National Park Fault, Raurimu Fault	Ruapehu	M	2, 3
RI Class II Faults (>2000 to ≤3500 Years)			
Saunders Rd Fault, Pa Valley Fault, Makuri-Waewaepa Fault, Weber Fault	Tararua	L	1, 2
Ruahine Fault	Tararua, Manawatū	L	1, 2
Hihitahi Fault	Ruapehu	L	1, 2
Raetihi North Fault, Raetihi South Fault	Ruapehu	L	1–3
Northern Ohariu Fault	Horowhenua, PNC	L	1, 2
RI Class III Faults (>3500 to ≤5000 Years)			
Otaki Forks Fault	Horowhenua	L	1, 2
Maunga Fault	Tararua	L	1, 2
Waitawhiti Fault	Tararua	L	1, 2
Kaweka Fault	Rangitikei	L	1, 2
Ruataniwha Fault	Tararua	L	1, 4
Rangefront Fault, Oruawharo Fault, Waipukurau Fault (Zone)	Tararua	L	1, 2, 4
RI Class IV Faults (>5000–≤10,000 Years)			
Tokomaru Fault	Horowhenua, PNC	M	4
Poroutawhao Fault	Horowhenua	M	4
Mangaoranga Fault	Tararua	L	1, 2
Leedstown Fault	Rangitikei, Manawatū	L	2
Nukumaru Fault	Whanganui	L	1, 2

Notes: *This table summarises data available prior to this study. PNC, Palmerston North City. ^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). #Data sources: 1, Van Dissen et al. (2003); 2, Villamor and Berryman (2006 a, b); 3, NZAFD (https://data.gns.cri.nz/af/); 4, Langridge and Morgenstern (2019).

Overall, the recurrence interval data have large uncertainties, except where fault-specific paleoseismic studies have been undertaken (Van Dissen et al. 2003). In the Manawatū District there are few faults that have published recurrence interval data (see Chapter 5), despite some of them being documented as active fault earthquake sources in the NSHM (Stirling et al. 2012) and simplified fault zones in the Active Fault Model (Litchfield et al. 2014).

Based on current data, the Horizons Region contains active faults in RI Classes I though V (Van Dissen et al. 2003; Langridge and Morgenstern 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 and the Raetihi North and 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 Ruataniwha 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 other faults recurrence intervals are qualitatively based on landscape and geomorphic inferences. Often when a fault recurrence interval is calculated from geologic data the results may span more than one of the recurrence interval classes, e.g. a fault with a recurrence interval range of 1500–4000 years overlaps RI Classes I, II and III. In such a case, the mean recurrence interval may be 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 a number of RI Classes. The data 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 Manawatū 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 report only three faults have RI Classes applied to them in the Manawatū District; these being the strike-slip Mohaka and Ruahine faults and the Leedstown Fault (Van Dissen et al. 2003; Langridge et al. 2016). In this report, many of the active faults and fault traces identified have a new and preliminary RI Class developed for them. This is typically achieved through a calculation of the slip rate, based on topographic profiling using the LiDAR and digital surface models (DSMs).

Derivation of slip rate for many of the faults in the district is possible because they are predominantly dip-slip (reverse and normal) faults, where the deformation is related to a dominantly vertical sense of motion, that can be characterised using LIDAR and/or DSM and in a GIS. Figure 3.3 shows an important example of how vertical slip rate can be derived for the active Rauoterangi Fault.

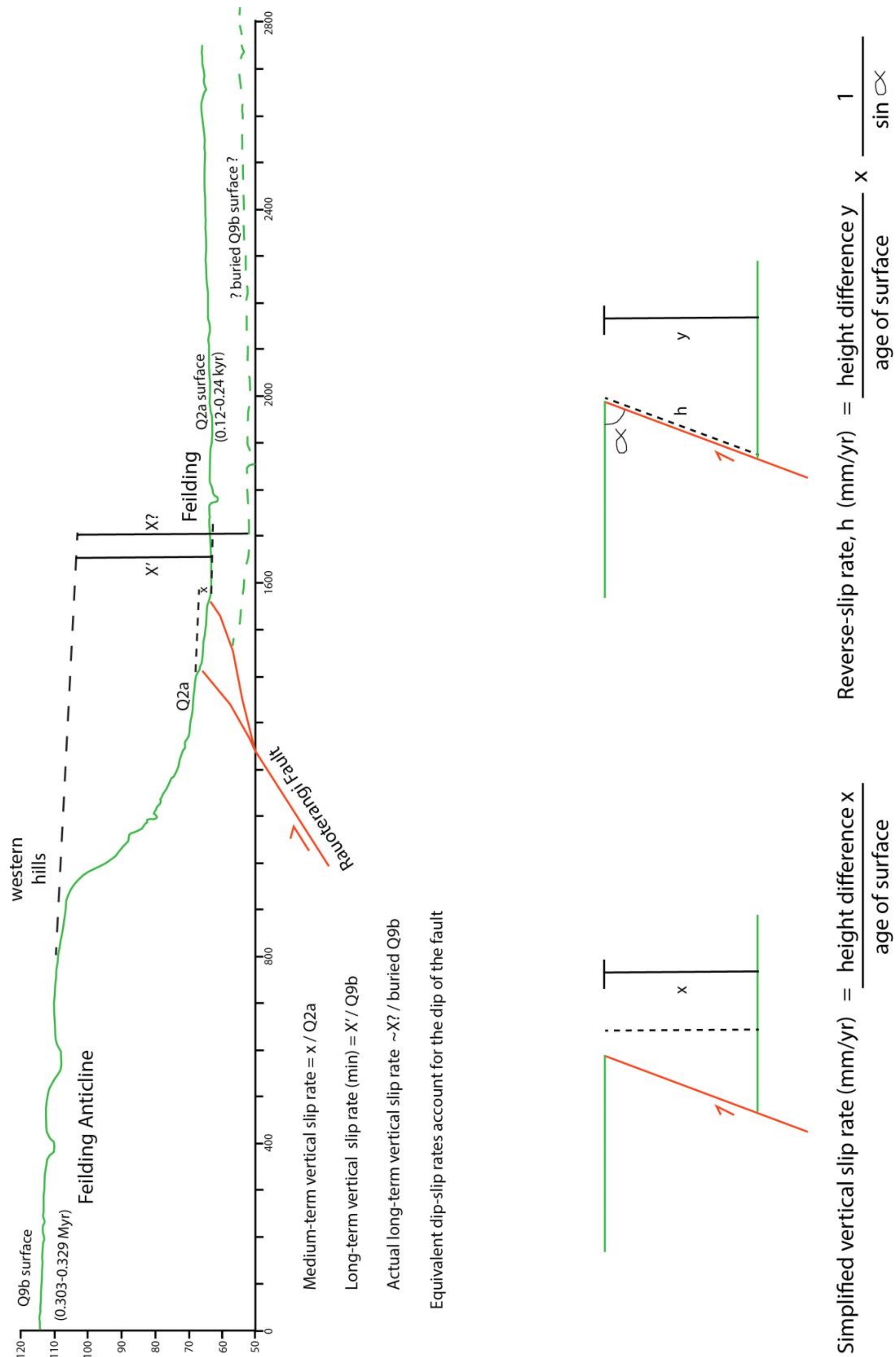

Figure 3.3 Cross-section spanning the western hills and town of Feilding showing how vertical and dip-slip rates are calculated for faults, using the Rauoterangi Fault as an example. Fault scarp heights (x) across the fault define medium term vertical slip rates. While offset of the older Q9b surface (X' or X?) defines a long-term vertical slip rate.

Slip rates applied to fault sources in the NZ national seismic hazard model (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 Manawatū District. For example, most fault sources with a slip rate of ≥1.5 mm/yr (or 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 (or <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, because of 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 Awatere 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 Rauoterangi Fault (which is assigned an RI Class of IV later 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 New Zealand national seismic hazard model (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 Building Importance Category (BIC) states the relative importance of assessing the suitability of a building within, or proposed for, a fault avoidance zone (Kerr et al. 2003). The Building Importance Categories 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).

Building Importance Category	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 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 >500 m^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 BIC categories to make decisions about resource consents and to require conditions on buildings within fault avoidance zones (see Appendix 2). Table 3.5 shows the relationship between the fault rupture recurrence interval and BICs in previously subdivided or developed areas, and in greenfield sites (Kerr et al. 2003).

Table 3.5 Relationships between Recurrence Interval Class, Average Recurrence Interval of Surface Rupture, and Building Importance Category for Previously Subdivided and Greenfield Sites. From Kerr et al. (2003).

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

4.0 METHODOLOGY OF FAULT MAPPING

4.1 Data Used for Fault and Fault Avoidance Zone Mapping

Active fault traces have been mapped using a combination of LiDAR DEM and hill-shade models (Figure 3.1) and a regional-scale 1-m DSM[6]. 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 program and for much of the NZAFD is at scales of 1: 50,000 to 1: 250,000. GIS data (linework) from the NZAFD and QMAP were also reviewed alongside our mapping (Heron 2018; Langridge et al. 2016).

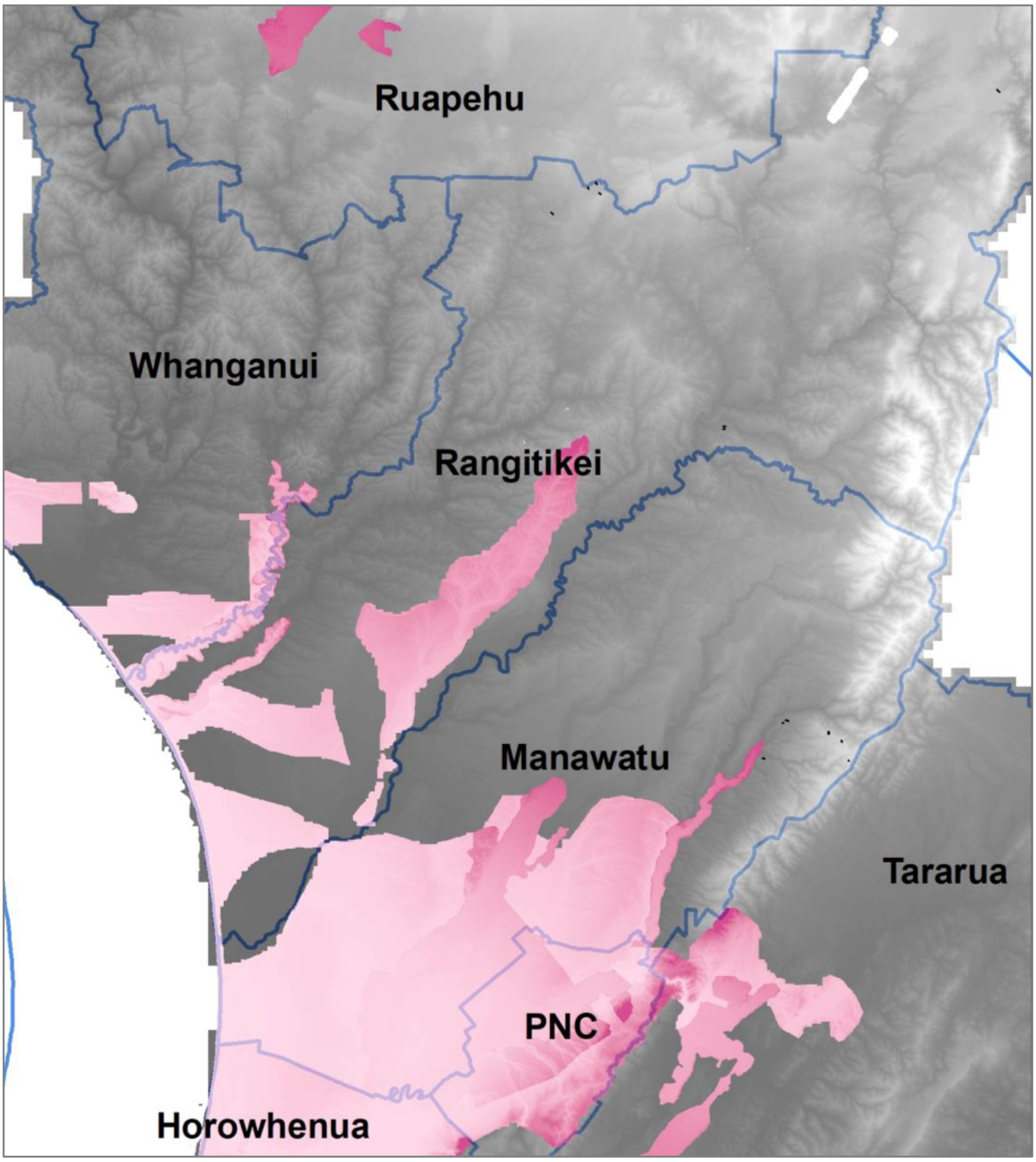

Figure 4.1 Digital topographic coverage across the central part of the Horizons Region used in this project. Airborne LiDAR is shown by pink shading and a regional 1-m DSM is shown with grey shading.

6 A DEM is a Digital Elevation Model and a DSM is a Digital Surface Model.

For current land use planning in regard to building on or adjacent to active faults, particularly in developed and developing areas (e.g. Begg et al. 1994), it is not appropriate to use features mapped at scales of 1:50,000 (or larger), because their locations are considered too imprecise. During the last decade, several campaigns of airborne LiDAR acquisition have been flown across the southern part of the Horizons Region. These acquisitions cover parts of the Manawatū, Pohangina and Rangitikei river floodplains and coastline (Figure 4.1). From these data, high quality 1-m DEMs and hill-shade models have been developed. The raw data from many of these acquisitions were supplied to GNS Science by Horizons for use in this project.

In areas where no LiDAR coverage exists, a 1-m DSM was developed by the Horizons Regional Council from aerial orthophotographs. Unlike the DEM developed from the LiDAR data, the DSM does not filter out vegetation or buildings, and so there is greater uncertainty in the fault mapping in those areas. However, the 1-m DSM allows for higher resolution mapping than the national scale 8-m DEM that was used for mapping active faults in the areas not covered by LiDAR data in the Horowhenua District and Palmerston North City by Langridge and Morgenstern (2019).

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

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

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, the features are somewhat less sharp or accurately located on the 1-m DSM compared to the LiDAR DEM due to vegetation cover (trees, scrub) or buildings. The diminished level of precision, and hence greater uncertainty in accurately locating the faults on the ground surface, in mapping on the DSM is reflected in the wider FAZs developed in those areas.

Table 4.1 Active fault data GIS attributes for the Manawatū 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
Fault_comp	The fault complexity term that is derived from the accuracy and the expression of the surface faulting. The Fault_comp terms are: trace 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
RI_Class	The average time between surface rupturing events on a fault, grouped into six classifications (RI Class I through 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 term called ‘Tect_origin’, which has descriptors of ‘definite’, i.e. definitely of tectonic origin, likely, or possible. Similarly, a decision was required on whether the feature or fault mapped was active. In most cases, features that were of definite or likely tectonic origin were deemed ‘active’ fault features, whereas features of possible tectonic origin were deemed ‘possibly active’ faults.

4.3 Fault Complexity

Fault complexity is an important parameter in the MfE Guidelines. It is defined within the MfE Guidelines 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, occurs between two *accurate* fault traces, over across a relatively short distance (200 m) or a greater distance (Table 4.1). For the former, the *approximate* trace could be termed ‘well-defined–extended’ because it is extended over a short distance, or in the latter case, termed ‘uncertain–constrained’. This is because at greater distances from an accurate fault location, the fault trace has the potential to waver or wiggle about where it cannot be mapped at the ground surface.

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

The term ‘uncertain’ is used for fault location and covers the fact that the location may be unclear due to subsequent deposition and/or erosion 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 A3.1).

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

Fault Location Accuracy	**Fault Complexity**	**Comment**
Accurate	Well-defined	Associated with a clear, sharp fault feature
Approximate	Well-defined–extended	Well-defined–extended, if the 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	Uncertain–constrained, if the constraint between two mapped traces is < 200 m
Uncertain	Uncertain–constrained	Uncertain–constrained, if the constraint between two mapped is < 200 m
	Uncertain–poorly constrained	Uncertain–poorly constrained, if the constraint between two mapped is < 200 m

4.4 Constructing Fault Avoidance Zones (FAZs)

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. In addition, the MfE Guidelines recommend that a '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 original mapped width of a given FAZ.

The slip type is relevant to understanding and anticipating the width of deformation in a future rupture. For strike-slip and normal faults we give no preference toward deformation on one side of the fault versus the other. However, for reverse faults, it has been demonstrated that deformation on the hanging-wall block (or uplifted side) generally occurs over a wider area relative to the footwall (Kelson et al. 2003). For example, folding, reverse drag faulting, and extension are typical on the upthrown 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 develop the FAZ is doubled on the hanging-wall side of reverse faults.

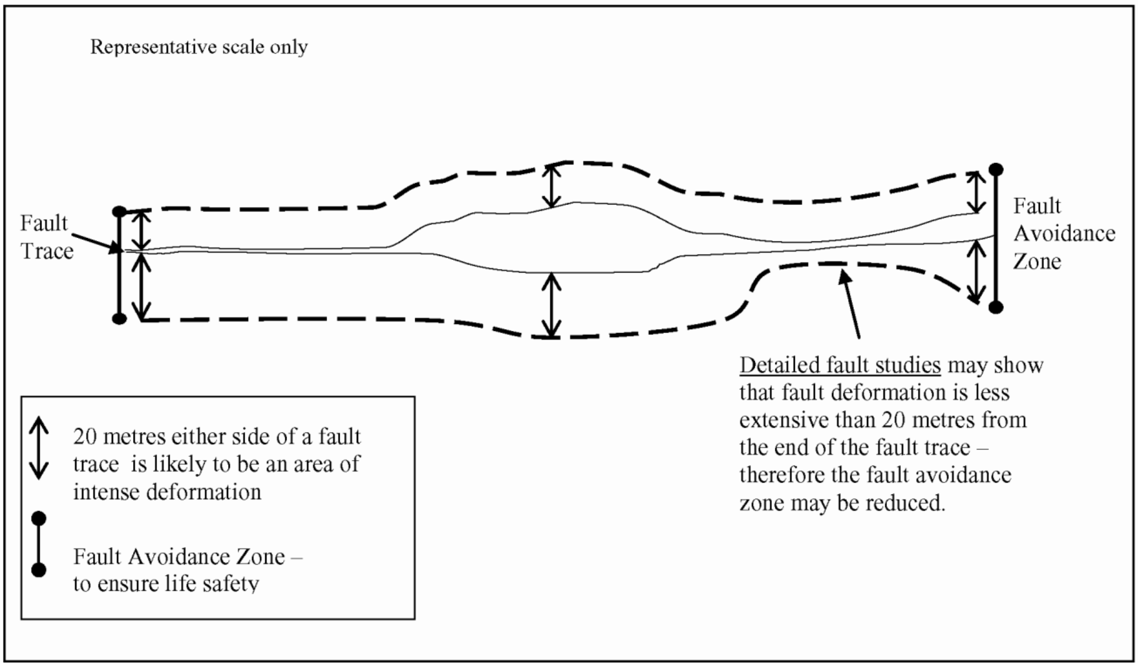

Figure 4.2 A Fault Avoidance Zone (FAZ; heavy dash) and how it may be developed for a district planning map (not drawn to scale), from Kerr et al. (2003). Note the 20 m 'margin of safety' buffer as part of the FAZ.

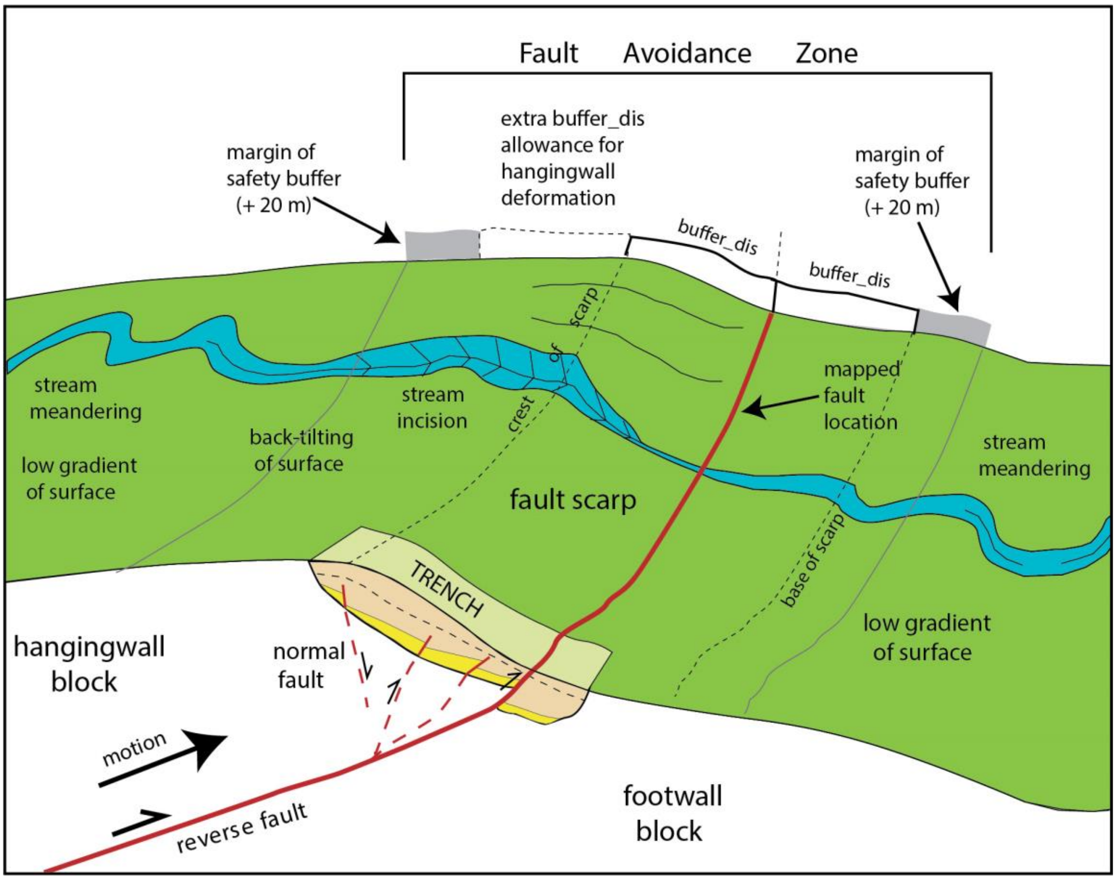

Figure 4.3 Schematic diagram of a dip-slip reverse fault and its scarp. In this case the mapped fault trace (rupture surface; bold red line) is mapped near the base of the scarp. The fault trace itself is 'accurately' mapped and the scarp is 'well-defined' on LiDAR data. The growth of such scarps affects the long-term morphology of streams that cross the structure. The trench shows the evidence for determining surface faulting events. 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 Fault Avoidance Zones may overlap. In these cases, the more accurate or higher-activity data (fault location, complexity) should dictate subsequent resource planning decisions. In the Manawatū 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 Fault Avoidance Zone map for a part of the active reverse-slip Mt Stewart-Halcombe Fault.

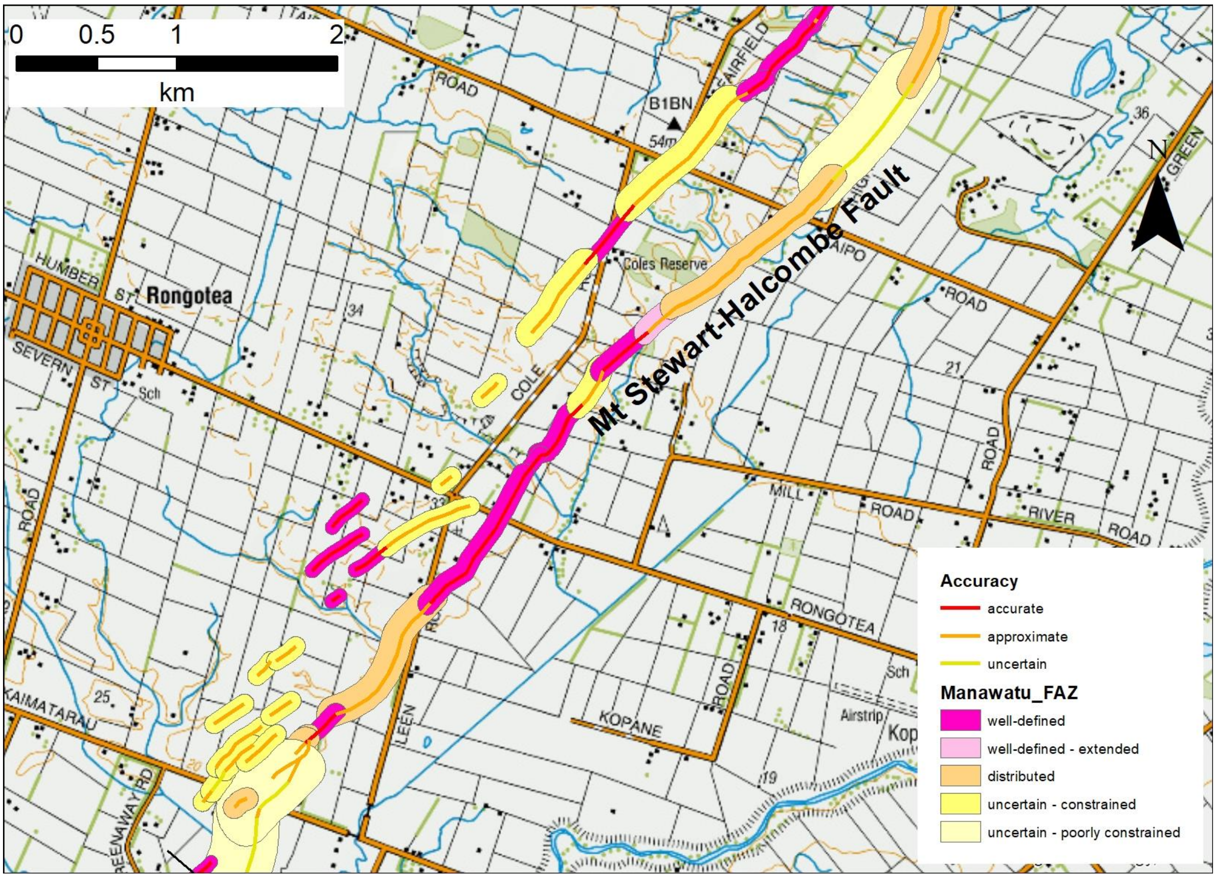

Figure 4.4 Fault Avoidance Zone map for part of the reverse-slip Mt Stewart-Halcombe Fault near Rongotea.

4.4.1 Fault Awareness Areas

Fault mapping at between 1:50,000 and 1:250,000 scale is 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 at 1:50,000 to 1:250,000 scale, a Fault Awareness Area (FAA) around the fault is recommended (Barrell et al. 2015). The purpose of a FAA is to highlight that there may be a tectonic future or 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 risk 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 of surface faulting and deformation. In this study, FAAs have been developed for parts of the strike-slip Ruahine Fault as illustrated in Figure 4.5, where we have used the fault linework from QMAP to define the location of the fault line against the DSM.

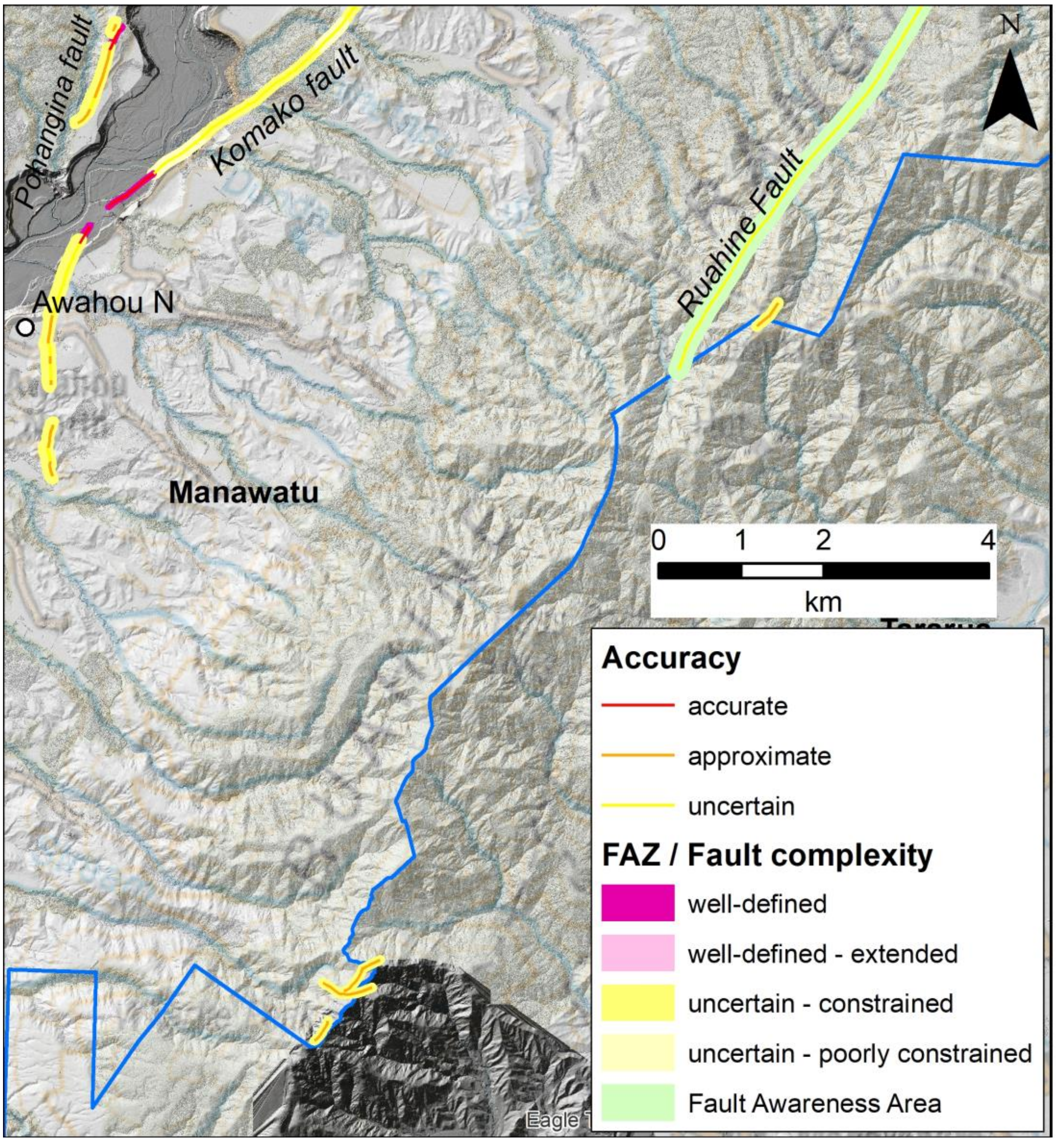

Figure 4.5 Fault Awareness Areas and FAZ map for the southern part of the Ruahine Fault in the Manawatū District.

4.5 Mapping Active Folds

Active folding is 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 have a blind or buried fault tip beneath the earth's surface (Figure 3.2). The axis of uplift along a fold on the upthrown (or hanging wall) side of a reverse fault is the measure of the high linear crest of uplift related to both the fault and the fold, called the axial trace of an anticline. In this study we have mapped several broad active anticlinal folds by mapping out the axial trace of the fold (see Chapter 5). We have mapped out the axial trace by surface profiling the DEM every 500–1500 m across the folded topography, picking either the highest point on the profile, or the area where the drainage changes direction.

While folds may be a manifestation of surface deformation related to fault movement, for the purposes of the MfE Guidelines, we do not treat active folds in the same way that we do active faults. It is not practical to develop a Fault Avoidance Zone (or 'Fold Avoidance Zone') for an active fold[7], 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.

7 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 FAULTS AND FOLDS OF MANAWATŪ DISTRICT

This study represents the first time that active fault mapping has specifically been collated for the Manawatū District (Figure 5.1). With the help of airborne LiDAR-derived DEM and a regional 1-m DSM, it was possible to map out several active faults, as well as 'possibly active' faults and folds, some of which were previously unrecognised. 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). Active (anticlinal) folds originally mapped by QMAP (e.g. Heron 2018) have been re-defined using airborne LiDAR and DSM datasets.

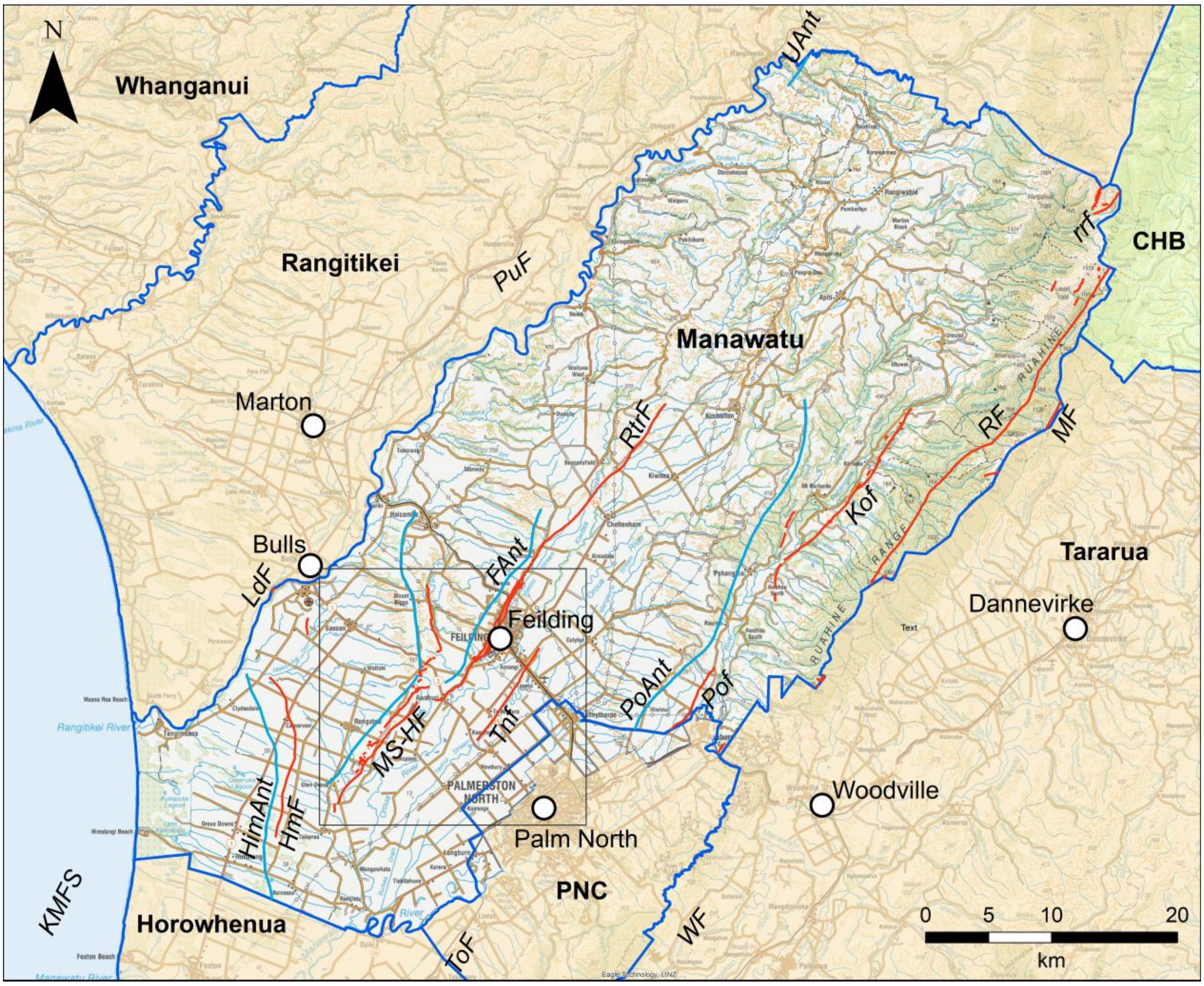

Figure 5.1 New and updated onshore active faults (red) and folds (blue) in the Manawatū District, as defined in this study. Active faults outside of Manawatū are shown by purple lines. Offshore active faults (orange lines) of the Kāpiti-Manawatū Fault System (KMFS) are from Nodder et al. (2007). Other districts in the Horizons Region are shaded orange. Fault name abbreviations are: ToF, Tokomaru Fault, WF, Wellington Fault; HmF, Himatangi Fault; MS-HF, Mt Stewart-Halcombe Fault; RtrF, Rauoterangi Fault; Tnf, Taonui fault; Pof, Pohangina fault; Kof, Komako fault; RF, Ruahine Fault; MF, Mohaka Fault, and rrf, short faults in the Ruahine Ranges. Fold names are: HimAnt, Himatangi; FAnt, Feilding, UAnt, Utiku and PoAnt, Pohangina anticlines. Box shows the area of Figure 5.2.

The Manawatū District straddles two major seismotectonic areas of the western North Island: the onshore-offshore Kāpiti-Manawatū Fault System (KMFS); and the North Island Dextral Fault Belt (NIDFB) bounding and within the Axial Ranges (Nodder et al. 2006; Litchfield et al. 2014). The KMFS is well-studied offshore and comes onshore between the Horowhenua and Rangitikei areas as a broad, NNE-striking zone of active reverse faulting (Figure 1.1). Onshore and within the Manawatū District, the KMFS broadly comprises the Himatangi Fault, Mt Stewart-Halcombe Fault, Rauoterangi Fault, Taonui fault and associated folds (Figure 5.1).

The NIDFB formed in association with oblique subduction along the Hikurangi margin and uplift of the Tararua Ranges (Beanland 1995; Litchfield et al. 2014). Within the Manawatū District, the NIDFB includes the Ruahine and Mohaka faults and other minor faults and fault traces (Figure 5.1).

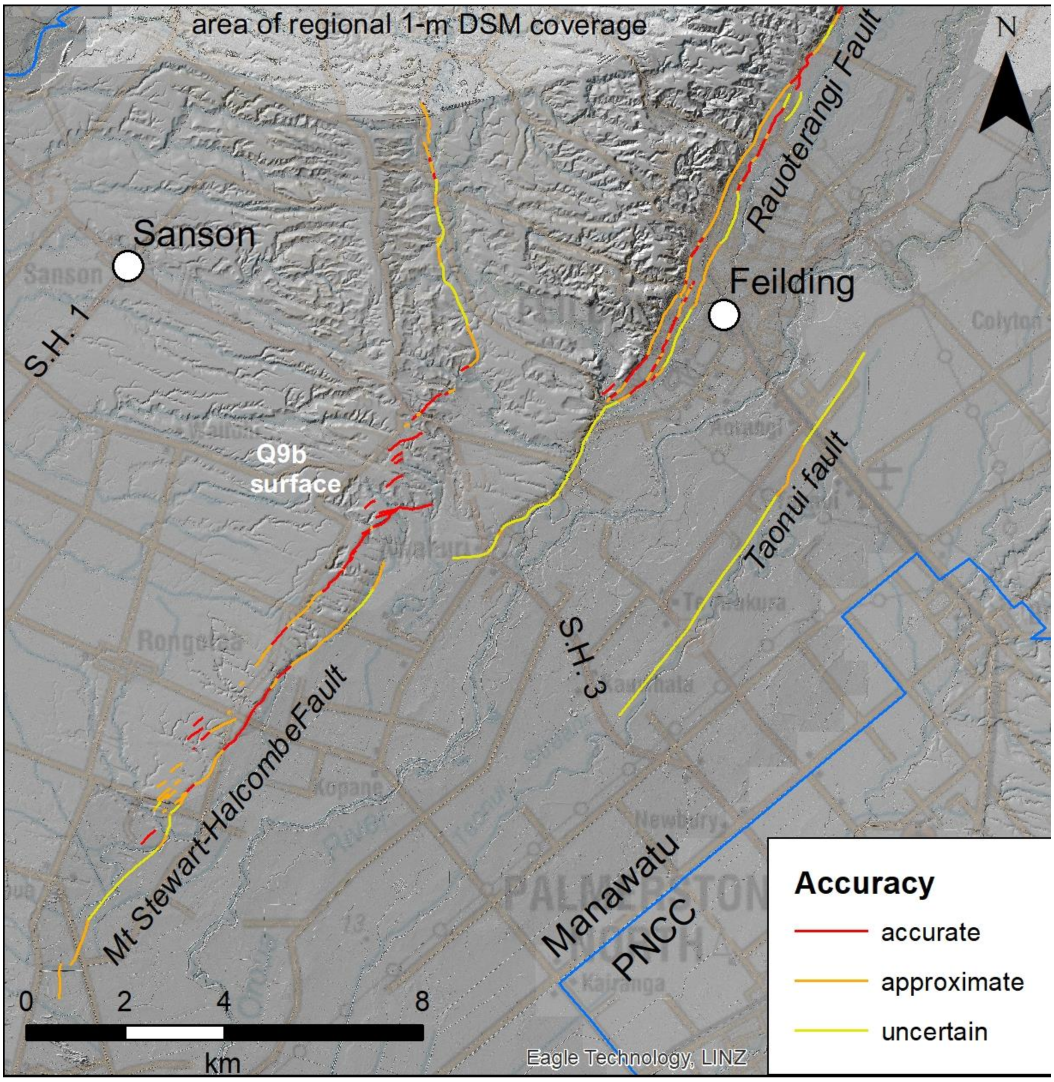

Figure 5.2 Fault mapping (defined in this study) for three active (or 'possibly active') faults in the southwestern part of the Manawatū District, highlighting fault accuracy designations.

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' is used to denote previously known faults or those that are recognised as 'definitely or likely' active faults; while the use of lower case 'fault' is used to denote features that are newly recognised/minor active faults, or are 'possibly' active faults.

5.1 Active Faults

This study represents the first time that active fault mapping has specifically been collated for the Manawatū District (Figure 5.1). Active faults are those that show definite or likely evidence of being active fault features, i.e. having evidence for movement or repeated movements during the last 125,0000 year (Langridge et al. 2016). Active faults, as defined in this study, are those for which FAZ are designed. These faults are generally described form southwest to northeast through the district.

5.1.1 Himatangi Fault (and Himatangi Anticline)

The 13-km long, north-striking Himatangi Fault is an active reverse fault located c. 10 km from the coastline (Figure 5.1). Mapping as part of this investigation has improved the location of what was formerly an unnamed and concealed active fault trace in regional geological (QMAP) mapping (Begg and Johnston 2000). The Himatangi Fault is defined by an up-to-the-west scarp that is largely mapped as approximate or uncertain (location) along its length between Makowhai Stream in the north and Downs Road near Oroua Downs in the south (Figure 5.3). The scarp is typically quite broad (10's to 100's of m wide), implying that warping may exist for a considerable distance to the west of the fault scarp. The exception is where it crosses Kaimatarau Road, where the fault scarp is relatively sharp and c. 10–12 m high and so is characterised as accurate in this location (Figure 5.4).

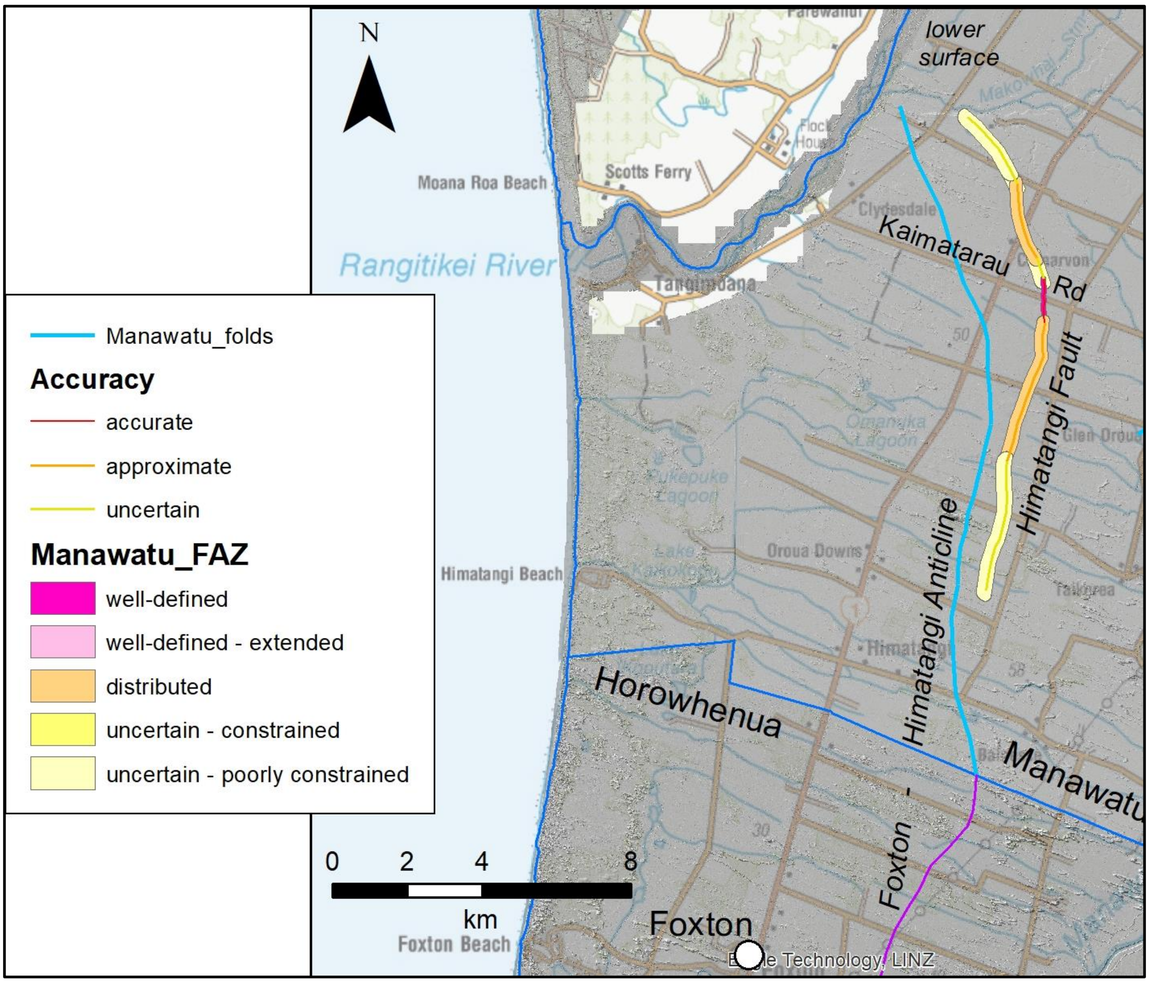

Figure 5.3 Active traces and fault avoidance zones developed for the Himatangi Fault. The mapped traces are shown as accurate, approximate, and uncertain. The Himatangi Anticline (blue) probably connects with the Foxton Anticline (purple line within Horowhenua) of Langridge and Morgenstern (2019).

Begg and Johnston (2000) had previously mapped the Himatangi Anticline as a north-trending ridge immediately west of a concealed active fault. The Himatangi Anticline is mapped here in the Manawatū District between Makowhai Stream and Horowhenua in the south, where it becomes the Foxton Anticline of Langridge and Morgenstern (2019). Townsend et al. (2008) show that the large scarp in the area of Kaimatarau Road is formed by older near-shore deposits (Q9b; 0.303–0.339 million years (Myr)) to the west, truncated and juxtaposed against Holocene dune deposits (Q1d; <12,000 years) on the downthrown side of the scarp.

The HimatangiAnt earthquake source is defined in the NSHM as a 26 km-long NW-dipping reverse fault that broadly links the Himatangi Fault/Anticline with the Foxton Anticline in the south (Figure 3.2). The NSHM assigns an average slip rate of 0.3 mm/yr, and calculates a magnitude (M_w) of 6.9, and an average recurrence interval of 6036 years (Stirling et al. 2012). Based on the amplitude of folding along the Foxton Anticline, Langridge and Morgenstern (2019) estimated a recurrence interval of >5000 years for uplift events on this anticline.

Figure 5.4 East-facing scarp of the Himatangi Fault along Kaimatarau Rd, delineated by white arrows. Across the road the scarp is c. 12 m high.

Estimations of vertical slip rate based on observations along the fault trace, e.g. scarp height of 10–20 m across the Q9b surface (Figure 3.2) suggest a slip rate of c. 0.03–0.06 mm/yr, which translates to a reverse dip-slip rate of 0.04–0.08 mm/yr for a fault with a dip range of 50–70°. This value at least four times less than that in the NSHM (Stirling et al. 2012), which may imply a considerably longer recurrence interval than calculated in the NSHM. Despite this difference, we tentatively place the Himatangi Fault within RI Class IV, having a recurrence interval of >5000–≤10,000 years, because of its relationship to the Himatangi Anticline and its similarity to other nearby structures.

FAZs developed for the Himatangi Fault range in width from 130 m at Kaimatarau Road (for an accurate: well-defined FAZ) to 415 m at the southern and northern ends of the fault (for an approximate: distributed FAZ) (Figure 5.3).

5.1.2 Mt Stewart-Halcombe Fault (and Mt Stewart-Halcombe Anticline)

The Mt Stewart-Halcombe Fault was formerly identified within the NZAFD as a single-trace, NNE- to north-striking, NW-dipping reverse fault in southwestern Manawatū (Langridge et al. 2016). Detailed mapping on LiDAR hill-shade models has allowed us to better characterise the location and width of deformation associated with the Mt Stewart-Halcombe Fault (Figure 5.5).

The Mt Stewart-Halcombe Fault is defined here as a 21-km long active reverse fault. It is associated with the Mt Stewart-Halcombe Anticline (Te Punga 1957), which occurs c. 1 km to the west of the fault traces. The southernmost 16 km of the mapped fault comprises a frontal reverse fault trace. In places the north-western side of the fault is characterised by secondary faults and lineaments which suggest secondary fault deformation in the hanging-wall block. A significant bend in the fault occurs near Mt Stewart. The change in strike (orientation) in the Mt Stewart-Halcombe Fault (from NNE to north) is accomplished in the Mt Stewart area through a series of NE-striking and left-stepping fault traces that link the northern and southern parts of the fault (Figure 5.5).

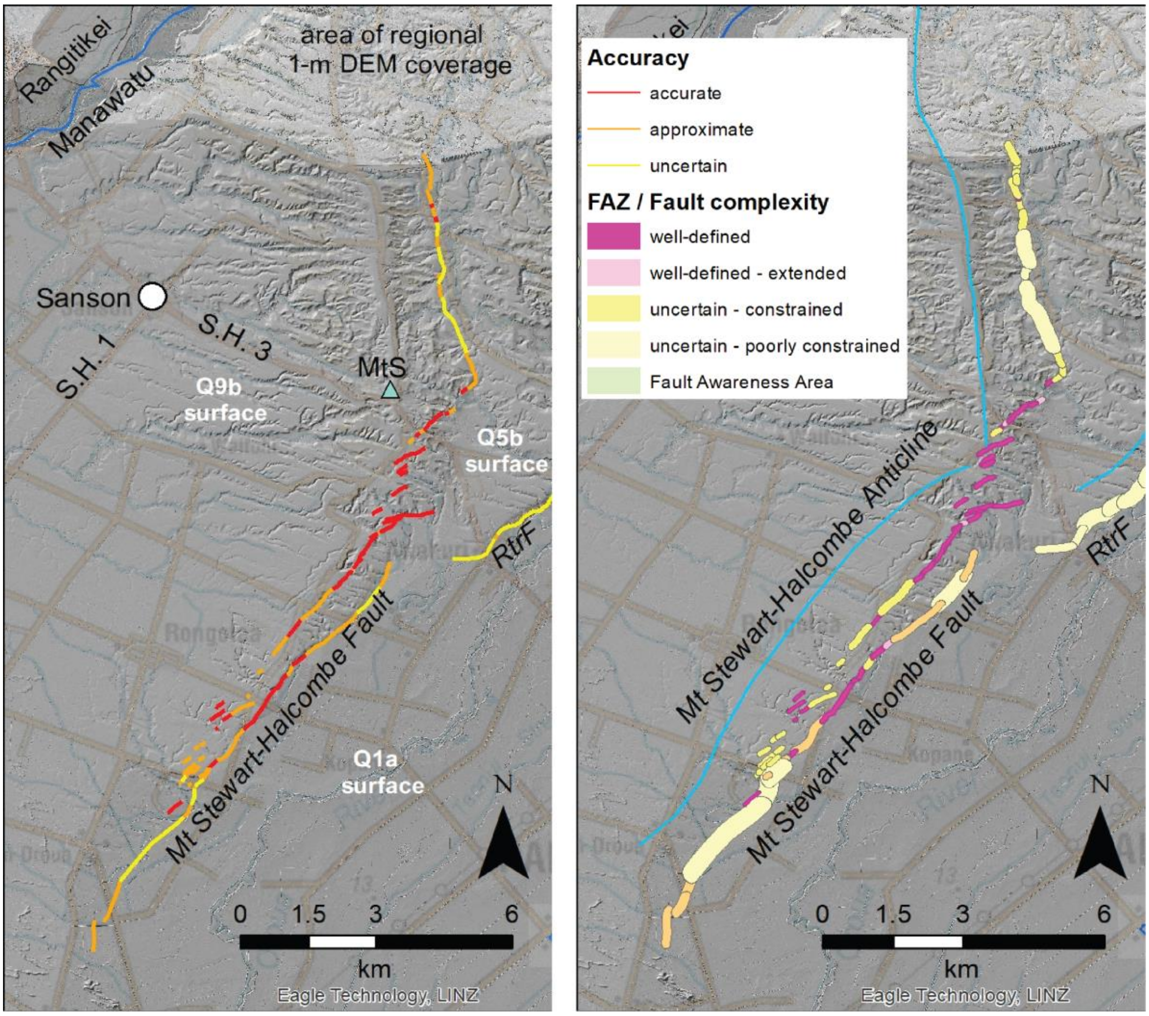

Figure 5.5 Maps of active (and likely active) faults and fault avoidance zones (FAZ) for the NNE- and north-striking Mt Stewart-Halcombe Fault and Rauoterangi Fault (RtrF). Left. The locations of active traces are mapped as either: accurate (green), approximate (orange) or uncertain (yellow) lines. MtS is Mt Stewart. Right. The axial trace of the Mt Stewart-Halcombe Anticline (pink) extends to the north of the mapped fault. FAZ designations range from well-defined to uncertain–poorly constrained.

Prior to this study, no RI Class was assigned to the Mt Stewart-Halcombe Fault in the NZAFD (Van Dissen et al. 2003; Langridge et al. 2016). We mapped and profiled scarp heights of up to 28 m across the fault east of Rongotea (Figure 5.6). The geological surface on the upthrown side of the fault is a Q9b shallow marine surface (0.303–0.339 Myr; Begg and Johnston 2000), while on the downthrown side of the fault the surface is a Q1a alluvial surface (<12,000 years). This means that the vertical separation across the Q9b surface we are measuring is likely a minimum (because on the downthrown side, it is likely to have been buried), and therefore a minimum vertical slip rate for the Mt Stewart-Halcombe Fault is c. 0.09 mm/yr. This translates to a reverse dip-slip rate of 0.10–0.12 mm/yr for a fault with a dip range of 50–70°.

The Mt Stewart Halcombe Anticline was defined by Melhuish et al. (1996) and Jackson et al. (1998). Townsend et al. (2008) show the anticline continuing north, beyond the mapped trace of the fault, as far as the village of Halcombe. The 'MtStew' earthquake source is defined in the NSHM as a 19 km-long west-dipping reverse fault structure that follows the Mt Stewart Halcombe Anticline (Figure 5.5). The NSHM assigns an average slip rate of 0.3 mm/yr and calculates a magnitude (Mw) of 6.7 and an average recurrence interval of 4411 years (Stirling et al. 2012). While we note that the average recurrence interval in the NSHM would imply it has a RI Class of III (>3500–≤5000 years), the length of traces of the Mt Stewart-Halcombe Fault that we have mapped would translate to a larger magnitude and longer recurrence time in the NSHM. Therefore, in this study we apply a RI Class IV to the Mt Stewart-Halcombe Fault (>5000 to ≤10,000 years), because the fault has a similar geology and appearance to other reverse fault/fold structures in faults in Horowhenua, Manawatu and Rangitikei (Jackson et al. 1998; Langridge and Morgenstern 2019).

FAZs developed for the Mt Stewart-Halcombe Fault range in width from 115 m for an accurate: well-defined FAZ up to 415 m in width for an uncertain–poorly constrained FAZ (Figure 4.4).

Figure 5.6 The southeast-facing scarp of the Mt Stewart-Halcombe Fault along Taipo Rd (arrows at the base of the scarp). The scarp at this location is c. 20 m high, across Q9b and Q5b geomorphic units on the upthrown side of the fault.

5.1.3 Rauoterangi Fault (and Feilding Anticline)

Active traces of the northeast-striking Rauoterangi Fault have been mapped along the rangefront of the Feilding Anticline for the first time because of the availability of airborne LiDAR for this study (Figure 5.2 and Figure 5.7). The Rauoterangi Fault was previously shown as a concealed and inactive thrust fault on QMAP geological maps (Townsend et al. 2008). The Rauoterangi Fault has long been recognised in association with the active Feilding Anticline which forms the western hills adjacent to Feilding (Te Punga 1957; Jackson et al. 1998).

In this study, active reverse fault traces of the Rauoterangi Fault have been mapped through the western suburbs of Feilding township adjacent to the western hills (Figure 5.8). The western hills are capped by Q9b deposits (Figure 5.9) (0.303–0.339 Myr; Townsend et al. 2008). In places along the rangefront, erosion through the Q9b surface has exposed older geological units. The downthrown side of the Rauoterangi Fault through Feilding is characterised by a Q2a alluvial surface (age 12,000–24,000 years) deposited by a former course of the Oroua River, and locally Kiwitea Stream. Incision by the river and stream and subsequent deposition has created Holocene alluvial terraces (Q1a; age <12,000 years). These units define the age and rates of deformation derived below for the Rauoterangi Fault.

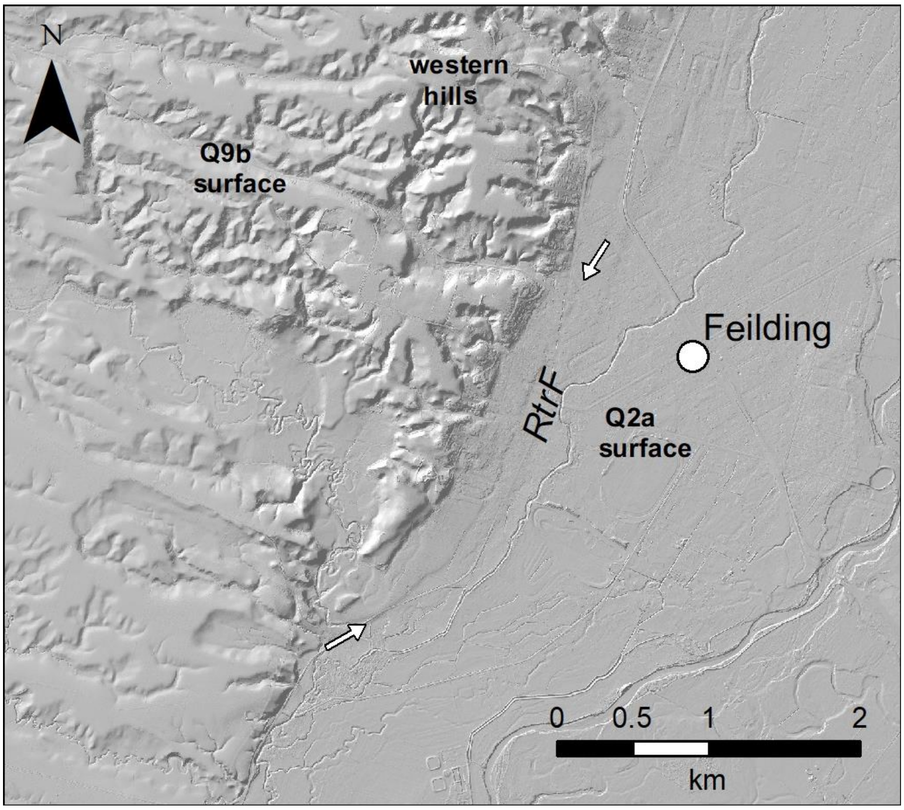

Figure 5.7 Identification of the active NNE-striking Rauoterangi Fault (RtrF) proximal to Feilding township. Active traces have been identified as linear scarps running near the base of the western hills in suburban Feilding (marked by white arrows). The western hills are formed by the uplift of a Q9b marine surface. In places the Rauoterangi Fault comprises two sub-parallel scarps (underneath and to the right of the RtrF label).

In this study we have also mapped the step rangefront edge of the western hills as being a ‘possibly active’ fault (Figure 5.10). This recognises that it is unclear whether this steep edge was formed by fluvial cutting, e.g. by the river systems during the last cold climate period, or by distinct tectonic activity (deformation).

Figure 5.8 A well-defined active trace of the Rauoterangi Fault forming a fault scarp (between arrows) at the end of Coronation Street in suburban Feilding. Houses at the end of the street are sited on the upthrown (western) side of the scarp. The raised elevation in the background is part of the western hills formed by the Feilding Anticline.

Figure 5.9 The east-dipping, uplifted Q9b marine surface forming the top of the western hills of Feilding (taken from Highfield Rd). The crest of the anticline is to the right of the photo and the Q9b surface warps downward toward the active traces of the Rauoterangi Fault within the township.

A minimum long-term vertical slip rate can be derived for the Rauoterangi Fault using a profile from the western hills to the Oroua River. The western hills are up to c. 48 ± 4 m above the Q2a surface of the Oroua River, yielding a minimum long-term vertical slip rate of c. 0.15 mm/yr. The vertical slip rate could be significantly higher than this, considering that the Q9b surface is likely buried on the downthrown side of the fault (see Figure 3.3). This translates to a reverse dip-slip rate of 0.17–0.20 mm/yr for a fault with a dip range of 50–70°. A medium-term vertical slip rate can be derived by profiling the deformation in the Q2a surface at the foot of the western hills. In this case, there appears to be c. 3–4 m of uplift and deformation of the Q2a surface, yielding a vertical slip rate of c. 0.13–0.33 mm/yr. This translates to a reverse dip-slip rate of 0.14–0.43 mm/yr for a fault with a dip range of 50–70°. Based on these two estimates we suggest a vertical slip rate for the Rauoterangi Fault of c. 0.3 ± 0.1 mm/yr. Such a value translates to a dip-slip rate of c. 3 m every 10,000 years.

From these calculations we infer that the Rauoterangi Fault may have a surface-rupturing earthquake event roughly every 5000–10,000 years, which would place it into RI Class IV (>5000–≤10,000 years). The NSHM assigns an average slip rate of 0.3 mm/yr, magnitude M_w 7.0 and an average recurrence interval of 7429 years to the 'FeildingAnt' source, i.e. the Feilding Anticline as an earthquake source (Stirling et al. 2012). These data are consistent with our designation of RI Class IV for the Rauoterangi Fault.

FAZs developed for the Rauoterangi Fault range in width from 100 to 115 m for accurate: well-defined FAZ to 190 m for an uncertain: uncertain–poorly constrained FAZ. Appendix 2 provides more context regarding FAZs and FAAs within suburban Feilding (Figure 5.10).

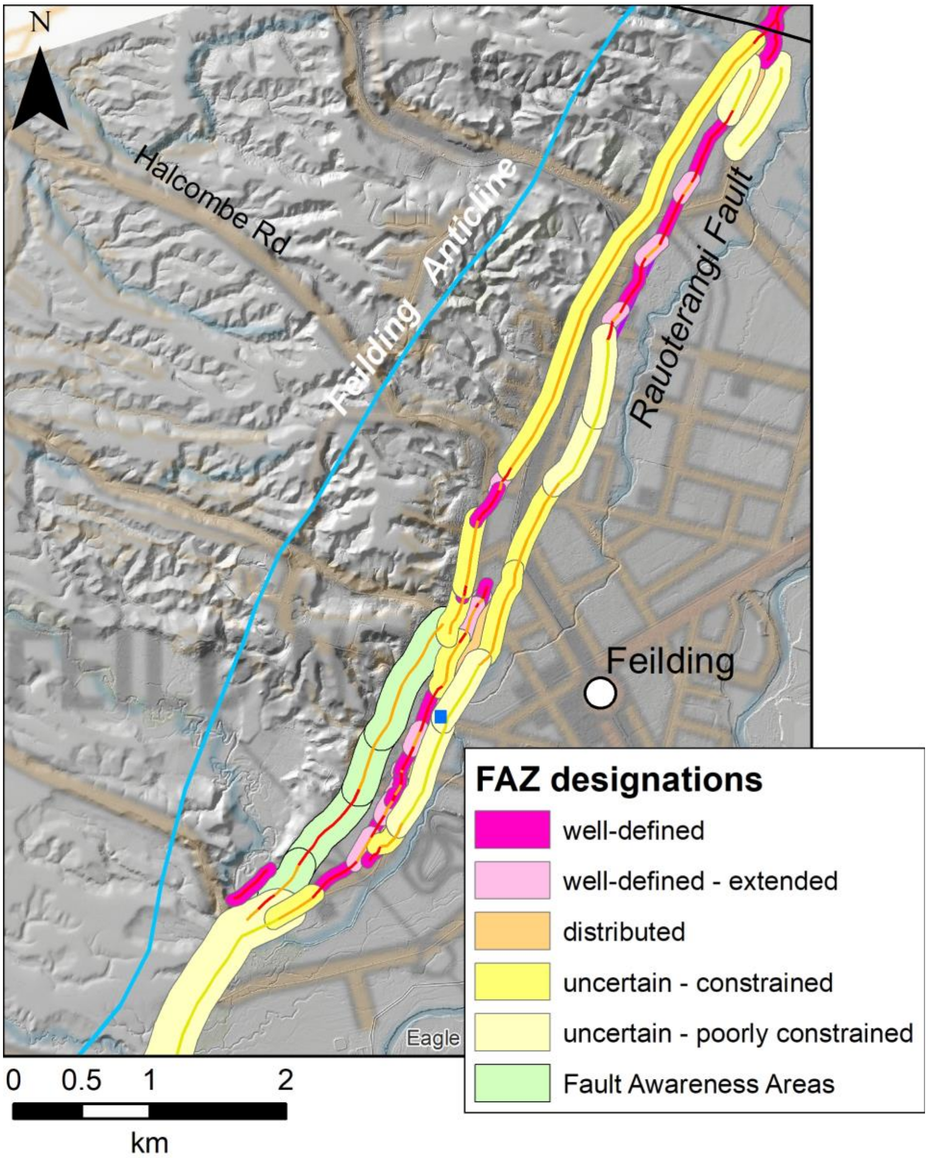

Figure 5.10 Fault Avoidance Zone (FAZ) and Fault Awareness Area (FAA) map for the Rauoterangi Fault in suburban Feilding. The FAA defines an area where there is less certainty regarding the origin of the linework along the range front of the western hills. Blue square highlights the location of the photo taken in Figure 5.8. The axis of the Feilding Anticline is shown by a blue line.

5.1.4 Ruahine Fault

The northeast-striking Ruahine Fault is a right-lateral (dextral) strike-slip fault located in the eastern part of the Manawatū District (Figure 5.11). Along with the Mohaka Fault that occurs c. 2.4 km to the southeast of it, the Ruahine Fault is one of the most active faults in the NIDFB. Past studies of the Ruahine Fault suggest a dextral slip rate of 1–2 mm/yr, a single-event displacement of 2–5 m, and a recurrence interval of 1000–5000 years (Beanland and Berryman 1987; Hanson 1995). Based on these data, a preliminary RI Class of II, i.e. recurrence interval of >2000 to ≤3500 years has been assigned to the Ruahine Fault (Van Dissen et al. 2003).

Within the Manawatū District, we have mapped the Ruahine Fault largely from the 1-m regional DSM using previous fault locations from QMAP and the NZAFD (Heron 2018; Lee et al. 2011; Langridge et al. 2016). Along much of its length, the location of an active trace of the Ruahine Fault is uncertain (Figure 4.5 and Figure 5.11), therefore we have used the pre-existing fault line data to define the Ruahine Fault with FAAs.

In some areas, particularly to the southwest of Pohangina Saddle (Figure 5.11) the fault has been mapped as accurate or approximate on the 1-m regional DSM, and FAZs have been developed for these traces. Short traces on the east side of the crest of the Ruahine Range have typically been mapped (named) with the Ruahine Fault, while a single trace on the west side of the range crest, 3 km from the Ruahine Fault, is left unnamed.

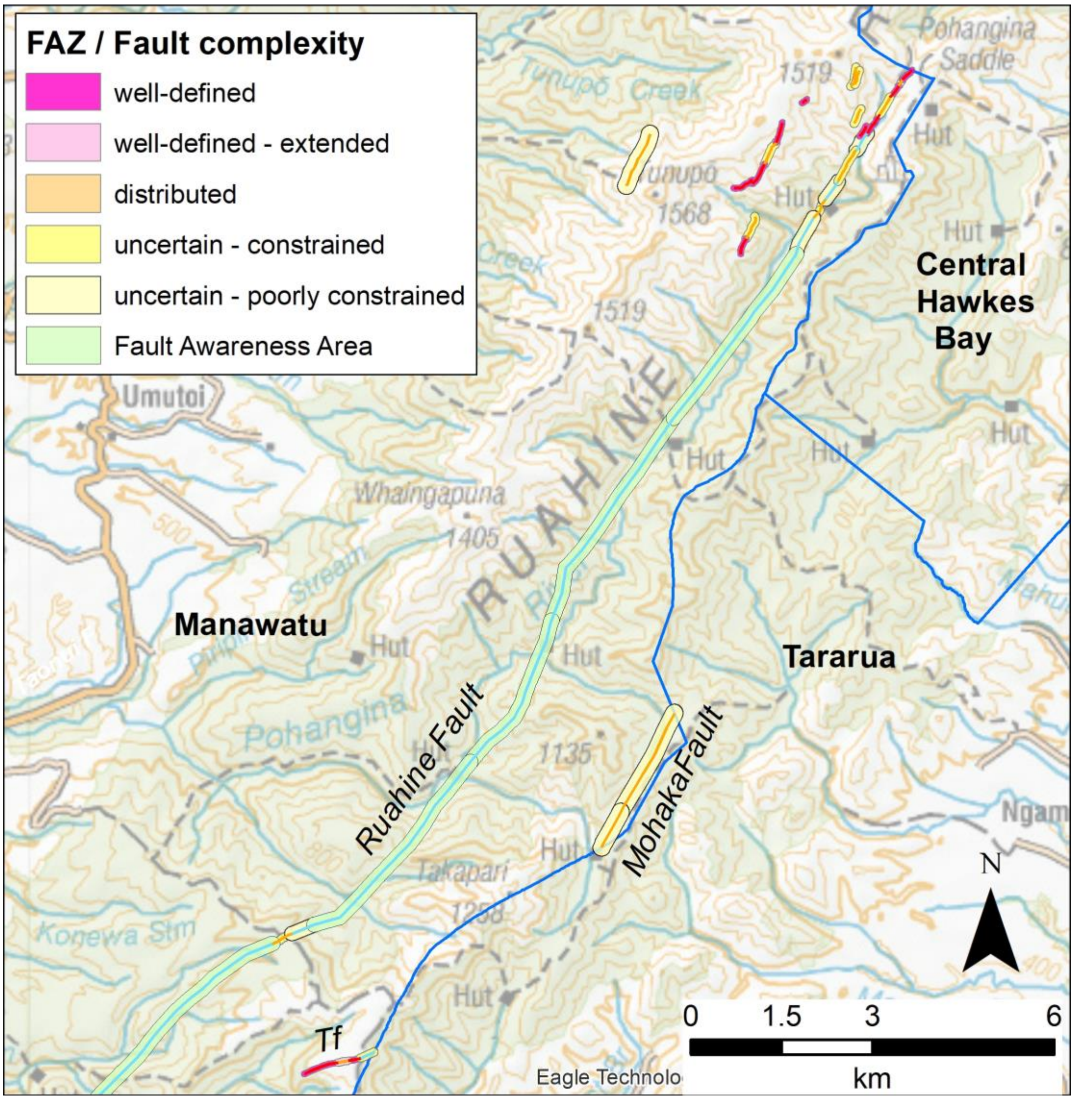

Figure 5.11 Fault Avoidance Zone and Fault Awareness Area map for the northern part of the Ruahine Fault, Mohaka Fault and Traverse fault (Tf) in the Manawatū District.

5.1.5 Mohaka Fault

The northeast-striking Mohaka Fault is a right-lateral (dextral) strike-slip fault and is the northward continuation of the Wellington Fault in the Horizons Region (Figure 5.1; Hanson 1995; Langridge et al. 2005). It is the most active fault in the Manawatū District and has a RI Class designation of I (≤2000 years) (Van Dissen et al. 2003). In this study, the Mohaka Fault is mapped over a distance of c. 2.5 km at the Manawatū-Tararua district boundary, between Cattle Creek Hut and Apiti Saddle (Figure 5.11).

Mapping of this stretch of the Mohaka Fault was undertaken using the 1-m regional DSM and previous fault location from the NZAFD and QMAP (Heron 2018; Langridge et al. 2016; Lee et al. 2011). The fault follows hillslopes and linear valleys in the headwaters of the Pohangina River (see Figure 5.12).

In this study we have developed a FAZ for the Mohaka Fault which has an 'uncertain–poorly constrained' fault complexity, and a subsequent FAZ of 290 m width along its length within the Manawatū District (Figure 5.11).

Figure 5.12 Oblique aerial photograph of the active trace of the Mohaka Fault along the foot of its range front (between white arrows) at Moorcock Stream in Central Hawke's Bay District. (source: L Homer: GNS Science).

5.1.6 Leedstown Fault

The Leedstown Fault is a major NNE-striking active fault which is almost entirely within the Rangitikei District. Here we include the Leedstown Fault as part of our description of the Manawatū District, because a short (300 m) section of the fault and associated FAZs occur within the district (Figure 5.1 and Figure 5.13).

A short trace with an uncertain fault location is mapped in the bed of the Rangitikei River near Parewanui Road at the outlet of Tutaenui Stream. The reverse-slip Leedstown Fault was formerly defined as being a RI Class IV fault (Van Dissen et al. 2003; Langridge et al. 2016). In this study we apply this RI Class (>5000 to ≤10,000 years) to the Leedstown Fault near Ohakea. Fault Avoidance Zones (FAZs) developed for the Leedstown Fault in the Manawatū District are shown on Figure 5.13.

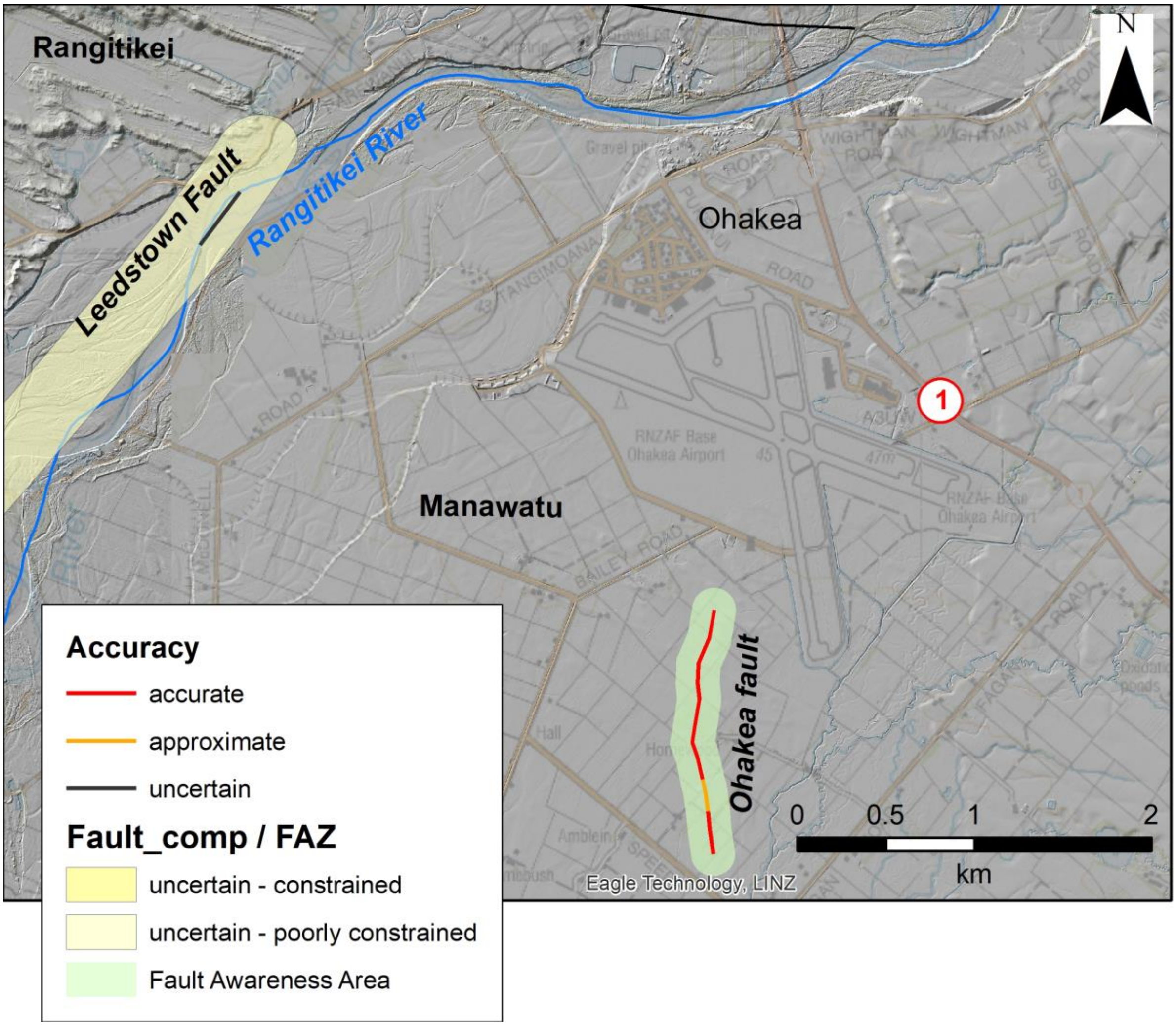

Figure 5.13 Fault linework (black) and FAZs for the active Leedstown Fault in the Manawatū District, and a Fault Awareness Area for the 'possibly active' Ohakea fault.

5.1.7 Other Active Faults

Several short (<3 km) sets of active fault traces have been mapped on the 1-m regional DSM in the eastern part of the Manawatū District in the Ruahine Ranges area. In this study, we denote these faults by a lower case (fault) name, because these are considered minor faults due to their length. We have identified and named the Traverse fault (Figure 5.11) and Howlett Creek, Taumataomekura, and Dirty Spur faults (Figure 5.13) after nearby landmarks in the Ruahine Ranges. Other shorter traces have been mapped and are unnamed or are associated more closely with the Ruahine Fault (Figure 5.11). In each case, a decision was made that these features were more likely to be of tectonic origin, as opposed to gravitational features or lineaments, because they formed, semi-continuous linear zones of ground deformation, that in many cases crossed (rather than paralleled) topographic ridgelines.

The 1.2 km long Traverse fault was previously identified as an active fault trace by QMAP and the NZAFD (Heron 2018; Lee et al. 2011; Langridge et al. 2016). This ENE-striking fault occurs near the Manawatū district boundary cutting across the NE-trending crest of the Ruahine Range.

The 2.9 km long, northeast-striking Howlett Creek fault was previously unmapped but has been identified from the 1-m regional DSM at the eastern edge of the Manawatū District between Daphne Ridge and the main crest of the Ruahine Range.

The 2.4 km long, NNE- striking Taumataomekura fault was previously unmapped but has been identified adjacent to the Howlett Creek fault, immediately west of the main crest of the Ruahine Range (Figure 5.13). Further traces have been mapped on trend with these active fault traces, c. 2.5 km to the north in the Rangitikei District, along with several prominent landslide scars within the ranges.

The 1.3 km long, northeast-striking Dirty Spur fault is mapped immediately east of Mt Pourangaki. The fault cuts across a SE-trending spur (Dirty Spur) and generally follows a NE-trending spur toward Pourangaki Hut in the Rangitikei District (Figure 5.13). The Taumataomekura and Dirty Spur faults have mapped traces in both the Manawatū and Rangitikei districts.

We provisionally place all of these faults and features into RI Class IV (>5000 to ≤10,000 years) because they have produced deformation across sub-alpine terrain during the Holocene, i.e. over the last 11,700 years or so. In other words, because they have produced fault traces since the end of the last glacial period, then they would arguably have a maximum RI Class of IV.

In this study we have developed FAZs for the Howlett Creek, Taumataomekura, Dirty Spur and Traverse faults. These range in width from 100 m for accurate: well-defined fault traces, to 200 m for approximate: uncertain–constrained fault traces.

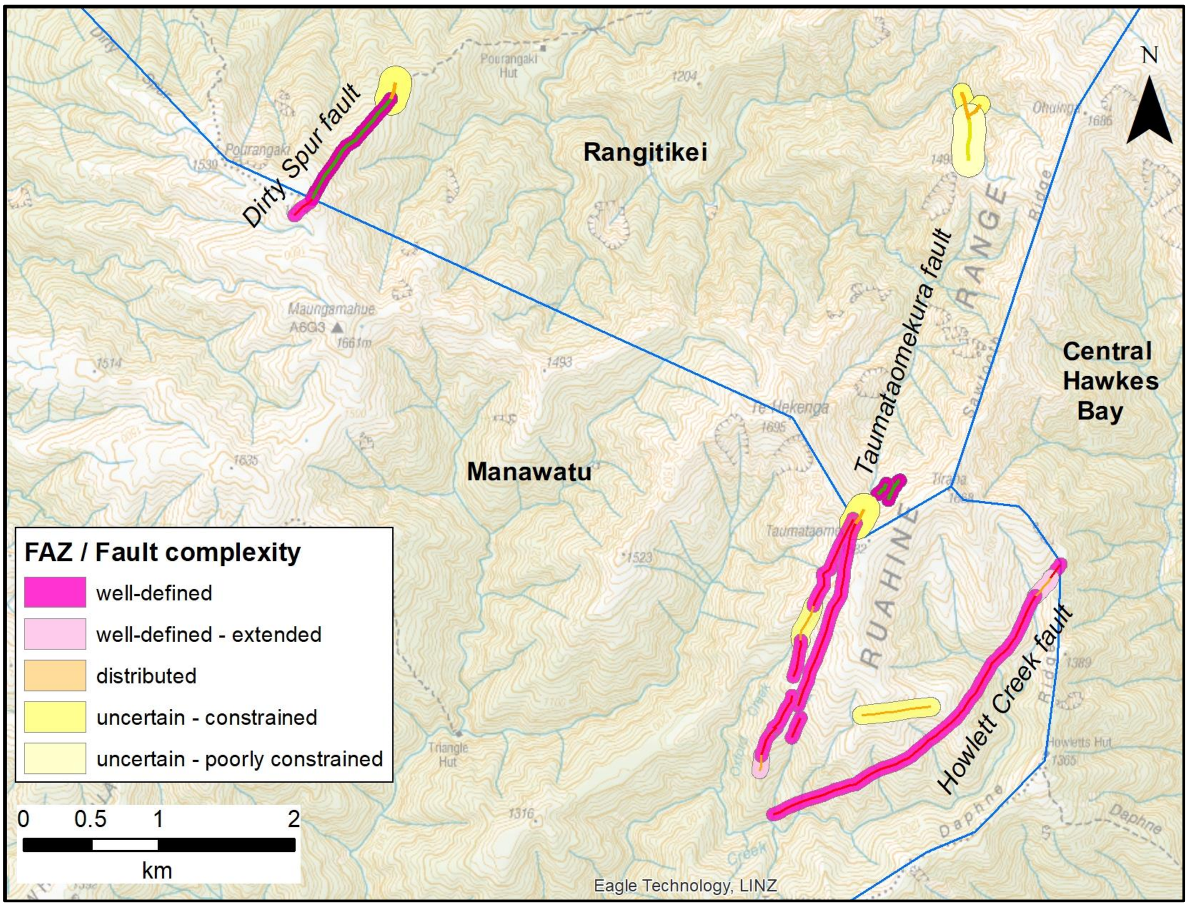

Figure 5.14 Active fault traces mapped (and FAZs) in the north-eastern corner of the Manawatū District and in the south-eastern corner of the Rangitikei District in the Ruahine Ranges area.

5.2 Possibly Active Faults

Possibly active faults are treated distinctly to active faults (those treated as 'definitely or likely') in this report. Possibly active faults are mapped features that have a significant amount of uncertainty as to whether they are active tectonic features because: (1) they may be scarps that have a fluvial origin; (2) they may be scarps that have a gravitational origin, e.g. ridge rents, landslide scars etc.; (3) they exist in an area where a geologic fault is known but no active fault trace has yet been identified, e.g. there may be a blind/buried fault, but no known surface trace. The data for possibly active faults will not be uptaken into the NZAFD at this time. In general, possibly active fault features require more work or evidence to elevate them to be active faults. In this study they are shown as Fault Awareness Areas, 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.

5.2.1 Ohakea fault

During this study we recognised a topographic feature near Ohakea, that we here define as the Ohakea fault (Figure 5.3 and Figure 5.15). As we cannot be certain that this feature is a fault and not simply of alluvial origin, we have classified it as a 'possibly active' fault here. This 9-km long NNE-trending feature has been recognised from an airborne LiDAR hill-shade model (Figure 5.15). An approximate fault trace has been mapped over a distance of c. 1.1 km NW of Taonui and east of Feilding. This trace is mapped as a scarp or warp in the landscape with c. 3–4 m height across a Q2a alluvial terrace (age 12,000–24,000 years), near Camerons Line. However, over most of its length, (between Kauwhata and near Colyton), the feature is mapped as an uncertain trace with a down-to-the-southeast sense. The mapped Taonui feature follows the same NNE-trending geomorphic grain as the Rauoterangi Fault and Pohangina Anticline (discussed below). As such, one of the main reasons for identifying it is that it forms a subtle ridge that separates the SW-flowing Oroua River from Taonui Stream.

If this feature is a fault, then a vertical slip rate can be derived by profiling the deformation across the Q2a surface. Using the scarp height across the Q2a surface (from above), yields a vertical slip rate of c. 0.12–0.33 mm/yr. This vertical slip rate translates to a reverse dip-slip rate of c. 0.13–0.43 m every 10,000 years. From these calculations we infer that the Ohakea fault may have a surface-rupturing earthquake event roughly every 5000 to 10,000 years, which would place this active reverse fault into RI Class IV (>5000 to ≤10,000 years).

A Fault Awareness Area (FAA) is developed for the Ohakea fault because we have defined it as a 'possibly' active fault (Figure 5.13). The designation of a FAA highlights presence of a possible active fault in the general area and recognises that more work needs to be undertaken to prove fault activity along the length of it. The preliminary recurrence interval range defined above is therefore only useful if it is proven as active and is also not applied in the context of a FAA.

5.2.2 Taonui fault

During this study we recognised a topographic feature near Taonui, that we here define as the Taonui fault (Figure 5.3). As we cannot be certain that this feature is a fault and not simply of alluvial origin, we have classified it as a 'possibly active' fault here. This 9-km long NNE-trending feature has been recognised from an airborne LiDAR hill-shade model (Figure 5.15). An approximate fault trace has been mapped over a distance of c. 1.1 km NW of Taonui and east of Feilding. This trace is mapped as a scarp or warp in the landscape with c. 3–4 m height across a Q2a alluvial terrace (age 12,000–24,000 years), near Camerons Line. However, over most of its length, (between Kauwhata and near Colyton), the feature is mapped as an uncertain trace with a down-to-the-southeast sense. The mapped Taonui feature follows the same NNE-trending geomorphic grain as the Rauoterangi Fault and Pohangina Anticline (discussed below). As such, one of the main reasons for identifying it is that it forms a subtle ridge that separates the SW-flowing Oroua River from Taonui Stream.

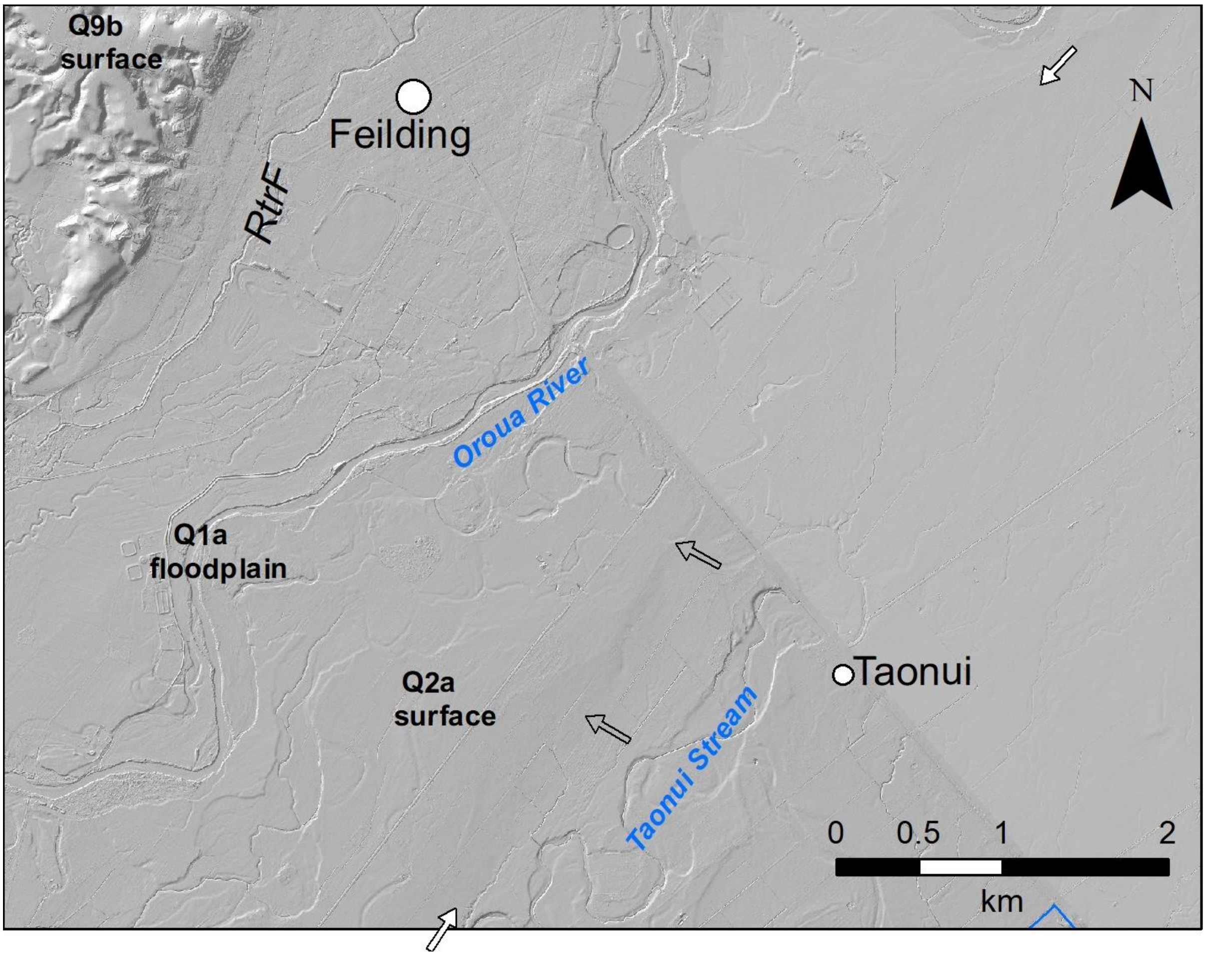

Figure 5.15 Location of the NE-striking Taonui fault (new) to the southeast of Feilding marked by white arrows on an uninterpreted LiDAR hill-shade image.The accurately located part of the Taonui Fault is bracketed by open arrows. The Taonui Fault separates the SW-directed Holocene (Q1) drainages of Taonui Stream from the Oroua River. RtrF = Rauoterangi Fault.

If this feature is a fault, then a vertical slip rate can be derived by profiling the deformation across the Q2a surface. Using the scarp height across the Q2a surface (from above), yields a vertical slip rate of c. 0.12–0.33 mm/yr. This vertical slip rate translates to a reverse dip-slip rate of c. 0.13–0.43 m every 10,000 years. From these calculations we infer that the Taonui fault may have a surface-rupturing earthquake event roughly every 5000–10,000 years, which would place this active reverse fault into RI Class IV (>5000–≤10,000 years).

A Fault Awareness Area (FAA) is developed for the Taonui fault because we have defined it as a ‘possibly’ active fault. The designation of a FAA highlights possible presence of an active fault in the general area and recognises that more work needs to be undertaken to prove fault activity along the length of it. The preliminary recurrence interval range defined above is therefore only useful if it is proven as active and is also not applied in the context of a FAA.

5.2.3 Raukawa Fault

The Raukawa Fault, c. 2 km southeast of Ashurst, is a named high-angle reverse fault striking northeast across the western flank of the main axial range dipping 80° southeast (Rees et al. 2017; Figure 5.16). The fault was not identified as being active by Rees et al. (2017), i.e. indicating no evidence of Late Quaternary faulting (Langridge et al. 2016), though it does deform Pliocene to Pleistocene sediments to the south and north of the Manawatū Gorge.

In this study we interpret the Raukawa Fault as a ‘possibly’ active fault. North of Saddle Road, Rees et al. (2017) map the fault as a concealed reverse fault. South of Saddle Road, they show the Raukawa Fault as having a trace continuing SW across the Manawatū Gorge. South of the gorge, the fault is mapped across alluvial terrace deposits spanning Q4 (59,000–71,000 years before present [BP]) to Q1 (<12,000 years BP) (Lee et al. 2011). However, mapping by Langridge and Morgenstern (2019) failed to identify an active trace on the south side of the Manawatū Gorge toward Raukawa Pa, within Palmerston North City (Figure 5.16).

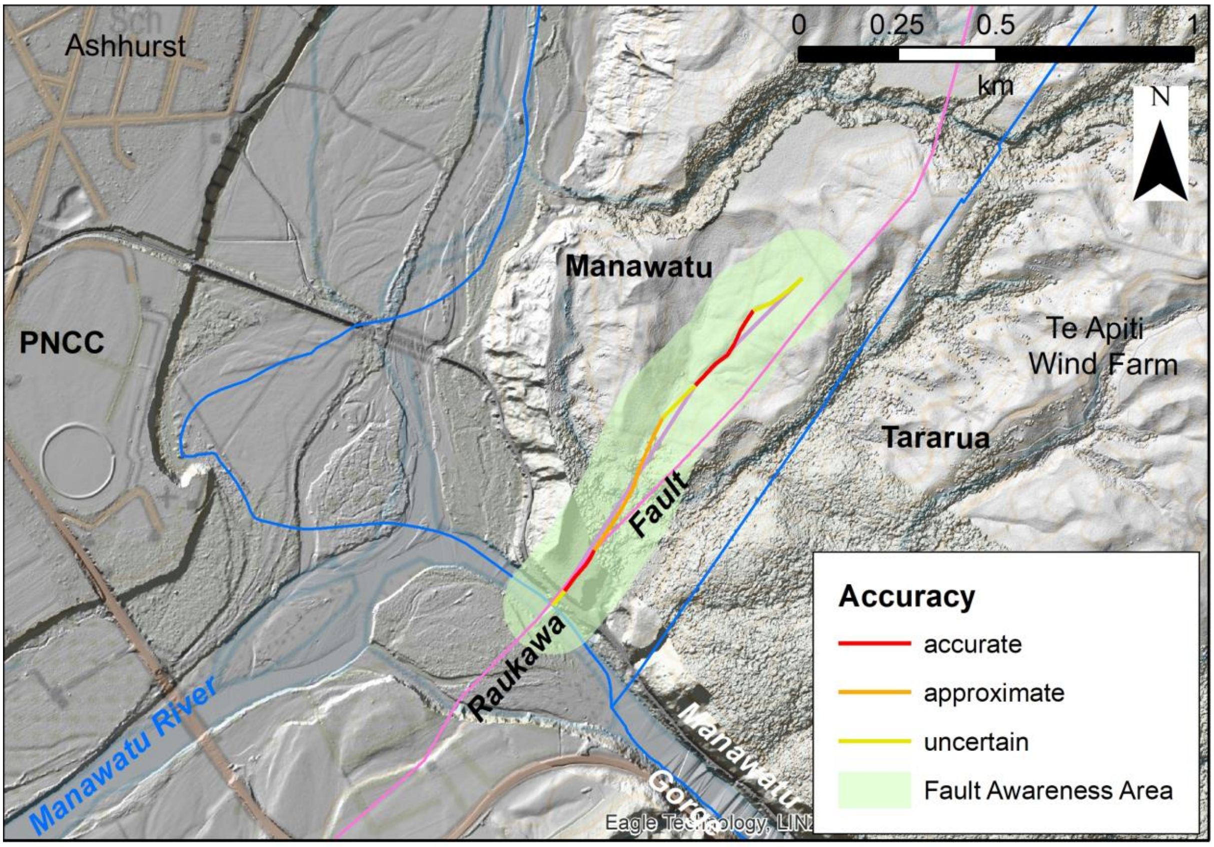

Figure 5.16 Mapped locations of the ‘possibly active’ Raukawa Fault near Manawatū Gorge. The pink line represents the trace of the fault from a geological map by Rees et al. (2017). The traces mapped in this project have an accuracy term (accurate, approximate or uncertain). The ‘possibly active’ Raukawa Fault is marked by a Fault Awareness Area in this study.

As part of this project we reviewed the LiDAR coverage of this area and looked for evidence of active faulting along the Raukawa Fault in both the Manawatū District and Palmerston North City. South of the gorge, it is possible that the fault is active, though no clear fault trace can be mapped for any significant distance across river terraces. This could signify that there have been no more than one fault movement since the abandonment of the Q2a (12,000–24,000 years BP) alluvial terrace in this area.

On the north side of the Manawatū Gorge we mapped an NNE-striking riser (scarp) within an unnamed stream valley, southwest of the Te Apiti Wind Farm. This riser is of unknown origin, but may be a fault scarp, or an alluvial terrace riser.

A FAZ has not been developed for the Raukawa Fault in this study, because it is not clear that the fault is active. Instead, we have developed a Fault Awareness Area (FAA) for the Raukawa Fault, with a dimension of 250 m width, centred around the features mapped in this study (Figure 5.16). The designation of a FAA highlights the presence of a possible active fault in the general area and recognises that more work needs to be undertaken to document and locate active faulting along the length of it.

5.2.4 Pohangina fault (and Pohangina Anticline)

In this study, the northeast-striking Pohangina fault[8] describes an active fault located to the southeast of the Pohangina Anticline (Figure 5.17) (Te Punga 1957; Jackson et al. 1998). The fault features mapped in this study follow the location of a concealed active fault shown on QMAP geological maps (Heron 2018; Lee et al. 2011). However, at its southern mapped extent in Manawatū District, it is not clear that this line marks the surface trace of an active fault, as opposed to an alluvial terrace riser.

Mapping by Langridge and Morgenstern (2019) did not find definitive evidence for an active Pohangina fault within Palmerston North City, and instead they re-mapped the axial trace of the Pohangina Anticline and extended it farther toward the city.

In this report, we identified three stretches of a mappable feature in the Manawatū District that we associate with the Pohangina fault. In the south, the first of these is a NNE-trending feature mapped for c. 6.2 km from Grove Road, near Ashhurst, to Pohangina Road on the west side of the Pohangina Valley (Figure 5.17 and Figure 5.18). This feature is well located across abandoned and uplifted alluvial terraces of the Pohangina River. However, a major uncertainty with confirming this feature as an active fault trace is whether it is of tectonic (i.e. a fault scarp) or of alluvial (i.e. a terrace riser) origin. The Pohangina Valley runs parallel to the Pohangina Anticline (and fault), and its course is dictated by the growth of the Pohangina Anticline. West of the Pohangina River, alluvial terraces are progressively uplifted and trimmed by the river; thus, an active fault trace would run parallel to the river and alluvial terrace risers. In this case, we assert that there is considerable uncertainty about the origin of the feature and so, rather than state that it is an active fault, we believe it is more useful to apply a FAA of width 250 m to this feature.

We have also mapped a short, 3 km long continuation of this possible active fault trace south of Grove Road within Palmerston North City (PNC; Figure 5.1), not previously shown in the GNS report for Horowhenua and Palmerston North by Langridge and Morgenstern (2019). This is treated in the same way as the southernmost of the mapped feature lengths described above, i.e. from Grove Road to Pohangina Valley Road and a FAA applied to it. An update of this finding will be supplied to the Horizons Regional and Palmerston North City councils.

The second of the mapped stretches within the Manawatū District occurs over a distance of c. 3.2 km near Awahou North on the east side of the Pohangina River (Figure 5.17). This stretch comprises several short, north-striking and east-facing active fault traces. These occur to the south of another fault feature (Komako fault; see below), although their

8 Note the use of lower case ‘fault’ for the Pohangina fault. This is because it is not clearly identified as an active fault at the Earth’s surface in this study.

association to the Pohangina fault (as mapped) is uncertain at this time. These features are likely to be of fault origin and therefore, FAZ with widths of 190 m have been defined for them.

The third of these stretches is mapped over a distance of c. 3.2 km parallel to Beehive Creek on the west side of Pohangina Valley (Figure 4.5). Several of the traces mapped have an accurate or approximate fault location. However, it is unclear whether they are primary fault traces, secondary fault traces related to deformation in the hanging-wall of another fault, or possibly even gravitational structures (e.g. landslide scarps), due to their proximity to the Pohangina River. Though there is some uncertainty regarding their origin, it seems apparent that the river and the fault are in close proximity in this area near Beehive Creek. In this case, because the features mapped are more likely to be of tectonic than alluvial origin, FAZs have been defined for them. These FAZs range in width from 190 m for an uncertain–constrained FAZ and 220 m in width for an uncertain–poorly constrained FAZ.

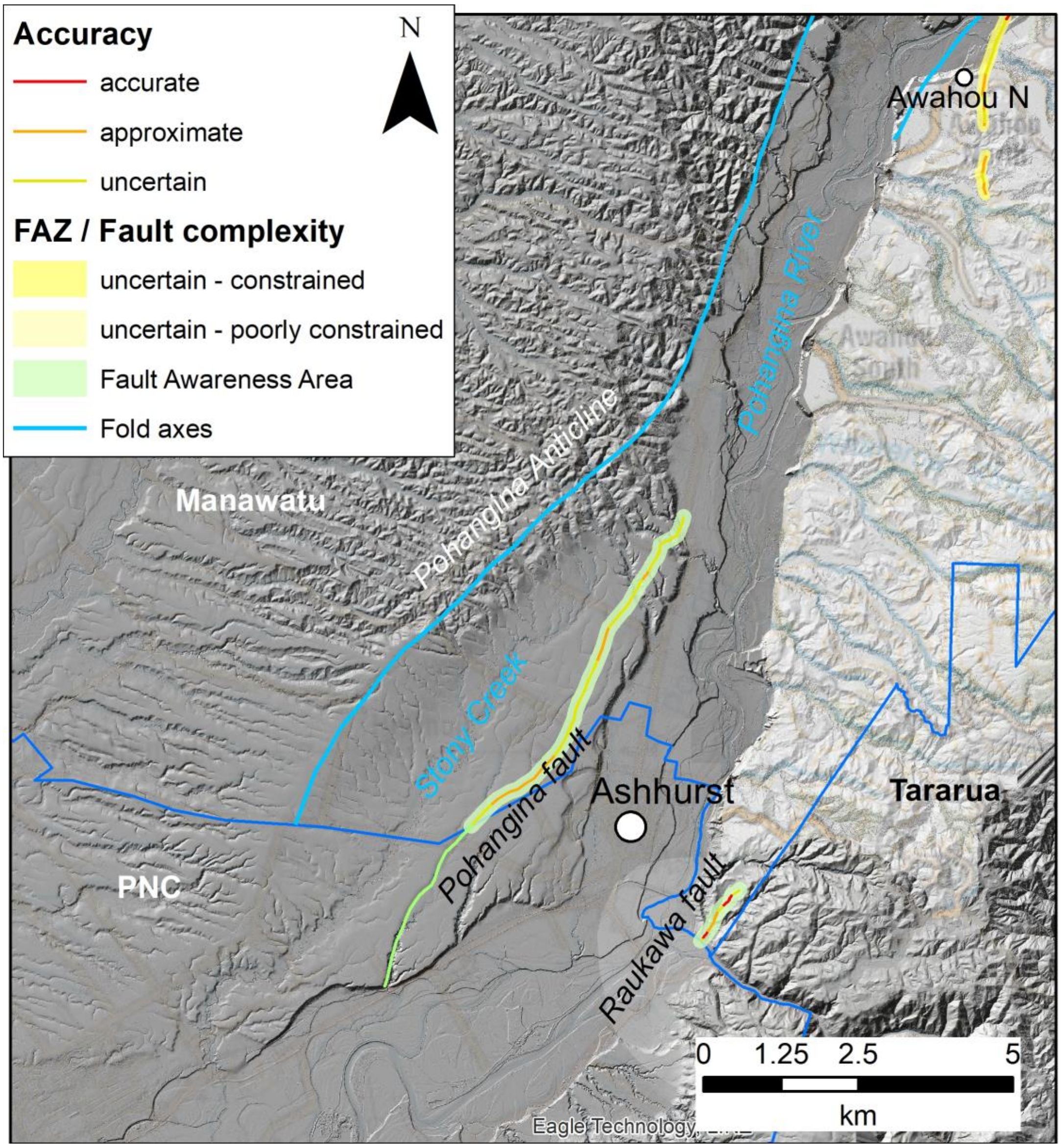

Figure 5.17 Possible fault traces and folds of the Pohangina Valley area. Fault Awareness Areas and FAZs at Awahou North are also shown. Possible fault traces are shown as either: accurate (red), approximate (orange) or uncertain (yellow) lines, and green within Palmerston North City (PNC). The axial trace of the Pohangina Anticline is shown in blue.

Figure 5.18 View to the west of a scarp across Grove Road, near Ashhurst (car on top of riser). The riser (identified by arrows) is interpreted as a 'possible' fault scarp relating to the Pohangina fault.

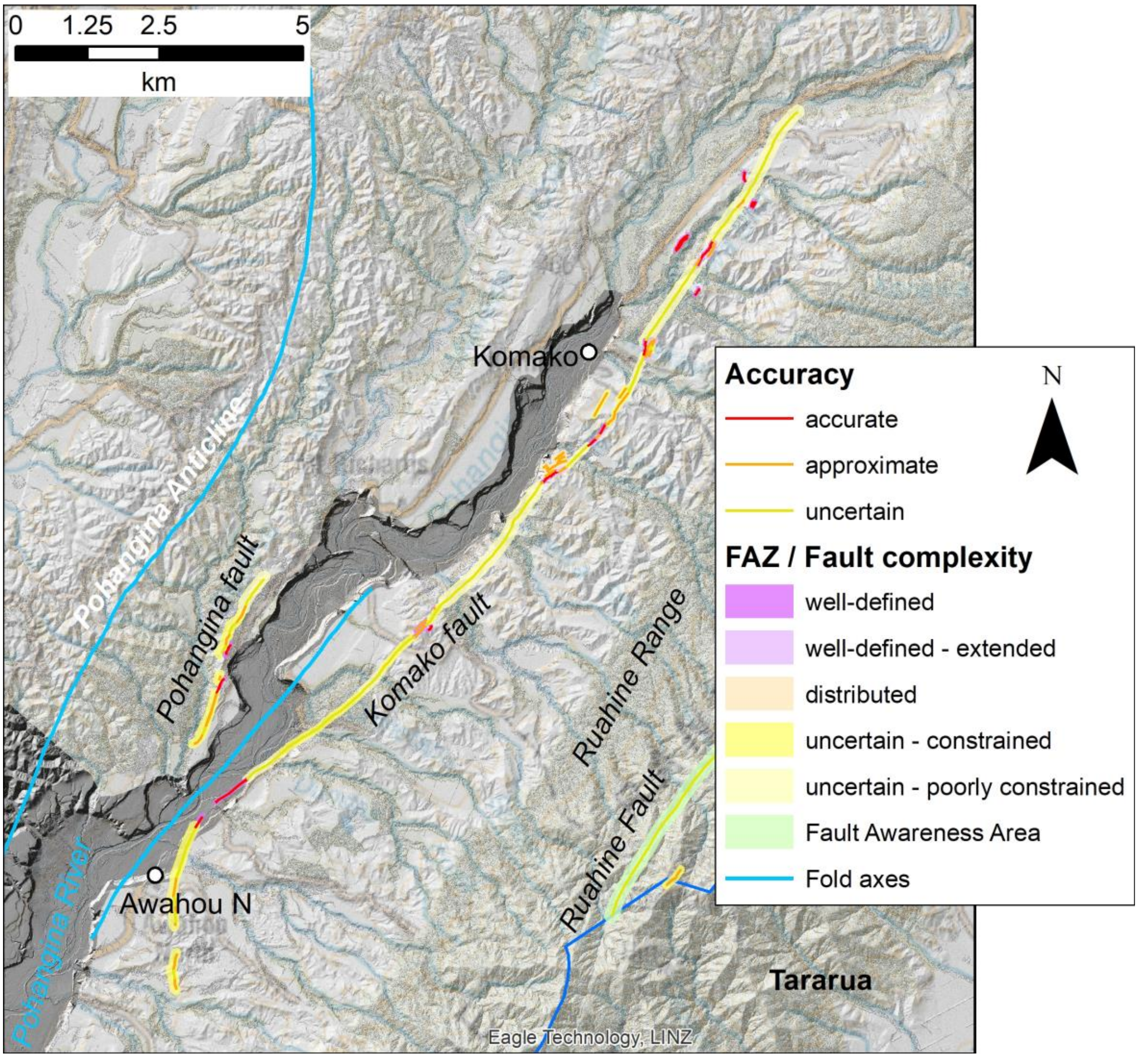

Figure 5.19 Active fault traces mapped, and FAZs and FAAs constructed for faults in the upper Pohangina Valley and Ruahine Range areas of the Manawatū District.

In summary, there is undoubtedly an active reverse fault associated with the Pohangina Anticline and Valley. However, as outlined above, it is not always clear that we have located active surface traces for this fault. We also consider it possible that deformation related to the Pohangina Anticline could occur in association with a concealed or buried reverse fault, as shown by QMAP geological maps (Heron 2018; Lee et al. 2011). For example, a concealed Pohangina fault would logically occur between the axis of the Pohangina Anticline and an active syncline mapped by QMAP near Awahou North, roughly following the axis of Stony Creek (Figure 5.17). Nevertheless, the features that are mapped may well be fault traces, and as such we have at this time assigned them FAZs in some cases, and FAAs in others.

In terms of its tectonic activity, Langridge and Morgenstern (2019) provide a discussion of the possible recurrence interval of fold growth for the Pohangina Anticline from several different aged alluvial surfaces preserved on the uplifted western flank of the anticline. They conclude that the appropriate recurrence interval for the Pohangina Anticline is RI Class IV, having a recurrence interval of fold growth of c. >5000 to ≤10,000 years. This value can be applied to the Pohangina fault, whether it is an emergent surface fault, or a buried or blind active fault.

5.2.5 Komako fault

Komako fault is a new fault name given to a mapped structure on the east side of the Pohangina River (Figure 5.1). A series of discontinuous active fault traces of the Komako fault have been mapped as part of this study over a distance of c. 16 km from near the Dundas Creek mouth to the Piripiri Campsite area in the north (Figure 5.19). The Komako fault represents an important structure shown in the NSHM of Stirling et al. (2012), which was informally named ‘RuahineRev’, denoting a reverse fault structure related to the adjacent Ruahine Range.

The exact relationship between the Komako fault and the Pohangina fault and Anticline are poorly understood at this time. Nevertheless, it has been important to map active traces for consideration as surface fault rupture hazards. In addition, the recurrence interval of the Komako fault is not well known at this time. However, due to its proximity to the Pohangina fault and Anticline, and the similarity in activity shown across several structures in the Manawatū District, it is reasonable to assume that the Komako fault has a similar recurrence interval to those other structures. We note that several of the mapped traces cut across flat but elevated terrace formations that can be ascribed to the Q2a (12,000–24,000 years BP) period of alluvial deposition. Therefore, we apply a preliminary RIC IV (>5000–≤10,000 years) to the Komako fault, assuming that the fault has produced ground deformation at least once in the last 24,000 years or less.

FAZs developed for the Komako fault range in width from 100 to 140 m in width for an uncertain–constrained FAZ up to 240 m in width for an uncertain–poorly constrained FAZ (Figure 5.19).

5.3 Active Folds

As discussed elsewhere, active folds are an important indicator of active tectonic deformation – particularly related to reverse faulting – in the coastal and alluvial areas of the Manawatū and neighbouring districts (Figure 5.20). FAZs are not developed for active folds because associated deformation is too broadly distributed to be considered a life-safety hazard for buildings.

Figure 5.20 indicates that active folding (and faulting) is more difficult to identify (or is not present) northeast of the Marton and Feilding anticlines. This is in part because the geology changes significantly from north to south, with dominantly late Quaternary marine and alluvial surfaces exposed and deformed in the south, and mainly Miocene to Pliocene bedrock exposed to the north (Begg and Johnston 2000; Townsend et al. 2008). This may coincide with the increased erodibility of the rock to the north, and with a decrease in the rates of tectonic motion from the offshore KMFS in the south to the onshore faults and folds of south-eastern Manawatū and Rangitikei, toward the northeast into Tertiary bedrock country of the central North Island.

The Himatangi Anticline, Mt Stewart-Halcombe Anticline, Feilding Anticline and Pohangina Anticline are discussed in more detail with respect to their adjacent faults in Section 5.1. The active Utiku Anticline occurs mostly within the Rangitikei District. An unnamed active syncline mapped in QMAP is shown sub-parallel to, and to the east of, the Pohangina Anticline in the Pohangina valley near Awahou North (Figure 5.20).

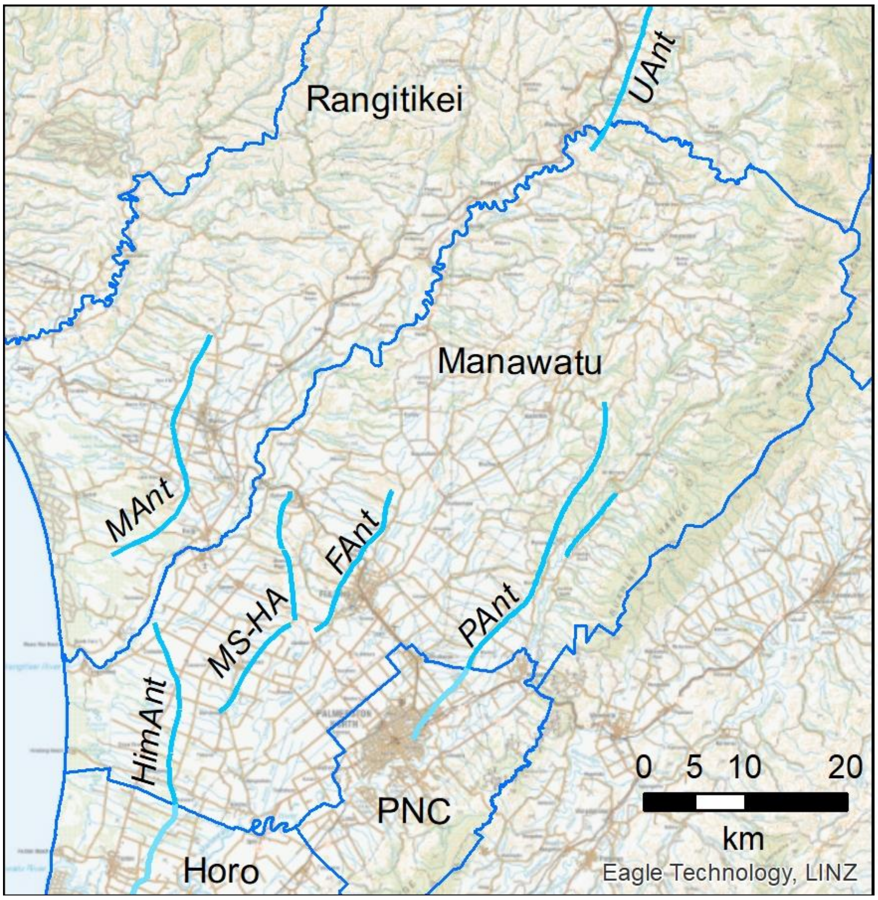

Figure 5.20 Axial traces of active anticlinal folds (light blue) in the southern part of Horizons Region, as defined in this study. Fold axis names are: HimAnt, Himatangi Anticline; MS-HA, Mt Stewart-Halcombe Anticline; FAnt, Feilding Anticline; PAnt, Pohangina Anticline; MAnt, Marton Anticline, and UAnt, Utiku Anticline.

5.4 Summary of Active Faults with FAZs in Manawatū District

We have defined FAZs for known active faults within the Manawatū District and have developed preliminary RI Classes for these faults (Table 5.1). For 'possibly active' faults, 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. In addition, because co-seismic fold deformation (as opposed to co-seismic surface rupture fault deformation) is of low intensity (i.e. low strain) 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 (RI) information for faults within the Manawatū District.

Fault	RI Class	RI Range (Years)	RI Class Confidence*	Data Source#
Mohaka Fault	I	≤2000	H	1,3
Ruahine Fault	II	>3500 to ≤5000	M	1,3
Himatangi Fault	IV	>5000 to ≤10,000	M	2,4,5
Mt Stewart-Halcombe Fault	IV	>5000 to ≤10,000	M	2,5
Rauoterangi Fault	IV	>5000 to ≤10,000	M	5
Leedstown Fault	IV	>5000 to ≤10,000	M	1,3
Pohangina fault	IV	>5000 to ≤10,000	M	4,5
Komako fault	IV	>5000 to ≤10,000	M	4,5
Traverse fault	IV	>5000 to ≤10,000	M	5
Howlett Creek fault	IV	>5000 to ≤10,000	M	5
Dirty Spur fault	IV	>5000 to ≤10,000	M	5
Taumataomekura fault	IV	>5000 to ≤10,000	M	5
Taonui fault	-	FAA^		5
Ohakea fault	-	FAA^		5
Raukawa Fault	-	FAA^		5

Notes: RI Class Confidence: H, High – fault has well-constrained recurrence interval; 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).

^ Faults that are considered 'possibly active' are without recurrence interval information and have an FAA.

Sources: 1: Van Dissen et al. (2003); 2: Litchfield et al. (2014); 3: NZAFD (https://data.gns.cri.nz/af/) and Langridge et al. (2016); 4: Langridge and Morgenstern (2019); and 5: this study.

Table 5.1 shows new and updated recurrence interval data for known active faults in the Manawatū 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 SUMMARY

Active fault mapping has been undertaken for Horizons Regional Council covering the Manawatū District for the purposes of planning with regards to active faults. A mappable active fault is usually defined as a geologic fault that has ruptured the ground surface during the last 125,000 years or less. A variety of mapping platforms have been 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 (RI) Class information has been provided, based largely on inferences from geomorphic relationships along the faults and via comparisons with better studied faults nearby.

In the Manawatū District, the active faults recognised and mapped include the Mohaka Fault, Ruahine Fault, Himatangi Fault, Leedstown Fault, Mt Stewart-Halcombe Fault, Rauoterangi Fault, Pohangina fault, and Komako fault. Several other short active faults – Taonui, Traverse, Howlett Creek, Dirty Spur, and Taumataomekura faults are newly recognised and mapped.

Several, or parts of, other mapped faults – the Ohakea, Taonui, Raukawa, Rauoterangi, and Pohangina faults – are currently treated as ‘possibly active’ because it is not clear that the mapped features are active fault traces. Because of ambiguity regarding the activity (or not) of these faults, FAZ and RI Class have not been defined for them, and instead FAAs have been designed for these features, which recognises that they may be possibly active.

The preliminary RI Classes defined in this study for the active faults in the Manawatū District are as follows: Mohaka Fault (RI Class I; ≤2000 years) and Ruahine Fault (RI Class II; >2000 to ≤3500 years). All other active faults described here, i.e. the Himatangi, Mt Stewart-Halcombe, Rauoterangi, Leedstown, Pohangina, Komako, Traverse, Howlett Creek, Dirty Spur, and Taumataomekura faults, have been assigned a RI Class IV status (RI >5000 to ≤10,000 years).

The township of Feilding is traversed by the active RI Class IV Rauoterangi Fault. FAZs for the Rauoterangi Fault have been developed for the western suburban part of the community. Along one stretch of the western hills a FAA has been develop because the lines mapped there are not clearly active fault traces. Appendix 2 provides some examples to assist planners in making resource consent decisions regarding the FAZs related to the Rauoterangi Fault.

Fault Awareness Areas are developed for parts of some faults in this study, e.g. the Ruahine, Pohangina, Taonui, Ohakea, Rauoterangi, and Raukawa faults. FAAs have a total width of 250 m, but do not carry the regulatory levels that are suggested in 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.

Active folds have also been mapped and defined within Manawatū District as part of this study. These are the Himatangi, Mt Stewart-Halcombe, Feilding, Utiku and Pohangina anticlines. This study does not present FAZs or RI Class information for active folds because the location and associated deformation is anticipated to be of such low intensity to warrant characterisation for fault avoidance purposes.

7.0 RECOMMENDATIONS

We recommend that the FAZs and FAAs developed for the Manawatū 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 Building Importance Category intended for the site (see Table A3.1). Fault Awareness Areas, developed for some faults, or parts of fault, in this study, carry no restrictive planning characteristics with respect to the MfE Guidelines. In future, more work needs to be undertaken to characterise the activity (or inactivity) 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 Rauoterangi Fault in the Feilding area.

8.0 ACKNOWLEDGEMENTS

We wish to thank Horizons Regional Council for adopting this work as part of its natural hazards program and for providing airborne LiDAR data and the regional 1-m DSM to GNS Science as part of the project. Particular thanks go to Ian Lowe (Podge) for driving this work. We thank Andrew Steffert for helping to develop the regional 1-m DSM. We wish to thank Russ Van Dissen and Nicola Litchfield for reviewing this report. Jeff Graham from the Manawatū District Council provided additional review comments.

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.

Barnes PM, Nicol A, Harrison T. 2002. Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. *Geological Society of America Bulletin.* 114(11):1379–1405.

Barrell DJA. 2015 General distribution and characteristics of active faults and folds in the Kaikoura District, North Canterbury. Lower Hutt (NZ): GNS Science. 59 p. (GNS Science consultancy report; 2014/210).

Barrell DJA, Andersen BG, Denton GH. 2011. Glacial geomorphology of the central South Island, New Zealand. Lower Hutt (NZ): GNS Science. 2 vol. (GNS Science monograph; 27).

Barrell DJA, Jack H, Gadsby M 2015. Guidelines for using regional-scale earthquake fault information in Canterbury. Lower Hutt (NZ): GNS Science. 30 p. (GNS Science consultancy report; 2014/211).

Barrell DJA, Townsend DB. 2012. General distribution and characteristics of active faults and folds in the Hurunui District, North Canterbury. Lower Hutt (NZ): GNS Science. 30 p. (GNS Science consultancy report; 2012/113).

Beanland S. 1995. The North Island Dextral Fault Belt, Hikurangi subduction margin, New Zealand [PhD thesis]. Wellington (NZ): Victoria University of Wellington.

Beanland, S, Berryman, KR. 1987: Ruahine Fault reconnaissance. N.Z. Geological Survey report EDS 109. 15 p.

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):73–92.

Begg JG, Hull AG, Downes GL. 1994. Earthquake hazards in Hawke's Bay: initial assessment. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences Limited. 59 p. (Institute of Geological & Nuclear Sciences client report; 333901.10).

Begg JG, Johnston MR, compilers. 2000. Geology of the Wellington area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences Limited. 1 sheet + 64 p., 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. (Institute of Geological & Nuclear Sciences client report; 2001/70).

Berryman K, Beanland S. 1991. Variation in fault behaviour in different tectonic provinces of New Zealand. *Journal of Structural Geology*. 13(2):177–189.

Cashman SM, Kelsey HM, Erdman CF, Cutten HNC, Berryman KR. 1992. Strain partitioning between structural domains in the forearc of the Hikurangi subduction zone, New Zealand. *Tectonics*. 11(2):242–257.

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. (GNS Science consultancy report; 2016/133).

Clement AJH, Fuller IC. 2018. Influence of systems 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.

Clement AJH, Fuller IC, Sloss CR. 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.

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

Downes GL. 1995. Atlas of isoseismal maps of New Zealand earthquakes. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences Limited. 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): Institute of Geological & Nuclear Sciences Limited. (Institute of Geological & Nuclear Sciences monograph; 25).

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

Jackson J, Van Dissen RJ, Berryman KR. 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.

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.

Kerr J, Nathan S, Van Dissen RJ, Webb P, Brunsdon D, King A. 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 and Nuclear Sciences Limited. 56 p. (Institute of Geological and Nuclear Sciences client report; 2002/124). Also available online at: https://www.mfe.govt.nz/sites/default/files/media/RMA/planning-development-faults-graphics-dec04%20%281%29.pdf

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 Fen 13–15; Christchurch, New Zealand. Wellington (NZ): New Zealand Society for Earthquake Engineering. Paper No.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.

Langridge RM, Morgenstern R. 2019. Active fault mapping and fault avoidance zones for Horowhenua District and Palmerston North City. Lower Hutt (NZ): GNS Science. 72 p. (GNS Science consultancy report; 2018/75).

Langridge RM, Ries WF. 2010. Active fault mapping and rupture avoidance zonation for the Alpine Fault in West Coast region. Lower Hutt (NZ): GNS Science. 40 p. (GNS Science consultancy report; 2009/18).

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. (GNS Science consultancy report; 2013/151).

Langridge RM, Ries WF. 2015. Active fault mapping and fault avoidance zones for Hastings District and environs. Lower Hutt (NZ): GNS Science. 50 p. (GNS Science consultancy report; 2015/112).

Langridge RM, Ries WF. 2016. Active fault mapping and fault avoidance zones for the Wairau Fault, Marlborough District. Lower Hutt (NZ): GNS Science. 49 p. (GNS Science consultancy report; 2016/25).

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 RM, Rowland J, Villamor P, Mountjoy J, Townsend DB, Nissen E, Madugo C, Ries WF, 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. 1785/012017036.

Langridge R, Villamor P. 2007. Hastings District LiDAR fault trace survey. Lower Hutt (NZ): GNS Science. 31 p. (GNS Science consultancy report; 2007/145).

Langridge RM, Villamor P, Basili R. 2006. Earthquake fault trace survey – Central Hawke's Bay District. Lower Hutt (NZ): GNS Science. 31 p. (GNS Science consultancy report; 2006/98).

Langridge RM, Zajac A, Ries WF. 2011. Fault avoidance zone mapping for Napier City and Wairoa District. Lower Hutt (NZ): GNS Science. 35 p. (GNS Science consultancy report; 2010/105).

Lee JM, Begg JG, compilers. 2002. Geology of the Wairarapa area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences Limited.1 sheet + 66 p, scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 11).

Lee JM, Bland KJ, Townsend DB, Kamp PJJ, compilers. 2011. Geology of the Hawkes Bay area [map]. Lower Hutt (NZ): GNS Science. 1 sheet + 71 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 8).

Litchfield NJ, Berryman KR. 2005. Correlation of fluvial terraces within the Hikurangi Margin, New Zealand: implications for climate and baselevel controls. *Geomorphology*. 68(3–4):291–313.

Litchfield NJ, Van Dissen RJ. 2014. Porirua district fault trace study. Lower Hutt (NZ): GNS Science. 53 p. (GNS Science consultancy report; 2014/213).

Litchfield N, Van Dissen R, Langridge R, Heron D, Prentice C. 2003. Timing of the most recent surface rupture event on the Ohariu Fault near Paraparaumu, New Zealand. *New Zealand Journal of Geology & Geophysics*. 47(1):123–128.

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris R, Beavan RJ, Langridge RM, Villamor P, Berryman KR, 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.

Litchfield NJ, Villamor P, Van Dissen RJ, Nicol A, Barnes PM, Barrell DJA, Pettinga JR, Langridge RM, Little TA, Mountjoy JJ et al. 2018. Surface rupture of multiple crustal faults in the 2016 MW 7.8 Kaikōura, New Zealand, earthquake. *Bulletin of the Seismological Society of America*. 108(3B):1496–1520. doi:10.1785/0120170300.

Little TA, Van Dissen RJ, Schermer E, Carne R. 2009. Late Holocene surface ruptures on the southern Wairarapa fault, New Zealand: link between earthquakes and the uplifting of beach ridges on a rocky coast. *Lithosphere*. 1(1):4–28. doi: 10.1130/L7.1.

Meigs A. 2013. Active tectonics and the LiDAR revolution. *Lithosphere*. 5(2):226–229. doi:10.1130/RF.L004.1.

Nodder SD, Lamarche G, Proust JE, 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:B12102. doi:10.1029/2007JB005019.

Palmer A, Van Dissen RJ. 2002. Northern Ohariu Fault: earthquake hazard assessment of a newly discovered active strike-slip fault in Horowhenua. Wellington (NZ): Earthquake Commission Research Foundation. 52 p.

Ries W. 2013. Location of active faults using geomorphic indices in eroded landscapes, South Taranaki, New Zealand [MSc thesis]. Wellington (NZ): Victoria University of Wellington. 158 p.

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

Shepherd MJ, Price DM. 1990. Thermoluminescence dating of late Quaternary dune sand, Manawatu/Horowhenua area, New Zealand: a comparison with ^{14}C age determinations. *New Zealand Journal of Geology and Geophysics.* 33(4):535–539.

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 MW, McVerry G, Gerstenberger M, Litchfield N, Van 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 MW, Wesnousky SG, Berryman KR. 1998. Probabilistic seismic hazard analysis of New Zealand. *New Zealand Journal of Geology and Geophysics*. 41(4):355–376.

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 Limited. 30 p. (Institute of Geological & Nuclear Sciences client report; 2002/58).

Townsend DB, Nicol A, Mouslopoulou V, Begg JG, Beetham RD, Clark D, Giba M, Heron DW, 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. 1 sheet + 77 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 7).

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 Mw 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*; 2011 Apr 14–16; Auckland, New Zealand. Auckland (NZ): 9PCEE. paper 186.

Van Dissen RJ, Begg JG, Robinson R. 2001. The Akatarawa Fault: a newly discovered active fault in the Wellington region, and implications for increased hazard on the Wellington fault. In: *New Zealand Society for Earthquake Engineering Inc Technical Conference and AGM*; 2001 Mar 23–25; Taupo, New Zealand. Wellington (NZ): New Zealand Society for Earthquake Engineering. 8 p.

Van Dissen RJ, Berryman K, Webb T, Stirling M, Villamor P, Wood PR, Nathan S, Nicol A, Begg J, Barrell D, 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. Paper No.155.

Van Dissen R, Heron DW. 2003. Earthquake Fault Trace Survey, Kapiti Coast District. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 45 p. (Institute of Geological & Nuclear Sciences client report; 2003/77).

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 : conference 2004 technical papers*; 2004 Mar 19–21; Rotorua, New Zealand. Wellington (NZ): New Zealand Society for Earthquake Engineering. 9 p.

Van Dissen RJ, Stahl T, King A, Pettinga JR, Fenton C, Little TA, Litchfield NJ, Stirling MW, Langridge RM, Nicol A, et al. Forthcoming 2018. 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*.

Van Dissen RJ, Yeats RS. 1991. Hope fault, Jordan thrust, and uplift of the Seaward Kaikoura Range, New Zealand. *Geology*. 19(4):393–396.

Villamor P, Berryman KR. 2006a. 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.

Villamor P, Berryman KR. 2006b. Evolution of the southern termination of the Taupo Rift, New Zealand. *New Zealand Journal of Geology and Geophysics.* 49(1):23–38.

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

Wallace LM, Beavan RJ, McCaffrey R, Berryman KR, Denys P. 2007. Balancing the plate motion budget in the South Island, New Zealand using GPS, geological and seismological data. *Geophysical Journal International.* 168(1):332–352. doi:10.1111/j.1365–246X.2006.03183.x.

Wallace LM, Beavan RJ, McCaffrey R, Darby DJ. 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 Limited. 36 p. (Institute of Geological & Nuclear Sciences client report; 2000/71).

APPENDICES

This page left intentionally blank.

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.

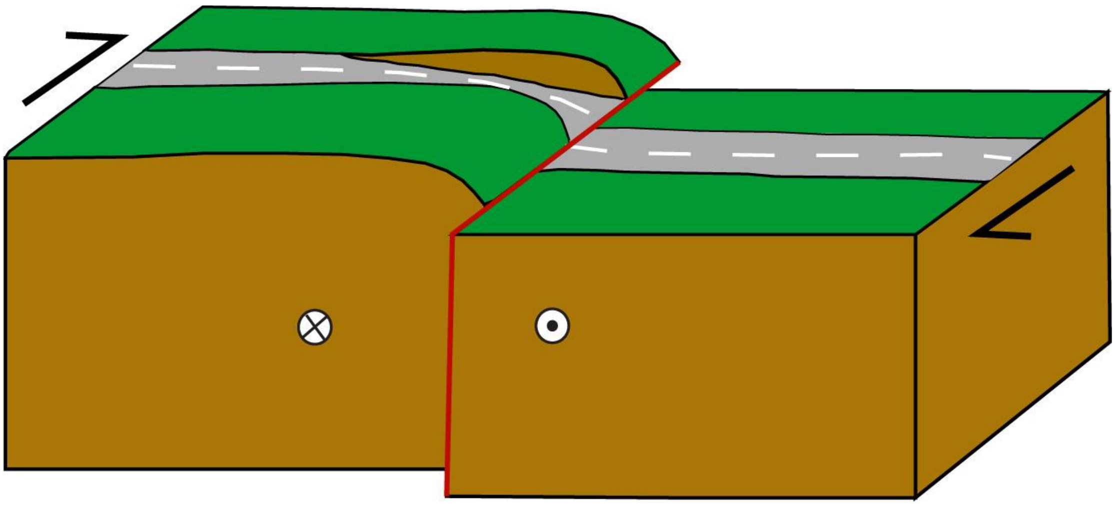

Figure A1.1 Block model of a strike-slip fault (red line).This is a right-lateral (dextral) fault, as shown by the black arrows and by the sense of movement across the two blocks and a separation towards the right across the road. A small amount of vertical movement is also implied by the mappable fault 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).

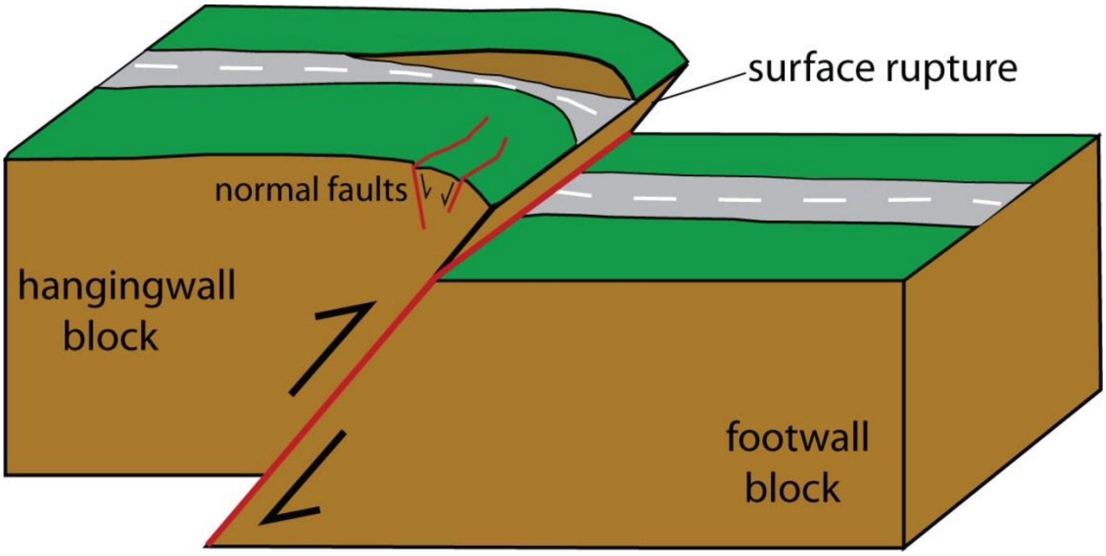

Figure A1.2 Block model of a reverse dip-slip fault that has recently ruptured. Relative movement between the blocks is vertical and along the dip direction of the fault plane. In this case, the hanging-wall block has been pushed up and over the footwall block. Folding (bending) and normal faulting are 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[9] 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 east coast of the North Island by NIWA (e.g. Barnes et al. 2002).

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).

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

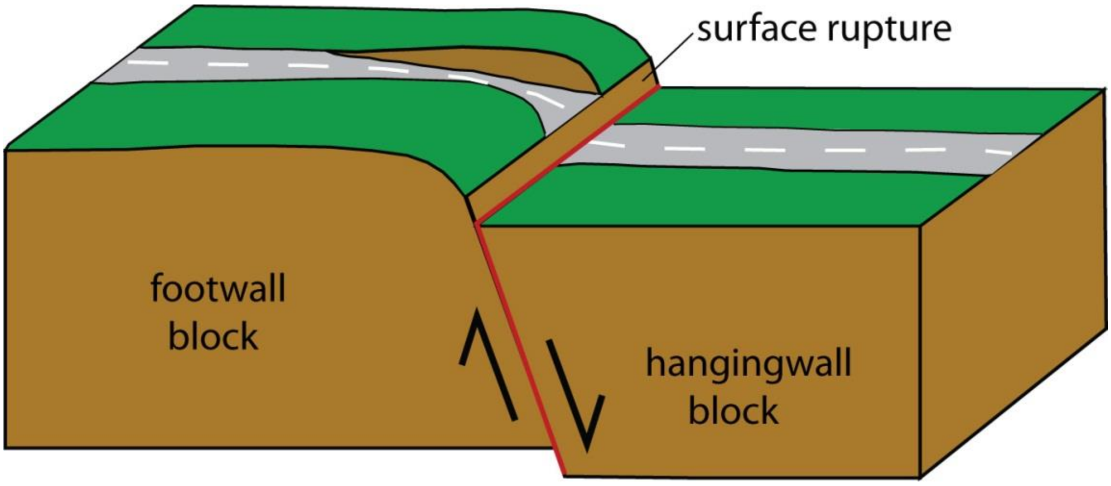

Figure A1.3 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

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.

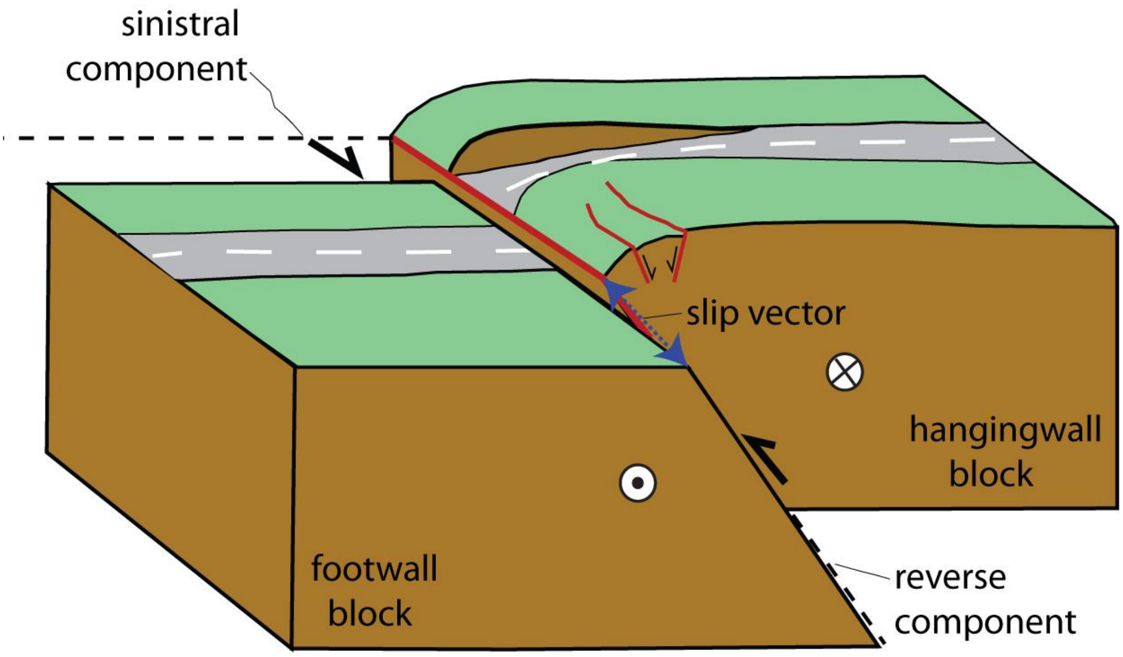

Figure A1.4 Block model of an oblique slip fault. In this case the fault is sinistral reverse. The relative movement of the blocks is both vertical (in the dip direction of the fault plane), and strike-slip (in the direction of the strike of the fault), as shown by the oblique blue arrow. Symbols on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

APPENDIX 2 THE RAUOTEANGI FAULT IN FEILDING

One of the most significant outcomes of active fault mapping and the development of FAZs in Chapter 5 is the identification of the active Rauoterangi Fault in suburban Feilding. In this chapter we present examples of how the information in this report can be treated with respect to future resource planning consents. These are equally applicable to the other active RI Class IV faults in the district, e.g. for the Himatangi or Mt Stewart-Halcombe faults.

In this study we have mapped active fault traces at the toe of the western hills of Feilding and a 'possibly active' fault marking the steep edge of the range front of the hills (Figure A2.1). shows the locations or imprint of FAZs in cross-section below the western hills.

The following summarises what is presented for the Rauoterangi Fault in this study:

1. The Rauoterangi Fault is an active fault assigned a preliminary RI Class IV (>5000 to ≤10,000 years) applied to it, i.e. the average time between large, surface-rupturing earthquakes on the Rauoterangi Fault is >5000 years.
2. Fault Avoidance Zones have been developed for the Rauoterangi Fault based on fault mapping.
3. The MfE Guidelines provides Resource Consent Tables for RI Class IV faults that provide guidance for councils to make clear planning decisions (Table A2.1).
4. A Fault Awareness Area (FAA) is proposed for the rangefront edge of the western hills because it is unclear in this case whether the linear edge is an active fault or a fluvial cut edge (Figure A2.1).

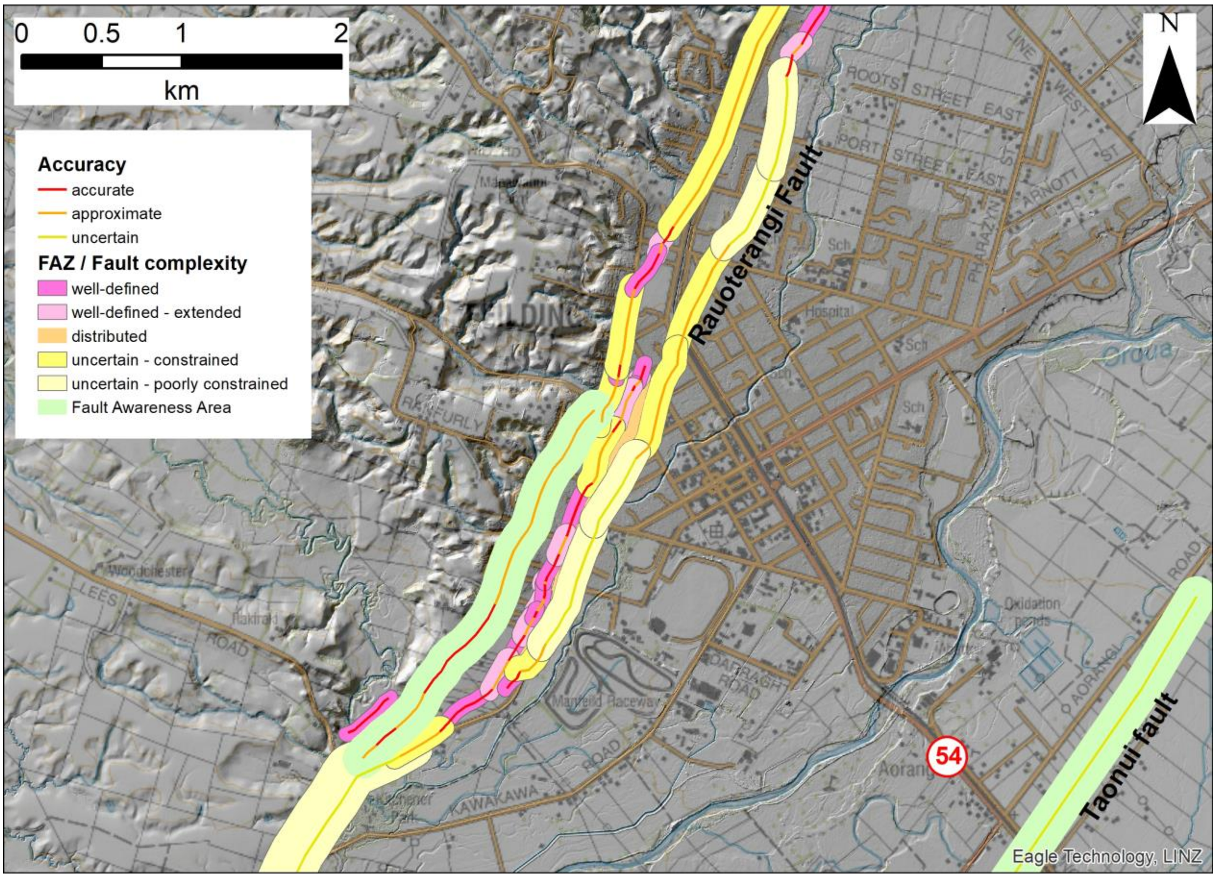

Figure A2.1 Map view of FAZs and FAAs for the Rauoterangi Fault in the Fielding area. A Fault Awareness Area is also shown for the Taonui fault.

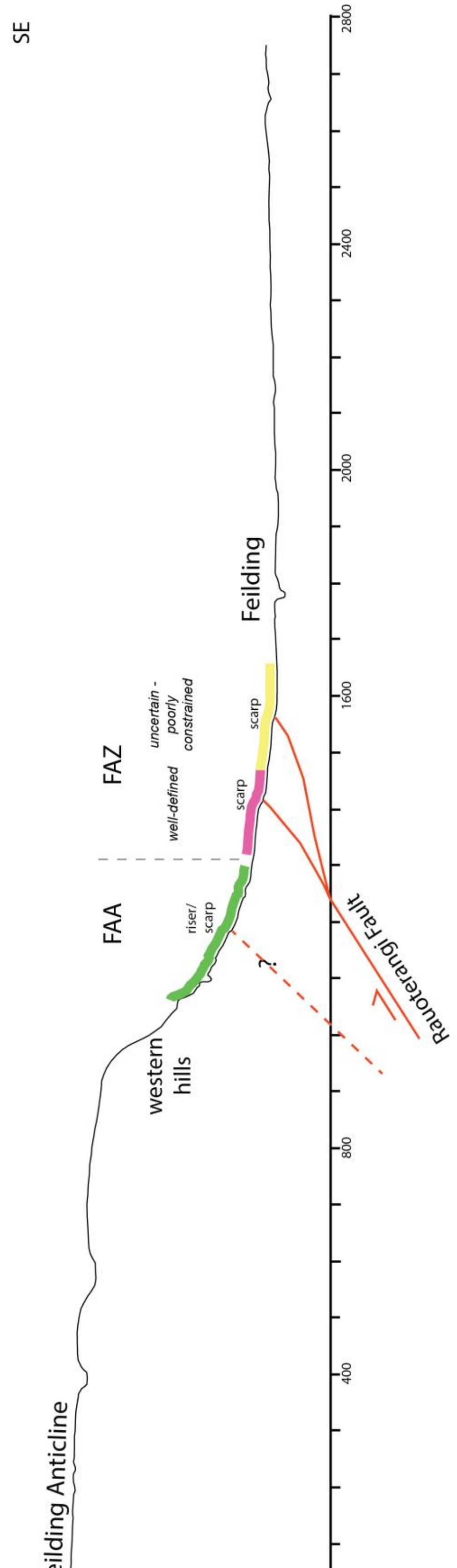

Figure A2.2 Cross-sectional view of the range front with FAZs and FAA for the Rauoterangi Fault in the Feilding area. The cross-section runs across the western hills south of the central business district of Feilding. Coloured bars show the position and width of FAZs and FAA as shown in Figure A2.1.

A2.1 Examples of the Application of FAZs in Feilding

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 Rauoterangi Fault in Feilding. 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 shown in Appendix 3.

A2.1.1 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 northeast of Feilding in the Makino Road area, straddling the Rauoterangi Fault (Figure 5.2). 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 for the Rauoterangi Fault. All of the traces are mapped as ‘approximate’ from LiDAR and the FAZs have a ‘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 Manawatū 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 of FAZs or to undertake further surveying or fault trenching to better locate the fault or areas of most intense ground deformation, which could be avoided.

A2.1.2 Renovations to a Home in Coronation Street

A family wish to extend their house in Coronation Street by adding an extra bedroom to the house which straddles the Rauoterangi Fault (Figure 5.8). 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 Manawatū District Council may wish to retain some flexibility about how it can exercise its planning and consent outcomes in such a case, because the risk to a low BIC structure on a RI Class IV fault is low.

A2.1.3 A School in Feilding Straddles a FAZ

Buildings within the Manchester Street Primary School in Feilding fall within an a 160-m wide ‘uncertain – constrained’ FAZ defined for the Rauoterangi Fault. Most of the traces mapped near the school are ‘approximate’ based on mapping from a LiDAR DEM and relate to a broad 2-m high warp 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 Ministry of Education and the Manawatū 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 (Manawatū)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-Defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain	Permitted	Permitted	Permitted	Permitted	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-Defined	Permitted	Permitted*	Permitted*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
Uncertain	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying

Notes:

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

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

This may be a case where it is important to better constrain the RI Class of the Rauoterangi Fault as it 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 fault.

A2.1.4 Consent for a Large House Along the Western Hills

In this example, a large BIC 2b house is proposed for a block at the end of Sunrise Heights, Feilding. The piece of land falls across the Fault Awareness Area on the rangefront of the western hills. There are no restrictions to development within a FAA and the MfE Guidelines consent tables cannot be directly applied to a FAA situation. In the case of a larger development or subdivision the council may deem it important to learn more about this feature, i.e. 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.

APPENDIX 3 ANOTHER EXAMPLE OF THE APPLICATION OF A FAZ

The following provides another hypothetical example of how the MfE Guidelines could be used to inform planning decisions and includes tables taken from Kerr et al. (2003) for RI Classes II, IV and V active faults in the Manawatū District.

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

In this example, a rural family that lives near Saddle Road in the Tararua District wants to build a new guest house (Building Importance Category [BIC] 2a structure) within a Fault Avoidance Zone along the Ruahine Fault (a RI Class II fault). 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 A3.1).

Table A3.1 Examples, based on the MfE Guidelines, of Resource Consent Categories for both Developed and/or Already Subdivided sites, and Greenfield sites along RI Class II faults. 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 (Manawatū)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	Permitted*	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	*Discretionary*	*Non-Complying*	Non-Complying
Uncertain	Permitted	Permitted	*Discretionary*	*Non-Complying*	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

Notes:

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

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

In a situation where the amount of available land for a building site is limited, a developer 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.

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