Active fault mapping for planning purposes across the western part of the Tararua District

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EXECUTIVE SUMMARY

GNS Science has been contracted by the Horizons Regional Council to provide active fault hazard information for its districts. Within the Horizons region, the Tararua District straddles the active Australian-Pacific plate boundary and has a history of large earthquakes and many known on-land active faults.

Active faults pose a metre-scale surface rupture (or ground deformation) hazard to buildings and infrastructure. New active fault mapping, along with Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs), are presented here for the western half of the Tararua District. Following the Ministry for the Environment's guidelines – *'Planning for Development of Land on or Close to Active Faults'* (MfE Guidelines; Kerr et al. 2003) – fault traces have been mapped and FAZs and FAAs developed, where appropriate, within eight priority areas (i.e. towns, discussed below) 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 (RI) of surface faulting and (iii) the Building Importance Category (BIC) of the structure(s) that may be impacted by fault rupture ground deformation. FAAs have been developed for faults across most of the mapped area. For planning decisions, a series of recommended actions for FAAs are included with this report.

Active fault mapping was undertaken using 1-m-resolution hillshade models developed from airborne Light Detection and Ranging (LiDAR) data and a Horizons region-wide Digital Surface Model (DSM), as well as from review of geological datasets and previous active fault mapping. 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) and are attributed by parameters such as method, accuracy, slip sense, deformation width and RI Class. These terms are used to help characterise the fault complexity, i.e. how the fault deformation is expressed at the Earth's surface, as well as the activity of the fault. Fault complexity can vary from well-defined to distributed or uncertain. The fault complexity term is ultimately used to define the width and parameterisation of FAZs.

In the western part of the district, there are three main strands of active faulting that parallel the plate boundary. These are: the western strand of the strike-slip North Island Dextral Fault Belt (NIDFB) (e.g. the Wellington, Mohaka and Ruahine faults); the eastern strand of the NIDFB (e.g. the Alfredton, Pa Valley, Makuri-Waewaepa, Mangatoro and Oruawharo faults); and, between them, predominantly reverse faults in a forearc basin (e.g. the Eketāhuna, Pahiatua, Woodville-Dannevirke Fault Zone and Ruataniwha faults). There are other named active faults, e.g. Hukanui fault[1], many unnamed active fault traces and parts of some faults that are designated as 'possibly active'.

The following summarises the current status of FAZs and FAAs for priority areas in this report:

Eketāhuna – the Eketāhuna fault (new) runs through the town and FAZs are developed along it. The Cliff Road Fault and the Waiwaka fault occur outside of the town, and FAZs have also been developed for these.

Alfredton – FAZs have been developed for active traces of the RI Class I Alfredton Fault near the township. The remaining traces have FAAs developed for them.

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 newly mapped in this study and require paleoseismic investigation to better characterise them.

Pahiatua – the Pahiatua Fault is poorly expressed along most of its length and has been designated as ‘possibly active’ near and within the town where FAAs have been developed for it. The Hukanui fault (new) occurs to the west of the town and has FAZs developed for its northern end near Pahiatua.

Woodville – the active Woodville-Dannevirke Fault Zone (WDFZ) projects south towards Woodville. However, near the town, the WDFZ is concealed and considered ‘possibly active’. Thus, FAAs are developed near the town. FAZs have been developed for parts of the RI Class I Mohaka Fault to the west of Woodville.

Kumeroa – active traces of the Pahiatua Fault occur west of the town, which have FAZs developed for them. FAZs have been developed for the Kohinui Fault to the east of Kumeroa.

Dannevirke – faulting associated with the WDFZ runs to the west of Dannevirke and steps across the landscape and possibly through the town. The WDFZ is assigned a preliminary RI Class IV status. FAAs have been developed for all traces in the Dannevirke priority area. We recommend that the features traversing through Dannevirke are investigated further.

Ormondville – the town lies between active traces of the Ruataniwha and Takapau faults. FAZs are developed for parts of these faults closest to the town and FAAs developed beyond.

Norsewood – no active faults; therefore no FAZs or FAAs were mapped near Norsewood.

As part of this project we have reviewed the RI Class information for many of the faults described. The RI Class I faults (which can host surface rupture at least once every 2000 years) are the Wellington, Mohaka, Dreyers Rock and Alfredton faults. RI Class II (>2000 to ≤3500 years) faults include the Ruahine, Pa Valley, Old Pa Valley, Makuri-Waewaepa and Mangaoranga faults. The Mangatoro, Oruawharo, Clear Hills, Mangaraupiu, Hukanui and Top Grass faults are designated as RI Class III faults (>3500 to ≤5000 years). The WDFZ, Beagley Road Fault Zone and the Cliff Road, Eketāhuna, Nireaha, Otope Road, Takapau, Traverse, Waiwaka, Ruataniwha, Kohinui and Maunga Road faults are defined as RI Class IV faults (>5000 to ≤10,000 years), as they have fault traces across alluvial terraces that post-date the last glacial period. Where there is no reasonable fault data to constrain one, neither a recurrence interval nor RI Class has been estimated for faults.

In a few places, active folds have been mapped. These broadly deform the ground surface but have no requirements related to the MfE Guidelines, as they are associated with buried faults or because associated deformation is too broad to mitigate practically.

We recommend that the MfE Guidelines are treated as a standard reference when considering resource consent applications in the Tararua District and that the active fault mapping, FAZs and FAAs developed 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 and RI Class. As outlined in the MfE Guidelines, this information, when combined with land-use status (i.e. Greenfield or Already Developed/Subdivided sites) and BIC of the intended structure, provides a risk-based rationale for making land-use planning decisions pertaining to the development of land on, or close to, active faults. To assist planners, a series of case examples of how the MfE Guidelines can be applied for various combinations of fault complexity, RI Class, land-use status and BIC are included. We also recommend that GIS data for FAZs and FAAs, 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 or near a given property.

1.0 INTRODUCTION

The southern North Island straddles the boundary between the Australian and Pacific tectonic plates (Figure 1.1 inset). This plate boundary is associated with large earthquakes, ground-surface fault rupture (causing permanent ground deformation) and volcanism. The area administrated by Horizons Regional Council (Horizons Region; Figure 1.1) straddles one of the more diverse and seismically active parts of this tectonic boundary zone. 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, Himatangi, 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. 2007; Schermer et al. 2004; Van Dissen et al. 2003).

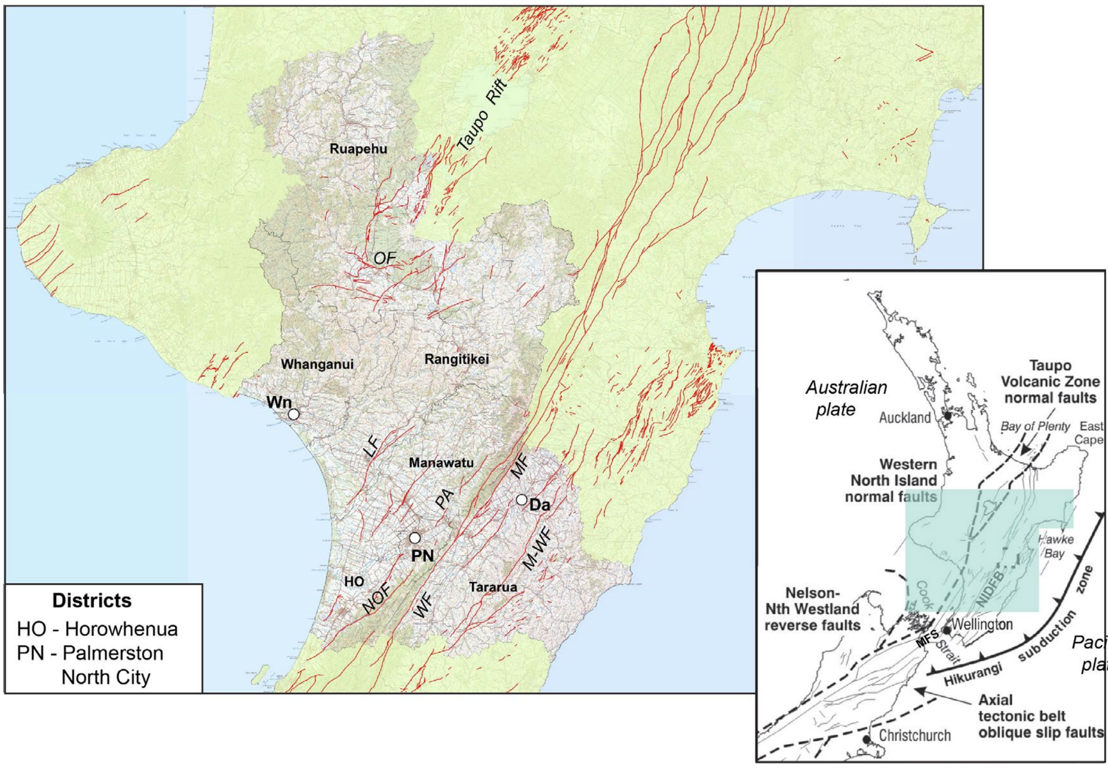

Figure 1.1 The area administered by Horizons Regional Council, showing its various districts. Onshore active faults (red) within the lower North Island area sourced from the New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al. 2016) as they appeared prior to this study. Fault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

Ground surface rupture of an active fault will usually 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. The 1931 Hawke's Bay, 1987 Edgecumbe, 2010 Darfield and 2016 Kaikōura earthquakes (Figures 1.2 and 1.3), provide examples of the scale of possible damage caused by ground-surface fault rupture (e.g. Hull 1990; Beanland et al. 1989; Van Dissen et al. 2011, 2019).

Figure 1.2 A house built along the scarp of the Papatea Fault in the Clarence River valley, Kaikōura District. The scarp is broadly defined by the pre-existing fence and line of boulders. Surface rupture across the fault in the 2016 Kaikōura earthquake resulted in vertical and horizontal ground deformation that warped and tilted the ground (to the right), damaging the house and causing the chimney to separate from it. There were no occupants in the house at the time of the earthquake. Image from Van Dissen et al. (2019).

Figure 1.3 Ground surface rupture south of the Heretaunga Plains associated with the 1931 Hawke's Bay earthquake. The style of movement on the faults in the 1931 event was dominantly reverse, causing the pictured surface 'moletrack'. Image from Henderson (1933).

1.1 Scope of Work

GNS Science (GNS) has been contracted by Horizons Regional Council to conduct a region-wide active fault mapping and fault avoidance zone programme in order to improve both understanding of the effects of surface fault rupture deformation associated with large earthquakes and mitigation design for resulting hazards. The fault mapping is being undertaken in a style that facilitates application of the Ministry for the Environment's guidelines for '*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 captured by the New Zealand Active Faults Database (NZAFD; https://data.gns.cri.nz/af/) and the Geological Map of New Zealand (QMAP; Heron 2020) to date. The Horizons Regional Council fault mapping and fault avoidance zone programme began in the two southernmost districts within the Horizons region: Horowhenua District and Palmerston North City (Phase 1; Langridge and Morgenstern 2019) and concludes in the Tararua District with Phase 4.

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 ground surface features, including active faults, is possible due to the advent and acquisition of airborne Light Detection and Ranging (LiDAR)-derived topographic data. In addition to available LiDAR data supplied to GNS by Horizons Regional Council, a 1-m-resolution Digital Surface Model (DSM) has been constructed from aerial imagery, resulting in a consistent digital topographic dataset across the region that can be used for mapping purposes.

To improve understanding of the hazard posed from surface faulting and to update the quality of fault mapping in the Tararua District, the scope of work is as follows:

- Provide a review on active tectonics, seismicity and faulting in the Horizons region.
- Incorporate and review active fault-line work and attributes from other mapping studies, such as Lee et al. (2011) (i.e. part of QMAP; Heron 2020), previous GNS reports and review data within the NZAFD (1:50,000 to 1:250,000 scale).
- Map active faults (and folds, where present) across the more developed and populated northwestern half of the district.
- Where airborne LiDAR-derived topographic data exists, map and attribute active fault traces at 1:10,000 scale or better.
- 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 district, where possible, so that more informed future research and planning decisions can be considered.
- Develop Fault Awareness Areas (FAAs) based on the updated fault-line data described above. The goal is to provide Horizons Regional Council with up-to-date geospatial datasets that can be used for future planning purposes, compatible with application of the MfE Guidelines.
- Provide more detailed FAZ and FAA maps for the towns and settlements within the Tararua District, specifically for Dannevirke, Woodville, Pahiatua, Norsewood, Ormondville, Eketāhuna, Alfredton and Kumeroa.
- Compile the results in this report and present those results to Horizons Regional Council and the Tararua District Council planning staff.

Chapter 2 of this report describes the tectonic and seismic character of the Horizons region, including a record of historical earthquakes, with an emphasis on the Tararua District.

Chapter 3 introduces the fundamental elements of the MfE Guidelines. It includes an introduction to what active faults are, why they should be mapped for hazard purposes and an outline of the history of recent active fault mapping in neighbouring regions. Chapter 3 concludes with a summary of up-to-date known fault recurrence interval information for the Horizons region (e.g. Langridge and Morgenstern 2020a; Morgenstern and Townsend 2021) as relevant to the MfE Guidelines (Kerr et al. 2003).

Chapter 4 describes the methodologies used for fault mapping and how FAZs were developed and attributed according to: the fault complexity terms defined in the MfE Guidelines, fault activity, BIC category and the resource consent activity status in relation to these three parameters. Chapter 4 also describes the methodologies for FAAs across most of the district.

Chapter 5 discusses the eight priority areas, with maps showing FAZs and FAAs. Case study examples of possible planning scenarios are included for these priority areas.

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 describes each of the major named active faults within the western part of the Tararua District and provides updated recurrence intervals for them, where possible. Unnamed faults, 'possibly active' faults and active folds are also discussed.

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

2.0 BACKGROUND TO THE HORIZONS REGION AND THE TARARUA DISTRICT

The Horizons region includes seven Territorial Authorities that span an area encompassing various tectonic domains, which result in many different landscape types across the central to southern North Island (Figure 1.1). The physiography of the region is diverse and varied. In the north, the region borders the Taupō Volcanic Zone and associated extensional Taupō Rift (Villamor and Berryman 2006a, 2006b) in the Ruapehu District. In the southwestern North Island, large rivers drain from the elevated central part 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 the Horowhenua District and Palmerston North City. In the southeast, the Tararua District covers an area from the elevated Tararua and Ruahine ranges to the east coast of the North Island.

The primary hazards from earthquakes include seismic shaking (ground motion), ground-surface fault rupture, uplift, liquefaction, earth movement (e.g. rock falls and landslides), subsidence and tsunami. This report focuses on active fault mapping in the Tararua 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 and impacts of surface fault rupture on the built environment, specifically in terms of planning for, and mitigating against, surface fault rupture hazard (Kerr et al. 2003). To augment this discussion of earthquake hazard, we also present a compilation of large historical earthquakes within and surrounding the Horizons region.

2.1 Tectonic and Geologic 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 that separates the down-going Pacific Plate from 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 in the southwest 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 is reflected across the breadth of the Horizons region.

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 ‘giant’ earthquake (M_W ≥8.6). 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 the Tararua District (Figure 2.1), and a significant tsunami would be generated. In addition, a magnitude M_W 8–9 earthquake on the plate interface would generate severe ground shaking throughout much of the North Island and beyond.

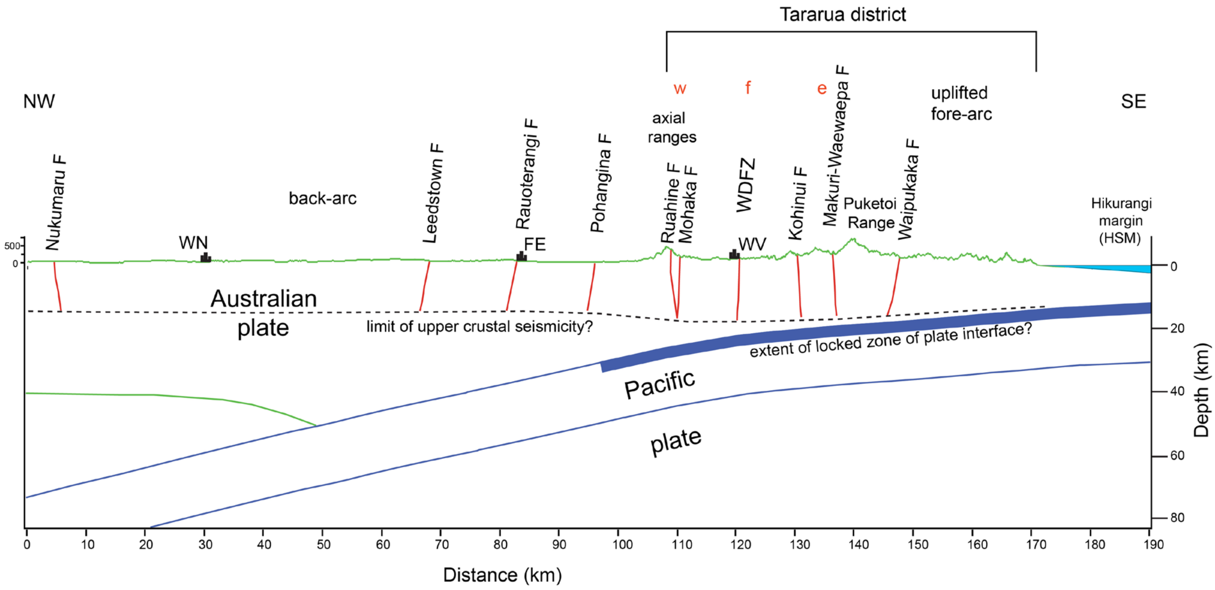

Figure 2.1 Simplified cross-section showing major tectonic features of the lower North Island in the Horizons region from offshore of Owahanga in the east to near Whanganui (WN) in the west. The cross-section intersects several active upper crustal faults and includes the Hikurangi Subduction Margin or Zone. Abbreviations: WDFZ, Woodville-Dannevirke Fault Zone; w,e, western and eastern strands of the NIDFB; f, forearc basin. The towns of Feilding (FE) and Woodville (WV) are also indicated. Vertical exaggeration is about two times.

Above the Hikurangi subduction interface in the Tararua District, the HSM comprises four main sub-parallel components: the western strand of the North Island Dextral Fault Belt (NIDFB), a forearc basin, the eastern strand of the NIDFB and Coastal Ranges (Beanland 1995; Beanland et al. 1998) (Figures 2.1 and 2.2). Major active faults and fault zones were established in the Late Miocene and Pliocene (upper Tertiary; 11.2–1.8 Ma = million years) to accommodate compression across the HSM as it developed. Thus, there is a history of reverse faulting in the eastern North Island that in part developed the range and basin topography that exists there today. For example, most of the Tertiary (65–1.8 Ma) cover rocks have been eroded back to Mesozoic (c. 150–99 Ma) greywacke bedrock during uplift and erosion across the axial ranges but are well preserved across other ranges and hills of lower elevations. In contrast, southeast of the axial ranges, there are only isolated exposures of Mesozoic greywacke, and these are typically found in association with major faults that have had a significant history of uplift themselves, e.g. the Rangefront and Makuri-Waewaepa faults (Figure 2.2).

Where tectonism, uplift and erosion have occurred at a slower rate, upper Tertiary rocks – and, locally, Late Cretaceous (c. 99–65 Ma) rocks – outcrop in fault-bounded blocks. The Tertiary geology is generally characterised by marine sedimentary rocks, which dominantly comprise mudstones, sandstones, limestones and minor conglomerate (Lee and Begg 2002; Lee et al. 2011). With uplift, the long period of deposition of Tertiary marine sedimentary rocks ended during the Early Pleistocene, when the on-land part of the HSM forearc became completely emergent. Differential uplift across major structures continued to develop the physiography of ranges and basins that we observe in the modern topography. Within the basins (or lower-lying areas), Quaternary (c. 1.8–0 Ma) non-marine and, locally, marine rocks were deposited.

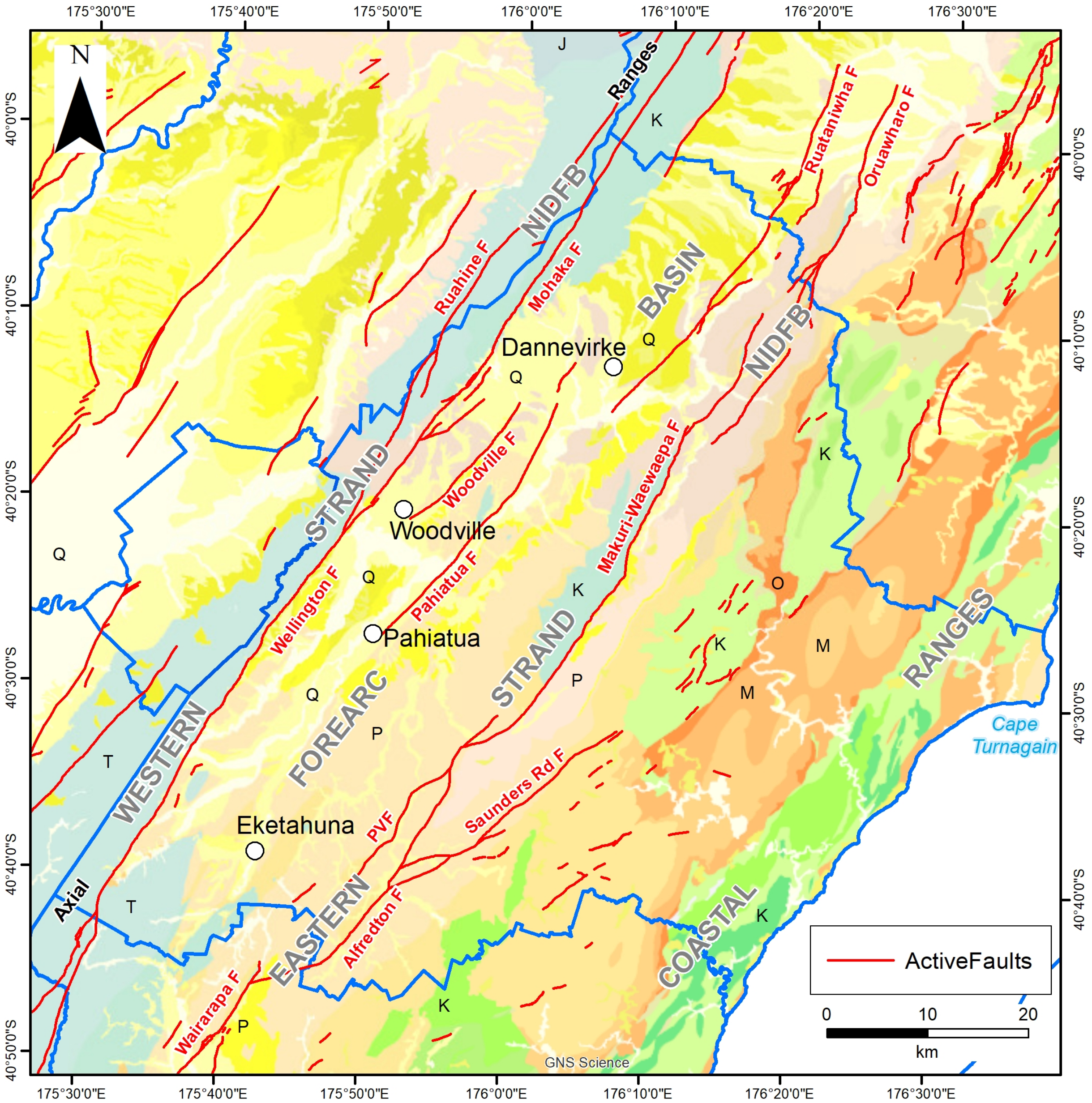

Figure 2.2 Simplified geology of the Tararua District and surrounds, with active faults as mapped prior to this study (Lee et al. 2011; Langridge et al. 2016). Major active faults (red) are named, including PVF, Pa Valley Fault. Broad geologic units are displayed according to age: T, Triassic (blue); J, Jurassic (blue); K, Cretaceous (blue, green); O, Oligocene (brown); M, Miocene (orange); P, Pliocene (l pink); Q, Quaternary (yellow). See text for age ranges of these rocks.

During the Quaternary period, an increase in the obliquity across the HSM resulted in a shift from a dominantly reverse style of deformation toward an oblique mode of deformation across the eastern North Island (Nicol and Beavan 2003; Wallace et al. 2004). Contraction was orthogonal to the structures (reverse), but an increasing component of strike-slip on the plate boundary zone meant that the contraction became oblique to the existing structures and eventually resolved into partitioning, where some structures are predominantly strike-slip and others are predominantly reverse (but, overall, the contraction is still oblique to those structures). Strike-slip motion was focused in two major sub-parallel northeast-striking belts within the Tararua District: the western and eastern strands of the NIDFB (Beanland 1995), which are separated by c. 22 km (Figure 2.2).

The western strand of the NIDFB includes the Wellington, Mohaka, Whakatane, Ruahine, Patoka and other branches of these faults. These faults are located both within, and at the southeastern border of, the axial ranges. The eastern strand of the NIDFB includes the Wairarapa, Alfredton, Pa Valley, Makuri-Waewaepa, Tukituki Thrust Fault, Waipukurau-Poukawa Fault Zone and other branches of these faults (Beanland 1995; Langridge et al. 2016). Faults of the eastern strand of the NIDFB are typically strike-slip faults in the south but change character with a shift toward reverse or oblique slip within the Hawke's Bay region (e.g. Schermer et al. 2004; Kelsey et al. 1998). An important feature of both the western and eastern strands of the NIDFB is that fault slip rates decrease to the north. As a corollary of this, recurrence intervals increase to the north, such that the RI Class value (e.g. I–IV) increases to the north, particularly along the eastern strand (Beanland 1995; Schermer et al. 2004).

Between the two strands of the NIDFB is an area called the 'forearc basin' in this study (Figure 2.2). The forearc basin typically has low topography and preserves Tertiary and Quaternary geology (Lee and Begg 2002; Lee et al. 2011). The active faulting described in this study highlights that the forearc basin comprises belts of reverse faults. These faults can be characterised as either: (a) developing parallel to the main western NIDFB strand (Wellington, Mohaka) faults, e.g. Top Grass and Rangefront faults; (b) splaying out to the northeast from the western NIDFB strand faults, e.g. Nireaha fault and Beagley Road Fault Zone; (c) running parallel to the grain of, and within, the forearc basin, e.g. Eketāhuna fault and WDFZ; or (d) possibly acting as antithetic structures to the main faults of the eastern NIDFB, e.g. the Otope Road Fault. Mapping in this study has increased both the number and accuracy of faults mapped, especially within the forearc basin, compared to what was previously mapped.

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 2.3 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 earthquakes, the faults ruptured the ground surface. However, it is important to note that this map does not show deeper earthquakes related to the subducting Pacific Plate that have also led to strong ground shaking during the historical period.

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, which includes shaking intensity reports from further afield, places the epicentral area of this event in the axial ranges of Hawke's Bay, bordering the Rangitikei District. Thus, the 1843 event has been renamed the 'Western Hawke's Bay earthquake' by Downes and Dowrick (2014).

The M_W ~8.2 Wairarapa earthquake occurred on 23 January, 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 earthquake followed the M_W ~7.5 1848 Marlborough earthquake, which caused similar levels of MMI shaking in the Horowhenua, Manawatū and

Whanganui districts (Downes and Dowrick 2014; Grapes et al. 1998). These two quakes were not recorded in the Tararua District, likely due to their small populations at that time.

On 23 February, 1863, the M_W ~7.5 Waipukurau earthquake occurred. This earthquake is believed to have originated on a reverse fault in the southern Hawke's Bay area (Grouden 1966; Downes and Dowrick 2014). The 1863 earthquake likely produced strong ground motions across the region, which was still relatively unpopulated at this time.

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

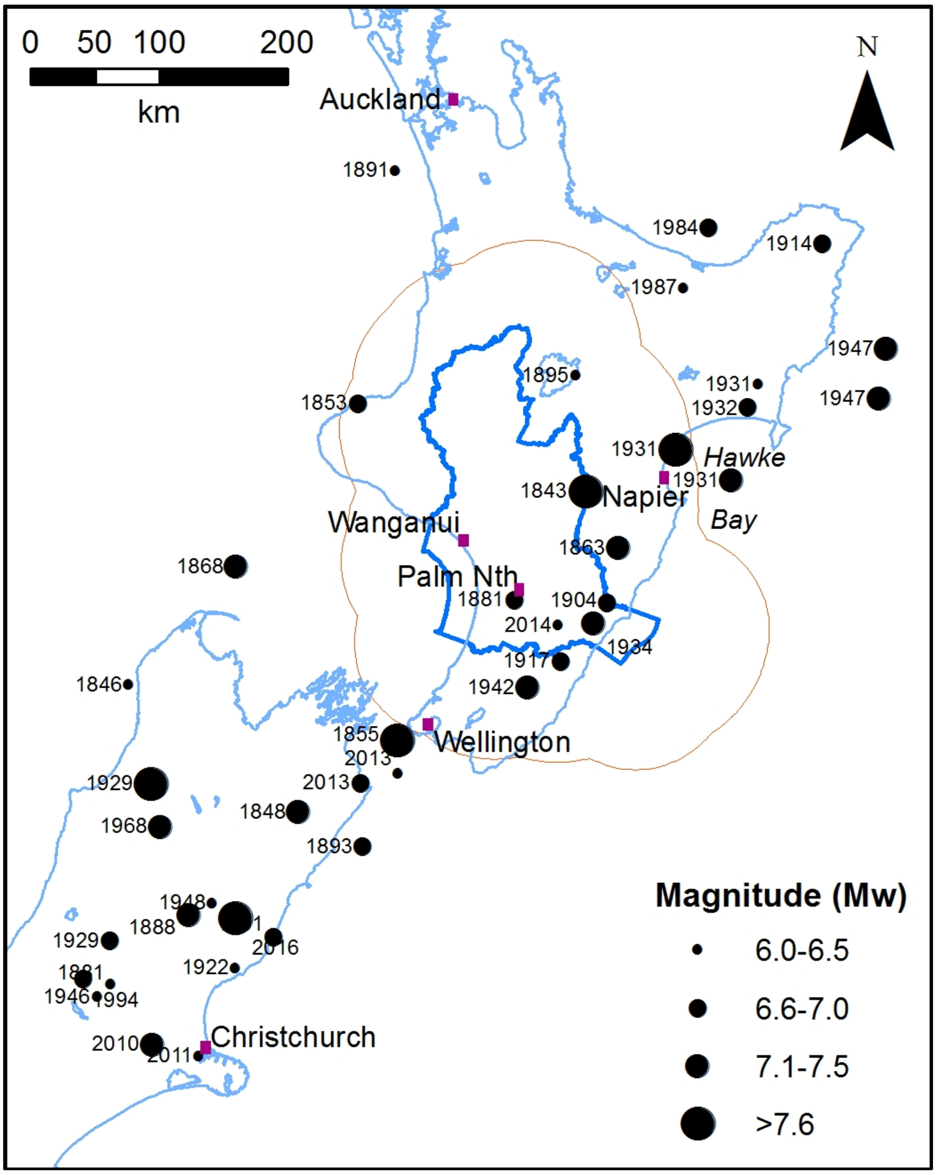

Figure 2.3 Epicentres of significant shallow (<30 km depth) earthquakes in central New Zealand that have occurred since 1843. Outlined in dark blue is the Horizons region, and the brown line is an area that extends a further 75 km around the region to consider impacts from earthquakes outside of the region. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

The August 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.

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

During the first half of the 20th century, the eastern North Island was rocked by numerous large earthquakes, including the 1931 M_W 7.6 Hawke's Bay earthquake, which killed 256 people and destroyed the cities of Napier and Hastings. During this earthquake, felt intensities of 'damaging' to 'very damaging' (MMI 6–8) were reported across the Horizons region (MMI 7–8 in the Tararua District). The Hawke's Bay earthquake was followed by a damaging aftershock in 1931 and the 1932 M_W 6.9 Wairoa earthquake (Figure 2.3).

The 1934 M_W 7.4 Pahiatua (Horoeka) earthquake caused ground-surface rupture on some 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. The shaking intensities for this event in the Tararua District were typically MMI 6–9 (Downes and Dowrick 2014).

In 1942, two earthquakes shook the lower North Island on 24 June and 2 August. They were large (M_W >7) 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 Eketāhuna 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 Eketāhuna earthquake (Rosser et al. 2014; Figures 2.3 and 2.4). 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 Eketāhuna 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 2.3, Figure 2.4 shows the shallow seismicity of the Horizons region over a seven-year period from 2013 to 2020 (Mw >2.6; depth <40 km), with almost 2000 earthquakes. Apart from the M_W 6.2 Eketāhuna earthquake and its aftershocks, the map also highlights clusters of seismicity related to the HSM, e.g. the Porangahau area, and local earthquake swarms, including earthquake swarms offshore of Levin and the Whangaehu River.

In summary, there have been several historic shallow earthquakes of M_W >6 that have occurred within the boundaries of the Tararua District (Figure 2.3), and the district typically has a relatively high level of background seismicity compared to other parts of the Horizons region (Figure 2.4).

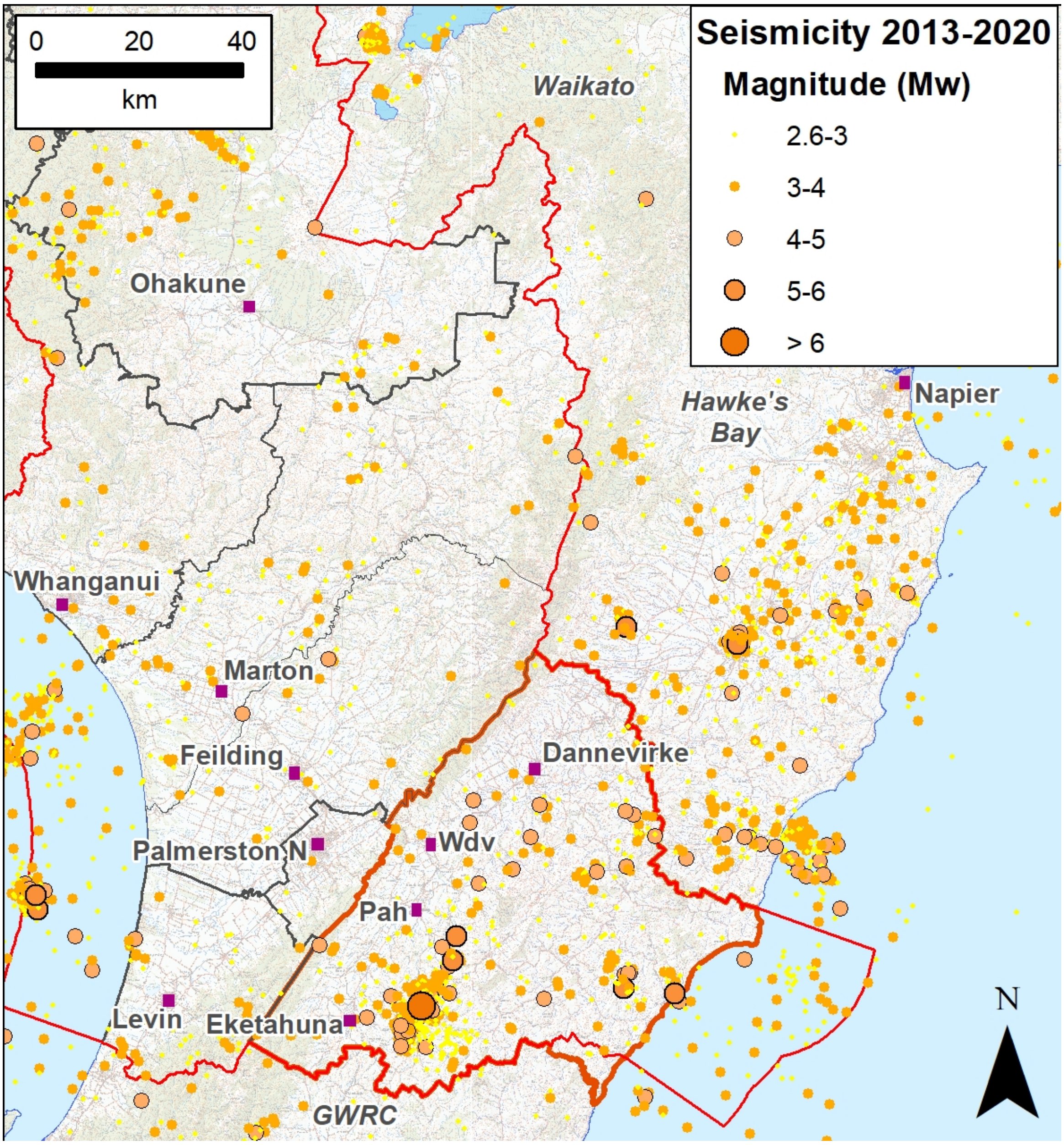

Figure 2.4 Epicentral locations of shallow (<40 km) earthquakes of M_W >2.6 that occurred between August 2013 and 2020 within, or nearby, the Horizons region (red outline; Tararua = dark red). Earthquakes are colour-coded in magnitude bands. The largest event is the 2014 M_W 6.2 Eketāhuna earthquake. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

3.0 ACTIVE FAULTS AND THE MFE GUIDELINES

3.1 What is an Active Fault?

In the context of this work, 'active' faults are those faults considered capable of generating strong earthquake shaking with associated ground-surface fault rupture or deformation.[2] These are therefore faults that can be mapped because they have had one or more earthquake ruptures that have deformed the ground surface. Surface-rupturing earthquakes are typically of magnitude M_W >6.5.[3] An active fault is generally defined within the NZAFD (https://data.gns.cri.nz/af/) as one that has deformed the ground surface at least once during the past 125,000 years (Langridge et al. 2016). This is defined, in part for practical reasons, for mapped faults that deform marine terraces and alluvial surfaces that formed during the 'peak Last Interglacial period'; that is, Marine Isotope Stage (MIS) 5 (71–128,000 years) or more recently (MIS 1–4; 0–71,000 years) (Heron 2020; Alloway et al. 2007). These Late Quaternary (MIS 1–5) surfaces form useful datums throughout New Zealand and are therefore a pragmatic choice for the definition of activity. An exception to this classification is within the Taupō Rift, 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 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 (Figure 3.2). 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).

Figures 3.1 and 3.2 show the example of a reverse fault and a dextral (right-lateral) fault, respectively. Other fault slip types include normal, sinistral (left-lateral) and oblique-slip (in which the components of vertical and horizontal slip are equivalent). Active folds, related to buried faults, are also discussed in this report.

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2 A fault is a plane that separates two bodies of rock and dips into the Earth. A fault is distinct from a fracture, which has no movement or slip across it. Faults can extend metres to kilometres into the Earth.

3 Surface rupture can also occur during smaller earthquakes when the earthquake epicentre is relatively close to the Earth's surface or, locally, from triggered slip from another nearby surface-fault-rupture earthquake.

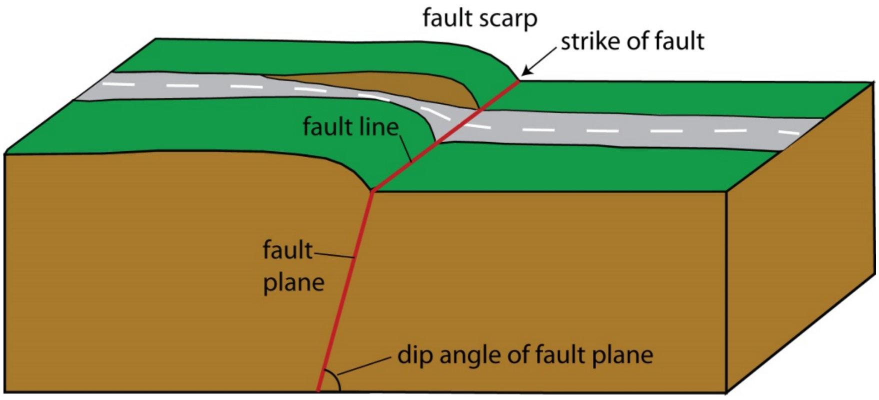

Figure 3.1 Block model of a generic active fault (shown in red). Fault displacement produces a scarp with offset features along the projection of the fault plane at the Earth's surface (fault line or trace). The dip direction defines this fault as a reverse (dip-slip) fault.

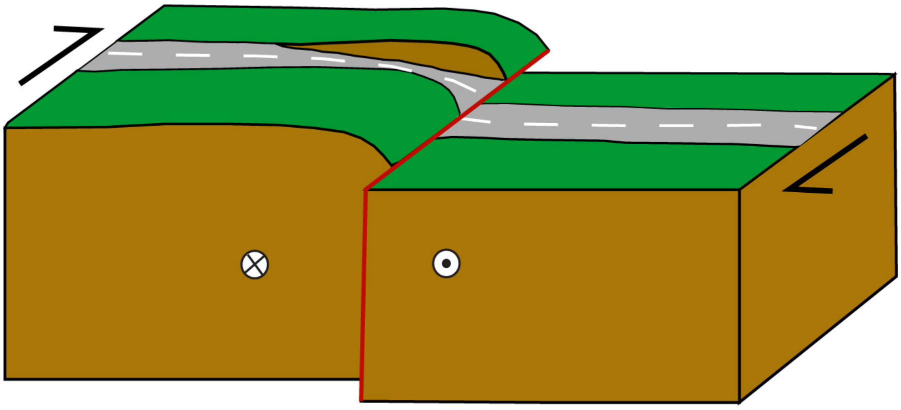

Figure 3.2 Block model of an active strike-slip fault (shown in red). Fault displacement produces a scarp and a horizontal offset (right-lateral, or dextral, in this case) that can impact built structures and infrastructure at the Earth's surface.

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

In 2003, the Ministry for the Environment 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 re-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 (FAZs), and; (c) classification of faults based on their recurrence interval (i.e. the time interval between large, surface-rupturing earthquakes on the same fault), which is an indicator of the likelihood of a fault rupturing in the near future.
2. The Building Importance Category (BIC), which indicates the acceptable level of risk of different types of buildings within a FAZ.

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

Aside from the results of phases 1–3 of the Horizons Regional Council active fault mapping programme, there has been extensive active fault mapping with a view toward developing FAZs in other parts of New Zealand. Examples of other studies include for Greater Wellington (e.g. Litchfield and Van Dissen 2014; Morgenstern and Van Dissen 2021; Van Dissen and Heron 2003; Zachariasen et al. 2000; Begg et al. 2001) and Hawke’s Bay (e.g. Clark and Ries 2016; Langridge and Ries 2014, 2015; Langridge et al. 2006, 2011) in the North Island, as well as Canterbury (Barrell 2015; Barrell and Townsend 2012; Litchfield et al. 2019), the West Coast (e.g. Langridge and Ries 2010) and Marlborough (Langridge and Ries 2016) in the South Island.

The Horizons region has a large number of active faults and folds, which have previously been mapped mostly at scales of >1:10,000 (typically 1:50,000 to 1:250,000) for QMAP and the NZAFD (Heron 2020; http://data.gns.cri.nz/af/) (Figure 2.2). The locations of active faults mapped at scales of >1:10,000 have significant location uncertainty and accordingly have limited use for planning purposes. Improved mapping of active faults in this study builds on phases 1–3 of the Horizons Regional Council active fault mapping programme (e.g. Langridge and Morgenstern 2019; Morgenstern and Townsend 2021). In these phases, two tools allowed for the improved location of active faults: (1) local coverage of airborne LiDAR across the region; and (2) the region-wide DSM, both of which have a resolution of 1 m.

3.3 Active Fault Recurrence Interval and the MfE Guidelines

Six RI Classes, each of which brackets 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’ (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

3.3.1 Pre-Existing Recurrence Interval Data for the Horizons Region

For phases 1–3 of the Horizons Regional Council active fault mapping programme, the GNS reports summarised the current state of knowledge regarding the recurrence intervals of faults in the region and defined preliminary recurrence interval classes for all faults across the other districts in the Horizons region. These data come from: (a) geologic studies (e.g. Jackson et al. 1998; Langridge et al. 2007; Villamor and Berryman 2006b; and summarised by Van Dissen et al. 2003); and (b) estimates based on determinations from geomorphology. In many cases, there is little or no geological or published data that can be used to directly categorise the RI Class of a fault. In such cases, estimates are developed based on the amount of landscape deformation apparent in the geomorphology or from geologic comparisons with other faults in the region that have better defined levels of activity or deformation.

Based on current data, the Horizons region contains active faults in RI Classes I though V (see summary below). All of the RI Class I (≤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 almost all districts in the Horizons region. These faults typically have moderate slip rates (e.g. Ruahine, Pa Valley and Raetihi South faults). Faults with lower slip rates typically have longer recurrence intervals and fall into RI Class III (>3500 to ≤5000 years), e.g. Waitawhiti and Kaweka faults; RI Class IV (>5000 to ≤10,000 years), e.g. Leedstown and Rauoterangi faults; and RI Class V (>10,000 to ≤20,000 years), e.g. Nukumaru Fault.

Overall, the recurrence interval data have large uncertainties, except where fault-specific paleoseismic studies have been undertaken (Van Dissen et al. 2003). The RI Class confidence is a measure of the quality of the geological data that is used to assess the fault recurrence interval (Van Dissen et al. 2003). Some faults have detailed slip rate and/or paleoseismic trenching studies that define the RI Class quantitatively, while, for 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 RI 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 low because the actual recurrence interval range spans a number of RI Classes. For the Tararua District, pre-existing data outlined in the next section are reviewed and updated in Chapter 5 and Appendix 1 using insights from the mapping described in this report.

3.3.2 Summary of Horizons RI Class Data

District by district for the Horizons region, the following summarises estimates of RI Class, incorporating the results of the Horizons region fault mapping programme prior to this report (roman numeral denotes RI Class, superscript denotes data source[4]):

- **Horowhenua**: Northern Ohariu Fault [1,2] (II), Otaki Forks Fault [1,2] (III), Tokomaru Fault [3], Poroutawhao Fault [3], Oturoa trace [3] (IV), Cluain traces [3] (V).
- **Palmerston North City**: Northern Ohariu Fault [1,2] (II), Pohangina Fault [5], Tokomaru Fault [3] (IV).

4 Data sources: [1] Van Dissen et al. (2003); [2] NZAFD (https://data.gns.cri.nz/af/; Langridge et al. 2016); [3] Langridge and Morgenstern (2019); [4] Villamor and Berryman (2006a, 2006b); [5] Langridge and Morgenstern (2020a); [6] Langridge and Morgenstern (2020b); [7] Townsend and Litchfield (2020); [8] Morgenstern and Townsend (2021); [9] Langridge et al. (2005, 2007); [10] Schermer et al. (2004); [11] Berryman and Cowan (1993); [12] Langridge and Ries (2014).

- **Rangitikei**: Snowgrass Fault [1,2,4,6] (II), Kaweka Fault [1,2,6], Mangaohane Fault [6] (III), Leedstown Fault [6], Putorino Fault [6], Jeffersons Line Fault [6], Marton Fault Zone [6], Mt Curl Fault Zone [6], Galpins Road Fault Zone [6], Taihape Fault [2,6], Dirty Spur fault [5,6], Taumataomekura fault [5,6] (IV).
- **Manawatū**: Mohaka Fault [1,2] (I), Ruahine Fault [1,2] (II), Leedstown Fault [4], Himatangi Fault [5], Mt Stewart-Halcombe Fault [5], Rauoterangi Fault [5], Pohangina Fault [5], Komako Fault [5], Dirty Spur fault [5,6], Taumataomekura fault [5,6], Howlett Creek fault [5], Traverse fault [5], Taonui fault [5] (IV).
- **Whanganui**: Nukumaru Fault [1,2] (V).
- **Ruapehu**: Waihi Fault [1,2,4,8], Ohakune Fault [1,2,4,8], National Park Fault [1,2,4,8], Raurimu Fault [1,2,4,8], Raetihi North Fault [2,4,8], Upper Waikato Stream Fault [2,4,8], Waikune fault [4,8] (I); Snowgrass Fault [1,2,4,6,8], Raetihi South Fault [2,4,8], Raetihi Middle fault [2,4,8], Hihitahi Fault [1,2,4,8], Rangipo Fault [1,2,4,8], Shawcroft Rd Fault [1,2,4,8], Karioi Fault [1,2,4,8], Moawhango fault [2,4,8] (II).
- **Tararua**[‡]: Wellington Fault [1,2,9], Mohaka Fault [1,2], Alfredton Fault [1,2,10], Waipukaka Fault, Dreyers Rock Fault [1,2] (I), Saunders Rd Fault [1,2], Pa Valley Fault [1,2], Makuri-Waewaepa Fault [1,2], Weber Fault [1,2], Ruahine Fault [1,2] (II), Maunga Rd Fault [2,11], Rangefront Fault [2,12], Waitawhiti Fault [1,2] (III), Mangaoranga Fault [1,2], Traverse fault [5] (IV).

  ‡ See Table 5.1 for updated RI Class data for the Tararua District.

The summary above highlights that the Tararua and Ruapehu districts have the largest number of named active faults with recurrence intervals applied to them and the greatest number of RI Class I and II faults across the Horizons region.

3.3.3 Derivation of Preliminary RI Class Categories for the Tararua 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. In this report, many of the active faults and fault traces identified have a new, preliminary or updated RI Class developed for them (see Chapter 5 and Appendix 1). This is typically achieved through a calculation of the slip rate. Derivation of new slip rate information for some of the faults in the district is possible because they have a dominantly dip-slip (reverse and normal) style, where the deformation is predominantly related to a vertical sense of motion, making the displacement relatively straightforward to measure by desktop topographic profiling of digital surface models.

A major advance for this study is the recent completion of a nationwide active fault data review for the New Zealand Community Fault Model (CFM; Van Dissen et al. 2021) that builds on the Active Fault Model of New Zealand (AFM; Litchfield et al. 2014). The CFM draws data from the ‘Paleoseismic Site Database’, which is a database of slip rate for faults across New Zealand (Litchfield, forthcoming 2021). These datasets ultimately supply data to the National Seismic Hazard Model (NSHM), which is currently being updated from the 2012 version (Stirling et al. 2012). Part of this review focused on the eastern North Island, including the Tararua and surrounding districts, as these had not received much attention since the work of Beanland (1995). The PhD thesis of Beanland includes the first attempt to develop a GIS database of faults and fault data point locations. Review of this dataset has allowed many more preliminary values for slip rates to be estimated on both strike-slip and dip-slip faults in the Tararua District and for review of pre-existing slip rates and recurrence intervals.

As a comparison of the assigned recurrence interval classes in this review, outputs from the 2012 NSHM model have been utilised to establish a relationship between RI Class and slip rate (Stirling et al. 2012; Litchfield et al. 2014). Slip rates applied to fault sources in the

NSHM can be used to assign a preliminary RI Class to faults that have little geologic or paleoseismic data (Table 3.2). 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 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 3.2 because of how the parametric equations are 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. However, it is reasonable to expect that this uncertainty represents the equivalent of ±1 RI Class. For example, the Rauoterangi Fault, which is assigned a RI Class of IV in Langridge and Morgenstern (2020a), may have a shorter average recurrence interval (RI Class III) or longer average recurrence interval (RI Class V) than expressed by those preliminary determinations. In many cases, it would take new geologic or paleoseismic studies to refine these preliminary assessments.

Table 3.2 Broad relationship between RI Class and slip rate for active fault earthquake sources in the National Seismic Hazard Model (from Stirling et al. 2012).

RI Class	Average Recurrence Interval (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.

3.3.4 Building Importance Category and the MfE Guidelines

Buildings sited across active faults are very likely to be damaged in a fault rupture event. A BIC states the relative importance of assessing the suitability of a building within, or proposed for, a FAZ (Kerr et al. 2003). The BICs listed in Table 3.3 are modified from the New Zealand Loading Standard classifications and are based on risk levels for building collapse according to building type, use and occupancy. Category one (BIC 1) carries the lowest importance; category four (BIC 4) the highest importance.

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

Building Importance Category	Description	Examples
1	**Temporary structures** with low hazard to life and other property	• Structures with a floor area of <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 the BIC categories to make decisions about resource consents and to require conditions on buildings within FAZs. Table 3.4 shows the relationship between the fault rupture recurrence interval and BICs in previously subdivided or developed areas and in greenfield sites (Kerr et al. 2003).

Table 3.4 Relationships between RI 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">RI 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>
</table>

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

4.0 METHODOLOGY OF FAULT MAPPING

4.1 Data Used for Fault and Fault Avoidance Zone Mapping

Active fault traces have been mapped using a combination of LiDAR DEM and hillshade models and a regional DSM[5] (Figure 4.1). For current land-use planning in regard to building on or adjacent to active faults, particularly in developed and developing areas, it is not appropriate to use fault features mapped at scales of 1:50,000 (or larger) because their locations are considered too imprecise (Barrell et al. 2015). During the last decade, several campaigns of airborne LiDAR acquisition have been flown across the southern part of the Horizons region (pink areas on Figure 4.1). From these data, high-quality (typically with 1 m ground pixel resolution) DEMs and hillshade models have been developed, which depict the ground surface free from vegetation and buildings.

In the Tararua District, airborne LiDAR coverage is concentrated in the central-west part of the district, east of the Manawatū Gorge (Figure 4.1). These LiDAR datasets cover the wider area around the confluence of the Manawatū, Mangahao and Mangatainoka rivers near the gorge, including coverage across Woodville and Pahiatua towns.

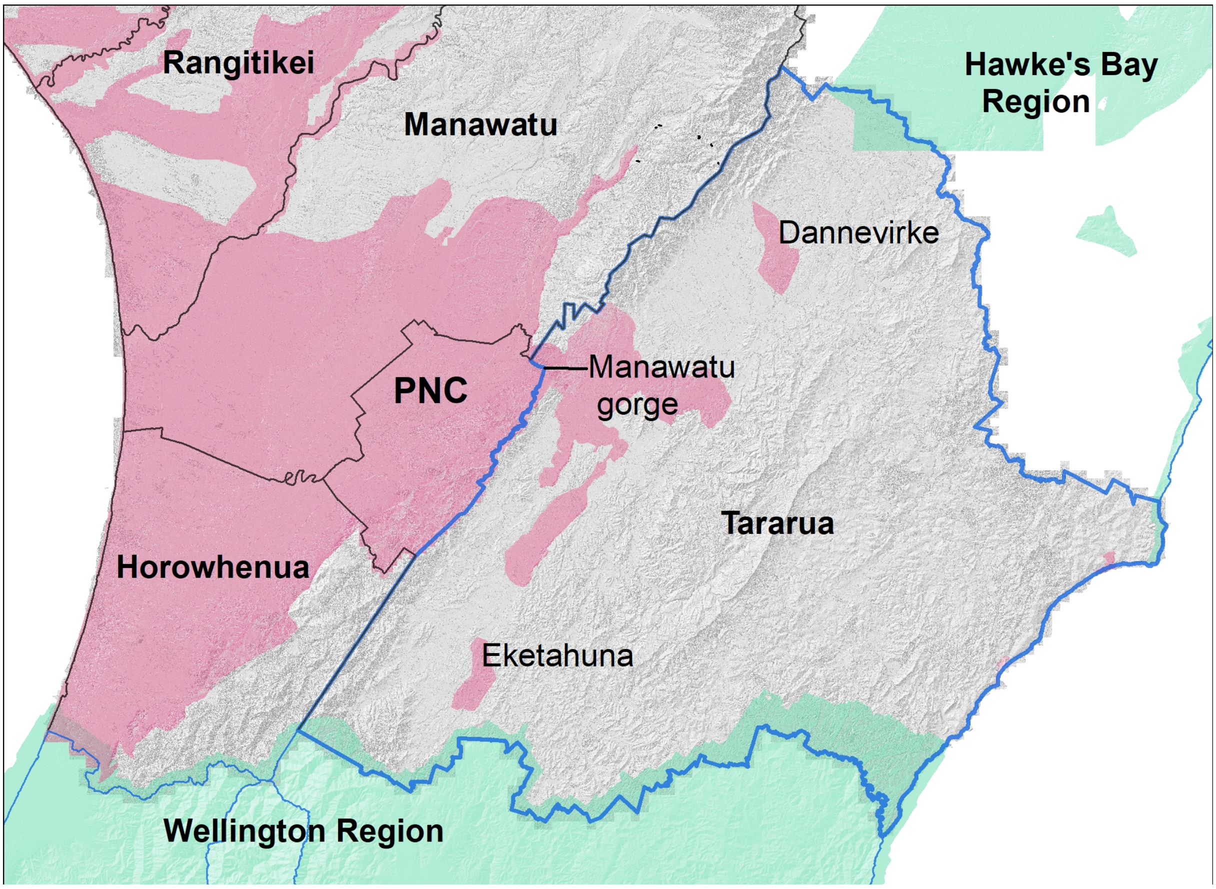

Figure 4.1 Map showing digital topographic data across the southern part of the Horizons region and beyond used for fault mapping in this project. Airborne LiDAR data in the region (pink) overlays the regional DSM (grey shading). LiDAR datasets (green) from north and south of the Tararua District are also used to inform and supplement the digital topographic data coverage. PNC, Palmerston North City.

5 A DEM is a 'bare-Earth' Digital Elevation Model which, through post-processing methods, typically has vegetation and buildings removed, and a DSM is a Digital Surface Model, produced from optical imagery (e.g. aerial photographs), which retains all objects in the image.

Two small LiDAR acquisitions cover the areas of Dannevirke and Eketāhuna. In addition, there is overlap from LiDAR acquisitions that cover the Greater Wellington and Hawke's Bay regions (green on Figure 4.1). Where these acquisitions overlap with the Tararua District, we have used that LiDAR to inform how active faults mapped from these regions cross into the district.

In areas where no LiDAR coverage exists, a DSM was developed by the Horizons Regional Council from aerial orthophotographs. The regional DSM covers the entire area of the district and is an extremely useful tool for mapping landscape features. Mapping on LiDAR is typically undertaken at scales of 1:5000 to 1:10,000. Unlike the DEM developed from the LiDAR data, the DSM does not filter out vegetation or buildings, so there is greater uncertainty in the fault mapping in those areas. However, the DSM allows for higher-resolution mapping than the national-scale 8-m DEM that was used for mapping active faults prior to the widespread availability of LiDAR or other high-resolution elevation models.

4.2 Mapping Fault Lines in a GIS

For this study, the location and attributes of active faults have been assembled in a GIS and are 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 (fault name), ***Accuracy*,** Tect_orig (tectonic origin), **RI_class** (RI Class), **Activity**, ***Fault_comp*** (fault complexity), DOWN_QUAD (downthrown quadrant), Method, DOM_SLIPTY (dominant slip type), SUB_SLIPTY (subordinate slip type), Deform_wid (deformation width) and Buffer_dis (buffer distance). For application of the MfE Guidelines, including developing a FAZ, the most important of these are highlighted in bold. The Accuracy and Fault_comp terms are used to define the Deform_wid and Buffer_dis (all highlighted in italics), which dictate the width of the FAZ. A brief glossary defining these attribute terms is presented in Table 4.1. The assignment 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 (Figures 1.2 and 3.1). Photograph examples of fault scarps in the district are included in Appendix 1 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 are the linear surface projection of a fault plane that can extend kilometres into the Earth. Scarps can extend for hundreds of metres in length and often consist of a zone of deformation 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 that 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 from historical earthquake ruptures (Figures 1.2 and 1.3). 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 database has been drawn near the base of (or slightly above) 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 such cases, the location where the fault will intersect the ground surface cannot be precisely identified. ‘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 fault assumes that there is some confidence in its location from a nearby exposed trace, i.e. typically either an accurate or approximate fault location adjacent to it (i.e. along strike), but there may be no geomorphic expression of this part of the fault itself.

Table 4.1 Active fault data GIS attributes for mapping in the Tararua 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 (e.g. river terrace edge) or gravitational (e.g. landslide head scarp, ridge rent). The tectonic origin terms are ‘definite’, ‘likely’ or ‘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 expression of the surface faulting. The fault complexity terms are ‘well-defined’, ‘well-defined extended’, ‘uncertain constrained’ and ‘uncertain poorly constrained’.
DOM_SLIPTY	The dominant or primary sense of movement (slip) on a fault (reverse, normal, dextral, sinistral or dip-slip).
SUB_SLIPTY	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 (1 m LiDAR DEM / hillshade, 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. In the case of reverse faults, the buffer distance is doubled on the hanging-wall side of the fault, reflecting asymmetric deformation across reverse faults.
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 Classes I through VI). Active faults in the Tararua District fall into RI Classes I–V.

The same terms: ‘accurate’, ‘approximate’ and ‘uncertain’, are applied to mapping on the regional DSM. Despite the fact that the LiDAR DEM and the DSM both have a 1 m pixel resolution, the fault traces are somewhat less sharp on the DSM compared to the LiDAR DEM, usually due to vegetation cover (trees, scrub) or buildings. The diminished level of precision, and hence greater uncertainty in ascertaining the ground surface expression of faults while mapping on the DSM, is reflected in the wider FAZs developed in those areas.

In some cases, it is not clear whether the feature mapped has a tectonic origin. For example, the eroded edges of a range front or a terrace edge could be linear and parallel to a known or suspected fault, or they may be related to erosion by a stream or river. 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 as to whether what is mapped is of tectonic (faulting) origin. Therefore, we have included a term in the GIS called ‘Tect_origin’, which has descriptors of ‘definite’ (i.e. definitely of tectonic origin), ‘likely’ or ‘possible’. In most cases, these features would be defined as ‘active’ because they are well expressed in the landscape.

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 definition of these terms is described in the MfE Guidelines (Kerr et al. 2003). In the context of this report, the fault complexity terms are roughly equated to the width of deformation across which intense ground deformation is likely to occur. No active faults have been assigned distributed fault complexity in this report. These three terms can be expanded to define whether, for example, an ‘approximate’ fault trace occurs between two ‘accurate’ fault traces 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 to acknowledge that the fault has the potential to deviate from the along-strike linear projection of its last known surface location (trace), and distances greater than 200 m from this are deemed too uncertain to be classified as ‘approximate’.

In this report, fault complexity is equated with line accuracy (Table 4.2). We realise that this was not the original intent of the MfE Guidelines 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 location term ‘uncertain’ is used for fault features that may be unclear due to subsequent deposition and/or erosion since the most recent fault movement, i.e. there is no clear trace, but the fault is assumed to underlie or extend through an area based on nearby exposed traces. 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 correspond directly into Resource Consent Category tables for the MfE Guidelines.

Table 4.2 Development of fault complexity terms for the Tararua District used in this study.

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

4.4 Constructing Fault Avoidance Zones

Once a fault trace has been identified and mapped, it is assigned GIS attributes according to 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 (where one may be required).

For this report, the width of FAZs has been defined by the accuracy, fault complexity and method 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 added onto either side of (encompassing) the deformation width buffer (Figure 4.2). This margin of safety 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 and an additional 20 m width, as recommended in the MfE Guidelines (Kerr et al. 2003).

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 middle of the figure, the fault is 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, as no clear deformation was found in that area.

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 (Figure 1.3; Kelson et al. 2001). 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 (as shown in the asymmetric FAZ in Figure 4.3).

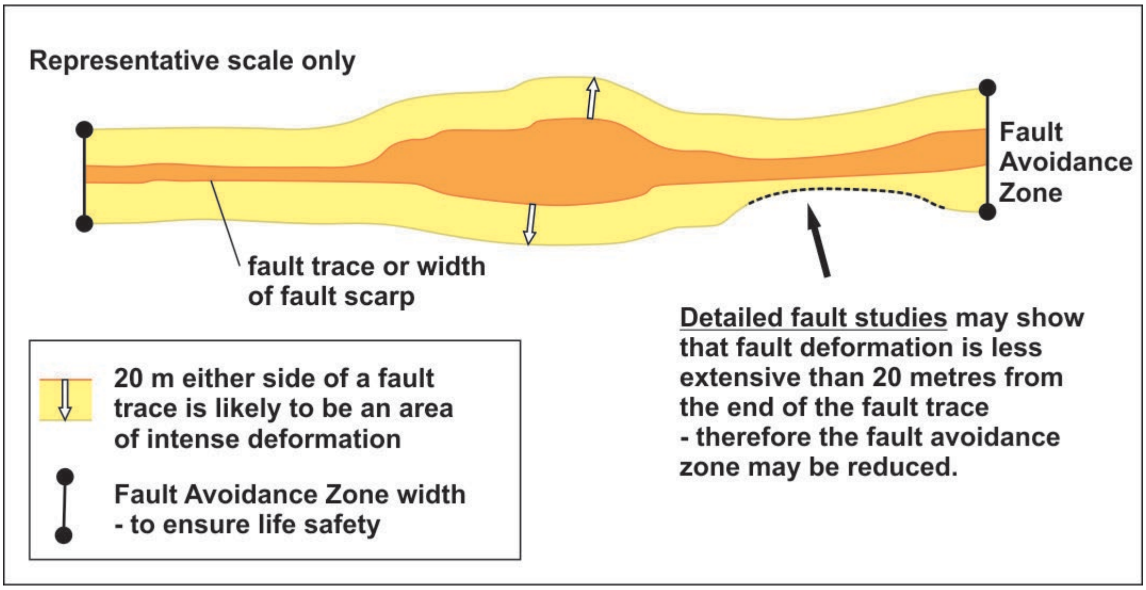

Figure 4.2 A Fault Avoidance Zone (FAZ; orange + yellow) and how it may be developed for a district planning map (not drawn to scale), modified from Kerr et al. (2003). Note the 20 m 'margin of safety' buffer as part of the FAZ and the area where the FAZ has been narrowed by undertaking detailed fault studies.

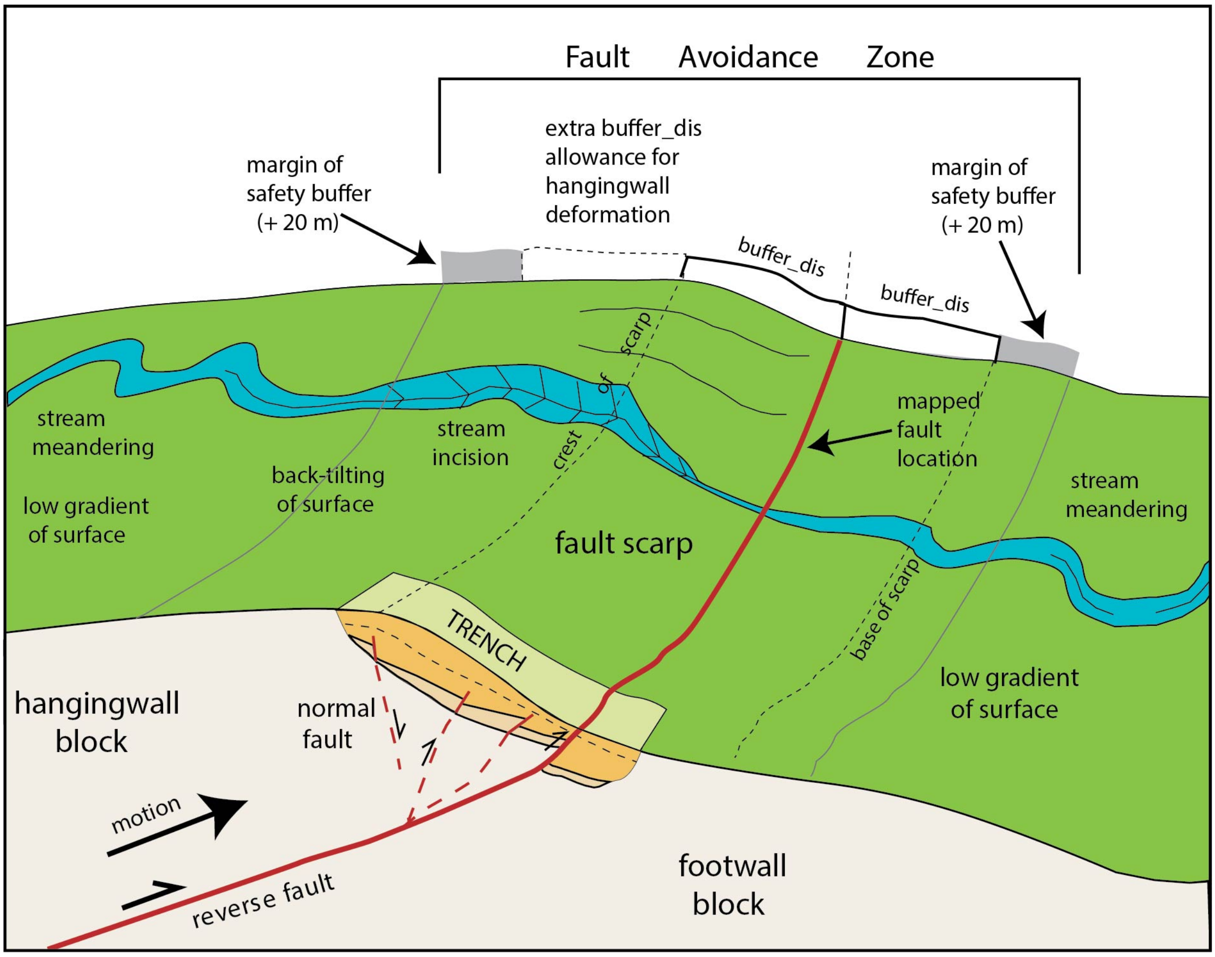

Figure 4.3 Schematic diagram of a dip-slip reverse fault and its scarp. In this case, the mapped fault trace (rupture surface; bold red line) is mapped near the base of the scarp. The fault trace itself is 'accurately' mapped and the scarp is 'well-defined' on LiDAR data. The growth of such scarps affects the long-term morphology of streams that cross the structure. The trench shows the evidence for determining surface faulting events. The complete FAZ comprises the mapped width of the scarp on LiDAR (Deform_Wid = 2 x buffer_dis), which is extended by an extra 'buffer_dis' on the hanging-wall side of the fault, after which the 20 m margin of safety buffer is added.

Where there is more than one fault trace making up a distributed or wide zone of faulting, individual FAZs may overlap. In these cases, the more accurate or higher-activity data (fault location, complexity) should dictate subsequent resource planning decisions. In the Tararua District, this is particularly evident for closely spaced splay fault traces associated with the Mohaka Fault and Woodville-Dannevirke Fault Zone.

Figure 4.4 illustrates an example of a FAZ map for a part of the active Eketāhuna fault, which is inferred to have a reverse sense of fault movement with dip direction to the northwest. Note that the FAZ is wider on the northwestern (upthrown) side of the mapped fault, in accordance with the buffer zones developed for reverse faults and as outlined above.

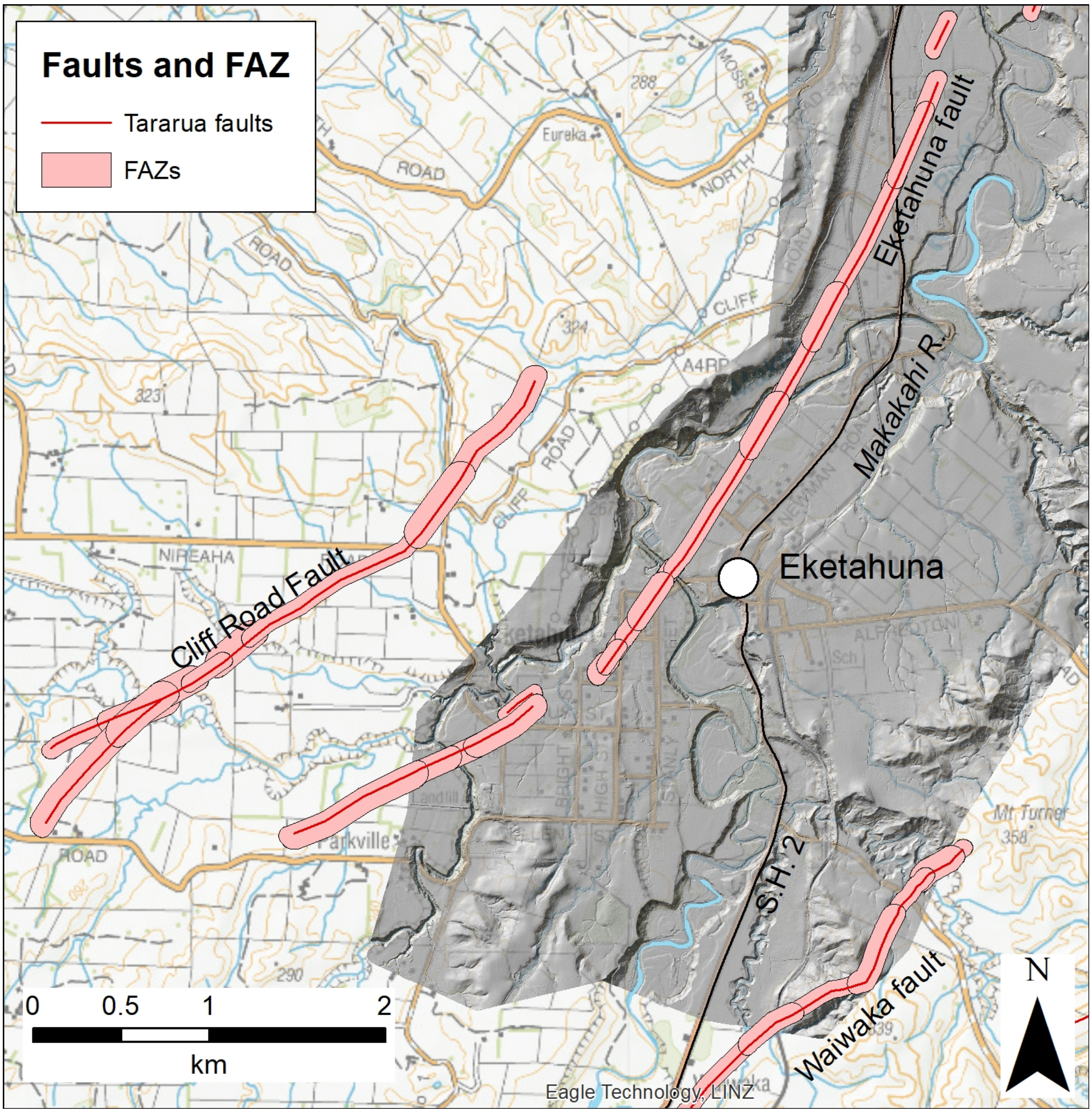

Figure 4.4 Fault Avoidance Zone (FAZ) map for the Eketāhuna priority area, highlighting the Cliff Road, Eketāhuna and Waiwaka faults. These FAZs are discussed in Section 5.2. The grey-shaded area indicates the LiDAR coverage near Eketāhuna.

4.4.1 Fault Awareness Areas

FAAs were first developed for the districts of the Canterbury region (Environment Canterbury; ECan) as an alternative to the use of FAZs (Barrell et al. 2015). This was in part undertaken because Canterbury has many districts with large undeveloped areas and with many of the faults having been mapped at scales of between 1:50,000 and 1:250,000. It was realised that the overall cost of mapping all faults in the region at more detailed scales was prohibitively expensive with respect to the benefit in terms of reduced risk from surface faulting. Thus, the concept of a FAA was developed to cover large areas of under-developed land where active faults were known to occur on QMAP geologic maps and in the NZAFD (Heron 2020; https://data.gns.cri.nz/af/). Notwithstanding, fault mapping at these scales is not detailed enough to delineate FAZs around the faults nor for directly applying the MfE Guidelines (Kerr et al. 2003) to mitigate fault rupture hazard. Thus, FAAs in the Canterbury region were developed to use regional fault mapping widely at 1:250,000 scale.

In the Canterbury region, the FAAs were delineated in two ways: (i) as relating to a fault mapped as ‘definite (well expressed)’, ‘definite (moderately expressed)’, ‘likely (well expressed)’ or ‘likely (moderately expressed)’ and some folds – in these cases the FAAs had a width of ±125 m about the mapped feature; and (ii) for all other faults and folds ±250 m about the mapped feature.

In consultation with ECan and its district councils, a set of ‘recommended actions’ were developed so that the FAAs would be useful for planning decisions for each district council in the region (Table 4.3; Barrell et al. 2015). Table 4.3 shows BIC in relation to fault expression (as above) and divides faults into two recurrence interval divisions: RI <5000 years (which corresponds to RI Class I, II and III) and RI >5000 years (which corresponds to RI Class IV and above). In addition, Table 4.3 outlines situations where a new subdivision might be considered or where the council is making a plan change. Specific actions in Table 4.3 refer to “fault maps *being used* in District Plans”, “fault information *being used* on LIMs and PIMs” [6] and “consideration *necessary for a* surface fault rupture hazard assessment”. Thus, the purpose of a FAA is to highlight that there may be a tectonic feature or fault within that area and facilitate action in regard to them. While this FAA approach is not part of the MfE Guidelines, the recommended actions for FAAs can be used in a similar way to the MfE Guidelines and still provide a way forward in terms of planning actions for active faults.

We were limited in this study by the scope of the project to define FAZs within the eight priority areas. However, extensive detailed mapping was undertaken on many other faults, including faults with RI Class I, such as the Wellington and Mohaka faults. In this study, we have modified the table of Barrell et al. (2015) to focus on recurrence interval; thus, Table 4.3 is headed by columns of RI <5000 years, RI >5000 years and a third column for faults without recurrence interval data. The modification removes the qualifier related to fault likelihood and expression (e.g. definite versus likely and well-expressed versus moderately or not expressed). While we have mapped all fault features with the terms accurate, approximate and uncertain (and these exist in the GIS attributes), we acknowledge that, for FAAs, it is relevant to divide faults based on recurrence interval.

6 Land (LIMs) and Property (PIMs) Information Memorandums.

Therefore, we have adopted a similar approach to Barrell et al. (2015) for zoning many of the active faults in the western part of the Tararua District that are outside the eight priority areas where FAZs are developed. In this study, FAAs are developed with a width of ±125 m about a mapped feature when it is accurate or approximate in terms of its fault location. When a mapped feature has an uncertain location, or where we have used the original 1:250,000-scale line work, we have adopted a width of ±250 m (Figure 4.5). In future, if development is proposed for areas with a FAA status, then further fault mapping and/or geologic studies would be recommended to better define the location of surface faulting and deformation. The recommended actions shown in Table 4.3 are appropriate for faults in the Tararua District that have an FAA.

Table 4.3 Recommended planning actions for faults assigned with Fault Awareness Areas (FAAs) in the Tararua District (modified from Barrell et al. 2015).

Proposed Activity	**Recommended Actions for FAAs**		
	For Faults with RI <5000 Years	**For Faults with RI >5000 Years**	**For Possibly Active Faults and Faults without RI Data**
Single residential dwelling (BIC 2a and 2b in part)	• Fault maps in District Plans *and* fault information on LIMs and PIMs.		
Normal structures and structures not in other categories (BIC 2b, apart from single dwellings)	• Consideration of the surface fault rupture hazard should be a specific assessment matter if resource consent for a new structure is required. • Site-specific investigation, including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures for the accurately mapped fault (e.g. set-back or engineering measures).	• Fault maps in District Plans *and* fault information on LIMs and PIMs.	
Important or critical structures (BIC 3 and 4)	• Consideration of the surface fault rupture hazard should be a specific assessment matter if resource consent for a new structure is required. • Site-specific investigation, including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures determined for the accurately mapped fault (e.g. set-back or engineering measures).		
New subdivision (excluding minor boundary adjustments)	• Consideration of the surface fault rupture hazard should be a specific assessment matter. • Site-specific investigation, including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures for the accurately mapped fault (e.g. set-back or engineering measures).		• Fault maps in District Plans *and* fault information on LIMs and PIMs.
Plan Changes	• Consideration of the surface fault rupture hazard should be a specific assessment matter. • Site-specific investigation, including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures for the accurately mapped fault (e.g. set-back or engineering measures).		

An example of FAAs developed in this study is shown in Figure 4.5, where the FAA widths are either ±125 or ±250 m. Following the approach of Barrell et al. (2015) is also useful as, in many cases, we were also able to apply RI Classes from the literature or define preliminary RI Classes from mapping and profiling the faults. This makes it relatively simple to distinguish between faults that have recurrence intervals of <5000 years (RI Class I–III) or > 5000 years.

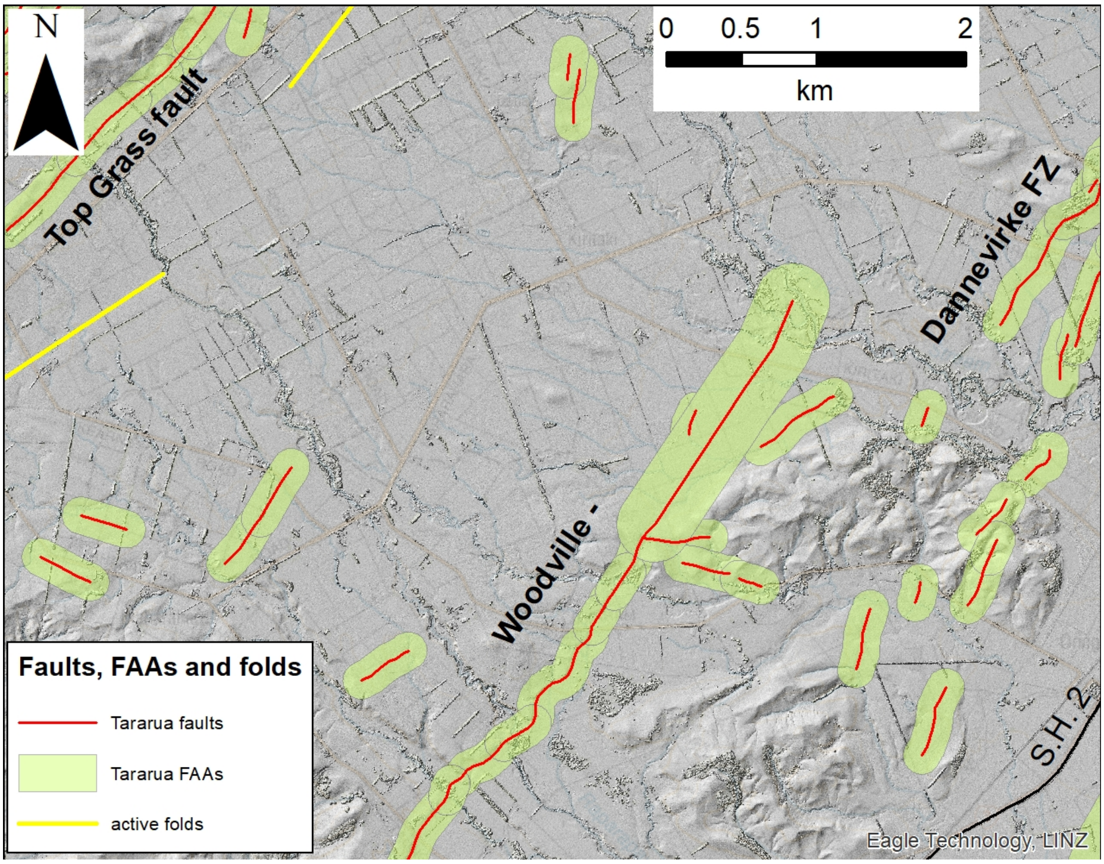

Figure 4.5 Fault Awareness Area (FAA) map for the area southeast of Dannevirke, showing part of the FAA for the Woodville-Dannevirke Fault Zone. Active fold traces have been mapped southeast of the Top Grass fault.

4.5 Mapping Active Folds

Active folding is a manifestation of slip on active, but blind, faults. While many faults rupture to the Earth's surface and have a fault scarp, some fail to do so and have a 'blind' or buried fault tip, which is expressed as folding at the surface (Figure 4.5). When mapping an active fold, the axial trace of the fold is delineated. In the case of an anticline, the axial trace is synonymous with the crest of the fold, or topographic high in the geomorphology, and it reflects uplift in the hanging wall of a reverse fault (Figure 4.6).

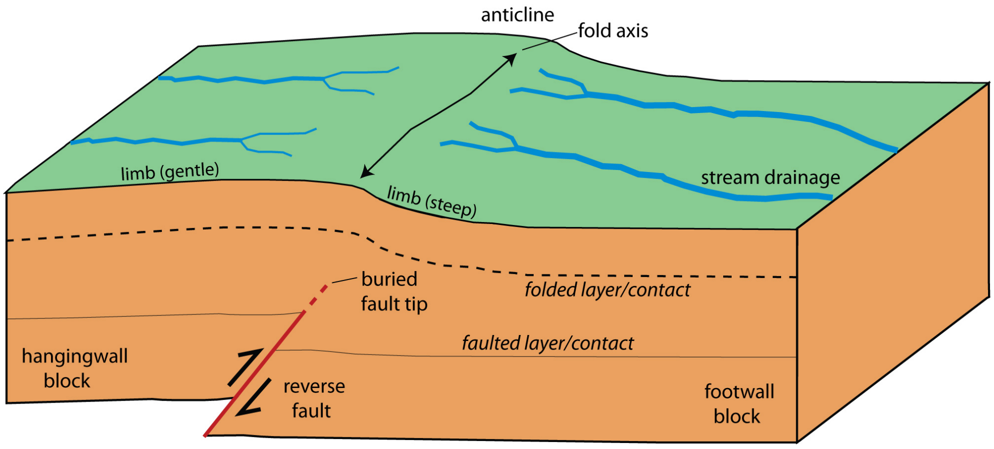

Figure 4.6 Schematic block model of an anticlinal fold that is related to a buried active reverse fault. Motion on the fault has driven the hanging-wall block upwards and folded the ground surface above the fault tip. The fold is asymmetric and defined at the surface by a fold axis and by the stream drainage pattern, where streams drain away from the fold axis. The scale and depth to the fault tip is not specified.

While folds are a manifestation of surface deformation related to fault movement, for the purposes of the MfE Guidelines, we do not treat active folds in the same way that we do active faults. It is not practical to develop a FAZ 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 for most building classes. In this study, while we have mapped several fold axes that are included in the GIS, we have not included folds within the definition of features that necessitate a FAZ or a FAA. It would be impractical to zone and buffer an active fold, due to: (i) the substantial breadth of subtle deformation across a fold; (ii) the lack of focused (high-intensity) ground deformation and clear location; and (iii) most importantly, the low risk to life safety posed by the lack of surface rupture.

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 PRIORITY AREAS, RECURRENCE INTERVAL CLASSES AND CASE EXAMPLES

An objective of this project was to treat the main towns of the Tararua District as priority areas for mapping and zoning active faults. In these areas, we constrained the location and activity of faults and developed FAZs, where appropriate. The priority area towns are, from southwest to northeast: Eketāhuna, Alfredton, Pahiatua, Woodville, Kumeroa, Dannevirke, Ormondville and Norsewood (Figure 5.1). Maps, descriptions and examples of how the MfE Guidelines could be applied are provided below for these towns. Detailed discussion of each active fault and their recurrence intervals (including outside the priority areas) is given in Appendix 1.

5.1 Summary of Active Faults in Tararua District

We have defined FAZs and FAAs for known active and possibly active faults within the Tararua District and have developed preliminary RI Classes for the majority of them where we could (Table 5.1). There are also many unnamed fault traces for which RI Classes have not been defined (see Figure 5.1). Recurrence interval data for many of these faults (particularly the RI Class III and IV faults) should be considered preliminary, as they are based on landscape-derived slip rate estimates and comparison to other faults with RI Class information that have a similar expression in the landscape.

Most of the faults mapped in this study have been assigned FAAs. The FAA status should be used by the council as an indication that there is likely to be an active fault within the FAA, and, in many cases, as shown above, these already have preliminary RI Classes assigned to them. FAAs are not discussed within the MfE Guidelines (Kerr et al. 2003) and therefore have a different status to FAZs. However, Barrell et al. (2015) provide recommended planning actions for dealing with faults that have FAAs applied to them. Therefore, there are measures that the council can consider applying for FAAs. As an example, a planning permit may be applied for to build a new residential structure at a property that is within the FAA for the Wellington Fault – the most active fault in the district. Because the fault has been assigned a RI Class I status, it would be prudent to undertake further work to accurately locate the fault and the zone of deformation through detailed surveying and/or excavation.

Neither FAZs, FAAs nor recurrence interval information are provided for active folds.

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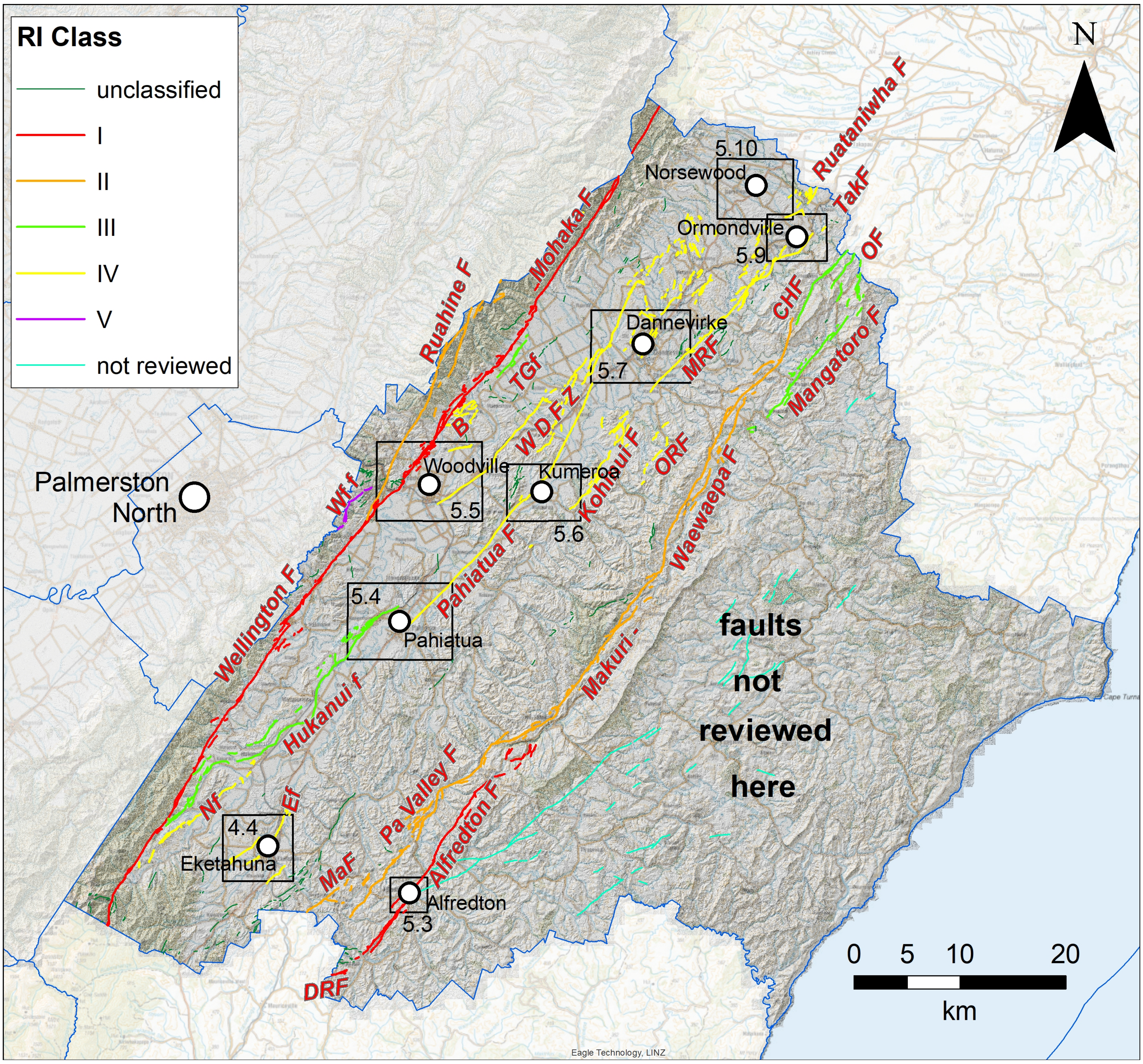

Figure 5.1 Map of active faults and priority study areas in the northwestern half of the Tararua District, defined according to RI Class. Priority areas (black boxes) are labelled by their town names and associated figure numbers (e.g. Figure 5.3). Fault abbreviations: B, Beagley Road Fault Zone; CHF, Clear Hills Fault; DRF, Dreyers Rock Fault; Ef, Eketāhuna fault; MaF, Mangaoranga Fault; MRF, Maunga Road Fault; Nf, Nireaha fault; OF, Oruawharo Fault; ORF, Otope Road Fault; Tg f, Top Grass fault; Wf f, Windfarm fault; WDFZ, Woodville-Dannevirke Fault Zone. Faults in the southeast of the district have not been reviewed in this project.

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Table 5.1 Recurrence Interval (RI) Class information for active faults within the Tararua District.

Fault	RI Class	RI Range (Years)	RI Class Confidence*	Data Source**
Wellington Fault, Mohaka Fault, Alfredton Fault	I	≤2000	H	1–3
Dreyers Rock Fault	I	≤2000	M	1–3
Mangaoranga Fault, Makuri-Waewaepa Fault	II	>2000 to ≤3500	M	1–3, 5
Ruahine Fault, Pa Valley Fault, Old Pa Valley Fault	II	>2000 to ≤3500	M	1–3
Hukanui fault	III	>3500 to ≤5000	M	5
Clear Hills Fault, Oruawharo Fault, Mangatoro Fault	III	>3500 to ≤5000	M	1–3, 5
Top Grass fault	III	>3500 to ≤5000	L	3, 5
Cliff Road Fault, Eketāhuna fault, Waiwaka fault	IV	>5000 to ≤10,000	L	4, 5
Woodville-Dannevirke Fault Zone, Pahiatua Fault	IV	>5000 to ≤10,000	L	2, 3, 5
Pahiatua Fault	IV	>5000 to ≤10,000	L	2, 3, 5
Ruataniwha Fault, Takapau Fault	IV	>5000 to ≤10,000	M	1, 4, 5
Maunga Road Fault, Otope Road Fault, Kohinui Fault	IV	>5000 to ≤10,000	M	4, 5
Beagley Road Fault Zone, Mangarawa fault, Nireaha fault	IV	>5000 to ≤10,000	L	3, 5
Windfarm fault	V	>10,000 to ≤20,000	L	5

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

** [1] Van Dissen et al. (2003); [2] Litchfield et al. (2014); [3] NZAFD (https://data.gns.cri.nz/af/; Langridge et al. 2016); [4] Berryman and Cowan (1993); [5] this study.

5.2 Eketāhuna Priority Area

Detailed fault mapping has resulted in the identification of three active reverse faults within, and in the vicinity of, Eketāhuna (Figures 4.4 and 5.1). These are the Cliff Road Fault, the Eketāhuna fault (new) and the Waiwaka fault (new) (see Appendix 1.4.2). The Eketāhuna and Waiwaka faults both have active fault traces that run across Q2a alluvial surfaces (12,000 to 24,000 years old) and have been assigned RI Class IV (>5000 to ≤10,000 years) activity. The Eketāhuna fault has a small but sharp scarp from the town through to the golf course (Figure 5.2). The dip direction of the fault is typically to the northwest; however, the southern-most mapped trace appears to be northwest-facing (implying a southeast-dipping fault plane). The Cliff Road Fault (Berryman and Cowan 1993) has been assigned RI Class IV based on its similarity to the other two faults. The Cliff Road Fault and Waiwaka fault are located a few kilometres outside of Eketāhuna township.

All three faults have been given asymmetric FAZs, with widths of 100–160 m designed for reverse faults.

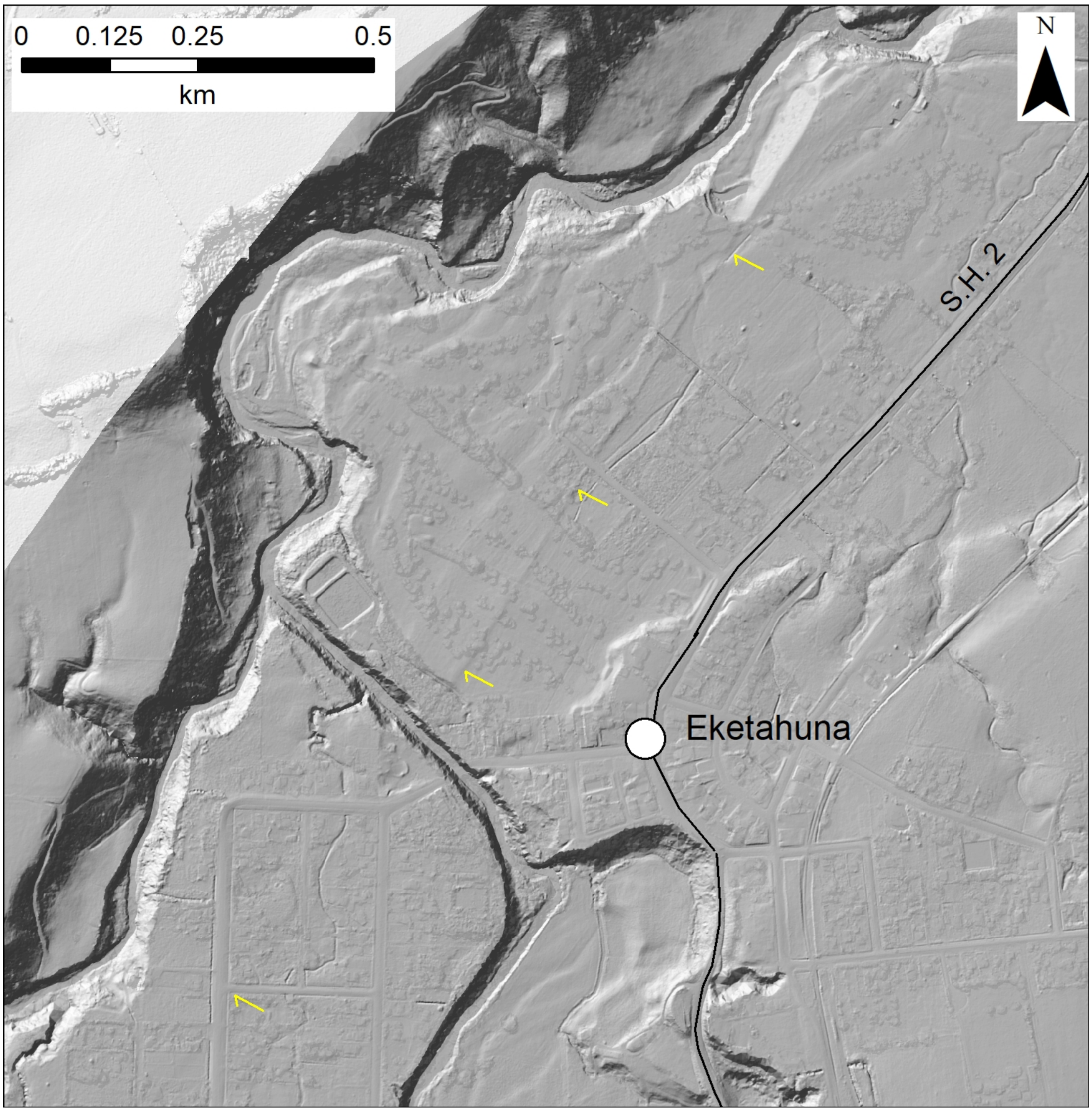

Figure 5.2 Detailed active traces highlighted for the Eketāhuna fault on a LiDAR hillshade model. Traces are identified by yellow arrows pointing at the southeast-facing scarp.

5.2.1 Case Example for the Eketāhuna Fault

For this test case, we consider a situation where a landowner on Bridge Street, Eketāhuna, wants to undertake renovations on their house. The house is a previously developed BIC 2a building but sits within a FAZ of the Eketāhuna fault. However, because the Eketāhuna fault has been assigned to RI Class IV (>5000 to ≤10,000 years), the MfE Guidelines (Table 5.2) suggest that any activity here would be Permitted (or Permitted*). In the latter case, Council has the flexibility to determine whether the planned activity could be Controlled or Discretionary.

Table 5.2 Resource Consent Category for both developed and/or already subdivided sites and greenfield sites along RI Class IV faults. Categories account for various combinations of Building Importance Category and fault complexity (Kerr et al. 2003).

Resource Consent Categories for Class IV faults (>5000 to ≤10,000 years) **e.g. Eketāhuna, Waiwaka, Pahiatua, Kohinui and Ruataniwha faults; Beagley Road Fault Zone**					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-Defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain	Permitted	Permitted	Permitted	Permitted	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-Defined	Permitted	Permitted*	Permitted*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
Uncertain	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying

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

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

5.3 Alfredton Priority Area

Alfredton is included as a priority area because of its proximity (0.5 km) to the RI Class I Alfredton Fault (Figure 5.3). FAZs have been developed for the dextral-slip Alfredton Fault within c. 1–2 km of the village. The symmetrical FAZs are 80–110 m wide, and they do not run through the built-up part of the village but locally occur over some houses on Castle Hill Road. FAAs have been developed for areas outside the proximity of the village. The Alfredton Fault is discussed in more detail in Section A1.1.4.

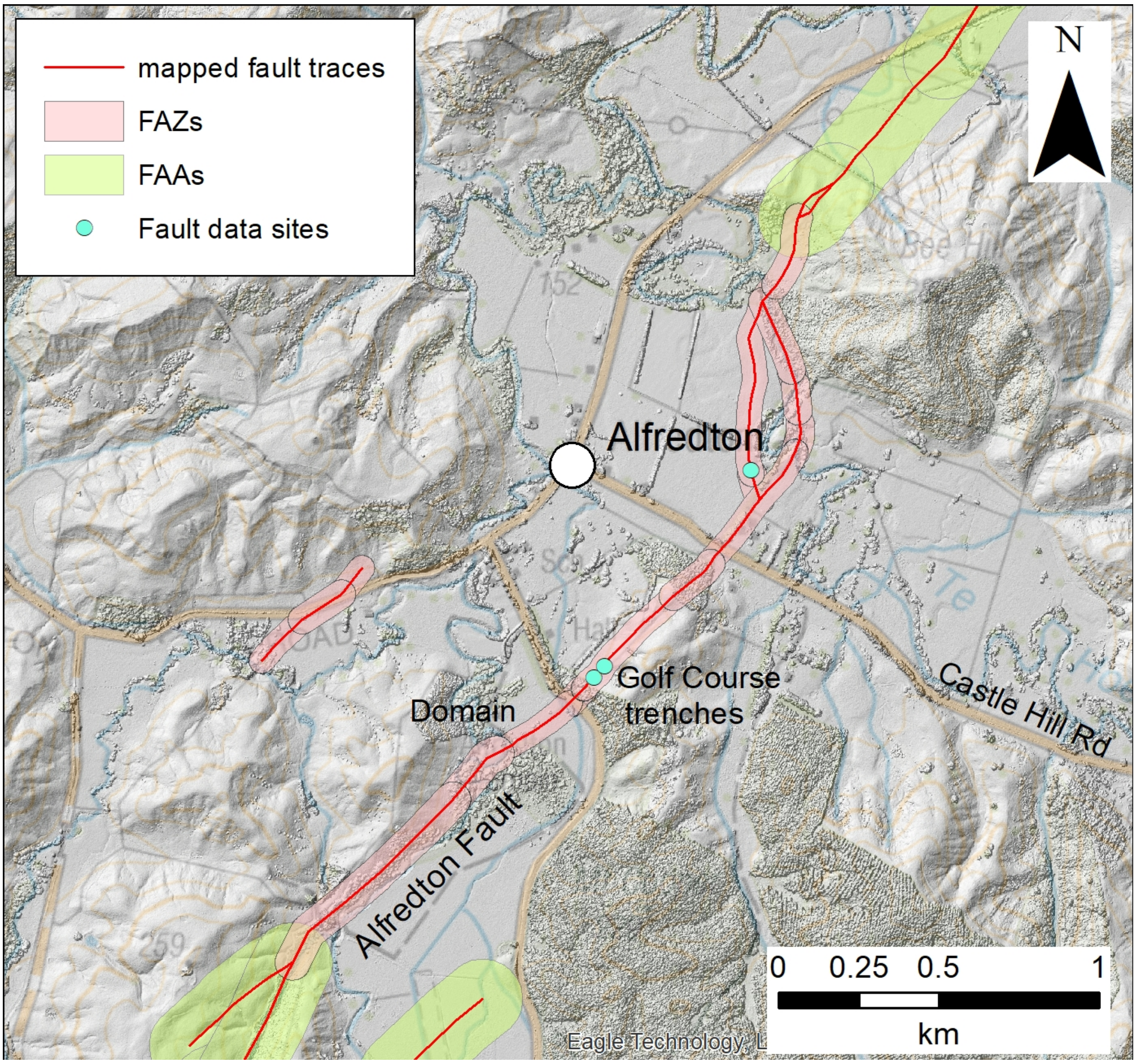

Figure 5.3 Active fault traces, Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs) for the RI Class I Alfredton Fault near Alfredton. Teal dots show sites where slip rate and paleoseismic data have been obtained (Schermer et al. 2004).

5.3.1 Case Example for the Alfredton Fault

RI Class I faults (recurrence ≤2000 years) include the most active on-land faults in New Zealand. These faults have the highest probability of hosting a large earthquake with ground surface deformation and therefore require the most consideration in terms of planning according to the MfE Guidelines. In this example, the local community want to build a new hall for sports groups in the Alfredton Domain. The greenfield site they have in mind is within the FAZ for the Alfredton Fault. Planners from the Tararua District Council are considering their application with reference to Table 5.3 from Kerr et al. (2003). The building is considered a BIC 2b category, i.e. it is a small building but occasionally hosts groups of people. Because the fault has been accurately mapped (well-defined) locally through the domain near the building site, the activity could be deemed *Non-Complying* (note italics). A sensible compromise for the community is to consider moving the hall footprint outside of the 80-m-wide FAZ, where there are no planning restrictions.

Table 5.3 Resource Consent Category for both developed and/or already subdivided sites, and greenfield sites along RI Class I faults. Categories account for various combinations of Building Importance Category and fault complexity (Kerr et al. 2003).

Resource Consent Categories for Class I faults (RI ≤2000 years) **e.g. Wellington, Mohaka, Dreyers Rock and Alfredton faults**					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-Defined	Permitted	Non-Complying	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	Discretionary	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	Discretionary	*Non-Complying*	*Non-Complying*	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

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

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

5.4 Pahiatua Priority Area

There are two mapped faults near Pahiatua (Figure 5.4). The Pahiatua Fault has been interpreted as an active reverse fault with dip direction to the northwest. The southern end of the Pahiatua Fault is shown on QMAP and the NZAFD as being a concealed active fault (Lee and Begg 2002; https://data.gns.cri.nz/af/). We discuss this fault in more detail in Appendix 1.4.3, where it is given a preliminary RI Class IV status (>5000 to ≤10,000 years). There are no known active traces associated with the fault in the vicinity of Pahiatua township, and it has a FAA applied to it with a width of 500 m using 1:250,000 map data from QMAP (Heron 2020).

The Hukanui fault (new) is discussed in more detail in Appendix 1.3.1, where it is given a preliminary RI Class III status (>3500 to ≤5000 years). The Hukanui fault is interpreted as a northwest-dipping reverse fault associated with the eastern edge of hills to the west of Pahiatua (Figure 5.4). Some faults mapped within these hills are interpreted as normal faults. FAZs have been developed for the northern end of the Hukanui fault where it occurs within c. 2 km of Pahiatua. Some of these FAZs cover the area of the dairy factory at Mangamutu and where the Pahiatua Track (highway) crosses the base of these hills. To the southwest of Pahiatua, FAAs are assigned to the rest of the Hukanui fault.

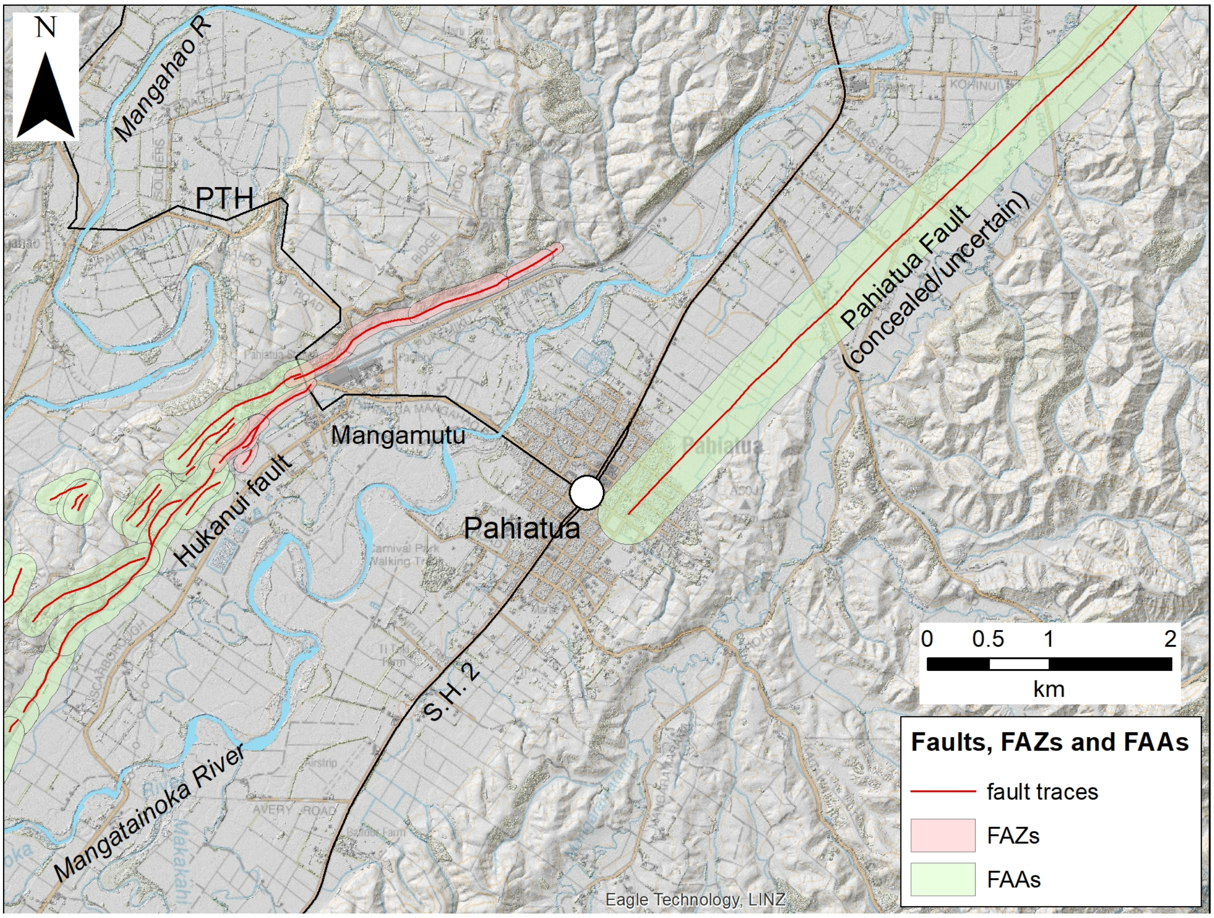

Figure 5.4 Active fault trace, FAZ and FAA map for the Pahiatua priority area. The map shows the Pahiatua and Hukanui faults, with FAZs (pink) and FAAs (green). PTH, Pahiatua Track highway.

5.4.1 Case Example for the Pahiatua Fault

For this test case, we consider a situation where a new cinema is proposed for Pahiatua. The site of this BIC 3 building is within the FAA for the RI Class IV Pahiatua Fault, which is mapped as uncertain through the town (Table 5.2). In such a case, the council could apply the recommended actions for FAA from Barrell et al. (2015) shown in Table 4.3. In this case, the recurrence interval has been defined as >5000 years, so it becomes important for the council to define whether the cinema would be considered a BIC 2b, i.e. whether the developers would need to undertake site-specific investigations for this activity. In either case, the FAA can be shown on LIMs and PIMs for this property (Barrell et al. 2015).

5.5 Woodville Priority Area

Figure 5.5 highlights that there are no FAZs within the main part of Woodville township. Our fault mapping has resulted in a new interpretation of the northeast-striking Woodville Fault (Heron 2020) as being part of a more extensive fault system termed the Woodville-Dannevirke Fault Zone (WDFZ; see Appendix 1.3.2). There are no accurate or approximate fault traces recognised at the southern end of the WDFZ near Woodville. In this area, we have mostly adopted the 1:250,000-scale mapping for fault lines east of Woodville, which were previously mapped as concealed and active (Heron 2020; Lee et al. 2011). Nevertheless, the RI Class adopted for these fault traces is the same as assigned to the WDFZ to the north, i.e. RI Class IV (>5000 to ≤10,000 years), and we have developed a FAA with a width of 500 m for these traces.

The RI Class I Mohaka Fault occurs within a few kilometres of Woodville (Figure 5.5; Appendix 1.1.2) and symmetric FAZs, 80–130 m wide, have been developed for it due to its dominantly dextral (strike-slip) style of deformation. There are a few traces at the front of the range with a dominantly reverse sense of movement, which have a wider hanging-wall buffer on the northwest side. These traces have been included as part of the Mohaka Fault rather than being classed as splay faults or distinct unnamed faults.

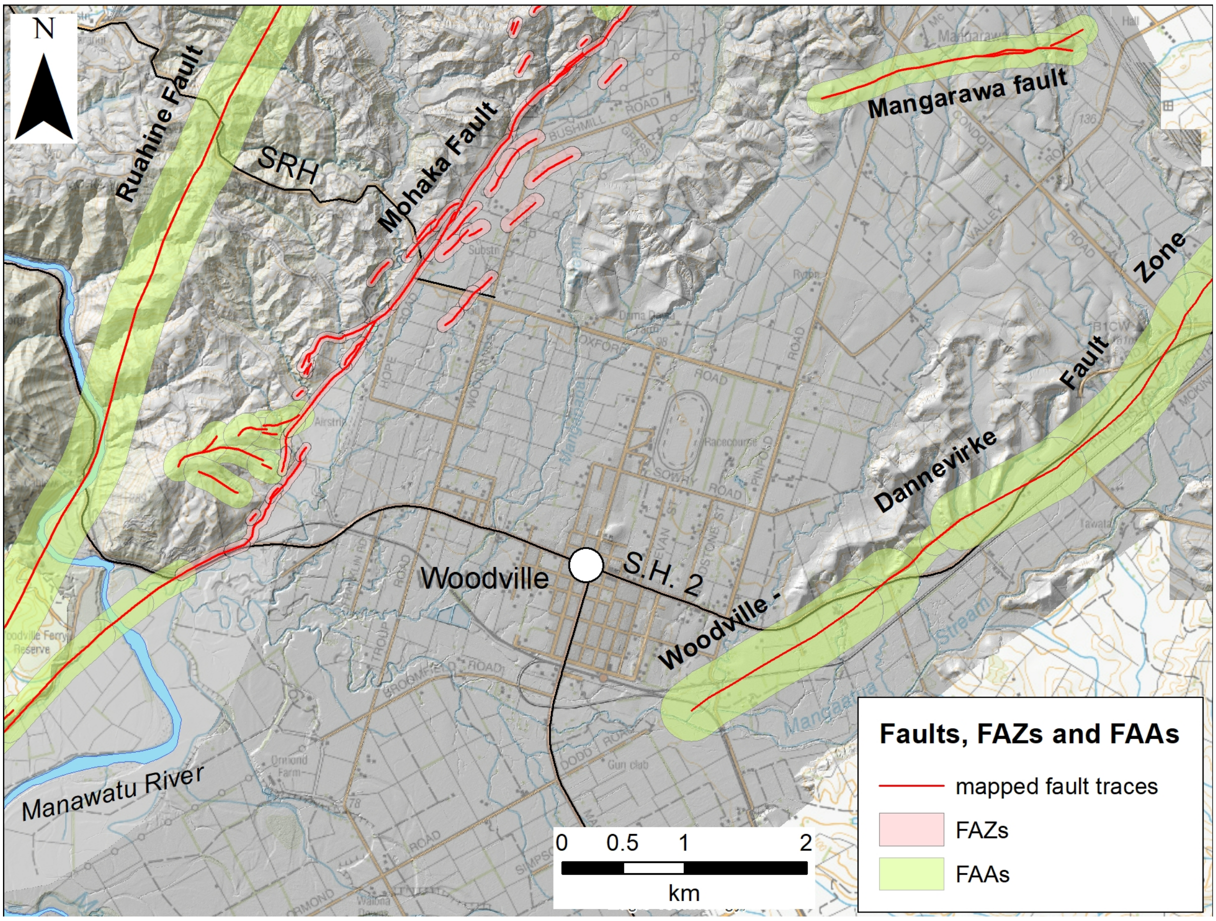

Figure 5.5 Active faults (red), Fault Avoidance Zones (FAZs; pink) and Fault Awareness Areas (FAAs; green) near Woodville. The basemaps come from LiDAR hillshade models. SRH, Saddle Road highway.

5.5.1 Case Example for the Woodville-Dannevirke Fault Zone near Woodville

A family wants to sub-divide to develop a lifestyle block with a single-storey home on Elliott Road, east of Woodville. The site is within the FAA defined for the WDFZ. No active surface traces have been definitively mapped along this part of the WDFZ. For this reason, a FAA covers the area of the planned building footprint. In such a case, the council could apply the recommended actions for FAA from Barrell et al. (2015) shown in Table 4.3. Because the fault has an uncertain location in this area – and because the WDFZ has an estimated recurrence interval of >5000 years – there may be no requirement for the council to seek site-specific investigations by the family. However, the FAA can be shown in District Plans and on LIMs and PIMs for this property.

5.6 Kumeroa Priority Area

There are no active faults mapped in Kumeroa, but the Pahiatua Fault (Appendix 1.4.3) lies c. 1 km across the Manawatū River (Figure 5.6). We mapped scarps over a length of c. 2.6 km along the previously mapped Pahiatua Fault near Kumeroa. In addition, an array of active traces occur in the hills west of Jackson Road within greywacke bedrock. One interpretation of this array is that it occurs within the hanging-wall block of the Pahiatua Fault. As a result of this, FAAs with a total width of 250 m or 500 m were developed for the Pahiatua Fault (see Section 5.4.4). The inferred hanging-wall faults have 250-m-wide (total width) FAAs, reflecting their clear scarps in the landscape. There are no planning restrictions associated with these FAAs in terms of the MfE Guidelines.

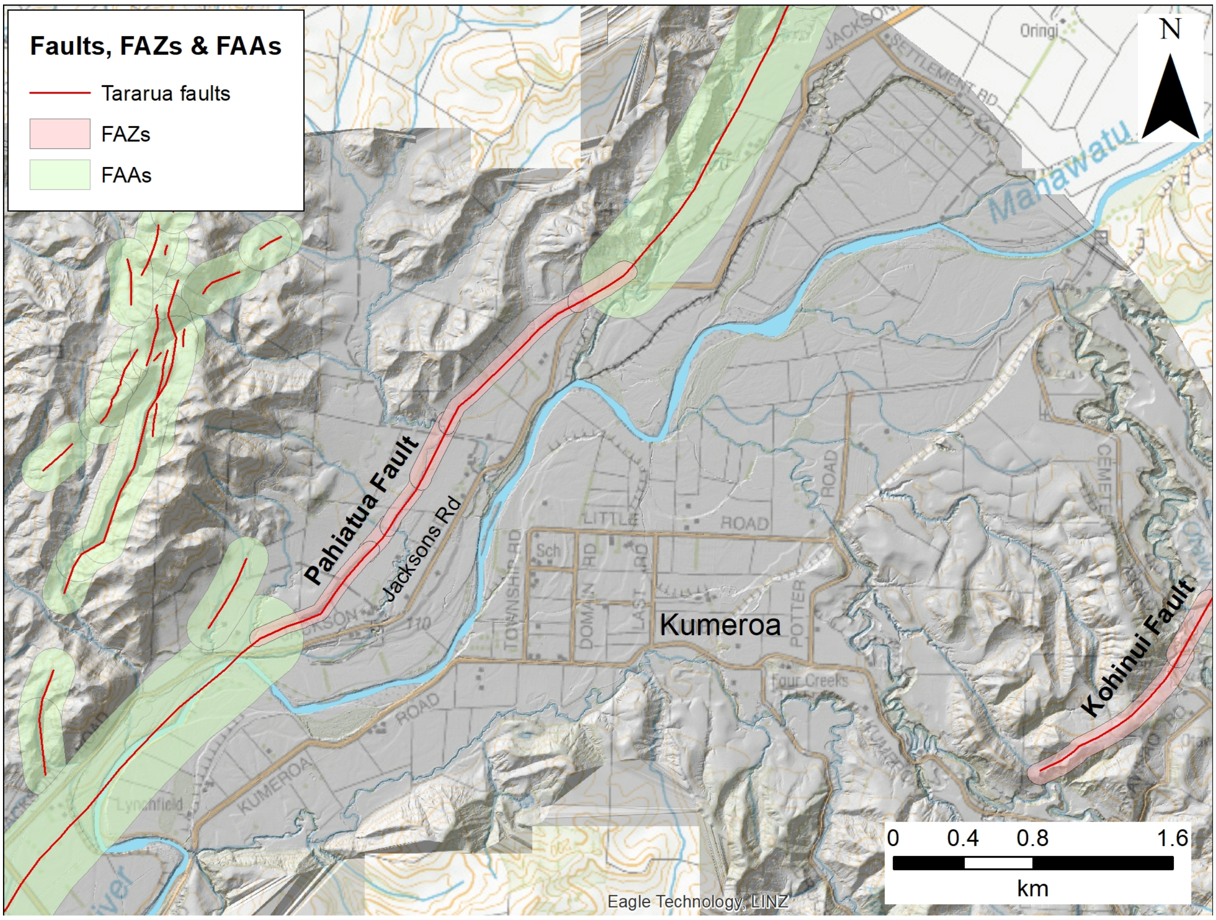

Figure 5.6 Active faults (red), Fault Avoidance Zones (FAZs; pink) and Fault Awareness Areas (FAAs; green) near Kumeroa. The grey-shaded basemap is a LiDAR hillshade model of the area.

A FAZ is defined for the Kohinui Fault that occurs c. 2 km east of Kumeroa. The reverse-slip Kohinui Fault has been assigned RI Class IV (>5000 to ≤10,000 years) activity (see Section A1.1.4). The FAZs are asymmetric, as the Kohinui Fault is dominantly a reverse fault, and these have widths of 100–135 m. See Table 5.2 for application of the MfE Guidelines for the Kohinui and Pahiatua faults.

5.7 Dannevirke Priority Area

Figure 5.7 shows the Dannevirke priority area. Detailed fault mapping across the forearc basin identified a generally right-stepping zone of discontinuous fault traces named the Woodville-Dannevirke Fault Zone (WDFZ) in this report (see Figure A1.18; Appendix 1.3.2). Based on profiling fault scarps across alluvial surfaces along the WFDZ, we estimate that this system of faults has a summed vertical slip rate of 0.2–0.7 mm/yr using Table 3.2, which is consistent with a fault of RI Class III or IV status. Due to the uncertainty around the activity of this fault system, we apply a preliminary RI Class IV (>5000 to ≤10,000 years) to the WDFZ. Detailed fault studies may indicate that the average recurrence interval for the WDFZ is <5000 years. Several prominent features interpreted as possible fault traces occur both within the town and its periphery, and these have been assigned FAAs because they are newly mapped faults with an uncertain tectonic origin (Figures 5.7 and 5.8). FAAs developed for fault features associated with the WDFZ and Maunga Road Fault within Dannevirke town or nearby have widths of 250 or 500 m. For these FAAs, the council can apply the recommended actions in Table 4.3.

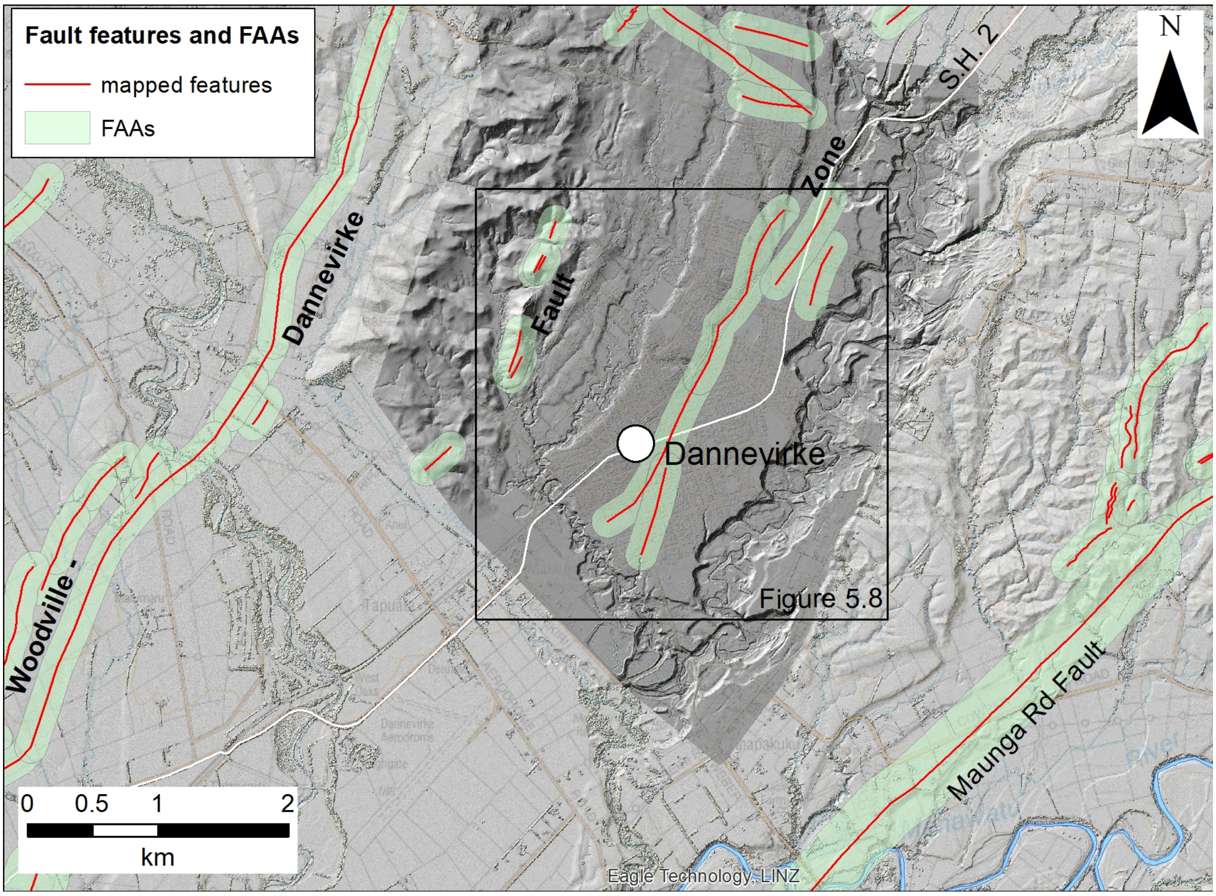

Figure 5.7 Active fault traces (red) and Fault Awareness Areas (FAAs; green) near Dannevirke. The Woodville-Dannevirke Fault Zone is assigned to RI Class IV.

Figure 5.8 presents a detailed LiDAR image across the central part of Dannevirke and shows how we have gone about identifying features on this study. The LiDAR highlights linear features that have been interpreted as active fault features that run obliquely through the town. These northeast-trending features are possibly associated with a reverse fault (part of the WDFZ) that uplifts land on the west side of the town. Profiles P1 and P2 were measured using the digital topographic data. The height of the topographic step (possible fault scarp) in P1 is 7 ± 1 m and in P2 is 14 ± 2 m, both down-to-the-southeast. Using QMAP geology and LiDAR data, we interpret that P1 is entirely on a Q2a (12,000–24,000 years old) alluvial terrace surface. The lower (eastern) part of Profile P2 may be the same Q2a surface, and the higher (western) part may be an older alluvial surface, probably Q3a (24,000–59,000 years) or Q4a (59,000–71,000 years) in age. For P1, a calculated vertical slip rate is c. 0.46 ± 0.2 mm/yr. Similarly, for P2, a calculated vertical slip rate is c. 0.2–0.7 mm/yr. If this is a fault scarp, then it is likely that such a feature would have metre-scale vertical displacements in a large earthquake rupture event. Section A1.3.2 gives a more detailed discussion about the WDFZ.

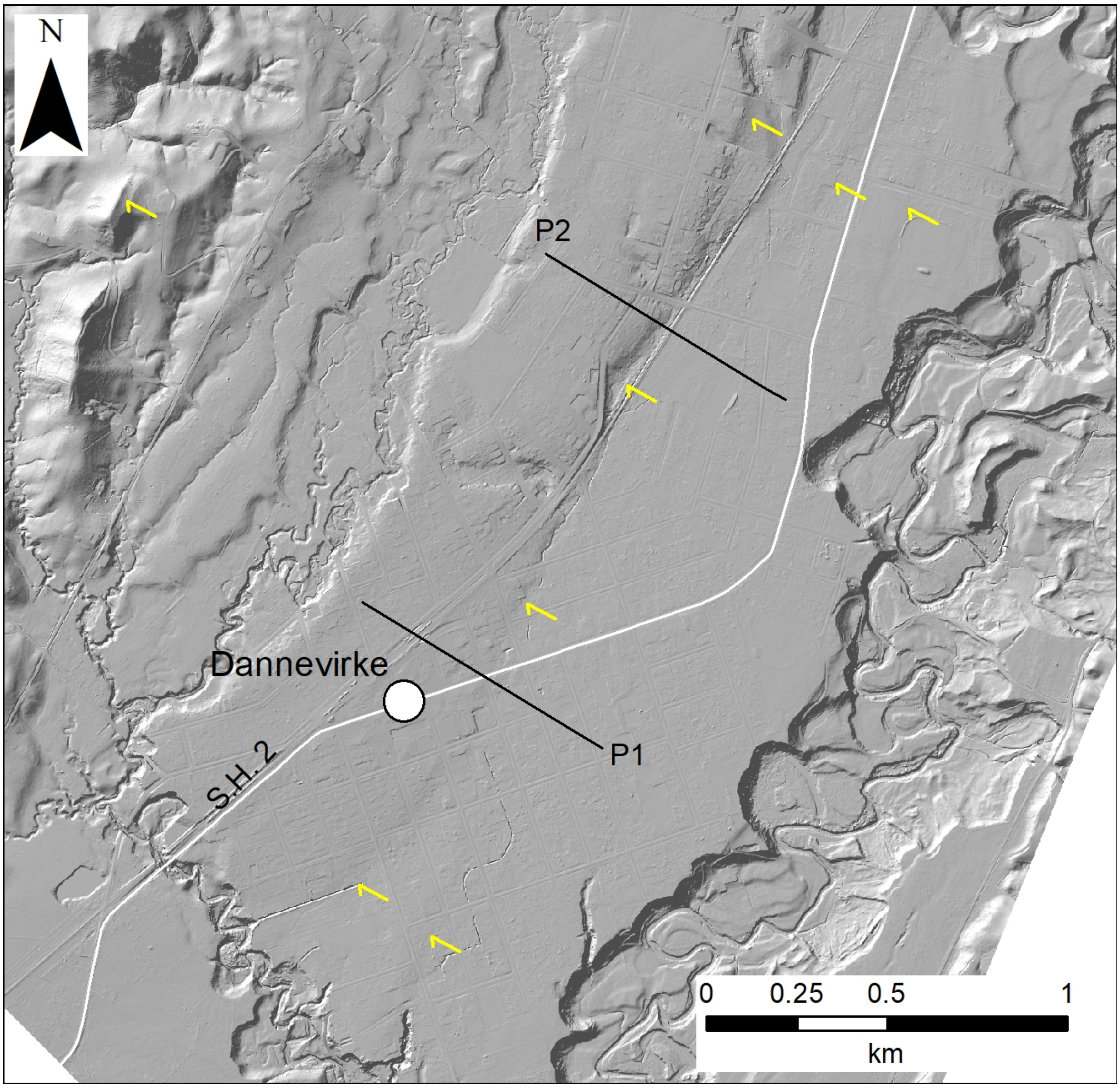

Figure 5.8 Detailed active traces highlighted by yellow arrows on a LiDAR hillshade model. Arrows point at southeast-facing fault scarps within the town of Dannevirke. P1 and P2 are profiles where the topographic scarp height was measured.

5.7.1 Case Example for the Woodville-Dannevirke Fault Zone in Dannevirke

A small subdivision is proposed to increase the housing stock (BIC 2a and 2b) in Dannevirke. The land is in the northeast part of the town (Mangatera) and falls inside a FAA) for the RI Class IV WDFZ. According to the recommended actions for FAAs in Table 4.3, for a new subdivision “consideration of the surface fault rupture hazard should be a specific assessment matter”. This can be achieved through “site-specific investigation including detailed fault mapping … and appropriate mitigation measures for the accurately mapped fault” (Table 4.3). This applies to all faults, such as the WDFZ, that have some definition of their recurrence interval.

5.8 Ormondville Priority Area

Ormondville is situated in between two northeast-striking zones of active faulting along the Ruataniwha and Takapau faults (Figure 5.1; Beanland 1995; Klos 2009). The village sits between these two fault zones, and there are no active fault traces mapped within the town (Figure 5.9). FAZs and FAAs do not impinge on the central part of the village.

The Ruataniwha and Takapau faults have both been assigned to RI Class IV (Klos 2009; Langridge et al. 2006), which is adopted here based on a slip rate of 0.2 ± 0.1 mm/yr estimated for the CFM (Van Dissen et al. 2021). FAZs have been developed for the Takapau Fault to the southeast of Ormondville, while the remaining traces have FAAs developed for them. The FAZs are asymmetric (wider on the northwestern, hanging-wall side) and have maximum widths of 160–190 m. See Table 5.2 for application of the MfE Guidelines to the Ruataniwha and Takapau faults. FAAs have a width of 250 or 500 m (Figure 5.9). Section A1.4.5 gives a broader description of these three faults.

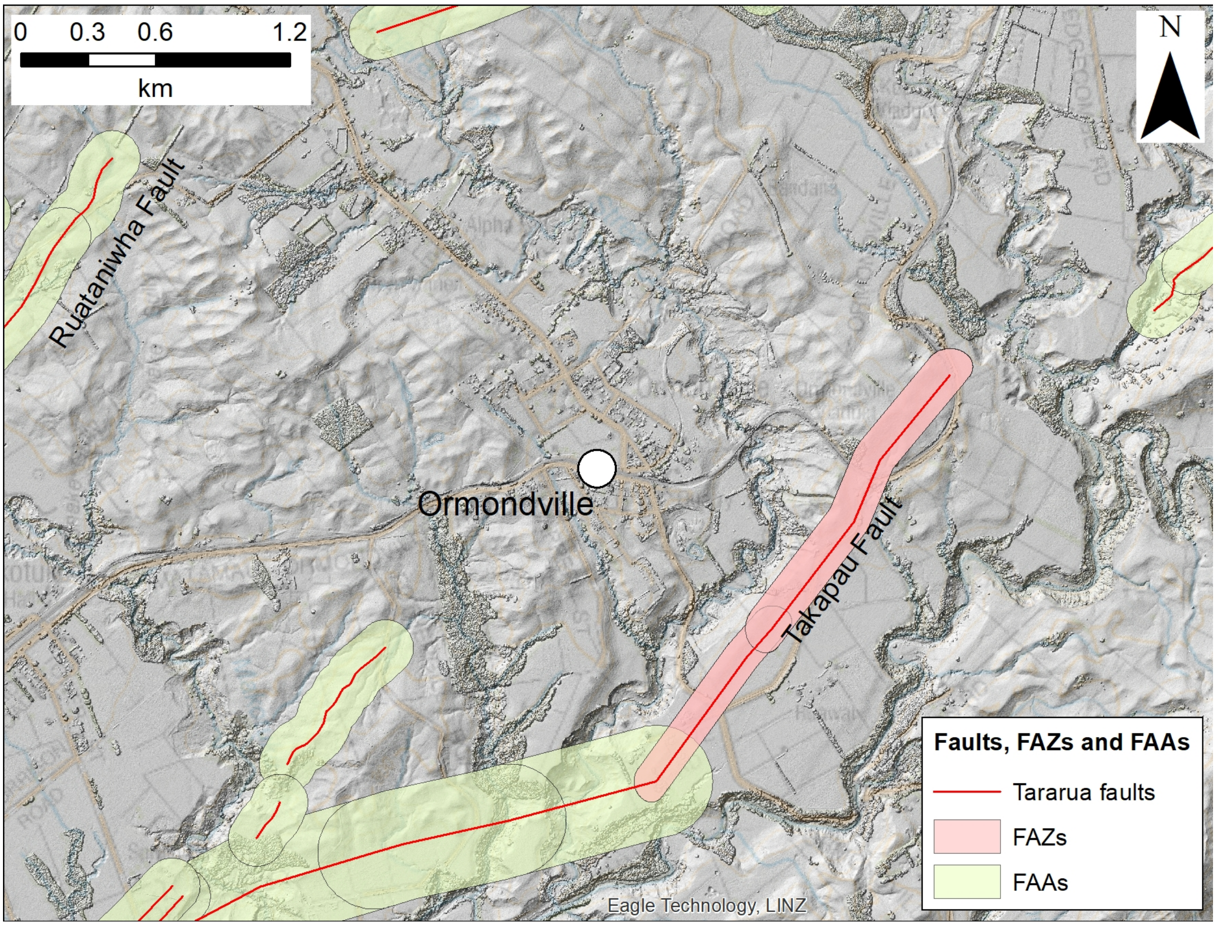

Figure 5.9 Active traces (red), Fault Avoidance Zones (FAZs; pink) and Fault Awareness Areas (FAA; green) in the vicinity of Ormondville.

5.9 Norsewood Priority Area

Figure 5.10 shows that there are no active faults, FAZs or FAAs near the township of Norsewood – the closest traces of the Ruataniwha Fault occur c. 4 km southeast of the town. The town is situated near the base of the Ruahine Range, where there are a series of mapped structures related to the eastern range front (Figure 5.1; Lee et al. 2011; Langridge and Ries 2014) (see Sections 5.3.2, 5.4.7 and 5.6).

In this study, we have given some attention to possible faults and folds to the northwest of Norsewood, including the Rangefront Fault (see Section A1.1.1) identified by Beanland et al. (1998). These previously mapped structures were defined using seismic stratigraphy and geology. Beanland et al. (1998) defined a series of sub-parallel active and inactive reverse faults and folds including, and southeast of, the Rangefront Fault (Langridge et al. 2011). These structures are all to the northwest of the Norsewood priority area and >5 km from the village.

In this study, we discontinued an active trace of the Rangefront Fault shown in the NZAFD at the northern boundary of the district (Langridge et al. 2016) due to a lack of evidence in the DSM of demonstrable activity across late Quaternary surfaces. In addition, some fault and fold traces shown as active in Beanland et al. (1998) northeast of Norsewood have not been defined as active in this study for the same reasons.

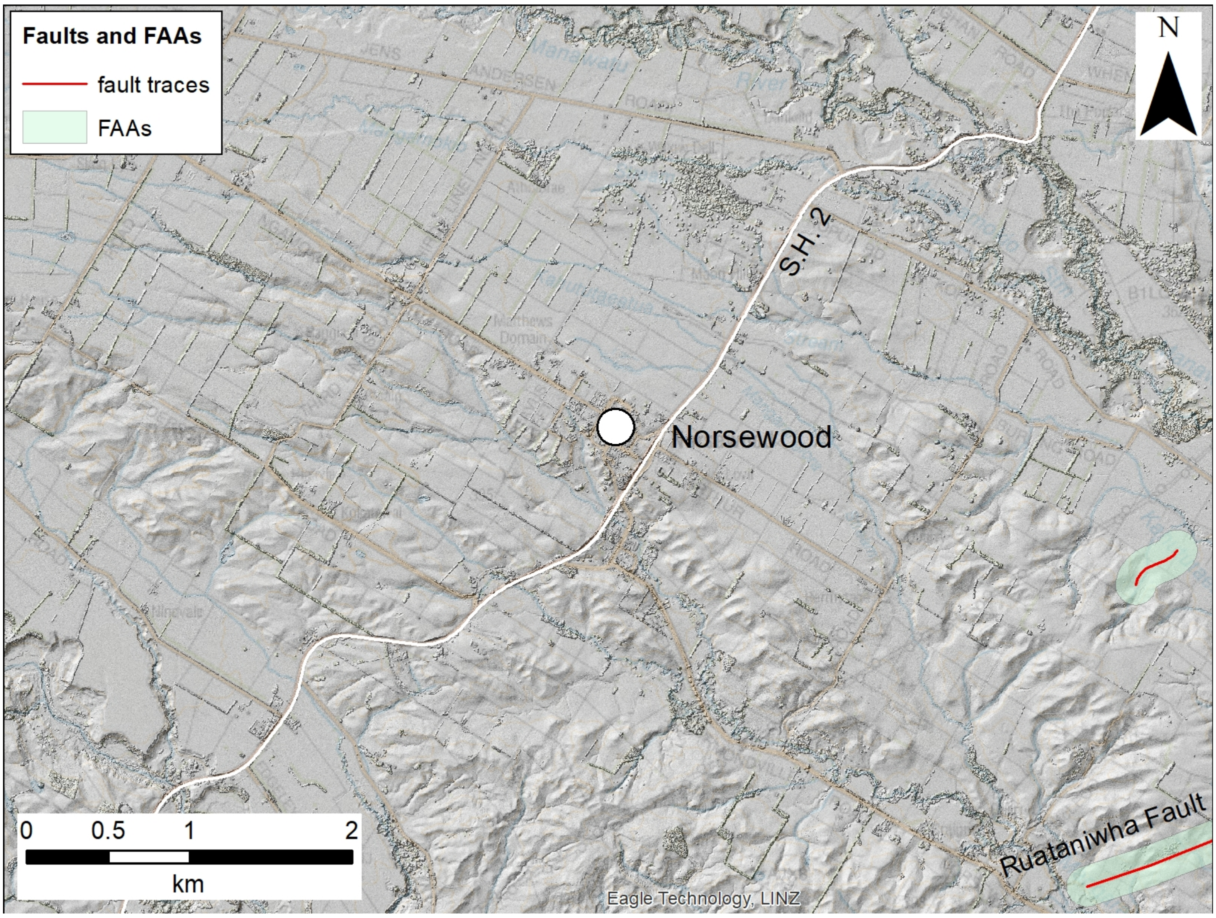

Figure 5.10 Active fault traces (red) and Fault Awareness Areas (FAAs; green) in the vicinity of Norsewood. The basemap is the regional DSM (hillshade model).

6.0 SUMMARY

Active fault mapping has been undertaken across the northwestern half of the Tararua District for the purposes of planning with regard to ground-surface fault rupture deformation. 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 (Langridge et al. 2016). A variety of mapping platforms have been useful for characterising the location and activity of active faults within the district, including airborne LiDAR data, a regional DSM and through review of existing data. This report comes with GIS data (and attributes) that includes mapped active fault and fold locations, Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs). FAZs are used in conjunction with the MfE Guidelines to inform land-use planning decisions. FAZs are only developed within eight priority areas linked to towns and villages. Elsewhere, FAAs are developed for all other named active faults.

Within the northwestern half of the Tararua District, there are many active faults recognised and mapped. RI Class information has been provided for many of these, based largely on data from previous studies and inferences from geomorphic relationships along the faults. These include the Wellington Fault, Mohaka Fault, Ruahine Fault, Alfredton Fault, Pa Valley Fault, Makuri-Waewaepa Fault, Hukanui fault, Woodville-Dannevirke Fault Zone (WDFZ) and Eketāhuna fault (new). Faults within the district cover RI Class I (repeated rupture every 2000 years or less), II (>2000 to ≤3500 years), III (>3500 to ≤5000 years), IV (>5000 to ≤10,000 years) and V (>10,000 to ≤20,000 years).

Specific case studies identifying faults, FAZs and FAAs have been undertaken for priority areas in the vicinity of the major towns in the district: Eketāhuna, Alfredton, Pahiatua, Woodville, Kumeroa, Dannevirke, Ormondville and Norsewood. Descriptions of the priority areas are augmented with examples and tables from the MfE Guidelines to assist planners with future decision-making. FAAs developed for the RI Class IV WDFZ occur within and on the outskirts of Dannevirke township. FAZs are developed for three short active faults near Eketāhuna (Eketāhuna, Waiwaka and Cliff Road faults); for parts of the Pahiatua, Kohinui, Ruataniwha and Takapau faults (all RI Class IV faults); and for parts of the RI Class I Alfredton and Mohaka faults.

Parts of some mapped faults, e.g. the Pahiatua Fault and WDFZ, are currently treated as ‘possibly active’ because it is not clear that previously mapped features represent active fault traces or because no features could be seen on the DEMs/DSMs (or on the ground) in the locations of some previously mapped faults. Because of ambiguity regarding the activity of these faults, FAAs have been designed for them. FAAs have a width of either 250 m or 500 m and relate to the accuracy of mapping and whether the linework comes from regional mapping studies. In this study, faults mapped with FAAs can have a set of recommended planning actions from Barrell et al. (2015) applied to them.

Several active or possibly active folds have also been mapped and defined within the Tararua District as part of this study. These are located in the forearc basin and are probably associated with buried reverse faults. This study does not present FAZs or RI Class information for active folds because the location and associated deformation is anticipated to be too broad to warrant characterisation for fault avoidance purposes.

7.0 RECOMMENDATIONS

Fundamentally, the purpose of this work has been to present relevant planning information that relates to the MfE Guidelines of Kerr et al. (2003) and to recommended actions for FAAs developed by Barrell et al. (2015). We recommend that the FAZs and FAAs developed here for the Tararua District, and the RI Class information provided in this report for those faults, be adopted in future planning decisions regarding development of land on or close to active faults. For use with the MfE Guidelines, these then need to be considered for individual planning decisions based on the status of the land (Greenfield versus Already Developed/ Subdivided) and the BIC intended for the site.

We recommend that the FAAs be used as a flag to denote the possibility of an active fault in that area. In future, more work needs to be undertaken to characterise the activity of such features. Nonetheless, we have provided RI Class information for many of the faults in the northwestern half of the district, and these can be used along with the recommended actions for FAAs.

We recommend that the MfE Guidelines (and FAA recommended actions) be treated as a standard reference when considering resource consent applications throughout the district. In addition, we recommend that GIS data for FAZs and FAAs be provided on LIM and PIM reports so that buyers and sellers of land are aware that a natural hazard exists there or nearby. The GIS data for accurate/approximate faults and the FAZs and FAAs presented with this report can be used at an individual property-specific scale.

This report represents a significant update of active fault hazard data for the Tararua District. Caveats to this are that we have only addressed faults within the northwestern half of the district, that several faults are shown as possibly active and that several of the RI Class designations are preliminary and based only on profiles used with the DEMs. We recommend that some of these issues are addressed in the future. More accurate mapping may be possible in the future with acquisition of district-wide airborne LiDAR coverage, and geologic studies, including paleoseismic trenching, could be undertaken to improve estimates of recurrence intervals and RI Classes presented in this report. This could be important for features identified in the priority areas.

Though quite unpopulated, we recommend that, in future, an active fault mapping review is undertaken for the southeastern half of the Tararua District.

8.0 ACKNOWLEDGEMENTS

We wish to thank Horizons Regional Council for adopting this work as part of its natural hazards programme and for providing airborne LiDAR data and the regional DSM to GNS Science as part of the project. Particular thanks go to Ian Lowe (Podge) for driving this work and providing oversight. We wish to thank Dr Dougal Townsend and Dr Nicola Litchfield for reviewing this report. Peter Wimsett from Tararua District Council provided additional review comments.

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APPENDICES

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APPENDIX 1 ACTIVE FAULTS OF THE WESTERN TARARUA DISTRICT

This study represents the first time that active fault mapping has specifically been collated for the Tararua District (Figure A1.1). The scope of this project has dictated that faults are mapped, and Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs) developed, across only the northwestern half of the district due to budgetary restraints.

Here we describe these active faults and provide information on their Recurrence Interval (RI) Classes, as these classes have impact on building and planning recommendations related to the MfE Guidelines (Kerr et al. 2003), i.e. for FAZs or with respect to FAAs. The faults are discussed according to RI Class using maps, references and local photographs at locations where fault traces and and/or scarps have been identified in the field. Throughout this section, the use of upper case 'Fault' is used to denote previously known faults, while the use of lower case 'fault' is used to denote features that are newly recognised faults. Many isolated fault traces remain unnamed, and these have typically not had a RI Class assigned to them.

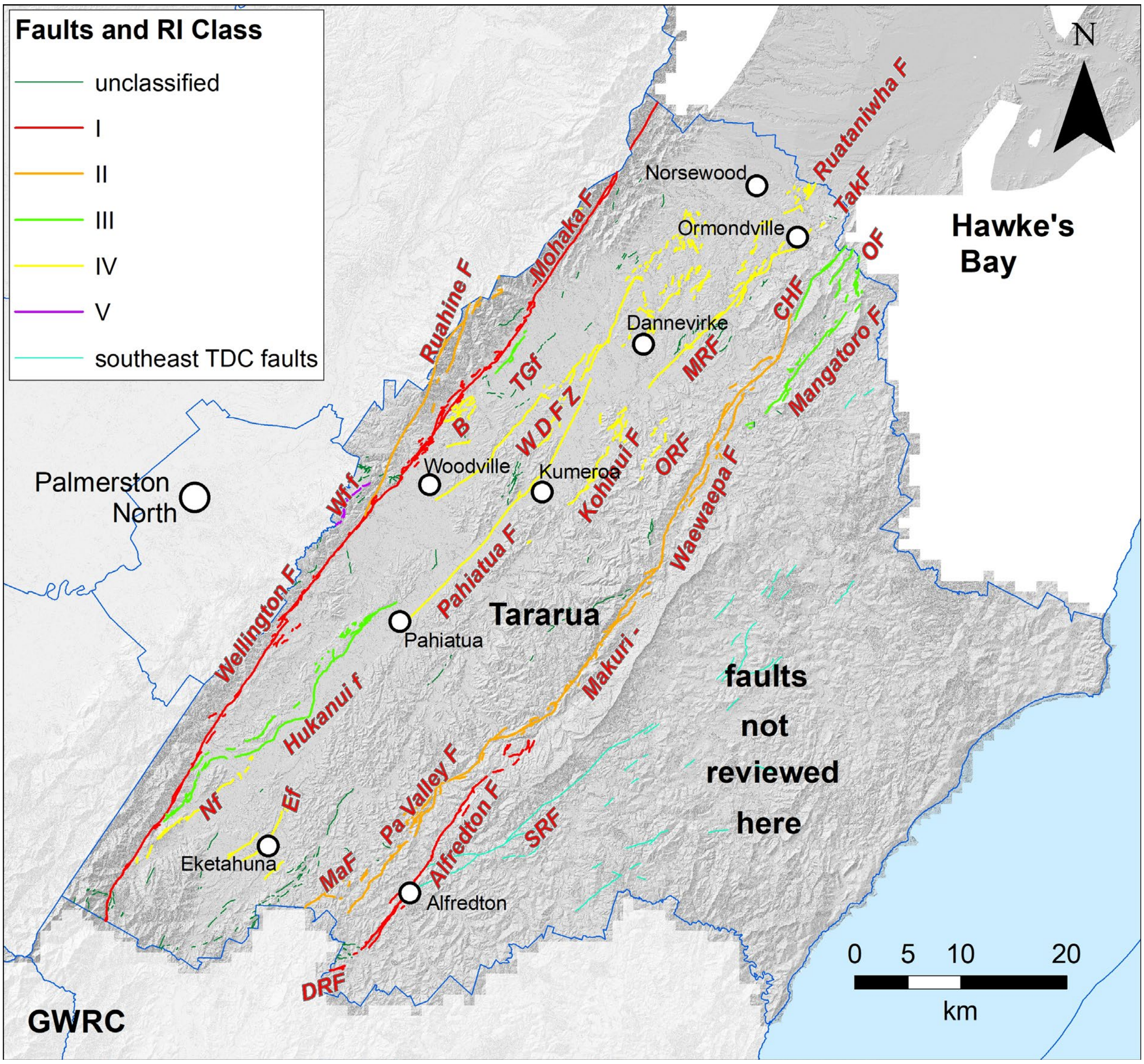

Figure A1.1 New and updated onshore active faults (marked by RI Class) in the northwestern half of the Tararua District. Fault name abbreviations are: Alfr F, Alfredton Fault; B, Beagley Rd Fault Zone; CHF, Clear Hills Fault; DRF, Dreyers Rock Fault; Ef, Eketāhuna fault; Huk f, Hukanui fault; KoF, Kohinui Fault; MaF, Mangaoranga Fault; MtoF, Mangatoro Fault; MRF, Maunga Rd Fault; Nf, Nireaha fault; OF, Oruawharo Fault; PVF, Pa Valley Fault; PahF, Pahiatua Fault; TGf, Top Grass fault; Wf f, Windfarm fault; WDFZ, Woodville-Dannevirke Fault Zone. Faults in the southeast of the district, including the Saunders Rd Fault (SRF), have not been reviewed in this project.

A1.1 RI Class I Active Faults

RI Class I faults are active faults that have an average recurrence interval of surface rupture of 2000 years or less (Kerr et al. 2003). For the western strand of the North Island Dextral Fault Belt (NIDFB) in the Tararua District, this includes the Wellington and Mohaka faults and some splays of these two faults. For the eastern strand of the NIDFB in the Tararua District, this includes the Dreyers Rock Fault and Alfredton Fault. Faults are described in this order. RI Class I faults have the most rigorous constraints in terms of the MfE Guidelines and with respect to FAAs (see Table 4.3).

A1.1.1 Wellington Fault

The Wellington Fault is an active strike-slip fault that, along with the Mohaka and Whakatane faults, is the main fault within the western strand of the NIDFB (Figures 2.2 and A1.1). The Wellington Fault has previously been mapped from within Cook Strait to around the Manawatū Gorge area (Lensen 1958; Langridge et al. 2005). North of the gorge, it changes name to the Mohaka Fault. The latter eventually becomes the Whakatane Fault in the Bay of Plenty region, where it is mapped as merging with the Taupō Rift offshore to the north (Mouslopoulou et al. 2007). These dextral-slip faults allow for translation and rotation of the eastern North Island in the obliquely convergent Hikurangi subduction margin (Wallace et al. 2004).

The Wellington Fault has traditionally been divided into sections that may represent individual rupture sections of the fault (Langridge et al. 2005). These are: the Wellington–Hutt Valley segment, the Tararua section (within the high Tararua Range) and the Pahiatua section. The Pahiatua section is a c. 45-km-long, N–NE-striking fault section that is entirely within the Tararua District. Fault slip rate and paleoseismic studies have been undertaken in trenches excavated across the Pahiatua section of the Wellington Fault (Figure A1.2; Langridge et al. 2005, 2007). Slip rate studies indicate that the Pahiatua section has a slip rate of 5.1–6.2 mm/yr. Trenches excavated at several sites along this section indicate that there have been four surface-rupturing earthquakes in the last 4000 years and that the average recurrence interval is 1200 ± 110 years (Langridge et al. 2007). These trenching studies indicate that the Wellington Fault is a RI Class I fault in the Tararua District.

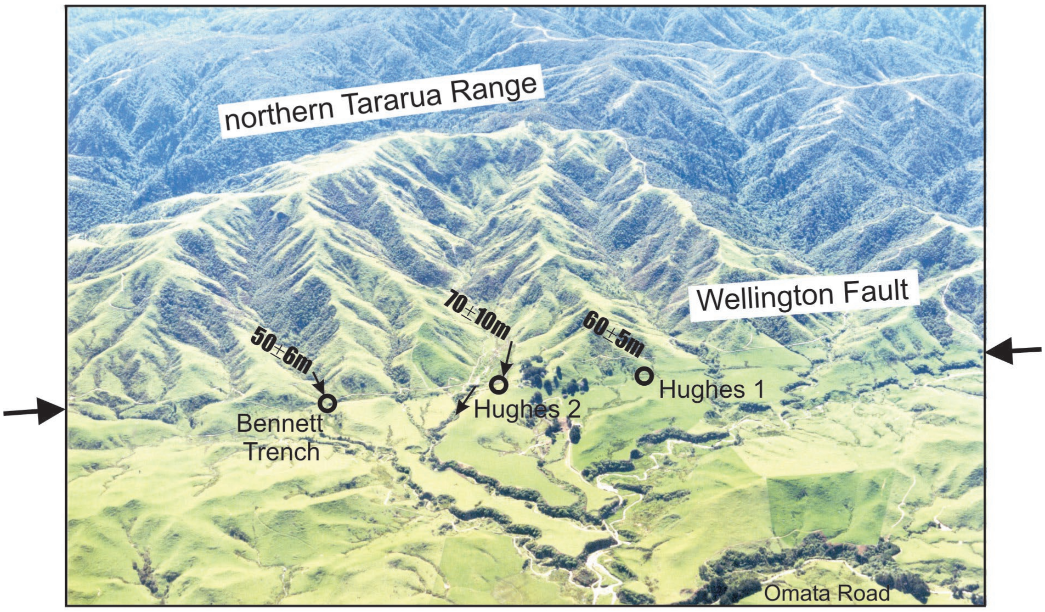

Figure A1.2 The range front and trace of the Pahiatua section of the Wellington Fault (between arrows), west of Pahiatua. The Bennett and Hughes trench sites (circles) are shown, along with prominent dextral offsets of topography (bold text) used to determine fault slip rate. Photo: L Homer, GNS Science.

In this project, we mapped the Wellington Fault on airborne LiDAR from Greater Wellington Regional Council (GWRC) in the south, from Horizons Regional Council LiDAR south of the Manawatū Gorge area and on the regional Digital Surface Model (DSM) in between these areas where there was no LiDAR coverage (Figure A1.4). The fault has been mapped in the past (Begg and Johnston 2000; Lee and Begg 2002; https://data.gns.cri.nz/af/), but improved Digital Elevation Models (DEMs) used in this study allowed for the fault to be mapped more precisely – at a scale of <1:10,000 – with accurate and approximate fault locations. In some places, the fault geomorphology is not evident, and there we have mapped the fault as uncertain or used the pre-existing active fault data (Heron 2020).

In the southwestern corner of the district, the Wellington Fault has a complex geometry, as the transpressive Tararua section of the fault evolves to become the strike-slip Pahiatua section in the north (Langridge et al. 2005). This is achieved by a bend in the fault form the Tararua to Pahiatua section (at the southern edge of the Tararua district). In this area, we have mapped some additional fault traces to the west of the Wellington Fault in its hanging wall. From Putara to the Manawatū Gorge, the Wellington Fault occurs at the edge of gently rolling farmland that backs onto the much steeper Tararua Range to the west (Figures A1.2 and A1.3).

Due to the scope of this project, FAAs have been developed for the Wellington Fault. Because we have reviewed and re-drawn the linework at detailed scales, the ensuing FAAs have been assigned a width of 250 m. The fault does not pass through any towns or villages in the district. However, the FAAs developed for the Wellington Fault do encompass some dwellings and BIC 1 structures, such as barns and farm sheds.

Figure A1.3 The rangefront and trace (between arrows) of the Wellington Fault at the end of Kakariki West Road. The house has been built on an uplifted alluvial surface that is elevated on the west side of the fault.

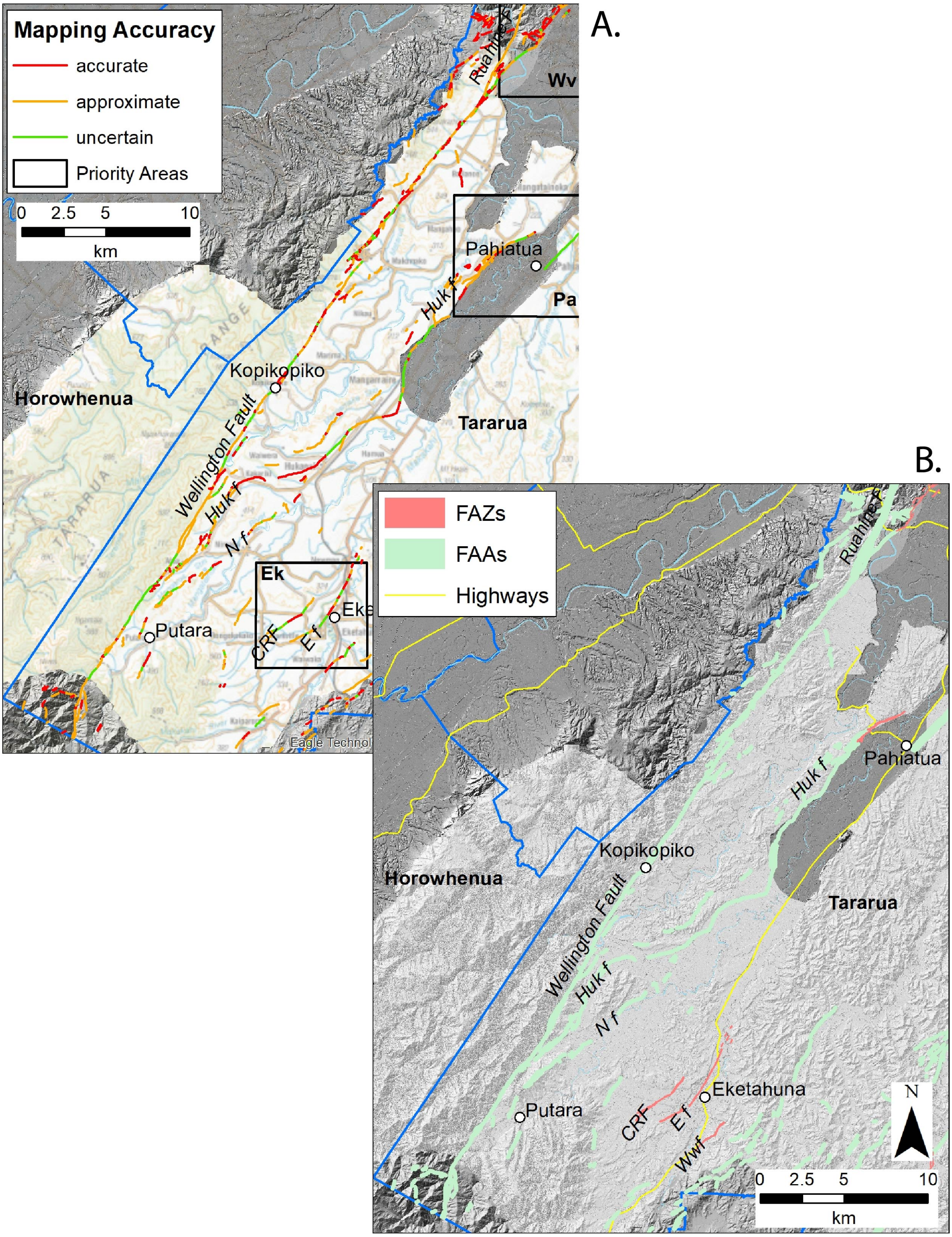

Figure A1.4 Maps showing the Wellington Fault and the southwestern part of the Tararua District. (A) Faults symbolised by locational accuracy, as shown in the legend, along with several of the Tararua District Council priority areas (Al, Alfredton; Ek, Eketāhuna; Pa, Pahiatua; Wv, Woodville). (B) FAZs and FAAs across the same area. Fault abbreviations: CRF, Cliff Road Fault; E f, Eketāhuna fault; Huk f, Hukanui fault; N f, Nireaha fault; Wwf, Waiwaka fault.

An outcome of the more detailed mapping in this study is the recognition and characterisation of several fault strands that splay or diverge from the Wellington Fault into the forearc basin (Figure A1.4). These are discussed in other sections below.

A1.1.2 Mohaka Fault

The Mohaka Fault is an active dextral-slip fault that forms the northern continuation of the Wellington Fault (Figures A1.1 and A1.5). It begins as a distinct fault in the south, where the Mohaka and Ruahine faults diverge from the Wellington Fault around the Manawatū Gorge area (Figure A1.6). In this study, the Mohaka Fault is mapped from where it changes name from the Wellington Fault up to the northern edge of the district in the Ruahine Range (Heron 2020). A short (2.5 km) stretch of the Mohaka Fault occurs within the Manawatū District (Langridge and Morgenstern 2020a). As with the Wellington Fault, the Mohaka Fault has been divided into sections (southern, central, northern) that may correspond to changes in the structure and/or slip rate of the fault (Langridge et al. 2016; Van Dissen et al. 2021). Only the southern section of the Mohaka Fault occurs in the Tararua District.

Specific fault slip rate and paleoseismic studies have been undertaken on the southern section of the Mohaka Fault (Hanson 1998; Litchfield et al. 2011). These results indicate that the southern section has a slip rate of 3–5 mm/yr. A thorough review of all unpublished data on the Mohaka Fault for the New Zealand Community Fault Model (CFM; Beanland 1995; Van Dissen et al. 2021) confirms that the dextral slip rate is in this range. Estimates of single-event displacement for the Mohaka Fault from small dextrally offset surface features (channels) in this region are c. 5 ± 1 m. From these estimates of slip rate and single-event displacement, earthquake recurrence interval is calculated to fall within a range of 1140–2400 years. Trenches excavated at the Trotter farm by Hanson (1998) and Langridge (unpublished data) in order to date pre-historic earthquakes support a RI Class I recurrence interval (Figure A1.7). While these results are also preliminary, they indicate that the southern section of the Mohaka Fault is likely a RI Class I fault in the Tararua District.

Figure A1.5 Oblique aerial photograph of the active trace of the Mohaka Fault along the foot of the Ruahine Range (between arrows) at Moorcock Stream in the Central Hawke's Bay District. Photo: L Homer, GNS Science.

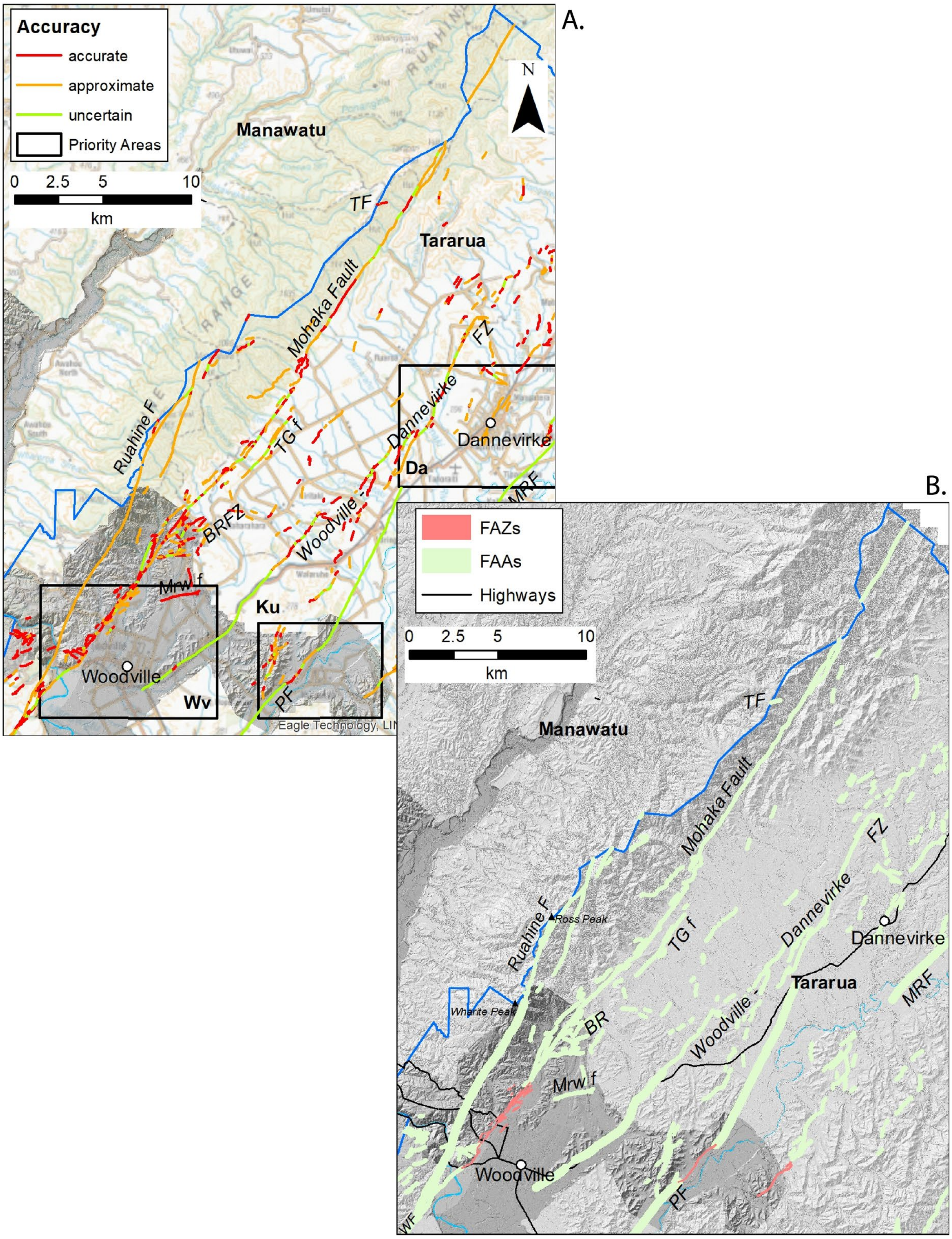

Figure A1.6 Maps showing the Mohaka Fault and the western part of the Tararua District. (A) Faults symbolised by locational accuracy, as shown in the legend. Tararua District Council priority areas (Wv, Woodville; Ku, Kumeroa; Da, Dannevirke). (B) FAZs and FAAs across the same area. Abbreviations: WF, Wellington Fault; PF, Pahiatua Fault; Mrw f, Mangarawa fault; BR, Beagley Road Fault Zone; TF, Traverse Fault; TG f, Top Grass fault; MRF, Maunga Rd Fault. Old, current and future SH 3 highway routes are shown near Woodville.

Figure A1.7 Range front geomorphology of the Mohaka Fault at the Trotter farm, west of Dannevirke. Ohakean (Oh/Q2a) age alluvial terrace surfaces flank a graben defined by a western (WT) and eastern (ET) trace of the fault. The Mohaka Fault converges to a single, main trace in the distance (at MF). The range-facing eastern trace and its eroded scarp ponds water flow and sediments, e.g. the 'broad young fan', against it. Person for scale in centre of photo.

In this project, we mapped the Mohaka Fault on Horizons Regional Council airborne LiDAR from the Manawatū Gorge area to Coppermine Road and on the DSM to the north where there was no LiDAR coverage.

The Mohaka Fault typically marks the eastern edge of the Ruahine Range (Figure A1.5). At its southern end, the fault has a complex geometry where the Ruahine Fault diverges from the Wellington–Mohaka fault structure (Langridge et al. 2005). North of Woodville, there are several sub-parallel secondary active faults and also splay faults that diverge from the Mohaka Fault into the wider forearc basin to the east of the Axial Ranges. Some of these faults are included with the Mohaka Fault and are given RI Class I status. In this study, we have defined the Beagley Road Fault Zone (renamed) and the Top Grass fault as being distinct faults, where the RI Class has been estimated as distinct from the Mohaka Fault. These are discussed in other sections below.

From its southern end and up towards the Tamaki River area, the Mohaka Fault occurs at the western edge of farmland that backs onto the Ruahine Range (Figure A1.7). From there to the northern boundary of the Tararua District, the fault occurs in bush-covered country maintained by the Department of Conservation.

FAAs are developed for most of the Mohaka Fault; however, for those traces that are within the Woodville priority area, FAZs are developed (Figure A1.6b). Because we have reviewed and re-drawn the linework at detailed scales, the ensuing FAAs have been assigned a width of 250 m. Mohaka Fault FAZs near Woodville are described in Section 5.5 of the main text.

A1.1.3 Dreyers Rock Fault

The Dreyers Rock Fault (formerly Dreyers Rock / Kowhai Fault) is part of an active dextral strike-slip fault zone at the southern border of the Tararua District (Figure A1.8; Schermer et al. 2004). The fault is recognised as an ENE-striking zone of faulting that links the northern end of the Wairarapa Fault with the southern end of the Alfredton Fault and, as such, is an important kinematic link within the eastern strand of the NIDFB (Lensen 1969b; Beanland 1995; Lee and Begg 2002). The Dreyers Rock Fault spans a length of only c. 1 km within Tararua District, and, at its eastern end, it merges with the northeast-striking Alfredton Fault (Figure A1.8).

Because of its relationship with the Wairarapa and Alfredton faults – both of which probably ruptured during the 1855 Wairarapa earthquake (Schermer et al. 2004) – the Dreyers Rock Fault has typically been assigned a moderately high slip rate and a short recurrence interval (RI Class I) in the New Zealand Active Faults Database (NZAFD; Langridge et al. 2016). However, there have been no specific slip rate or paleoseismic studies undertaken for the Dreyers Rock Fault. For the recent update of the National Seismic Hazard Model (NSHM) and development of the CFM, the Dreyers Rock Fault has been assigned a slip rate of 4–6 mm/yr (Van Dissen et al. 2021). For these reasons, we maintain a RI Class of I (RI ≤2000 years) for the Dreyers Rock Fault.

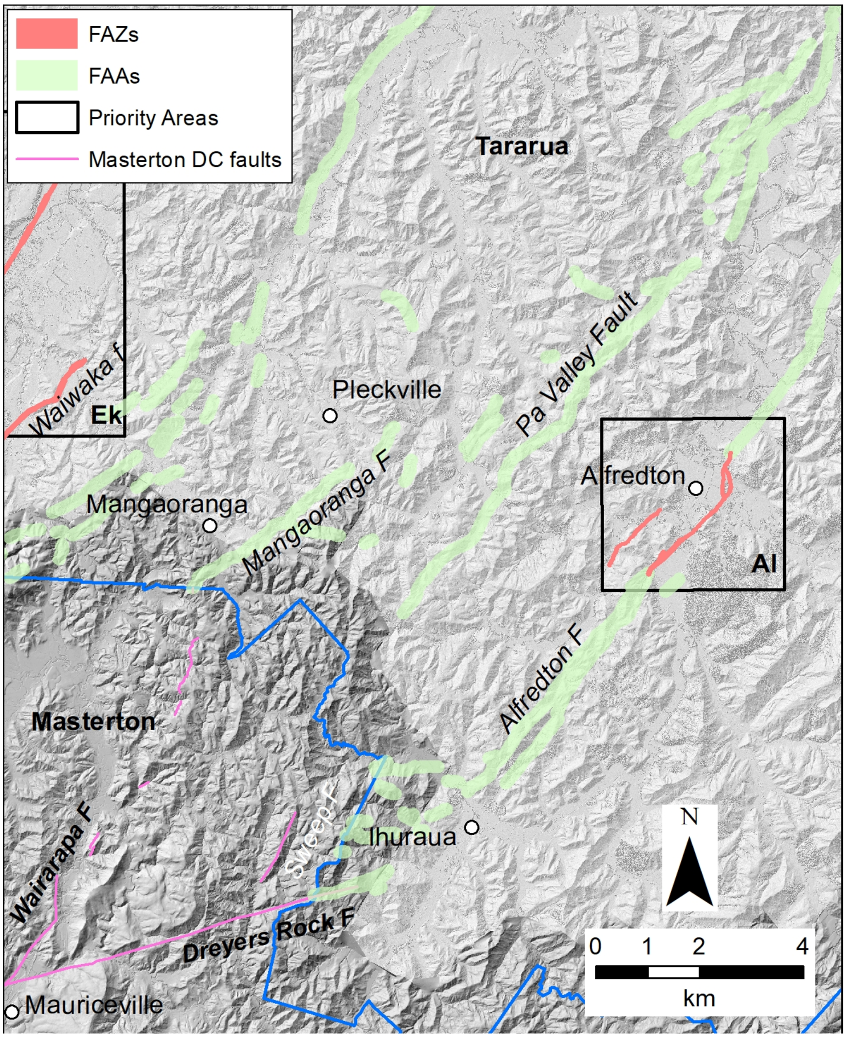

Figure A1.8 Fault Avoidance Zones (FAZs; red) and Fault Awareness Ares (FAAs; green) in the southwestern part of the Tararua District. This area depicts a transfer zone between the northern Wairarapa Fault and the faults of southern Tararua. Mapping within the northern part of Masterton District (pink lines on GWRC LiDAR) has helped understand the kinematic link between the Wairarapa and Mangaoranga faults. Boxes mark the priority areas.

A1.1.4 Alfredton Fault

The RI Class I Alfredton Fault is a major northeast-striking active fault within the eastern strand of the NIDFB (Figure A1.8; Van Dissen et al. 2003). It forms part of a semi-continuous zone of faulting that extends from the Wairarapa Fault through the Dreyers Rock Fault and northwards as the Makuri-Waewaepa Fault (Schermer et al. 2004). The Alfredton Fault was mapped by Lensen (1969a) and documented in Lee and Begg (2002). The NZAFD indicates that it is a RI Class I dextral-slip fault. The fault is characterised by traces and scarps associated with risers, streams and ridges that have been dextrally offset by tens of metres (Beanland 1995). These offsets have been used to develop preliminary dextral slip rates for the Alfredton Fault of 2.5 ± 1 mm/yr for the CFM (Van Dissen et al. 2021).

In this study, the Alfredton Fault has been mapped semi-continuously over a length of 23 km from near Ihuraua in the south to Mt Marchant in the north, close to the ends of the Pa Valley and Makuri-Waewaepa faults. The Alfredton Fault is mapped with accurate and approximate fault location certainty in this study, where there are clear fault traces across valleys and hillslopes formed in soft Tertiary marine rocks (Lee and Begg 2002). However, the location of the fault is uncertain in many places, and it is mapped as such.

Paleoseismic studies undertaken on the Alfredton Fault by Schermer et al. (2004; Figure A1.9) provide evidence for two earthquake ruptures since 2900 cal yr BP. The youngest of these earthquake displacements is associated with the M_W 8.2 1855 Wairarapa earthquake. These results are consistent with a RI Class I (RI ≤2000 years) assigned to the fault in the NZAFD.

In this study, the Alfredton Fault is mostly assigned a FAA with a width of 250 m, because we have reviewed the linework at detailed scales. Where the fault is within 1–2 km of Alfredton village, FAZs have been developed. These are described in Section 5.3 of the main text.

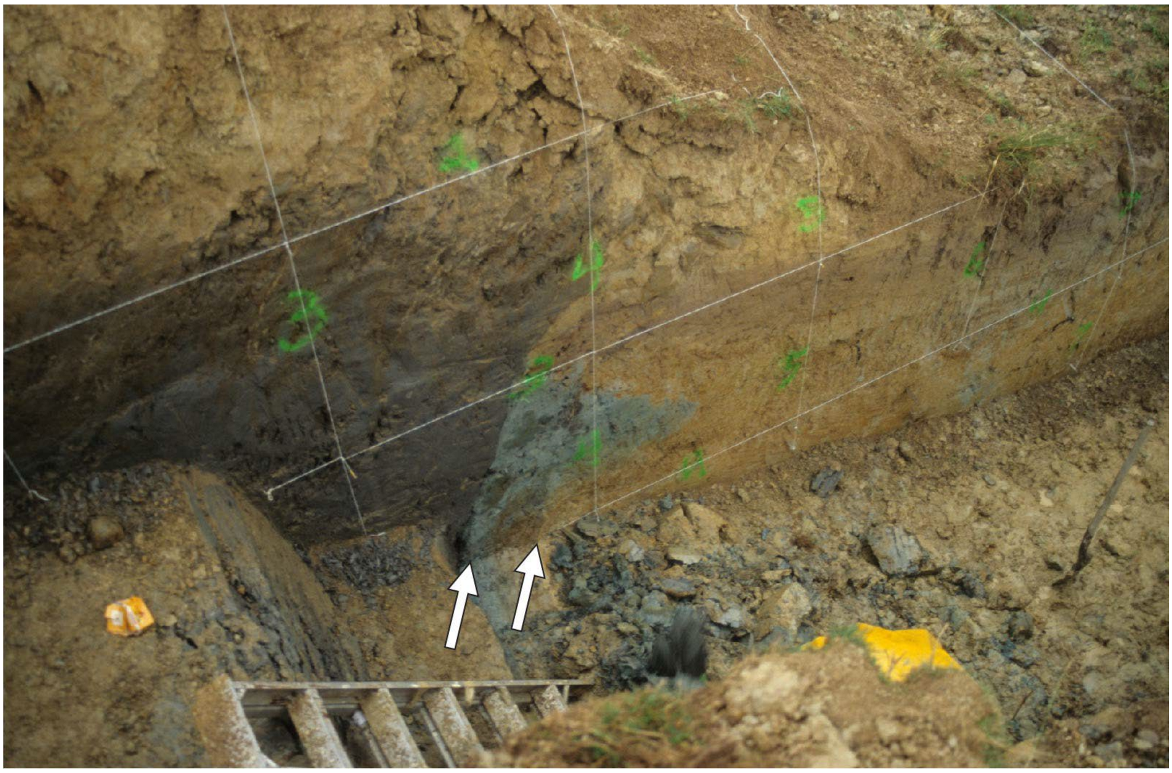

Figure A1.9 North wall of the Percy trench excavated across the Alfredton Fault; see Schermer et al. (2004). The main fault zone dips sub-vertically and is indicated by the white arrows at the edges of the dark grey/blue material. Photo: P Villamor, GNS Science.

A1.2 RI Class II Active Faults

RI Class II faults are active faults that have an average recurrence interval of surface faulting of >2000 to ≤3500 years (Figure A1.1; Van Dissen et al. 2003). Within the western strand of the NIDFB, this includes the Ruahine Fault. Within the eastern strand of the NIDFB in the Tararua District, RI Class II faults include the Mangaoranga Fault (revised here), Pa Valley Fault and Old Pa Valley Fault. These faults are discussed below from southwest to northeast. Where FAZs are developed, RI Class II faults have somewhat less rigorous constraints in terms of the MfE Guidelines, compared to RI Class I faults. For the recommended actions applied to FAAs, RI Classes I, II and III are treated equally (see Table 4.3).

A1.2.1 Ruahine Fault

The NNE-striking Ruahine Fault is a right-lateral (dextral) strike-slip fault located in the Ruahine Range in the western part of the district (Figure A1.5). Along with the Mohaka Fault, the Ruahine Fault is an important component in the western strand of the NIDFB (Beanland 1995). Previous 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 1998). While the recurrence interval overlaps three RI classes, a preliminary RI Class II (Van Dissen et al. 2003), i.e. recurrence interval of >2000 to ≤3500 years, has been assigned to the Ruahine Fault from paleoseismic data in the central part of the Ruahine Fault (Beanland and Berryman 1987).

Within the Tararua District, approximately half the length of the Ruahine Fault has been reviewed using airborne LiDAR (Figure A1.5) and the remaining half using the regional DSM. Our mapping has highlighted the uncertainty in the location of surface traces of the southern Ruahine Fault. Along much of its length, the location of an active trace of the Ruahine Fault is uncertain, mapped through bush-covered country (e.g. Figure A1.10). Therefore, in some places, we have adopted pre-existing fault mapping to define the Ruahine Fault.

As portrayed in regional geological maps, the southern end of the Ruahine Fault is shown as diverging from the Wellington Fault south of the Manawatū Gorge (Heron 2020; Lee and Begg 2002). Nevertheless, there is a lack of clear active fault traces observable on LiDAR between Wharite Peak and the fault junction near Gorge Road. Thus, there is little evidence from surface geomorphology for this interpretation of the fault to carry the active trace of the Ruahine Fault south of Wharite Peak to join the Wellington Fault south of Manawatū Gorge.

We also re-visited a second branch of the Ruahine Fault north of the Manawatū Gorge, shown on QMAP and NZAFD (Figure 2.2; Heron 2020; Langridge et al. 2016). This branch follows a possible strand of the fault from the range divide near Ross Peak south towards Coppermine Stream. This trace is marked by some clear geomorphology related to stream capture and deflection, which could be fault-related. We have mapped an additional trace along this trend.

Due to a lack of certainty in this study, we have had to include both options for the southern end of the Ruahine Fault. For these we have developed FAAs, which typically have a width of 250 m, or 500 m where the fault location or the tectonic origin is uncertain. Insights into the location and structure of both the Ruahine and Mohaka faults can be gleaned from the current SH 3 (Te Ahu a Turanga) roading project north of the Manawatū Gorge.

Figure A1.10 View to the south of the Ruahine Range from Rocky Knob, looking toward Tunupō peak (in cloud). The Ruahine Fault is indicated between the arrows in rugged country in the headwaters of the Pohangina River (in the Manawatū District). Photo: L Homer, GNS Science.

A1.2.2 Mangaoranga Fault

The Mangaoranga Fault refers to a short (up to 10 km long), northeast-striking active fault zone at the southern border of the Tararua District (Figures A1.1 and A1.8; Lensen 1969a). Mapping of the northern end of the Wairarapa Fault from Mauriceville to Mangaoranga on GWRC LiDAR and the Horizons Regional Council DSM indicates that the Mangaoranga Fault is an important part of the overall transfer of strain from the Wairarapa Fault to the Makuri-Waewaepa Fault within the eastern strand of the NIDFB (Figure A1.8; Beanland 1995). This transfer is generally considered to occur via the Dreyers Rock, Pa Valley and Alfredton faults. Here, we also assert that a significant proportion of the tectonic strain from the northern end of the Wairarapa Fault is transferred across to the Mangaoranga Fault. Thus, the entire transfer zone forms a 5–6-km-wide, right-stepping zone of faults from the Mangaoranga to the Alfredton Fault. In this study, the Mangaoranga Fault has been mapped semi-continuously over a length of 5 km from Mangaoranga to near Pleckville in the north, where strain may thence step over to the east towards the Pa Valley Fault (Figure A1.8).

The Mangaoranga Fault has been assigned to RI Class IV (RI >5000 to ≤10,000 years) in the NZAFD (Van Dissen et al. 2003). No paleoseismic studies have been undertaken on this fault. However, the fault has been well-mapped in previous studies (Lensen 1969a; Lee and Begg 2002), and two sites have been recognised that host dextral displacements of streams (Beanland 1995). These offsets may imply a dextral slip rate of c. 1 mm/yr for the Mangaoranga Fault. Using the simple slip rate guide for fault sources in the 2010 NSHM (Table 3.2), this fault could be considered as a RI Class II fault (i.e. RI >2000 to ≤3500 years). Thus, we tentatively raise the Mangaoranga Fault to RI Class II (i.e. RI >2000 to ≤3500 years), which is in keeping with the other RI Class I and II faults in this wider strain transfer zone. In this study, the Mangaoranga Fault is given a FAA with a total width of 250 m, based on detailed review and mapping from the regional DSM.

A1.2.3 Pa Valley and Old Pa Valley Faults

The northeast-striking Pa Valley Fault (Figure A1.11) and Old Pa Valley Fault form part of the eastern NIDFB, where tectonic strain is transferred from the Wairarapa Fault to the Makuri-Waewaepa Fault (Figures A1.8 and A1.12).

The Pa Valley Fault is an active dextral-slip fault, originally mapped by Lensen (1969a) and documented in Lee and Begg (2002). The fault is characterised by sharp traces associated with offset streams, with roughly 10–20 m of dextral deflection (Figure A1.11; Beanland 1995). These offsets have been used to develop preliminary dextral strike-slip rates for the Pa Valley Fault of 1 ± 0.5 mm/yr for the CFM (Van Dissen et al. 2021). Using this slip rate with Table 3.2, the Pa Valley Fault could be considered as a RI Class II fault, as suggested by Van Dissen et al. (2003).

In this study, the Pa Valley Fault has been mapped semi-continuously over a length of 20 km from near Mt Baker in the south to Mt Marchant in the north, where it approaches the tips of the Alfredton and Makuri-Waewaepa faults (Figure A1.12). The Pa Valley Fault is mapped with accurate and approximate fault location certainty in this study, where there are clear fault traces across valleys and hillslopes formed in soft Tertiary marine rocks (Lee and Begg 2002). However, the location of the fault is uncertain in many places, and it is mapped as such.

Figure A1.11 One of the active strands of the strike-slip Pa Valley Fault near Pa Valley Road (between arrows). The fault forms an uphill-facing scarp, behind which a pond has formed (at centre). Photo: D Townsend, GNS Science.

A single paleoseismic trench has been excavated across the Pa Valley Fault at the Estcourt site (Beanland 1995). This trench showed evidence for active faulting, with 1–2 paleoearthquake ruptures recorded, but they were unable to be dated. Nonetheless, RI Class II status (RI >2000 to ≤3500 years) has been assigned for the Pa Valley Fault because of its slip rate and similarities to other faults nearby.

The Old Pa Valley Fault (OPVF) refers to a short (5-km-long) splay fault near the junction of the Alfredton, Pa Valley and Makuri-Waewaepa faults (Langridge et al. 2016). The OPVF has many of the same characteristics as the Pa Valley Fault and so is described here along with it. It has been assigned to RI Class II (RI >2000 to ≤3500 years).

In this study, both the Pa Valley Fault and Old Pa Valley Fault have been given FAAs. Because we have reviewed and updated previous mapping using the regional DSM, these FAAs have a width of 250 m.

A1.2.4 Makuri-Waewaepa Fault

The 40-km-long, Makuri-Waewaepa Fault, an active dextral-slip fault, is an important fault in the eastern strand of the NIDFB (Figures A1.1 and A1.12; Beanland 1995). The northeast-striking fault runs most of the length of the central part of the Tararua District. In the south, the fault is mapped from the Makuri River gorge (Figure A1.13) and extends northwards to Whetukura, where the fault evolves into three distinct faults: the Clear Hills, Oruawharo and Mangatoro faults (Berryman and Cowan 1993). This transition marks a change along the eastern strand of the NIDFB from dominantly strike-slip faulting (reverse dextral) in Tararua District to reverse faulting (dextral reverse) in the Hawke's Bay region.

The northwest-dipping Makuri-Waewaepa Fault bounds the Waewaepa Range (elevations approaching 800 m) where basement greywacke rocks overthrust Tertiary rocks (limestones, sandstones, mudstones). The Makuri-Waewaepa Fault is mapped with accurate and approximate fault location certainty in this study where there are clear fault traces across valleys and hillslopes (Lee and Begg 2002). However, along much of its length where Tertiary rocks are on both sides of the fault, the location is uncertain and is mapped as such.

The Makuri-Waewaepa Fault has previously been defined as a RI Class II (RI >2000 to ≤3500 years) fault in the NZAFD (Van Dissen et al. 2003; Langridge et al. 2016). The fault is characterised by fault scarps and a stream with a 30 ± 5 m dextral offset (Beanland 1995). These offsets have been used to develop preliminary dextral slip rates for the Makuri-Waewaepa Fault of 3.5 ± 0.5 mm/yr (southern) and 3.0 ± 0.5 mm/yr (northern) for the CFM (Van Dissen et al. 2021). In terms of fault slip, these rates equate to c. 5–8 m of fault slip every 2000 years. Results from an exploratory trench near Makuri by Francis et al. (1993) suggest that there may have been three earthquake ruptures on the fault since 6200 years BP. Collectively, these data suggest a recurrence interval of close to 2000 years. While it could be valid to raise the RI Class of this fault from II to I, there is still some uncertainty regarding this fault, due to a lack of data. Therefore, a pragmatic approach would be to maintain a RI Class II status for the Makuri-Waewaepa Fault (RI >2000 to ≤3500 years), with the proviso that the fault could be more active than that.

The Makuri-Waewaepa Fault does not pass through any towns or priority areas in the district. The fault has been mapped along its length using the DSM and is given a FAA with a total width of 250 m, where accurate or approximate, and 500 m where the fault location is uncertain or the linework comes from 1:250,000 scale QMAP linework (Heron 2020).

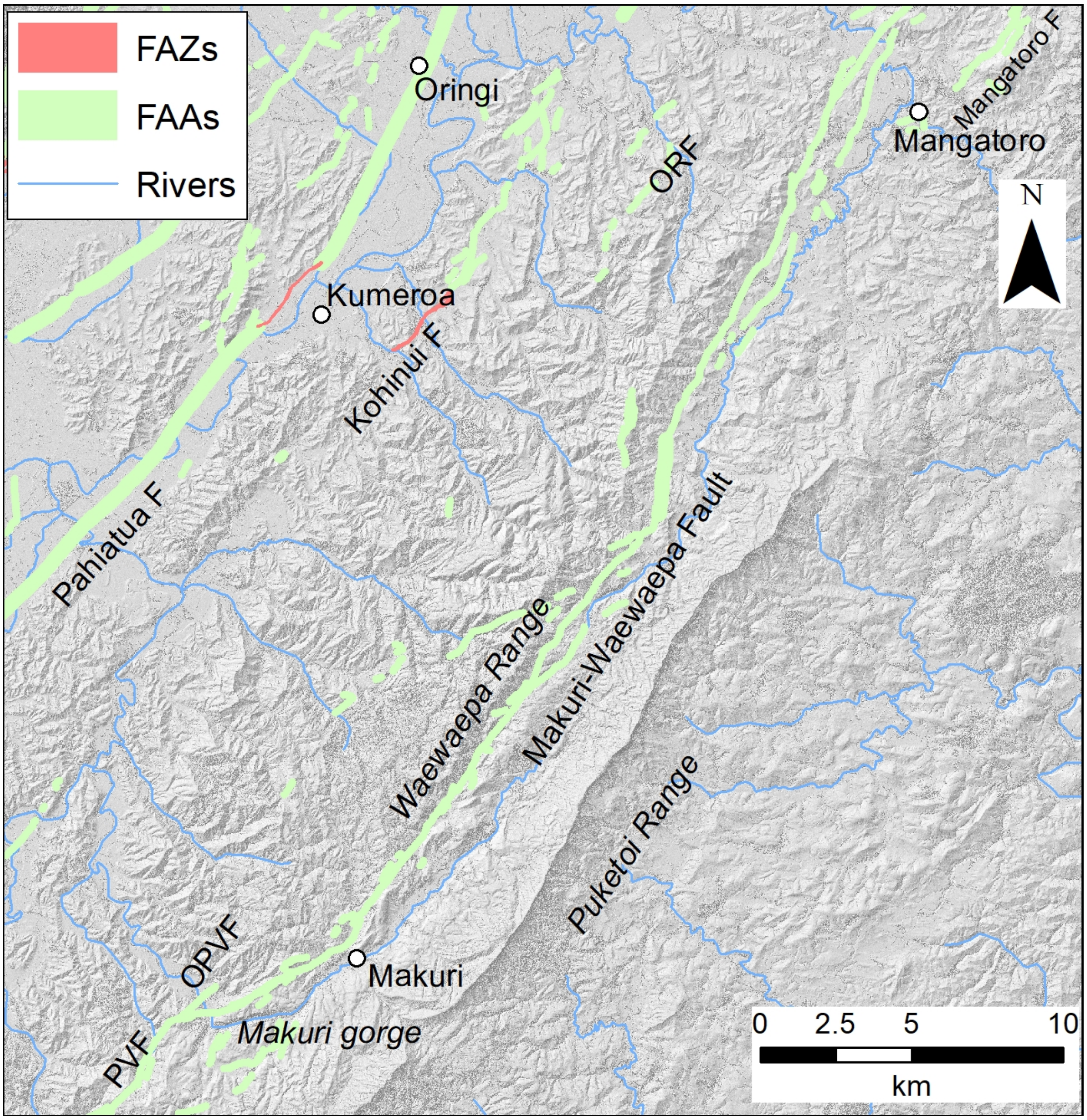

Figure A1.12 Fault Avoidance Zones (FAZs; red) and Fault Awareness Ares (FAAs; green) for the Makuri-Waewaepa Fault and the central part of the Tararua District. The grey hillshade model is the regional DSM. Abbreviations: PVF, Pa Valley Fault; OPVF, Old Pa Valley Fault; ORF, Otope Road Fault.

Figure A1.13 The Makuri-Waewaepa Fault (between arrows) in the Makuri area. MLQ, Makuri Limestone quarry. Photo: L Homer, GNS Science.

A1.3 RI Class III Active Faults

RI Class III faults are active faults that have an average recurrence interval of surface faulting of >3500 to ≤5000 years (Kerr et al. 2003). In the northeast-trending forearc basin that encompasses most of the Tararua District priority areas, we assign RI Class III to the Hukanui and Top Grass faults (Figure A1.1). Within the eastern strand of the NIDFB, there are three RI Class III faults near the northern boundary of the district, the Clear Hills Fault, Oruawharo Fault and Mangatoro Fault (Beanland 1995; Berryman and Cowan 1993). For FAAs, the recommended actions in Barrell et al. (2015) define faults with a recurrence interval of <5000 years (i.e. RI Class I, II and III) as being of higher importance than other less active faults.

A1.3.1 Hukanui fault

The Hukanui fault is one of two newly named faults that splay off of the Pahiatua section of the Wellington Fault in the southwestern part of the district (Figure A1.3). The Hukanui and Nireaha faults strike northeast and bound the southeastern edge of low hills cored by Tertiary rocks. Some traces of the Hukanui fault were formerly included in the NZAFD, but all other traces presented in the GIS of this study are newly mapped (accurate, approximate and uncertain) fault traces.

Figure A1.14 Fault scarp of the Hukanui fault along Mangaraupiu Road, east of Eketāhuna. The scarp (arrowed) runs from left to right, directly behind the large macrocarpa tree in the middle of the photo.

The southern end of the Hukanui fault is northeast-striking, with scarps adjacent to Mangaraupiu Road (Figure A1.14). Fault scarps mapped here have an up-to-the-northwest sense and are located c. 1 km east of the Wellington Fault. Scarps of up to 9 m height across probable Q2a (12,000–24,000 years old) alluvial surfaces suggest a RI Class II status (>2000 to ≤3500 years). However, with no paleoseismic data available for this fault, it is possible that it has a higher or lower activity than suggested by the RI Class stated here. For example, it is possible that the southern end of the Hukanui fault ruptures at times with the Wellington Fault.

North of Hukanui Stream, traces of the Hukanui fault are mapped slightly farther away (4–8 km) from the Wellington Fault, at the eastern edge of a low set of hills. The Hukanui fault has a slightly sinuous mapped trace, making it possible that it is a bedding-plane slip fault following a deeper fault or fold structure in bedrock. However, because of its relationship with uplifted hills cored by Tertiary rocks, we have attributed it as a northwest-dipping reverse fault. Further north, the Hukanui fault has been mapped semi-continuously at the eastern edge of a low ridge, as far north as Pahiatua (see Section 5.4).

Scarp heights of 5 ± 1 m occur along the central mapped parts of the Hukanui fault. These scarps are typically formed across the toe of hillslopes and across alluvial terraces (Q2a; 12,000–24,000 years old). Vertical slip rates calculated from these steps in the landscape are c. 0.2–0.5 mm/yr. Scarp heights are 5–8 m high near Mangamutu. These scarp heights suggest recurrence intervals consistent with RI Class III (>3500 to ≤5000 years), which we apply to the entire length of the Hukanui fault. However, there is considerable uncertainty attached to this designation, so this should be considered as a preliminary estimation.

FAZs have been developed for the northern end of the Hukanui fault. FAAs with a total width of 250 m are developed for the remainder of the Hukanui fault mapped in this study because we have reviewed and updated previous mapping using the regional DSM.

A1.3.2 Top Grass fault

The Top Grass fault (new name) refers to a c. 5-km-long active fault trace that runs parallel to (and c. 0.8 km southeast of) the Mohaka Fault and Top Grass Road in the western part of the Tararua District (Figures A1.5 and A1.6). The Top Grass fault was formerly identified as an unnamed active trace in the NZAFD (Langridge et al. 2016). Uplifted terrace surfaces on the northwest side of the Top Grass fault indicate that it is probably a reverse-slip fault, and its proximity to the Mohaka Fault implies that it has an important structural connection to that fault, i.e. it is a splay that connects to the Mohaka Fault at depth.

It is not easy to define a RI Class for this fault, as it is unknown whether it ruptures in every Mohaka Fault surface-rupturing earthquake or whether it ruptures with it sometimes or entirely independently and so has a longer recurrence interval. Profiles across the fault show that it has c. 6–8-m-high scarps across a Q4a to Q2a terrace (scarp) riser along the fault. This could equate to a vertical slip rate of 0.4–0.7 mm/yr. At this time, we suggest that a preliminary RI Class III (>3500 to ≤5000 years) is appropriate for the Top Grass fault. In this study, the Top Grass fault has been given a FAA with a total width of 250 m.

A1.3.3 Clear Hills Fault

The northeast-striking Clear Hills Fault is the westernmost of three distinct active faults located to the northeast of the Makuri-Waewaepa Fault (Figure A1.15). The Clear Hills Fault was described by Berryman and Cowan (1993), and two neotectonic sites appear in the database of Beanland (1995) for this fault.

The Clear Hills Fault is considered to be a reverse fault and, in one location, is associated with basement greywacke mapped against Tertiary rocks to the east (Lee et al. 2011). In this study, the Clear Hills Fault is mapped with accurate and approximate fault location certainty where there are clear fault traces across valleys and hillslopes.

In this report, we assign a preliminary RI Class III (>3500 to ≤5000 years) status to the Clear Hills Fault. This is mainly because of its relationship to the nearby Makuri-Waewaepa, Oruawharo and Mangatoro faults. FAAs have been generated for the Clear Hills Fault, which have a total width of 250 m, because the fault has been mapped in detail from digital datasets.

A1.3.4 Oruawharo Fault

The northeast-striking Oruawharo Fault is the middle of three distinct active faults located to the northeast of the Makuri-Waewaepa Fault at the northern edge of the Tararua District (Figure A1.15). The Clear Hills, Mangatoro and Oruawharo faults are mapped as converging within the southern border of Central Hawke's Bay District (Langridge et al. 2016), after which the main fault is named the Oruawharo Fault. This fault is described in some detail in Beanland (1995), who collated data from four sites along it (e.g. Figures A1.16 and A1.17). One of these sites (Pukeawa1; Figure A1.16) hosts three offset ridges and valleys that indicate c. 15 ± 5 m of dextral displacement in association with a scarp c. 3 m high. These values have been used in the CFM to develop a slip rate of 1.4 ± 0.6 mm/yr for the Oruawharo Fault (Van Dissen et al. 2021).

The Oruawharo Fault has previously been assigned to RI Class III in the NZAFD (Langridge et al. 2016; Van Dissen et al. 2003), and we maintain that status in this report. Fault traces have been mapped with an accurate, approximate or uncertain fault location certainty in this study, and we have developed FAAs along the length of the Oruawharo Fault with a total width of 250 m, as the fault has been mapped in detail from digital datasets.

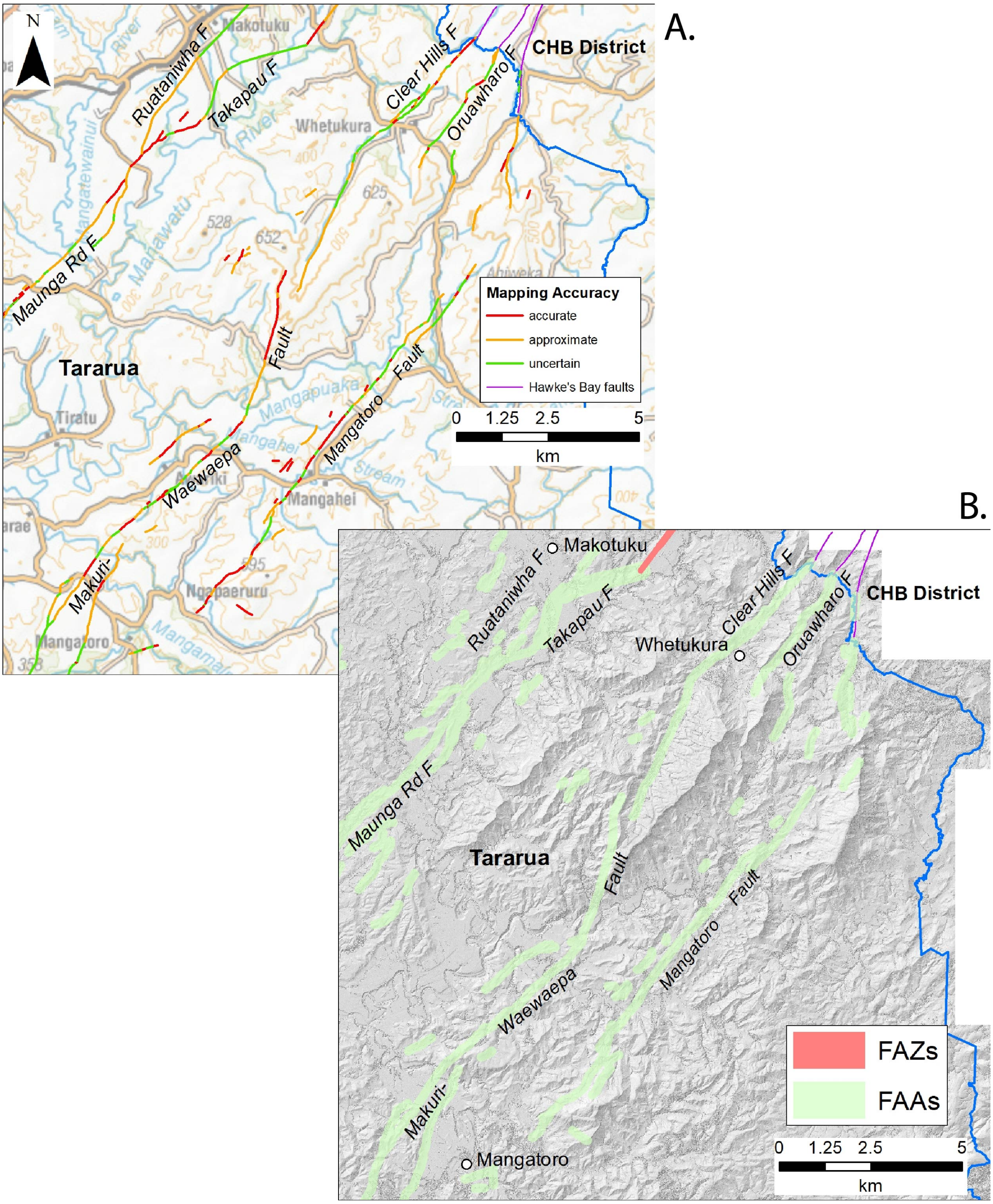

Figure A1.15 The northern end of the Makuri-Waewaepa Fault and the Clear Hills, Oruawharo and Mangatoro faults in the northern part of the Tararua District. (A) Faults symbolised by locational accuracy. (B) FAZs and FAAs for the same area. Purple lines show the continuations of these faults in the Hawke's Bay region.

Figure A1.16 View to the northeast along the trace of the Oruawharo Fault (marked by lines). The photo shows the greywacke basement of the Oruawharo Range to the west and a limestone ridge to the east. Photo: S Beanland.

Figure A1.17 View to the southwest along the trace of the Oruawharo Fault (marked by lines). The image shows an uphill-facing scarp, with arrows indicating dextrally offset channel topography. Photo: S Beanland.

A1.3.5 Mangatoro Fault

The northeast-striking Mangatoro Fault is the easternmost of three distinct active faults located to the northeast of the Makuri-Waewaepa Fault (Figure A1.15). The 20-km-long Mangatoro Fault was first named by Berryman and Cowan (1993). The Mangatoro Fault is considered to be a strike-slip fault and is associated in one location (Glen Tui) with a stream with 13 ± 2 m right-lateral offset (Beanland 1995). In this study, the Mangatoro Fault is mapped with accurate and approximate fault location certainty where there are clear fault traces across valleys and hillslopes.

In this report, we have adopted a slip rate of 1.4 ± 0.6 mm/yr from the CFM for the Mangatoro Fault (Van Dissen et al. 2021). For its recurrence interval, because the neighbouring Oruawharo Fault has previously been assigned to RI Class III, we also apply this RI Class to the Mangatoro Fault (i.e. RI Class III; >3500 to ≤5000 years). We have developed FAAs along the length of the Oruawharo Fault with a total width of 250 m.

A1.3.6 Rangefront Fault

The Rangefront Fault refers to a northeast-striking reverse fault that was formerly mapped in the northwestern part of the Tararua District and to the north (Lee et al. 2011; Langridge et al. 2011). In the Central Hawke's Bay District, where there are active fault scarps, preliminary slip rates were estimated, along with a RI Class III status. The NZAFD (https://data.gns.cri.nz/af/) included an active trace of the Rangefront Fault extending into the Tararua District. However, following further mapping and investigation as part of this study, we have discontinued a 3 km section of active fault shown to the northwest of Norsewood due to a lack of evidence for its activity – there are no traces visible on the DSM. Thus, in this study, the Rangefront Fault is not identified as an active fault in the district.

A1.4 RI Class IV Active Faults

RI Class IV faults are active faults that have an average recurrence interval of surface faulting of >5000 to ≤10,000 years (Kerr et al. 2003). In this study, there are no RI Class IV faults that are included as part of the western strand of the NIDFB in the Tararua District (Figures A1.1 and A1.3). However, there are splay faults of both the Wellington and Mohaka faults that strike to the northeast and splay into the forearc basin that are classified as RI Class IV faults. In the forearc basin, between the two strands of the NIDFB, there are several other faults that are assigned to RI Class IV, including the Woodville-Dannevirke Fault Zone (WDFZ), Eketāhuna fault and Ruataniwha Fault. In general, the rates of deformation within the forearc are lower than within the two main strands of the NIDFB, and thus the recurrence intervals of the faults are somewhat longer. Within the eastern strand of the NIDFB, there are no faults that have been given a RI Class IV designation because the faults there are typically more active.

A1.4.1 Woodville-Dannevirke Fault Zone

The Woodville-Dannevirke Fault Zone (WDFZ) refers to a major NNE-striking active fault zone located within the forearc basin in the central part of the Tararua District (Figure A1.1). The WDFZ is a semi-continuous zone of reverse faulting that extends from near Woodville to north of Dannevirke, sub-parallel to the State Highway 2 corridor (Figure A1.18).

In this project, we focused on fault surface traces and reviewed the Woodville and Pahiatua faults from previous mapping compilations (e.g. Heron 2020; Lee et al. 2011); significant differences between observable fault traces on digital models and geological (bedrock) faults previously mapped became apparent. This is in part due to the regional scale of the earlier compilation and the need to generalise detailed features for legibility. Based on the new mapping, the Woodville and Pahiatua faults were over-simplifications of semi-continuous fault traces with right ('en echelon') steps and jogs making up a broad, distributed zone of faulting that crosscut the bedrock geology shown in QMAP and adopted into the NZAFD (Lee et al. 2011; Langridge et al. 2016). The DSMs used here provide a much clearer and more detailed picture of surface traces than was discernible in the past from aerial photographs, and the fault traces in this area have been substantially updated. Thus, we use the term 'WDFZ' to highlight a difference between what is mapped now and the faults formerly mapped as the Woodville and Pahiatua faults.

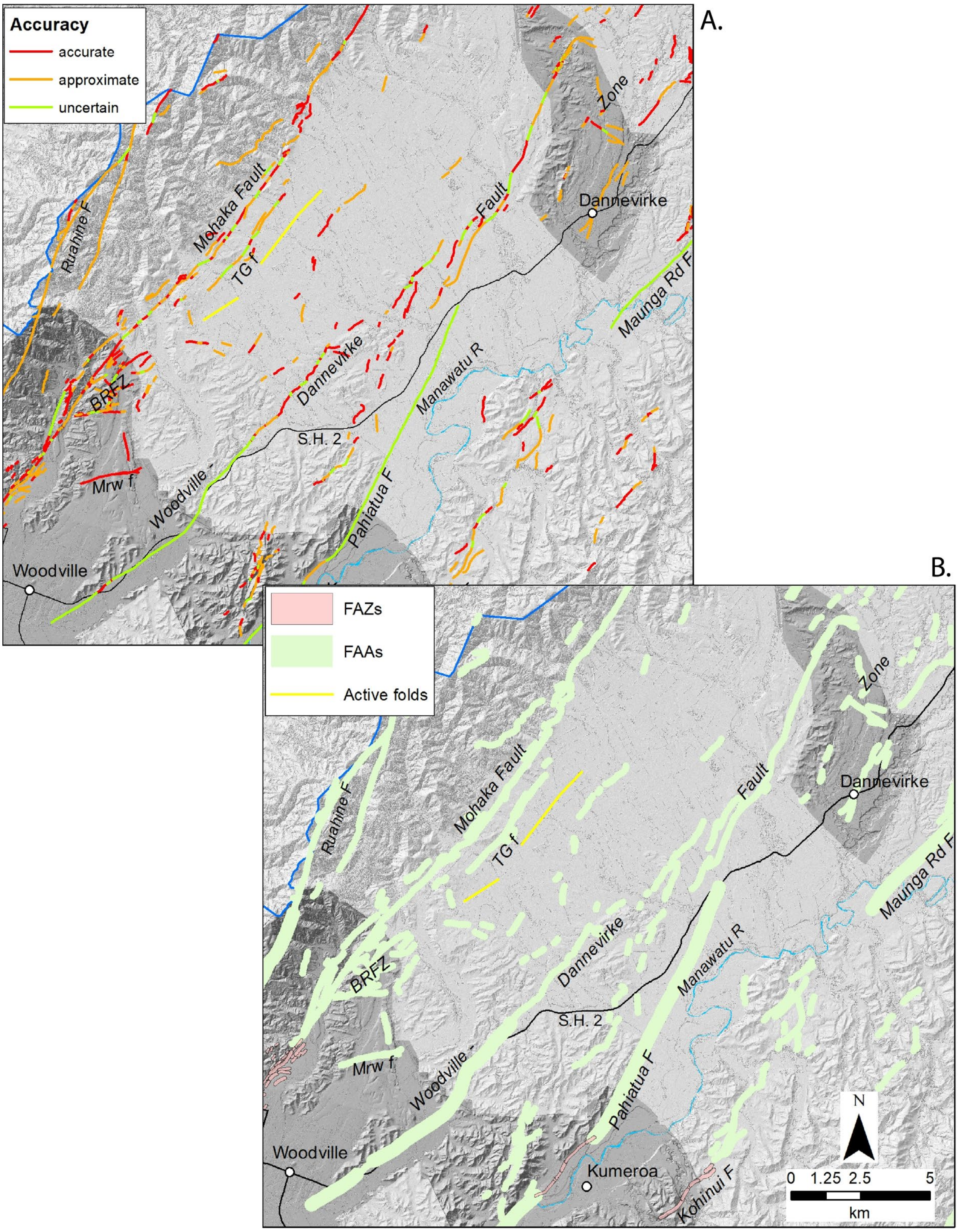

Figure A1.18 Maps showing the Woodville-Dannevirke Fault Zone (WDFZ) and the central part of the Tararua District. (A) Faults symbolised by locational accuracy, as shown in the legend. (B) FAZs and FAAs for the same area. Abbreviations: Mrw f, Mangarawa fault; BRFZ, Beagley Rd Fault Zone; TG f, Top Grass fault. Axes of active and possibly active folds are shown in yellow.

Where active traces are present (Figure A1.18a), we have mapped them as accurate, approximate or uncertain in terms of fault location accuracy. Where there are gaps in the mapped traces, we have either filled the gap with an uncertain trace; left the traces as strictly stepping across country; or adopted a regional geological fault trace, where it remains relevant (e.g. Heron 2020). For example, in the south, due to a lack of surface geomorphic expression, it was difficult to identify active traces from Woodville to near Waiaruhe. In areas such as these, we have adopted the regional mapping and have applied a wider FAA to the linework, as we are uncertain whether an active trace exists for that stretch of the fault.

Figure A1.19 Double fault scarp of the Woodville-Dannevirke Fault Zone (WDFZ) along Heretaunga Road, northeast of Woodville. The active trace of the WDFZ is mapped here at the base of the scarp between the arrows.

Topographic profiles measured across scarps in the WDFZ are used to develop preliminary fault slip rates (Figure A1.19). Vertical slip rates measured across terrace surfaces of known age (Q2a and Q3a, 24,000–59,000 years old) within the zone yield rates of 0.2–0.7 mm/yr. These rates are associated with faults that fall into either RIC III or IV. Due to the lack of available geological data, and because of the stepping and distributed nature of this fault system, we tentatively assign the WDFZ a RI Class IV (>5000 to ≤10,000 years) status. It is possible that RI Class IV under-estimates (or even over-estimates) the activity of this fault system; however, there are currently no detailed paleoseismic studies that can address this uncertainty.

FAAs have been developed for all of the WDFZ. Sections of the fault zone that were re-mapped during this study have a total width of 250 m; however, those based upon the adopted regional-scale mapping linework have a total width of 500 m to reflect this location uncertainty. FAAs are provided for traces that are within the Woodville and Dannevirke priority areas (see Section 5 of this report).

A1.4.2 Beagley Road Fault Zone, Mangarawa and Nireaha Faults

The Beagley Road Fault Zone (BRFZ) refers to a complex array of active fault traces that splay away to the northeast from the Mohaka Fault northeast of Woodville (Figures A1.1 and A1.5). The NZAFD originally showed the 'Beagley Road Fault' as a simple, northeast-striking splay; however, our mapping has identified many active traces with variable strike. The BRFZ is mapped in this study as a 2–4-km-wide northeast-trending zone of distributed deformation that comprises both NNE-striking and ENE-striking active traces. Due mainly to their strikes in the known stress field for faults in this region, the former set of traces are defined as having dextral and reverse characteristics, while the latter are defined as having dextral and normal characteristics.

The BRFZ was formerly described as an active reverse fault, but there was no paleoseismic information for it (e.g. slip rate, recurrence interval, etc.). In this study, we assign a preliminary RI Class IV to all traces of the BRFZ. This is because we observe evidence for active traces across Q2a surfaces (12,000–24,000 years) with heights of 1–2 m in an area where there are two or three distinct fault traces. Scarps across Q2a surfaces yield vertical slip rates of 0.1–0.25 mm/yr. In addition, there are larger scarps across older surfaces; however, these do not imply a higher slip rate than observed across younger surfaces, just more accrued displacement. These rates are consistent with RI Class IV (>5000 to ≤10,000 years) faults.

The Mangarawa fault is a newly recognised fault that splays from the Mohaka Fault c. 2 km south of the BRFZ (Figure A1.5). The fault was mapped using LiDAR and confirmed through field reconnaissance of that area. It has a mapped length of 2.3 km, strikes east-northeast, and has south-facing fault scarps (Figure A1.20). The Mangarawa fault is defined as a dextral-normal fault, based on its strike with respect to the regional stress field. It cuts across low hills of Pliocene rocks and across terraces of Q2a age. Based on the expression of scarps across such young surfaces, it is appropriate to assign this fault to RI Class IV.

Figure A1.20 View through trees to fault scarp of the Mangarawa fault along Condoit Road, northeast of Woodville. The fault trace is mapped at the base of the scarp between the arrows.

In the southwestern part of the Tararua District, two faults splay off the southern end of the Pahiatua section of the Wellington Fault; the Hukanui fault (see Section A.1.3.1) and the Nireaha fault (Figure A1.3). Like the Hukanui fault, it is considered to be a dominantly reverse-slip fault, with fault traces and scarps located 1–2 km east of the Wellington Fault.

While there is very little neotectonic data to constrain its activity, we have assigned the Nireaha fault a preliminary RI Class IV classification (>5000 to ≤10,000 years) in this study. Future targeted work on any of these faults may result in an update of this recurrence interval classification.

Revisions to the fault mapping undertaken in this study on the LiDAR DEMs and on the regional DSM allow us to develop FAAs for the BRFZ and the Mangarawa and Nireaha faults with widths of 250 m.

A1.4.3 Eketāhuna, Cliff Road and Waiwaka Faults

The Eketāhuna, Cliff Road and Waiwaka faults are three short active faults in the Eketāhuna area (Figure A1.3). Collectively, these faults are NNE-striking and are considered to host a dominantly reverse style of faulting. These faults are described here and in Section 5.2 in regard to the Eketāhuna priority area.

The Eketāhuna fault is a newly recognised fault in this study. The Eketāhuna fault is northeast striking and comprises a semi-continuous zone of faulting over a length of c. 5 km. The fault is parallel to the Makakahi River valley and runs through the town of Eketāhuna (Figure 5.2). The southernmost trace of the fault is observable in the western subdivided part of the town; the northernmost traces are located 4–5 km north of Eketāhuna. The fault traces are mapped across Q2a (12,000–24,000 years) and Q1a (0–12,000 years) alluvial surfaces (Lee and Begg 2002), with typically small scarps of 10–30 cm height. Based on these data, the Eketāhuna fault has been placed in RI Class IV (>5000 to ≤10,000 years). The small scarps may reflect a single faulting event during the Holocene period.

The Cliff Road Fault was first identified by Berryman and Cowan (1993). It is mapped in this study as a 2.4-km-long fault c. 2 km west of Eketāhuna. The Cliff Road Fault typically crosses older Q3 (24,000–30,000 years) and Q4 (30,000–74,000 years) alluvial surfaces (see Lee and Begg 2002) that occur above the Makakahi River and has little expression across Q2 surfaces in the area. However, due to its proximity to the Eketāhuna fault, we assign a preliminary RI Class IV classification to the Cliff Road Fault.

The Waiwaka fault is a newly recognised fault in this study. The Waiwaka fault is NNE-striking with a length of c. 2.3 km, occurring c. 2 km southeast of Eketāhuna. The fault is mapped across Tertiary hill country and Q2a alluvial surfaces near the settlement of Waiwaka. Due to its expression across Q2a surfaces and its proximity to the Eketāhuna fault, we assign a preliminary RI Class IV classification to the Waiwaka fault.

While there is very little neotectonic data to constrain their activity, we have given all three faults a preliminary RI Class IV classification (>5000 to ≤10,000 years) in this study. This reflects the typically low rates of activity of features within the forearc basin. FAZs are developed for the Eketāhuna, Waiwaka and Cliff Road faults, as they fall within the Eketāhuna priority area.

A1.4.4 Pahiatua Fault

The Pahiatua Fault is a previously mapped 30-km-long northeast-striking fault extending northeast from Pahiatua (Figures A1.3 and A1.5; Lee and Begg 2002; Langridge et al. 2016). Lee and Begg (2002) show it as an active but concealed fault in the Pahiatua area. Our detailed mapping has shown that there are several definite and likely fault features in the area west of Kumeroa and the Manawatū River (Figure A1.21). These occur at the eastern edge of hills that comprise both Tertiary and Mesozoic bedrock. The structure in this area guides the course of the Manawatū River, which implies that there is a fault associated with these hills. However, we acknowledge that some features mapped in this area as faults could have been formed by downcutting and trimming by the river (as opposed to being from faulting); thus, their tectonic origin is attributed as 'possible'. Nonetheless, these mapped features do correspond with an area of mappable active traces within bedrock greywacke adjacent to and west of the possible faults discussed above.

The implication of these observations is that the central part of the Pahiatua Fault shown in Figure A1.21 should be considered active, while the sections to the north and south are possibly active due to the absence of traces and the mapping based on geologic data alone.

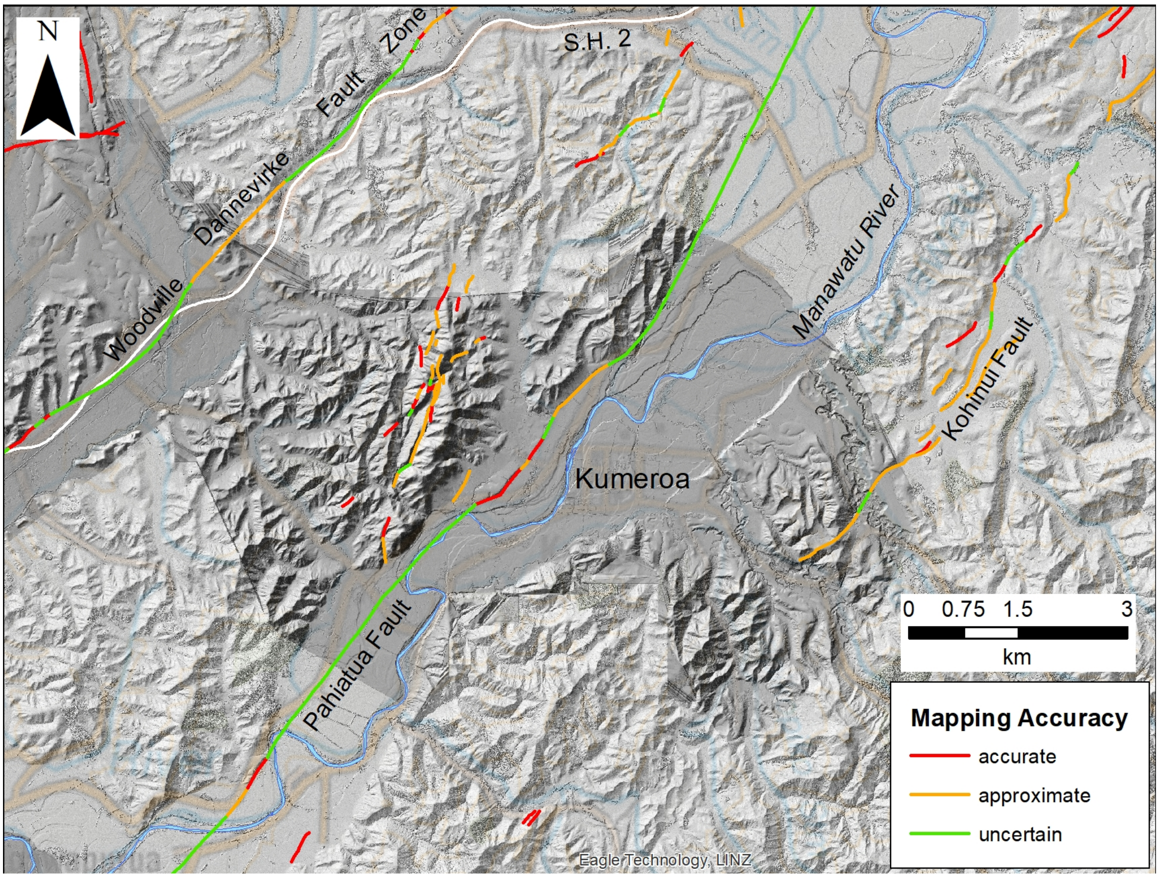

Figure A1.21 The central part of the Pahiatua Fault, associated with the eastern edge of hills that guide the Manawatū River. Definite and likely traces of the Pahiatua Fault are identified near Kumeroa. The dark-grey-shaded basemap is a LiDAR hillshade model; light grey is the DSM. Figure 5.6 shows FAZs and FAAs in the Kumeroa area.

We undertook a limited field inspection of the southern part of the fault from the Manawatū River south to Pahiatua. We noted a complete lack of visible scarps and traces along this part of the structure, which is consistent with the QMAP depiction of the fault as a 'concealed' active fault (Lee and Begg 2002). Similarly, the northern 10 km of the inferred Pahiatua Fault is described as a 'concealed' active fault (Lee et al. 2011). The legacy linework from QMAP is retained in places where there are no discernible scarps, mainly as a 'placeholder' to acknowledge that there could yet be an active (if concealed) structure in this location.

A recurrence interval or RI Class has not previously been assigned to the Pahiatua Fault (see Van Dissen et al. 2003). The current NSHM includes a Pahiatua earthquake source fault with an average recurrence interval of 5700 years (Stirling et al. 2012). Based on this data, we assign the Pahiatua Fault to RI Class IV in this study. Given the uncertainty in the location, origin and RI Class of the fault features mapped, we have mostly assigned FAAs to the Pahiatua Fault. These have total widths of 250 m and 500 m, which reflect whether the trace has a geomorphic expression or whether the regional-scale mapping was used, respectively.

A1.4.5 Kohinui and Otope Road Faults

The Kohinui and Otope Road faults are two discontinuous sets of fault traces that occur at the eastern edge of the forearc basin (Beanland 1995; Berryman and Cowan 1993; Figure A1.1). These faults are considered to have a reverse sense of displacement and are included as part of the Maunga Road Fault within the Active Fault Model (AFM) and NSHM of New Zealand (Litchfield et al. 2014; Stirling et al. 2012).

The Kohinui Fault of Berryman and Cowan (1993) is a northeast-striking zone of active traces north of Kohinui (Figure A1.18). Near Kumeroa, these traces coincide with a previously mapped inactive reverse fault expressed within Pliocene marine rocks, which are faulted in places against Pliocene Totaranui Limestone (Lee and Begg 2002). In this study, we have mapped active traces (accurate, approximate or uncertain) along this trend, where they are visible.

The Otope Road Fault of Berryman and Cowan (1993) comprises a series of north- to northeast-striking active traces, located between Otope and Pukeatua roads. The Otope Road Fault is c. 4–5 km to the southeast of the Kohinui and Maunga Road faults.

In this study, the Kohinui and Otope Road faults have been assigned to RI Class IV because these have limited expression across alluvial surfaces, e.g. Q2a alluvium (12,000–24,000 years old). This assignment to RI Class IV is also consistent with the Ruataniwha Fault (see below) to the north, which is better expressed across alluvial terrace landscapes.

We developed FAAs for the Otope Road and Maunga Road faults in this study. The width of these FAAs is 250 m for the Otope Road Fault, as all traces correspond to geomorphic features in the regional DSM. FAAs for the Maunga Road Fault are either 250 m or 500 m wide, where the wider FAAs correspond to traces identified through previous regional-scale mapping. FAZs are developed for part of the Kohinui Fault, as it is located within the Kumeroa priority area and is presented in more detail in Section 5.6.

A1.4.6 Maunga Road, Ruataniwha and Takapau Faults

The Maunga Road, Ruataniwha and Takapau faults are a set of faults at the northern edge of the Tararua District that are broadly related to the Kohinui and Otope Road faults at the eastern edge of the forearc basin (Figure A1.1). The reverse-slip Maunga Road Fault comprises a 8.5-km-long, northeast-striking zone of active traces. In this study, these are mapped between Knight and Rakaiatai roads, and the northern end splays into the Ruataniwha and Takapau faults. The term 'Maunga' describes an 'active fault earthquake source' in the AFM of Litchfield et al. (2014). For the CFM, the Maunga 'source' has been adopted with a slip rate of 0.5 ± 0.2 mm/yr (Van Dissen et al. 2021). Van Dissen et al. (2003) assigned the Maunga Road Fault to RI Class IV (>5000 to ≤10,000 years), which we have adopted in this study.

The Ruataniwha Fault is a NNE-striking active reverse fault with a length of 28 km spanning the Tararua and Central Hawke's Bay districts (Heron 2020; Klos 2009). The fault was mapped in detail within the Central Hawke's Bay District by Langridge and Ries (2014) and extends for a further 11 km within the Tararua District (Figure A1.15).

The Ruataniwha Fault occurs sub-parallel to the western and eastern strands of the NIDFB within the broad forearc basin separating them. The fault is typically mapped as crossing early Quaternary Kidnappers Group rocks and alluvial terrace surfaces ranging from middle to upper Quaternary, including Q2a terraces (12,000–24,000 years; Lee et al. 2011). In some places, Holocene fault traces are evident (Langridge and Ries 2014). Klos (2009) studied the Ruataniwha Fault and derived estimates of reverse fault slip rates. These values were reviewed for the current version of the CFM and a range of 0.1–0.3 mm/yr was used for the Ruataniwha Fault. Klos (2009) derived an average recurrence interval of c. 7500 years, suggesting a RI Class IV status for the fault, which is adopted in this study, rather than an earlier estimate of RI Class III (Van Dissen et al. 2003). In the Southern Star Abbey area, the Ruataniwha Fault has a distributed character with many short normal fault traces.

The northeast-striking Takapau Fault is an active reverse fault located to the east of the Ruataniwha Fault and northeast of the Maunga Road Fault (Figure A1.15; Berryman and Cowan 1993; Langridge and Ries 2014). The reverse-sense Takapau Fault was previously defined by fault mapping studies in the Central Hawke's Bay District (e.g. Langridge and Ries 2014). The Takapau Fault has similarities to other faults in the forearc basin between the western and eastern strands of the NIDFB, i.e. reverse sense of slip; dip to the northwest, down to the southeast motion; and low slip rates (e.g. 0.1–0.5 mm/yr). Therefore, based on previous studies and similarities to other faults in this zone, we assign RI Class IV activity (RI >5000 to ≤10,000 years) to the Takapau Fault.

In summary, the Maunga Road, Ruataniwha and Takapau faults are similarly active reverse faults and are all assigned to RI Class IV. We have developed FAAs and FAZs for these faults in this study. The width of these FAAs is either 250 m or 500 m, depending on whether there are new traces mapped using the LiDAR DEM or the regional DSM or whether the linework comes from previous regional-scale mapping (e.g. Lee et al. 2011). FAZs have been developed where the Ruataniwha and Takapau faults occur within the Ormondville priority area, and these are presented in more detail in Section 5.7.

A1.4.7 Traverse Fault

A short set of active fault traces was mapped on the regional DSM in the eastern part of the Manawatū District in the Ruahine Range and named the Traverse Fault (Figure A1.1; Langridge and Morgenstern 2020b). The 1.2-km-long Traverse Fault was previously mapped as an unnamed active fault by QMAP and the NZAFD (Heron 2020; Lee et al. 2011; Langridge et al. 2016). In this study, we have continued the mapping of that structure across the main divide of the Ruahine Range into the Tararua District for a further 0.6 km. Langridge and Morgenstern (2020b) decided that the mapped features associated with the Traverse Fault 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 obliquely cut across the main topographic divide.

Langridge and Morgenstern (2020b) assigned the Traverse Fault a preliminary RI Class IV (RI >5000 to ≤10,000 years) because it clearly crosscuts the main dividing ridge of the Ruahine Range. Such a landform has probably been reset by erosion related to the last glacial cycle; therefore, the form of the main divide probably has a Holocene age (i.e. <12,000 years). Thus, deformation of the main divide ridge must have occurred during the Holocene. This RI Class of IV has been adopted for the Traverse Fault in this study, and we have generated FAAs with a total width of 250 m for it.

A1.5 RI Class V Active Faults

RI Class V faults are active faults that have an average recurrence interval of surface faulting of >10,000 to ≤20,000 years (Van Dissen et al. 2003). This classification is usually reserved for faults that have a low slip rate or have little demonstrable evidence in the landscape in the form of fault traces or scarps.

A1.5.1 Windfarm fault

The Windfarm fault (new) refers to a series of broad fault traces mapped at the eastern edge of the Tararua Range near the Manawatū Gorge (Figure 5.1). The name 'Windfarm' refers to its proximity to the Tararua Windfarm. The broad deformation associated with the Windfarm fault occurs across a relatively smooth geomorphic surface (peneplain) that is probably related to erosion of the flank of the Tararua Range in this area. In the Wellington area, this erosion surface is called the 'K Surface'. There are differing opinions as to the age of this surface in the Wellington region, including across the Tararua Range, ranging from millions of years to Late Quaternary in age. Alternatively, some hillslope erosion surfaces could have been reset during the last cold climate period (12,000–24,000 years ago).

In the Manawatū Gorge area, higher sea level that could be associated with peneplanation is ascribed to the retreat of the sea and exposure of marine rocks, which are up to one million years old. However, there is some evidence from mapping Q5b surfaces (74,000–128,000 years) for an intrusion of seawater (sea-level rise) within the Manawatū Gorge during this time.

It is difficult to characterise the activity of the Windfarm fault. At this time, we choose to assign the fault to RI Class V (>10,000 to ≤20,000 years), with an associated uncertainty of one RI Class (i.e. RI Class IV–VI). This reflects the possibility that the fault is significantly more or less active than stated here. We have developed FAAs with a total width of 250 m for the Windfarm fault in this study.

A1.6 Unnamed Active Fault Traces

There are many active fault traces mapped in this study that have not been assigned a name (Figure 5.1). This is because they are either: (a) short in length or continuity; (b) geographically separated from continuous sets of named fault traces; or (c) it is unclear whether they have a tectonic origin or are related to another process, such as landsliding. In such cases, we have attributed the line data in the GIS accordingly and have developed FAAs for these traces. The width of the FAAs is 250 m due to the traces having been mapped using the LiDAR DEM and/or regional DSM. However, unnamed active fault traces have not been assigned recurrence interval classes in this report.

A1.7 Active Folds

Active folds are an important indicator of tectonic deformation, and, in New Zealand, these are often related to reverse faulting. Three active folds have been mapped in this study within the Tararua District (Figure A1.18). These folds have been identified by linear shadows on the DEM and/or DSM that relate to broad warps (folds) in the landscape. Folds are often represented by a fold axis, which (for anticlines) is the highest part of the fold expressed in the landscape. Broad folds are identified southeast of the Mohaka Fault and Top Grass fault, west of Dannevirke (Figure A1.18). Structurally, there is likely to be a relationship between these faults and folds, such that the folds are associated with a buried (probably northwest-dipping) reverse fault that merges with the Top Grass and Mohaka faults at some depth beneath the plains.

Despite being important structures to map, active folds are not described in the MfE Guidelines in relation to ground deformation hazard or life safety risk (Kerr et al. 2003). This is because the deformation associated with active folds is too broadly distributed to pose a life-safety hazard with respect to built structures. In this study, neither FAZs nor FAAs are developed for active folds. For more detail, refer to Section 4 of this report.

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