Active fault mapping and fault avoidance and awareness zones for Ruapehu District

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EXECUTIVE SUMMARY

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

New active fault mapping, Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs) are presented here for Ruapehu District. The district is traversed by active faults that pose a surface rupture (or ground deformation) hazard to buildings and infrastructure. Following the Ministry for the Environment's guidelines – *Planning for Development of Land on or Close to Active Faults* (Kerr et al. 2003; the 'MfE Active Fault Guidelines') – fault traces have been mapped, and, within certain Priority Areas in accordance with the scope of this project, FAZs that buffer the active faults at a scale that is suitable for district planning use have been developed. In terms of life safety, the MfE Active Fault Guidelines focus on: (i) the location and complexity of faulting, (ii) the characterisation of recurrence interval of surface faulting and (iii) the Building Importance Category of the structure(s) that may be impacted by fault rupture ground deformation. FAAs have been developed for active faults outside of the Priority Areas.

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

Within the Priority Areas of Ruapehu District, there are several previously known active faults that have been re-mapped: the Upper Waikato Stream, Ohakune, Raurimu, National Park, Rangipo, Shawcroft Road, Karioi, Snowgrass, Raetihi North and Raetihi South faults. There are also several unnamed active faults and/or fault traces that have been re-mapped, some of which have also been renamed (e.g. Raetihi Middle and Waikune faults). The Moawhango Fault was previously recognised as an inactive fault, which has now been redefined as active in places. Many active or possibly active faults have been mapped or re-mapped outside of the Priority Areas during this study, but a detailed discussion of these are outside the scope of this project.

The Recurrence Interval (RI) Classes defined in this study for the active faults in the Priority Areas are as follows: Upper Waikato Stream, Ohakune, Raetihi North, Raurimu, National Park and Waikune faults (RI Class I; ≤2000 years); and Rangipo, Shawcroft Road, Karioi, Snowgrass, Raetihi Middle, Raetihi South and Moawhango faults and unnamed faults in Priority Areas C and D (RI Class II; >2000 to ≤3500 years). FAZs have been defined for these active faults according to the MfE Active Fault Guidelines. FAAs have been developed for active faults outside of the Priority Areas; however, their use differs from the other Horizons Region active fault mapping reports. It is recommended that further work is undertaken to develop FAZs and RI Classes for active faults outside of the Priority Areas that have been mapped or re-defined during this study. In future, if development is proposed for areas with a FAZ or FAA status, it is recommended that further fault mapping and/or geologic studies are undertaken to better define the location, origin, activity and/or nature of surface faulting and deformation.

We recommend that the active fault mapping, FAZs and FAAs developed for Ruapehu District in this study should be adopted for use with regard to future planning decisions. In the supplied GIS dataset, the FAZs are attributed according to their Fault Complexity; i.e. well-defined, well-defined extended, distributed and uncertain constrained; and according to RI Class. As outlined in the MfE Active Fault Guidelines, this information, when combined with land-use status (i.e. Greenfield site or Already Developed/Subdivided site) and intended or existing Building Importance Category, provides a risk-based rationale for making land-use planning decisions pertaining to the development of land close to, or on, active faults.

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

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1.0 INTRODUCTION

1.1 Preamble

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 seismically active parts of this tectonic boundary zone, overlying the subducted Pacific Plate, and includes the North Island Dextral Fault Belt (NIDFB) and the transition to an area of extension in the north known as the Taupō Rift (Beanland and Haines 1998; Villamor and Berryman 2006b). The Horizons region is crossed by numerous active crustal faults (and folds) that have ruptured and deformed the ground surface in the past. These faults include the Wellington, Ruahine, Leedstown, Mt Stewart-Halcombe, Ohakune and Makuri-Waewaepa faults. Previous studies indicate that several of these faults, including the Wellington Fault, have a moderately high rate of activity (i.e. relatively short recurrence interval, on the order of 2000 years or less) and are capable of generating large earthquakes (moment magnitude M_w >7.0) associated with large (i.e. metre-scale) single-event ground surface-rupture displacements (e.g. Langridge et al. 2006; Schermer et al. 2004; Van Dissen et al. 2003).

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

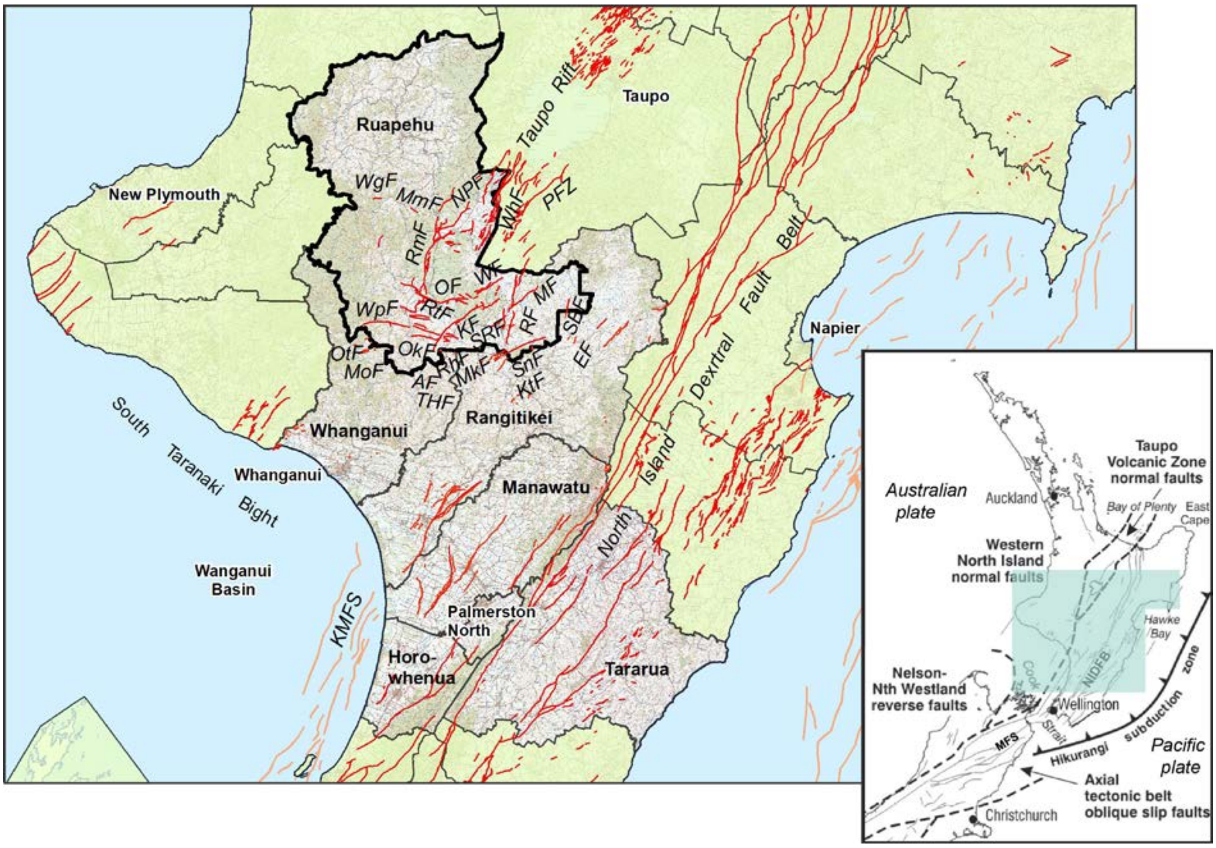


Figure 1.1 The area administered by Horizons Regional Council, showing its various districts. Onshore active faults (red) within the lower North Island area sourced from the New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al. 2016) as they appeared prior to this study. Fault names in italics are: AF, Ahurangi Fault; EF, Erewhon Fault; KF, Karioi Fault; KtF, Kanturk Fault; MF, Moawhango Fault; MkF, Maketu Fault; MmF, Mangamaire Fault; MoF, Morikau Fault; NPF, National Park Fault; OF, Ohakune Fault; OtF, Otaranoho Fault; OkF, Oruakukuru Fault; RF, Rangipo Fault; RhF, Rangiahu Fault; RmF, Raurimu Fault; RtF, Raetihi (North and South) Fault; PFZ, Poutu Fault (Zone); SBF, Swinburne Bush Fault; SnF, Snowgrass Fault; SRF, Shawcroft Road Fault; THF, Te Hue Fault; WF, Wahianoa Fault; WgF, Waldegraves Fault; WhF, Waihi Fault; WpF, Waipuna Fault. KMFS = Kāpiti-Manawatū Fault System and other offshore faults (orange) compiled from NIWA data. Inset: Active tectonic map of central New Zealand with seismotectonic regions. NIDFB = North Island Dextral Fault Belt; MFS = Marlborough Fault System. Shaded area shows the location of the larger map. PN = Palmerston North.

1.2 Scope of Work

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

The main objective for this work is to produce high-quality digital geospatial data and maps suitable for planning use at scales that are relevant to the current and expected future land-use requirements in the Horizons Region. A significant improvement in the accuracy of mapping active faults is possible due to the advent and acquisition of airborne Light Detection and Ranging (LiDAR)-derived topographic data across much of the coastal plain and riverine areas, supplied by Horizons Regional Council. In addition, we worked with Horizons Regional Council to construct a region-wide 1 m Digital Surface Model (DSM) from aerial imagery to develop a digital topographic dataset across the whole region.

To improve understanding of the hazard posed from surface faulting and to update the quality of fault mapping for the Horizons region – with this report focusing on the Ruapehu district – the scope of work is as follows:

- Provide a review of active tectonics, seismicity and faulting in the Horizons region.
- Where airborne LiDAR-derived topographic data exists, map and attribute active fault traces at 1:10,000 scale or better. This effort has been facilitated by the acquisition of several airborne LiDAR datasets funded by Horizons and provided to GNS.
- Use a 1 m DSM of the Horizons region in order to improve the mapping of active fault traces where LiDAR data does not exist.
- Incorporate active fault line work and attributes from other mapping studies, such as the QMAP Geological Map of New Zealand Project (Heron 2018), previous GNS reports, and review data within the NZAFD (1:50,000 to 1:250,000 scale; Langridge et al. 2016).
- Develop Fault Avoidance Zones (FAZs) and Fault Awareness Areas (FAAs) based on the updated fault line data described above. The goal is to provide Horizons with up-to-date geospatial datasets that are valid for planning purposes and are wholly compatible with application of the MfE Active Fault Guidelines. Note that FAZs will be provided for any active faults identified near Taumarunui and within the Priority Areas (Figure 1.2) and that FAAs will be provided for any active faults outside of these areas.
- Map active folds in order to better locate and characterise their tectonic activity.[1]
- 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.[2]
- Provide an update on active fault recurrence interval data for the Ruapehu district, where possible, so that more informed future research and planning decisions can be considered.
- Compile the results in this report and present those results to the Horizons Regional Council and Ruapehu District planning staff.
- Provide support and outreach in delivering project results to the Councils and general public.

1 No active folds were identified in the Ruapehu district in this study and so are not discussed further.
2 A field review was not undertaken during this study due to budgetary constraints.

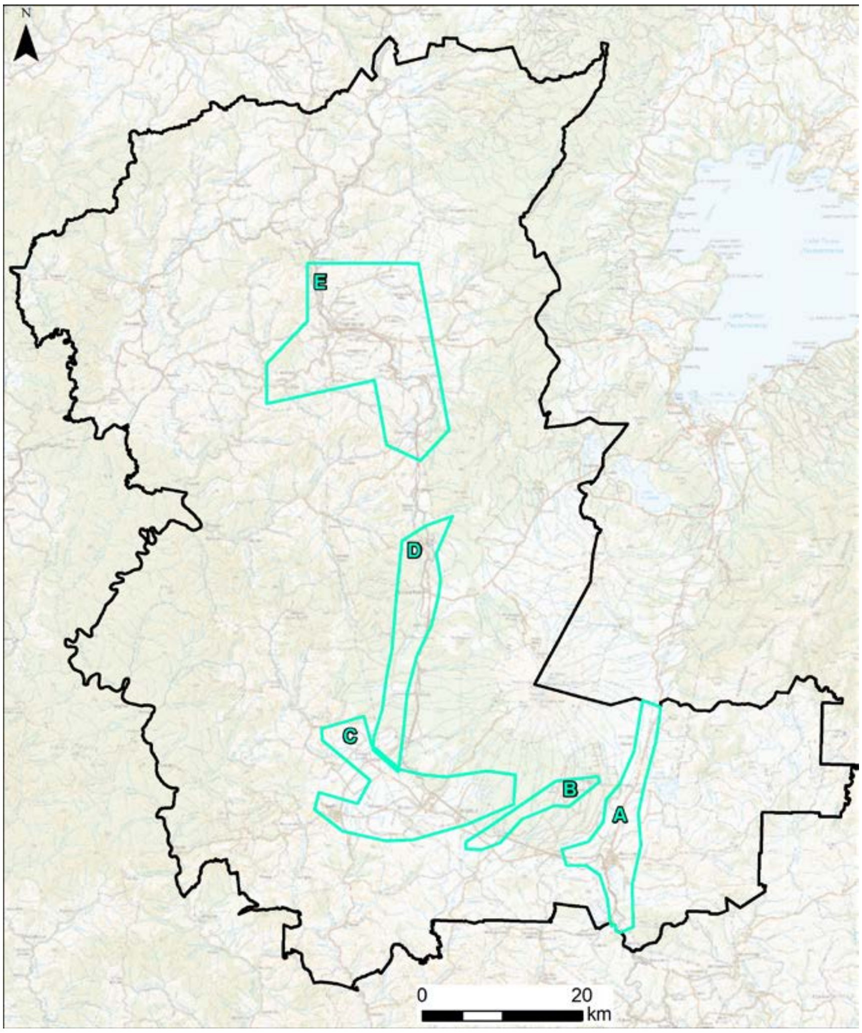


Figure 1.2 Map of Ruapehu District showing the Priority Areas (A–E) within which Fault Avoidance Zones have been developed during this study. Fault Awareness Areas have been developed for all other faults outside of the Priority Areas (green). Townships within Priority Areas include: Waiouru (A); Karioi (B); Rangataua, Ohakune, Mokaranui and Raetihi (C); Erua, Waikune, National Park and Raurimu (D); and Owhango to Taumarunui and surrounds (E).

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

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

Section 4 describes the methodologies used to map active faults and to develop FAZs and FAAs and, in the case of FAZs, how they can be applied to the MfE Active Fault Guidelines in terms of fault complexity (i.e. well-defined, distributed, uncertain), fault activity (recurrence interval of fault rupture) and building type (single-storey timber-framed house, cinemas, hospitals, etc.), and resource consent activity status in relation to these three parameters.

Section 5 describes the results and implications for active faults in the Priority Areas and, where possible, provides new or updated recurrence interval information and FAZs and/or FAAs for those faults that are considered active.

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

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

This report is accompanied by digital geospatial (GIS) data, including active fault mapping (lines), FAZs and FAAs (polygons). These should facilitate the direct incorporation of FAZs into District Plans, which, in turn, will facilitate application of the MfE Active Fault Guidelines and provide a rational, risk-based approach for dealing with land-use decisions pertaining to the development of land on, or close to, active faults.

2.0 THE HORIZONS REGION

2.1 Physiographic Setting

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

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

2.2 Tectonic Setting

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

Technically, the largest fault in the region is the Hikurangi subduction interface (dark blue bold line on Figure 2.1), where the Pacific Plate subducts to the northwest under the Australian Plate, beneath the North Island. The plate interface is considered capable of generating a 'great' earthquake (M_W >8) and possibly a megaquake (M_W >9). In such a scenario, rupture of the Hikurangi subduction interface (i.e. as a gently-dipping thrust fault plane) would propagate to the seafloor off the east coast of Tararua District (Figure 2.1), and a significant tsunami impacting the east coast and beyond could be generated. In addition, a magnitude M_W 8–9 earthquake on the plate interface would generate severe ground shaking throughout much of central New Zealand and beyond.

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

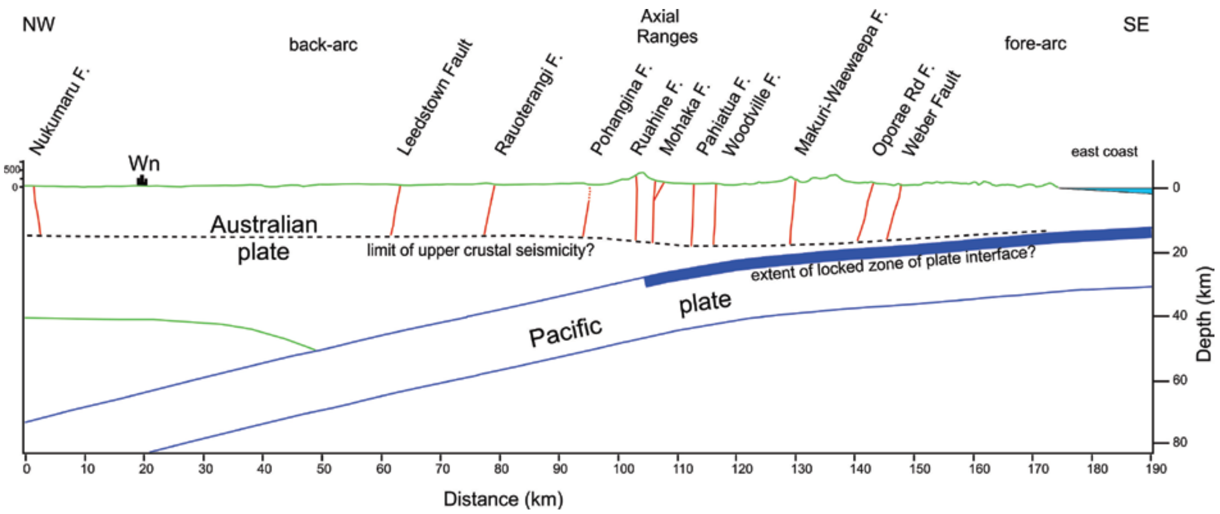


Figure 2.1 Simplified cross-section of the lower North Island from west of Whanganui (Wn) to offshore of Cape Turnagain in the east, showing the tectonic features that are relevant to the Horizons region. The cross-section intersects several active upper crustal faults and includes the Hikurangi Subduction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

The geology of the Ruapehu district is diverse (Figure 2.2). The oldest exposed rocks are Mesozoic greywacke – a type of bedded sandstone and mudstone that has been buried and heated to a low metamorphic grade. These rocks underlie the Kaimanawa Mountains and are exposed to a lesser degree along the western shoulder of the Taupō Rift in the north of the district. Resting on top of the greywacke in places are thin limestone and mudstone deposits of Paleogene age. Neogene rocks, including conglomerate, sandstone, siltstone and mudstone, rest on either the Paleogene sequences or directly on greywacke where the Paleogene rocks had been eroded away. These rocks form thick sequences in the west and south of the district. As the Taupō Rift and Taupō Volcanic Zone began to form, voluminous ignimbrites were erupted from calderas to the north and deposited in several sheets that are now partly preserved in the north of the district. Continued rifting and southward propagation of volcanism into the area saw the growth of the Tongariro National Park volcanoes with Hauhungatahi at about 1 million years ago (Cameron et al. 2010), Tongariro at half a million years ago (Pure et al. 2020) and Ruapehu at about 200 thousand years ago (Gamble et al. 2003; Conway et al. 2018). Periods of heightened volcanic activity coincide with periods of accelerated slip on some of the Taupō Rift faults, indicating a linked process or genesis at depth (Villamor et al. 2004, 2007). Quaternary sediments are deposited as terraces and fans on many of the valley floors and sides and form wide ring plains around the Tongariro National Park volcanoes.

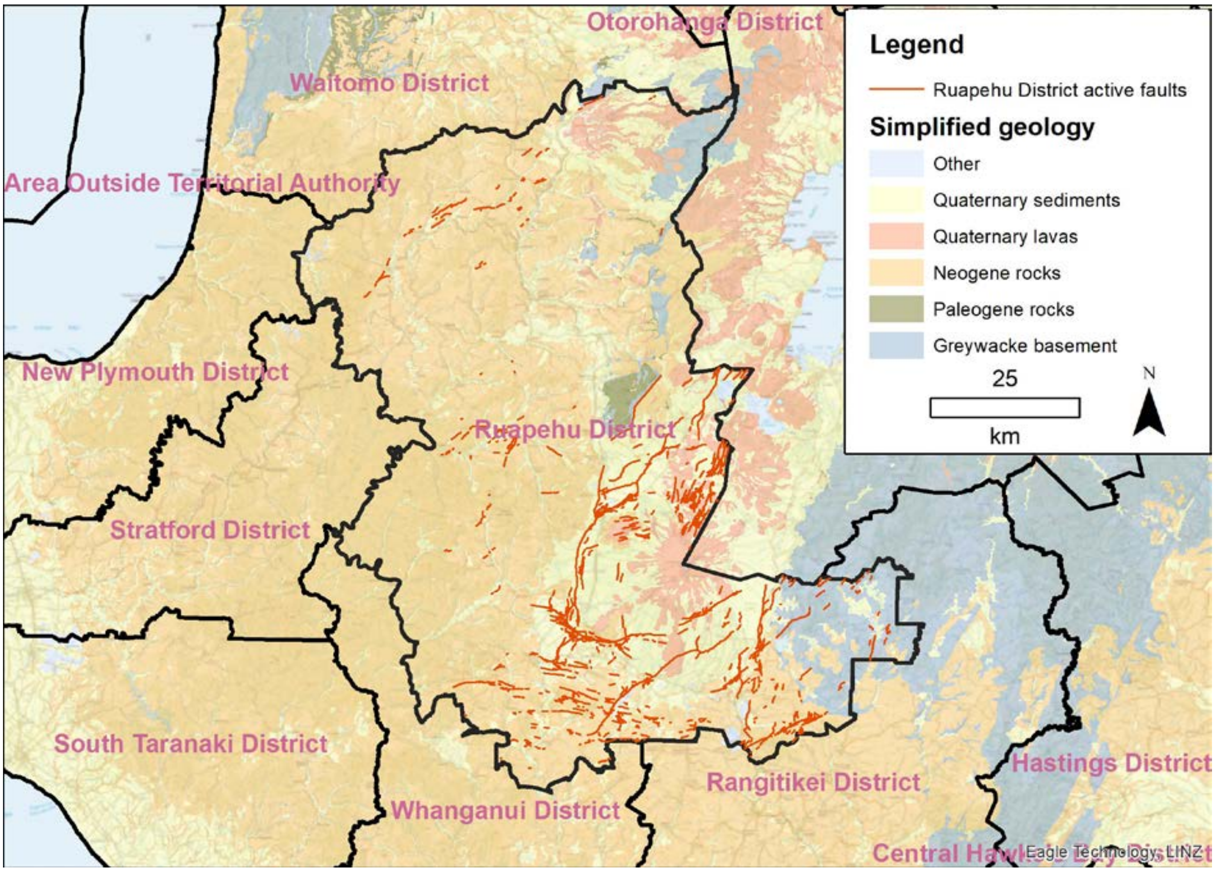


Figure 2.2 Map showing the simplified geology of Ruapehu District (after Heron 2018) and active faults as mapped during this study.

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

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

Ruapehu District includes some of the volcanoes within the southern part of the Taupō Rift. Any mass movement of material (including landslides and debris flows) that occurs on a volcano is termed a ‘lahar’. Lahars can form due to the same processes that occur in non-volcanic environments (e.g. those triggered by intense rainfall events and/or earthquake shaking) but can also form through volcanic eruption processes. Because volcanoes grow mainly by eruption and addition of material to their exteriors, they can form unstable slopes that are prone to failure. This is particularly relevant for Ngauruhoe, which is essentially a pile of unconsolidated scoria and tephra (at or close to the angle of repose), and for Ruapehu, which has formed alongside valley-filling glaciers that have influenced the distribution of its lava flows (Conway et al. 2015; Townsend et al. 2017). Ruapehu has had at least three significant collapse events in the last c. 11,000 years (Townsend et al. 2017 and references therein), forming hummocky deposits such as those exposed beside State Highway 48 near Whakapapa Village.

Additionally, Ruapehu Crater Lake is a potential source of break-out floods, and eruption of scoria and tephra onto snowfields can lead to melting, forming water-saturated sediment (debris) flows – as occurred last in 2007.

These forms of erosion can rapidly alter the landscape, often removing or burying evidence of faulting activity. Additionally, landslide scarps may have the appearance of tectonic fault features, so extra care must be taken with interpretations of features in terrain that is susceptible to landsliding. Care was taken during this study to only map features relating to active faulting; however, this was difficult in some instances. In such cases, the feature has been included, but its origin uncertainty is captured in the Tectonic Origin attribute field (*definite, likely, possible* or *unknown*).

2.3 Regional and Historical Seismicity

The Horizons region has a well-documented record of historical (post-1840 AD) earthquakes that have been both damaging and destructive. Figure 2.3 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, in some cases, ground surface rupture. The Horizons Region boundary is shown in dark blue to highlight large earthquakes that have occurred within or close to the region.

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

The M_W ~8.2 Wairarapa earthquake occurred on 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 Tararua District. In the 1855 Wairarapa earthquake, shaking intensities of Modified Mercalli Intensity (MMI)[4] 8–9 were experienced at Paiaka, south of the Manawatū River, and MMI 7 at Whanganui (Downes and Dowrick 2014). The 1855 quake followed after the M ~7.5 1848 Marlborough earthquake, which caused similar levels of strong shaking in Horowhenua, Manawatū and Whanganui (Downes and Dowrick 2014; Grapes et al. 1998).

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

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

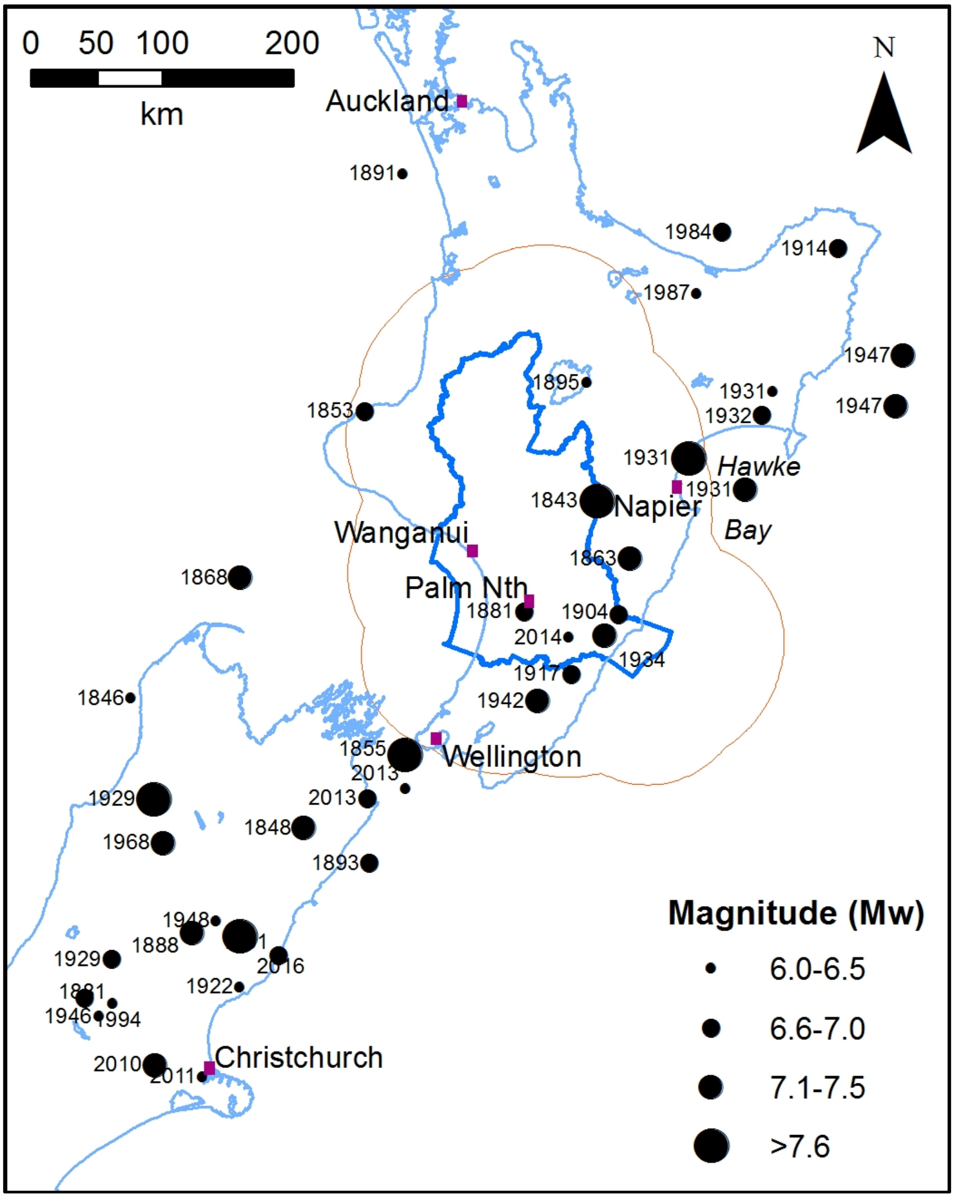


Figure 2.3 Epicentres of significant shallow (<30 km depth) earthquakes in central New Zealand that have occurred between 1840–2016. Highlighted in dark blue is the Horizons region, and the orange line is an area that extends a further 75 km around the region to consider impacts from nearby earthquakes. Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

In June 1881, a M_W ~6.7 earthquake occurred with an epicentre located very close to Palmerston North, where it was strongly felt. The August 1904 Cape Turnagain earthquake was a shallow (~16 km) M_W 7.2 earthquake that caused heavy regional damage to the landscape and personal property, and it resulted in one death. Shaking intensities (MMI 8–9) were most strongly felt on the North Island's east coast (in the Tararua district) near Cape Turnagain. Reported maximum shaking intensities decreased in all directions from this area but ranged from MMI 5–7 across much of the Horizons region.

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

During the second quarter of the 20th century, Hawke's Bay and surrounding regions were rocked by a number of large earthquakes, including the 3 February 1931 M_W 7.6 Hawke's Bay earthquake (also known as the Napier earthquake), which killed 256 people and devastated the cities of Napier and Hastings. During this event, felt intensities of 'damaging' to 'very damaging' (MMI 6–7) were reported across the Horizons region. The Hawke's Bay earthquake was followed by a damaging aftershock on 13 February 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 faults in Tararua District. Geologic studies show that this earthquake caused surface rupture on the Waipukaka Fault, which has had at least two other Holocene surface-rupturing earthquakes (Schermer et al. 2004). The earthquake in 1934 caused extensive damage from the northern Wairarapa to Hawke's Bay, particularly between Porangahau and Castlepoint. The worst damage was noted in Pahiatua, the largest town near the earthquake epicentre. There were no deaths caused by this earthquake, although one person required hospitalisation.

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

The largest earthquake to occur within the Horizons region this century was the 2014 M_W 6.2 Eketahuna earthquake (Figure 2.3; note that this earthquake sequence is not shown on Figure 2.4 as it occurred prior to 2015). This event occurred at a depth of c. 34 km and was felt strongly across the country from Auckland to Dunedin, with more than 9000 felt reports submitted by the public to GeoNet. The Eketahuna earthquake resulted in three injuries. Ground motions at Hokowhitu Lagoon in Palmerston North were reported to have caused damage leading to water leaking away from the oxbow lagoon into the subsurface. Many rockfalls were reported in the area between Palmerston North and Puketoi Range, some larger slips and slumping of local roads also occurred and minor liquefaction was reported in Castlepoint and Palmerston North (Rosser et al. 2014).

As a comparison to the record of large historical earthquakes in Figure 2.3, Figure 2.4 shows the seismicity of the Horizons region over a five-year period from August 2015 to August 2020. The seismicity (M >2.6; depth <40 km) in and around Ruapehu District in Figure 2.4 shows almost 1000 earthquakes. It also highlights clusters of seismicity broadly related to the Hikurangi Subduction Zone and local earthquake swarms, including long-lived swarms near Raurimu, between Ohakune and Whangamomona, around Lake Taupō, and offshore near Whanganui.

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

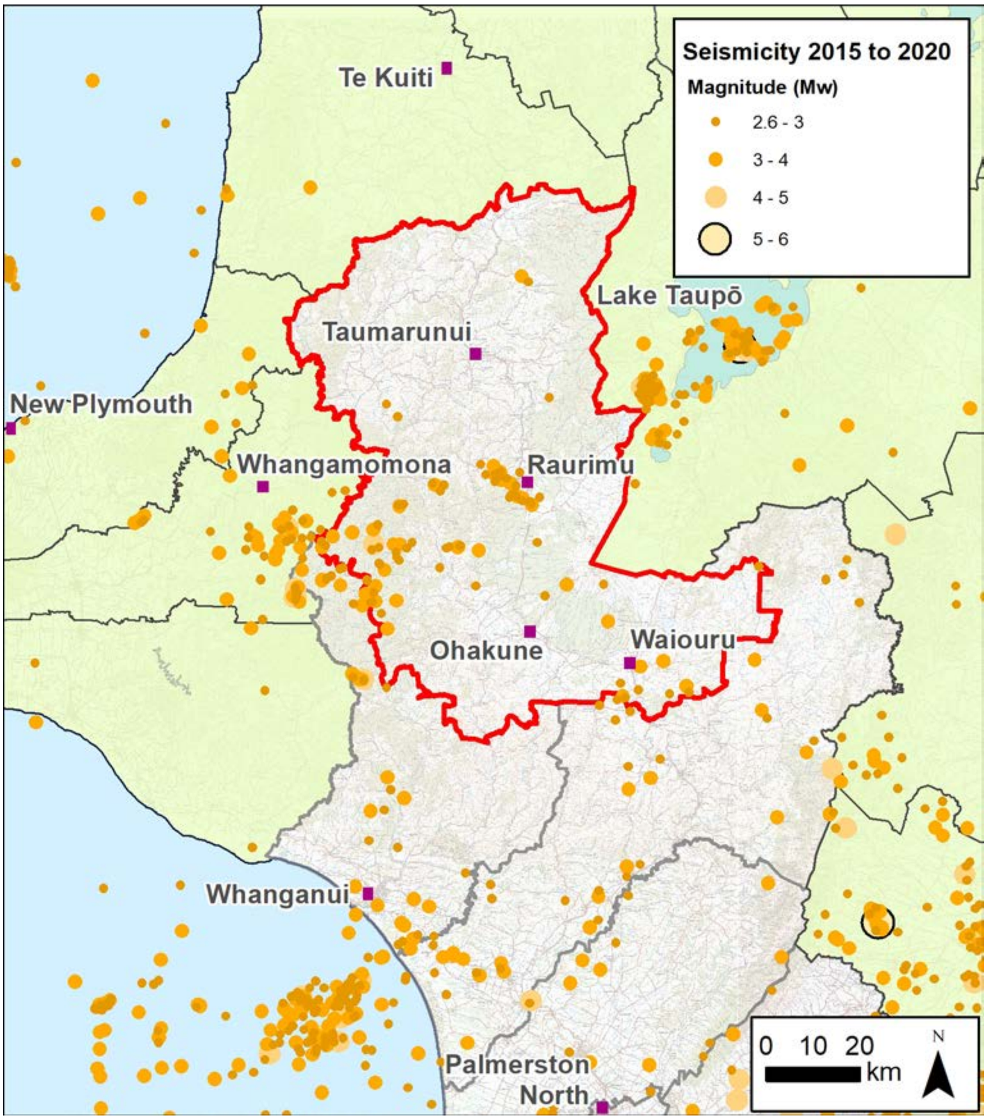


Figure 2.4 Epicentral locations of shallow (<40 km) earthquakes of M_w >2.6 that occurred between August 2015 and 2020 within, or close to, Ruapehu District (outlined in red). Earthquakes are colour-coded in magnitude bands. The largest event is a M_W 5.1 that occurred in 2018 near Waipukurau (bottom right of figure). Data are from GeoNet (https://www.geonet.org.nz/data/types/eq_catalogue).

3.0 ACTIVE FAULTS AND THE MFE ACTIVE FAULT GUIDELINES

The Horizons region has a large number of active faults, which have previously been mapped mostly at scales of >1:10,000 (1:250,000 [Heron 2018] or 1:50,000 [Langridge et al. 2016], NZAFD: http://data.gns.cri.nz/af/) (Figure 1.1). The locations of active faults mapped at scales of >1:10,000 have significant locational uncertainty and accordingly have limited use for planning purposes. Phases 1, 2 and 3a of the Horizons region active fault mapping programme were undertaken across Horowhenua, Manawatū, Rangitikei and Whanganui districts and Palmerston North City to refine active fault locations and to produce FAZs that can be utilised within the risk-based planning context of the MfE Active Fault Guidelines (Kerr et al. 2003; Langridge and Morgenstern 2018, 2019, 2020; Townsend and Litchfield 2020). The earlier projects drew on the significant extent of available airborne LiDAR coverage, which facilities very detailed mapping of active fault features. For Phase 3 (Whanganui District and this study) there is less LiDAR coverage available and more reliance has been placed on the regional DSM.

3.1 What is an Active Fault?

Active faults are those faults considered capable of generating strong earthquake shaking and ground-surface fault rupture. Ground-surface-rupturing earthquakes are typically of magnitude M_W >6.5.[5] An active fault is generally defined within the NZAFD and here as one that has deformed the ground surface within the past 125,000 years (Langridge et al. 2016). This is defined in part for practical reasons for mapped faults that deform marine terraces and alluvial surfaces that formed during the 'peak Last Interglacial period' or Marine Isotope Stage (MIS; see Table A2.1 in Appendix 2) 5e, or younger (MIS 1–4; e.g. Alloway et al. 2007). These MIS 5e surfaces form a useful datum throughout much of New Zealand and are therefore a pragmatic choice for the definition of activity. The only exception to this classification is within the Taupō Rift (part of which is within Ruapehu District), where active faults are defined as those with evidence of activity within the last 25,000 years (Langridge et al. 2016; Villamor et al. 2017).

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

Active faults are often defined by a fault scarp. A fault scarp is formed when a fault displaces or deforms a surface and produces an abrupt linear step, which may smooth out over time due to erosion (Figure 3.1). In some cases, where a fault moves horizontally rather than vertically, surface features such as streams may be deflected, but only a subtle linear trace may be

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

preserved along the fault trace. Traditionally, faults have been mapped from aerial photographs using stereoscopy, i.e. pairs of overlapping aerial photographs that can be used to visualise the ground surface in 3D. The acquisition of airborne LiDAR used to develop Digital Elevation Models (DEMs) has greatly improved the accuracy to which active fault traces can be mapped (Meigs 2013; Langridge et al. 2014).

An expanded description of the main styles of active faulting is presented in Appendix 1. This includes a description of strike-slip, reverse and normal dip-slip faults and oblique-slip faults where there is both a significant strike-slip and dip-slip component of motion.

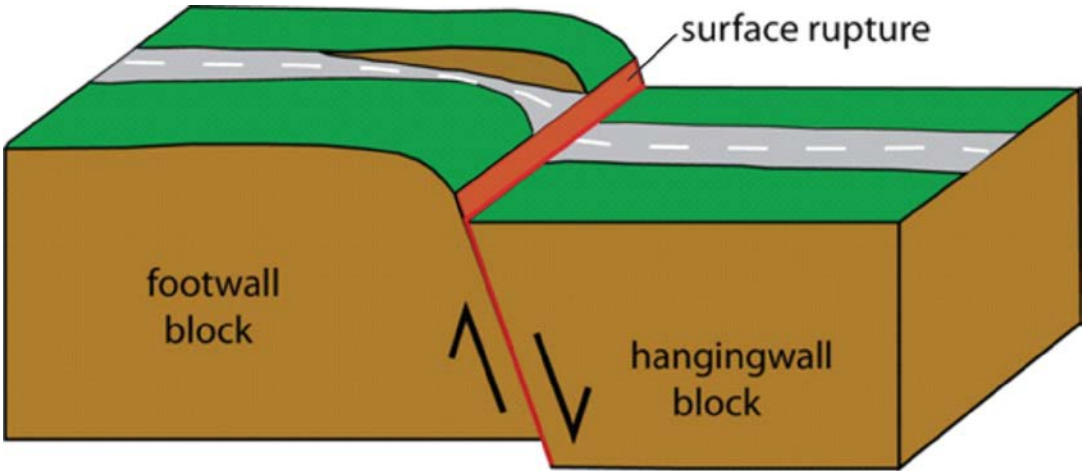


Figure 3.1 Block model of a generic active fault (shown in red). Fault displacement produces a scarp with offset features along the intersection of the fault plane at the Earth's surface, forming a fault line or trace. Modified from Langridge and Morgenstern (2018).

3.2 MfE Active Fault 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 Active Fault Guidelines'. The aim of the MfE Active Fault 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 Active Fault 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 Active Fault Guidelines are designed primarily for life safety purposes; however, what has increasingly become relevant to councils and landowners is post-event functionality of built structures, i.e. built structures that can be readily repaired and safely occupied or used after a natural disaster event.

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

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

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

Phases 1 through 3a of the Horizons active fault mapping programme build on an extensive history of recent fault mapping undertaken with a view toward developing FAZs in other regions of New Zealand. These studies have been, for example, in Greater Wellington (e.g. Litchfield and Van Dissen 2014; Morgenstern and Van Dissen 2021; URS Corporation 2006; Van Dissen and Heron 2003; Zachariasen et al. 2000; Begg et al. 2001; Townsend et al. 2002), Waikato (Litchfield et al. 2020), Bay of Plenty (Villamor et al. 2010), and Hawke's Bay (e.g. Clark and Ries 2016; Langridge and Ries 2014, 2015; Langridge et al. 2006, 2011) in the North Island and Canterbury (Barrell and Townsend 2012; Barrell 2015; Litchfield et al. 2019), West Coast (e.g. Langridge and Ries 2010) and Marlborough (Langridge and Ries 2016) in the South Island.

3.3 Active Fault Recurrence Interval and the MfE Active Fault Guidelines

Six Recurrence Interval classes (RI Class), each of which define a distinct range of time, are defined within the MfE Active Fault Guidelines (Table 3.1; Kerr et al. 2003). The MfE Active Fault 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 Active Fault Guidelines as permissible to be built across active faults with average recurrence intervals of surface rupture less than 2000 years (i.e. RI Class I). In a 'Greenfield' (i.e. undeveloped) setting, more significant structures, such as schools, airport terminals and large hotels (BIC 3 structures), should not be sited across faults with average recurrence intervals shorter than 10,000 years (i.e. RI Class I–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 1–3a of the Horizons active fault mapping programme, the state of knowledge regarding the recurrence intervals of faults in the region and preliminary recurrence interval classes for all faults in the Horowhenua, Palmerston North, Manawatū, Rangitikei and Whanganui districts were summarised by Langridge and Morgenstern (2018, 2019, 2020) and Townsend and Litchfield (2020).

Based on current data, the Horizons region contains active faults in RI Classes I–V (Van Dissen et al. 2003; Langridge and Morgenstern 2018, 2019, 2020; Townsend and Litchfield 2020). Most 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 the Tararua, Manawatū, Horowhenua and Ruapehu districts. These faults typically have moderate slip rates (e.g. Ruahine, Makuri-Waewaepa, Raetihi North and Raetihi South faults). Faults with lower slip rates typically have longer recurrence intervals and fall into RI Class III (>3500 to ≤5000 years), e.g. Waitawhiti and Kaweka faults, and RI Class IV (>5000 to ≤10,000 years), e.g. Leedstown and Nukumaru faults.

3.3.2 RI Class Categories for the Ruapehu District

An important part of utilising the MfE Active Fault Guidelines is to be able to apply RI Class information to active faults in a given territory. Prior to this study, all active faults in Ruapehu District that have published recurrence interval information fall into RI Class I (≤2000 years), except for the Snowgrass, Raetihi North and Raetihi South faults, which are RI Class II (Langridge and Morgenstern 2020; Van Dissen et al. 2003). These include: National Park and Waihi faults (https://data.gns.cri.nz/af/; Litchfield et al. 2020; Van Dissen et al. 2003); Karioi, Ohakune and Raurimu faults (https://data.gns.cri.nz/af/; Van Dissen et al. 2003; Villamor and Berryman 2006b); Shawcroft Road Fault (https://data.gns.cri.nz/af/; Van Dissen et al. 2003; Villamor et al. 2004); Upper Waikato Stream Fault (Gómez-Vasconcelos et al. 2016; Litchfield et al. 2020); and Rangipo Fault (Gómez-Vasconcelos et al. 2016; Villamor et al. 2007).

There are also a number of active faults in the district where no recurrence interval information has existed prior to this study (e.g. Mangamaire, Moawhango, Ohura, Oruakukuru, Waipuna, Waldegraves and Whenuakura faults, as well as a number of other unnamed faults), despite some of them being documented as active fault earthquake sources in the National Seismic Hazard Model (NSHM; Stirling et al. 2012) and as simplified fault zones in the Active Fault Model of Litchfield et al. (2014). In the Priority Areas (Figure 1.2), where there is little or no available geological or paleoseismic data for these active faults, recurrence interval estimates are developed based on the amount of associated landscape deformation by using slip rates applied to fault sources in the NSHM (Stirling et al. 2012) or from geologic comparisons with other faults in the region that have better-defined levels of activity.

Derivation of slip rate for the faults in Ruapehu District with previously undocumented slip rates or recurrence intervals is possible because they are predominantly dip-slip (normal) faults, where the deformation is resolved in a dominantly vertical sense of motion that can be measured from digital ground models. Figure 3.2 shows an example of how the vertical slip rates can be derived for an active dip-slip fault (Langridge and Morgenstern 2019). This methodology was also applied to dip-slip faults within the Priority Areas in Ruapehu District where no paleoseismic data exist.

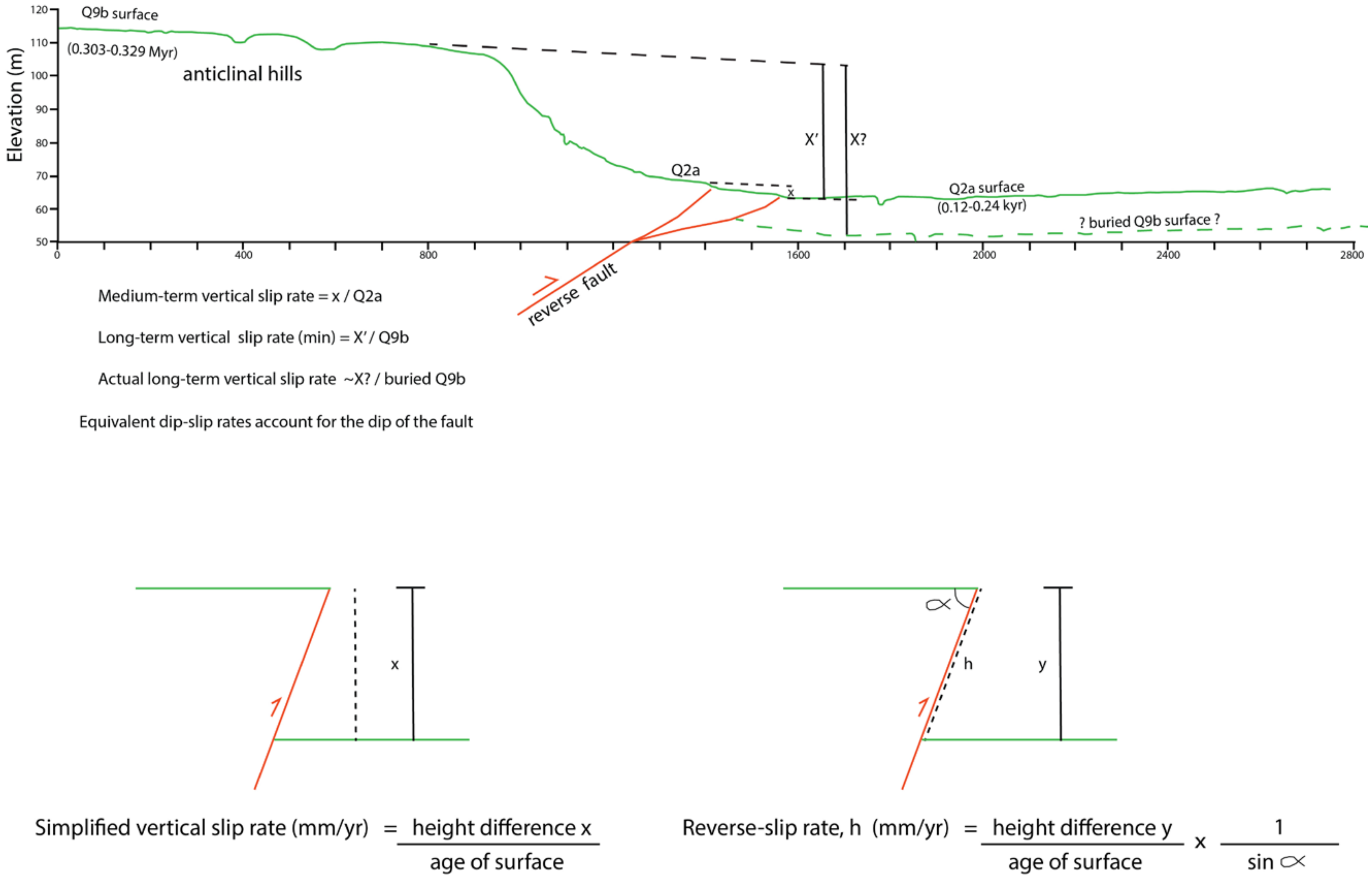


Figure 3.2 Cross-section spanning a generic dip-slip (reverse in this case) fault zone, showing how vertical and dip-slip rates are calculated for such faults. Fault scarp heights (x) across a Q2a river terrace define medium-term vertical slip rates, while offset of an older Q9b surface (X' or X?) defines a long-term vertical slip rate. Modified from Langridge and Morgenstern (2019).

When using slip rates applied to fault sources in the NSHM (Stirling et al. 2012) to estimate recurrence interval, most fault sources with a slip rate of ≥1.5 mm/yr (1.5 m / 1000 yr) 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 (<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 the nature of the parametric equations used in the NSHM and how some faults have been segmented (based on their length) or used as shared source scenarios, e.g. the Alpine Fault sources. Therefore, there are cases where fault sources with relatively high slip rates have a predicted longer recurrence interval and other cases where fault sources with lower slip rates have a shorter recurrence interval (lower RI Class). In general, it is reasonable to expect that this uncertainty represents the equivalent of ±1 RI Class. If this method is used in determination of preliminary recurrence intervals, it would, in many cases, take new geologic or paleoseismic studies to refine these.

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

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

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

In this report, we review and revise the RI Classes for all active faults in the Priority Areas, where possible. Several of the active faults and fault traces identified have a new and preliminary RI Class developed for them. This is typically achieved through an estimation of the slip rate based on scarp heights measured from topographic profiling using the LiDAR and regional DSM.

3.4 Building Importance Category and the MfE Active Fault Guidelines

Buildings sited across active faults are very likely to be damaged in a fault surface-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 Building Importance Categories 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 Active Fault Guidelines, a distinction is made between single-storey timber-framed dwellings (that are common throughout New Zealand) and other 'normal' structures (BIC 2b). A distinction is also made between 'previously subdivided or developed areas' and 'greenfield' sites. Councils can use BICs to make decisions about resource consents and to require conditions on buildings within FAZs (see Section 5.2). Table 3.4 shows the relationship between the fault rupture recurrence interval and BICs in previously subdivided or developed areas and greenfield sites (Kerr et al. 2003).

Table 3.4 Relationships between Recurrence Interval Class, average recurrence interval of surface rupture and Building Importance Category for previously subdivided and greenfield Sites. From Kerr et al. (2003).

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

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

4.0 METHODOLOGY OF FAULT MAPPING

4.1 Data Used for Fault and Fault Avoidance Zone Mapping

Active fault traces have been mapped for this project using a combination of LiDAR DEMs and hillshade models and a regional-scale 1 m DSM (Figure 4.1). Several small airborne LiDAR acquisitions with a 1 m resolution were supplied by Horizons Regional Council. Mapping on LiDAR is typically undertaken at scales of 1:5000 to 1:10,000. Previous mapping for the QMAP geological programme and for much of the NZAFD was undertaken well before the high-resolution and highly accurate digital models were available; additionally, the linework for those projects is generalised for depiction at scales of between 1:50,000 to 1:250,000. GIS linework from the NZAFD and QMAP (Heron 2018; Langridge et al. 2016; Lee et al. 2011; Townsend et al. 2008, 2017) were reviewed alongside our mapping.

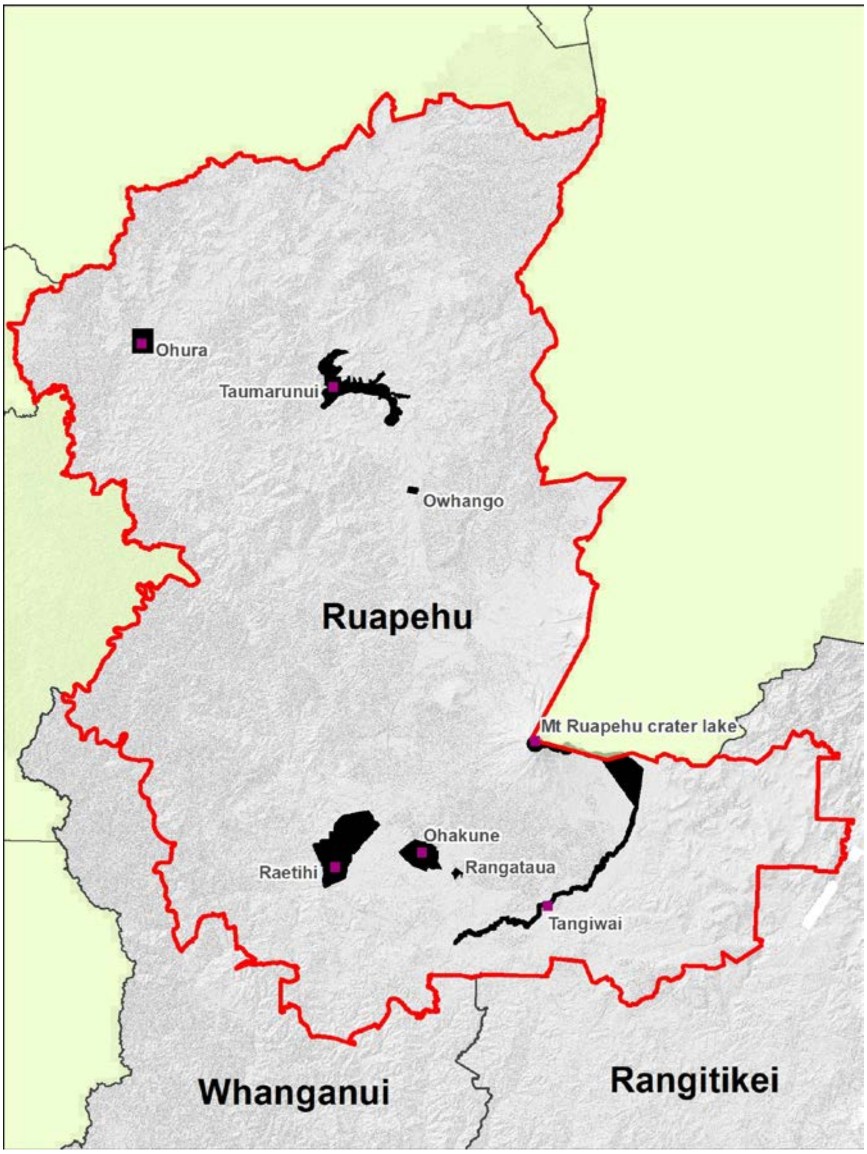


Figure 4.1 Digital topographic coverage across the Ruapehu District (red outline) used in this project. Airborne LiDAR is shown in black, underlain by the regional 1 m DSM shown in grey shading. Areas in light green fall outside of Horizons Region.

For current land-use planning in regard to building on or adjacent to active faults, particularly in developed and developing areas, it is not appropriate to use features mapped at scales of 1:50,000 (or larger), because their locations are considered too imprecise. During the last decade, several campaigns of airborne LiDAR acquisition have been flown across the Horizons region. These acquisitions cover small parts of the Ruapehu District, particularly around the townships of Ohura, Taumarunui, Owhango, Raetihi, Ohakune and Rangataua, and the Whangaehu River corridor from Mt Ruapehu’s crater lake to southwest of Tangiwai (Figure 4.1). The raw data from many of these acquisitions were supplied to GNS by Horizons Regional Council.

A 1 m DSM was developed by Horizons Regional Council from aerial orthophotographs for Phase 2 onward (Langridge and Morgenstern 2019), and this is relied upon for mapping in areas where no LiDAR coverage exists. Unlike the DEM developed from the LiDAR data, the DSM does not filter out vegetation or buildings, which hinders the interpretation of ground features such as active fault traces. Therefore, there is less precision in the fault mapping in those areas. However, the 1 m DSM allows for higher-resolution mapping than the national-scale 8 m DEM and hillshade model that are otherwise the best available elevation models.

4.2 Mapping Fault Lines in a GIS

For this study, the location and attributes of active faults have been assembled in a GIS and recorded in a digital geospatial database (provided as supplementary to this report). The attributes listed in the GIS attribute table (see Table 4.1) are:

Fault_Name, **ACCURACY,** Tect_origi, **RI_Class, Activity, Fault_comp**, DOWN_QUAD, Method, DOM_SLIPTY, *Deform_wid* and *Buffer_dis*. For application of the MfE Active Fault Guidelines, including developing a FAZ, the most important of these are highlighted in bold. The ACCURACY and Fault_comp attributes are used to define the Deform_wid, and Buffer_dis (in italics), which dictate the width of the FAZ. A brief glossary defining these attribute terms is presented in Table 4.1. The assignation of attributes to the GIS linework is as important as drawing the lines themselves.

The mapping of active faults requires expert interpretation and recognition of tectonically displaced geomorphic landforms and a good understanding of the local geology. The most obvious landform feature associated with ground-surface fault rupture is a fault scarp (e.g. Figure 3.1). Fault scarps are linear steps (risers) in the land surface that mark the locations of fault planes where they have broken through to the ground surface. Individual scarps and traces can extend for hundreds of metres in length and are often many metres to tens of metres wide. They can also manifest at the surface as a series of short, overlapping scarps that join to a single fault plane at depth. Therefore, representing a scarp as a line within a GIS requires generalisation. In theory, a line within a GIS database has a width of zero and, in the case of fault mapping, is meant to represent the exact location where a 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 fault plane, as observed, for example, in the 2010 surface rupture of the Greendale Fault (Villamor et al. 2012). This is embodied in the Fault Complexity term described in Kerr et al. (2003) (see below).

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

The same terms: *accurate, approximate* and *uncertain* are applied to mapping on the 1 m DSM. Despite the fact that the LiDAR DEM and the regional DSM both have a 1 m pixel resolution, features that are obvious on the LiDAR DEM are somewhat less sharp or less easily locatable on the 1 m DSM compared to the LiDAR DEM due to vegetation cover (trees, scrub) or buildings. The diminished level of precision attainable from the DSM, and hence greater uncertainty in locating the faults on the model, is reflected in either wider or more uncertain (i.e. rather than well-defined) FAZs constructed for areas without LiDAR data.

Table 4.1 Active fault data GIS attributes for Ruapehu 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_origi	The confidence with which we can be certain that the feature mapped has a tectonic origin as opposed to erosional or gravitational. The Tect_origi 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 ≤25,000 years old (in the Taupō Rift) or deposits of that age that are faulted.
Fault_comp	The Fault Complexity term, which is derived from the accuracy and expression of the surface faulting. The Fault_comp terms used in this study are: well-defined, well-defined extended, distributed, uncertain constrained and uncertain poorly constrained.
DOM_SLIPTY	The dominant or primary sense of movement (slip) on a fault (all normal for this study).
DOWN_QUAD	The direction of the down-thrown side of the fault described in terms of compass quadrants.
Method	Method used to locate and draw the fault trace (e.g. LiDAR, regional DSM, NZAFD or regional geological mapping).
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.
RI_Class	The average time between surface-rupturing events on a fault, grouped into six classifications (RI Class I–VI).

In some cases, it is not clear whether the feature mapped is of tectonic origin. For example, eroded edges of a range-front or a terrace edge could be linear and parallel to a known or suspected fault. In another case, linear features in the ranges could be related to gravitational processes, known as ridge renting in New Zealand, or even landsliding. In either case, there may be uncertainty as to whether what is mapped is actually of tectonic (faulting) origin. Therefore, we have included a GIS field called 'Tect_origi', which has descriptors of 'definite', i.e. definitely of tectonic origin; 'likely'; or 'possible'. Similarly, a decision was required on whether the feature or fault mapped was active. Generally, features that were of definite or likely tectonic origin were attributed as 'active' fault features (see Table 4.1), whereas features of possible tectonic origin were attributed as 'possibly active' faults.

4.3 Fault Complexity

Fault Complexity is an important parameter in the MfE Active Fault Guidelines. It is defined within the MfE Active Fault Guidelines by three terms: w*ell-defined*, *distributed* and *uncertain*. The terms *well-defined* and *distributed* roughly equate to the width of deformation across which intense ground deformation is likely to occur. The definition of these terms is described in the MfE Active Fault Guidelines (Kerr et al. 2003). These three terms can be expanded to define whether, for example, an *approximate* fault trace links together two *accurate* fault traces over a relatively short distance (200 m) or a greater distance (Table 4.2). Where a fault is joined in the GIS across a 'gap' of <200 m, the *approximate* trace would be attributed as *well-defined extended* because it is extended over a short distance; if a gap of >200 m is joined in the GIS, this segment would be termed *uncertain constrained*. This is due mainly to natural irregularity in the fault plane so that, with greater along-strike distance from the last known location, there is the potential for the buried or eroded fault to deviate more from its projected (inferred) location.

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

The term *uncertain* is used where the fault's location may be unclear due to deposition and/or erosion since the most recent fault movement. The corresponding Fault Complexity can be *uncertain constrained*, if the distance across which the uncertainty occurs is relatively short (<200 m); or *uncertain poorly constrained*, if the distance across which the uncertainty occurs is wide (>200 m). These Fault Complexity terms link directly into Resource Consent Category tables for the MfE Active Fault Guidelines (e.g. Table A2.1).

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

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

4.4 Recurrence Interval Classes

Recurrence interval classes are assigned to the active faults within the Priority Areas for which FAZs are defined (Figure 1.2). These recurrence interval classes are based on available paleoseismic data or comparison of relative slip rates and geomorphic expression (i.e. faults with a lower slip rate and subtler geomorphic expression typically have a longer recurrence interval than faults with faster slip rate and sharper geomorphic expression). One challenge with assigning RI Class to the multi-trace Taupō Rift faults is that not all traces rupture in each earthquake (e.g. Gómez-Vasconcelos et al. 2019). This is diagrammatically illustrated in Figure 4.2, whereby earthquakes recorded in a hypothetical trench – where the fault is represented by a single trace – may suggest a recurrence interval of 500 years. However, further along the fault, where the fault may comprise many traces, each of those may only rupture in some earthquakes and therefore may have longer recurrence intervals. Because there is currently no robust method to estimate RI Class for every individual trace, we therefore assign the same RI Class to each trace, acknowledging that it is possible this could be a minimum (conservative) RI Class assignment for some traces. This approach was also used in Taupō District to the north (Litchfield et al. 2020) and, for consistency, we attribute faults that span the boundary between the Ruapehu and Taupō districts with the RI Class assigned in Taupō District.

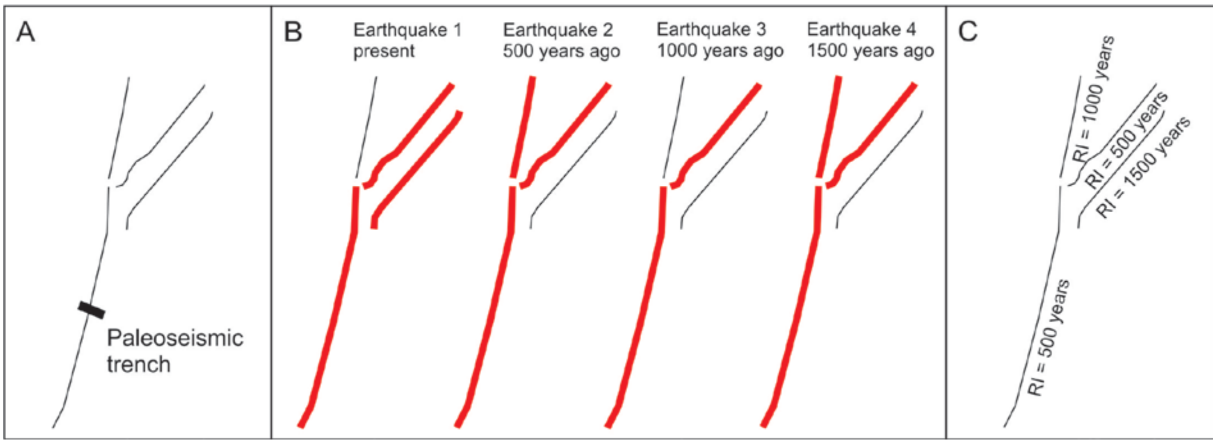


Figure 4.2 Schematic showing how recurrence intervals can vary for different traces on a Taupō Rift fault. (A) Hypothetical paleoseismic trench where past earthquake information is obtained, (B) specific earthquakes may rupture different combinations of fault traces and (C) illustrative recurrence intervals (RIs) for individual fault traces. In this hypothetical case, and considering the RI values shown, even though the RI of individual traces may vary considerably (in this case by a factor of 3), all traces would be assigned to RI Class I (≤2000 years). From Litchfield et al. (2020).

4.5 Constructing Fault Avoidance Zones

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

For this report, the width of FAZs has been defined by the accuracy and Fault Complexity attributes in a qualitative fashion, i.e. the width of fault deformation has been assessed on-screen for each trace. The MfE Active Fault Guidelines recommend that an additional margin of safety ('setback zone') buffer of 20 m be included on each side of (encompassing) the FAZ (Figure 4.3). This buffer is added to acknowledge that there is likely to be 'sub-resolution' deformation outside of the geomorphically expressed fault scarp. Thus, the total width of each FAZ in this study includes consideration of the fault location and its uncertainty, the Fault Complexity, with an additional encompassing 20 m width around both sides of that, as is recommended in the MfE Active Fault Guidelines.

An example of a FAZ is shown in Figure 4.3. On the left side of the figure, the fault is accurately mapped and has a *well-defined* Fault Complexity. In the centre, the fault may be mapped approximately and has a *distributed* (or possibly *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 'setback zone' buffer has been included on each side to develop the full FAZ. As noted in the lower right of Figure 4.3, where detailed fault studies have been undertaken it may be possible to reduce the width of a given FAZ, i.e. the certainty of fault deformation is better understood.

The slip type is relevant to understanding and anticipating the width of deformation in a future rupture. For normal faults (i.e. all faults mapped in this study), we give no preference toward deformation on one side of the fault versus the other, and the FAZs are symmetrical. Where there is more than one fault trace making up a distributed, wide or dense zone of faulting, individual FAZs may overlap. In these cases, the more accurate or higher-activity data (fault location, Fault Complexity, RI Class) should dictate subsequent resource planning decisions.

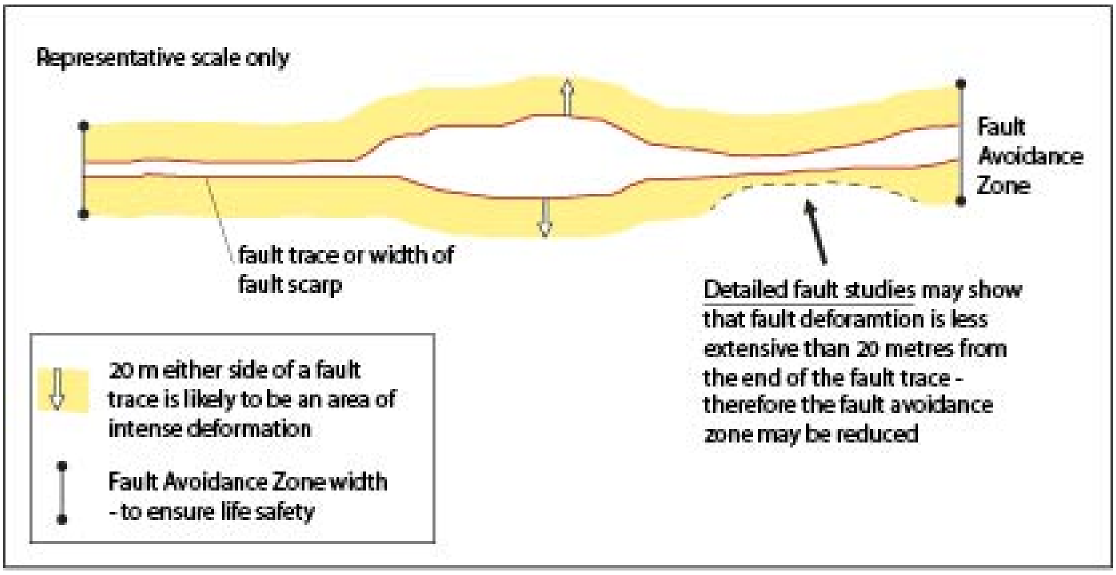


Figure 4.3 A Fault Avoidance Zone (encompassing fault zone and orange bars) for a stretch of a fault and how it may be developed for a district planning map (modified from Kerr et al. 2003).

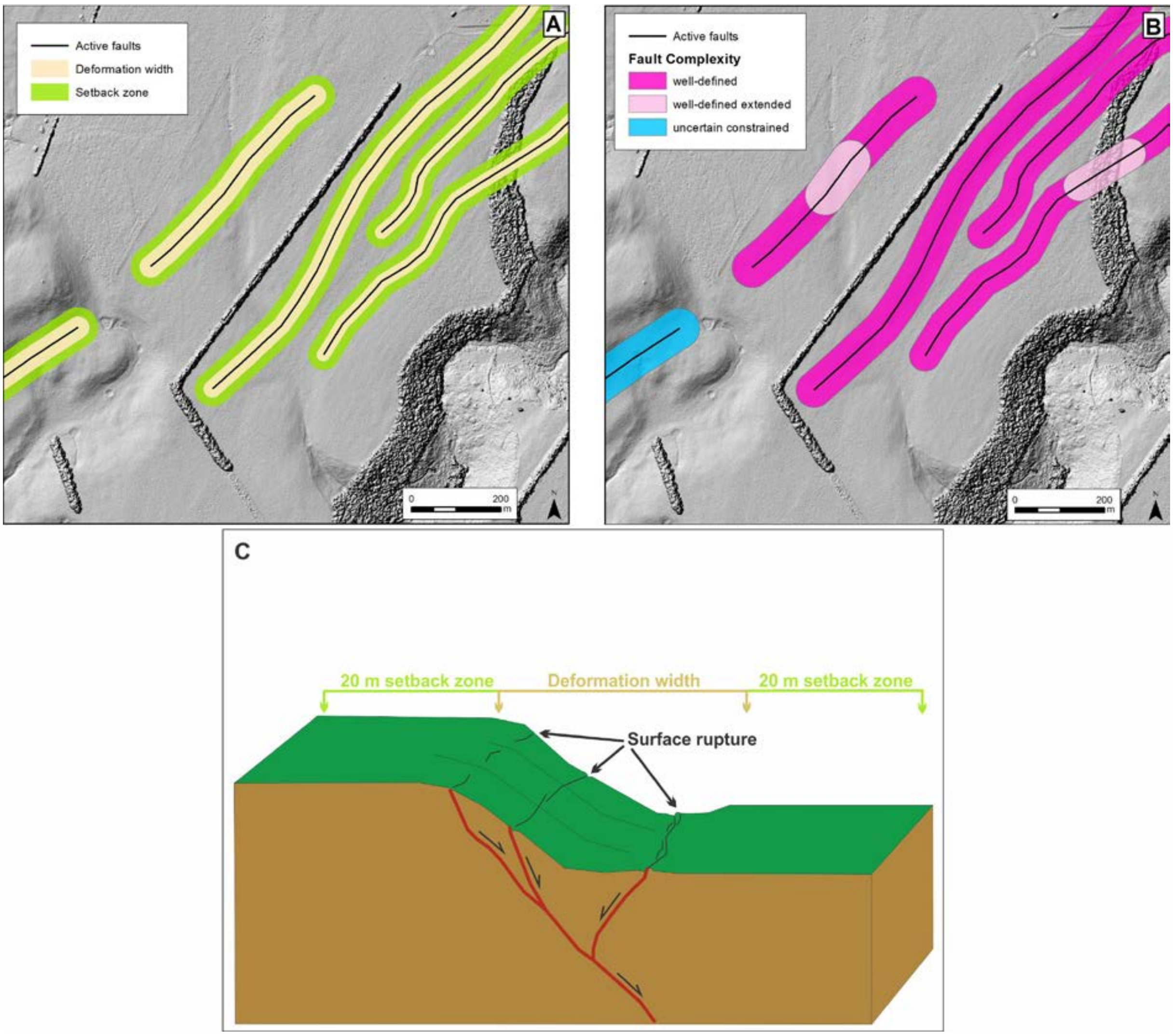


Figure 4.4 Components of the Fault Avoidance Zones. (A) Individual buffer zones used to create Fault Avoidance Zones, (B) the resulting Fault Avoidance Zones classified by Fault Complexity and (C) schematic block diagram showing how the buffer zones relate to fault features in the field.

4.5.1 Fault Awareness Areas

Faults mapped at a scale of 1:50,000 or those faults rendered at 1:250,000 scale are generally not detailed enough to delineate FAZs around the faults, nor for directly applying the MfE Active Fault Guidelines (Kerr et al. 2003) to mitigate the fault rupture hazard. For faults mapped or depicted at 1:50,000 to 1:250,000 scale, a FAA around the fault is recommended (Barrell 2015; Barrell et al. 2015). The purpose of a FAA is to highlight that there may be a tectonic feature (fault) within that area. In previous fault hazard mapping studies, GNS has developed FAAs for active faults that have been mapped at a regional-scale (Barrell et al. 2015), in lower priority areas for planning purposes (Litchfield et al. 2019) and/or in areas currently not covered in LiDAR data (Litchfield et al. 2020). This is useful in cases where the fault location uncertainty is high or in cases where there is considerable uncertainty about the origin of geomorphic features, i.e. it is more reasonable to develop a FAA than an FAZ for such areas because it carries a lower level of certainty and therefore likelihood of hazard associated with it. FAAs also highlight the need to undertake further work to test whether a mapped feature is related to tectonic (fault) deformation or to some other geomorphic process.

In this study, FAAs are developed for active faults outside of the Priority Areas, in accordance with the scope of this study (see Section 1.2). Note that their use differs from the other Horizons Region active fault mapping reports, where they were previously only used, for example, for faults mapped at 1:250,000 scale, possibly active faults and features with possible tectonic origin. The methodology for developing FAAs varies slightly from that developed by Barrell et al. (2015), in that most mapped faults have been buffered by ±125 m either side (total width 250 m). This is because of the higher level of locational certainty associated with using the regional 1 m DSM for mapping, rather than, for example, aerial photographs or data from QMAP (Heron 2018). In a few cases, where fault mapping is at a scale of 1:250,000 (generally due to the poor surface expression of the fault and/or vegetation cover obscuring the fault), the FAAs have a width of ±250 m (total width of 500 m).

5.0 ACTIVE FAULTS OF RUAPEHU DISTRICT

This study represents the first time that active fault mapping has specifically been collated for the entire Ruapehu District (Figure 5.1). With the help of airborne LiDAR-derived DEMs and a regional 1 m DSM, we have mapped and redefined many active faults and have identified some ‘possibly active’ faults. The new mapping builds on data from QMAP (Edbrooke 2005; Lee et al. 2011; Townsend et al. 2008, 2017; Heron 2018), the NZAFD (Langridge et al. 2016) and select detailed studies (Gómez-Vasconcelos et al. 2016, 2017, 2019; Van Dissen et al. 2003; Villamor and Berryman 2006a, b; Villamor et al. 2004, 2007), which identified the Karioi, Mangamaire, Moawhango, National Park, Ohakune, Oruakukuru, Raetihi North, Raetihi South, Rangipo, Raurimu, Shawcroft Road, Snowgrass, Wahianoa, Waihi, Waipuna and Waldegraves faults as the only named active faults within the district (Figure 1.1).

The majority of active faults in Ruapehu District (specifically the southeast half of the district; Figure 5.1) are part of the Taupō Rift. Faults in the northwest half belong to the tectonic domain known as the Back-arc (Litchfield et al. 2014), and much of this half of the district was previously devoid of known or mapped active fault traces (Figure 1.1). Both of these tectonic domains are characterised by extensional faulting, thus all active and possibly active faults in the district have been classified as normal faults. Much of the district is underlain by Neogene sandstone and mudstone (see Figure 2.2), which erodes into a distinctive dissected hill country geomorphology (Townsend et al. 2008) or young Quaternary volcanics, both of which make mapping of active faults difficult.

Here we describe each of the active faults and ‘possibly active’ faults in the Priority Areas from southeast to northwest through the district (A–D). No active faults were found in Priority Area E. Although active faults were mapped outside of the Priority Areas, a detailed discussion of these was beyond the scope of this project, and only a short summary is included in Section 5.5. Throughout this section, the use of capitalised ‘Fault’ denotes previously known and named faults or those that are recognised as ‘definitely or likely’ to be active (having evidence for movement or repeated movements during the last 125,000 years; Langridge et al. 2016), while the use of lower case ‘fault’ is used to denote features that are newly recognised / minor active faults, or are denoted as ‘possibly’ active faults. FAZs are defined for those that occur in the Priority Areas, while FAAs have been generated for all others in the district in accordance with the scope of this project (see Section 1.2). RI Class has been assigned for active faults within the Priority Areas in accordance with Section 4.4.

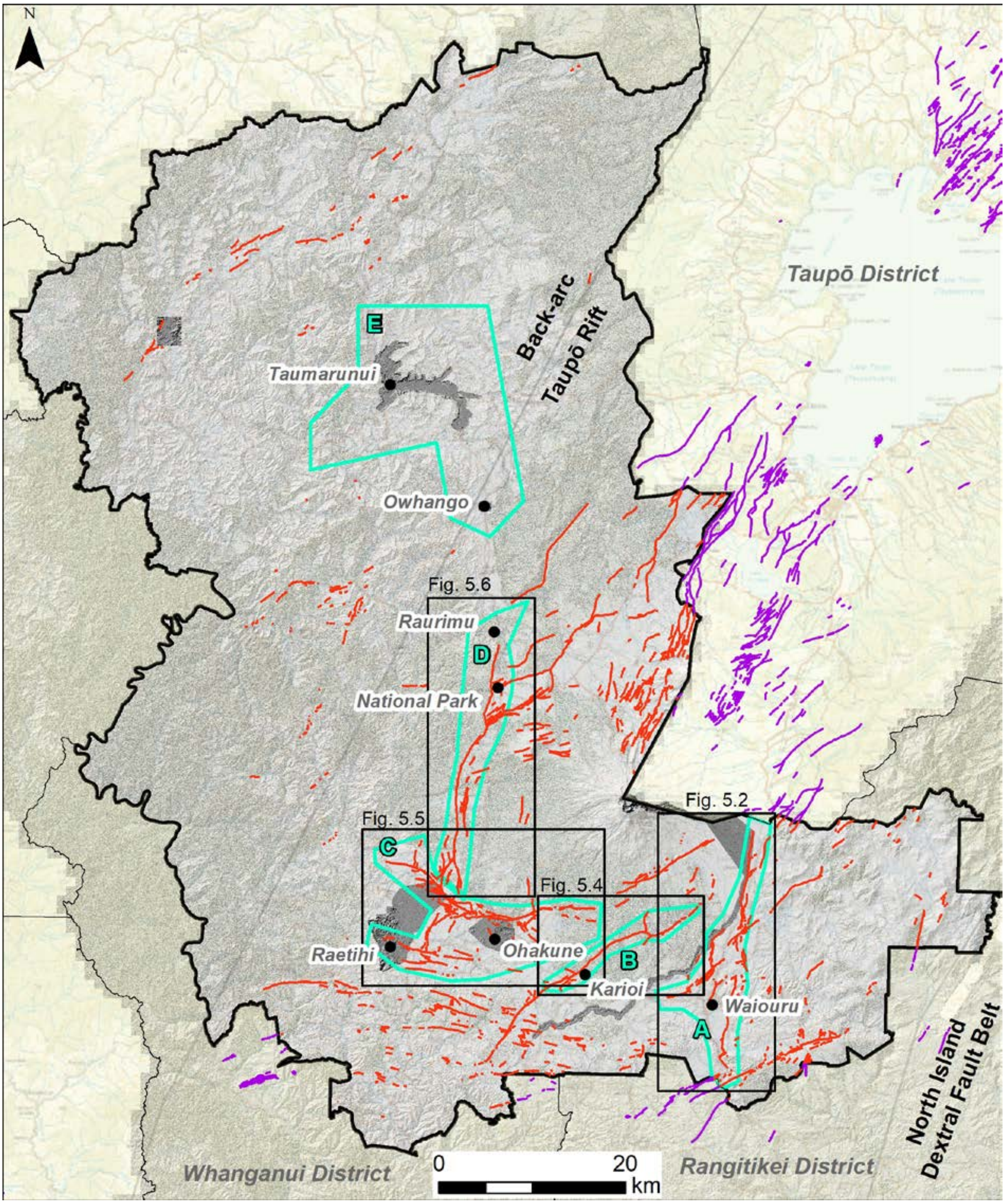


Figure 5.1 New and updated active faults (red) in Ruapehu District, as defined in this study. Active faults outside of Ruapehu District are shown by purple lines and are from Langridge and Morgenstern (2020) (Rangitikei District), Litchfield et al. (2020) (Taupō District) and Townsend and Litchfield (2020) (Whanganui District). Teal boxes show Priority Areas (A–D) where Fault Avoidance Zones were defined. No active faults were found in Priority Area E during this study. Areas include: Waiouru (A); Karioi (B); Rangataua, Ohakune, Mokaranui and Raetihi (C); Erua, Waikune, National Park and Raurimu (D); and Owhango to Taumarunui and surrounds (E). Black boxes show the areas of detailed maps presented in Section 5. LiDAR data are shown in dark grey.

5.1 Priority Area A

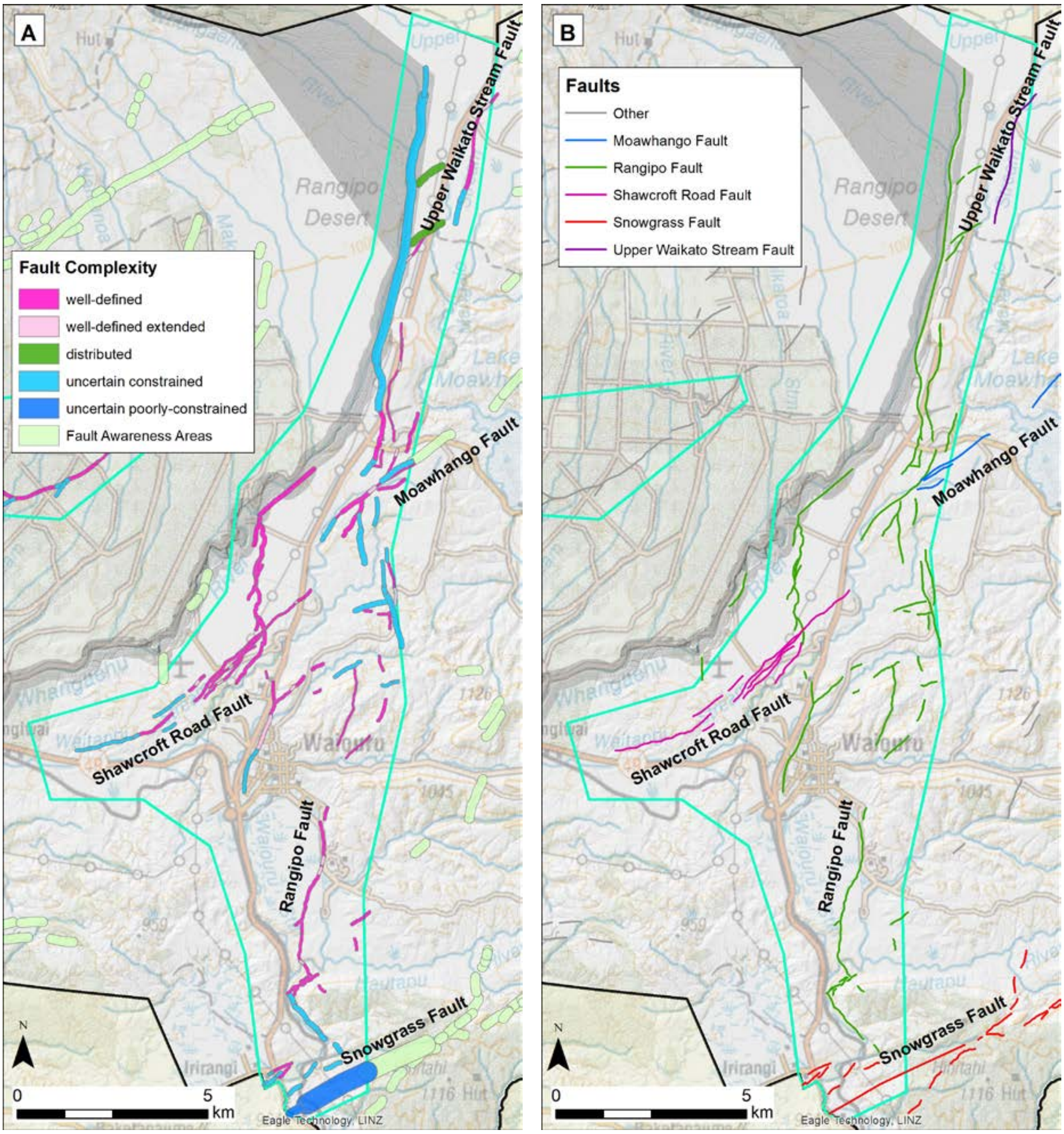


Figure 5.2 Active faults coloured by Fault Complexity (A) and fault name (B) mapped in the south-eastern Priority Area (Area A) of Ruapehu District, displayed on LiDAR and DSM hillshade models of the area.

5.1.1 Snowgrass Fault

The Snowgrass Fault is located at the southern end of Priority Area A near to the township of Irirangi (Figure 5.2). It is downthrown to both the northwest and southeast, striking NE–SW for a length of c. 15 km in Ruapehu District, and continues southwest into Rangitikei District (Langridge and Morgenstern 2020) for another c. 10 km. As part of this study, we reviewed active fault data for the Snowgrass Fault from QMAP (Heron 2018; Lee et al. 2011), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Langridge and Morgenstern 2020; Villamor and Berryman 2006a, b); and re-mapped fault traces using the 1 m DSM.

The Snowgrass Fault is mapped as a complex zone of discontinuous normal faulting, with both *active* and *possibly active* traces due to the age range of the underlying geology (71 thousand to 5.3 million years old) and the poorly known age of the landscape. Only two traces can be clearly observed on the regional DSM, and these have been given an accuracy classification of *accurate* and a Fault Complexity (FAZ classification) of *well-defined*. One of these fault traces is exposed in a road cutting on State Highway 1 near Irirangi (Figure 5.3). There are several eroded scarps that have been mapped as *approximate*, with short *uncertain* segments joining them across State Highway 1, which correspond to *uncertain constrained* Fault Complexity. The main strand of the Snowgrass Fault in this area has been mapped as a fault-guided valley at 1:250,000 scale. Within Priority Area A, the main trace has been given an accuracy classification of *uncertain* and a Fault Complexity of *uncertain poorly constrained*. The FAZ width narrows on the southwest side of the Priority Area to match the width of the FAA previously mapped in the Rangitikei District (Langridge and Morgenstern 2019) where it is clearer in the 1 m DSM.

Figure 5.3 Exposure of the active Snowgrass Fault in a State Highway 1 roadcut near Irirangi, identified by white arrows. The fault forms the sharp break between light grey Tertiary rocks and orange-brown Late Quaternary lahars and tephra deposits, mostly from Mt Ruapehu. The scarp, highlighted by the fenceline, is c. 5 m high. Photo credit: Pilar Villamor.

The Snowgrass Fault has formerly been designated as a RI Class I fault in the District, i.e. repeating ground surface-rupturing earthquakes every 2000 years or less (Van Dissen et al. 2003; Langridge et al. 2016). Villamor and Berryman (2006a) estimate a slip rate range of 0.4–0.7 mm/yr from scarp heights along the fault (Figure 5.3). Using a magnitude-length regression equation for normal faults of the Taupō Rift (see Van Dissen et al. 2003), Langridge and Morgenstern (2020) derived a slightly longer recurrence interval for the Snowgrass Fault, i.e. RI Class II (or possibly III). In this case, we infer that the recurrence interval is RI Class II (>2000 to ≤3500 years) rather than RI Class I, based on unpublished geological information (Villamor 2019, pers. comm.), which compare it to the activity observed on faults that are part of the southern Taupō Rift (Villamor and Berryman 2006a, b).

5.1.2 Rangipo Fault

The Rangipo Fault (also known as the Desert Road Fault) extends almost the entire length of Priority Area A (Figure 5.2) from the Snowgrass Fault in the south to beyond where the Upper Waikato Stream Fault splays off it in the north. It is a complex and wide (up to c. 6 km wide), NNE–SSW-striking zone of normal faulting that extends for c. 26 km, and the main structure is downthrown to the west. One strand runs through the township of Waiouru alongside State Highway 1, and another strand of the fault crosses State Highway 1 on the Desert Road (Figure 5.4) near Mangaio Tunnel. As part of this study, we reviewed active fault data for the Rangipo Fault from QMAP (Heron 2018; Lee et al. 2011), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Gómez-Vasconcelos et al. 2016; Villamor et al. 2004, 2007; Villamor and Berryman 2006b); and re-mapped fault traces using LiDAR and the 1 m DSM. To be consistent with recent active fault mapping in the neighbouring Taupō District (Litchfield et al. 2020), the northeast strand has been renamed the Upper Waikato Stream Fault.

Figure 5.4 The Rangipo Fault exposed in a State Highway 1 (Desert Road) road cut. Photo credit: Pilar Villamor.

The Rangipo Fault has both *active* and *possibly active* traces, and, for the most part, it has a reasonably clear geomorphic expression, especially on the Late Pleistocene laharic surfaces. Its locational accuracy is a mixture of *accurate, approximate* and *uncertain*, depending on the level of erosion that the scarps have undergone. To reflect this, it has been assigned a Fault Complexity (FAZ classification) of *well-defined, well-defined extended* and *uncertain constrained* (Figure 5.2). Two short traces in the west fall either partially or entirely outside of the Priority Area, thus FAAs have been generated for these.

Villamor et al. (2004) excavated two trenches across the Rangipo Fault near Access Road No. 17 and showed that the single-event displacement (SED; 0.1–1.2 m since 14 cal. ka) and mean slip rate (from 2.6–5.8 mm/yr to 0.2 mm/yr at c. 13,800 years ago) of the fault is highly variable through time (Villamor et al. 2004, 2007). This variability is interpreted to reflect changes in both fault rupture mode (primary, both segmented and unsegmented, versus secondary rupture resulting in large variability of SED) as well as interaction with the large nearby andesitic cone volcano Mt Ruapehu, whereby faster slip rates correlate with episodes of heightened eruptive activity. The Rangipo Fault has the potential to rupture at the same time as the Upper Waikato Stream and Kaimanawa (Taupō District) faults (Gómez-Vasconcelos et al. 2016). It is capable of generating earthquakes in the order of M_W 6.3–7.1, and the last primary rupture on the fault was between 3400 and 2500 years ago (Villamor et al. 2004). The recurrence interval for segmented earthquake ruptures is c. 3400–4600 years (i.e. 3–4 events in c. 14,000 years) (Villamor et al. 2007), therefore we have classified the Rangipo Fault as a RI Class II fault.

5.1.3 Shawcroft Road Fault

The Shawcroft Road Fault is located in the west of Priority Area A, to the northwest of Waiouru (Figure 5.2). It is downthrown to the southeast and strikes NE–SW for a length of c. 7.5 km in Ruapehu District, cross-cutting the Rangipo Fault at Waiouru Station. As part of this study, we reviewed active fault data for the Shawcroft Road Fault from QMAP (Heron 2018; Lee et al. 2011), the NZAFD and high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Villamor et al. 2004; Villamor and Berryman 2006b); and re-mapped fault traces using the 1 m DSM.

The Shawcroft Road Fault comprises a zone, up to 700 m wide, of semi-parallel traces and has both *active* and *possibly active* traces. Its geomorphic expression is very clear, with sharp scarps dissecting an extensive 0–186,000-year-old laharic surface (Q1 to Q6), and it has been predominantly mapped as *accurate* with a Fault Complexity (FAZ classification) of *well-defined.* Its surface expression becomes less clear towards its northeast and southwest extent due to the older Miocene to early Pliocene rocks, and, as a result, it has generally been assigned an *approximate* locational accuracy and *uncertain constrained* Fault Complexity (Figure 5.2) and has been mapped as *possibly active* in those areas.

Topographic profiles using a high-resolution digital terrain model found it to vertically displace the laharic surface by an average of 10.5 ± 1.5 m, providing a dip-slip rate of 0.6 ± 0.2 mm/yr (Villamor et al. 2004). Scarps of the Shawcroft Road Fault cross-cut the Rangipo Fault, creating a complex scallop-like geomorphic pattern, and the relative timing suggests that the Shawcroft Road Fault has ruptured more recently than the Rangipo Fault (Villamor et al. 2004). Villamor et al. (2004) excavated two trenches across the fault near Shawcroft Road and State Highway 1 and found that it displays similar variability of slip rate with time as the Rangipo Fault: at c. 13,800 years ago, the slip rate of the Shawcroft Road Fault changed from 0.8–2.0 mm/yr to 0.07 mm/yr, which again correlates with variations in the eruptive activity of Mt Ruapehu. The last primary rupture on the fault occurred 3400–1700 years ago, although this time interval is less well constrained than the time interval of last surface rupture on the Rangipo Fault (3400–2500 years) (Villamor et al. 2004; Villamor and Berryman 2006b). Given the likely relationship with the Rangipo Fault and the variability of activity through time, our best estimate of recurrence interval for the Shawcroft Road Fault is RI Class II, the same as the Rangipo Fault.

5.1.4 Moawhango Fault

The Moawhango Fault is located in the central eastern part of Priority Area A (Figure 5.2). Only a short section of the fault is within the Priority Area, so the majority of the fault has a FAA defined for it. It is downthrown to the southeast, splaying off the Rangipo Fault near Access Road No. 17, and striking in a NE–SW direction for c. 11 km, past the northwest edge of Lake Moawhango toward the peak of Manukaiapu. As part of this study, we reviewed active fault data for the Moawhango Fault from QMAP (Lee et al. 2011; Heron 2018) and the NZAFD, and re-mapped fault traces using the 1 m DSM.

The Moawhango Fault was first depicted in QMAP Hawke's Bay (Lee et al. 2011), based on an aerial photo lineament, and is also included in the map of Townsend et al. (2017). It is a semi-continuous, normal fault that has a similar orientation to the Shawcroft Road Fault and may link with this fault via the Rangipo Fault. It has been mapped as an eroded scarp for the majority of its length. It was classified by Townsend et al. (2017) as a *possibly active* fault, a designation that we maintain due to the age range of the underlying geology (middle Jurassic to late Miocene). Only two traces, although they are eroded, can be clearly observed on the regional DSM. These have been given a Fault Complexity (FAZ classification) of *well-defined.* One other trace of the Moawhango Fault that occurs in the Priority Area (the main strand) has an *uncertain constrained* Fault Complexity, and all other traces have FAAs provided for them.

No previous work has been conducted to better constrain slip rates or earthquake timings on the Moawhango Fault, and it is not recognised as a separate seismic source in the NSHM. Scarp heights of up to 2 m can be seen on the regional DSM in the Priority Area, and, although the fault is not as well expressed at the surface as the Rangipo Fault, it is unclear whether it could rupture together with the Rangipo Fault based on the current information. Our best estimate of recurrence interval for the Moawhango Fault in the Priority Area is RI Class II, based on its relationship and proximity with the adjacent Rangipo Fault, although we acknowledge that the recurrence interval likely spans a range from RI Class II–III.

5.1.5 Upper Waikato Stream Fault

The Upper Waikato Stream Fault intersects with and splays off the Rangipo Fault in the northern part of Priority Area A near State Highway 1 (Figure 5.2). It has strands downthrown to both the northwest and southeast and strikes NNE–SSW for at least 7 km, continuing on into the neighbouring Taupō District (Litchfield et al. 2020) and bounding the eastern side of the Tongariro Graben. As part of this study, we reviewed active fault data for the Upper Waikato Stream Fault from QMAP (Lee et al. 2011; Heron 2018), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Gómez-Vasconcelos et al. 2016, 2017, 2019; Litchfield et al. 2020); and re-mapped fault traces using LiDAR and the 1 m DSM.

This fault has previously been mapped as part of the Rangipo Fault and is not yet recognised as its own seismic source; however, we have adopted the name and fault characteristics from Gómez-Vasconcelos et al. (2016) (Figure 5.5). The Upper Waikato Stream Fault may also link to the similarly striking Wahianoa Fault to the west, a similar intersecting fault geometry as is observed between other faults further south in the rift (Gómez-Vasconcelos et al. 2016).

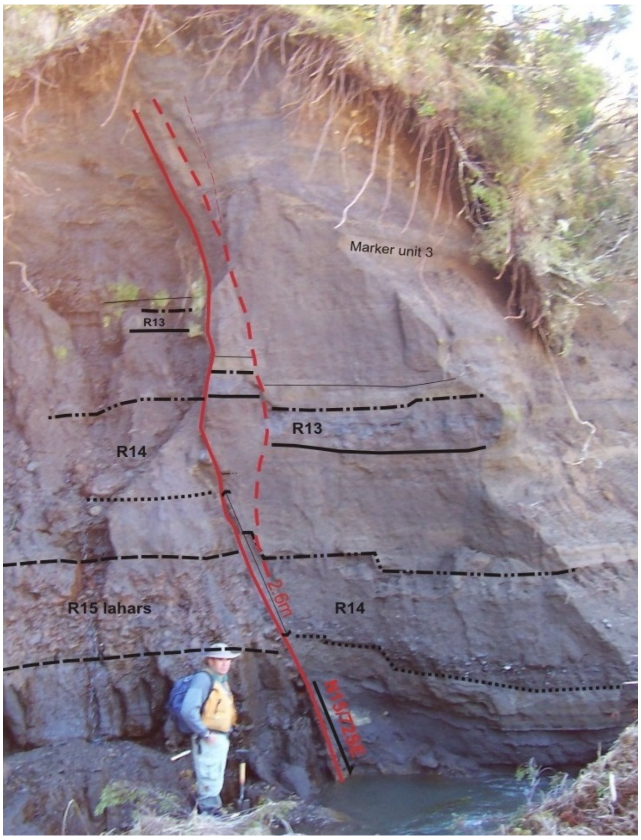


Figure 5.5 The Upper Waikato Stream Fault displacing Late Quaternary lahar deposits on the eastern Ruapehu ring plain. Taken from Gómez-Vasconcelos et al. (2016).

The Upper Waikato Stream Fault is mapped as a complex zone of semi-continuous normal faults, with both *active* and *possibly active* traces due to the age range of the underlying geology (71 thousand to ~180 million years old). Only a few traces can be clearly observed on the regional DSM in Ruapehu District and these have been given an accuracy classification of *accurate* or *approximate* and, accordingly, a Fault Complexity (FAZ classification) of *well-defined*. The other traces in the Priority Area have been assigned *distributed* and *uncertain constrained* Fault Complexity due to their subtle, broad and/or eroded surface expression. Several traces of the Upper Waikato Stream Fault also occur outside of the Priority Area and for these FAAs have been defined.

Based on geological evidence, the Upper Waikato Stream Fault can rupture on its own or in conjunction with the nearby Rangipo, Wahianoa and/or Treetrunk (Taupō District) faults (Gómez-Vasconcelos et al. 2016). If it ruptures at the same time as these faults, it is capable of generating earthquakes with magnitudes of between M_W 6.5 and M_W 7.1. Gómez-Vasconcelos et al. (2016) interpreted a minimum of 12 surface-rupturing earthquakes on the Upper Waikato Stream Fault that occurred in the last c. 45,000 years, which converts to a mean slip rate of c. 0.5 ± 0.06 mm/yr. As with the Rangipo, Shawcroft Road and Wahianoa faults, periods of increased slip rates on the Upper Waikato Stream Fault correspond to periods of heightened eruptive activity, in this case, Taupō Volcano. The minimum recurrence interval of this fault was estimated to be 1600 years between c. 36,000 and 22,000 years ago and 3500 years between 45,000 and 3520 years ago (Gómez-Vasconcelos et al. 2016). Based on this recurrence interval range (1600–3500 years; RI Class I–II), Litchfield et al. (2020) classified the Upper Waikato Stream Fault as a RI Class I fault, which we have adopted, and is a conservative minimum.

5.2 Priority Area B

5.2.1 Karioi Fault

The Karioi Fault is a major thoroughgoing structure in Ruapehu District, orientated parallel to the Shawcroft Road Fault. It extends for the entire length of Priority Area B, as well as continuing further to the northeast and southwest (Figure 5.1) and has a total length of c. 35 km (Figure 5.6). It is downthrown to the southeast and strikes NE–SW for the majority of its length but changes strike to an E–W orientation at its southern mapped extent (different to the previously mapped N–S orientation) and to a N–S orientation at its northern mapped extent. The fault traverses rural hill country in the south and cuts through Karioi Forest in the north, crossing State Highway 49 and the North Island Main Trunk (NIMT) Railway Line near Karioi. As part of this study, we reviewed active fault data for the Karioi Fault from previously published maps (Heron 2018; Lee et al. 2011; Townsend et al. 2008, 2017), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Villamor and Berryman 2006a, b); and re-mapped fault traces using the 1 m DSM.

As mapped, the Karioi Fault has a nearly continuous surface trace, with a few gaps between sections only towards its northern and southern ends. It curves along its length, and there are also a few splays branching off at oblique angles to the main structure. Where crossed by the NIMT Railway Line, it is a single scarp, but this bisects towards the southwest so that State Highway 49 surmounts a double scarp with traces c. 440 m apart. Much of the fault is mapped as *active,* with several *possibly active* traces located in the northeast and off the main strand in the southern Priority Area due to the age range of the underlying geology (~64 thousand to 5.3 million years old). Sharp scarps are clearly observed to dissect the landscape on the regional DSM in the southern part of the Priority Area, especially to the west of Karioi, where it is mostly mapped as *well-defined* to *well-defined extended* (FAZ classification). In the southwest of the Priority Area, a splay off the main trace has a clear scarp but dies out c. 1 km southwest of State Highway 49; however, it may continue further as an inactive fault or heavily eroded scarp bounding a ridge underlain by the Matemateaonga Formation (Heron 2018). The main scarp can also be clearly traced for a reasonable distance in several areas further north in Karioi Forest, where it is also classified as *well-defined.* For the remainder of its length, it is subtler, eroded and/or obscured beneath the forest canopy and has been classified as *uncertain constrained* accordingly (Figure 5.6). FAAs have been defined for the sections of the Karioi Fault that fall outside of the Priority Areas.

The Karioi Fault has a predominantly normal sense of slip, although three streams with ‘possible right-lateral offset’ near their intersection with the Mangaehuehu Stream indicate that a very minor dextral component of displacement is possible (Villamor and Berryman 2006b). The main scarp is a minimum of c. 30 m high from the top surface (early Pliocene Matemateaonga Formation onlapped by Waimarino Formation) to MIS 1–2 Late Glacial (Table A2.1) fan deposits, and c. 10 m high on the Late Glacial fan deposits themselves (Townsend et al. 2017). The splay (south-eastern scarp) is 6–7 m high, measured from the same fan deposits on the upthrown side, but this is a minimum displacement if the lower side is younger material that has accumulated against the fault scarp (Heron 2018).

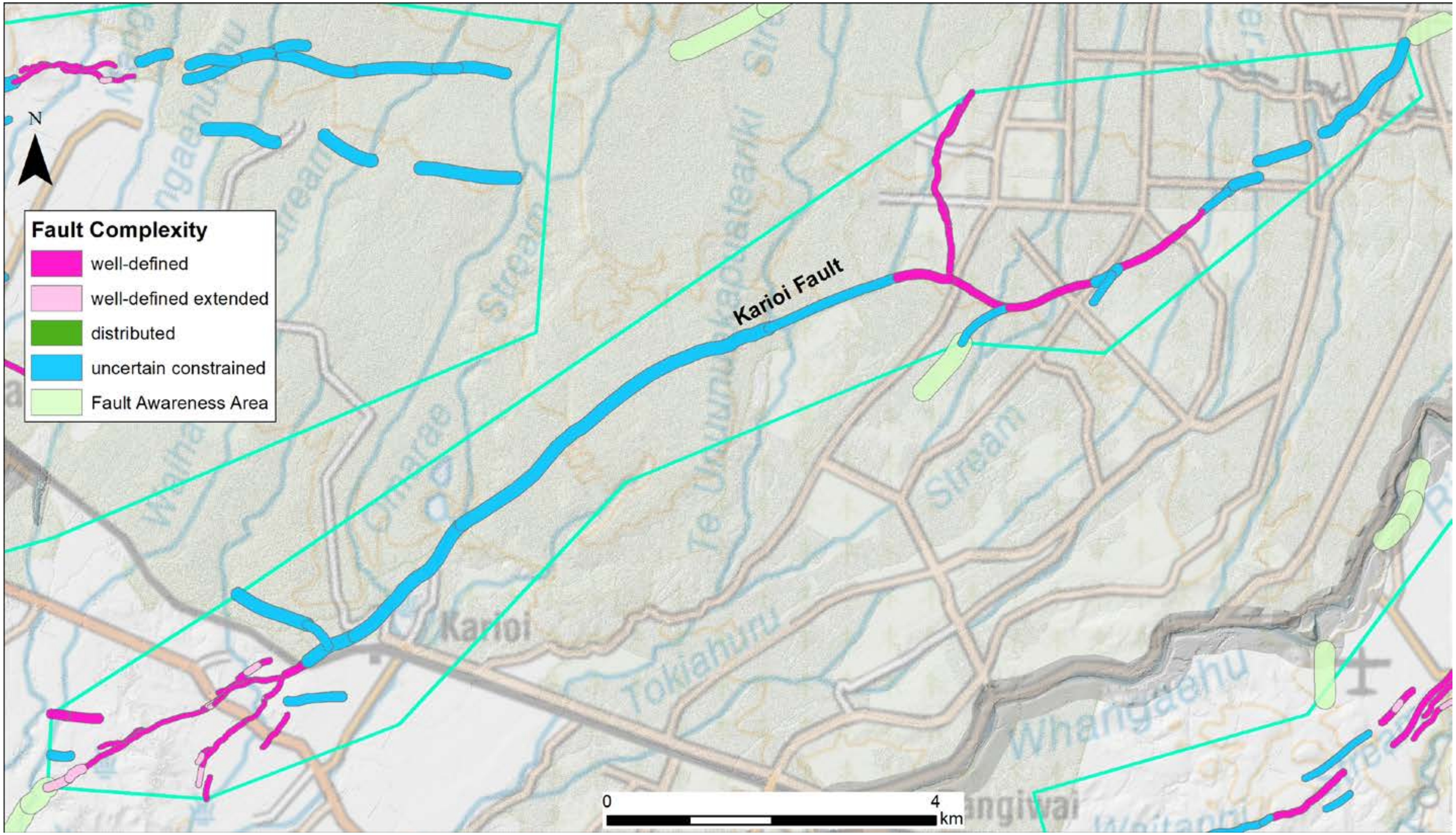


Figure 5.6 Active faults (coloured by Fault Complexity) mapped in the central-eastern Priority Area B of Ruapehu District, displayed on LiDAR and DSM hillshade models of the area.

Villamor and Berryman (2006b) excavated two trenches across a 2.4-m-high scarp on a strand of the fault c. 2.5 km south of the Priority Area, near Mangawherawhera Stream. The exposures showed that the fault has undergone 10.5 ± 3.3 m of dip-slip displacement in the last c. 26,500 years, which equates to a slip rate of c. 0.4 ± 0.1 mm/yr. We have defined the Karioi Fault as a RI Class II fault based on unpublished paleoseismic data (Villamor 2020, pers. comm.), which is consistent with a mean recurrence interval of c. 2400 years in the NSHM (Stirling et al. 2012).

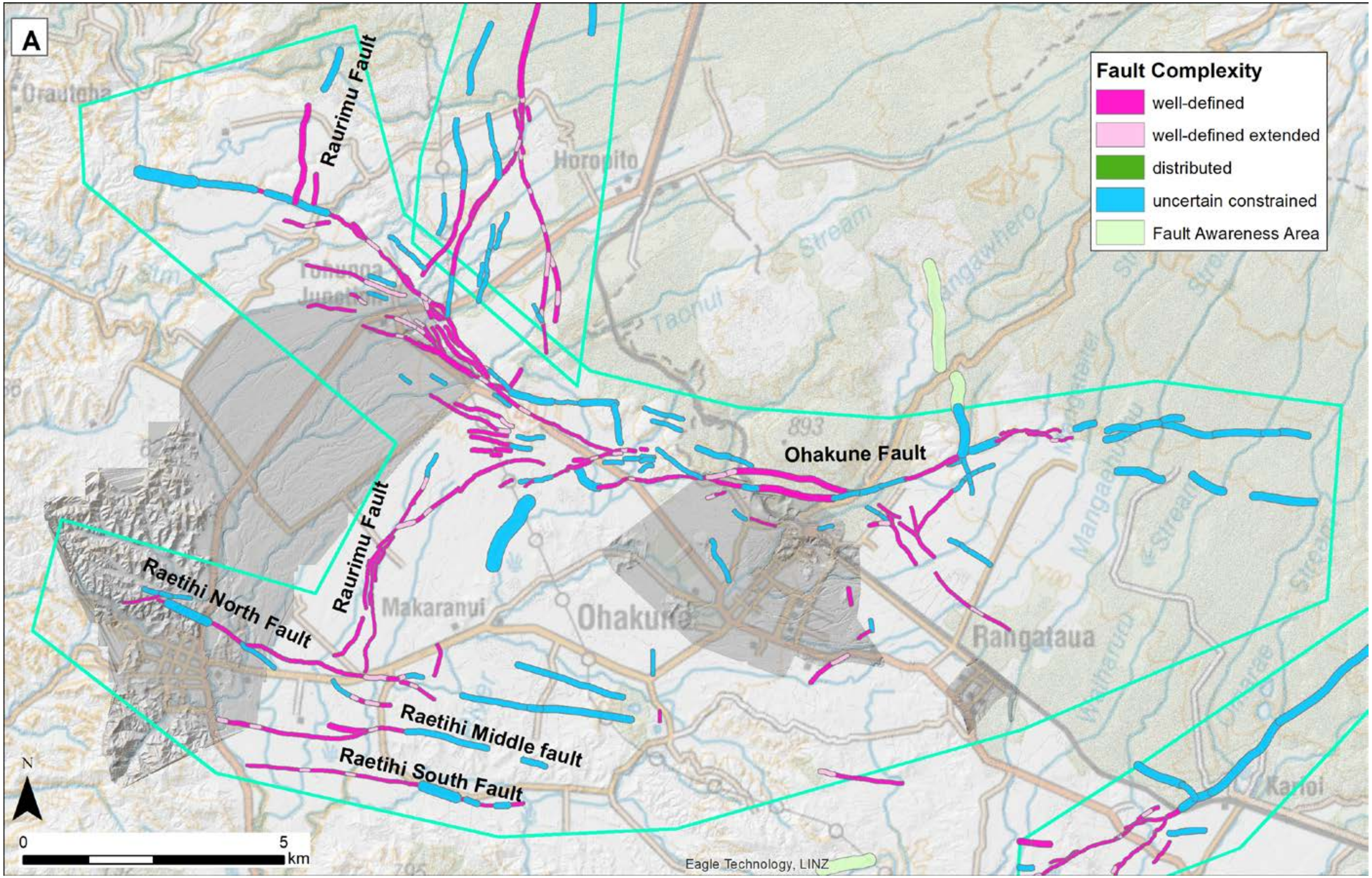
5.3 Priority Area C

5.3.1 Raetihi South Fault

The Raetihi South Fault strikes WNW–ESE for a length of c. 5 km in the south of Priority Area C, southeast of the Raetihi township (Figure 5.7), and is downthrown to the north. It is one of three sub-parallel faults (Raetihi North, Middle and South) and, along with the Raetihi Middle fault, defines a small graben within the Raetihi fault set. As part of this study, we reviewed active fault data for the Raetihi South, Middle and North faults from QMAP (Heron 2018; Townsend et al. 2008), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Villamor and Berryman 2006b); and re-mapped fault traces using the 1 m DSM.

The Raetihi South Fault has previously been mapped at 1:250,000 scale, where it was inferred to extend 1.7 km further east. Villamor and Berryman (2006b) infer that it could extend even further east than this (up to 5 km), suggesting that it is bounding a horst structure to the south (the Waipuna Fault defining the other side of the horst). It is possible that the fault continues both east and west into the adjacent Pliocene mudstone as eroded scarps, and a series of E–W-trending valleys may mean that the Raetihi faults continue eastwards to the Karioi Fault as bedrock structures. However, any connections between these faults are difficult to determine from the regional DSM, and the scarps are not well preserved across the eroded mudstone hill country, nor do they cross any mapped deposits of appropriate age to ascertain this.

The Raetihi South Fault is mapped as an *active* normal fault with almost continuous traces and a single scarp that is c. 3–4 m high. It forms an obvious scarp across the Mangawhero River valley, where it displaces lahar, fan and river deposits that are up to about 0.5 million years old. It has been mapped as *accurate* with a *well-defined* FAZ classification along most of its length, with a few short sections mapped as *uncertain* accuracy with *well-defined extended* or *uncertain constrained* Fault Complexity that link *accurate* to *approximate* traces.


A
Fault Complexity
well-defined
well-defined extended
distributed
uncertain constrained
Fault Awareness Area
Raurimu Fault
Raurimu Fault
Ohakune Fault
Raetihi North Fault
Raetihi Middle fault
Raetihi South Fault
Horopito
Makaranui
Ohakune
Rangataua
Karioi
893
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Eagle Technology, LINZ

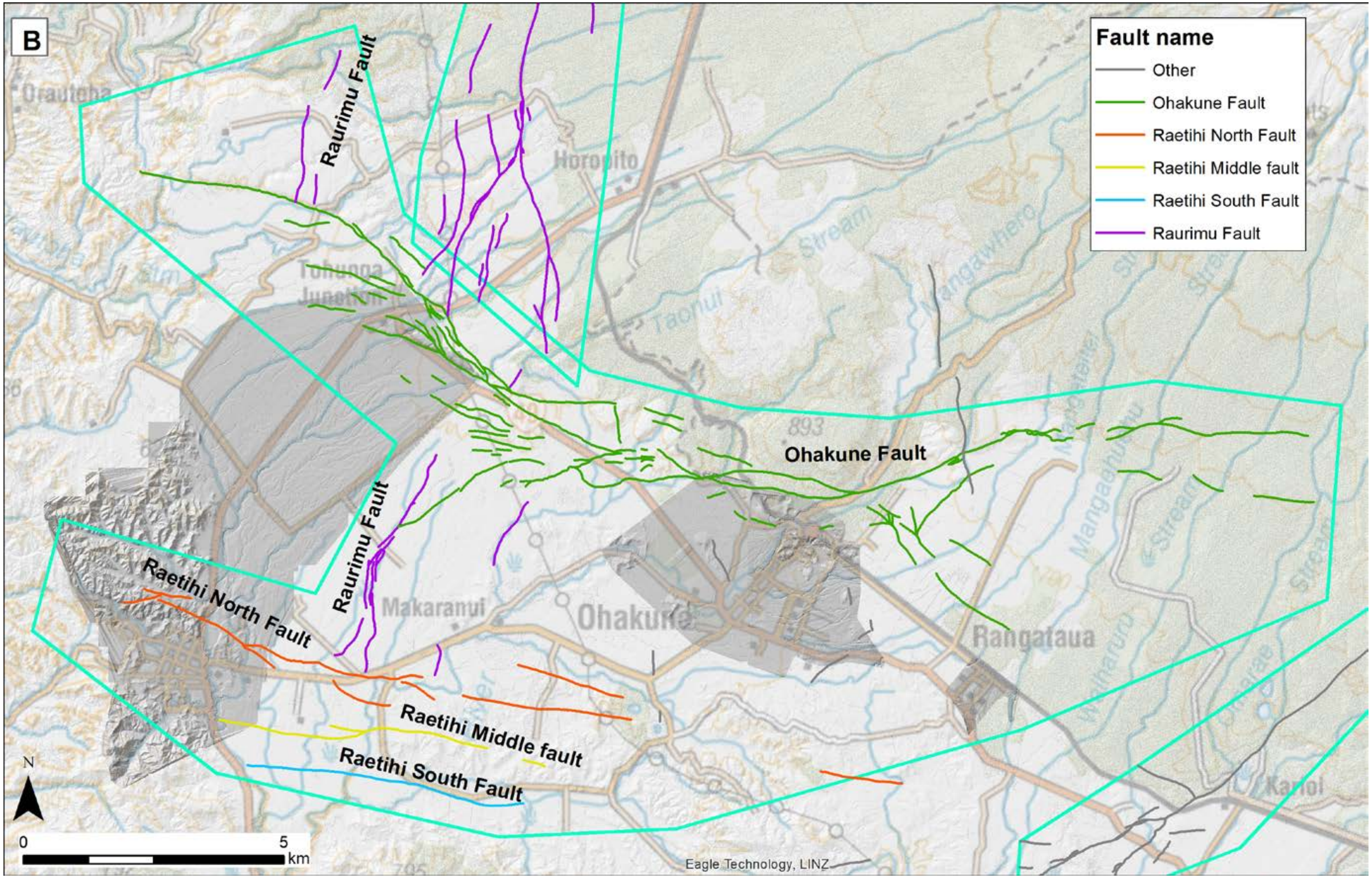

Figure 5.7 Active faults coloured by Fault Complexity (A, previous page) and fault name (B) mapped in the central-western Priority Area (Area C) of the Ruapehu District, displayed on LiDAR and DSM hillshade models of the area.

Villamor and Berryman (2006b) estimated a 6-m-high scarp on the higher (Ohakean) terrace and a 0.8–2.1-m-high scarp on the lower terrace. They converted the throws on the higher terrace (18,000 ± 3000 years old) into a dip-slip displacement of 6.9 ± 1.8 m (6.0 ± 1.6 m throw), which converts to a slip rate of 0.4 ± 0.1 mm/yr. New mapping using the regional DSM shows that the Raetihi fault set has a c. 18 m dip-slip displacement (converted from a c. 16 m throw) on the Waimarino Formation surface (59,500 ± 14,500 years; Townsend et al. 2017). This gives a new best-estimated slip rate of 0.31 ± 0.08 mm/yr for the Raetihi fault set (P Villamor, unpublished data). Using this and the methodology and fault parameters from Stirling et al. (2012), a new recurrence interval of 2040 years (1900–2295 years) has been calculated for the Raetihi fault set (P Villamor, unpublished data). Although this recurrence interval has been calculated using all three Raetihi faults, it is unlikely that they all rupture together. The Raetihi North Fault is the main trace and, to be consistent with the methodology used for other faults, when viewed individually, its recurrence interval would be at the lower end of the range given above (i.e. RI Class I), while the Raetihi South and Raetihi Middle faults would fall into RI Class II. This is consistent with the mean recurrence interval of the Raetihi earthquake source in the NSHM (c. 2100 years; Stirling et al. 2012).

5.3.2 Raetihi Middle fault

The Raetihi Middle fault strikes WNW–ESE for a length of c. 6 km in the south of Priority Area C, southeast of the Raetihi township (Figure 5.7), and is downthrown to the south. See Section 5.3.1 for an introduction to all three faults within this fault set. The Raetihi Middle fault was previously unnamed and was mapped with low locational accuracy at a scale of 1:250,000 (Heron 2018). During this study it has been redefined: its eastern and western ends now both extend further west than their previously mapped extent.

The Raetihi Middle fault is mapped as an *active* normal fault with almost continuous traces and a single scarp that reaches a maximum height of c. 5 m. Two subtle strands branch off near the middle of its mapped extent and splay towards the Raetihi North Fault (Figure 5.7). It is subtler than the Raetihi North and Raetihi South faults, but clear scarps can be observed traversing lahar and fan gravels in the Mangawhero River valley on the regional DSM. In this area, it has generally been mapped as *accurate* with *well-defined* to *well-defined extended* Fault Complexity (FAZ classification). Further east, the scarp is more eroded as it crosses into the Pliocene mudstone hill country, where it is generally mapped as *uncertain* accuracy with *uncertain constrained* Fault Complexity. The more-northern splay has also been classified as *uncertain constrained* due to its subtle nature.

Due to its relationship with the other faults in the Raetihi fault set (Villamor and Berryman 2006b), the Raetihi Middle fault has been classified as a RI Class II fault. (Villamor and Berryman 2006b; P Villamor, unpublished data; see Section 5.3.1 for more information).

5.3.3 Raetihi North Fault

The Raetihi North Fault strikes WNW–ESE and is downthrown to the south, except for the c. 2-km-long trace closest to the Makaranui Stream, which is downthrown to the north and defines a small horst between the two structures. Two volcanic explosion craters and associated deposits (at Ohakune Lakes Reserve), which are part of the >25.5 ka Ohakune Formation, (Houghton and Hackett 1984) are situated between these fault traces, and their formation may be related to faulting activity (Townsend et al. 2017). The fault is c. 15 km long and is located in the south of Priority Area C, east and north of the Raetihi township (Figure 5.7). See Section 5.3.1 for an introduction to all three faults within this fault set.

The Raetihi North Fault has previously been mapped at 1:50,000 scale, where its western end was inferred to extend c. 1 km further west and its eastern end truncated against the southern section of the Raurimu Fault. The Raetihi North Fault east of the Raurimu Fault has now been redefined (previously an unnamed active fault in AF.Traces), and the southern of the two traces has been redefined from Townsend et al. (2017). It is possible that the fault continues further, both east and west, into the adjacent Pliocene mudstone as eroded scarps, and a series of E–W-trending valleys may mean that the Raetihi faults continue eastwards to the Karioi Fault. One similarly trending (WNW–ESE) *active* fault trace is preserved on a Q1 alluvial surface in the southeast of the Priority Area along one of these valleys. It is 1.5 km long and has been grouped with the Raetihi North Fault in this study due to its along-strike location and similar characteristics (downthrown to the south).

The Raetihi North Fault is depicted as a semi-continuous normal fault trace and has the sharpest scarps out of all of the Raetihi fault set structures. It is mapped as an *active* fault where it crosses lahar, fan and alluvial gravels 64,000–589,000 years in age in and adjacent to the Mangawhero River valley. Here, the fault scarp is obvious and has a typical height of 6–10 m where it cuts the Waimarino Formation (64,000–128,000 years old; Heron 2018). Both eastern strands and the far west trace have been mapped as *possibly active* where the scarp crosses over into the Pliocene mudstone and becomes very eroded. The central section that crosses the Mangawhero River valley and the far east trace are generally mapped as *accurate* with a *well-defined* Fault Complexity (FAZ classification), while most of the other traces are mapped as *approximate* with a *well-defined, well-defined extended* or *uncertain constrained* Fault Complexity, depending on the level of erosion and the width of the feature.

Villamor and Berryman (2006b) estimated a 7.4-m-high scarp on the higher (likely Ohakean) terrace and a 3.4-m-high scarp on the lower terrace. They converted the throws on the higher terrace (18,000 ± 3000 years old) into a dip-slip displacement of 8.5 ± 2.6 m (7.4 ± 2 m throw), which converts to a slip rate of 0.5 ± 0.2 mm/yr. Following recent mapping (Townsend et al. 2017) and due to its relationship with the other faults in the Raetihi fault set (Villamor and Berryman 2006b; P Villamor, unpublished data; see Section 5.3.1 for more information), the Raetihi North Fault is classified as a RI Class I fault.

5.3.4 Ohakune Fault

The Ohakune Fault is located along the northern edge of Priority Area C near the township of Ohakune (Figure 5.7) and consists of many curvilinear, overlapping and branching splays that overall form a zone of NW–SE-striking normal faults with a length of c. 25 km. A short c. 3.5-km-long trace splays off the main trace northeast of Ohakune, striking NW–SE towards Rangataua. This section of the fault was previously unnamed and has now been included as part of the Ohakune Fault in this study. To the west of Ohakune, another trace splays off and curves to join onto the N–S-trending Raurimu Fault. Several traces cross State Highway 49 and the NIMT Railway northwest of Ohakune and State Highway 4 near Tohunga Junction (Figure 5.7). It is downthrown to the southeast away from the Taupō Rift and Mt Ruapehu, which is unusual for a graben fault (Villamor and Berryman 2006a, b). As part of this study, we reviewed active fault data for the Ohakune Fault from QMAP (Heron 2018; Townsend et al. 2008), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces), relevant parts of Townsend et al. (2017) and previous active fault studies in the area (Villamor and Berryman 2006b); and re-mapped fault traces using LiDAR and the 1 m DSM.

The complex Ohakune Fault zone is up to c. 2 km in width and displays a curvature that is convex to the south. In the northwest, the N–S-orientated Raurimu Fault is truncated against the Ohakune Fault, and here the Ohakune Fault is composed of one large scarp. It is possible that the Ohakune Fault continues further west than mapped here into Tertiary bedrock, but this cannot be ascertained at this stage due to the level of erosion (Villamor and Berryman 2006b). Further east, it breaks up into several sub-parallel splays in the Tohunga Junction-Ohakune area and has two main traces east of Ohakune. In the central section (Figure 5.7), it has branching traces that swing both southwest (towards the Raurimu Fault) and southeast (towards Rangataua). These branching traces were previously unnamed and have been grouped with the Ohakune Fault in this study. Just north of Rangataua township and parallel to the NIMT Railway Line, the most south-eastern trace runs towards a NW–SE-trending splay of the Karioi Fault. There is a gap of c. 3.5 km with no visible traces in between, but this area is heavily forested, and it is possible that these two faults connect. East of Ohakune township, the strike of the main strand of the Ohakune Fault abruptly swings to ENE–WSW, then gradually curves to become E–W-striking near its mapped end. The abrupt change in strike coincides with the location of the splay of the Ohakune Fault that swings southeast towards Rangataua and may also be influenced by the nearby NE–SW-trending Wahianoa Fault (Villamor and Berryman 2006b). North of Rangataua, an unnamed NNW–SSE-striking fault intersects the Ohakune Fault. The Ohakune Fault may continue further east and join with the Wahianoa Fault or Karioi Fault, but currently this is difficult to assess due to thick forest cover and the presence of a large, late Pleistocene lava flow from Ruapehu volcano (Rangataua Member of the Whakapapa Formation; Townsend et al. 2017). Acquisition of LiDAR data may help to validate any fault connections in the forested areas.

All traces are mapped as *active,* except for a handful of traces near where the southwest traces splay off towards the Raurimu Fault, which are mapped as *possibly active* due to their eroded nature on early Pliocene hill country. The fault is mapped as *accurate* along much of its length due to the clear nature of the scarps. These are classified as *well-defined* and *well-defined extended* Fault Complexity (FAZ classification), including two clear scarps that cross State Highway 49 just northwest of Ohakune. At the western end, although the location can be accurately defined, the scarp becomes very large (65–75 m high) and broad and has thus been classified as *uncertain constrained* Fault Complexity. In forested terrain, where it is obscured on the DSM, and where it is eroded or concealed beneath recent deposits, it is mapped as *approximate* to *uncertain* accordingly, with a Fault Complexity of *well-defined, well-defined extended* or *uncertain constrained*.

The Ohakune Fault has a relatively large scarp compared with the other faults in the district. In this study, the Ohakune Fault is estimated to have a minimum throw of 75 m in the west, which is evidenced by scarps at Tohunga Junction that are this high, where the upper surface is MIS 4 (Waimarino Formation) and the lower surface are composed of MIS 6–2 (probably c. 3) lahar deposits (Table A2.1). A further 50 m throw can be measured across a complex zone of scarps near Mangarewa Road (width of zone is c. 1.5 km), where the southwest traces splay off towards the Raurimu Fault on the MIS 4 surface (Waimarino Formation). Longer-term slip on the Ohakune Fault can be gauged by exposure of the early Pliocene Matemateaonga Formation, which includes erosion-resistant limestone beds that form a high plateau just north of the town. Equivalent beds are buried below the surface on the southern side of the fault, but the vertical offset is at least 300 m.

Near Ohakune township, the Ohakune Formation includes monogenetic scoria/lava cones and craters that have erupted on or near the Ohakune Fault (Houghton and Hackett 1984). About 4.5 km northwest of the town, there is a small explosion crater near where the southwest traces splay off towards the Raurimu Fault. The crater has been excavated through the mid- to late Pleistocene (likely c. MIS 2–3; Table A2.1) fan deposits and has subsequently been displaced by one strand of the Ohakune Fault (Townsend et al. 2017). Displacement here (as measured on the fan) is about 2 m, down to the southwest. Closer to Ohakune township, several overlapping scoria and lava cones have built up on the scarp of the Ohakune Fault, themselves having been displaced by subsequent fault movement. The age of these volcanic features predates the 22,500-year-old Oruanui eruption, but not by much (Houghton and Hackett 1984). This is strong evidence for activity of the Ohakune Fault within the last c. 20,000 years.

Villamor and Berryman (2006b) estimated a late Quaternary slip rate of 3.5 ± 1.2 mm/yr using the displaced Porewan (65,000 ± 8000 years) and Ohakean (18,000 ± 3000 years) laharic surfaces (based on a throw of 55 ± 14 m converted to a dip-slip displacement of 63 ± 18 m). However, the latter (Ohakean) surface has now been disregarded because it probably includes a mixture of younger and older terraces, and recent mapping by Townsend et al. (2017) shows the former Porewan surface to be younger (Waimarino Formation) at 59,500 ± 14,500 years. A new slip rate of 1.18 ± 0.33 mm/yr has now been calculated using the Waimarino Formation surface and a 70.5 m dip-slip displacement (converted from a c. 61 m throw) measured on the regional DSM (P Villamor, unpublished data). Using this and the methodology and fault parameters from Stirling et al. (2012), a new recurrence interval of 1035 years (670–1195 years) has been calculated for the Ohakune Fault (P Villamor, unpublished data). This fits into RI Class I, which is consistent with the mean recurrence interval of c. 610 years in the NSHM (Stirling et al. 2012).

5.3.5 Raurimu Fault

A small part of the Raurimu Fault is in Priority Area C, but the majority is in Priority Area D and so is discussed in Section 5.4.1 (Priority Area D).

5.3.6 Other Unnamed Faults

There are several short fault traces in the eastern part of Priority Area C that have not been named (Figure 5.7). These include: (1) two short N–S-trending traces near Ohakune Lakes Reserve; (2) a series of three traces orientated NE–SW to NW–SE to the east of Ohakune township; (3) a single NW–SE-trending trace northwest of Ohakune parallel to State Highway 49; and (4) a NNW–SSE-orientated structure that intersects the Ohakune Fault north of Rangataua. None of these traces have previously been mapped.

The majority of these traces are mapped as *active* due to clear scarps observed on the DSM across the relatively young laharic (Waimarino Formation) and fan (OIS 6–2) surfaces, while the northern two (numbers 3–4 above) are only mapped as *possibly active.* Almost all of these traces have an *approximate* accuracy, and Fault Complexity (FAZ classification) is defined as either *well-defined, well-defined extended* or *uncertain constrained*, depending on how broad/subtle the features are and the level of erosion. The trace to the north of the Ohakune Fault has a wider FAZ, due to erosion and being obscured beneath forest canopy, and transitions into a FAA outside of the Priority Area.

There is no recurrence interval information for these faults, but they appear to have relatively low (2–4 m) scarps on relatively old geological surfaces (64,000–186,000 years), so we infer them to be less active than the nearby Ohakune and Raetihi North faults. We therefore conservatively assign them to RI Classes II–III and use RI Class II as a conservative best estimate.

5.4 Priority Area D

5.4.1 Raurimu Fault

The Raurimu Fault is located along the length of Priority Area D, and several traces also occur in the west and northwest of Priority Area C (Figure 5.8 and Figure 5.7, respectively). The northern section (north of the Ohakune Fault) strikes NNE–SSW for a length of c. 28 km from Tohunga Junction, where several scarps cross State Highway 4, almost to the township of Raurimu, where it runs alongside the NIMT Railway and crosses the highway again. One trace also runs along the eastern boundary of National Park village (Figure 5.8). The southern section of the Raurimu Fault (south of the Ohakune Fault) is located between the townships of Raetihi and Ohakune (Figure 5.7) and is separated from the rest of the Raurimu Fault by a c. 2-km-wide intersecting zone of Ohakune Fault traces. This section is c. 9 km long and comprises an anastomosing and branching wide (up to c. 2 km) zone of normal faulting. The main structure forming the Raurimu Fault is downthrown to the east, while an eastern segment near Pokaka is downthrown to the west, defining a small graben between the two strands. As part of this study, we reviewed active fault data for the Raurimu Fault from QMAP (Heron 2018; Townsend et al. 2008), published mapping by Townsend et al. (2017), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Villamor and Berryman 2006b); and re-mapped fault traces using the 1 m DSM.

Previously, only the main continuous strand was defined as the Raurimu Fault, including the branching strands south of the Ohakune Fault (Langridge et al. 2016; Townsend et al. 2008). In this study, all N–S-trending traces have been named as part of the Raurimu Fault, including those in the northwest of Priority Area C; south of Priority Area D; the traces to the east of National Park village (Priority Area D), which were previously unnamed and/or unmapped; and two newly mapped traces to the east of the main southern strand (south of the Ohakune Fault; Priority Area C) (Figures 5.7 and 5.8).

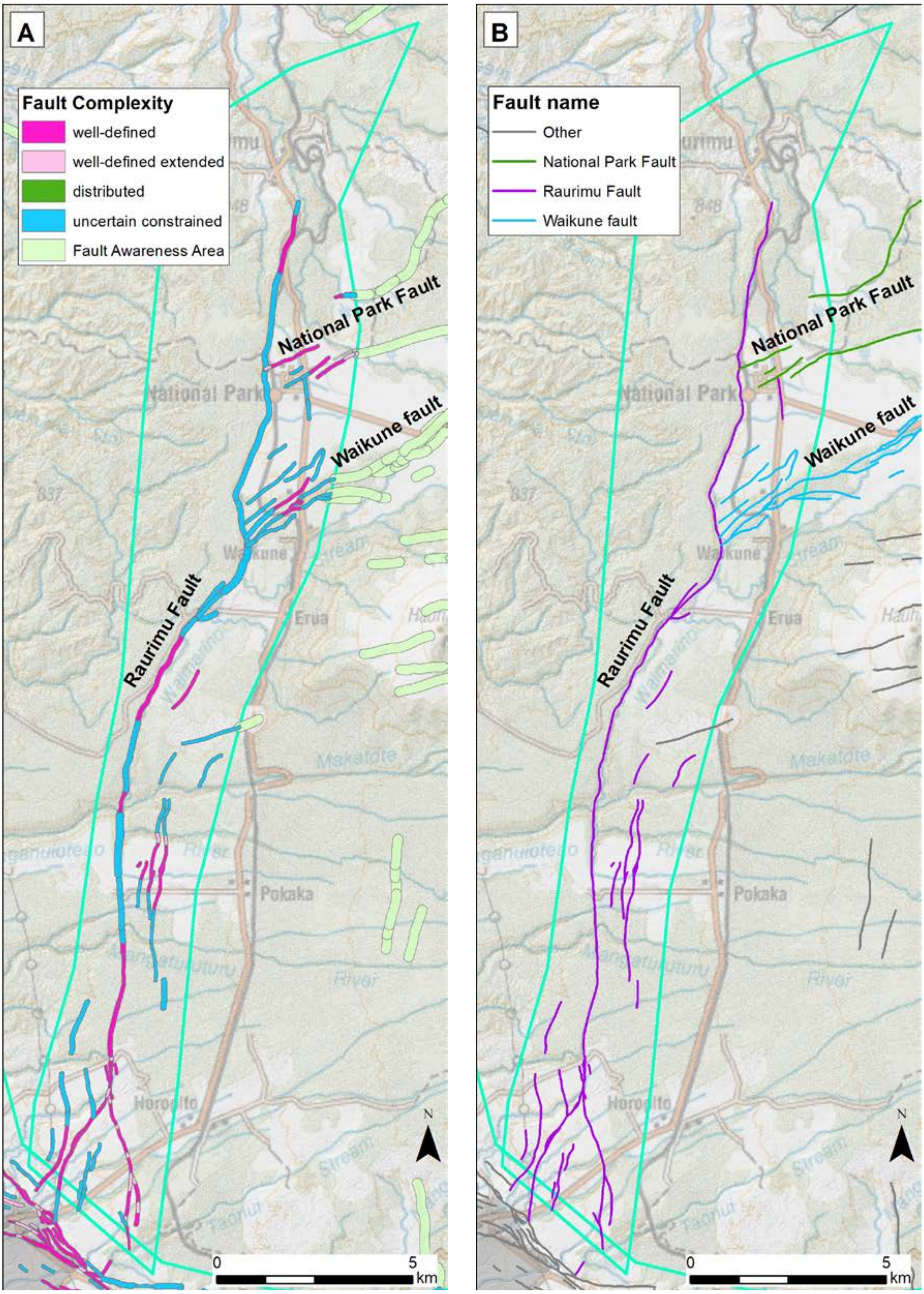

Figure 5.8 Active faults coloured by Fault Complexity (A) and fault name (B) mapped in the north-western Priority Area (Area D) of Ruapehu District, displayed on LiDAR and DSM hillshade models of the area.

The Raurimu Fault forms the western boundary of the Ruapehu Graben and is comprised of a very wide (up to 6 km), complex zone of normal faulting. The main strand north of the Ohakune Fault (Figure 5.8) is sinuous and mapped as entirely continuous; at its southern mapped extent it branches into two main splays near Horopito that are truncated against the Ohakune Fault. At its northern mapped extent, its surface expression on the DSM disappears as it crosses into vegetated hill country underlain by Miocene rocks. Further north of Priority Area D, another continuous, 14-km-long unnamed fault has a similar orientation and dip, and it is possible that that fault connects to the Raurimu Fault. If so, it would increase the total mapped length of the Raurimu Fault to almost 48 km. In the north of Priority Area D, several NE–SW-trending faults branch off the Raurimu Fault at prominent bends: the Waikune fault near the Waikune township and the National Park Fault near National Park village. The strand south of the Ohakune Fault (Figure 5.7) makes a gentle loop across the OIS 6–2 lahar/fan deposits where it is evident as a ‘bulge’ on the fan surface and is truncated by the Raetihi North Fault. There is no evidence of continuation, or any other N–S active structures, south of its intersection with the Raetihi North Fault.

All traces of the Raurimu Fault are mapped as *active*, and it has very clearly defined scarps, particularly in the southern half of Priority Area D and the section south of the Ohakune Fault (Priority Area C), where most are mapped as *accurate*. The majority of the remaining scarps are only expressed as subtle warps, or are obscured by the extensive forested areas, so are mapped as *approximate* or *uncertain*. In the northern half of Priority Area D, the fault forms a distinct scarp, but it is relatively broad here due to the level of erosion and is thus attributed as *approximate* to *uncertain*. The eastern-most trace in Priority Area C is cutting an older surface (119,000–186,000 years old) and is very eroded. The Raurimu Fault has a Fault Complexity of *well-defined, well-defined extended* and *uncertain constrained* (FAZ classification), depending on the width of the feature, level of erosion and vegetation cover.

Raurimu Fault scarp heights south of the Ohakune Fault are typically c. 2–10 m, while to the north they are typically c. 50–80 m high (up to c. 100 m in places). The eastern segment near Pokaka that comprises multiple traces is downthrown overall by c. 30 m (projected) to the west. Villamor and Berryman (2006b) excavated a trench across a 2.8-m-high double-strand trace of the fault that displaces a Holocene terrace at Orautoha Stream. This showed that a 3 ± 0.1 m dip-slip displacement has occurred since 2020 ± 320 cal. yr BP, giving a slip rate of 1.5 ± 0.2 mm/yr. The best estimate of a displacement rate on the Raurimu Fault comes from recent measurements using the regional DSM and slip rate calculations that are in line with others in the southern TVZ (Stirling et al. 2012). A 40.5 m dip-slip displacement (converted from a c. 35 m throw) was found on the Waimarino Formation surface (59,500 ± 14,500 years; Townsend et al. 2017), which gives a new best-estimated slip rate of 0.68 ± 0.19 mm/yr. Using this and the methodology and fault parameters from Stirling et al. (2012), a recurrence interval of 1670 years (1530–1935 years) has been calculated (P Villamor, unpublished data). The Raurimu Fault is thus classified as a RI Class I fault, which is consistent with its mean recurrence interval in the NSHM (c. 760 years; Stirling et al. 2012).

5.4.2 Waikune fault

The Waikune fault branches off the Raurimu Fault just north of the Waikune township in the northern part of Priority Area D (Figure 5.8). It strikes NE–SW out of Priority Area D and has a total length of c. 10 km. It crosses the NIMT Railway and State Highway 4 near its southwest mapped extent, where it is truncated against the Raurimu Fault, and State Highway 47 near its northern mapped extent, where it meets the National Park Fault (Figure 5.8). The structure is predominantly downthrown to the southeast. As part of this study, we reviewed active fault data for the Waikune fault from QMAP (Heron 2018; Townsend et al. 2008), published mapping by Townsend et al. (2017), the NZAFD and the high-resolution GNS active faults dataset (AF.Traces); and re-mapped fault traces using the 1 m DSM.

The fault was previously mapped at a scale of 1:250,000 (Townsend et al. 2008; Heron 2018) and 1:60,000 (Townsend et al. 2017) but remained unnamed, and very little is known about it. It has been redefined during this study and now extends further east than previously mapped. A strand of the fault was previously interpreted to join to the southern end of the National Park Fault, but no evidence of active faulting in this area was observed on the DSM during this study.

The Waikune fault is comprised of a wide (up to c. 2 km), complex, anastomosing zone of normal faulting. The main strand is sinuous and entirely continuous, with segments branching and splaying off the main structure, and there are also several isolated traces mapped. The traces are all attributed as *active*, and, within Priority Area D, they are generally quite subtle and predominantly mapped as *approximate* with an *uncertain constrained* Fault Complexity (FAZ classification). Several clear scarps can be seen crossing the highway just north of the Waikune township, and these have been given a *well-defined* Fault Complexity accordingly. Overall, the maximum throw within Priority Area D is 12 m. Outside of Priority Area D, FAAs have been defined for the Waikune fault.

A recurrence interval has not previously been defined for the Waikune fault. Although its surface expression is not as clearly defined as the nearby RI Class I Raurimu and National Park faults, it has previously been grouped with the National Park Fault Zone in QMAP (Heron 2018). While it is possible that the Waikune fault falls into a range of recurrence intervals (RI Class I–II), our best estimate using current knowledge is that it is a RI Class I fault.

5.4.3 National Park Fault

The National Park Fault includes a series of overlapping splays branching off the Raurimu Fault in National Park village in the northern part of Priority Area D (Figure 5.8). It is a major structure in the district, with a normal sense of slip, forming the western boundary of the Tongariro Graben (Gómez-Vasconcelos et al. 2017). It strikes ENE–WSW out of Priority Area D and has a total length of c. 32 km. It continues into the neighbouring Taupō District (Litchfield et al. 2020) for another c. 13 km and is predominantly downthrown to the southeast. Only the main southern half of the fault has previously been defined as the National Park Fault in the NZAFD and QMAP; however, some of the other traces existed in these databases as an unnamed active fault prior to this study. As part of this study, we reviewed active fault data for the National Park Fault from previously published mapping (Heron 2018; Lee et al. 2011; Townsend et al. 2008, 2017), the NZAFD, the high-resolution GNS active faults dataset (AF.Traces) and previous active fault studies in the area (Gómez-Vasconcelos et al. 2017; Litchfield et al. 2020); and re-mapped fault traces using the 1 m DSM. Only the portion that is within the Priority Area is discussed in this section.

The National Park Fault has been redefined in this study: the southern (main) strand, previously interpreted to cross National Park village and connect to the Raurimu Fault, has been partially removed, and no evidence of the previous N–S strand can be seen on the DSM. The middle two traces have now been mapped further west, where they can be seen to extend into National Park village. In and around National Park village, traces of the fault cross the NIMT Railway and State Highway 4 near its southwest mapped extent, where it is truncated against the Raurimu Fault (Figure 5.8).

All traces in the Priority Area are mapped as *active.* The majority of the scarps are clearly observed, albeit broad, on the DSM and mapped as *accurate* to *approximate* with a *well-defined* to *well-defined extended* Fault Complexity (FAZ classification). Within National Park village, the traces are more subtle due to the level of surface modification in the township and have therefore been defined as *uncertain constrained* Fault Complexity.

Scarp heights on the National Park Fault in the Priority Area are typically 2–10 m, displacing the Waimarino Formation. Outside of the Priority Area, along a northern strand of the fault, vertical displacements of 20 ± 3 m were measured on a c. 25,000-year-old surface and 60 ± 7 m was measured on a 60,000-year-old debris fan surface, which gives a calculated long-term slip rate of 1.1 mm/yr over the last 60,000 years (Gómez-Vasconcelos et al. 2017). In the NSHM, the fault is estimated to have a mean slip rate of 0.2 mm/yr and a mean recurrence interval of c. 2100 years (Stirling et al. 2012). While this falls into a range of recurrence intervals (RI Class I–II), we have assigned the National Park Fault as a RI Class I fault, consistent with the class assigned in the Taupō District by Litchfield et al. (2020), which may be a conservative minimum.

5.4.4 Other Unnamed Faults

One unnamed fault trace is present in the central eastern part of Priority Area D, just north of Pokaka (Figure 5.8). It strikes NE–SW and appears to be part of a similar branching set of faults, albeit less well developed and more eroded, as the Waikune and National Park faults in the north. There are similarly orientated traces mapped further east outside of the Priority Area cutting the flank and plateau associated with the c. 1 million-year-old Hauhungatahi volcano that it may be grouped with. It crosses State Highway 4 between Pokaka and Erua and forms a continuous trace c. 2 km long, with a normal sense of slip, and is downthrown to the southeast. It was originally mapped by Townsend et al. (2017), and only the portion that is within the Priority Area is discussed in this section.

It is mapped as *active* for its entire length and forms an eroded *approximate* scarp, which has been given a Fault Complexity (FAZ classification) of *uncertain constrained* that transitions into a FAA outside of the Priority Area. A recurrence interval has not previously been defined for this trace but, based on its eroded surface expression and proximity and relationship to the Raurimu, Waikune and National Park faults, we conservatively attribute it as a RI Class II fault.

5.5 Other Faults in the District with Fault Awareness Areas

There are many other active faults in the district that have been mapped for the first time or redefined during this study. These include previously named faults such as the Mangamaire, Oruakukuru, Wahianoa, Waihi, Waipuna and Waldegraves faults, as well as other unnamed fault traces. FAAs (Barrell et al. 2015) have been developed for these following the methodology set out in Section 4.5.1, but a detailed discussion or recurrence interval classification is outside the scope of this project.

5.6 Summary of Active Faults with FAZs in Ruapehu District Priority Areas

Table 5.1 summarises the available recurrence interval data for active faults in the Priority Areas within Ruapehu District. We have defined FAZs for all traces mapped within the Priority Areas and FAAs for all other traces outside of the Priority Areas within the District.

The RI Class Confidence is a measure of the quality of the geological data that are used to assess the fault recurrence interval (Table 3.1; Van Dissen et al. 2003). Some faults have detailed slip rate and/or paleoseismic trenching studies that tightly define the RI Class, whereas, for other faults, recurrence intervals might be well-defined yet variable over time or are qualitatively based on observations of landscape or geomorphic deformation. In such cases, the results may span more than one of the recurrence interval classes (e.g. a fault with a recurrence interval range of 1500–4000 years overlaps RI Classes I, II and III), and the mean recurrence interval may be used to assign a RI Class of II; however, the confidence in that assignment is medium or low because the actual recurrence interval range spans three RI Classes.

Table 5.1 Fault Recurrence Interval (RI) information for faults in the Priority Areas within Ruapehu District.

Fault	RI Class	RI Range (Years)	RI Class Confidence	Data Source
National Park Fault	I	≤2000	M	2, 6, 8
Ohakune Fault	I	≤2000	M–H	1, 8, 9
Raetihi North Fault	I	≤2000	M–H	1, 8, 9
Raurimu Fault	I	≤2000	H	1, 8, 9
Upper Waikato Stream Fault	I	≤2000	M	6, 7
Waikune fault	I	≤2000	L	9
Karioi Fault	II	>2000 to ≤ 3500	M–H	1, 8
Moawhango Fault	II	>2000 to ≤ 3500	L	9
Raetihi South Fault	II	>2000 to ≤ 3500	M–H	1, 8, 9
Raetihi Middle fault	II	>2000 to ≤ 3500	M–H	1, 8, 9
Rangipo Fault	II	>2000 to ≤ 3500	H	4, 5, 7
Shawcroft Road Fault	II	>2000 to ≤ 3500	L–M	4, 8
Snowgrass Fault	II	>2000 to ≤ 3500	M	3
Unnamed faults (Priority Areas C and D)	II	>2000 to ≤ 3500	L	9

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

Sources: 1, Villamor and Berryman (2006b); 2, Gómez-Vasconcelos et al. (2017); 3, Langridge and Morgenstern (2020); 4, Villamor et al. (2004); 5, Villamor et al. (2007); 6, Litchfield et al. (2020); 7, Gómez-Vasconcelos et al. (2016); 8, Stirling et al. (2012); 9, this study.

Table 5.1 shows new and updated recurrence interval data for known active faults in the Priority Areas within Ruapehu District. Recurrence interval data for those only defined during this study should be considered preliminary, as they are based on landscape-derived slip rate estimates and on comparison to other nearby faults that have a similar expression in the landscape. In the future, geologic studies, including paleoseismic trenching, could be undertaken to improve estimates of recurrence intervals and RI Classes shown here.

Based on the MfE Active Fault Guidelines (Kerr et al. 2003), which take a risk-based approach formulated around life safety, recommended resource consent categories for activities within the FAZs are given in Tables 5.2 and 5.3. Building Importance Categories and the relationships between RI Class and building importance class from the MfE Active Fault Guidelines are contained in Section 3.4.

Table 5.2 Recommended resource consent categories for **greenfield sites** in relation to Fault Complexity for the Fault Avoidance Zones generated in this study from Kerr et al. (2003).

Greenfield Sites						
Building Importance Category (see Table 3.3 for definitions)		**1**	**2a**	**2b**	**3**	**4**
RI Class	**Fault Complexity**	**Resource Consent Category**				
Upper Waikato Stream, Ohakune, Raetihi North, Raurimu, National Park and Waikune faults						
I <2000 years	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
Rangipo, Shawcroft Road, Karioi, Snowgrass, Raetihi Middle, Raetihi South and Moawhango faults and unnamed faults (Priority Areas C and D)						
II >2000 to ≤3500 years	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

Italics show that the activity status is more flexible. For example, where '*Discretionary*' is indicated, controlled activity status may be considered more suitable.

Table 5.3 Recommended resource consent categories for **developed and already subdivided sites** in relation to Fault Complexity for the Fault Avoidance Zones generated in this study from Kerr et al. (2003).

Developed and Already Subdivided Sites						
Building Importance Category (see Table 3.3 for definitions)		**1**	**2a**	**2b**	**3**	**4**
RI Class	**Fault Complexity**	**Resource Consent Category**				
Upper Waikato Stream, Ohakune, Raetihi North, Raurimu, National Park and Waikune faults						
I <2000 years	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
Rangipo, Shawcroft Road, Karioi, Snowgrass, Raetihi Middle, Raetihi South and Moawhango faults and unnamed faults (Priority Areas C and D)						
II >2000 to ≤3500 years	Well-defined	Permitted	Permitted*	*Non-complying*	*Non-complying*	Non-complying
	Distributed	Permitted	Permitted	*Discretionary*	*Non-complying*	Non-complying
	Uncertain	Permitted	Permitted	*Discretionary*	*Non-complying*	Non-complying

* The recommended resource consent category is permitted but could be controlled or discretionary, given that the fault location is well-defined.

Italics show that the activity status is more flexible. For example, where '*Discretionary*' is indicated, controlled activity status may be considered more suitable.

6.0 CONCLUSIONS

Active fault mapping has been undertaken for Horizons Regional Council covering Ruapehu District for the purposes of planning with regards to active faults. Active faults are those faults considered capable of generating strong earthquake shaking and ground surface fault rupture. A variety of mapping basemaps and techniques have been useful for characterising the location and activity of active faults within the district, including airborne LiDAR data and a regional 1 m Digital Surface Model (DSM), as well as consideration of previous active fault studies in the area. Fault Avoidance Zones and Recurrence Interval (RI) Class information have been provided for all of the active faults within the Priority Areas. Some of these are based on inferences from geomorphic relationships along the faults and through comparisons with better-studied faults nearby, and these carry a lower level of confidence. Outside of the Priority Areas, Fault Awareness Areas have been developed for each of the mapped active faults.

Within the Priority Areas in Ruapehu District, the active faults and fault zones mapped include the Upper Waikato Stream, Ohakune, Raurimu, National Park, Rangipo, Shawcroft Road, Karioi, Snowgrass, Raetihi North, Raetihi Middle, Raetihi South, Moawhango and Waikune faults and are described by area. Several other short unnamed active fault traces are also recognised and mapped. The report also identifies active faults outside of the Priority Areas, for which FAAs have been defined, but a detailed discussion is outside the scope of this project (see Section 1.2). No active folds were identified within the Ruapehu District.

The RI Classes defined in this study for the active faults in Ruapehu District are as follows: Upper Waikato Stream, Ohakune, Raetihi North, Raurimu, National Park and Waikune faults are RI Class I (≤2000 years); and Rangipo, Shawcroft Road, Karioi, Snowgrass, Raetihi Middle, Raetihi South and Moawhango faults and unnamed faults in Priority Areas C and D are RI Class II (>2000 to ≤3500 years).

In future, if development is proposed for areas with a Fault Avoidance Zone or Fault Awareness Area status, it is recommended that further fault mapping and/or geologic studies are undertaken to better define the location, origin, activity and/or nature of surface faulting and deformation. This is particularly the case for Fault Awareness Areas, as their use differs from the other Horizons Region active fault mapping reports.

The outcomes of fault mapping and Fault Avoidance Zone and Fault Awareness Area development are in keeping with the goals of the 'MfE Active Fault Guidelines' (Kerr et al. 2003) and Barrell et al. (2015) and the accompanying GIS products developed in this study can be used at detailed scales for planning purposes, according to those guidelines.

7.0 RECOMMENDATIONS

We recommend that the Fault Avoidance Zones and Fault Awareness Areas developed for Ruapehu District during this study and the RI Class information provided in this report for those faults, along with the MfE Active Fault Guidelines (Kerr et al. 2003), be adopted in future planning decisions regarding development of land on or close to active faults. For use with the MfE Active Fault Guidelines, these then need to be considered for individual planning decisions based on the status of the land (Greenfield vs. Already Developed/Subdivided) and the Building Importance Category intended for the site (see Tables 5.2 and 5.3).

In future, if development is proposed for areas with a Fault Awareness Area status, it is recommended that further fault mapping and/or geologic studies are undertaken to better define the location, origin, activity and/or nature of surface faulting and deformation. This is particularly the case for Fault Awareness Areas in Ruapehu District, as their use differs from the other Horizons Region active fault mapping reports. It is recommended that further work is undertaken to develop Fault Avoidance Zones and RI Class for active faults outside of the Priority Areas that have been mapped or redefined during this study.

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

A caveat to this work is that some of the effort put into developing RI Classes for these faults is preliminary. We recommend that a planned approach is developed between GNS, Horizons Regional Council and funding agencies to attain better geologic constraints on the slip rate, recurrence interval and/or timing of past surface-rupturing earthquakes on some of the active faults described in this report, e.g. the Waikune, Moawhango and Shawcroft Road faults.

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

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APPENDICES

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APPENDIX 1 STYLES OF FAULT MOVEMENT

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

A1.1 Strike-Slip Faults

Strike-slip refers to a style of faulting where the dominant sense of motion is horizontal, and therefore slip occurs along the strike of the fault. Strike-slip faults are defined as either right-lateral (dextral), where the motion on the opposite side of the fault is to the right (Figure A1.1), or left-lateral (sinistral), where the opposite side of the fault moves to the left.

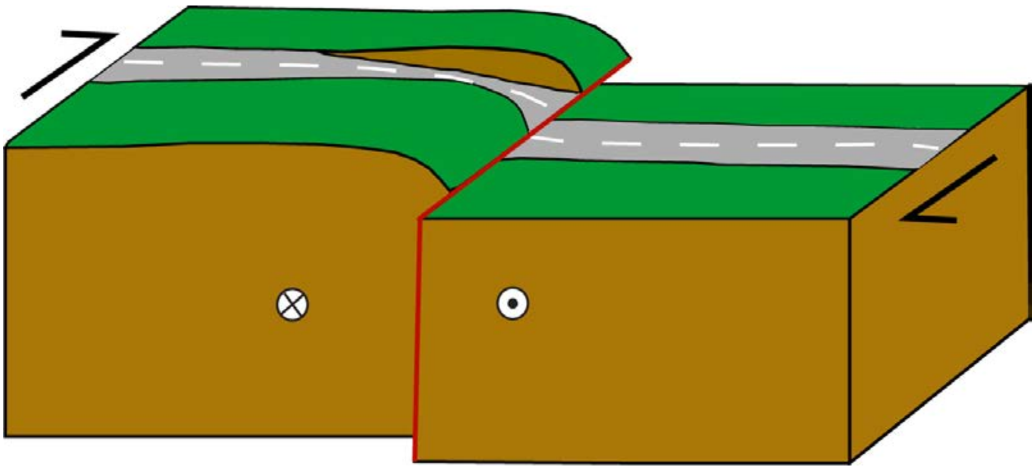

Figure A1.1 Block model of a strike-slip fault (red line). This is a right-lateral (dextral) fault, as shown by the black arrows and by the sense of movement across the two blocks and a separation towards the right across the road. A small amount of vertical movement is also implied by the mappable fault trace and scarp. Symbols on the front of the blocks indicate movement away (circle with cross) and movement towards (circle with dot) the viewer.

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

A1.2 Reverse Faults

Reverse faults form under compression and are characterised by vertical motion of the hanging-wall block up and over the footwall block (Figure A1.2). Reverse faults typically create topography ranging from the scale of a fault scarp, which can be mapped, to a mountain range, e.g. the Seaward Kaikōura Range (Van Dissen and Yeats 1991).

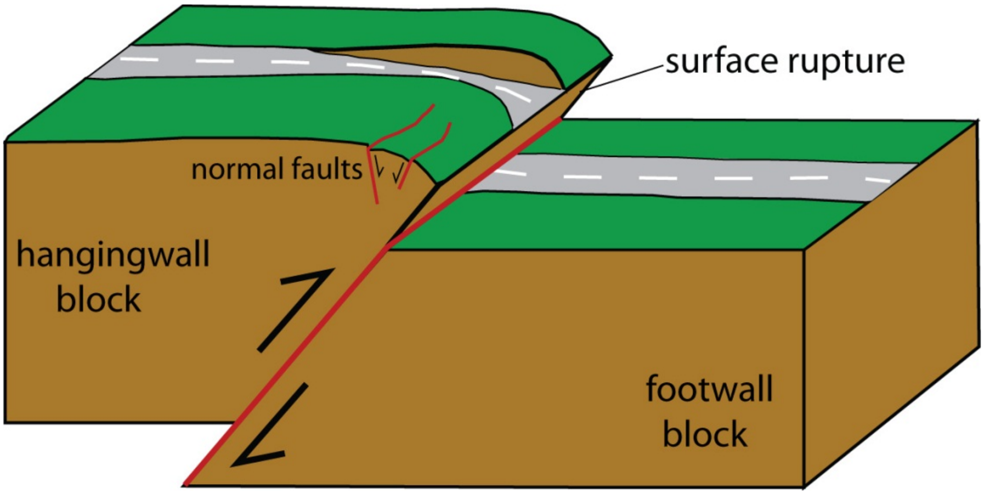

Figure A1.2 Block model of a reverse dip-slip fault that has recently ruptured. Relative movement between the blocks is vertical and along the dip direction of the fault plane. In this case, the hanging-wall block has been pushed up and over the footwall block. Folding (bending) and normal faulting are common features of deformation in the hanging-wall block of reverse faults.

Reverse faulting predominates within the southern and central part of the Horizons region and is often inferred (in cases when no faulting is evident at the surface) through association with active folds (described below). Examples of these include the Leedstown, Himatangi and Rauoterangi faults and the Pohangina Anticline. A common feature of the tectonics in the Horizons Region are these sub-parallel, typically east-directed sheets of reverse and thrust [6] faults that occur in the upper crust above the plate interface, i.e. within the thin upper sliver of the Australian Plate overlying the Hikurangi subduction zone in the eastern North Island (Cashman et al. 1992; Kelsey et al. 1995). Reverse faults have also been mapped off the west coast of the North Island by NIWA (e.g. Nodder et al. 2007).

A1.3 Normal Faults

Normal faults are dip-slip faults that form under conditions of extension and are characterised by downward motion of the hanging-wall block relative to the footwall block along the dip direction (Figure A1.3).

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

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

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

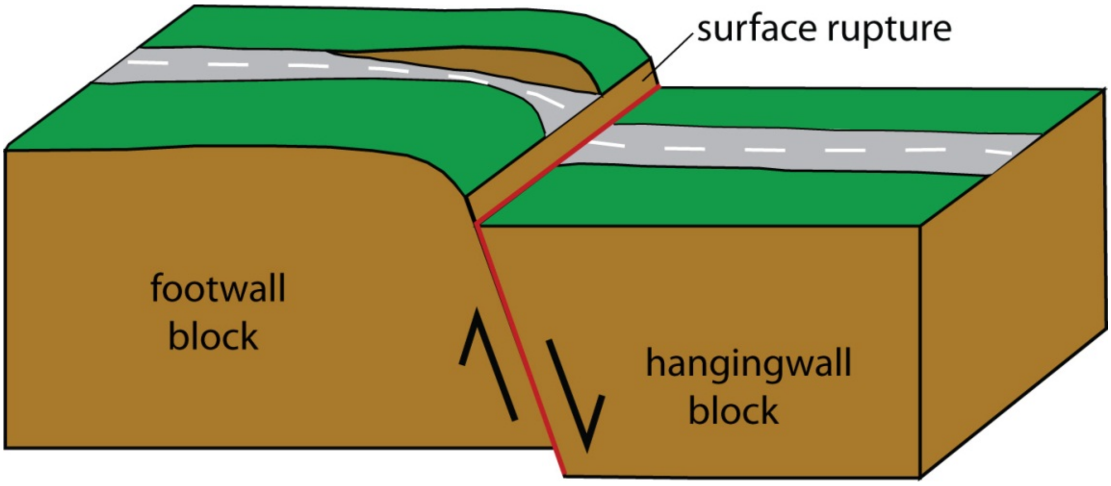

Figure A1.3 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

A1.4 Oblique-Slip Faults

In the New Zealand Active Faults database (NZAFD, Langridge et al. 2016), both the dominant and subordinate (or secondary) sense of fault movement are usually described, e.g. reverse dextral or sinistral normal (in these cases the first descriptor is an adjective). This is useful in New Zealand because of the oblique-compressional (transpressional) tectonics of the Australian-Pacific plate boundary. Faults will typically have a dominant sense; however, in some cases, active faults also have a significant subordinate sense and can be termed oblique-slip faults (Figure A1.4). A good example is the sinistral reverse Papatea Fault, which ruptured in the 2016 Kaikōura Earthquake (Langridge et al. 2018; Litchfield et al. 2018), where several metres of sinistral slip was exceeded by the reverse component of fault motion.

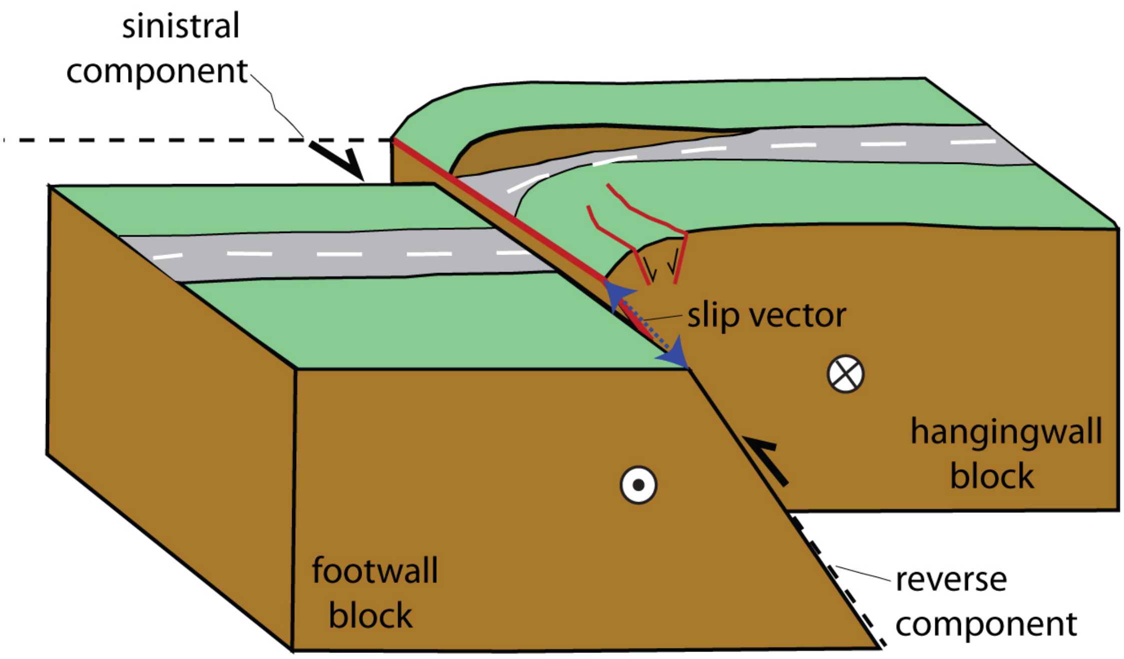

Figure A1.4 Block model of an oblique-slip fault. In this case, the fault is sinistral reverse. The relative movement of the blocks is both vertical (in the dip direction of the fault plane) and strike-slip (in the direction of the strike of the fault), as shown by the oblique blue arrow. Symbols on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

APPENDIX 2 MARINE ISOTOPE STAGES

Table A2.1 Key to name of glacial and interglacial stages for the last c. 300,000 years from Townsend et al. (2017), based on Barrell et al. (2011). Names of South Island stages are shown in brackets. MI/OI refers to Marine (or Oxygen) Isotope Stages as defined by Lisiecki and Raymo (2005).

<table>
<tr><th colspan="2">Glaciation</th><th>Interglaciation</th><th>Approximate Age (ka)</th><th>MI/OI Stage</th></tr>
<tr><td colspan="2">-</td><td>Holocene</td><td>0–11.7</td><td>1</td></tr>
<tr><td colspan="3">Late Glacial</td><td>11.7–14.5</td><td rowspan="2">2</td></tr>
<tr><td rowspan="4">Last (Otira) Glaciation</td><td rowspan="2">Late Last Glacial</td><td rowspan="4">-</td><td rowspan="2">14.5 – ~45</td></tr>
<tr><td rowspan="2">3</td></tr>
<tr><td rowspan="2">Early Last Glacial</td><td rowspan="2">~45 – ~74</td></tr>
<tr><td>4</td></tr>
<tr><td>-</td><td>-</td><td>Last Interglacial</td><td>~74–130</td><td>5</td></tr>
<tr><td>(Waimea)</td><td>Penultimate Glaciation</td><td>-</td><td>~130 – ~190</td><td>6</td></tr>
<tr><td>-</td><td>-</td><td>(Karoro)</td><td>~190 – ~244</td><td>7</td></tr>
<tr><td>(Waimunga)</td><td>-</td><td>-</td><td>~244 – ~303</td><td>8</td></tr>
</table>

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