Updated Alpine Fault mapping and Fault Avoidance Zones for priority areas in the West Coast region

RM Langridge
GL Coffey
R Morgenstern
LB Clarke

GNS Science Consultancy Report 2022/08
July 2022

DISCLAIMER

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited (GNS Science) exclusively for and under contract to West Coast Regional Council. Unless otherwise agreed in writing by GNS Science, GNS Science accepts no responsibility for any use of or reliance on any contents of this report by any person other than West Coast Regional Council and shall not be liable to any person other than West Coast Regional Council, on any ground, for any loss, damage or expense arising from such use or reliance.

Use of Data:

Date that GNS Science can use associated data: July 2022

BIBLIOGRAPHIC REFERENCE

Langridge RM, Morgenstern R, Coffey GL, Clarke LB. 2022. Updated Alpine Fault mapping and fault avoidance zones for priority areas in the West Coast region. Lower Hutt (NZ): GNS Science. 63 p. Consultancy Report 2022/08.

CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

APPENDIX TABLES

EXECUTIVE SUMMARY

GNS Science was commissioned by the West Coast Regional Council (WCRC) to re-evaluate the location and nature of ground-surface rupture hazard posed by the Alpine Fault across the three districts for use within the 'one-district' Te Tai o Poutini Plan (TTPP).

This report provides updated GIS-based active fault location data for 18 specified priority areas where development is present or anticipated This report defines Fault Avoidance Zones (FAZs) for the identified priority areas, created by establishing a buffer zone either side of the known fault trace (or the identified likely fault rupture zone that appears on the land surface). The use of recently acquired airborne Light Detection and Ranging (LiDAR) data for priority areas along the Alpine Fault has resulted in a regionally consistent approach where planning decisions can be applied down to the property scale.

The Alpine Fault ruptures in very large to great earthquakes every 300 years or so, and thus it is a Recurrence Interval (RI) Class I (≤2000 years) fault. Single-event rupture displacement along the Alpine Fault could be up to 9 m, including c. 7 ± 2 m of horizontal movement and 1–2 m of vertical movement. The elapsed time since the last rupture of the Alpine Fault is equivalent to its recurrence interval. This information has been used to derive a 75% probability of rupture in the next 50 years, meaning that there is a significant risk of this event occurring.

The new mapping using the LiDAR data has identified new traces along the Alpine Fault and has allowed for a revision of older mapped features. In some cases, the LiDAR strips cover areas where other named RI Class I faults intersect the Alpine Fault, e.g. the Awatere and Hura faults.

A summary of the 18 priority areas in the Buller, Grey and Westland districts, covering the most-developed parts established along the Alpine Fault in each, are as follows:

- Buller District (Section 3 of this report): three priority areas – Marble Hill, Palmer Flat and Newcombes.
- Grey District (Section 4): three priority areas – Ahaura, Haupiri and Lake Poerua.
- Westland District (Section 5): 12 priority areas – Taipo, Arahura, Hokitika-Styx, Waitaha, Harihari, Whataroa, Franz Josef, Fox Glacier, Paringa, Haast, Okuru and Turnbull.

In defining the FAZ associated with the Alpine Fault (and associated faults), this study follows the principles of the Ministry for the Environment Active Fault Guidelines (MfE Guidelines) related to building on or near active faults. The MfE Guidelines assume a risk-based approach, with a focus on life safety, but also aim to help local authorities minimise the risk and time that it takes for individuals and communities to recover from fault rupture events.

FAZs are supplied with this report in a GIS format. Maps of each priority area with FAZs and Land Information New Zealand 1:50,000-scale building locations are presented in Sections 3–5 of this report. Of the 18 priority areas, the village of Franz Josef is the most developed area located in proximity to the Alpine Fault and therefore has the highest density of mapped building footprints within FAZs. Most of these priority areas have LiDAR coverage. The exceptions are Waitaha, Harihari and Paringa, and, as a result, the accuracy of fault mapping is lower there. Based on a mapping term called 'Fault Complexity', FAZs have been defined with widths of as little as 80 m (well defined) to as wide as 300 m (uncertain poorly constrained) where the fault trace location and breadth of deformation is hard to characterise. Each FAZ includes a 'setback' zone of 20 m around the deformation width buffer (or fault

location uncertainty buffer). The setback provides a margin of safety on the designation of individual FAZs. Site-specific investigation may further refine the FAZs presented in this study.

We recommend that the active faults and FAZs developed in this study be considered the most accurate and up-to-date information locating the Alpine Fault (and other fault traces) and defining associated FAZ buffers. Based on the quality of the data and analysis, these maps should supersede existing active fault datasets for these 18 locations. The FAZs defined in this study are suitable to inform the TTPP and guide future land-use planning decisions. Planning consent decision-making tables from the MfE Guidelines are supplied with this report.

Consideration needs to be given to joining the fault mapping between each of the priority areas to create a continuous Alpine Fault line map and continuum of Alpine Fault FAZs through the region. Future work may also be undertaken to map other active faults in the West Coast region and to provide further engagement to augment the application of the FAZs in areas of critical need.

1.0 INTRODUCTION

1.1 Background and Context

New Zealand lies within the deforming boundary zone between the Australian and Pacific tectonic plates. The area administrated by the West Coast Regional Council (WCRC) straddles one of the more active parts of this boundary zone in the South Island (Figure 1.1). Data collected from the Alpine Fault indicate that it is capable of generating very large (M_W >7.6) to great (M_W >8) earthquakes every 300 years or so (Cochran et al. 2017; Sutherland et al. 2007), with multi-metre surface-rupture displacements (Berryman et al. 2012b; De Pascale et al. 2014). The elapsed time since it ruptured last is close to 300 years. These observations give it a likelihood of 75% of rupturing in the next 50 years (Howarth et al. 2021). Surface rupture along the Alpine Fault will likely occur within a zone of intense ground deformation as opposite sides of the fault move past and over each other during an earthquake. Property damage can be expected, and loss of life may occur where buildings and other structures have been constructed across, or in close proximity to, the fault.

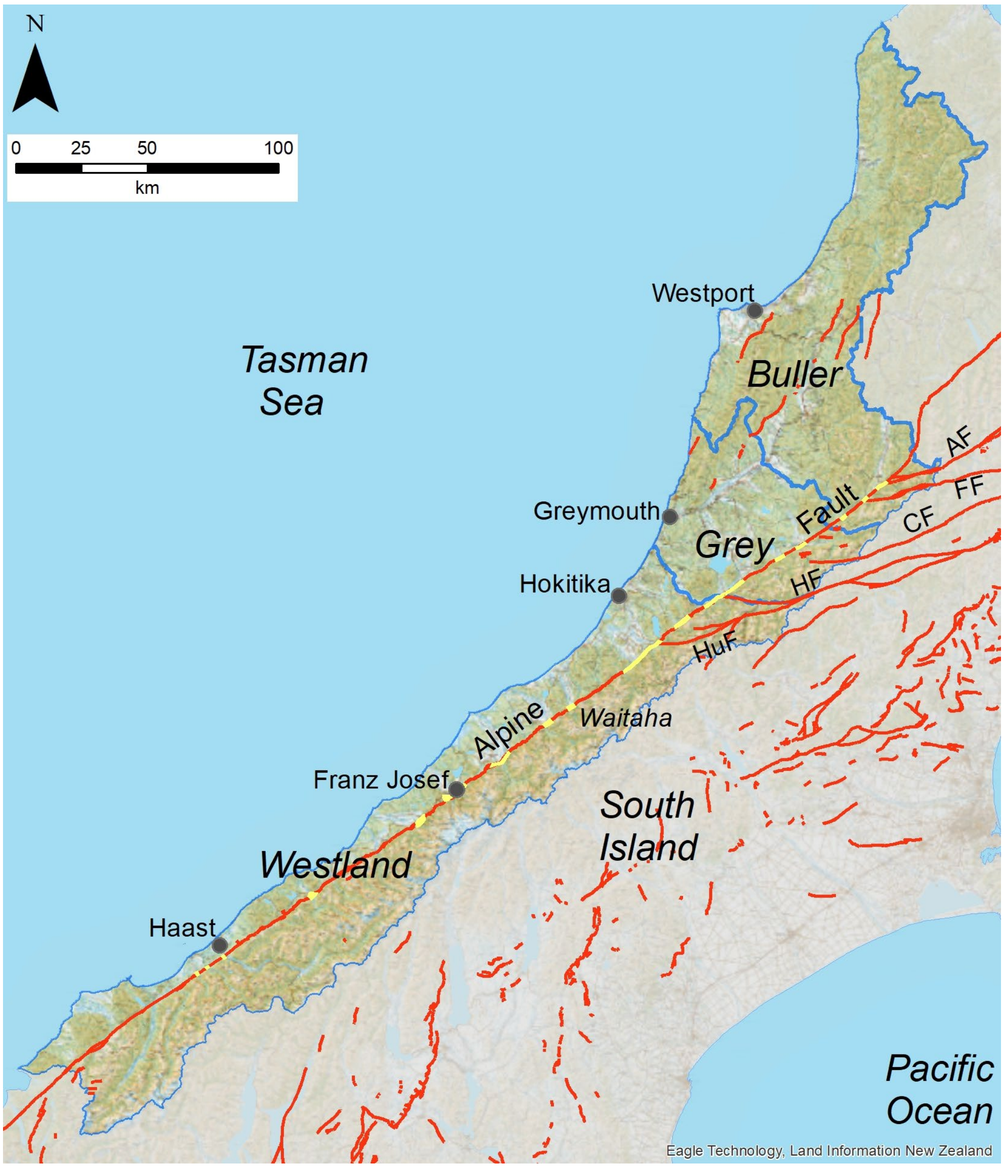

Figure 1.1 The West Coast region (blue outline) highlighting the Alpine Fault and other active faults across the South Island (red lines; source: Langridge et al. 2016b). WCRC priority areas are indicated in yellow. Abbreviations: AF, Awatere Fault; FF, Fowlers Fault; CF, Clarence Fault; HF, Hope Fault; HuF, Hura Fault, which is an extension of the Kelly Fault.

At a regional scale, the entire Alpine Fault was most recently mapped for ground-surface rupture hazard purposes by Langridge and Ries (2010). These authors also provided the first region-wide Fault Avoidance Zones (FAZs) for the Alpine Fault to the WCRC. Local updates to active fault locations and FAZs have been provided for Franz Josef village by Langridge and Beban (2011) and later by Langridge et al. (2016b). However, since then, Light Detection and Ranging (LiDAR) swath data have been acquired for wider parts of the West Coast region, enabling the Alpine Fault to be mapped in detail suitable for land-use planning purposes.

1.2 Objectives and Scope

GNS Science was commissioned by the WCRC to re-evaluate the location and ground-surface rupture hazard posed by the Alpine Fault across its three districts for use within the 'one-district' Te Tai o Poutini Plan (TTPP). The objectives of this report are to provide updated GIS-based active fault location data and FAZ polygons for several priority areas and to provide recommendations around their application.

These priority areas are focused on developed areas ranging from towns to farm settlements and where airborne LiDAR data have previously been acquired along the Alpine Fault since 2014 (Figure 1.1). This study follows the principles of the Ministry for the Environment Active Fault Guidelines (MfE Guidelines) related to building on or near active faults (Kerr et al. 2003[1]). An example of the scope of airborne LiDAR and the priority areas within the Buller District is shown in Figure 1.2.

The key tasks were to:

1. Compare the existing fault mapping for the Alpine Fault with available high-resolution (1 m) LiDAR data and update/modify accordingly for designated priority areas. Priority 1 areas included Franz Josef, Inchbonnie, Haupiri, Springs Junction, Fox Glacier and Whataroa. Additional priority areas were added where LiDAR coverage became available (e.g. Palmer Flat, Ahaura River, Arahura, Haast).
2. Where LiDAR data did not exist for selected priority areas, update the existing fault mapping using other digital tools (such as the WCRC 9 m DSM[2]), or adopt pre-existing mapping. Priority 2 areas included Harihari, Waitaha and Paringa.
3. Develop FAZs for all mapped traces.
4. Review recurrence intervals and attribute information for the Alpine Fault and other active faults where applicable.
5. Document the results in a report (this report), a GIS database and a presentation to councils.

An important goal of the project was to have a useful and useable FAZ product that would facilitate adoption of a region-wide FAZ approach for the Alpine Fault.

---

[1] https://environment.govt.nz/publications/planning-for-development-of-land-on-or-close-to-active-faults-a-guideline-to-assist-resource-management-planners-in-new-zealand/

[2] This refers to a digital surface model (DSM) supplied by the West Coast Regional Council.

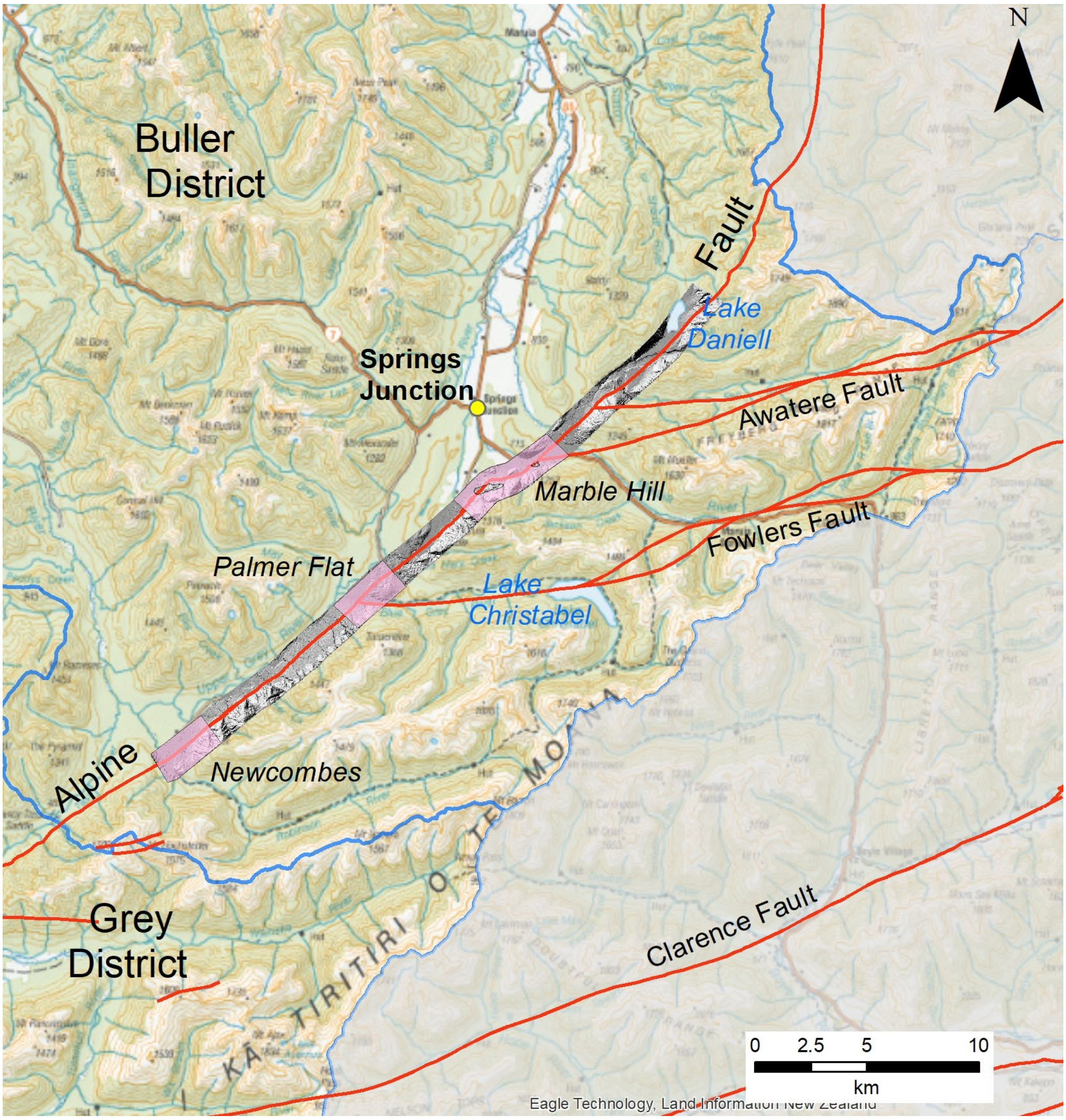

Figure 1.2 Priority mapping areas for the Alpine Fault in the Buller District (pink polygons, names in italics) along a strip of 2014 airborne LiDAR data (grey). Additional mapping was possible for the western end of the Awatere Fault. Red lines are 1:250,000-scale active faults from the New Zealand Active Faults Database (Langridge et al. 2016b).

1.3 Fault Avoidance Zones for Te Tai o Poutini Plan Purposes

Ground-surface rupture hazard is the potential for permanent breakage and buckling of the ground along an active fault[3] that can cause considerable damage to any infrastructure upon or near the fault. However, compared with earthquake shaking, which can be widespread, the likely location of ground-surface rupture hazard can often be located to within a few metres to tens of metres, so potential damage can be avoided or mitigated. Risk-based land-use planning tools are applicable to managing this risk (Saunders et al. 2013). This study utilises FAZs as developed in the MfE Guidelines; the approach is summarised below.

---

[3] See Appendix 1 for definitions and descriptions of types of active faults during an earthquake.

FAZs are a recommended risk-based tool to mitigate surface-rupture hazard and are implemented for land-use planning purposes, as described in the MfE Guidelines (Kerr et al. 2003). The aim of these guidelines is to assist resource management planners tasked with formulating land-use policy and decision-making about development of land on, or near, active faults. The MfE Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas subject to ground-surface fault rupture hazard. We note that the MfE Guidelines represent the most recent national guidance for land-use planning. In these guidelines, the surface-rupture hazard of an active fault at a specific location is characterised by two parameters:

1. Location/complexity of surface rupture of the fault.
2. Activity of the fault, as measured by its average recurrence interval of surface rupture.

The MfE Guidelines also advance a hierarchical relationship between fault Recurrence Interval (RI) Class and Building Importance Category (BIC), such that the greater the importance of a structure with respect to life safety and recovery planning, the longer the recurrence interval of the fault is required before a plan should enable construction (Appendix 2). For example, only low-occupancy structures, such as farm sheds and fences (i.e. BIC 1 structures), are permitted across active faults with average recurrence intervals of surface rupture less than 2000 years (i.e. RI Class I). As another example, in a ‘greenfield’ (i.e. undeveloped) setting, while residential buildings are permitted, more significant structures such as schools, airport terminals and large hotels (i.e. BIC 3 structures) are not permitted across faults with average recurrence intervals shorter than 10,000 years (i.e. RI Class ≤IV), depending on the local Fault Complexity.

Applying a risk-based approach, priority areas have been agreed between GNS Science and the WCRC that reflect where settlements exist and where further development pressures are anticipated. We have developed FAZs for 18 priority areas through the three West Coast districts. Three of these are in Buller District (Section 3), three are in Grey District (Section 4) and 12 are in Westland District (Section 5). Maps shown in Sections 3–5 indicate not only the FAZs designed for priority areas but also known building locations from the 1:50,000-scale Land Information New Zealand (LINZ) topographic series within and adjacent to these FAZs. FAZ mapping and identification at these locations is therefore the focus of this report.

A key feature of FAZs is that they are developed in accordance with detailed mapping of the surface expression of active faults. These maps are usually compiled at scales of 1:1000–1:18,000, which is appropriate for cadastral purposes. A description of the construction of FAZs is contained in Section 2.3.

1.4 Report Contents and Layout

This report summarises the results of this project and describes the active fault (GIS) map data provided.

- Section 2 describes the methodology for mapping active faults, developing FAZs and using RI Classes.
- Section 3 describes the results for Priority Areas in Buller District.
- Section 4 describes the results for Priority Areas in Grey District.
- Section 5 describes the results for Priority Areas in Westland District.

- Section 6 outlines how the results from Sections 3–5 can be applied by the three districts. This section contains example FAZ Resource Consent Category tables for the RI Class I Alpine Fault.
- Section 7 provides a summary of the information in this report, and Section 8 provides recommendations for use of the data and future work.
- The report appendices contain sections on active fault definitions (Appendix 1), tables from the MfE Guidelines for Building Importance and Recurrence Interval and FAZ Resource Consent Category tables (Appendix 2).

2.0 METHODOLOGY

2.1 Data Sources

A review was undertaken of existing sources of data for the Alpine Fault and adjacent active faults in the West Coast region, including:

1. The high-resolution version of the New Zealand Active Faults Database.
2. The 1:250,000-scale version of the New Zealand Active Faults Database (Langridge et al. 2016; http://data.gns.cri.nz/af/), which is largely derived from the 1:250,000 Geological Map of New Zealand (QMAP; see Heron 2020).
3. Published papers, maps and GNS Science reports, including more detailed digital geology data from the compilation of QMAP.
4. Unpublished GNS Science consultancy reports.
5. The authors' first-hand knowledge of the geology and active faulting in the district.

Arguably, the most important data source for state-of-the-art detailed fault mapping studies are Digital Elevation Models (DEMs) and Digital Surface Models (DSMs). The two main sources of these come from regional airborne LiDAR surveys (DEMs) and from regional photogrammetry (DSMs). The following are sources of LiDAR for this study:

1. The first LIDAR acquisition along the Alpine Fault in 2010, funded by the Natural Hazards Research Platform (NHRP), spanning the Franz Josef to Whataroa areas (see Langridge et al. 2014).
2. A set of four NHRP-funded LiDAR strips spanning the northern and central Alpine Fault between the Springs Junction and Hokitika areas (see Langridge and Howarth 2018).
3. Additional LiDAR projects flown along the Fox and Waiho rivers in central Westland for ongoing flood protection and landslide hazard projects.
4. A 2020 National Science Foundation (NSF)-funded LiDAR acquisition spanning the northern Fiordland to Haast areas (the data is owned by Dr Nic Barth, University of California, Riverside).
5. Additional LiDAR acquired by the WCRC as part of the Provincial Growth Fund (PGF) project. This acquisition was useful for mapping the Arahura priority area.

The LiDAR datasets used in this study are DEMs and hillshade models (illuminated from the northwest and northeast), with ground-pixel resolution varying between 1 and 3 m (Langridge et al. 2014). This resolution allows geomorphic features to be mapped at a level of detail suitable for identifying fault traces and defining FAZs at a scale that can be utilised for land-use planning purposes. The WCRC also supplied a 2017 9 m DSM developed from photogrammetry, which was used to map active faults in priority areas that did not have LiDAR coverage. ESRI orthophoto-mosaics were also utilised to help define landforms.

2.2 Mapping and Attributing Active Fault Traces

An active fault is a plane of weakness in the Earth's crust that has the potential to break under plate tectonic stresses. On a broad scale and at depth, these faults may be thought of as a single plane, but, in detail, and particularly near the ground surface, faults are commonly made up of multiple parallel and/or overlapping fault structures. A fault trace is the intersection of a fault plane with the ground surface, as this may inform the likely location of future displacement (permanent ground deformation) on that fault and also its activity. For this report, traces have been mapped using the digital hillshade models, and they are most commonly evident as fault scarps, which range from relatively sharp to more rounded or subtle. These more-rounded fault scarps may reflect erosion or possibly folding and distributed deformation rather than discrete surface rupture (faulting). Traces are generally best preserved on low-lying river terraces and fans, but, in other places, such as hillslopes, fault scarps may be eroded, and traces are often expressed instead as guided drainages and aligned topography. Fault scarps may also be destroyed by river erosion or, alternatively, buried by younger river alluvium, landslides deposits or anthropogenic fill. Where there are gaps between faulted features that lack topographic evidence of faulting but there is certainty that the fault exists, traces are inferred using a straight line or a geometrically reasonable curve.

The accuracy with which the location of an active fault trace can be captured in a database is influenced by two types of uncertainty or error. The first is the error associated with how accurately the feature can be located on the ground. The second is the error associated with capturing that position into the database.

Where fault features are preserved, the Accuracy (Table 2.1) with which the fault can be located on the ground depends on the type of feature. A fault scarp is one of the more diagnostic features that can be used to define the location of a fault. For example, the scarp of the Alpine Fault is, in some places, sharp and distinct (less than about 10 m wide), and here it is possible to define the location of the fault quite accurately.

Table 2.1 Attributes for mapped active fault traces along the Alpine Fault used for the purposes of developing Fault Avoidance Zones.

Attribute	Field Name	Definition
Fault Name	Fault_name	The name given to an active fault.
Accuracy	Accuracy	Locational accuracy of the fault on the ground surface (accurate, approximate or uncertain).
Activity	Activity	Activity of the fault (active or possibly active).
Dominant Slip Type	DOM_SLIPTY	Dominant or primary sense of movement on the fault (dextral, normal or reverse – see Appendix 1 for definitions).
Subordinate Slip Type	SUB_SLIPTY	Subordinate or secondary sense of movement on the fault (dextral, normal or reverse – see Appendix 1 for definitions).
Down-thrown Quadrant	DOWN_QUAD	The direction of the down-thrown side of the fault described in terms of compass quadrants.
Mapping Method	Method	The method used for locating the fault trace (e.g. LiDAR).
Tectonic Origin	Tect_orig	Certainty that the feature is of tectonic (i.e. earthquake) origin (definite, likely or possible).
Fault Complexity	Fault_comp	The Fault Complexity classification used by the MfE Guidelines based on the width and distribution of the deformed land around the fault trace (well defined, well-defined extended, uncertain constrained, uncertain poorly constrained or distributed – see Table 2.2 for further details).

However, in other places, the fault trace may be associated with a broad or ill-defined topographic feature (e.g. saddle or fault-guided valley) expressed over a width of tens of metres or more. Without additional investigations at these sites, the position of the fault cannot be mapped more accurately than the distinctness/sharpness of the topographic expression of the fault feature. So, even when topographic fault features are preserved, the ability to use these features to define the precise location of the fault, and therefore future surface-rupture hazard, varies according to the distinctness of the feature itself. The width of the fault feature is captured in the Deformation Width field (Deform_wid). The attributes assigned to each fault trace are listed in Table 2.1.

An additional uncertainty with regard to using topographic fault features to define the location of surface-rupture hazards based on past ruptures is that the preservation potential of fault scarps and other fault-generated topographic features typically varies according to size. That is, a large scarp or displacement is more likely to be preserved in the landscape than a small scarp or displacement. So, even when a distinct fault feature is identified at a site, it is possible that smaller, but still life-threatening, displacements occurred elsewhere but are now no longer preserved in the landscape. Thus, the identified fault feature may not indicate or record the true scale of fault-rupture hazard at a site. As is discussed in more detail in Section 2.3, this type of uncertainty is typically addressed by prescribing a 20 m ‘setback’ distance either side of the fault.

The error associated with capturing the position in the database refers to the errors introduced in the transfer of the fault location to a map. In this study, most traces were mapped in a GIS using LiDAR data, so this uncertainty is considered to be relatively small (3 m) and consistent for all traces. In this study, we have subsumed this into the overall location uncertainty.

Another important uncertainty for the mapped features is whether they are in fact active fault traces or could have formed by some other geologic process, such as river or lake erosion. This uncertainty is captured in the Tectonic Origin attribute and is an expert assessment of confidence in whether the feature has formed as a result of ground-surface rupture. As a result, a narrow trace may be accurately mapped along a feature using the LiDAR data, but this does not necessarily mean that it is an active fault.

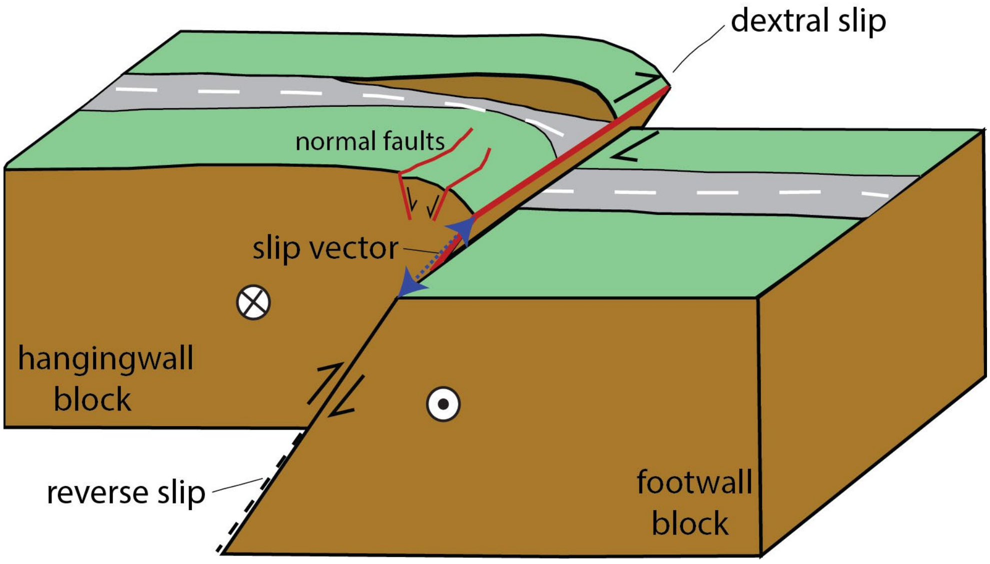

Figure 2.1 Block model of a reverse dextral fault (red line) such as the Alpine Fault. The dominant motion on the fault is horizontal movement, as shown by the pair of black arrows. The dextral sense of movement across the blocks is shown by the road offset and away/toward markers. The reverse sense of motion causes the hanging wall to go up and across the footwall block (the ground shortens). Normal faulting can occur in the hanging-wall block due to bending of the ground. The slip vector (blue arrows) matches points that were together prior to displacement.

The style of the fault movements on the Alpine Fault is reverse dextral (Figure 2.1). In this terminology, ‘dextral’ (right-lateral) is the dominant sense of movement and ‘reverse’ is the secondary sense of movement. This means that, in general, the Alpine Fault slips horizontally but with some uplift that occurs on the southeastern, hanging-wall side of the fault. In some cases, normal (extensional) fault movement is possible on traces mapped on the hanging-wall side of the fault.

Table 2.2 Definitions of Fault Complexity terms, adapted from the MfE Guidelines (Kerr et al. 2003).

Fault Complexity	Definition
Well defined	Fault rupture deformation is well defined and of limited geographic width (e.g. metres to tens of metres wide).
Well-defined extended	Fault rupture deformation has been either buried or eroded over short distances, but its position is tightly constrained by the presence of nearby distinct fault features.
Distributed	Fault rupture deformation is distributed over a relatively broad, but defined, geographic width (e.g. tens to hundreds of metres wide), typically as multiple fault traces and/or folds.
Uncertain constrained	Areas where the location of fault rupture is uncertain because evidence has been either buried or eroded, but where the location of fault rupture can be constrained to a reasonable geographic extent (≤300 m).
Uncertain poorly constrained	The location of fault rupture deformation is uncertain and cannot be constrained to lie within a zone less than 300 m wide, usually because evidence of deformation has been either buried or eroded away or the features used to define the fault’s location are widely spaced and/or very broad in nature.

Adjacent to several of the priority areas, e.g. Haupiri River, Lake Poerua, Taipo, we have noted significant structure within the hanging wall of the Alpine Fault. The lineaments mapped more than 300 m to the southeast of the main Alpine Fault are considered to be related to secondary bedrock structure within the mylonite zone of the Alpine Schist. As such, we made a decision to not include these as part of this FAZ study. While they are clearly related to Holocene deformation (they must have formed following glacial retreat), we cannot intimately link them to the Alpine Fault and have no recurrence interval information on them.

2.3 Defining Fault Avoidance Zones

FAZs are created by mapping the location of faults and developing a buffer around them that incorporates both the hazard and the uncertainty. In practice, faults can be mapped where they have repeatedly ruptured in the past and therefore can be expected to rupture in the future. These fault deformation zones – essentially, FAZs – define the likely rupture zone of faults, i.e. the ground-surface location that will be displaced when a fault ruptures.

The deformation zones are themselves generated from buffers surrounding the detailed fault mapping linework. The lines represent the best estimate location of a main fault line itself, with the width of these zones generally determined by an expert assessment of fault location accuracy and the Fault Complexity (secondary or distributed faulting), as well as the resolution and georeferencing uncertainty of the data.

As is suggested in the MfE Guidelines, a FAZ is created by defining a ‘Likely Fault Rupture Zone’ buffered by an additional 20 m ‘setback zone’. This additional 20 m accommodates the possibility of secondary deformation and ruptures that can occur close to primary fault ruptures.

Along the Alpine Fault, the ‘Likely Fault Rupture Zone’ is defined by buffering the mapped traces using the Deformation Width (Figure 2.2). In this study, we have treated the Alpine Fault as a reverse dextral fault[4], i.e. it is primarily a dextral-slip fault with a secondary component of reverse motion. Therefore, we have adopted in this project a symmetrical buffer approach for strike-slip faults. This is in part due to the sheer number of mapped fault traces, acknowledging that the Alpine Fault is dominantly dextral-slip, and treating the dip-slip component (reverse or normal) as the secondary component of deformation for any given fault feature within the deformation zone. The Likely Fault Rupture Zone is then buffered (using the Buffer Distance), and 20 m is added either side to account for the setback zone. The combined area under the total buffer is then termed the FAZ (Figure 2.2).

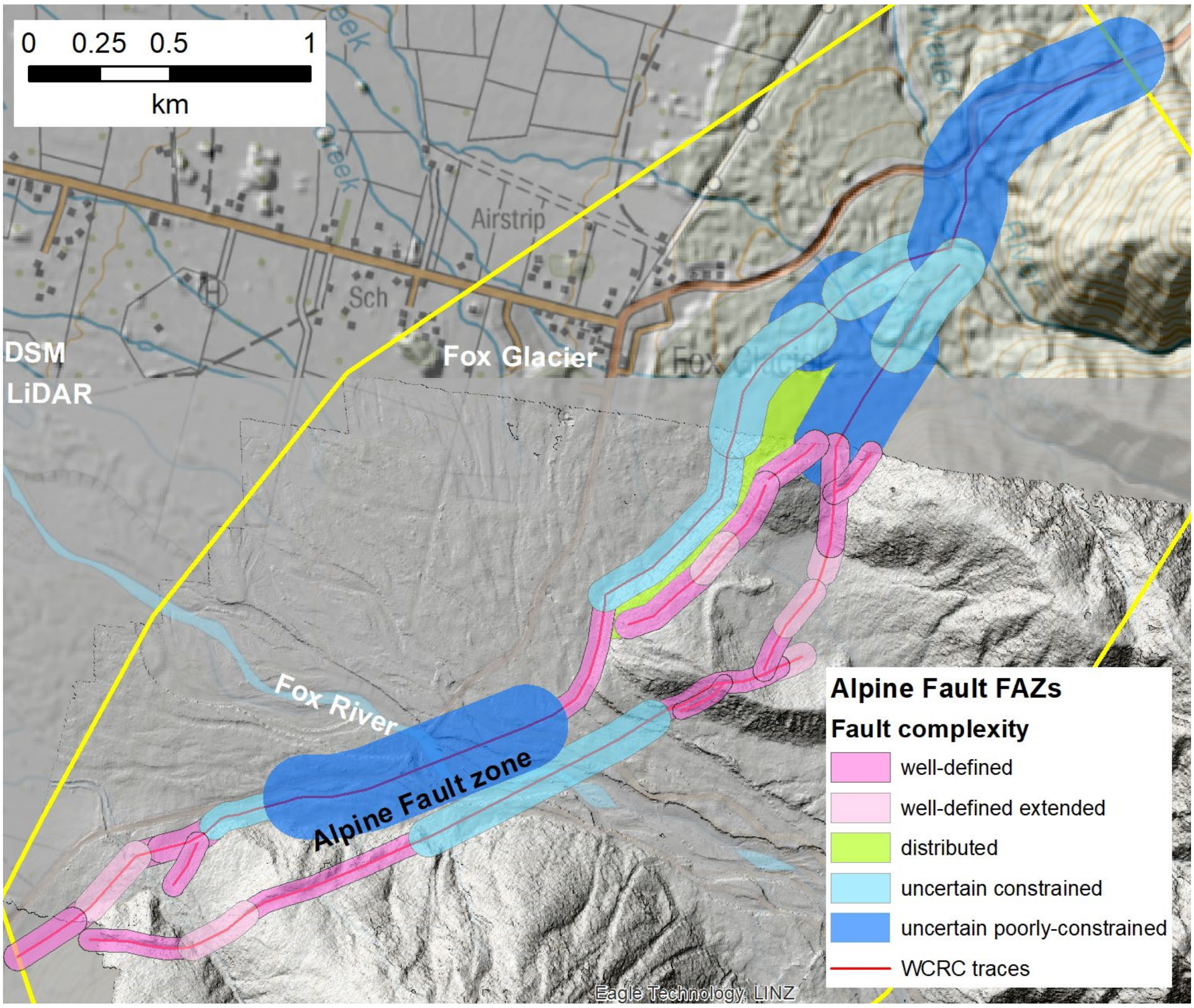

Figure 2.2 Fault trace mapping (red lines bisecting Fault Avoidance Zones [FAZs]) and development of FAZs for the Fox Glacier priority area (yellow outline). Mapping was undertaken on a LiDAR hillshade model (south) and a DSM (north). FAZs are classified by Fault Complexity (Fault_comp). See text and Table 2.2 for details. Other maps presented in this report do not show the fault line data because the focus of this report is on FAZs.

Surface-rupture Fault Complexity is an important parameter used in the MfE Guidelines to define rupture hazard at a site and was defined for all areas where a FAZ was constructed in this study. When fault-rupture deformation is distributed over a wide area, the amount of deformation at a specific point within the distributed zone is less compared to where the

---

[4] This is a departure from previous studies (e.g. Langridge and Ries [2010]; Langridge and Beban [2011]), where some Alpine Faut traces were treated as dominantly reverse-slip faults and were double-buffered on their upthrown side to account for an increased component of deformation on the hanging-wall side of the fault.

deformation is concentrated on a single well-defined trace. The relative fault-rupture hazard/ risk is therefore less within a zone of distributed deformation than within a narrow well-defined zone. In some areas, we have defined distributed deformation (see green field on Figure 2.2) as a zone that fills a narrow strip between two better-defined FAZ buffers. This reflects the fact that there is likely to be some faults deformation (minor faulting, warping) between more active, sub-parallel zones of faulting.

Table 2.2 lists the Fault Complexity terms and definitions used for FAZs throughout the rest of the report, including tables and figures. These Fault Complexity terms link directly into Resource Consent Category tables for the MfE Guidelines (Section 6.4 and Appendix 2). These are also the same definitions used in similar active fault mapping projects elsewhere throughout the country (e.g. Kāpiti, Upper Hutt, Porirua, Horizons Region, Kaikōura and Taupō districts; Van Dissen and Heron 2003; Van Dissen et al. 2005; Langridge and Morgenstern 2019, 2020a, 2020b; Litchfield et al. 2019, 2020; Townsend and Litchfield 2020; Langridge et al. 2021a; Morgenstern and Townsend 2021).

A lower level of planning control for ground-surface-rupture hazard along active fault zones was initiated by Fault Awareness Areas (FAAs; Barrell et al. 2015). FAAs were originally developed for districts within the Canterbury region from 1:250,000-scale fault maps produced for each district within the region (e.g. Barrell and Townsend 2012). The scale of such maps is not appropriate to define FAZs; however, Canterbury Regional Council (Environment Canterbury) requested an alternative way by which preliminary decisions could be made around those faults that were not mapped in detail.

For three reasons, we have not adopted the concept of FAAs in this project. First, FAZs were already defined for the entire Alpine Fault in the original (and subsequent) WCRC fault rupture hazard reports (Langridge and Ries 2010; Langridge et al. 2016a). Second, this project relies almost entirely on high-resolution LiDAR data and the mapping is undertaken at detailed scales. Third, the Alpine Fault is a RI Class I fault and so should be treated as a high hazard, with appropriate planning decisions made along its entire length.

2.4 Recurrence Interval Classes

The average recurrence interval of surface rupture is the average number of years between successive ground-surface-rupturing earthquakes along a specific section or length of fault. Typically, the longer the average recurrence interval of surface rupture on a fault, the less likely the fault is to rupture in the near future. Likelihood of rupture is also a function of other variables, such as elapsed time since the last rupture of the fault, and the size, style and timing of large earthquakes on other nearby faults; however, these variables are not used to define rupture hazard in the MfE Guidelines. Broadly speaking, a fault with a long recurrence interval typically poses less of a hazard than one with a short recurrence interval. In the MfE Guidelines, active faults are grouped according to RI Class (Table 2.3) such that the most hazardous faults, i.e. those with the shortest recurrence intervals, are grouped within RI Class I. The next most active group of faults are those within RI Class II, and so on.

Table 2.3 Definition of Recurrence Interval (RI) Classes from the MfE Guidelines, with some examples of RI Class for faults in New Zealand (**bold**, within the WCRC).

RI Class	Average RI of Surface Rupture	Examples of Faults in New Zealand
I	≤2000 years	**Alpine**, **Hope**, **Awatere**, Wellington
II	>2000 to ≤3500 years	**Fowlers**, Elliott, Ohariu, Masterton
III	>3500 to ≤5000 years	Poulter, Waimea, Akatarawa, Rangefront
IV	>5000 to ≤10,000 years	**Lyell**, **Lower Buller**, Rauoterangi, Ruataniwha
V	>10,000 to ≤20,000 years	Pisa, Greendale, **White Creek**, Whitemans Valley
VI	>20,000 to ≤125,000 years	-

The RI Class for the Alpine Fault is well established as RI Class I (≤2000 years). This means that a large surface-rupturing earthquake can be expected every 2000 years or less. On-fault and off-fault paleoseismic studies along the Alpine Fault indicate that the recurrence interval of faulting is 300 years or less (Berryman et al. 2012a, 2012b; Cochran et al. 2017; Howarth et al. 2018, 2021). The most recent rupture of the central section of the Alpine Fault (spanning the Westland district) is considered to have occurred around 1717 CE (Wells et al. 1999; Yetton and Wells 2010; Howarth et al. 2018). The probability of a large to great earthquake occurring on the Alpine Fault is currently 75% in the next 50 years (Howarth et al. 2021), highlighting the importance of mitigating against surface-rupture hazard.

Strike-slip faults of the Marlborough Fault System (MFS) join into the Alpine Fault from the east and have been mapped in some of the northern priority areas where applicable, e.g. the Awatere and Hura faults (Figure 1.1). Active fault data for the Awatere and Hura (a branch of the Kelly Fault) faults place these in RI Class I (Van Dissen et al. 2003; Litchfield et al. 2014; Vermeer et al., submitted).

3.0 PRIORITY AREA MAPPING IN BULLER DISTRICT

Three priority areas were defined for the Alpine Fault within the Buller District (Figure 1.2), which are described below. In each of the maps, we have shown the known building locations from the 1:50,000 topographic map series (data from LINZ Topo 50). These are mainly BIC 1 and sometimes BIC 2 structures and highlight the proximity of buildings to FAZ.

3.1 Marble Hill Priority Area

The Marble Hill priority area is located c. 3 km southeast of the village of Springs Junction (Figure 3.1). Dextral-slip traces of the Alpine Fault have been mapped through the priority area, which straddles the fault for c. 5 km from the Maruia River southwest to the end of Hunters Road. At its northeast end, the priority area occurs within the Marble Hill Conservation Area (Figure 3.2). Geologic studies in this Department of Conservation (DOC) area have defined a dextral slip rate of 10 ± 2 mm/yr, with up to four paleoseismic ruptures during the last 1800 years or so (Langridge and Howarth 2018; Langridge et al. 2017).

Southwest of State Highway 7 (SH 7), the Alpine Fault is mapped at the fringe between native forest and farmland associated with the Lewis Pass Motel property. Southwest beyond that, the fault largely crosses through native forest above farming properties adjacent to Hunters Road. At least two significant landslides and their deposits occur along this range front and thus the fault is difficult to map across this terrain, as indicated by the uncertain fault locations.

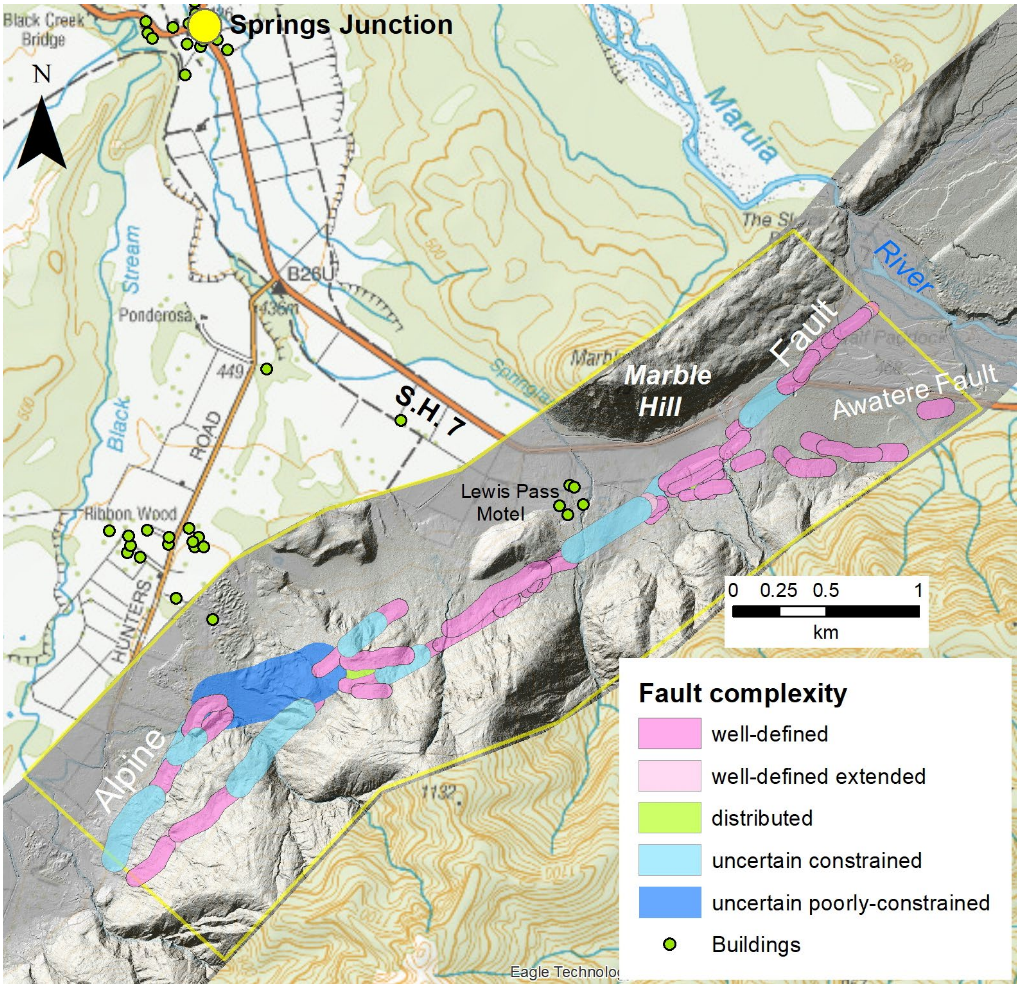

Figure 3.1 Fault Avoidance Zones in the Marble Hill priority area (yellow box) near Springs Junction include traces of both the Alpine and Awatere faults. Fault traces are not shown in this view. Buildings are from LINZ Topo 50 digital map data.

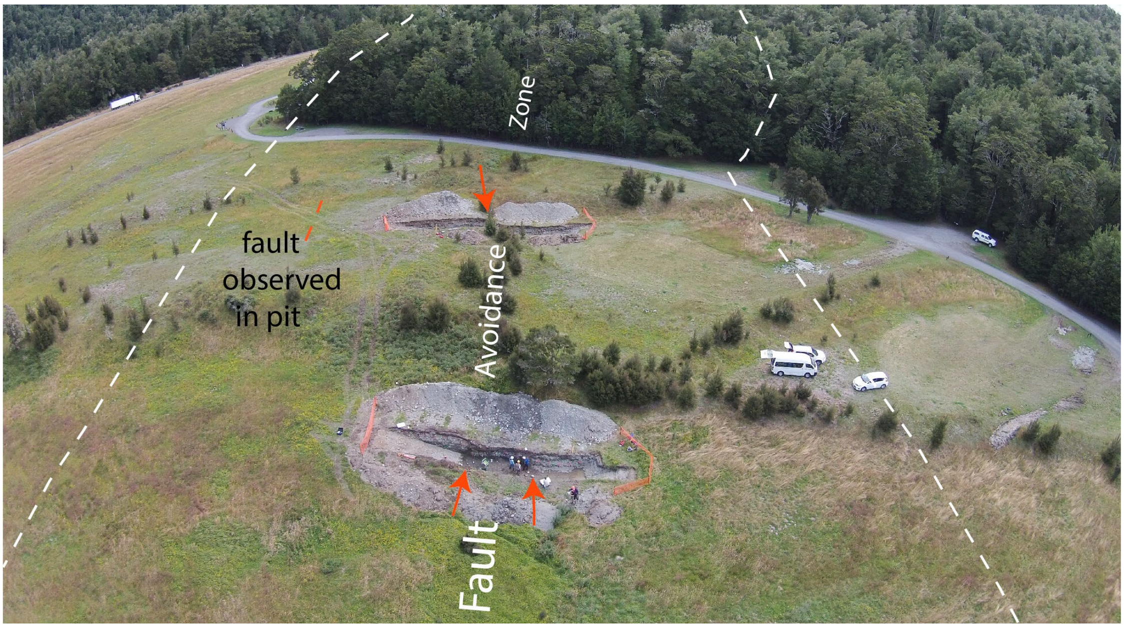

Figure 3.2 Example of a Fault Avoidance Zone (FAZ; white dashed area) in practice at Marble Hill. Mapping indicates a well-defined fault trace, and the FAZ here has a total width of 80 m. Trenches reveal one or two rupture traces (arrows), and a minor fault was recognised in a pit dug previously and adjacent to the trench in the background.

South of SH 7 and Marble Hill, we have mapped several traces that we associate with the southwestern end of the strike-slip Awatere Fault, which is one of the main faults of the MFS (Litchfield et al. 2014). The Awatere Fault is designated with a RI Class I status (Langridge et al. 2016b), so, in terms of the MfE Guidelines, it can be treated in the same way as the Alpine Fault.

In the Marble Hill priority area, FAZ buffers range in width from a minimum of 60 m for accurate, well-defined traces to up to 160 m for uncertain poorly constrained traces (Figure 3.1). In the example shown in Figure 3.2, it may be possible to reduce the width of the FAZs indicated by considering the data from the paleoseismic trenches excavated there.

3.2 Palmer Flat and Newcombes Priority Areas

The Palmer Flat and Newcombes priority areas both occur adjacent to Palmers Road, southwest of Springs Junction. The Alpine Fault runs through these areas, though locally there is limited development. The majority of this part of the priority area is covered in native forest on DOC conservation lands, and, currently, the main land-use in cleared areas is farming.

The new mapping in this study using the LiDAR data shows that the Alpine Fault is more complex than previously mapped, with multiple dextral-slip traces mostly assigned a well-defined Fault Complexity. For the Palmer Flat priority area (Figure 3.3), we mapped a 3 km length spanning where the Blue Grey River flows out across the fault. The fault is mostly characterised by a northeast-trending scarp with several mappable traces (Figure 3.4). At the southwestern end of the priority area, the fault traces take on a right-stepping ‘*en echelon*’ character.

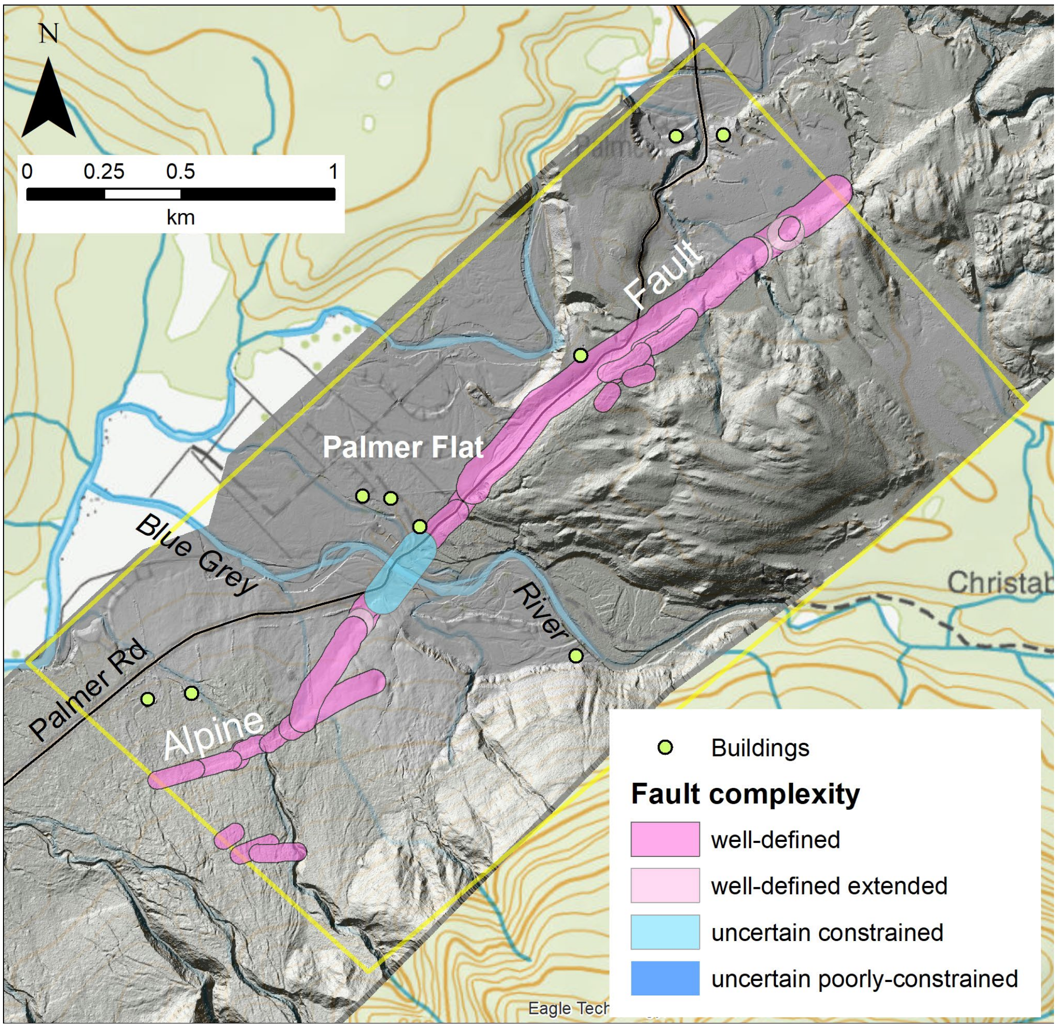

Figure 3.3 Fault Avoidance Zones (FAZs) in the Palmer Flat priority area (yellow polygon), southwest of Springs Junction. FAZ buffers have been developed for all fault traces (not shown).

Figure 3.4 The scarp of the Alpine Fault parallel to Palmer Road at Palmer Flat, southwest of Springs Junction. The interpreted location of the main rupture trace is between the red arrows.

For the Newcombes priority area, we mapped a 2.8 km length of the Alpine Fault mostly to the northeast of the Robinson River in the Newcombes station area (Figure 3.5). There, the Alpine Fault forms a northwest-facing scarp across uplifted alluvial terraces at the foot of the ranges. The fault has an uncertain location across young terraces associated with the Robinson River but can be projected across it from well-defined scarps on either side. Throughout the Newcombes priority area, the fault is predominantly located within native forest inland from the cleared farmland. An unnamed north-trending, reverse splay fault has been mapped in this priority area (Figure 3.5, pale blue FAZ). It has not been given a RI Class in this study because we currently have no data to constrain it.

For both of these priority areas, we have defined FAZ buffers that range in width from a minimum of 60 m for accurate, well-defined traces to up to 120 m for uncertain constrained traces.

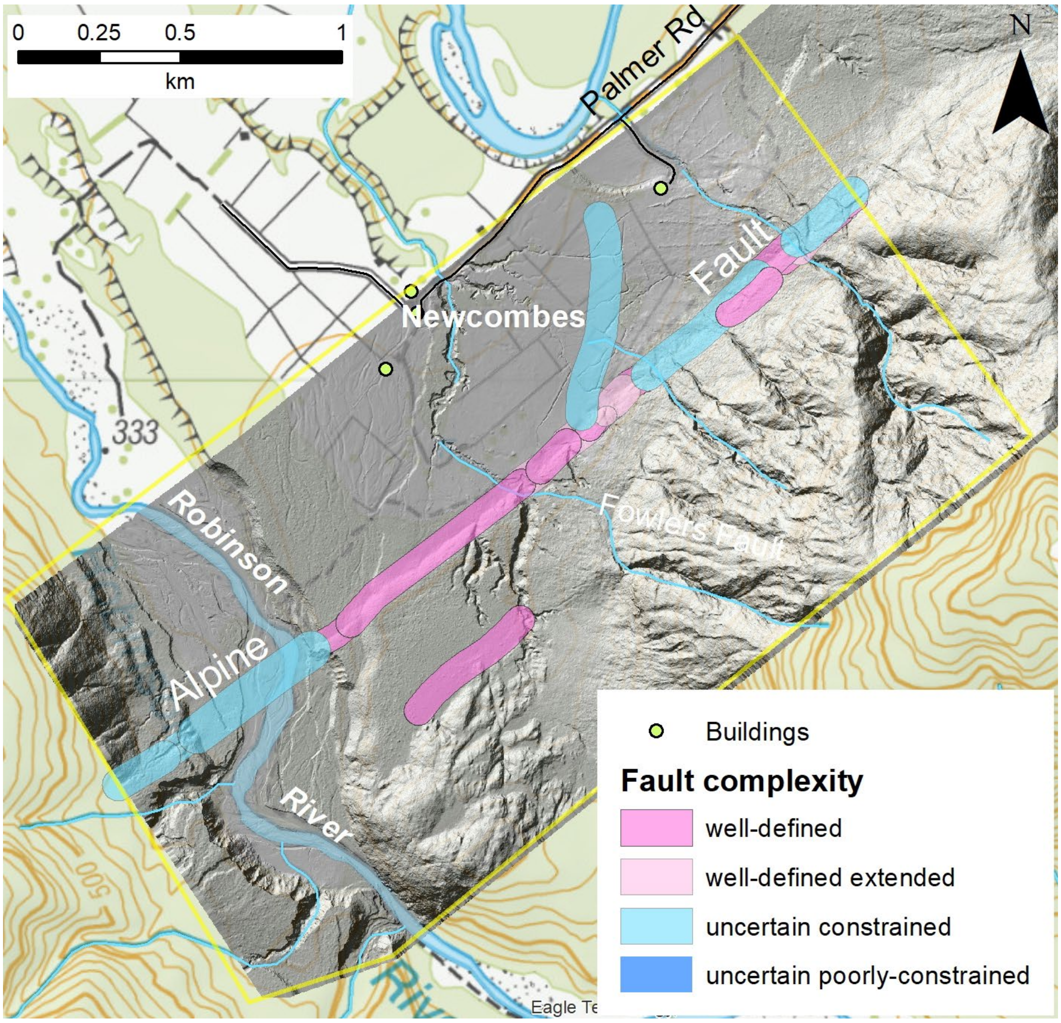

Figure 3.5 Fault Avoidance Zones (FAZs) in the Newcombes priority area (yellow outline), southwest of Springs Junction. Symmetric FAZ buffers have been developed for all traces (faults not shown in this view).

4.0 PRIORITY AREA MAPPING IN GREY DISTRICT

Figure 4.1 shows the three priority areas defined within Grey District: Ahaura, Haupiri and Lake Poerua. In their accompanying maps, we show known GIS building points to highlight the proximity of buildings to FAZs. These are mainly BIC 1 and sometimes BIC 2 structures.

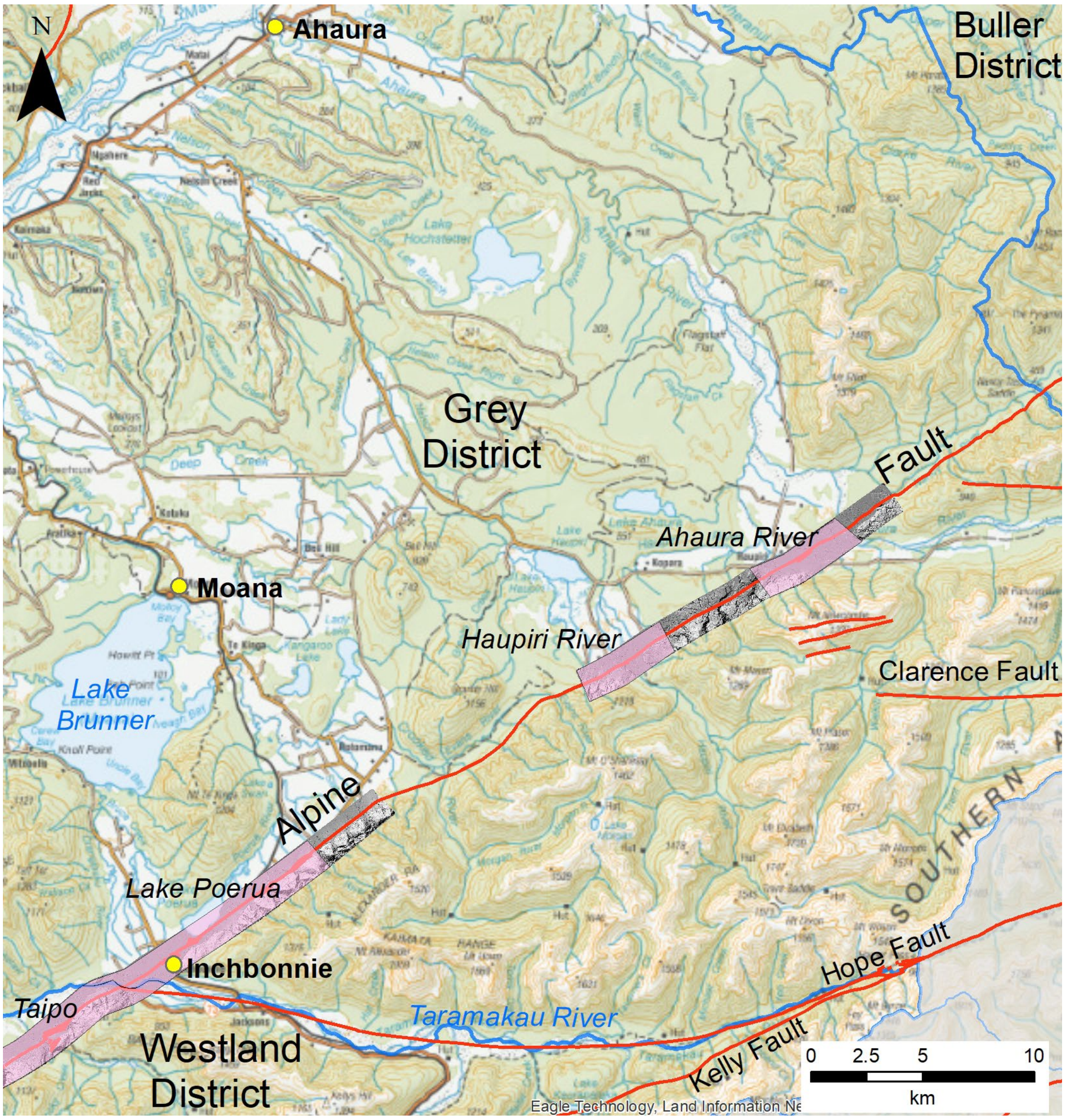

Figure 4.1 Priority mapping areas for the Alpine Fault in Grey District (pink polygons, names in italics) along a strip of 2014 airborne LiDAR data (grey). The Taipo priority area is within Westland District and is discussed in Section 5.1. Red lines are 1:250,000-scale active faults from the New Zealand Active Faults Database (Langridge et al. 2016b).

4.1 Ahaura River Priority Area

The Ahaura River and Haupiri River priority areas are both inland to the southeast of Ahaura township (Figure 4.1). The new mapping in this study using the LiDAR data shows that the Alpine Fault is more complex than previously mapped, with multiple dextral-slip traces.

For the Ahaura River priority area, we mapped a 4.5 km reach of the Alpine Fault from the Ahaura River southwest across the Haupiri-Amuri Road to beyond Coates Creek (Figures 4.2 and 4.3). The priority area spans a stretch of land that has mostly been cleared for dairy farming. Some houses and other buildings are presently sited within a few hundred metres of the fault but not within the FAZs developed for this report.

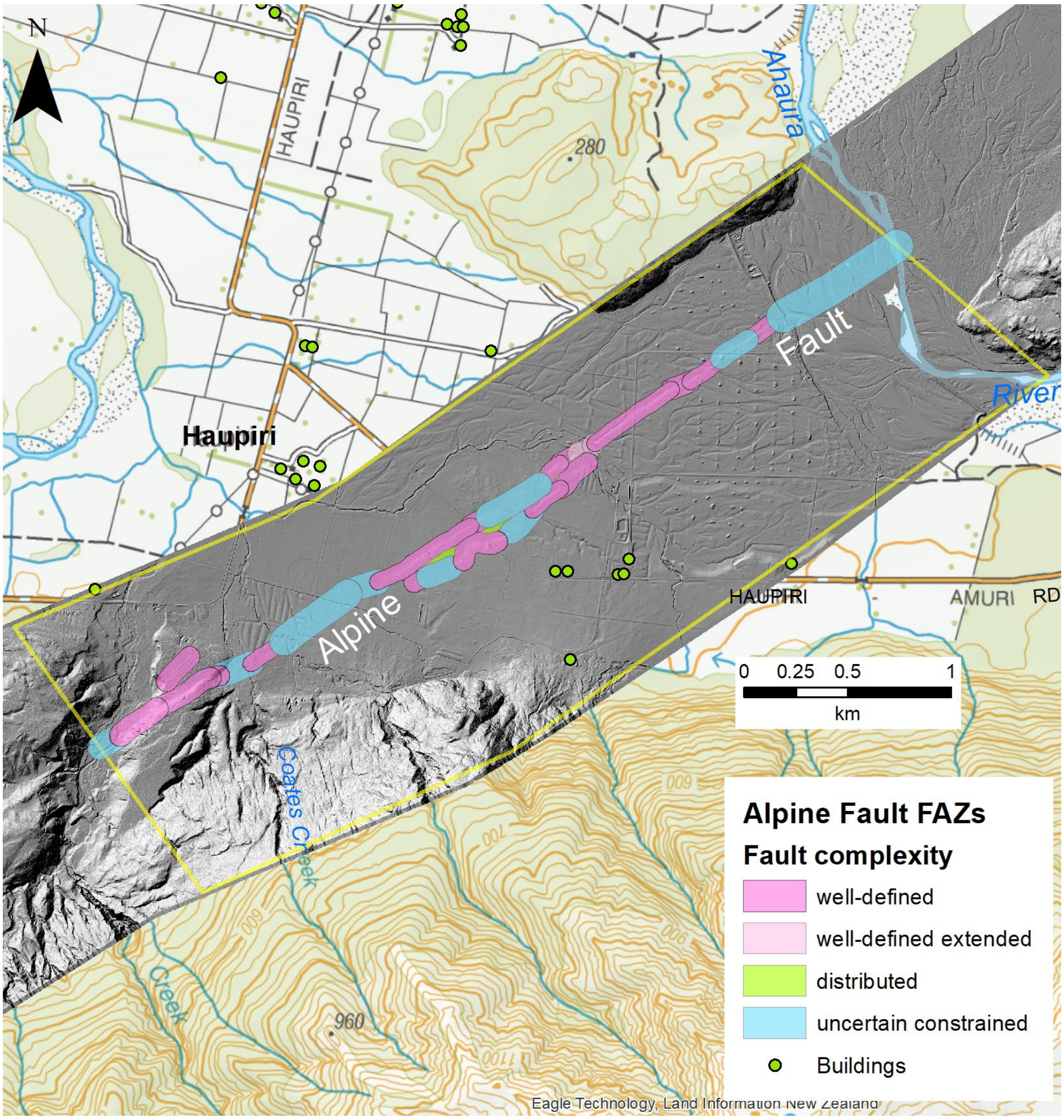

Figure 4.2 Fault Avoidance Zones (FAZs) in the Ahaura River priority area (yellow polygon), adjacent to the Ahaura River. Symmetrical FAZ buffers have been developed for all traces (faults not shown in this view).

Figure 4.3 Trench site on the Coates farm at the Ahaura River. The trace of the Alpine Fault is marked in red. The axis of a channel, formed in association with a terrace riser edge (left of it), is dextrally offset (as indicated by arrows) by c. 7 m.

The Ahaura River priority area has a mixture of well defined (minimum width 80 m), well-defined extended, uncertain constrained and uncertain poorly constrained (maximum width 140 m) FAZ buffers (Figure 4.2). Small distributed FAZs have been constructed to fill parts of the broad scarp that were not buffered by the FAZ process, acknowledging the distributed character of the deformation between two closely spaced main fault traces.

4.2 Haupiri River Priority Area

For the Haupiri River priority area, we mapped a 4 km length of the Alpine Fault either side of the Haupiri River between Wallace Road and Muddy Creek (Figure 4.4). This priority area occurs in proximity to the Gloriavale community, which is located entirely >500 m from the FAZs. Northeast of the Haupiri River, the fault is expressed as a large northwest-facing scarp across remnants of glacial moraines and latest Pleistocene and Holocene alluvial surfaces. Two buildings are located within FAZs in this area. South of the Gloriavale community, the fault cuts across the toes of large alluvial fans that are likely deposited across alluvial terrace surfaces. Our mapping follows the fault traces into native forest southwest of Gloriavale.

FAZ buffers developed here range in width from a minimum of 60 m for accurate, well-defined traces to up to 120 m for uncertain poorly constrained traces (Figure 4.4).

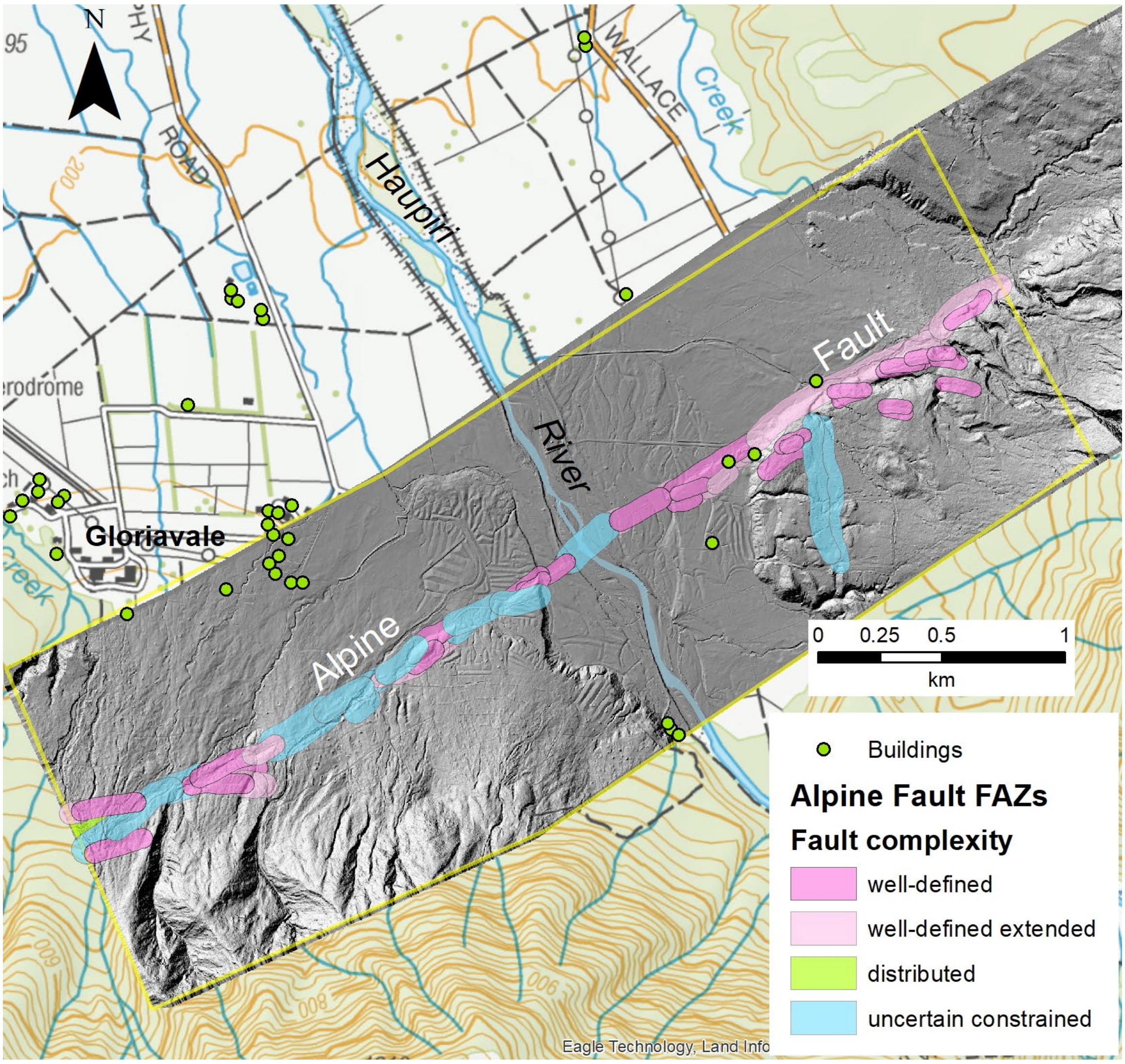

Figure 4.4 Fault Avoidance Zones (FAZs) in the Haupiri River priority area (yellow box), adjacent to the Haupiri River. Symmetrical FAZ buffers have been developed for all traces (faults not shown in this view).

4.3 Lake Poerua Priority Area

The Lake Poerua priority area spans a c. 10 km stretch of the Alpine Fault along a strip of LiDAR data that extends from the Taramakau River to the northeast beyond Lake Poerua to Brown River (Figure 4.5). Northeast of Brown River, the fault is largely situated within native forest east of Rotomanu. There are some indications, particularly from Evans Creek to Brown River, that the fault is located along the range front. In these areas, fault scarps and traces have a complex geomorphology, indicating a suite of overlapping thrusts and strike-slip traces (Upton et al. 2017). These sorts of features were also mapped along the Alpine Fault in the Whataroa and Franz Josef areas (Barth et al. 2012; Langridge et al. 2014).

FAZ buffers developed for the Lake Poerua priority area range in width from a minimum of 60 m for accurate, well-defined traces to up to 300 m for uncertain poorly constrained traces (Figure 4.5).

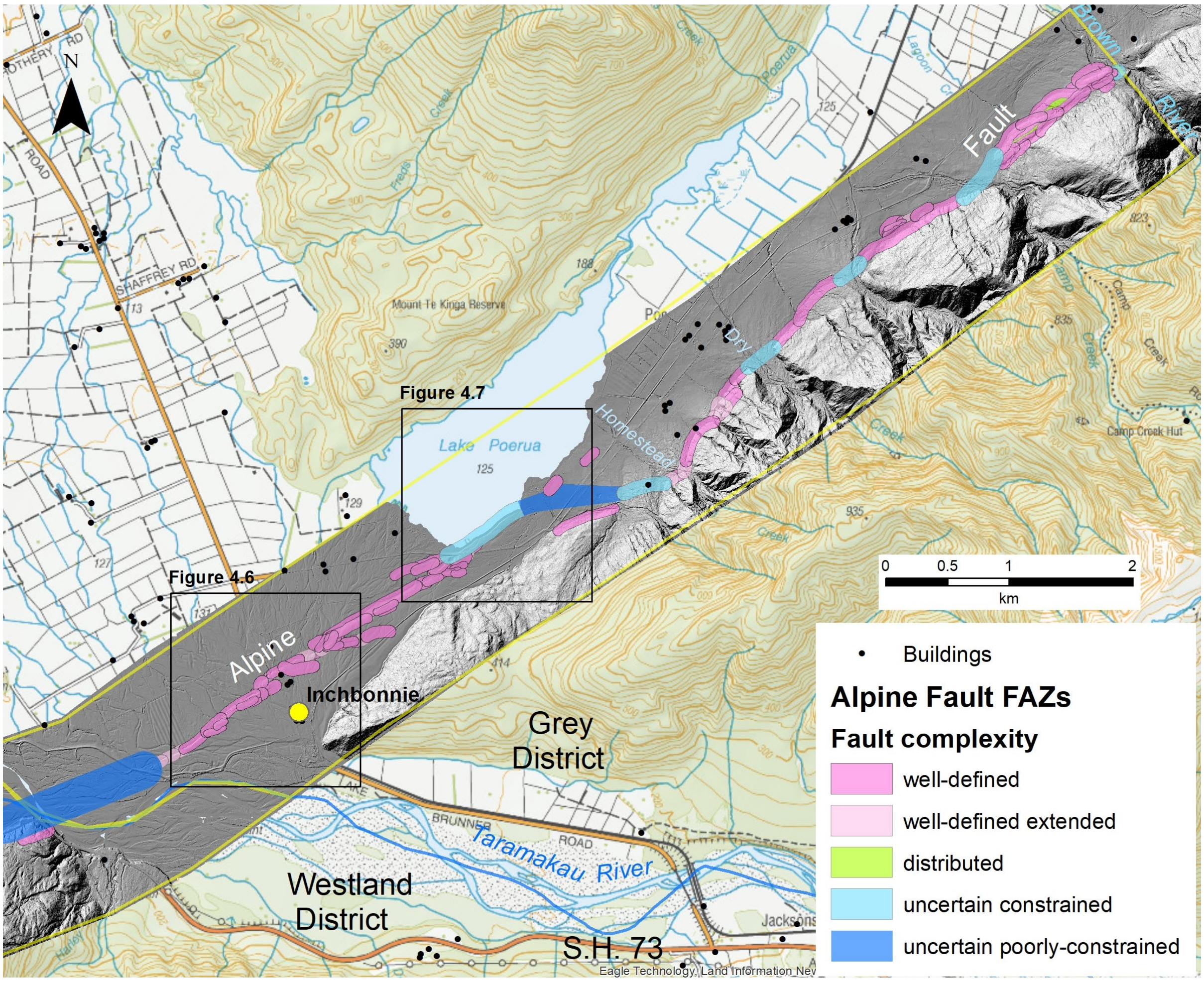

Figure 4.5 Fault Avoidance Zones (FAZs) in the Lake Poerua priority area (yellow polygon), northeast of the Taramakau River in Grey District. FAZ buffers have been developed for all traces (faults not shown in this view). Buildings are from LINZ Topo 50 digital map data. Detailed maps of Inchbonnie and Lake Poerua are indicated by black boxes.

4.3.1 Inchbonnie Case Example

The Alpine Fault is well-studied in the Inchbonnie area, with slip rate and paleoseismic data coming from a site northeast of the village and from Lake Poerua (Berryman et al. 1992; Langridge et al. 2010, 2012; Howarth et al. 2018). The fault location is uncertain across the Taramakau River. Between the Taramakau River and Lake Poerua, fault traces and scarps have a left-stepping *en echelon* pattern (Figure 4.6). In the stepover areas between the longer traces/scarps, there are many short fault traces mapped, and distributed deformation is likely within these stepover areas.

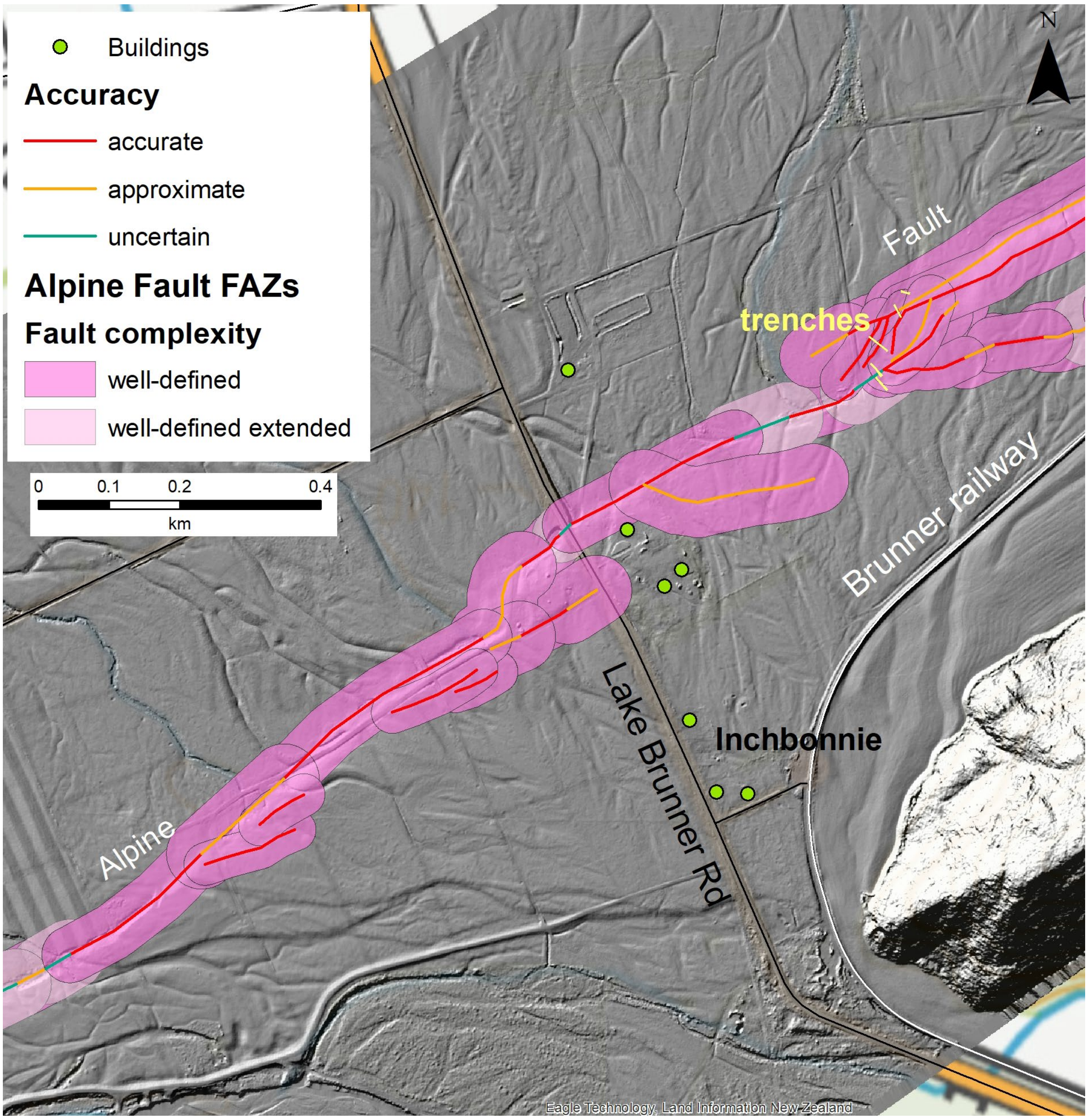

Figure 4.6 Alpine Fault traces and Fault Avoidance Zones (FAZs) in the Inchbonnie village area near the Taramakau River in Grey District. Trenches excavated across fault traces by GNS Science are shown in yellow; green dots represent buildings.

Research trenches excavated on the Harris farm (Figure 4.6) confirmed the location and origin of each of the mapped fault traces there (Langridge et al. 2010; Howarth et al. 2018). At Inchbonnie, there are a few buildings close to the FAZs defined there, one of which is probably a dwelling, i.e. BIC 2a (Figure 4.6).

4.3.2 Lake Poerua Case Example

GNS Science undertook reviews of the location of the Alpine Fault for a proposed subdivision at Lake Poerua (Langridge and Hancox 2006; Langridge and McSaveney 2008). The straight northeast-trending southern shoreline of Lake Poerua was interpreted as being the eroded fault trace of the Alpine Fault (Langridge et al. 2010, 2012). These authors inferred that the fault was located just offshore in the shallows of the lake. In this study, we have tried to emulate the dimensions of the FAZ defined by Langridge and McSaveney (2008) and taken up by the Grey District Council. Nevertheless, even with the luxury of airborne LiDAR, there is considerable uncertainty as to where the fault is located to the northeast of the lake, as indicated by an uncertain poorly constrained FAZ (Figure 4.7).

Northeast of the lake, we interpret the fault as departing from its left-stepping pattern and stepping to the right toward the range front. Where the fault steps right, there is large uncertainty in its location and orientation, resulting in a FAZ width of 300 m in the Homestead Creek area. It is possible that the fault is more northeast-striking in this area than what is mapped and that its trace is buried beneath large, recently active alluvial fans, such as those emanating from Homestead and Dry creeks. Thus, our current interpretation is to step the fault across from Lake Poerua to the base of the range front at Homestead Creek (Figure 4.5).

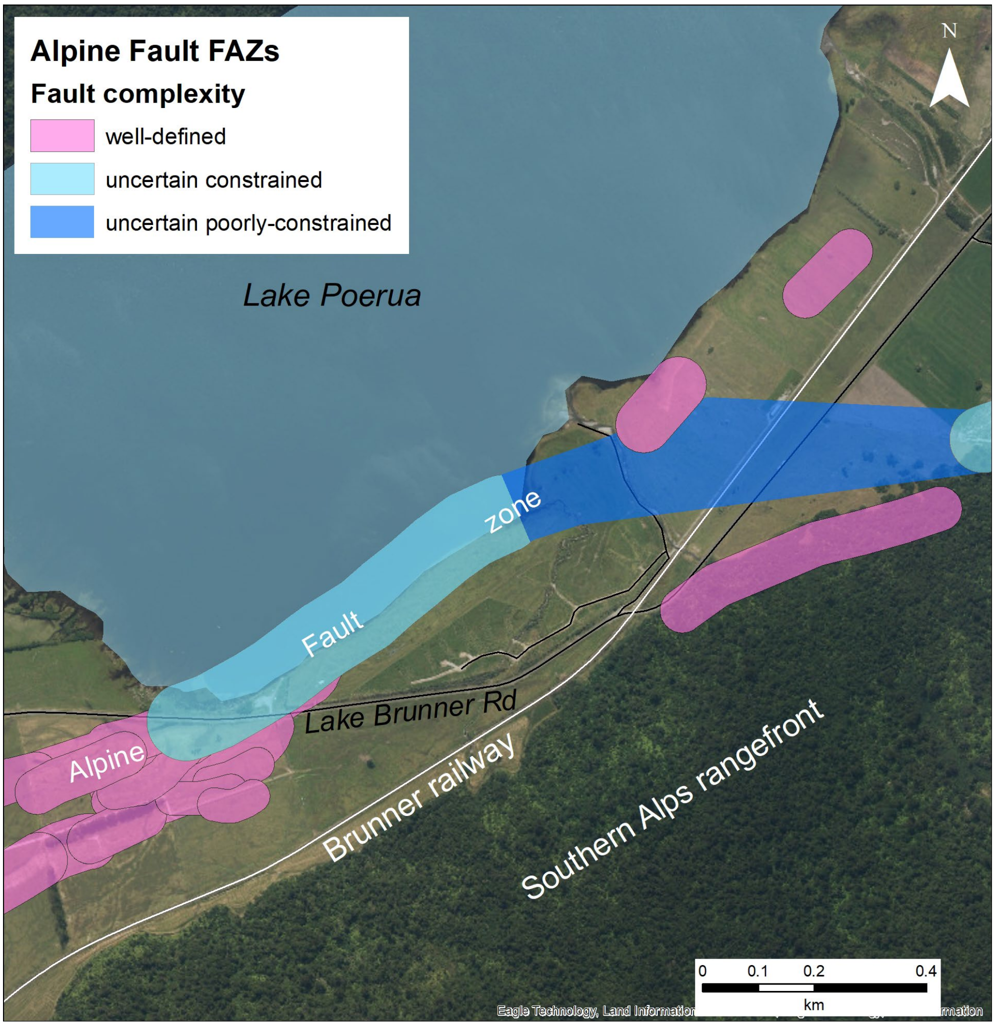

Figure 4.7 Alpine Fault traces and Fault Avoidance Zones (FAZs) in the Lake Poerua area northeast of Inchbonnie in Grey District. FAZs in the vicinity of the lake have been designed to follow the size and shape of previously defined FAZs.

5.0 PRIORITY AREA MAPPING IN WESTLAND DISTRICT

Due to its shape and proximity to the Alpine Fault, Westland District has 12 separate priority areas associated with it (Figure 1.1). Figure 5.1 highlights three priority areas defined in the northern part of the Westland district: Taipo, Arahura and Styx-Hokitika.

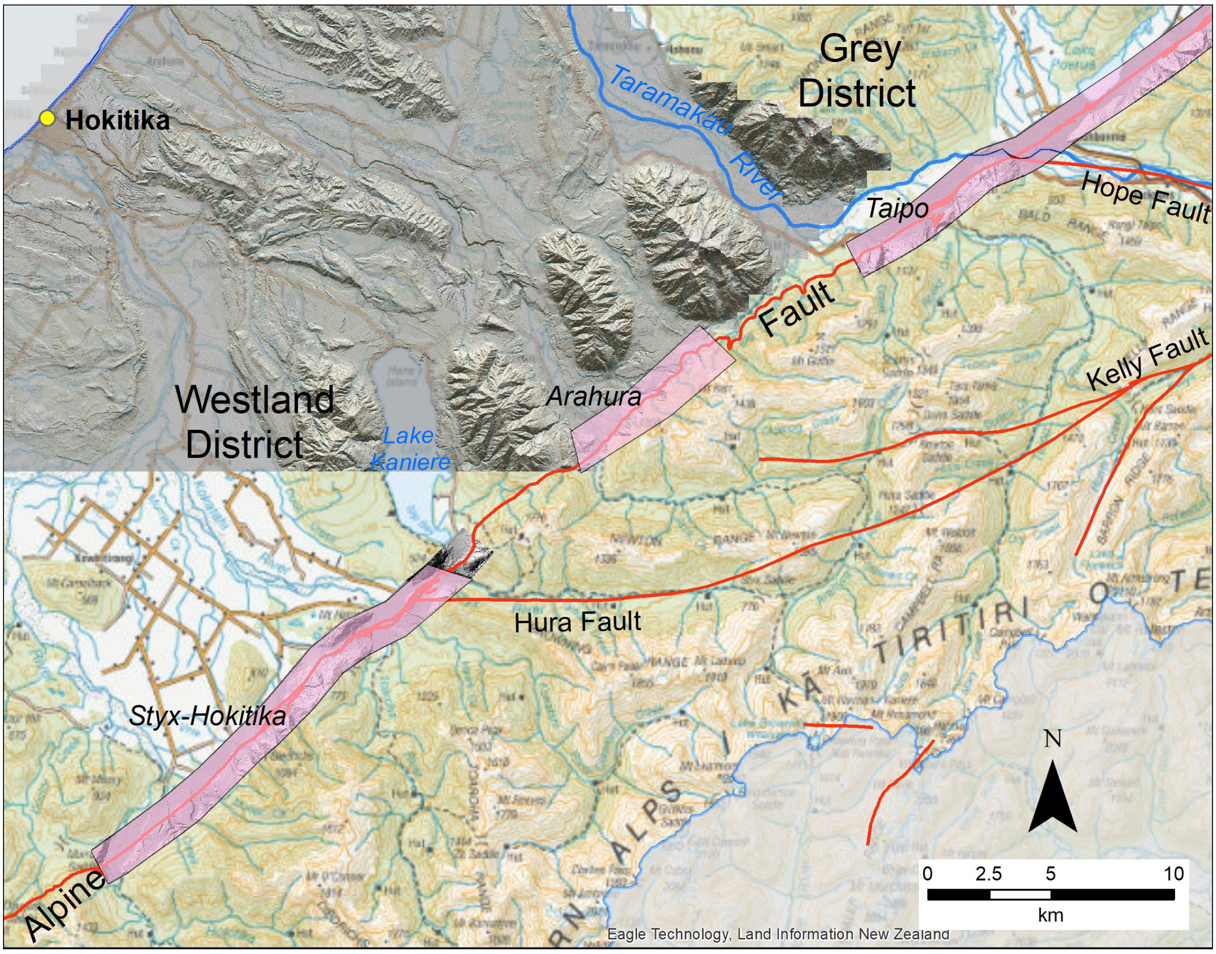

Figure 5.1 Priority mapping areas for the Alpine Fault in the northern part of Westland District (pink polygons, italics) along a strip of 2014 airborne LiDAR data (grey). The regional LiDAR data in the northwest was acquired by WCRC though the PGF. Red lines are 1:250,000-scale active faults from the New Zealand Active Faults Database (Langridge et al. 2016b).

5.1 Taipo Priority Area

The Taipo priority area covers the southwestern half of a strip of LiDAR data that extends from Rotomanu to Harrington Creek. The Taipo and Lake Poerua priority areas were split because they are within two different districts. Mapping in the Taipo priority area covers an 8.6 km length of the fault from the Taramakau River to Harrington Creek at the southwest edge of this LiDAR strip (Figure 5.2).

From the southwest, the Alpine Fault is mapped with both a frontal trace and a range-facing scarp near Harrington Creek. To the northeast of there, the fault has a left-stepping character, as documented by Berryman et al. (1992). This is particularly evident on the true left of the Taipo River, where Berryman (1975) recognised range-facing scarps with dextral offsets (Figure 5.2).

This left-stepping pattern continues towards Macs Creek and Rocky Point. The Alpine Fault has previously been mapped along the range front immediately southeast of State Highway 73

(SH 73) in this area. However, this is at odds with the bedrock geology, as schist-derived mylonitic rocks outcrop on the highway near Rocky Point. GNS Science's Petlab database (http://pet.gns.cri.nz/) identifies many observations of Aspiring Terrane rocks downslope (to the northwest) of the highway near Rocky Point. These observations support the assertion that the trace of the Alpine Fault is also downslope of SH 73 in that area. Based on these observations, we have mapped an uncertain fault location around the Rocky Point headland within the active bed of the Taramakau River. The fault has not been located in this area, but it is the most plausible geometry based on local geology and geomorphology. Field reconnaissance may in future provide more certainty as to where the fault is located in this area. No active traces related to the westernmost end of the Hope Fault were identified on the LiDAR strip. If present, the Hope Fault probably occurs within the bed of the Taramakau River (Nathan et al. 2002).

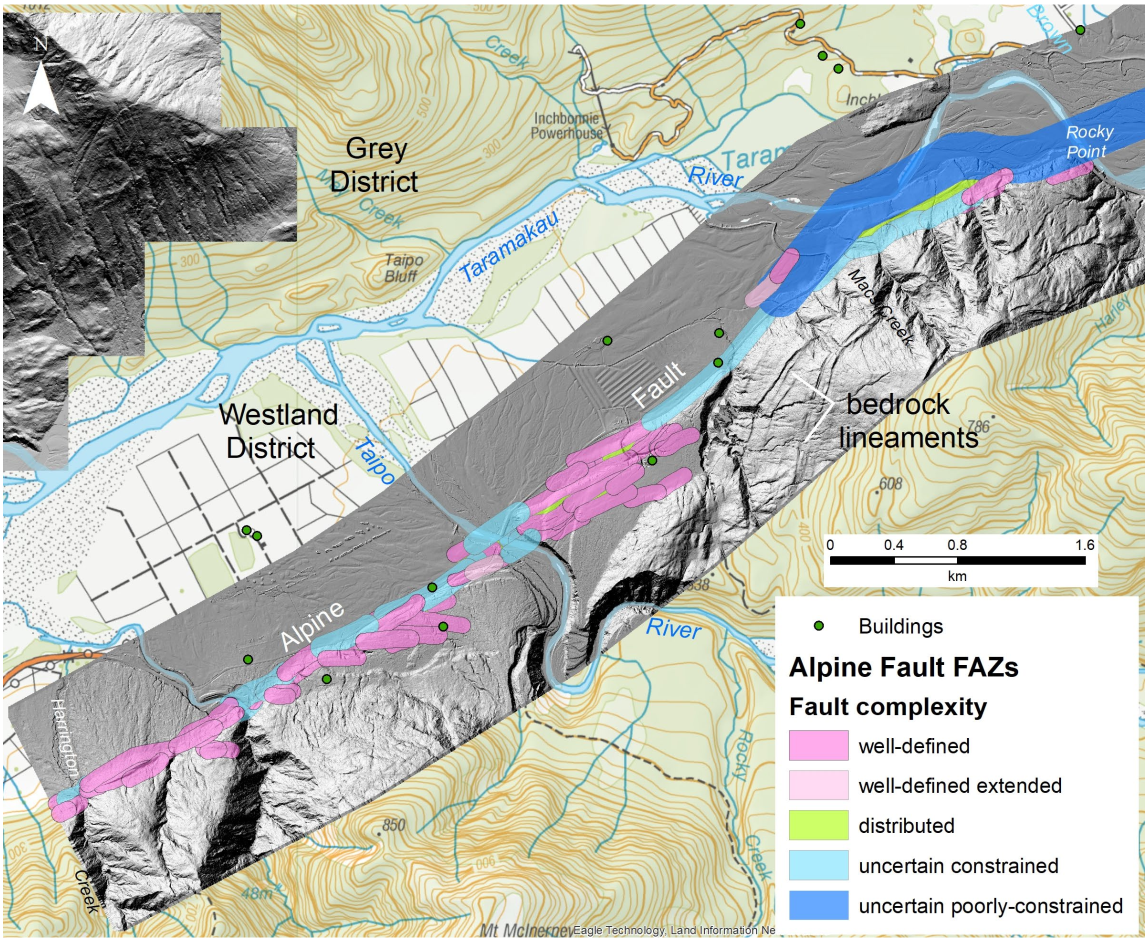

Figure 5.2 Fault Avoidance Zones (FAZs) in the Taipo priority area south of the Taramakau River in Westland District. FAZ buffers have been developed for all traces (faults not shown in this view). Buildings are from LINZ Topo 50 digital map data.

Also within the Taipo priority area are many obvious scarps within the bedrock of the range front southeast of the mapped faults (Figures 5.2 and 5.3). We interpret these as ridge rents and not as tectonic components of the Alpine Fault *per se*. These have therefore not been included as active faults, nor have they been assigned a name or recurrence interval class. Nevertheless, they are features of active surface deformation, and displacement on them may be reliant on movement on the Alpine Fault. An important observation related to these bedrock lineaments is that they curve around the hill towards Rocky Point and are sub-parallel in form to the FAZs that we have developed for the Rocky Point area.

Symmetric FAZ buffers developed here range in width from a minimum of 60 m for accurate, well-defined traces to up to 300 m for uncertain poorly constrained traces (Figure 5.2).

Figure 5.3 View to the northeast along the Alpine Fault from north of the Taipo River to Rotomanu (in the distance) in Westland District. Traces of the Alpine Fault are marked by the white line; extensional bedrock structures in the hanging wall of the fault are marked by arrows. The latter are not included in this study. The Alpine Fault crosses the Taramakau River at Rocky Point. (Photo: DL Homer #7868, GNS Science).

5.2 Arahura Priority Area

The Arahura priority area describes an area along the range front of the Alpine Fault adjacent to the Arahura River, accessed via Milltown Road (Figure 5.4). In this 9-km-long area, recently acquired airborne LiDAR data funded by the PGF is used to characterise the location of fault traces. The WCRC 9 m DSM was also used to help map the fault in this priority area, as the fault traverses along the very edge of LiDAR coverage.

In the Arahura priority area, the Alpine Fault has a lobate (convex to the northwest) map pattern, consistent with previous mapping by Rattenbury (1987). This pattern is particularly evident south of Kawhaka Pass (Figure 5.4). This map pattern is indicative of faults with low dip angles; thus, in this region, between the Hope and Kelly faults, it is interpreted that the Alpine Fault has a lower dip than along other parts of the fault (Vermeer et al. 2021). Nevertheless, we have attributed the fault with a dominant dextral mode of slip. A zone of southeast-dipping brecciated rock was identified in the true right bank of the Arahura River in 2018 by the lead author. However, the location of the fault is poorly constrained southwest of the Arahura River, which has the widest (300 m width) FAZ (Figure 5.4) in this area. Where the Fault Complexity is well defined, the FAZs in the Arahura priority area have a minimum width of 80 m.

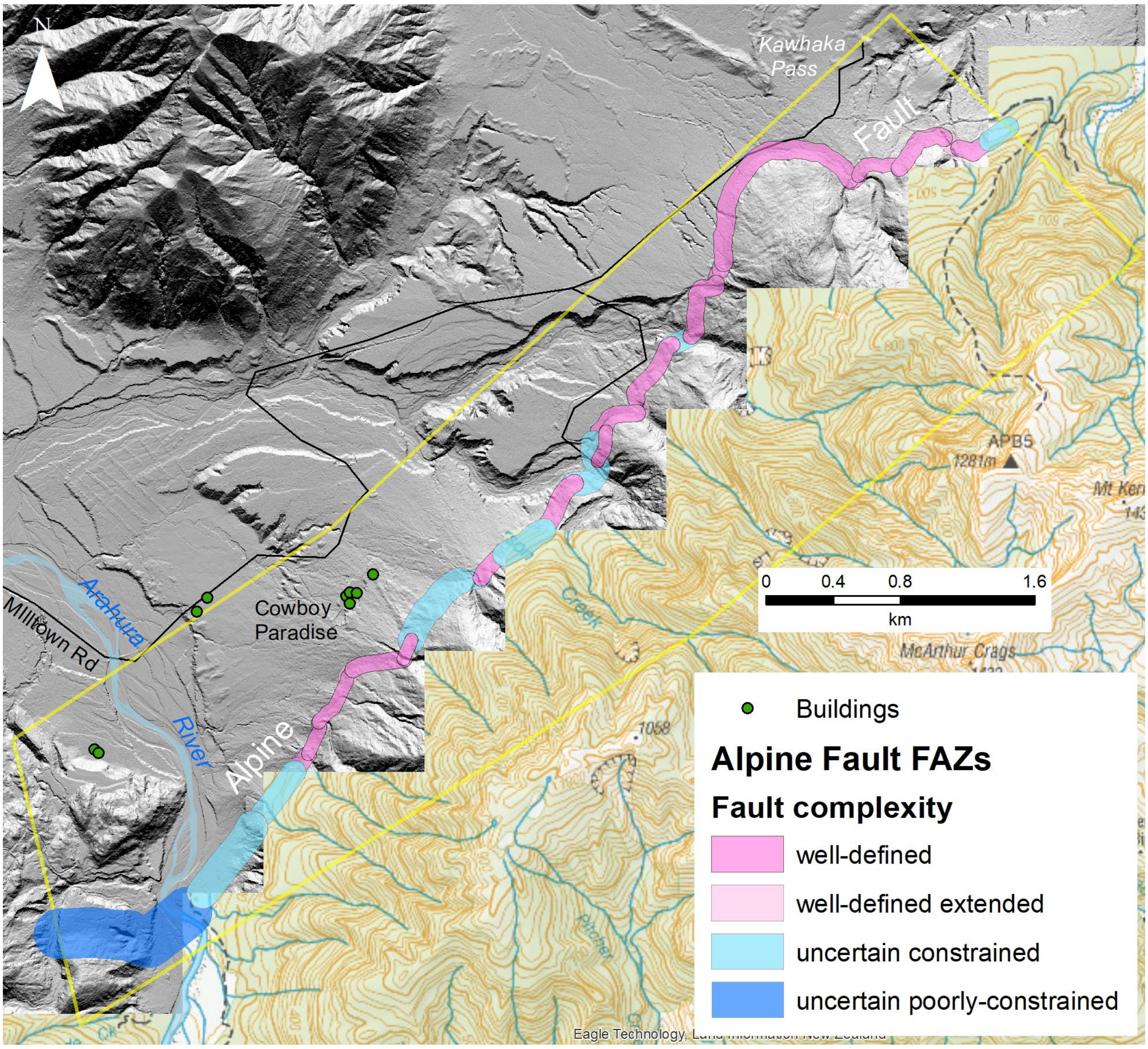

Figure 5.4 Fault Avoidance Zones (FAZs) in the Arahura priority area (yellow polygon), southeast of Hokitika in Westland District. Traces of the Alpine Fault are mapped using recent WCRC LiDAR data (grey). Symmetrical FAZ buffers have been developed for all traces (faults not shown in this view).

5.3 Hokitika-Styx Priority Area

The Hokitika-Styx priority area is 27 km long and runs from the Hokitika River in the southwest to the Styx River in the northeast (Figure 5.5). The priority area traverses the boundary between farmland and native bush along the fault range front. LiDAR data reveals that the map pattern of the Alpine Fault is more complex along this section than previously mapped. The Alpine Fault is not typically defined by a single trace, nor is it as straight as previously thought in this area (Barth et al. 2012). For example, the fault is fairly straight from Hokitika River towards the Round Top massif. At Round Top, the fault bends to the north and around that massif. There is a similar bend to the north around Meharry Spur, where a late Quaternary alluvial terrace is contorted within the fault zone, adjacent to the projected junction with the Hura Fault (Figure 5.5).

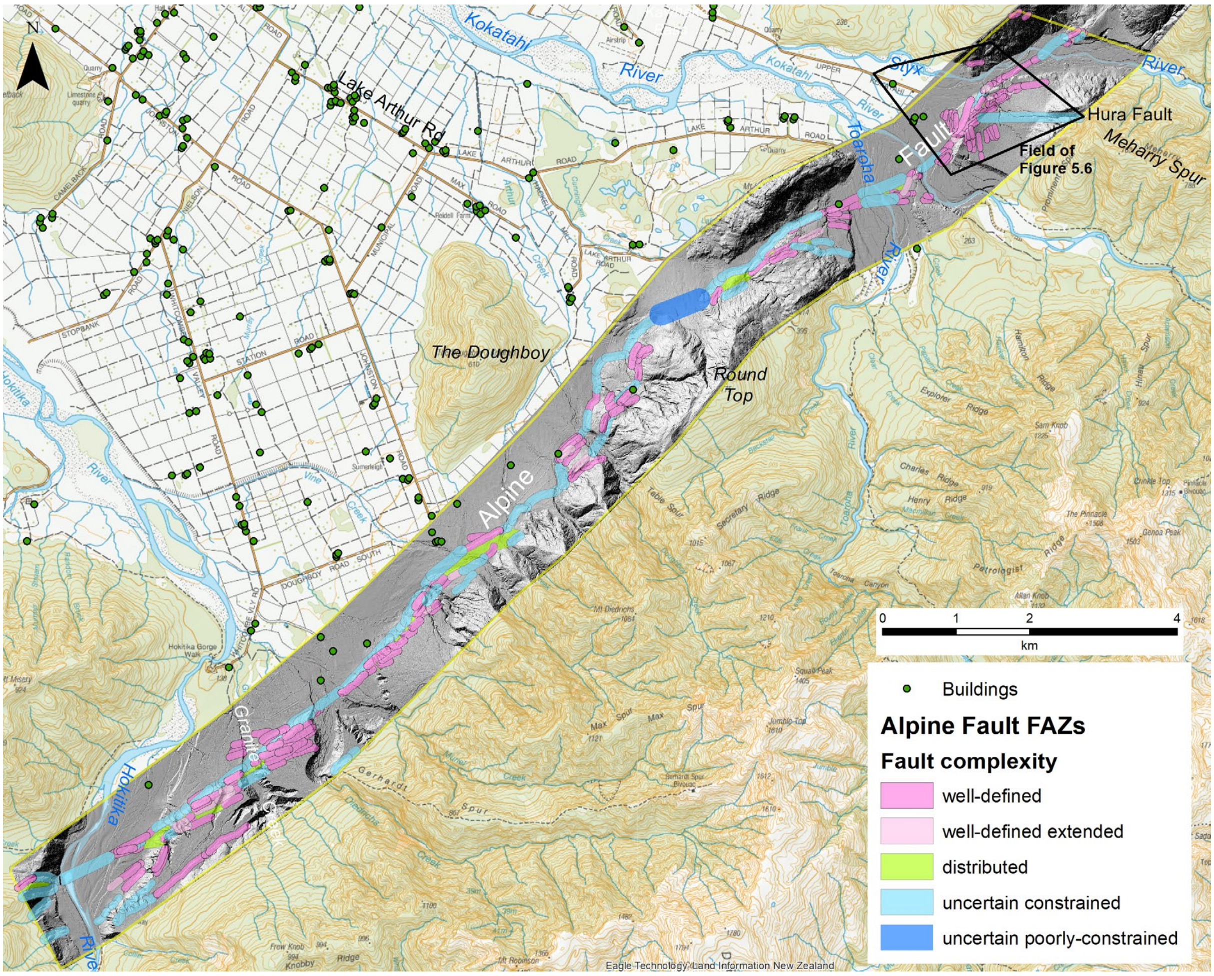

Figure 5.5 Fault Avoidance Zones (FAZs) in the Hokitika-Styx priority area (yellow outline), southeast of Hokitika. Traces of the Alpine Fault are mapped onto a LiDAR hillshade model (grey). FAZ buffers have been developed for all traces (faults not shown in this view).

From the Hokitika River to The Doughboy, fault traces cut across alluvial terraces and range-front fans. A fault trace can be mapped across the lowest of the terraces related to the Hokitika River, attesting to the recency of the last earthquake rupture there. In places along the range front northeast of the Hokitika River, the scarp height across older alluvial terraces (probably the Q2a alluvial terrace; 12,000–24,000 years old) cut by the fault is greater than 80 m. About 700 m southeast of the main fault zone near Granite Creek, a new northwest-facing fault trace has been mapped. This trace exhibits scarps up to 5 m in height across the same (Q2a) alluvial surface. At this time, this trace has been assigned to the Alpine Fault and accordingly is included as a RI Class I fault.

West of Round Top, two main north-striking fault zones have been mapped. This provides a new interpretation of the Alpine Fault in this area, with frontal lobate traces at the range front and straighter fault traces inboard within the hanging wall. The fault returns to northeast-striking toward the Toaroha and Kokatahi river junction. Trenches were excavated on the true left side of the Toaroha River by Yetton et al. (1998) and Langridge et al. (2021b) to investigate the paleoseismicity of the fault.

Figure 5.6 A representation of Fault Avoidance Zones developed for the Alpine Fault (purple) and Hura Fault (blue) in the Styx-Kokatahi valley area. These areas are bush-covered and are unlikely to be developed in the future.

The Hura Fault is a branch of the Kelly Fault and has been included in this study using a 1:250,000 (uncertain constrained) trace sourced from the New Zealand Active Faults Database (Figure 5.6; Langridge et al. 2016b). It is considered to be a RI Class I fault (like the Alpine Fault) and therefore has the same planning recommendations under the MfE Guidelines.

FAZ buffers developed for the Hokitika-Styx priority area range in width from a minimum of 70 m for accurate, well-defined traces to up to 300 m for uncertain poorly constrained traces (Figure 5.5).

5.4 Waitaha Priority Area

The Waitaha priority area occurs between Hokitika and Harihari (Figure 1.1). It represents a small (3.7 km long) area of interest in the area where the Waitaha River exits from the range front of the Southern Alps across the Alpine Fault (Figure 5.7). There is currently no LiDAR coverage along this part of the Alpine Fault; in its absence, we used the WCRC 9 m DSM to interpret the location of the fault. In reality, the 9 m DSM provides a small improvement in location precision compared to previous mapping in this area, undertaken as part of the 1:250,000 QMAP geology program (Cox and Barrell 2007) and used in the New Zealand Active Faults Database (Langridge et al. 2016b).

We have re-mapped some of the linework from Cox and Barrell (2007) and applied accurate, approximate and uncertain line accuracy to traces in the Waitaha priority area. Symmetric FAZ buffers developed here range in width from 190 to 300 m for uncertain constrained traces (Figure 5.7).

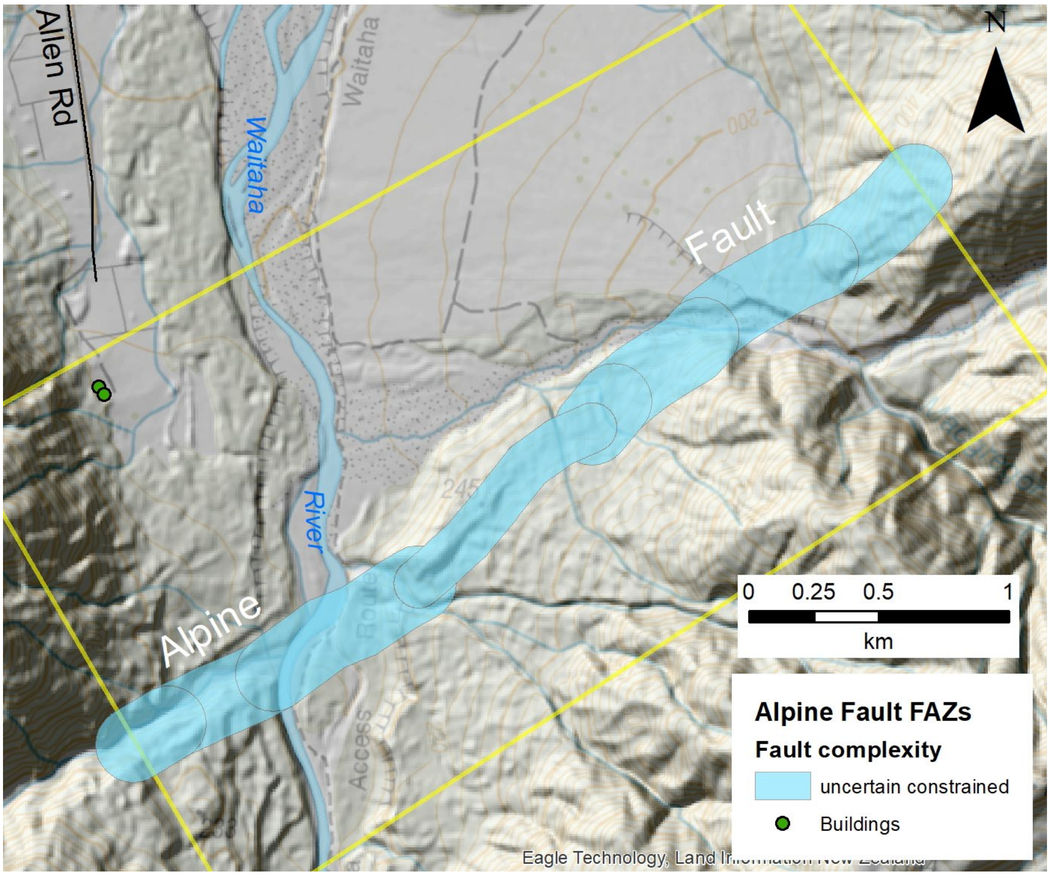

Figure 5.7 Fault Avoidance Zones in the Waitaha priority area (yellow polygon) in Westland District. Traces of the Alpine Fault are re-mapped using the WCRC 9 m DSM (grey background). Faults are not shown in this view.

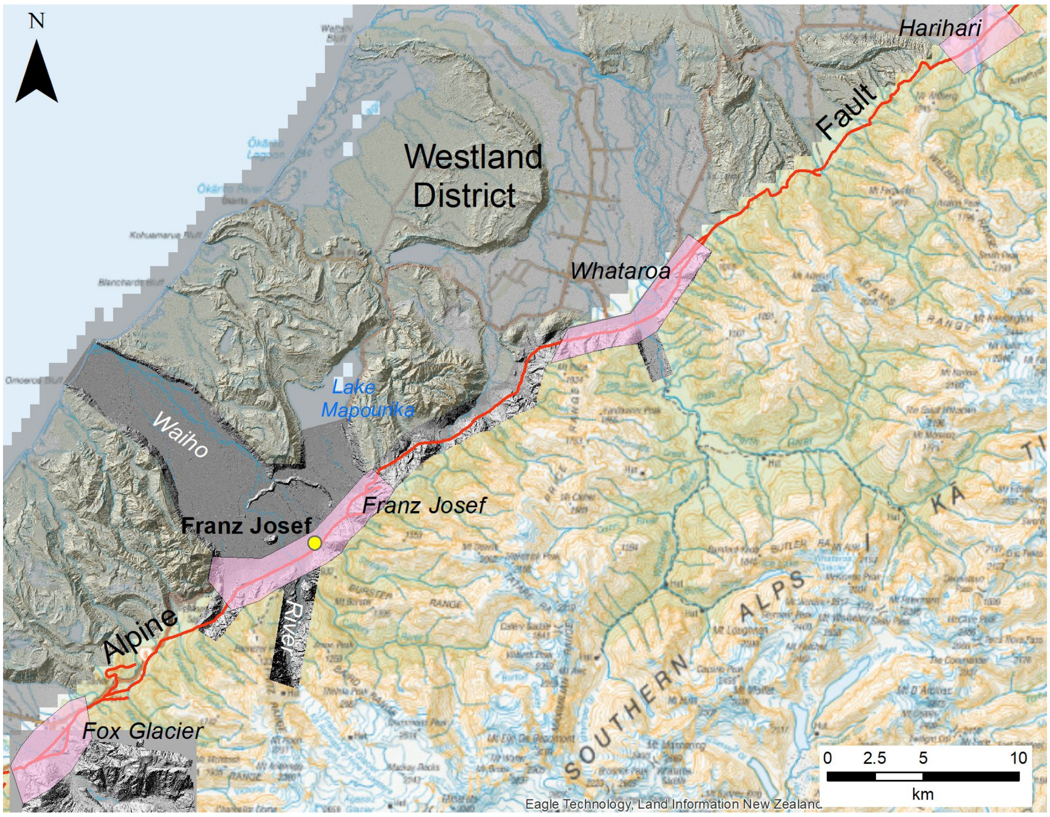

Figure 5.8 Priority mapping areas for the Alpine Fault in the central part of Westland District (pink polygons, italics) and various airborne LiDAR data acquisitions (grey). Red lines are 1:250,000-scale active faults from the New Zealand Active Faults Database (Langridge et al. 2016b).

5.5 Harihari Priority Area

Figure 5.8 highlights four priority areas defined in the central part of the Westland District: Harihari, Whataroa, Franz Josef and Fox Glacier.

The Harihari priority area is a small (4 km long) area where the Wanganui River exits from the range front of the Southern Alps across the Alpine Fault (Figure 5.9). The town of Harihari itself is located c. 4 km northwest of the Alpine Fault. There is currently no LiDAR coverage across the Wanganui River, but there is a small amount of PGF LiDAR coverage to the west of the priority area that provides some clues as to the structure of the fault near the river. For example, the PGF LiDAR elucidates clear reverse fault traces in the bush-covered country west of the Wanganui River.

In the absence of LiDAR for the Harihari priority area, we utilised the WCRC 9 m DSM to interpret the location of the fault. We have re-mapped some of the linework from Cox and Barrell (2007) and applied approximate and uncertain line accuracies to traces in the Harihari priority area. FAZ buffers developed here range in width from 120 m for uncertain constrained traces to 300 m for the uncertain poorly constrained section across the Wanganui River floodplain, for which there is no mapped trace (Figure 5.9).

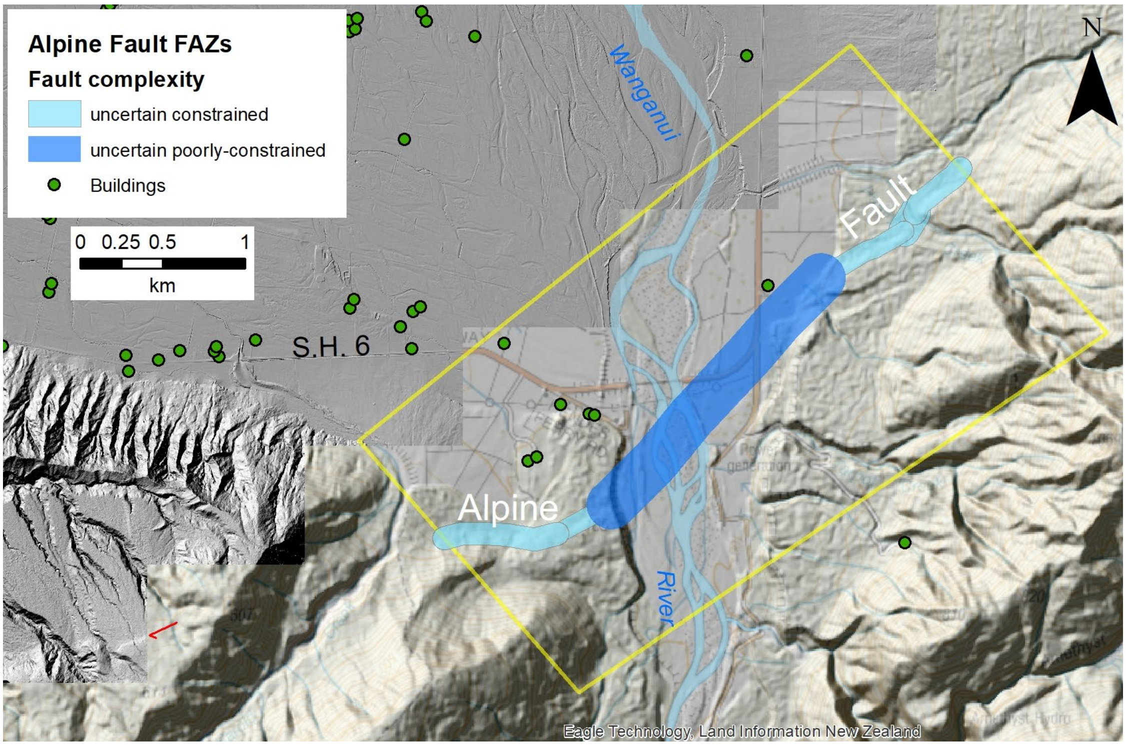

Figure 5.9 Fault Avoidance Zones in the Harihari priority area (yellow polygon) in Westland District. Traces of the Alpine Fault were re-mapped using the WCRC 9 m DSM (grey background), with the aid of other regional LiDAR data (dark grey overlay in northwest; see red arrow marking fault trace). Fault traces are not shown in this view.

5.6 Whataroa Priority Area

The Whataroa priority area is a 9-km-long dog-leg-shaped area along the Alpine Fault near the township of Whataroa (Figure 5.10). This priority area spans c. 4 km either side of the Whataroa River as it exits from the range front of the Southern Alps, from Matainui Creek in the southwest to Vine Creek in the northeast. A LiDAR strip acquired in 2010 was used as the primary source of digital elevation data for mapping. The town of Whataroa is located c. 4 km northwest of the Alpine Fault.

In this study, we have compared and reviewed previous interpretations of the Alpine Fault in the Whataroa area (Cox and Barrell 2007; Barth et al. 2012; Langridge et al. 2014). More recent interpretations apply the parallel and serial partitioning models of Norris and Cooper (2007) to map the fault at detailed scales. This model highlights zones of ENE-striking dextral-dominated faulting (Figure 5.11), as seen west of the Whataroa River, transitioning to northeast-striking zones of reverse-dominated faulting (as seen northeast of the Whataroa River). These two domains of faulting define the dog-leg across the Whataroa River. In this area, where the fault changes strike across the river, the mapping is uncertain due to river incision and/or aggradation that has occurred since the most recent faulting event (Langridge et al. 2018a).

The fault is mapped with accurate, approximate and uncertain traces in this priority area. West of the river, there are two or three sub-parallel strike-slip fault zones and a frontal reverse fault trace (Langridge et al. 2014). Northeast of the river, the fault is characterised by a frontal dextral reverse trace, a partitioned strike-slip zone with range-facing scarps and many short normal fault traces that occur as a result of extension in the Alpine Fault hanging wall (Figure 5.10).

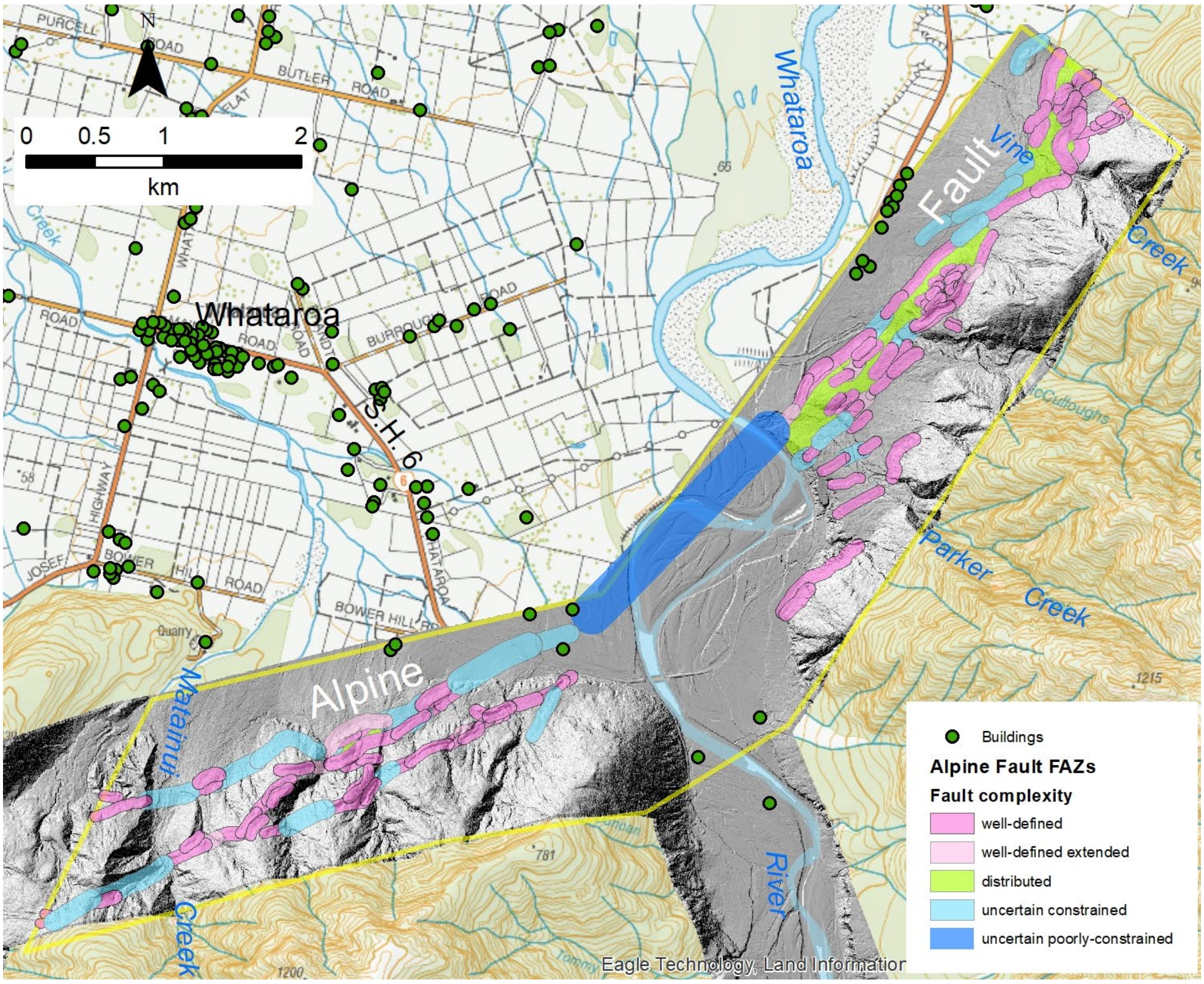

Figure 5.10 Fault Avoidance Zones (FAZs) in the Whataroa priority area (yellow polygon) extending from Matainui Creek to Vine Creek. Traces of the Alpine Fault are mapped onto LiDAR (grey band). Fault traces are not shown in this view.

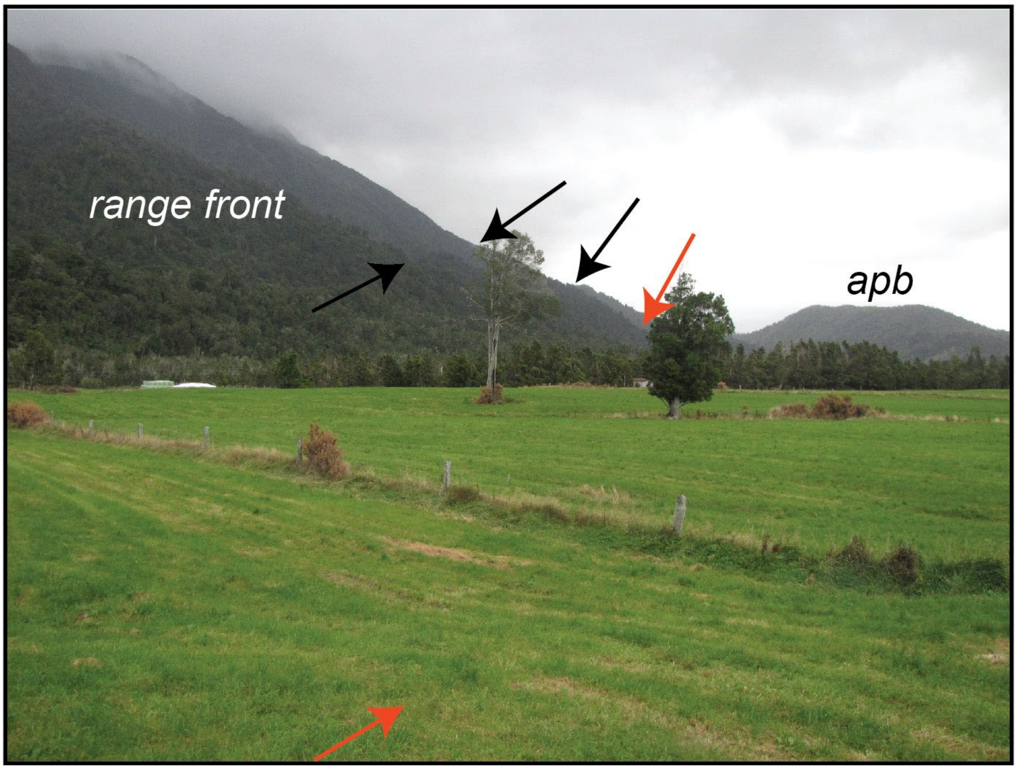

Figure 5.11 View to the southwest toward the Southern Alps range front near Whataroa. A trench was excavated near the lower arrow, which demarcates the frontal fault system (red arrows). Black arrows highlight uphill-facing scarps of dextral-slip faults. The saddle between the range front and a bedrock knob (apb) broadly defines the fault.

Despite the variable, partitioned styles of faulting, symmetric FAZ buffers have been developed for all fault traces. These range in width from a minimum of 70 m for well-defined traces to up to 290 m for the uncertain poorly constrained section across the Whataroa River, for which there is no mapped trace (Figure 5.10).

5.7 Franz Josef Priority Area

The Franz Josef priority area is an 11-km-long, dog-leg-shaped area straddling the Waiho River in the vicinity of Franz Josef township (Figure 5.12). This priority area covers part of the Alpine Fault from Dochertys Creek in the southwest to Potters Creek in the northeast and includes the Waiho River. A LiDAR survey acquired in 2010 was used as the primary source of topographic data for mapping (Langridge et al. 2014).

Faulting in this priority area is described from southwest to northeast. Norris and Cooper (1995) identified a partitioned style of faulting in the Dochertys Creek area, with typically NNE-striking dextral reverse fault sections separated by ENE-striking fault sections characterised by reverse dextral faulting (Barth et al. 2012). We have mostly taken up the mapping of Langridge et al. (2016a) across the entire Franz Josef priority area. The main difference in how the faults are treated in this study is that the dominant sense of faulting for every trace is considered to be dextral, i.e. dextral, or dextral with reverse, or sometimes normal, secondary motion. This is relevant when we develop FAZ buffers that, in this study, are all symmetrical about the mapped fault traces. In previous studies, some fault traces were assigned asymmetric buffers that are doubly buffered on the upthrown, or hanging-wall side, of dextral-reverse traces.

An additional change to how the FAZs were developed in Franz Josef, compared to previous studies (Langridge and Beban 2011; Langridge et al. 2016a) is the inclusion of distributed FAZ buffers (see green areas on Figure 5.12). These generally account for the possibility of minor faulting, bending and warping in the hanging wall of the Alpine Fault (see Figure 2.1). The distributed FAZs also fill in areas between main fault traces, acknowledging that distributed fault deformation is likely between them.

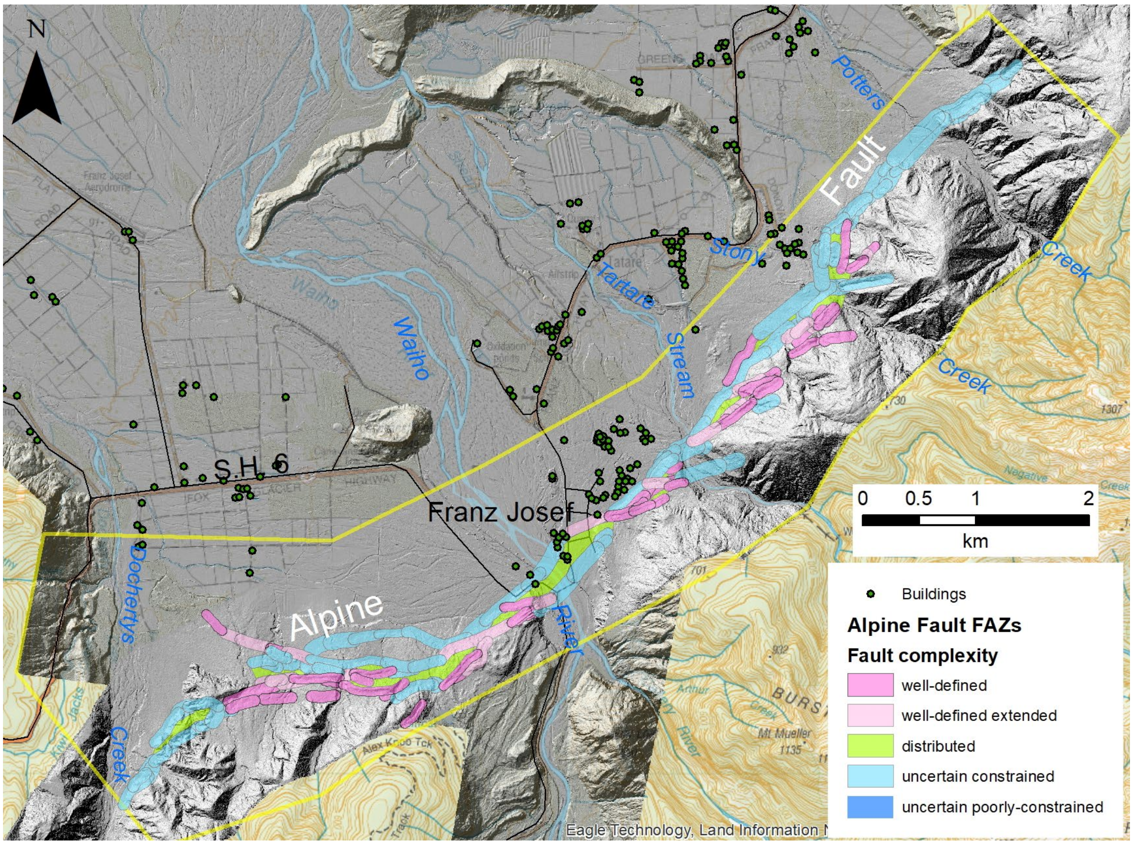

Figure 5.12 The Franz Josef priority area (yellow polygon) extending from Docherty Creek to Potter Creek. Traces of the Alpine Fault were mapped using LiDAR data (grey). Symmetrical FAZ buffers were developed for all traces (faults not shown in this view). Building locations (dots) are not provided for the inner built-up part of the town.

Symmetric FAZ buffers have been developed for all fault traces. These range in width from a minimum of 80 m for well-defined traces to up to 140 m for uncertain constrained traces (Figure 5.12). The widths of FAZ buffers within the Franz Josef village are discussed separately below.

5.7.1 The Alpine Fault and Franz Josef Township

The town of Franz Josef has always been an important exemplar regarding the mapping of the Alpine Fault and the application of FAZs through it. The first regional Alpine Fault study undertaken for the WCRC (Langridge and Ries 2010) crudely located the fault through the town and provided a FAZ for the first time. This was followed in 2011 by a Franz-Josef-specific fault-rupture hazard report (Langridge and Beban 2011; Langridge et al. 2011). At this time, a GPS-RTK map was constructed from survey data and, together with the 2010 airborne LiDAR data, used to better characterise the location of fault-related geomorphology in the vicinity of the town, including peer-reviewed GIS linework from Barth et al. (2012). FAZs developed for these reports included asymmetric or double-buffering of the upthrown side of fault traces. However, these FAZs were not widely accepted by the community and consequently not adopted for use by the Westland District Council. GIS fault linework and FAZs were later updated for a project that considered the multiple natural hazards posed to Franz Josef village (Langridge et al. 2016a). Each iteration of FAZs reflects an increase in knowledge or understanding.

The Alpine Fault has been recognised and mapped through the town of Franz Josef for many decades (Wellman 1953). Rupture of the Alpine Fault will cause 7–9 m of horizontal (dextral) slip across the fault zone and 1–2 m of vertical slip (Berryman et al. 2012b; De Pascale et al. 2014), with upthrow on the southeast side of the frontal fault traces (Langridge et al. 2017). The recurrence interval of faulting on the Central section of the Alpine Fault has recently been revised to 249 ± 58 years, with an elapsed time of 305 years since the last major rupture of the fault in 1717 CE, leading to a probability of rupture of the Alpine Fault of 75% in the next 50-year period (Howarth et al. 2021). Without doubt, rupture of the Alpine Fault during its next major earthquake will cause significant and life-threatening damage to buildings and other structures within the fault zone. Thus, it is highly important to characterise the surface-rupture hazard along the Alpine Fault, most particularly for Franz Josef.

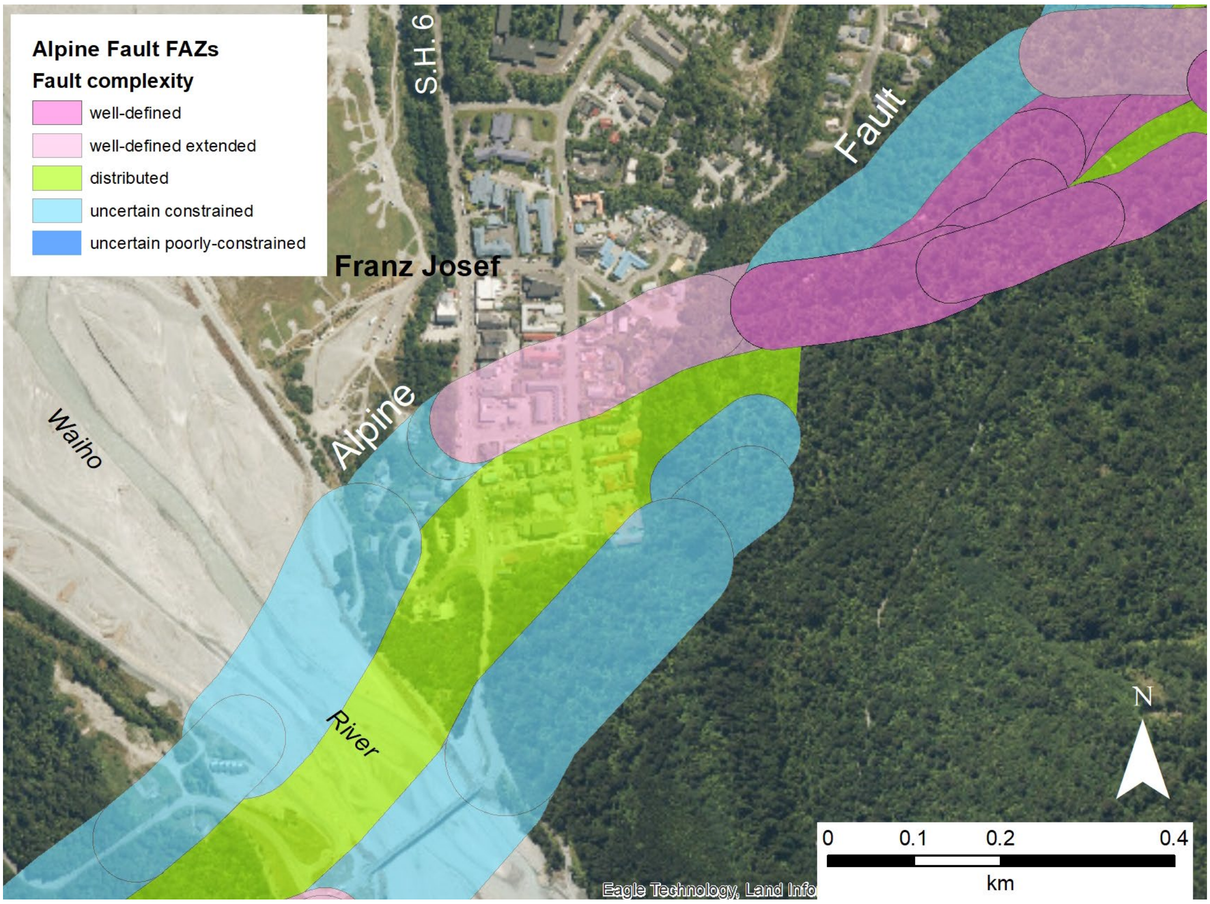

Figure 5.13 Revisions to Alpine Fault Fault Avoidance Zones (FAZs) in the Franz Josef village area. In general, FAZs have been narrowed on the southeast-facing side of scarps; this narrowing has been offset by including a FAZ of distributed deformation through the southeastern part of the village. Transparent FAZ allow for the visualisation of building footprints underneath.

As discussed above, all fault traces mapped in the vicinity of Franz Josef are now mapped with a dominantly dextral sense of motion because the main component of slip across the fault zone is dextral (right-lateral horizontal motion). In addition, we have assigned widths for the FAZs that are defined by the fault accuracy and deformation width, with the additional 20 m setback applied. All FAZ buffers are symmetrical about the mapped traces. The outcome of this is that FAZ widths through the village range from a minimum of 80 m for well-defined traces to 140 m for uncertain constrained traces (Figure 5.13). The main scarp mapped through the centre of town has a FAZ width of 100 m and a well-defined extended Fault Complexity, as the scarp has been smoothed for development within the town. However, in addition, distributed FAZs that fill in much of the upthrown part of the fault scarp through the village have been included, as described above.

5.8 Fox Glacier Priority Area

The Fox Glacier priority area spans c. 5 km of the Alpine Fault near the town of Fox Glacier (Figure 5.11). It stretches from Stony Creek in the southwest to Clearwater River in the northeast. Mapping is focused along a strip of LiDAR data acquired for studies of the Fox River catchment. Mapping was extended to the Clearwater River using the WCRC 9 m DSM and through review of previous mapping. The town of Fox Glacier is located c. 400 m west of the closest known trace of the Alpine Fault. In most cases, the fault traces are mapped within native forest or across active stream and river channels.

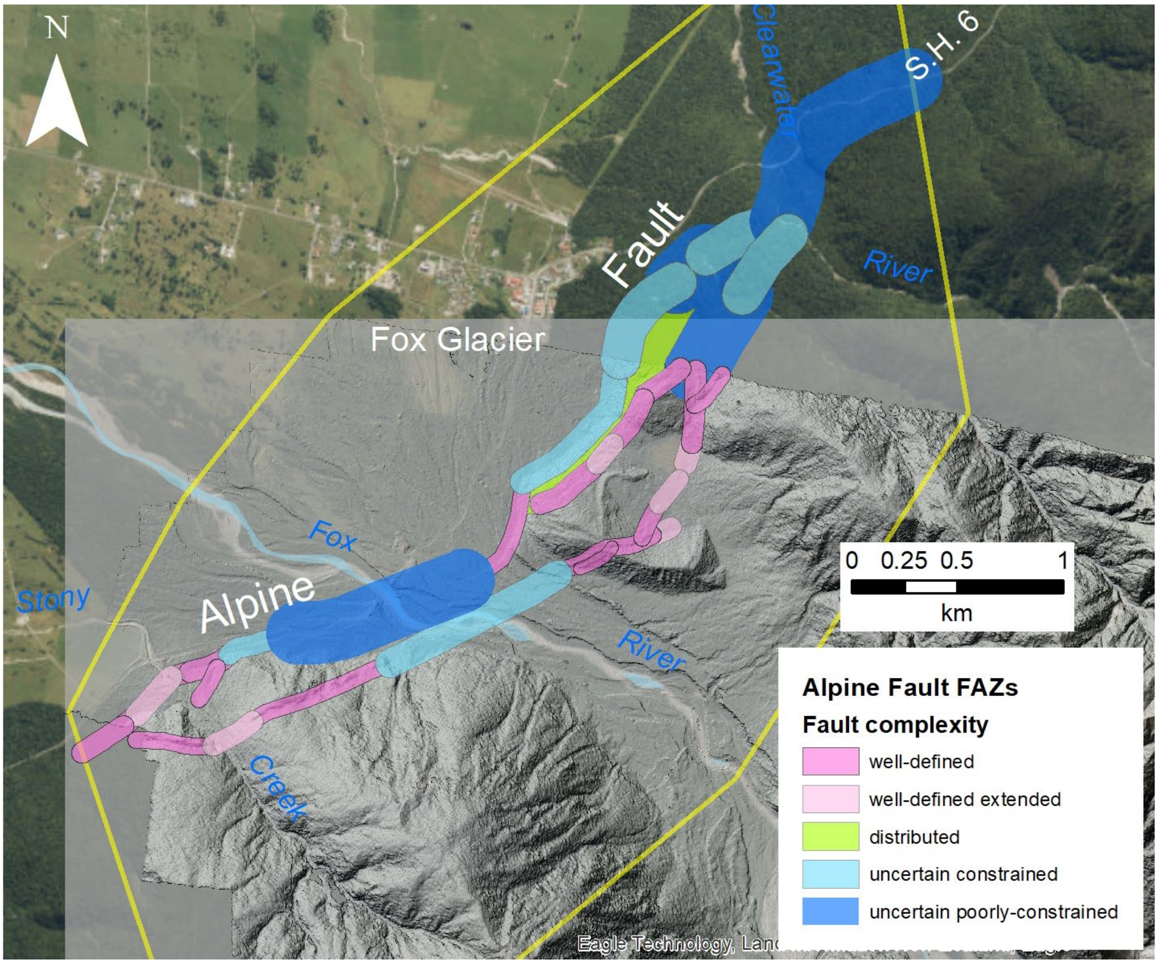

Figure 5.14 Fault Avoidance Zones (FAZs) in the Fox Glacier priority area (yellow polygon) extending from Stony Creek to Clearwater River. Traces of the Alpine Fault are mapped using LiDAR data (grey) and the WCRC 9 m DSM adjacent to the town. Symmetrical FAZ buffers have been developed for all fault traces (not shown in this view).

Within the Fox Glacier priority area, the Alpine Fault is mapped with similar partitioning as described for the Whataroa and Franz Josef priority areas (Norris and Cooper 1995; Barth et al. 2012). Zones of ENE-striking dextral-dominated faulting (e.g. west of the Fox River) transition to NE-striking zones of reverse-dextral faulting (e.g. northeast of the river).

Symmetric FAZ buffers developed using LiDAR data range in width from a minimum of 60 m for well-defined traces to up to 190 m for the uncertain poorly constrained trace across the Fox River, for which there is no mappable trace (Figure 5.14). Equivalently wide and wider FAZ buffers (190 and 300 m) have been developed for the areas mapped using the 9 m DSM.

5.9 Paringa Priority Area

Figure 5.15 indicates four priority areas defined in the southern part of Westland District: Paringa, Haast, Okuru and Turnbull.

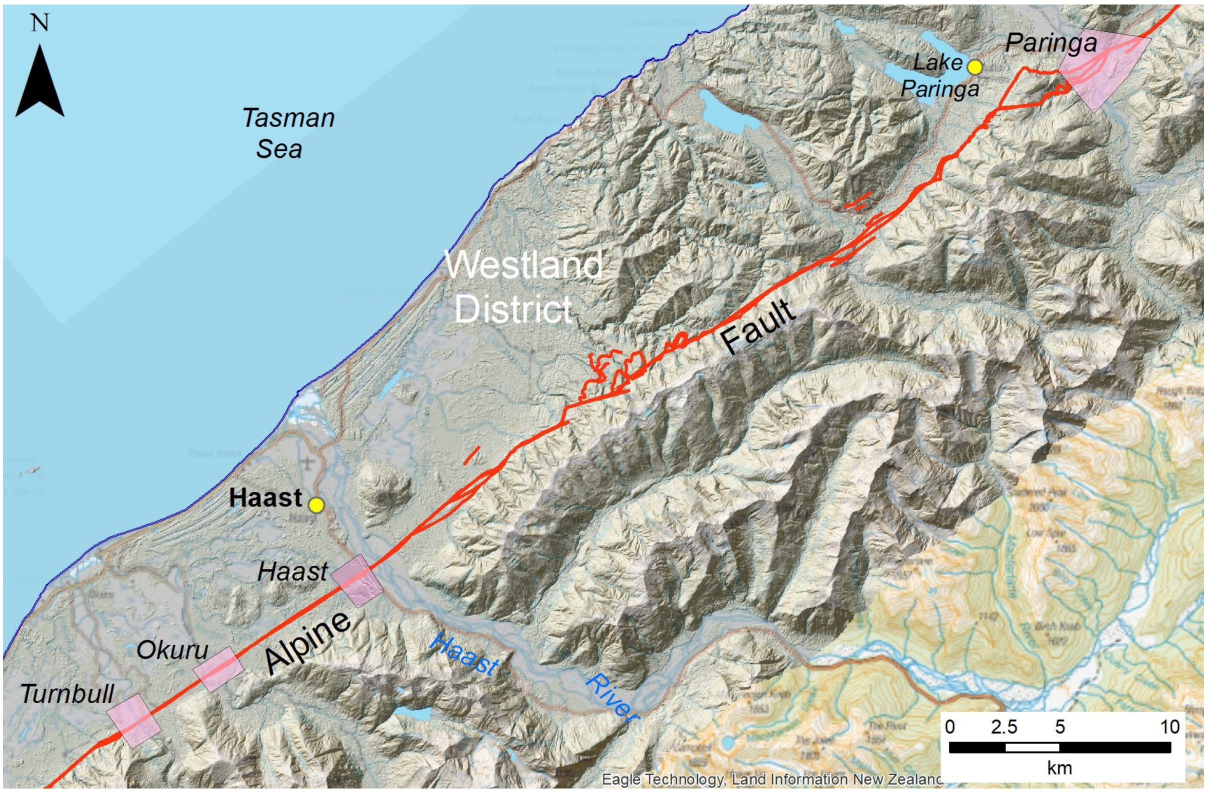

Figure 5.15 Priority mapping areas for the Alpine Fault in the southern part of Westland District (pink polygons, italics) shown on the WCRC 9 m DSM (grey). Red lines are 1:250,000-scale active faults from the New Zealand Active Faults Database (Langridge et al. 2016b).

The Paringa priority area is a small (4 km long) area where the Paringa River crosses the Alpine Fault (Figure 5.16). The village of Lake Paringa is located c. 5 km west of the priority area (Figure 5.15). There is currently no LiDAR coverage for this area. In the absence of LiDAR data, we utilised previous fault mapping and the WCRC 9 m DSM to interpret the location of the Alpine Fault here. The location of the fault in this area is mostly uncertain and is based on mapping by Rattenbury et al. (2010). Locations of the fault are constrained by outcrops of Australian or Pacific plate rocks and some geomorphological lineaments in the landscape.

FAZ buffers for the Paringa priority area are typically 300 m wide, reflecting the uncertain poorly constrained trace of the Alpine Fault in this area (Figure 5.16). The fault traces and FAZs mostly span areas of native bush and the active floodplain of the Paringa River. In one case, the fault trace is shown in proximity to the South Westland Salmon company, although with high location uncertainty because it is on the Paringa river floodplain and there is no visible scarp or trace there.

Two FAZ areas are indicated with well-defined fault complexity; these are traces mapped using the 9 m DSM as a base. A distributed FAZ is created for the area between Waituna Creek and the Paringa River because it is unclear how each of these fault strands connects up across the Little Paringa Hill area.

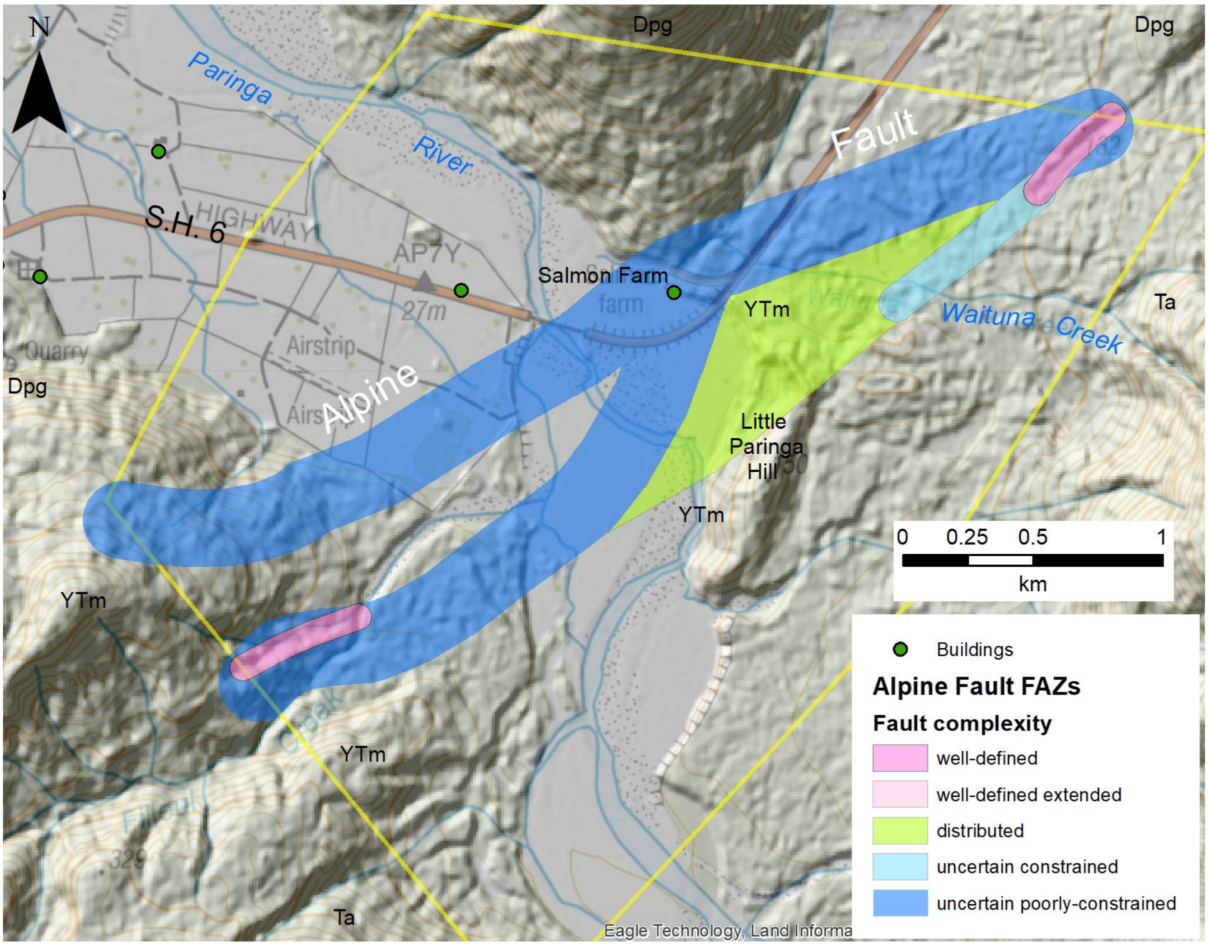

Figure 5.16 Fault Avoidance Zones (FAZs) in the Paringa priority area (yellow polygon) extending either side of the Paringa River. The location of the Alpine Fault was defined from bedrock localities i.e. those separating undifferentiated Paringa suite (Dpg) from Rakaia Terrane mylonite/schist (YTm and Ta,) (Rattenbury et al. 2010; dashed lines), and from geomorphology. Symmetrical FAZ buffers have been developed for all traces.

5.10 Haast Priority Area

The Haast priority area spans a short (1.6 km long) section of the Alpine Fault (Figure 5.17). The town of Haast is located c. 4 km northwest of the priority area (Figure 5.15). A small parcel of airborne LiDAR data was made available by Dr Nic Barth (University of California, Riverside) in order to map the area adjacent to the Haast River and State Highway 6 (SH 6). No mapping was undertaken outside of this area.

Paleoseismic studies, including trenches and measurements of displaced geomorphic features, were undertaken within c. 200 m of SH 6 by Berryman et al. (2012b; Figure 5.18). The area was subsequently modified for dairy farming (hump and hollow topography), and the original fault geomorphology has been destroyed. Nevertheless, the former trench and offset locations were captured with GPS surveying. Southwest of these surveyed sites, the fault is associated with a broad sag pond and a northwest-facing fault scarp of up to 9 m height.

Symmetric FAZ buffers developed using the LiDAR data range in width from a minimum of 80 m for well-defined traces to up to 160 m for uncertain constrained and uncertain poorly constrained traces (Figure 5.17).

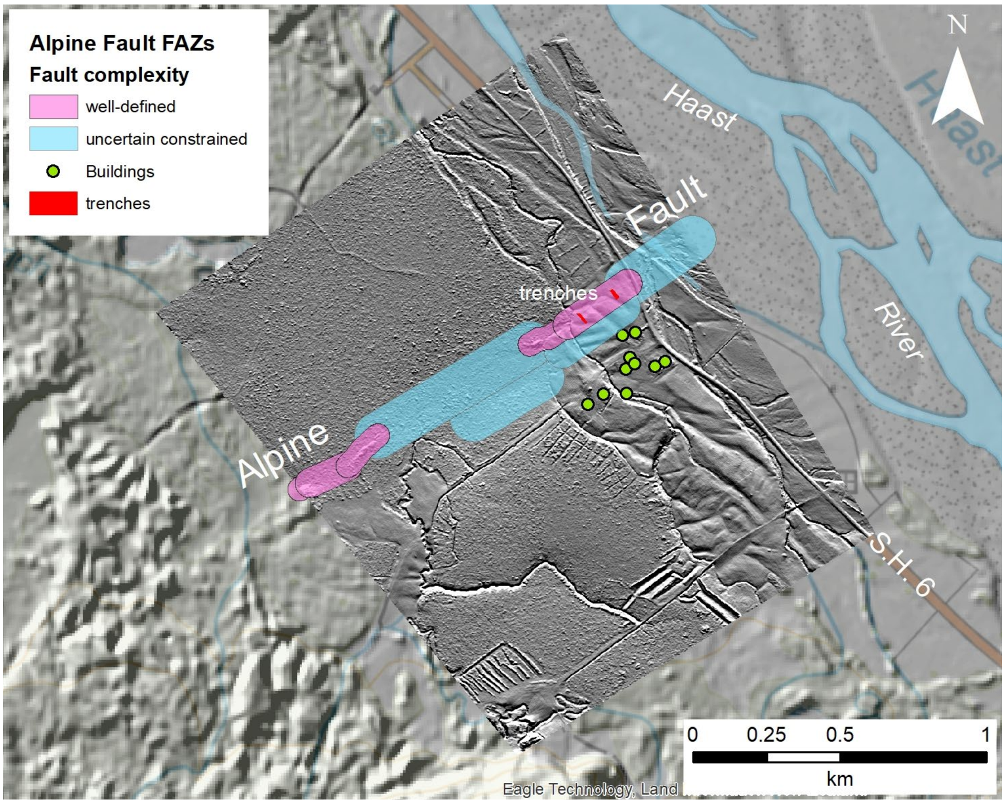

Figure 5.17 Fault Avoidance Zones (FAZs) in the Haast priority area (dark grey polygon) that indicate the extent of LiDAR coverage, adjacent to the Haast River. Fault traces are not shown here. Trench locations (red) from Berryman et al. (2012b).

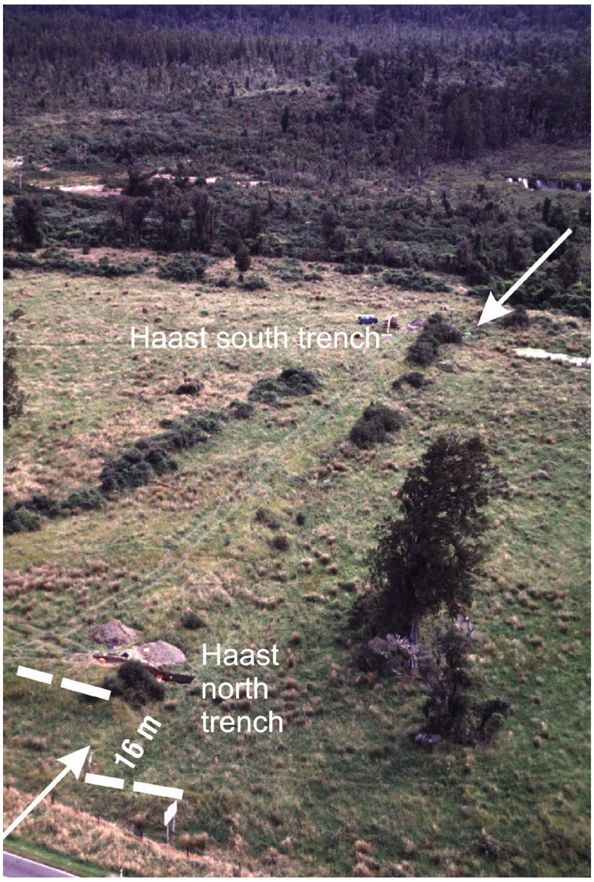

Figure 5.18 View to the south of the Alpine Fault (between arrows) in the Haast priority area. Two trenches were excavated here in 1998 adjacent to an abandoned channel that was offset c. 16 m dextrally. SH 6 is at lower left.

5.11 Okuru and Turnbull Priority Areas

The Okuru and Turnbull priority areas (Figure 5.15) are two small areas to the southwest of the Haast priority area, centred around the Okuru and Turnbull rivers (Figure 5.19). There is currently little or no development associated with these areas. They are of interest because the fault is well mapped here and paleoseismic studies (trenches and offset measurements) were undertaken in both areas by Berryman et al. (2012b). An airborne LiDAR swath acquired by Dr Nic Barth spans this part of the Alpine Fault. Despite the LiDAR data not being supplied at this time, Dr Barth provided us with detailed fault mapping in these two areas. Therefore, we have used that linework in this report to define the fault and FAZs. No new mapping was undertaken outside of the priority areas.

For the Okuru priority area, 9 km southwest of Haast, FAZ buffers developed from the fault trace mapping range in width from a minimum of 80 m for well-defined traces to 140 m for uncertain constrained traces (Figure 5.19). For the Turnbull priority area, 13 km southwest of Haast, FAZ buffers developed from fault trace mapping range in width from a minimum of 100 m for well-defined traces to 140 m for uncertain constrained traces. Several of these FAZs overlap in each area, creating a wider Alpine Fault FAZ.

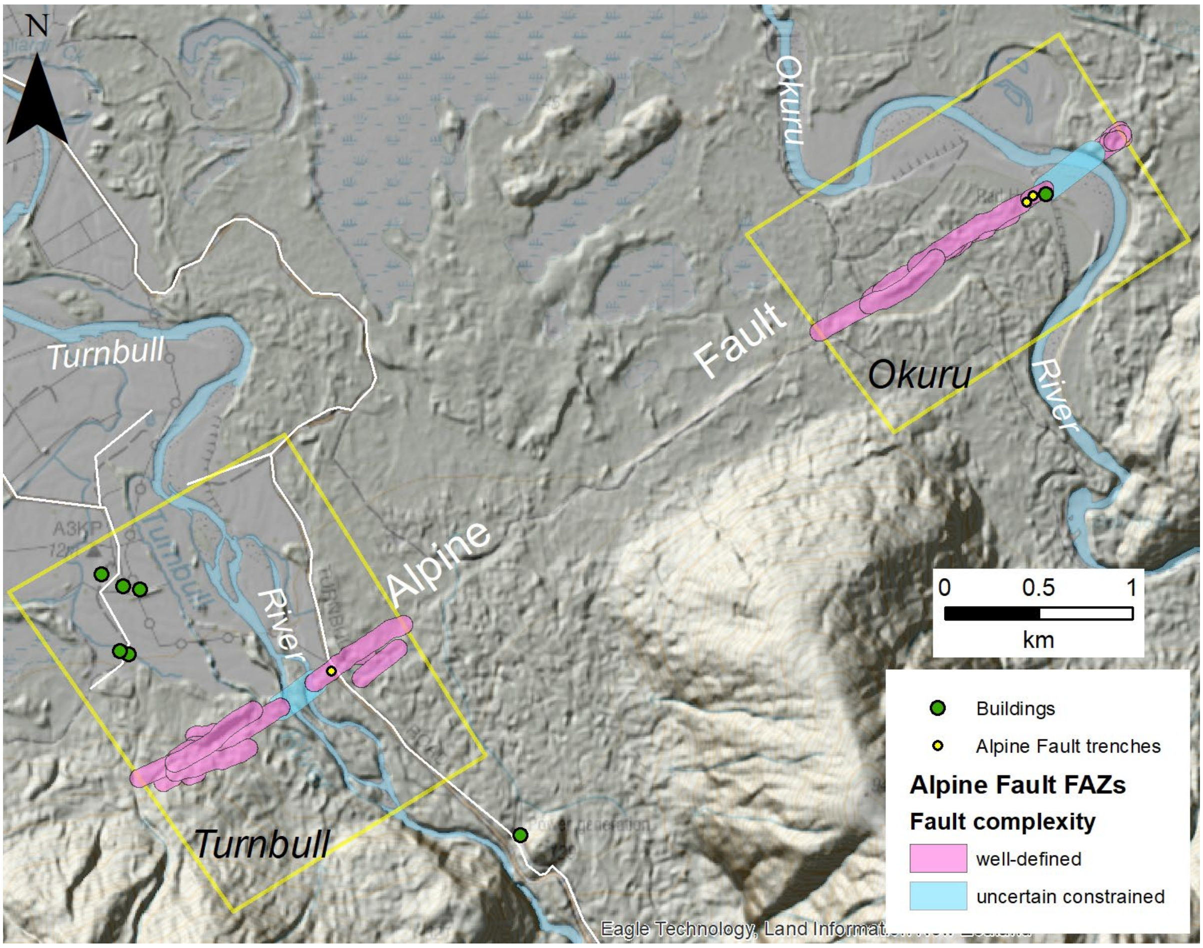

Figure 5.19 Fault Avoidance Zones in the Okuru and Turnbull priority areas, defined by yellow polygons. Fault traces are not shown in this view. Trench locations (yellow) from Berryman et al. (2012b); building locations are shown as green dots.

6.0 IMPLICATIONS OF FAULT AVOIDANCE ZONES AND THE MINISTRY FOR THE ENVIRONMENT ACTIVE FAULT GUIDELINES

This report outlines the methodologies for mapping the Alpine Fault, using advanced digital topographic datasets such as LiDAR data and DSMs, and for the development of FAZs district by district along the West Coast for use within the Te Tai o Poutini Plan (TTPP). The Alpine Fault is a RI Class I fault (RI ≤2000 years), although, in reality, its average recurrence interval is c. 300 years (Cochran et al. 2017; Howarth et al. 2021).

The science surrounding the likelihood of a large to great earthquake occurring on the Alpine Fault is advanced, with a statistical probability of 75% occurrence in the next 50 years assigned to it (Howarth et al. 2021). This represents a high risk of occurrence, and therefore it is critical to seriously consider the life-safety hazard posed by buildings and infrastructure along the fault. At present, the MfE Guidelines provide the only clear pathway to applying land-use planning evaluation in regard to avoidance of surface fault-rupture hazard (Kerr et al. 2003). In this report, we have followed the methodologies of the MfE Guidelines with respect to the methods for quantifying the accuracy of fault line mapping and the uncertainties around the fault location and width of fault deformation.

Single-event displacements along the Alpine Fault are considered to occur with multi-metre horizontal (dextral) and vertical components (Berryman 1975; Berryman et al. 2012b). Uniform dextral slip of c. 7.1 ± 2.1 m per event is suggested for a 350 km length of the fault from Milford Sound to Inchbonnie (De Pascale et al. 2014). Single-event vertical displacement is on the order of 1–2 m along the length of the fault (Berryman 1975; Berryman et al. 2012b; Langridge et al. 2017). Therefore, in terms of durability, buildings constructed on or near the fault are unlikely to cope well with such large displacements and therefore not have post-event functionality. The challenge with characterising this displacement is estimating the width over which this displacement will occur and what examples of such displacements we can refer to.

Life safety from building collapse is the main driver within the MfE Guidelines, while the consideration of post-event functionality has become more relevant since the 2010–2012 Canterbury earthquakes and 2016 Kaikōura earthquake (Van Dissen et al. 2019). It may not be possible nor cost effective to design foundations to sustain such large displacements to avoid building collapse in order to protect lives, albeit even if lives are saved there is no guarantee that such buildings will have post-event functionality.

6.1 Comparison to an Earthquake with Similar Single-Event Displacements

The 2016 M_W 7.8 Kaikōura earthquake provides many examples of lateral and oblique-slip movements that would be similar in scale to Alpine Fault single-event displacements. Figure 6.1 highlights observations of offset across the dextral-slip Kekerengu Fault, which had the largest fault displacements in the Kaikōura earthquake (Kearse et al. 2018; Litchfield et al. 2018; Van Dissen et al. 2019). These images show that the fault can have multiple traces or have both complex vertical and horizontal displacement, particularly in surficial materials. Horizontal motion is often difficult to visualise or measure unless there are man-made markers, e.g. roads or ditches, that can record it. Nevertheless, the three examples in Figure 6.1 are all associated with 6–10 m of dextral motion, which is in the range of Alpine Fault single-event displacement. The complexity observed in the ruptures is a lesson that helps us to consider how wide FAZs should be. For example, these faults were mapped as single traces prior to 2016, but have complex rupture zones. In some areas, three traces of the Kekerengu Fault were mapped and had been trenched prior to the earthquake; however, only two of these traces showed surface displacement in the 2016 earthquake (Little et al. 2018).

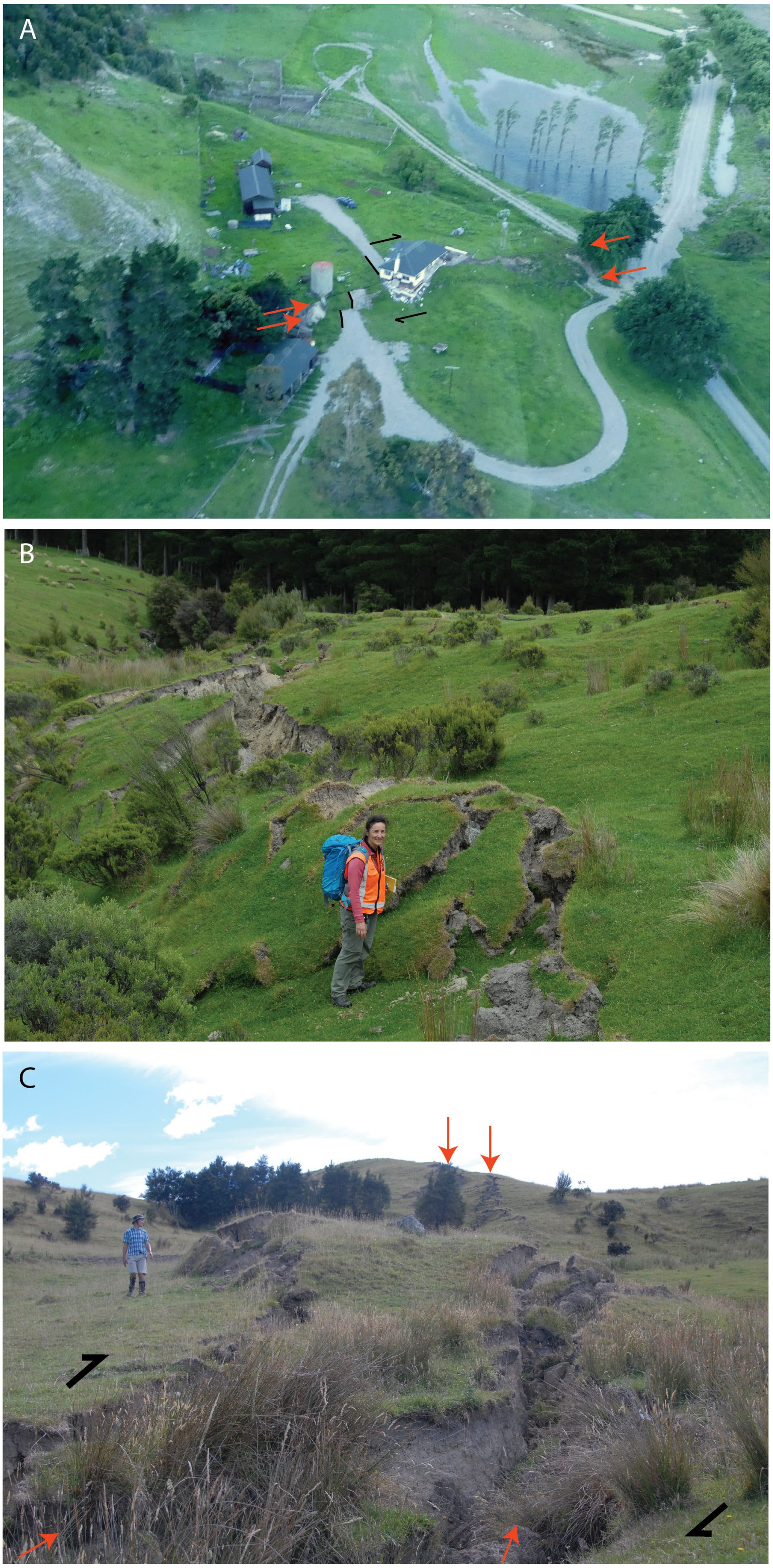

Figure 6.1 Photos of surface rupture along the Kekerengu Fault in the 2016 Kaikōura earthquake. (A) Dextral-slip rupture at Bluff Station; red arrows mark dual rupture traces. Black arrows show dextral sense. Black lines highlight dextral offsets summing to c 10 m. (B, C) Complexity of surface rupture deformation at Bluff Station and near Shag Bend, respectively, in the Waiau Toa / Clarence River valley.

For Figure 6.1A, we would likely map these traces as accurate and apply a 20 m location certainty to the mapped line. This is an unusual case, because the fault movement has just happened and the traces at the Earth's surface are known exactly. For faults that have not ruptured historically, we cannot know absolutely where the main line or zone of deformation will be, or how complex. Therefore, the FAZs we develop carry inherent uncertainties. In fact, they are designed to address the uncertainty on the location of the fault.

In Figure 6.1B and C, the vertical motion of 'turf rafts', or blocks of soil formed in fine-grained sediment, is caused by local complexities along the fault, related to changes in strike or slope direction, and the soil material properties. These surface features are known as 'push-ups' or 'pull-aparts' where the ground rucks up or opens up, respectively (Figure 6.1C). Such dramatic rupture features smooth out or heal over time by a process known as scarp degradation. Many decades after the 2016 Kaikōura earthquake, it may be possible to observe a degraded fault zone where two or even only one clear fault trace can be mapped, but with less certainty than immediately after the event. This also speaks to the uncertainty in our ability to know exactly where and how complex the main zone of deformation will be. Figure 6.2 highlights this and demonstrates why we define a FAZ around a mapped fault trace.

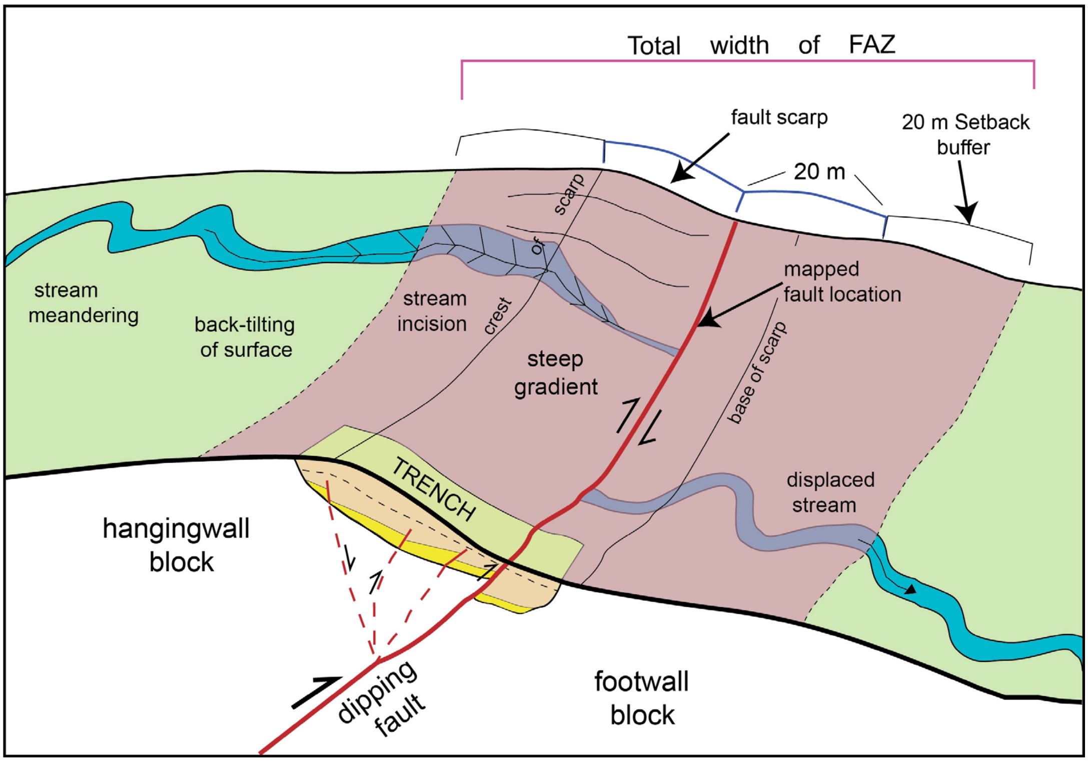

Figure 6.2 A schematic diagram of a Fault Avoidance Zone (pink) for a well-defined fault trace along the Alpine Fault. Here, the fault location certainty is given an accuracy of ±20 m and a setback zone of 20 m is added to that. Dextral motion will offset geomorphic features, such as streams, across the fault. Trenches may confirm the main zone of faulting and expose secondary faults.

Figure 6.3 highlights observations of offset across the oblique-slip (sinistral reverse) Papatea Fault, which had similar-sized displacements to the Kekerengu Fault in 2016 (Diederichs et al. 2019; Langridge et al. 2018b). These images show that several metres of deformation can be distributed across a significant width (Figure 6.3A) and cause damage to buildings and other structures (Figure 6.3B and C; Van Dissen et al. 2019). For fault traces in Figure 6.3A, a 20 m location accuracy would be applied, with an additional setback distance of 20 m added to them (Figures 6.2 and 6.4). These buffers may overlap; however, where they do not overlap, it may be appropriate to design a buffer for distributed deformation, as we have done in this report.

Figure 6.3 Photos of surface rupture along the Papatea Fault in the 2016 Kaikōura earthquake. (A) Distributed zone of surface rupture at Glen Alton; red arrows mark rupture traces. Black arrows show sinistral (left-lateral) sense of motion, also seen in bent tree rows. (B) Red-roofed house from (A), showing bending deformation on top of one the rupture scarps. (C) Vertical deformation across SH 1 on the western strand of the Papatea Fault at the coast.

In general, FAZs are features of limited geographic extent, being tens of metres wide around mapped faults. Because of their uncertainties, FAZs have a built-in conservatism within them, i.e. it is possible that there is little to no life-threatening deformation or displacement near the outer edges of FAZs. For this reason, it is appropriate to consider detailed fault studies involving geological and/or surveying methods to determine the exact width of deformation. Figure 6.4, taken from the MfE Guidelines, shows an idealised FAZ, in which the yellow area is the setback zone of 20 m.

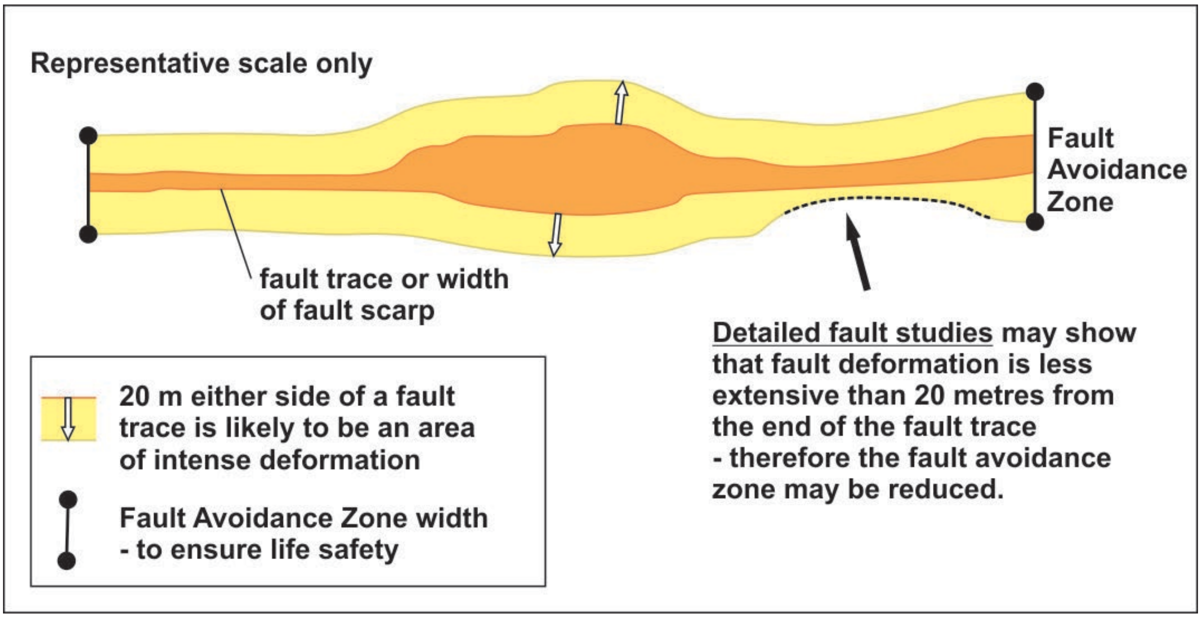

Figure 6.4 A Fault Avoidance Zone (FAZ; orange + yellow) and how it may be developed for district planning purposes (not drawn to scale), modified from Kerr et al. (2003). The orange area denotes the zone developed considering Fault Complexity. The 20 m setback zone is part of the FAZ and the area where the FAZ has been narrowed by undertaking detailed fault studies.

Similarly, because of this conservatism, there is an assumption of no significant fault-related ground deformation outside of the FAZs, so a house or building with no foundations inside the FAZ should be clear of the hazard of fault-related ground-surface deformation. Nevertheless, the ground motions (shaking) from a very large earthquake will be very high both inside and outside the FAZ. This topic will be elaborated on in Section 6.3 below.

Figure 3.2 shows how a FAZ covers the ground at a site where considerable geological work has been done. At Marble Hill, three trenches and four pits have been excavated to estimate the age of terraces, fault slip rate and timing of past earthquakes on the Alpine Fault (Yetton 2002; Langridge et al. 2017). Research trenches shown in Figure 3.2 are c. 26 m long and straddle the scarp, which is mapped with an accurate fault trace on open ground. The main zone of faulting was confined to the scarp (the sloping landform of the fault, expressed between flat terrace surfaces), with some minor faults observed on the hanging-wall side of the trenches (Langridge and Howarth 2018). In addition, a pit excavated adjacent to that trench showed another minor fault in the subsurface not expressed at the ground surface. These observations show that the FAZ designed for this site (80 m wide, symmetric about the mapped fault) adequately covers the ground-surface rupture deformation hazard. Nevertheless, if two 20-m-long trenches were excavated by a developer in the two outer parts of the FAZ (spanning the setback zone; Figure 6.2), it may be deemed that the observed deformation was older (>2000 years) or not of sufficient displacement to warrant a life-safety hazard. Herein is the utility of the setback zone, as it allows for the opportunity to test, through geology or by surveying, the efficacy of the FAZ width. We note also that this project is undertaken at a regional scale and site-specific studies at property scale are outside the scope of this report.

6.1 Impacts of Alpine Fault Rupture on Buildings within a Fault Avoidance Zone

In this report, we have provided maps of 18 priority areas with FAZs and building locations. The latter come from GIS points taken from 1:50,000-scale topographic maps but do not include buildings within built-up areas where the building density is greater (Figure 5.12). The GIS does not provide attribute information on the Building Importance Category (BIC); however, in many cases, we assume that the buildings are BIC 1 buildings (mostly barns and farm sheds) due to their location on the Alpine Fault where it typically crosses farmland and forested country with little habitation. The MfE Guidelines do not support the need for planning restrictions for BIC 1 structures located within FAZs associated with a RI Class I fault, such as the Alpine Fault (Tables 6.1 and 6.2; Kerr et al. 2003).

Most of these maps show only a few buildings close to or within the FAZs. For example, Figure 4.4 at the Haupiri River shows many buildings associated with the Gloriavale community, most of which are well outside the FAZs. Some buildings are notably within the FAZs northwest of the river; however, based on a site visit, it is likely that these are BIC 1 farm buildings. At Inchbonnie, there are a few buildings close to the FAZs defined there, one of which is probably a dwelling, i.e. BIC 2a (Figure 4.6).

Figure 6.5 Examples of damage to a BIC 2a house caused by surface rupture of the dextral-slip Greendale Fault, near Darfield, during the 2010 Darfield earthquake. Timber-framed, brick-clad house with concrete slab foundation (at most, only lightly reinforced) and light-weight roof that is located within a ~150-m-wide deformation zone accommodating 4–5 m of dextral displacement. The house was badly damaged by distributed deformation and ~0.5 m of discrete strike-slip rupture (red arrows) that enters the house (modified from Van Dissen et al. [2011]).

The overwhelming exception to this discussion is the village of Franz Josef (Figures 5.12 and 5.13). Franz Josef represents the largest built-up area along the entire length of the Alpine Fault. Previous mapping efforts have defined the Alpine Fault as a zone of deformation through the village, with development of FAZs from regional mapping and detailed LiDAR data (Langridge and Ries 2010; Langridge and Beban 2011; Langridge et al. 2016a). Presentation of these FAZs has not been met with acceptance by the local community, which has meant that FAZs as a means of mitigating ground-surface rupture hazard have not been widely adopted by Westland District Council.

Nevertheless, there are at least 30 buildings within the FAZs shown in Franz Josef, including motels, a petrol station, a supermarket, cafes and restaurants and many homes (Figure 5.13). Displacement within the main (northwestern) FAZ through the town will likely accommodate most of the 7–9 m of reverse dextral movement expected when the fault ruptures. This will ultimately pose a serious life-safety hazard for occupants of BIC 2a and 2b structures within the FAZ (Figure 6.5). Occupancy of various buildings, e.g. motels and cafes, will vary on a day-to-day basis and at different times during the day or night.

More recently acquired LiDAR data has also allowed for a detailed look at the neighbouring village of Fox Glacier, which is also sited close to the fault range front (Figure 5.14). In this case, the mapped fault traces are mapped to the east of town at the edge of the bush-covered range front. Thus, there are no known buildings within the FAZs in the Fox Glacier priority area.

6.2 Surface Fault Rupture versus Strong Ground Motion

During a very large earthquake, there will be both permanent ground deformation along the fault and very strong ground motions (seismic shaking) felt over a much wider area. Seismic shaking for future events is modelled through understanding the likely earthquake magnitude, properties of the crust, distance from the fault or epicentre and sub-surface material conditions, as well as known shaking from historical earthquakes.

In proximity to the Alpine Fault, ground motions will be very strong irrespective of whether a parcel of land is within or outside of a FAZ. Figure 6.6 highlights the predicted ground motions using the Felt Intensity or Modified Mercalli Intensity (MMI) scale (for New Zealand) for a M_W 8.1 rupture involving the southern and central sections of the Alpine Fault – that which has a 0.8 x 75% of occurrence in the next 50 years[5] (see Howarth et al. [2021] for probabilities). According to the GeoNet website (https://www.geonet.org.nz/earthquake/intensity), MMI 9 shaking in New Zealand would result in "some buildings … damaged and many weak buildings … destroyed". The envelope for MMI 9 shaking in Figure 6.6 has a width of 20–25 km and covers the entirety of Westland District. Close to the Alpine Fault, MMI 10 (or higher) shaking is likely; however, at what localities and to what distance from the fault this occurs depends on the parameters used to model it. In essence, MMI 10 shaking – which equates to effects of "many buildings are damaged and most weak buildings are destroyed" – would likely occur within both Franz Josef and Fox Glacier villages.

Regulation of structures and buildings for ground motions for seismic shaking are primarily addressed by the Building Act 2004, which dictates the strength and engineering measures required for buildings across New Zealand. Seismic hazard is not equal in New Zealand, and a factor of seismic hazard, called the Z factor, is applied across the country. The Z factor used to determine the seismic risk is in accordance with the Standard cited in the Verification Method for Building Code Clause B1-Structure and applied when the new system for identifying, assessing and managing earthquake-prone buildings came into force on 1 July 2017 (Standards NZ 1170.5:2004). The area in which a building is located has a low seismic risk if the area has a Z factor that is <0.15, a medium seismic risk if the area has a Z factor that is ≥0.15 and <0.3 and a high seismic risk if the area has a Z factor that is ≥0.3. The Z factor for the Franz Josef, Fox Glacier, Harihari and Hokitika-Styx priority areas is between 0.44 and 0.46. This is the appropriate means for dealing with ground-motion hazard to buildings in New Zealand (i.e. outside of the FAZs and where no other planning controls are present).

---

[5] 75% in 50 years applies to rupture of the central or combined central + southern sections of the fault.

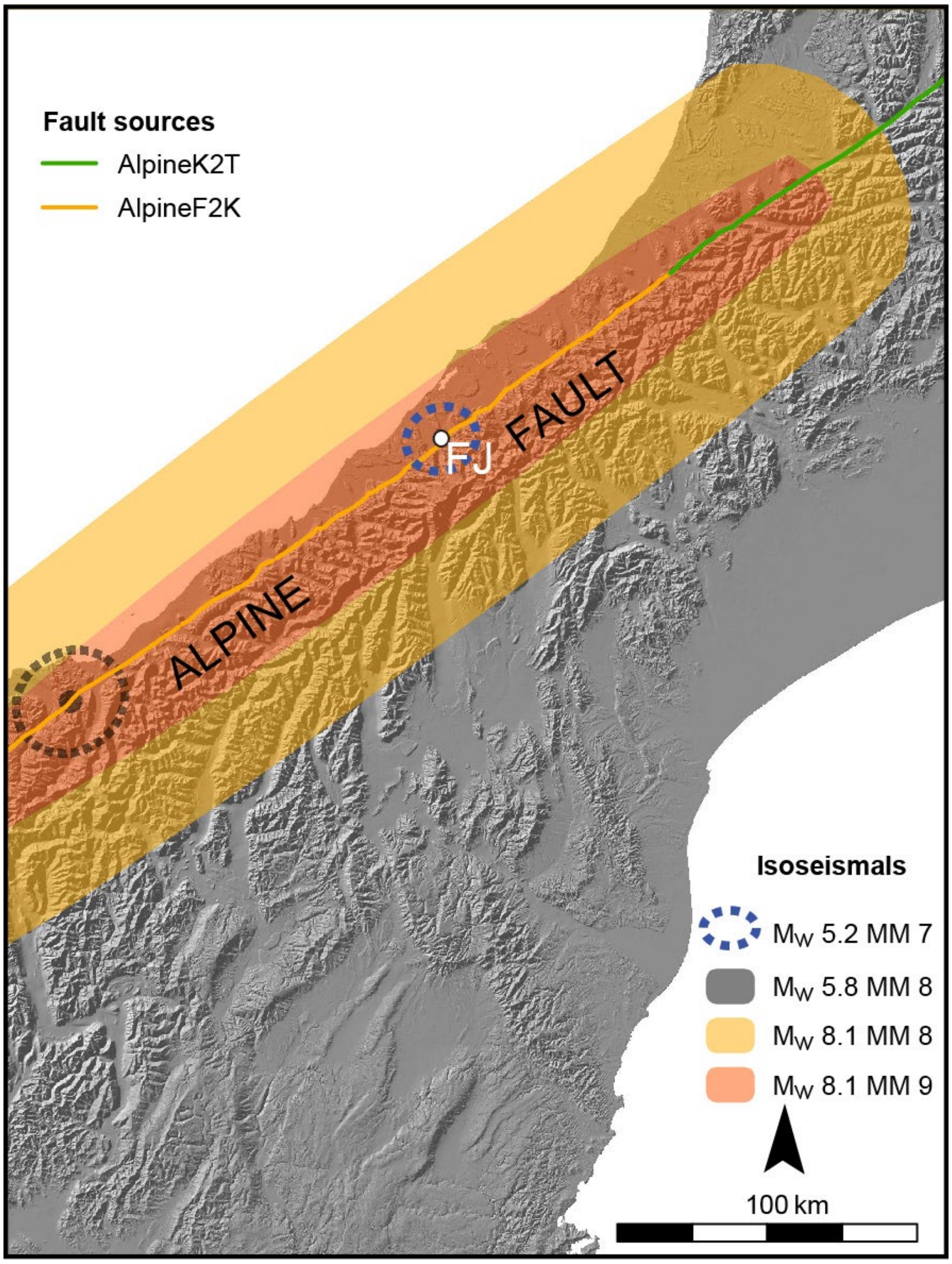

Figure 6.6 Examples of estimated strong ground motions measured in Modified Mercalli Intensity for three different earthquake scenarios along the Alpine Fault (from Langridge et al. 2016a). Alpine K2T and F2K represent two fault source sections within the New Zealand seismic hazard model of Stirling et al. (2012).

6.3 What Buildings are Appropriate in an Alpine Fault Fault Avoidance Zone?

Tables 6.1 and 6.2 present examples of the relationships between BIC and Fault Complexity, and the subsequent Resource Consent Category, for both previously developed and greenfield sites along RI Class I faults with FAZs in the West Coast region. These examples are modified from the MfE Guidelines based on recommendations made for a similar fault mapping study for the Kāpiti Coast District Council (Van Dissen and Heron 2003).

Table 6.1 The relationship between Building Importance Category (BIC) and Fault Complexity for developed and/or already subdivided sites on a Recurrence Interval (RI) Class I fault, based on the MfE Guidelines (Kerr et al. 2003).

Developed and/or Already Subdivided Sites					
ALPINE, AWATERE and KELLY/HURA FAULTS (based on fault RI Class I, ≤2000 years)					
BIC	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well defined and well-defined extended	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain constrained and uncertain poorly constrained	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

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

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

This re-assessment of the FAZs in Franz Josef substitutes a double-buffered scarp for a symmetrically buffered scarp crossing obliquely through, and a distributed FAZ in the upper part of, the village (Figure 5.13). According to Table 6.1, only BIC 1 structures should be permitted within FAZs. BIC 2a structures are *Non-Complying* within well-defined and well-defined extended FAZs (based on fault complexity). However, we note that, for distributed and uncertain FAZs in Franz Josef (see Table 6.1), existing and even new BIC 2a structures may be considered *Discretionary* activities where the FAZ is Distributed or Uncertain (i.e. green and blue areas in Figure 5.13). In other words, normal single-storey timber-framed homes may be possible, as the risk profile differs from those higher BIC structures. This is because the life-safety risk in an individual single-storey New Zealand home is relatively low (see Figures 6.1A and 6.5). Nevertheless, in all cases, BIC 2b or higher buildings are associated with *Non-Complying* to Prohibited planning consent activities in an Alpine Fault FAZ (Kerr et al. 2003).

Table 6.2 relates to greenfield sites. This table is very similar to Table 6.1 but stipulates that BIC 4 structures are Prohibited within well-defined and well-defined extended FAZs. This essentially prohibits the construction of new structures that require post-event functionality (e.g. hospitals, schools, police and fire stations, etc.) being located within well-defined FAZs.

Table 6.2 The relationship between Building Importance Category (BIC) and Fault Complexity for Greenfield sites on a Recurrence Interval (RI) Class I fault, based on the MfE Guidelines (Kerr et al. 2003).

Greenfield Sites					
ALPINE, AWATERE and KELLY/HURA FAULTS (based on fault RI Class I, ≤2000 years)					
BIC	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well-defined and well-defined extended	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain constrained and uncertain poorly constrained	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

7.0 SUMMARY

The Alpine Fault is a RI Class I active fault (RI ≤2000 years) and has a high probability (75%) of generating a very large earthquake in the next 50 years. In this study, the fault has been mapped by assessing available airborne LiDAR data and other mapping techniques across the three districts of the West Coast region for the purpose of understanding fault deformation and to develop Fault Avoidance Zones (FAZs) for 18 priority areas where airborne LiDAR coverage currently exists. These priority areas were chosen to reflect areas where there is currently, or may be, development in future. The mapping provides an update of and builds on previous studies (e.g. Langridge and Ries 2010; Langridge et al. 2016a).

Alpine Fault priority areas within the three districts are as follows:

- **Buller District:** Marble Hill, Palmer Flat and Newcombes.
- **Grey District:** Ahaura, Haupiri and Lake Poerua.
- **Westland District:** Taipo, Arahura, Hokitika-Styx, Waitaha, Harihari, Whataroa, Franz Josef, Fox Glacier, Paringa, Haast, Okuru and Turnbull.

Our approach and methodology to mapping fault traces are based on those laid out in the MfE Guidelines with a view to developing FAZs, applying the categories identified in Kerr et al. (2003). The width of FAZs depends on the accuracy of fault mapping (accurate, approximate or uncertain traces) and Fault Complexity (ranging from well-defined to uncertain poorly constrained), defined by the deformation width observed. FAZs are made up of a deformation width plus a setback zone, which is always an additional 20 m around the deformation width. In general, well-defined FAZs for this study can be as narrow as 80 m, and the widest FAZs can have a width of up to 300 m for uncertain poorly constrained Fault Complexity.

FAZs have also been provided for the westernmost ends of the RI Class I Awatere and Hura faults that intersect the Alpine Fault within designated priority areas.

Maps have been presented in this report for all of the priority areas. These show FAZs and the location of buildings near to or within FAZs that are in the LINZ Topo 50 digital data. In most areas, there are few buildings near to or within the FAZs and, where present, most of these are likely to be BIC 1 structures, such as farm buildings.

The village of Franz Josef is the largest developed area along the Alpine Fault, with the greatest number of buildings located within any of the Alpine Fault FAZs. These buildings include motels, a petrol station, a supermarket, several cafes and restaurants and many homes, which are classed as BIC 2a to 3 structures. Single-event displacement within the FAZ through the village will be on the order of 9 m, including c. 7 ± 2 m of horizontal movement and 1–2 m of vertical movement.

GNS Science understands that the TTPP aims to develop a consistent framework for all natural hazards across all three West Coast districts (including flood, landslide, tsunami and sea-level rise). Based on the nature of the hazard and our ability to identify and map this, as undertaken in this report, fault rupture avoidance can be treated consistently across the identified priority locations in this report. In between these priority areas, it may be necessary to adjust and join the locations of the Alpine Fault and FAZs with previously supplied GIS datasets.

8.0 RECOMMENDATIONS

Based on the findings in this report, GNS Science recommends:

- Consideration of the Alpine Fault datasets from this study as the most up-to-date and accurate information for the 18 priority areas described. Previous Alpine Fault trace and FAZ datasets from these 18 areas should be replaced with the new data from this study. An important aspect of adopting this work will be to reconcile (cut and join) GIS data sourced from previous studies in between each of the priority areas.
- Development of planning consent provisions by WCRC using the information provided in this report, based on the guiding principles and the risk-based decision-making tools of the MfE Guidelines.
- Inclusion of the newly mapped FAZs in the TTPP. The FAZs should be used in future district planning consent and regional policies until the data have been further updated as new knowledge and datasets become available.
- Consideration of mapping other active faults (and other parts of the Alpine Fault) as more airborne DEM data becomes available through PGF LiDAR acquisitions, particularly in areas where future population growth or shift is expected.

9.0 ACKNOWLEDGEMENTS

We thank Jo Paterson, Edith Bretherton and Alex Ching at the West Coast Regional Council for supporting this work and providing airborne LiDAR as it became available. We also thank Dr Nic Barth of the University of California: Riverside for providing airborne LiDAR and fault trace mapping for southern areas. Dr Pilar Villamor and Dr Dougal Townsend reviewed the active fault mapping (GIS) and this report. Their feedback improved the quality of this work.

10.0 REFERENCES

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

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

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

Barth NC, Toy VG, Langridge RM, Norris RJ. 2012. Scale dependence of oblique plate-boundary partitioning: new insights from LiDAR, central Alpine fault, New Zealand. *Lithosphere*. 4(5):435–448. doi:10.1130/l201.1.

Berryman KR. 1975. Immediate report, earth deformation studies reconnaissance of the Alpine Fault. Lower Hutt (NZ): New Zealand Geological Survey. 30 p. Report EDS 30.

Berryman KR, Beanland S, Cooper AF, Cutten HN, Norris RJ, Wood PR. 1992. The Alpine Fault, New Zealand: variation in Quaternary structural style and geomorphic expression. *Annales Tectonicæ*. VI(suppl):126–163.

Berryman KR, Cochran UA, Clark KJ, Biasi GP, Langridge RM, Villamor P. 2012a. Major earthquakes occur regularly on an isolated plate boundary fault. *Science*. 336(6089):1690–1693. doi:10.1126/science.1218959.

Berryman KR, Cooper A, Norris R, Villamor P, Sutherland R, Wright T, Schermer E, Langridge RM, Biasi G. 2012b. Late Holocene rupture history of the Alpine Fault in South Westland, New Zealand. *Bulletin of the Seismological Society of America*. 102(2):620–638. doi:10.1785/0120110177.

Cochran UA, Clark KJ, Howarth JD, Biasi GP, Langridge RM, Villamor P, Berryman KR, Vandergoes MJ. 2017. A plate boundary earthquake record from a wetland adjacent to the Alpine Fault in New Zealand refines hazard estimates. *Earth and Planetary Science Letters*. 464:175–188. doi:10.1016/j.epsl.2017.02.026.

Cox SC, Barrell DJA, compilers. 2007. Geology of the Aoraki area [map]. Lower Hutt (NZ): GNS Science. 1 folded map + 71 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 15).

De Pascale GP, Quigley MC, Davies TRH. 2014. LiDAR reveals uniform Alpine fault offsets and bimodal plate boundary rupture behavior, New Zealand. *Geology*. 42(5):411–414. doi:10.1130/g35100.1.

Diederichs A, Nissen EK, Lajoie LJ, Langridge RM, Malireddi SR, Clark KJ, Hamling IJ, Tagliasacchi A. 2019. Unusual kinematics of the Papatea fault (2016 Kaikōura earthquake) suggest anelastic rupture. *Science Advances*. 5(10):eaax5703. doi:10.1126/sciadv.aax5703.

Heron DW, custodian. 2020. Geological map of New Zealand 1:250,000: digital vector data [map]. 3rd ed. Lower Hutt (NZ): GNS Science. 1 USB. (GNS Science geological map; 1).

Howarth JD, Barth NC, Fitzsimons SJ, Richards-Dinger K, Clark KJ, Biasi GP, Cochran UA, Langridge RM, Berryman KR, Sutherland R. 2021. Spatiotemporal clustering of great earthquakes on a transform fault controlled by geometry. *Nature Geoscience*. 14(5):314–320. doi:10.1038/s41561-021-00721-4.

Howarth JD, Cochran UA, Langridge RM, Clark K, Fitzsimons SJ, Berryman K, Villamor P, Strong DT. 2018. Past large earthquakes on the Alpine Fault: paleoseismological progress and future directions. *New Zealand Journal of Geology and Geophysics*. 61(3):309–328. doi:10.1080/00288306.2018.1464658.

Kearse J, Little TA, Van Dissen RJ, Barnes PM, Langridge R, Mountjoy J, Ries W, Villamor P, Clark KJ, Benson A, et al. 2018. Onshore to offshore ground-surface and seabed rupture of the Jordan–Kekerengu–Needles fault network during the 2016 Mw 7.8 Kaikōura earthquake, New Zealand. *Bulletin of the Seismological Society of America*. 108(3B):1573–1595. doi:10.1785/0120170304.

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

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

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

Langridge RM, Basili R, Basher L, Wells AP. 2012. Late Holocene landscape change history related to the Alpine Fault determined from drowned forests in Lake Poerua, Westland, New Zealand. *Natural Hazards and Earth System Sciences*. 12(6):2051–2064. doi:10.5194/nhess-12-2051-2012.

Langridge RM, Beban JG. 2011. Planning for a safer Franz Josef-Waiau community, Westland District: considering rupture of the Alpine Fault. Lower Hutt (NZ): GNS Science. 54 p + 1 CD. Consultancy Report 2011/217. Prepared for West Coast Regional Council.

Langridge RM, Hancox GT. 2006. Review of proposed Lake Poerua subdivision, Grey District. Lower Hutt (NZ): GNS Science. 31 p. Consultancy Report 2006/221. Prepared for Grey District Council.

Langridge RM, Howarth JD. 2018. A new paradigm for Alpine Fault paleoseismicity: the northern section of the Alpine Fault. Lower Hutt (NZ): GNS Science. 49 p. (GNS Science miscellaneous series; 121).

Langridge RM, Howarth JD, Buxton R, Ries WF. 2016a. Natural hazard assessment for the township of Franz Josef, Westland District. Lower Hutt (NZ): GNS Science. 61 p. Consultancy Report 2016/33. Prepared for Environlink Fund / West Coast Regional Council.

Langridge RM, Howarth JD, Cox SC, Palmer JG, Sutherland R. 2018a. Frontal fault location and most recent earthquake timing for the Alpine Fault at Whataroa, Westland, New Zealand. *New Zealand Journal of Geology and Geophysics*. 61(3):329–340. doi:10.1080/00288306.2018.1509878.

Langridge RM, McSaveney MJ. 2008. Updated review of proposed Lake Poerua subdivision, Grey District. Lower Hutt (NZ): GNS Science. 19 p. Consultancy Report 2008/11. Prepared for BECA.

Langridge RM, Morgenstern R. 2019. Active fault mapping and fault avoidance zones for Horowhenua District and Palmerston North City. Lower Hutt (NZ): GNS Science. 72 p. Consultancy Report 2018/75. Prepared for Horizons Regional Council. Revised May 2019.

Langridge RM, Morgenstern R. 2020a. Active fault mapping and fault avoidance zones for the Manawatū District. Lower Hutt (NZ): GNS Science. 69 p. Consultancy Report 2019/123. Prepared for Horizons Regional Council. Revised December 2020.

Langridge RM, Morgenstern R. 2020b. Active fault mapping and fault avoidance zones for the Rangitikei District. Lower Hutt (NZ): GNS Science. 66 p. Consultancy Report 2019/168. Prepared for Horizons Regional Council.

Langridge RM, Morgenstern R, Coffey GL. 2021a. Active fault mapping for planning purposes across the western part of the Tararua District. Lower Hutt (NZ): GNS Science. 85 p. Consultancy Report 2021/03. Prepared for Horizons Regional Council.

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

Langridge RM, Ries WF, Dolan JF, Schermer ER, Siddoway C. 2017. Slip rate estimates and slip gradient for the Alpine Fault at Calf Paddock, Maruia River, New Zealand. *New Zealand Journal of Geology and Geophysics*. 60(2):73–88. doi:10.1080/00288306.2016.1275707.

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

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

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

Langridge RM, Trayes M, Ries W. 2011. Designing and implementing a fault avoidance zone strategy for the Alpine Fault in the West Coast region. In: *Ninth Pacific Conference on Earthquake Engineering: building an earthquake resilient society*; 2011 Apr 14–16; Auckland, New Zealand. Auckland (NZ): 9PCEE. Paper 202.

Langridge RM, Villamor P, Basili R, Almond P, Martinez-Diaz JJ, Canora C. 2010. Revised slip rates for the Alpine Fault at Inchbonnie: implications for plate boundary kinematics of South Island, New Zealand. *Lithosphere*. 2(3):139–152. doi:10.1130/l88.1.

Langridge RM, Villamor P, Howarth JD, Ries WF, Clark KJ, Litchfield NJ. 2021b. Reconciling an early nineteenth-century rupture of the Alpine Fault at a section end, Toaroha River, Westland, New Zealand. *Bulletin of the Seismological Society of America*. 111(1):514–540. doi:10.1785/0120200116.

Litchfield NJ, Morgenstern R, Van Dissen RJ, Langridge RM, Pettinga JR, Jack H, Barrell DJA, Villamor P. 2019. Updated assessment of active faults in the Kaikōura District. Lower Hutt (NZ): GNS Science. 71 p. Consultancy Report 2018/141. Prepared for Canterbury Regional Council (Environment Canterbury).

Litchfield NJ, Morgenstern R, Villamor P, Van Dissen RJ, Townsend DB, Kelly SD. 2020. Active fault hazards in the Taupō District. Lower Hutt (NZ): GNS Science. 114 p. Consultancy Report 2020/31. Prepared for Taupō District Council.

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

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

Little TA, Van Dissen R, Kearse J, Norton K, Benson A, Wang N. 2018. Kekerengu Fault, New Zealand: timing and size of late Holocene surface ruptures. *Bulletin of the Seismological Society of America*. 108(3B):1556–1572. doi:10.1785/0120170152.

Morgenstern R, Townsend DB. 2021. Active fault mapping and fault avoidance and awareness zones for the Ruapehu District. Lower Hutt (NZ): GNS Science. 68 p. Consultancy Report 2020/87. Prepared for Horizons Regional Council.

Nathan S, Rattenbury MS, Suggate RP, compilers. 2002. Geology of the Greymouth area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 1 map + 1 book, scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 12).

Norris RJ, Cooper AF. 1995. Origin of small-scale segmentation and transpressional thrusting along the Alpine Fault, New Zealand. *GSA Bulletin*. 107(2):231–240. doi:10.1130/0016-7606(1995)107<0231:Oosssa>2.3.Co;2.

Norris RJ, Cooper AF. 2007. The Alpine Fault, New Zealand: surface geology and field relationships. In: Okaya D, Stern T, Davey F, editors. *A continental plate boundary: tectonics at South Island, New Zealand*. Washington (DC): American Geophysical Union. p. 157–175. (Geophysical monograph series; 175).

Rattenbury MS. 1987. Fraser Complex and Alpine Fault tectonics, central Westland, New Zealand [PhD thesis]. Dunedin (NZ): University of Otago. 2 vol.

Rattenbury MS, Jongens R, Cox SC, compilers. 2010. Geology of the Haast area. Lower Hutt (NZ): GNS Science. 1 folded map + 58 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 14).

Saunders WSA, Beban JG, Kilvington M. 2013. Risk-based land use planning for natural hazard risk reduction. Lower Hutt (NZ): GNS Science. 97 p. (GNS Science miscellaneous series; 67).

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

Sutherland R, Eberhart-Phillips D, Harris RA, Stern TA, Beavan RJ, Ellis SM, Henrys SA, Cox SC, Norris RJ, Berryman KR, et al. 2007. Do great earthquakes occur on the Alpine Fault in central South Island, New Zealand? In: Okaya DA, Stern TA, Davey FJ, editors. *A continental plate boundary: tectonics at South Island, New Zealand*. Washington (DC): American Geophysical Union. p. 235–251. (Geophysical monograph; 175).

Townsend DB, Litchfield NJ. 2020. Active fault mapping and fault avoidance and awareness zones for the Whanganui District. Lower Hutt (NZ): GNS Science. 53 p. Consultancy Report 2020/73. Prepared for Horizons Regional Council.

Upton P, Langridge RM, Stahl T, Van Dissen RJ, Howarth JD, Berryman KR, Clark KJ, Kelly K, Hammond K. 2017. 8th International PATA Days, Blenheim, New Zealand. Three-day post-conference fieldtrip: northern South Island, Alpine Fault and ruptures of the 2016 Kaikōura earthquake, 17–19th November 2017. Lower Hutt (NZ): GNS Science. 64 p.

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

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

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

Van Dissen RJ, Litchfield NJ, Begg JG. 2005. Upper Hutt City fault trace project. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 28 p. Client Report 2005/151. Prepared for Greater Wellington Regional Council, Upper Hutt City Council.

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

Vermeer JL, Quigley MC, Duffy BG, Langridge RM, Pettinga JR. 2021. Structure and kinematics of active faulting in the Hope-Kelly and Alpine Fault intersection zone, South Island, New Zealand. *Tectonophysics*. 813:article 228928. doi:10.1016/j.tecto.2021.228928.

Vermeer JL, Quigley MC, Langridge RM, Duffy BG, Mildon ZK, Diercks M-L. Submitted. Fault slip-rates and Coulomb stress interactions in the intersection zone of the Hope, Kelly and Alpine faults, South Island, New Zealand. *Tectonophysics*.

Villamor P, Berryman KR. 2001. A Late Quaternary extension rate in the Taupo Volcanic Zone, New Zealand, derived from fault slip data. *New Zealand Journal of Geology and Geophysics*. 44(2):243–269. doi:10.1080/00288306.2001.9514937.

Wellman HW. 1953. Data for the study of recent and late Pleistocene faulting in the South Island of New Zealand. *New Zealand Journal of Science and Technology*. B34(4):270–288.

Wells A, Yetton MD, Duncan RP, Stewart GH. 1999. Prehistoric dates of the most recent Alpine fault earthquakes, New Zealand. *Geology*. 27(11):995–998. doi:10.1130/0091-7613(1999)027<0995:Pdotmr>2.3.Co;2.

Yetton MD. 2002. Paleoseismic investigation of the north and west Wairau sections of the Alpine Fault, South Island, New Zealand. Christchurch (NZ): Geotech Consulting Ltd. 96 p. Earthquake Commission Research Report 99/353. Prepared for the Earthquake Commission Research Foundation.

Yetton MD, Wells A. 2010. Earthquake rupture history of the Alpine Fault over the last 500 years. In: Williams AL, Pinches GM, Chin CY, McMorran TJ, Massey CI, editors. *Geologically active: proceedings of the 11th IAEG Congress*. 2010 Sep 5–10; Auckland, New Zealand. Leiden (NL): CRC Press / Balkena. p. 881–891.

Yetton MD, Wells A, Traylen NJ. 1998. Probability and consequences of the next Alpine Fault earthquake. Christchurch (NZ): Geotech Consulting Ltd. 161 p. EQC Research Report 95/193. Prepared for the Earthquake Research Commission.

APPENDICES

This page left intentionally blank.

APPENDIX 1 ACTIVE FAULT DEFINITIONS

A1.1 What is an Active Fault?

Active faults are those faults considered capable of generating strong earthquake shaking and ground-surface fault rupture, causing significant damage.[6] Motion between the land on either side of the fault causes permanent ground deformation. Ground-surface-rupturing earthquakes are typically of magnitude $M_W > 6.5$.[7]

An active fault in New Zealand is generally defined as one that has deformed the ground surface within the past 125,000 years (Langridge et al. 2016b). This is defined in part, for practical reasons, as those faults that deform marine terraces and alluvial surfaces that formed during the 'Peak Last Interglacial period' or Marine Isotope Stage (MIS) 5e or younger (MIS 1–4; e.g. Alloway et al. 2007). The exception to this definition is the Taupō Rift, which is considered to be evolving so rapidly that an active fault is defined as one that has deformed the ground surface within the past 25,000 years (Villamor and Berryman 2001; Langridge et al. 2016b).

The purpose of this Appendix is to introduce how active faults express themselves, i.e. their behaviour, styles of deformation, activity and geomorphic expression. Active faults are typically expressed in the landscape as linear traces displacing surficial geologic features, which may include hillslopes, alluvial terraces and fans. The age of these displaced features can be used to define how active a fault is.

Active faults are often defined by a fault scarp or trace. A fault scarp is formed when a fault displaces or deforms the land surface or seafloor and produces an abrupt linear step, which may smooth out with time to form a scarp (Figure A1.1). In some cases, where a fault moves horizontally, only a linear trace or furrow may be observed.

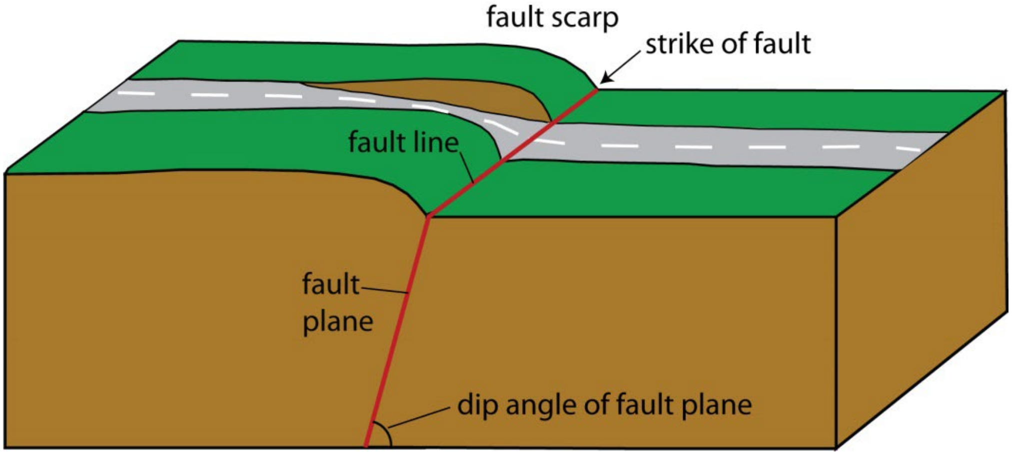

Figure A1.1 Block model of a generic active fault. Fault displacement produces a scarp along the projection of the fault plane at the Earth's surface (fault line or trace).

---

[6] A faut is a plane that separates two bodies of rock, whereby one side moves relative to the other side. A fault differs from a fracture, which has no movement across it. Faults can extend metres to kilometres into the Earth.

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

A1.1 Styles of Fault Movement

Faults can be categorised as strike-slip faults, where the dominant style (sense) of motion is horizontal (movement in the strike direction of the fault), and dip-slip faults, where the dominant sense of motion is vertical (defined by movement in the dip direction 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 A1.2), or left-lateral (sinistral), where the opposite side of the fault moves to the left. The Alpine and Awatere faults described in this report are predominantly dextral strike-slip faults.

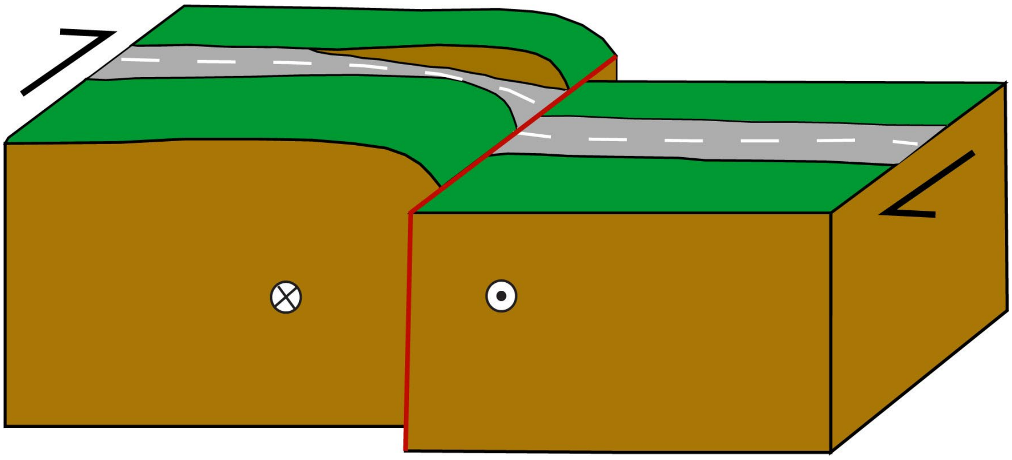

Figure A1.2 Block model of a vertical strike-slip fault (red line). The fault is a right-lateral (dextral) fault, as shown by the black arrows, the sense of movement shown by the right separation across the road.

Dip-slip faults can be divided into reverse faults, formed mainly under contraction (where the hanging-wall block of the fault is pushed up; Figure A1.3) and normal faults, formed under extension (where the hanging-wall block of the fault drops down; Figure A1.4). The Alpine Fault has an additional and significant component of reverse, dip-slip motion, which results in the uplift of the Southern Alps. For purely reverse faults, asymmetric (double) buffering of the upthrown side of the fault has been used in reports for other districts (Langridge and Morgenstern 2020a), based on observations from historical earthquakes (Kelson et al. 2001). Thrust faults are a subset of shallow-dipping (inclined) reverse faults. Both reverse and normal faults occur in proximity to the main zone of deformation associated with the Alpine Fault.

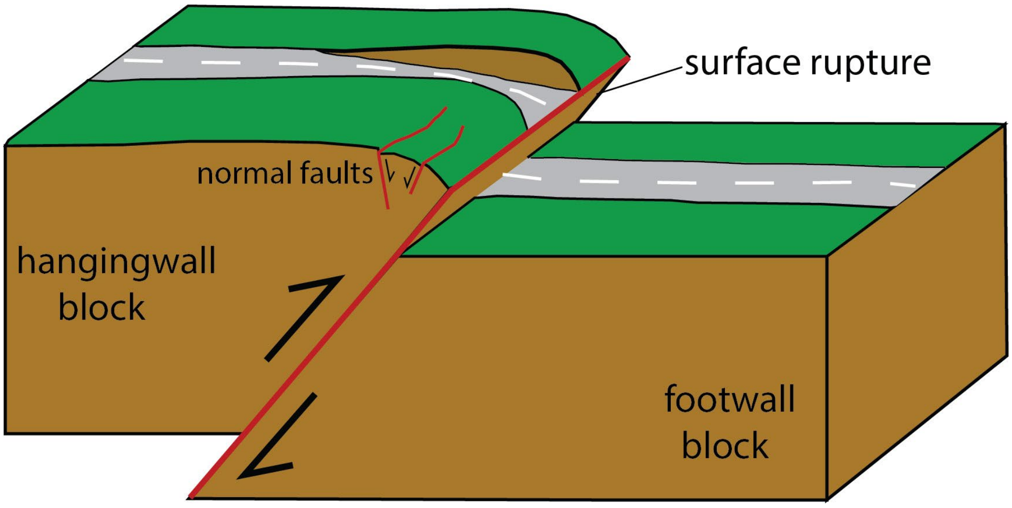

Figure A1.3 Block model of a reverse dip-slip fault. Movement of the blocks is vertical and in the dip direction of the fault plane. In this case, the hanging-wall block has been pushed up over the footwall block. Folding and normal faulting are common features of deformation in the hanging wall of reverse faults.

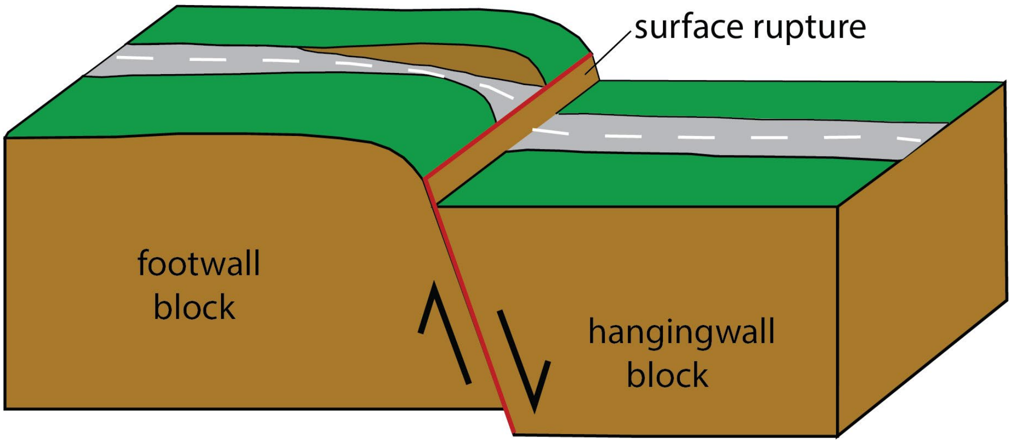

Figure A1.4 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

APPENDIX 2 FAULT AVOIDANCE ZONE BUILDING IMPORTANCE CATEGORY AND RECURRENCE INTERVAL CLASS

A2.1 Building Importance Category

In the event of fault rupture, buildings constructed across the fault will experience significant stress and can suffer extensive damage. Buildings adjacent to the fault and within the Fault Avoidance Zone may also be damaged. MfE Guidelines define five Building Importance Categories (BIC; Table A2.1) based on accepted risk levels for building collapse considering building type, use and occupancy. This categorisation is weighted toward life safety, but also allows for the importance of critical structures and the need to locate these wisely.

Table A2.1 Building Importance Categories (BIC) from the MfE Guidelines (Kerr et al. 2003).

BIC	Description	Examples
1	**Temporary structures** with low hazard to life and other property	• Structures with a floor area of <30 m^2 • Farm buildings, fences • Towers in rural situations
2a	**Timber-framed** residential construction	• Timber-framed single-storey 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

A2.1 Relationship between Recurrence Interval Class and Building Importance Category

The MfE Active Fault Guidelines advocate a risk-based approach to dealing with development of land on, or close to, active faults. The risk is a function not only of the location and activity of a fault but also the type of structure/building that may be impacted by rupture of the fault.

For a site on or immediately adjacent to an active fault, risk increases both as fault activity increases (i.e. fault recurrence interval and Recurrence Interval Class decrease) and BIC increases. In order to maintain a relatively constant/consistent level of risk throughout the district, it appears reasonable to impose more restrictions on the development of sites located on or immediately adjacent to highly active faults, compared to sites located on or immediately adjacent to low-activity faults. This hierarchical relationship between fault activity (Recurrence Interval Class) and building type (BIC) is presented in Table A2.2.

The MfE Guidelines also make a pragmatic distinction between previously subdivided and/or developed sites and undeveloped 'greenfield' sites, allowing for different conditions to apply to these two types of sites of differing development status (see Table A2.2). The rationale for this is that, in the subdivision/development of a greenfield area, a change of land usage is usually being sought, and it is much easier, for example, to require a building setback distance from an active fault or to plan subdivision of land around the location of an active fault. However, in built-up areas, buildings may have been established without knowledge of the existence or location of an active fault, and the community may have an expectation to continue to live there, despite the potential danger. Also, existing use rights under the Resource Management Act mean that, where an existing building over a fault is damaged, it can be rebuilt, even after the hazard/risk has been identified.

Table A2.2 Relationships between Recurrence Interval Class, average recurrence interval of surface rupture, and Building Importance Category (BIC) for previously subdivided and greenfield sites. For more details, see Kerr et al. (2003) and King et al. (2003).

Recurrence Interval Class	**Average Recurrence Interval of Surface Rupture**	**BIC Limitations (Allowable Buildings)**	
		Previously Subdivided or Developed Sites	**'Greenfield' Sites**
I	≤2000 years	**BIC 1** Temporary buildings only	**BIC 1** Temporary buildings only
II	>2000 to ≤3500 years	**BIC 1 and 2a** Temporary and residential timber-framed buildings only	
III	>3500 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 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 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 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 of ≤20,000 years	

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

www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657