Active Fault Mapping and Fault Avoidance Zones for the Wairau Fault, Marlborough District

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CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

EXECUTIVE SUMMARY

Active fault traces and Fault Avoidance Zones are presented for the Wairau Fault in Marlborough District. The district is traversed by sets of active strike-slip, reverse and normal faults that pose a surface rupture hazard to buildings and infrastructure. The Wairau Fault is the focus of this study as it is the most critical fault in the district in terms of surface rupture hazard. Following the Ministry for the Environment's (MfE) Guidelines – "Planning for Development of Land on or Close to Active Faults" (Kerr et al., 2003) faults have been mapped to produce Fault Avoidance Zones surrounding the active faults at a scale suitable for cadastral zoning. For life safety purposes, the MfE Guidelines focus on: (i) the location and complexity of faulting; (ii) the characterisation of recurrence interval of surface faulting, and (iii) the building importance category with respect to land zonation for a site.

Due to the acquisition of a considerable amount of new airborne LiDAR data along the Wairau Fault it is timely to provide more accurate fault line mapping along its length within Marlborough District. Active traces of the strike-slip Wairau Fault have been mapped in a GIS database across Marlborough District using LiDAR digital hillshade models, an orthophotograph basemap, and pre-existing active fault trace linework, i.e. active fault traces mapped as lines in a GIS. This work builds on and supersedes previous fault linework and zones by Geotech Consulting Ltd. (2003a). In this report, Fault Avoidance Zones and GIS attributes, including the fault location uncertainty (or accuracy; FAULT_LOC_UNC) of fault traces are presented along with the active fault linework.

Fault Avoidance Zones have been defined based on the FAULT_LOC_UNC, and an additional setback zone of ±20 m in accordance with the MfE Guidelines. The FAULT_LOC_UNC depends on the accuracy of mapping. While our best estimate of the fault location is mapped as a line, there is uncertainty on the exact location where the fault plane will rupture the surface and thus fault location is mapped as a band defined as the FAULT_LOC_UNC. Where LiDAR is available, faults have been mapped as either *accurate* (±20 m), *approximate* (±40 m), or *uncertain* (±100 m) in terms of their fault location accuracy. An exce

ption to this scheme is on areas where a fault trace is buried or eroded (not expressed) over distances of >1600 m on the LiDAR. Where there is no LiDAR coverage (or where an *uncertain* trace is projected over a distance of >1600 m), pre-existing linework reviewed using a GIS-based orthophotograph basemap is less accurate and has been assigned ±125 m accuracy/uncertainty. Fault Avoidance Zones (combined fault location uncertainty and ±20 m setback) range in width from 80 m for *accurate* fault traces, to 290 m for *uncertain* fault locations as described above. Individual Fault (trace) Avoidance Zones are merged within a GIS to create a seamless Fault Avoidance Zone for the Wairau Fault.

Paleoseismic trenching and offshore geologic studies indicate that the average recurrence interval for ground surface faulting along the Wairau Fault spanning the last 4-5 earthquakes is c. 1400-1800 years. In contrast, methods that use slip rate (SR) and single-event displacement (SED) data suggest a mean recurrence interval of c. 2200 years. We argue that the average recurrence interval is probably <2000 years, and in addition it has been at

least c. 1000 years since the last ground surface rupturing earthquake. Therefore, we conclude that the Wairau Fault should be considered a RI Class I fault (RI ≤2000 yr).

Example Resource Consent Activity tables have been provided to aid the council in the consent process. These tables provide guidance with respect to different land use and building types related to Fault Avoidance Zones for the Wairau Fault.

Possibly the greatest uncertainty related to mapping the Wairau Fault is its location across the lower Wairau valley between Renwick and Spring Creek. In combination with the LiDAR and previous data, our preferred interpretation is that the fault strikes ENE across the lower Wairau valley between Renwick (northern strand) and Spring Creek (coastal strand of the Wairau Fault) as previously suggested. We recognise that the fault or traces of the fault may exist buried or eroded in other parts of the lower Wairau Valley. As such, we recommend that the council consider undertaking geophysical studies that could identify the buried traces of the Wairau Fault, and thus help improve the location of the fault through this important area.

Fault line data should be used to indicate the general location of active fault traces only. Planning approvals and decisions should be made on the basis of the FAZs which include the uncertainty regarding the location and width of fault deformation.

1.0 INTRODUCTION

New Zealand straddles the boundary between the Australian and Pacific tectonic plates (Figure 1.1 inset), where active faults rupture to the Earth's surface during large earthquakes. The area administrated by Marlborough District Council (MDC) lies within one of the more seismically active parts of this tectonic boundary zone. Marlborough District is underlain by the leading edge of the subducting Pacific plate and is crossed by numerous active upper crustal faults that can rupture and deform the ground surface, including the Wairau, Awatere, Waihopai, Vernon and Clarence faults (Figure 1.1). Previous studies indicate that several of these faults, including the Wairau Fault, h

ave a moderately high rate of activity (i.e. relatively short recurrence interval, on the order of 1500-2500 years), and are capable of generating large earthquakes (M_w >7.0) associated with large (i.e. metre-scale) single-event ground surface rupture displacements (e.g., Geotech Consulting Ltd., 2003a,b; 2005; Van Dissen and Nicol, 2009; Zachariasen et al., 2006).

Surface rupture of an active fault will result in a zone of intense ground deformation as opposite sides of the fault move past or over each other during an earthquake. Property damage can be expected and loss of life may occur where buildings, and other structures, have been constructed across the rupturing fault. The 1931 Hawke's Bay and 2010 Darfield (Canterbury) earthquakes are good examples of the types of effects that can be caused by ground surface rupture along faults, notwithstanding the damage that can occur to man-made built structures in such events (e.g. Hull, 1990; Van Dissen et al., 2011).

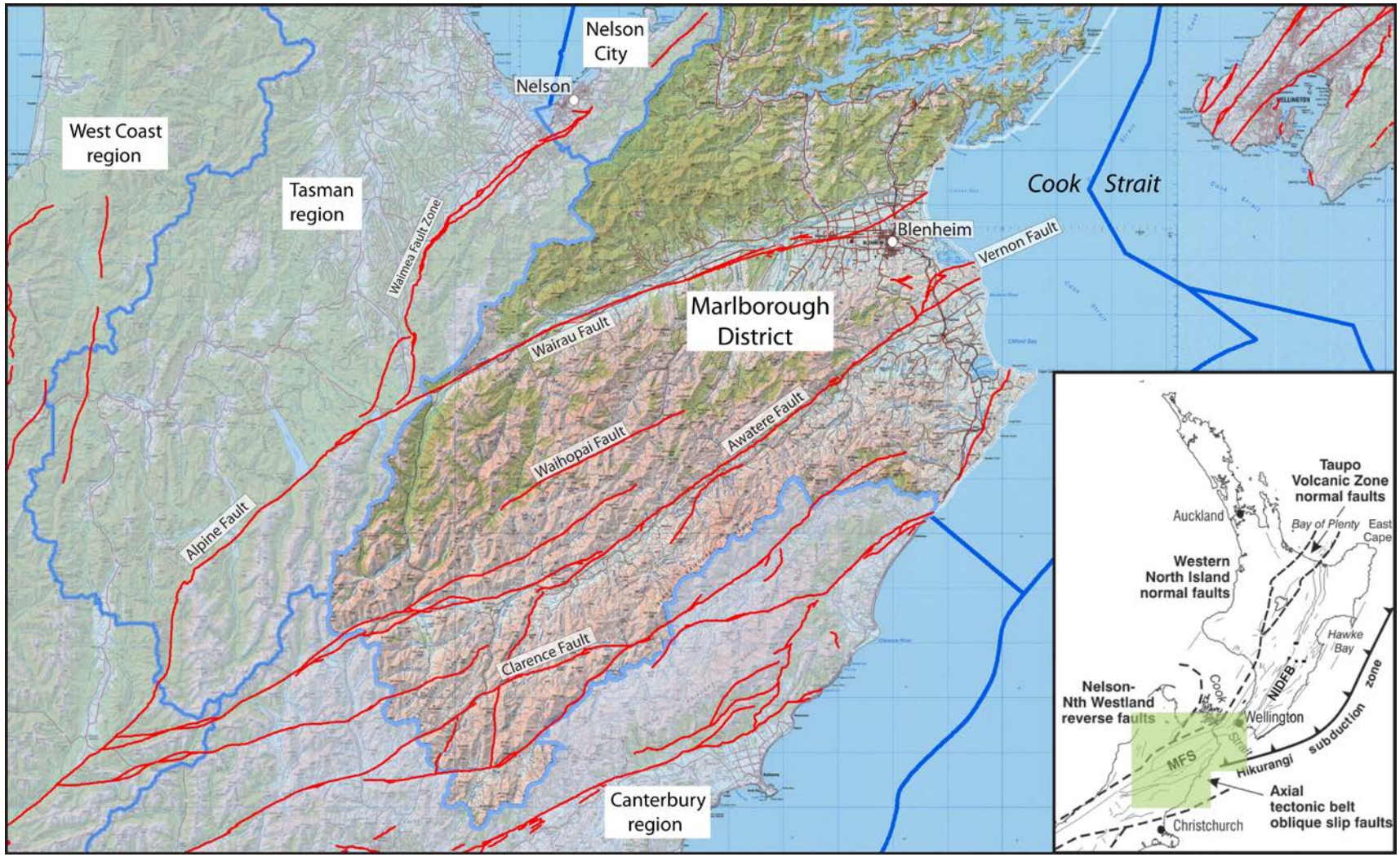

Figure 1.1 Onshore active faults (red) within the upper South Island area-. Marlborough District is highlighted at centre. Inset: Simplified active tectonic map of central New Zealand. MFS = Marlborough Fault System. Source: New Zealand Active Faults Database (http://data.gns.cri.nz/af/; Langridge et al., 2016).

1.1 SCOPE OF WORK

This work was undertaken by the Institute of Geological and Nuclear Sciences Limited (GNS Science) for an Envirolink (Medium Advice Grant) project developed with MDC, to provide an update of mapping of the Wairau Fault. This project builds upon, but supersedes, previous work by Geotech Consultants (2003a, b and 2005) that was undertaken to map active fault traces in Marlborough District and to provide paleoseismic data from trenches across the Wairau Fault. A significant step change in the accuracy of mapping is possible due to the advent and acquisition of airborne LiDAR data along much of the length of the Wairau Fault and its inclusion within a Geographic Information System (GIS).

The main objective for this work is to produce high-quality digital geospatial data and maps suitable for planning use along the Wairau valley at scales that are relevant to the current and expected future land use requirements.

Marlborough District has a high number of active faults, which are mostly mapped at scales of >1:10,000 (see QMAP – the Geological Map of New Zealand programme at 1:250,000, and the New Zealand Active Fault Database - NZAFD; http://data.gns.cri.nz/af/) (Langridge et al., 2016) at 1:50,000 (Figure 1.1). The location of active faults at scales of >1:10,000 have large locational uncertainty and are of limited use for planning purposes.

To improve understanding of faulting hazard and update the quality of fault mapping for the Wairau Fault the scope of work is as follows:

- Provide a review on active tectonics and faulting in Marlborough District, focusing on the Wairau Fault.
- Where airborne LiDAR coverage exists, map and attribute active fault traces at 1:10,000 scale or better. This effort has been facilitated by the acquisition of several airborne LiDAR datasets along the Wairau valley since the Geotech Consulting Ltd. (2003a) report.
- Incorporate active fault line work and attributes from other mapping studies, e.g. QMAP (Rattenbury et al., 1998), previous MDC reports, and review data within the NZAFD (1:50,000 to 1:250,000 scale).
- Update these datasets upon review of previous fault mapping exercises and using georeferenced orthophotograph imagery within a GIS.
- Develop Fault Avoidance Zones based on the fault line data described above. The goal is to provide MDC with up-to-date geospatial datasets that will be valid for planning purposes
- Produce a report for MDC and present results to Marlborough District staff.

Chapter 2 describes the methodology we used to map the Wairau Fault and how we developed the GIS attributes, uncertainties and Fault Avoidance Zones for individual fault traces. Chapter 3 describes the active tectonics of the region and the Wairau Fault as mapped across Marlborough District. Chapter 4 provides a discussion of the Wairau Fault recurrence interval derived for the MfE Guidelines. Chapter 5 presents example planning and consent tables to help inform decision making by way of three planning case studies. Chapter 6 provides a summary of the results of this work and Chapter 7 contains recommendations for the use of this work. The report is accompanied by digital geospatial data including active fault linework and Fault Avoidance Zones (buffers) (Appendix 1).

Appendix 2 of this report provides background material on what active faults are and discusses their styles of movement.

1.2 MFE GUIDELINES FOR DEVELOPMENT OF LAND ON OR CLOSE TO ACTIVE FAULTS

The Ministry for the Environment (MfE) published guidelines on "Planning for Development of Land on or Close to Active Faults[1] (Kerr at al., 2003, see also King et al., 2003; Van Dissen et al., 2003). The aim of the MfE Guidelines is to assist resource management planners tasked with developing land-use policy and making decisions about development of land on, or near, active faults. The MfE Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas that are subject to fault rupture hazard.

The guidelines were developed because:

> *"There is no technology to prevent earthquake damage to buildings built across faults."*
>
> (Kerr et al., 2003)

The main elements of the risk-based approach presented by the guidelines are:

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

For these reasons this report focuses on aspects of accurate fault location (Chapter 2), fault recurrence interval (Chapter 4) and recommendations pertinent to the MfE Guidelines.

The MfE Guidelines also advance a hierarchical relationship between recurrence interval and building importance, such that the greater the importance of a structure, with respect to life safety, the longer the recurrence interval needs to be for that building to be permissible. For example, only low occupancy or risk structures, such as farm sheds and fences (e.g. Building Importance Category 1 structures), are recommended to be built across active faults with average recurrence intervals of surface rupture less than 2000 years. In a "Greenfield" (i.e. undeveloped) setting, more significant structures such as schools, airport terminals, and large hotels (Building Importance Category 3 structures) should not be sited across faults with average recurrence intervals shorter than 10,000 years (i.e. RI Class ≤ IV).

[1] Throughout the remainder of this report, the Ministry for the Environment's Guidelines will be referred to as the 'MfE Guidelines'.

1.3 PREVIOUS FAULT MAPPING

Within Marlborough District there are many generally NE-striking active fault traces that form a transitional area across the Australia-Pacific plate boundary, known as the Marlborough Fault System (Van Dissen and Yeats, 1991; Bourne et al., 1998). Since the development of the MfE Guidelines in 2003, GNS Science has been working with councils to improve data regarding the activity and location of active faults nationwide (Kerr et al., 2003). For example, active fault mapping projects have been undertaken across the Wellington, Canterbury, West Coast and Hawke's Bay regions (e.g. Van Dissen and Heron, 2003; Langridge and Ries, 2010, Langridge and Beban 2011; Barrell and Townsend; 2012).

An initial study of active faults within Marlborough District was undertaken in 2003 by Geotech Consulting Ltd. (Geotech Consulting, 2003; Yetton et al., 2003). This mapping work was undertaken more than a decade ago at about the time when the MfE Guidelines were being developed. The advent of the MfE Guidelines means that the management of hazard from ground surface deformation has changed from the time that the Geotech Consulting report was published. Furthermore, Fault Avoidance Zones as discussed in the MfE Guidelines were not included in the Geotech Consulting (2003) report. In addition, during this decade airborne LiDAR has been acquired and used widely across New Zealand. Airborne LiDAR has been particularly useful in defining the geomorphology of landforms, including the presence and accurate location of active faults, especially under dense vegetation.

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2.0 METHODOLGY OF FAULT MAPPING

2.1 FAULT AND FAULT AVOIDANCE ZONE MAPPING

Fault Avoidance Zones (FAZs) are the areas that define where an active fault is likely to rupture the ground surface and cause ground deformation. FAZs are defined based on the faults' Location Uncertainty and additional setback zone. While our best estimate of the fault location is mapped as a line, there is uncertainty on the exact location where the fault plane will rupture the surface and thus fault location is mapped as a band that contains the Location Uncertainty. The Location Uncertainty depends on the accuracy of mapping and is described in detail below. An additional setback zone of ±20 m is added to the Location Uncertainty in accordance with the MfE Guidelines to create the FAZs. The fault mapping presented here is geared toward developing FAZs that are in keeping with the MfE Guidelines (Kerr et al., 2003).

We first delineate our best estimate of the fault trace (i.e. the location where the fault plane will likely rupture the surface). We have mapped the areas with LIDAR at different resolutions than areas without LIDAR. There is a large difference between the locational accuracy of mapped fault traces when comparing LiDAR DEMs with either the 10-m national-scale Digital Elevation Model (DEM), QMAP or NZAFD data. The main difference relates to the scale with which the mapped trace has been digitised, i.e. LiDAR typically at 1:5,000 to 1:10,000, QMAP 1:50,000 (but published at 1:250,000) and the NZAFD typically at 1:50,000 scale.

For current land use planning in regard to building on or adjacent to active faults, it is not appropriate to use 1:50,000 scale (or larger) active fault mapping to define the fault location in developed and developing areas (e.g. Kerr et al., 2003; Langridge et al., 2016), In the case where LiDAR is available, we have mapped the fault traces at scales of 1:5,000 to 1:10,000. In areas where LIDAR is not available, surface fault traces have been mapped using a combination of LiDAR DEM's and hillshade mod

els, review of other data sources (QMAP, NZAFD, Geotech Consulting Ltd.) and through comparison with a GIS orthophoto basemap. Accordingly, we have placed a higher level of uncertainty on the location of these traces compared to where LiDAR is available and we recommend that these areas be remapped once LIDAR become available. In the meantime we have provided the best mapping possible with the resources available. In addition, fault mapping undertaken by Geotech Consulting Ltd., while at a high standard, is not accompanied by Fault Avoidance Zone data as defined in the MfE Guidelines (Kerr et al., 2003).

Once the fault trace is mapped we have added the uncertainty on the exact location of the fault surface rupture and the 20 m setback. These are explained below.

2.2 FAULT LOCATION UNCERTAINTY

For this study, the location and attributes pertaining to active faults have been assembled in a Geographic Information System (GIS) and recorded in a digital geospatial database (provided as supplementary to this report). A detailed description of the attributes assigned to fault locations is contained in Appendix 1.

The uncertainty in mapping the location of a fault arises from the scientific interpretation based on expert recognition of fault-influenced geomorphic landforms and an understanding of the local geology. The most obvious landform feature associated with surface fault rupture is a fault scarp (Figure A2.1). Fault scarps are steps in the land surface produced by the deformation the ground surface by fault displacement. They can extend for hundreds of metres in length and are often many metres wide. Therefore, representing a scarp as a line within a GIS is problematic. In practice, a line within a GIS database has a width of zero and is meant to represent the location where it is estimated the fault would exactly rupture the ground surface. Active faults are more appropriately defined as zones rather than lines to incorporate the uncertainty of the exact location of the fault when it ruptures (i.e., where exactly the fault will rupture within the fault scarp that is visible in the landscape). The exact location of the fault plane can only be identified in an exposure. Also, faulting close to the ground surface often occurs not only as a single fault plane but rather as a complex set of intricate fault planes and folding (ground deformation). Therefore the actual ground deformation is likely to be somewhat wider than the main fault plane. This wider zone of deformation is often referred to as 'fault complexity' (see Kerr et al., 2003).

The accuracy with which the location of a fault feature can be represented in a GIS is influenced by three types of uncertainty that are represented by the GIS attributes DATA_SOURCE, MAP_SCALE, and ACCURACY. The first is the uncertainty of the source data relative to a global datum. This uncertainty can be quantified and is differentiated in this study with the attribute in the field **DATA_SOURCE**. The second is the resolution of the source data, (i.e. the scale at which a geomorphic landform is able to be resolved from the data). This can be expressed as an average scale at which the fault has been digitised and has been attributed in the field **SCALE**. The third has been described above and is the uncertainty associated with how accurately the feature can be identified from a geomorphic study, including the "fault complexity" of the surface deformation associated to a given fault feature (see more below on fault complexity). In this study the **ACCURACY** attribute encompasses this expression uncertainty.

These distinctions concerning locational uncertainty are important because of how: (i) they relate to the accuracy of the fault linework; (ii) we build Fault Avoidance Zones from that linework; (iii) this fault data is applied by Councils; and, (iv) the scale and accuracy that would affect individual land and building owners.

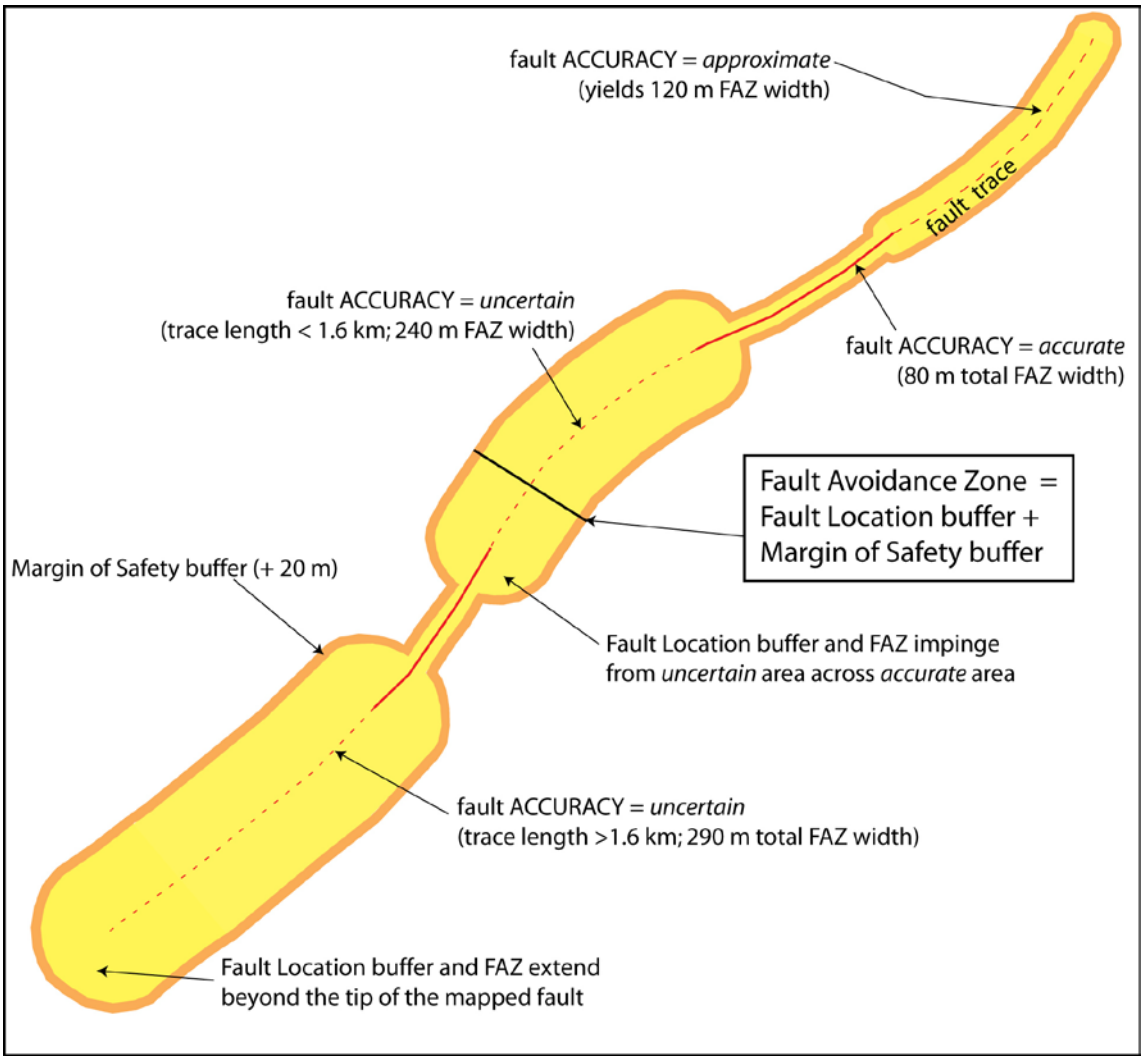

Figure 2.1 Fault Avoidance Zones (sum of yellow and orange) for a strike-slip fault with varying Fault Location accuracy along strike. Fault location attributes are: Accurate, Approximate or Uncertain. The zones at the ends of fault traces are extended and rounded to account for the possibility of deformation extended beyond their tips.

Once a fault trace location has been mapped, the GIS attributes **DATA_SOURCE, MAP_SCALE** and **ACCURACY**, are used to define the location uncertainty and a value in metres is assigned to the field **FAULT_LOC_UNC**. To construct the FAZs the MfE Guidelines recommend that a *Margin of Safety Buffer* (setback) of +20 m be included as part of the FAZ. This buffer gives some assurance that there is unlikely to be any fault deformation outside the entire width of the FAZ. The 20 m buffer is added to both sides of the FAULT_LOC_UNC attribute. A visual representation of the varying width of a FAZ is presented in Figure 2.1.The widths of FAZs for this study are presented in Table 2.1.

In general, fault traces can be mapped more accurately where there is LiDAR coverage. Hence, depending on how well we can map each fault trace, we use the terms *accurate*, *approximate* and *uncertain* to define the fault location accuracy on LiDAR. Each term has a numerical value attached to it (±20, ±40, ±100 m, respectively) which is subsequently used to build a FAZ. Typically, *accurate* and *approximate* traces can be seen (i.e. mapped), but *uncertain* traces cannot be seen and are typically projected across country (based on strike) from where there is *accurate* or *approximate* fault location data. In practice though, we acknowledge that some of the *uncertain* fault locations are projected across significant distances where essentially no data exists. Therefore in this study we have made a distinction between *uncertain* (projected) traces where LiDAR exists, that are less than 1.6 km long, versus those that are projected across distances of >1.6 km. For the former, we use

a fault location uncertainty of ±100 m, while for the latter we use ±125 m. This reflects an uncertainty that the fault has remained straight along its previous strike (when accurate or approximate), or whether it has deviated in strike or complexity where the fault cannot be visibly mapped.

This is of particular importance in the lower Wairau valley between Renwick and Spring Creek, where there is little control on the fault location over a distance of c. 10 km. This example will be discussed further in Chapter 3.

In addition, the MfE Guidelines recommend that a *Margin of Safety Buffer* (setback) of +20 m be added to both sides of the fault location uncertainty, as part of the FAZ. This additional buffer gives some assurance that there is unlikely to be any fault deformation outside the entire width of the FAZ. The widths of FAZs for this study are presented in Table 2.1.

Table 2.1 Widths of Fault Avoidance Zones (FAZs) for the Wairau Fault, Marlborough District.

Data Source	Accuracy	Map Scale	Fault_Loc_Unc (m)	Margin of Safety buffer (m)	FAZ width (m)
LiDAR	*accurate*	1:5000	±20	±20	**80**
LiDAR	*approximate*	1:5000	±40	±20	**120**
LiDAR (trace length <1.6 km)	*uncertain*	1:5000	±100	±20	**240**
LiDAR (trace length >1.6 km)	*uncertain*	1:5000	±125	±20	**290**
Orthophoto + previous mapping	*uncertain*	1:20,000	±125	±20	**290**

Where there is more than one fault trace making up a distributed or complex zone of faulting, individual FAZs may overlap. In this case, a merging function in the GIS amalgamates individual zones together. For the Wairau Fault, this is particularly evident when the fault zone is expressed in a more complex fashion, or in areas where the fault has splayed into two or more traces.

In addition, some fault traces terminate in open country without any obvious connection to other faults or to deformed surfaces (see Figure 2.1). In such cases the FAZ is rounded surrounding the fault tip. This helps account for the uncertainty of where the fault goes or terminates, but recognises that at some distance, it is difficult to identify or map the continuation of a fault.

Fault complexity is defined within the MfE Guidelines by three terms: 'Well-defined' (fault location), 'Distributed' (deformation) or 'Uncertain' (fault location). These three terms are used directly in Resource Consent tables (e.g. Table 4.2). In this study, we refer to Well-Defined fault locations as those that are accurately (±10 m) or approximately (±25 m) located from LiDAR DEMs. Where fault locations are 'Uncertain' from the LiDAR (±40 m) we apply the term 'Distributed'. For fault linework that comes from the orthophoto basemap, NZAFD or QMAP (±100 m) we use the term 'Uncertain' with respect to its fault complexity.

3.0 MAPPING THE WAIRAU FAULT

3.1 TECTONIC SETTING OF THE MARLBOROUGH REGION

The Wairau Fault lies in the Wairau river valley and is defined as the northeastern continuation of the Alpine Fault (Berryman et al., 1992; Langridge et al., 2016; http://data.gns.cri.nz/af/). Traditionally, the Wairau Fault was called the Alpine Fault to recognise its role in the very large geologic offsets of bedrock terranes across the Alpine Fault (Wellman, 1953; Rattenbury et al., 1998). However, in terms of recent tectonics the Wairau Fault has been recognised as one of the key structures that make up the Marlborough Fault System (Lensen 1968, 1976). The Marlborough Fault System (MFS) comprises at least four major onland strike-slip faults including the Wairau, Awatere, Clarence and Hope faults (Figure 1.1; Van Dissen and Yeats, 1991; Zachariasen et al., 2006). The MFS accounts for a significant component of the tectonic strain accommodated across the Australia-Pacific plate boundary in the northern South Island (Bourne et al., 1998). For example, the total strain measured through geodetic and geologic studies for the northern South Island is c. 39 mm/yr, of which on average c. 37 mm/yr can be accounted for on these four faults (Wallace et al., 2007; 2012; Langridge et al., 2003). In this regard, the strain release from such faults is important to characterise as they are expected to rupture in large to very large (M_w 7.0-7.6) earthquakes associated with major ground surface displacements (Nicol et al., 2011, Litchfield et al., 2014).

3.2 THE WAIRAU FAULT

The Wairau Fault extends northeast-ward across the entire width of Marlborough District. The western end of the Wairau Fault is defined by the intersection of the Alpine Fault with the Waimea Fault Zone, which broadly occurs between Lake Rotoiti (St Arnaud village) and Tophouse (Figures 1.1, 3.1). The Wairau Fault extends the length of the Wairau valley east of Tophouse northeastward to the coast at Cloudy Bay. The fault extends offshore into Cloudy Bay, where it has been mapped from seafloor observations and in sections of seismic stratigraphy (Pondard and Barnes 2010; Barnes and Pondard, 2010).

The bedrock geology of the Wairau valley is characterised by Permian to Triassic age terranes (including the Dun Mountain, Maitai and Caples terranes) to the north of the Wairau Fault and Triassic and Cretaceous greywacke rocks of the Torlesse terrane, Esk Head Belt and Pahau subterrane (Begg and Johnston, 2000; Rattenbury et al., 1998; 2006).

There are few places where the bedrock is exposed in proximity to the active trace of the Wairau Fault. This is because the fault follows the axis of the valley where Quaternary (Pleistocene and Holocene) deposits have been laid down over bedrock during the last c. 2 million years. Near the village of Wairau Valley, the Wairau Fault cuts through early Pleistocene Hillersden gravels (Rattenbury et al., 1998).

As discussed, along most of the Wairau valley the Wairau Faults cuts deposits of Pleistocene and Holocene age, or is buried beneath alluvial deposits of likely late Holocene age, i.e. buried beneath material that has been deposited since the last surface faulting event. The vast majority of these units are late Pleistocene and Holocene alluvial and till deposits and are typically <125,000 years in age. This is important as this age defines the time period over which faults are defined as active in New Zealand (Litchfield et al., 2014; Langridge et al.,

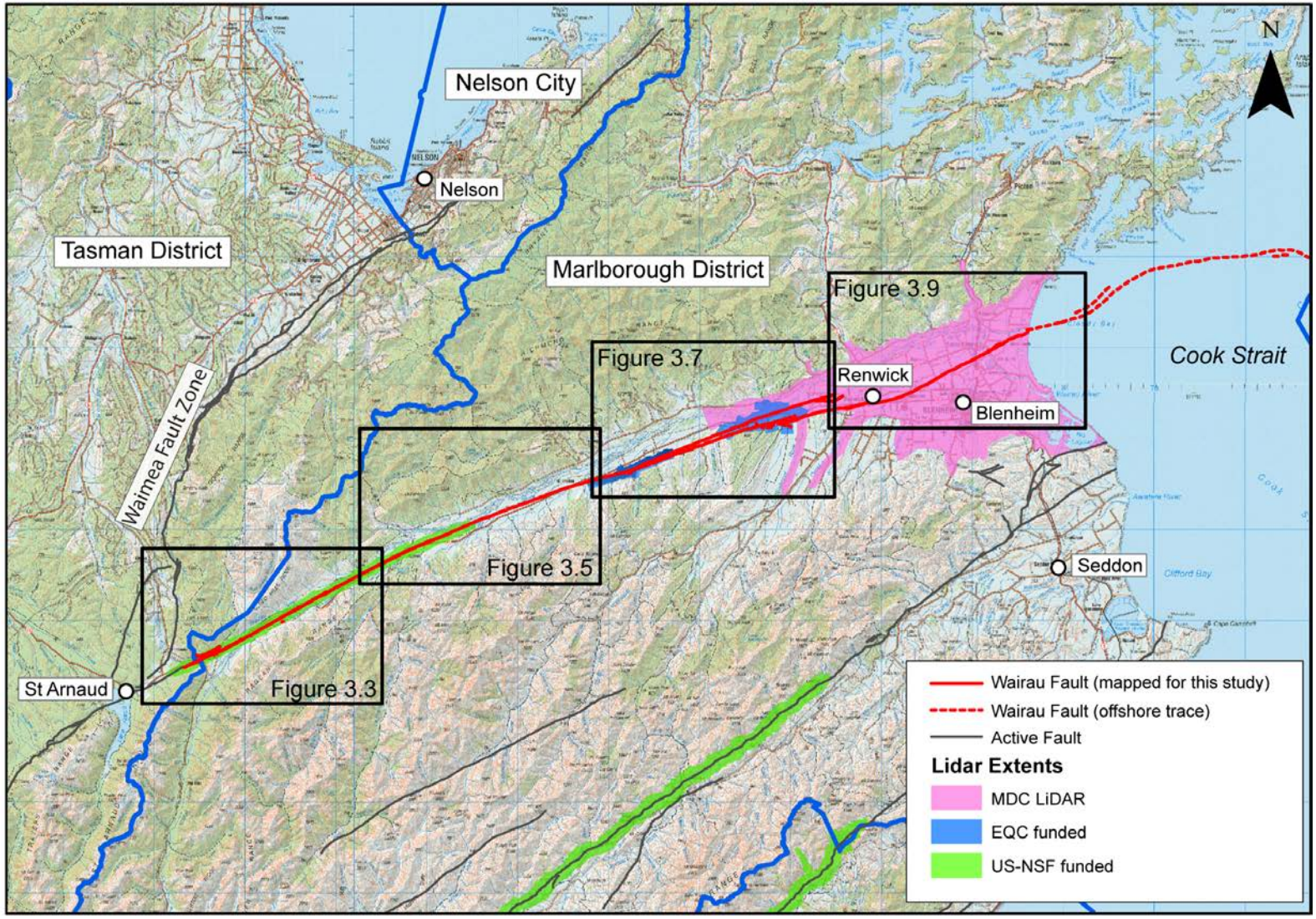

Figure 3.1 Extents of LiDAR coverage along the Wairau valley and Wairau Fault in Marlborough District. Towns and locally important villages within the district are also shown.

2016). There is therefore ample evidence along the length of the Wairau Fault that it has been active throughout the late Pleistocene and Holocene and is therefore an active fault. Later we will discuss the recurrence interval of faulting for the Wairau Fault, which is important in defining its Recurrence Interval Class and therefore the Planning Recommendations that can be applied to it.

3.3 LIDAR ACQUISITIONS AND PARTS OF THE FAULT

During the last few years, several campaigns of LiDAR acquisition have been flown along the Wairau Fault and wider region (Figure 3.1). These acquisitions have been made by Marlborough District Council (the lower Wairau valley), GNS Science (mid Wairau valley; funded by the Earthquake Commission, EQC), and the University of Southern California in the upper Wairau valley area (funded by the US National Science Foundation, NSF). The NSF LiDAR dataset extends for c. 38 km from near the Highway 63-Moutere Road junction northeast to near Wyeburn Station. The swath is c. 1.4 km wide and has been processed to produce a DEM with a 0.33 m pixel size due to an enhanced acquisition using a LiDAR instrument brought over from the USA.

The EQC-funded LiDAR dataset is comprised of two short (10 and 11 km) acquisitions that have been processed to produce 0.5 m DEMs. The western of the these two swaths (11 km long and 1 km wide) covers the area from near Hillersden to the township of Wairau Valley, while the eastern swath (10 km length) covers the area from near Centre Valley Stream to Bankhouse Station and the Waihopai River. This swath is irregular in shape and overlaps in part with the MDC LiDAR acquisition.

Unlike the other acquisitions, the MDC LiDAR was not flown specifically for the purposes of active tectonics or fault mapping and covers the lower Wairau valley in its entirety including the lower flanks of the Wither Hills, the coastline of Cloudy Bay, Big Lagoon and parts of side valleys such as the Waihopai River. This dataset has been processed to produce a 1-m DEM.

The following sections briefly describe the character of the Wairau Fault as divided into four geographic parts from west to east for this study.

3.3.1 Western end of the Wairau Fault

In this study, the western end of the Wairau Fault is that part of the fault between the Marlborough District boundary near Tophouse, and Branch River (Figure 3.2; Figure 3.3). From west to east, in this area, the fault initially descends from higher country at Tophouse to the floor of the Wairau River where it is recognised as faulting Q6t till and Q6a alluvial deposits (c. 128,000-186,000 years) (Rattenbury et al., 2006), showing right-lateral strike-slip offsets across moraine edges and alluvial terrace risers (Nicol et al., 2011). On these older surfaces the fault is sometimes expressed as a more complex and wider zone of deformation comprising several fault traces.

This study identifies a series of newly-recognised active fault traces immediately east of Tophouse and on the north side of the Wairau valley (Figure 3.1). These traces typically form south-facing fault scarps that are parallel to and c. 250 m north of the main trace of the Wairau Fault, and occur at the foot of the hillslopes where the bedrock is of Maitai and Dun Mountain affinity (Rattenbury et al., 1998). Because these traces are within 300 m of the main zone of faulting we have also attributed these faults with the name Wairau Fault (Figures 3.3, 3.4). These appear to be normal faults as expressed by fault scarps of c. 5 m in

height that are downthrown on the valley side. The recurrence interval of ground surface displacement on these features is not known. In this case, we assume that these faults have

Figure 3.2 Aerial photographs looking east (A) and west (B) along the Wairau Fault at the Branch River site. The fault is marked by white arrows. Photographs by D.L. Homer.

the potential to move as often as, or at the same times as, movements on the main zone of faulting associated with the Wairau Fault.

The fault is expressed as a relatively narrow zone of deformation (c. 40 m width) where it cuts across Q2a alluvial surfaces (c. 12,000-24,000 years). In places the fault has been shown within the recent bed of the Wairau River, mapped as Q1a (Holocene alluvium; c. 0-12,000 years) on geological maps (e.g. Rattenbury et al., 2006). On such maps the fault is dashed, because it is either eroded away or buried by recent deposits. Therefore, for this study these fault traces have been attributed as *uncertain* in terms of fault location because its location is concealed. This is because surficial evidence for the fault or the last rupture of the fault is not preserved in the active floor of the river. The fault right-laterally offsets a Q6t moraine north of the Wash Bridge and then continues northeastward to Branch River, crossing surfaces comprised of Q2a and Q1a alluvium.

3.3.2 West-central part of the Wairau Fault

The west-central part of the Wairau Fault is defined as that part of the fault between Branch River and Hillersden of which the western 10 km is expressed on LiDAR (Figures 3.1, 3.5). From west to east, in this area, the fault cuts the well-studied offset terrace sequence on the east side of Branch River (Figures 3.1, 3.2; Lensen 1968). In this area the width of deformation as shown from mappable fault traces is typically <30 m across Q2a alluvial terraces (Figures 3.6; Zinke et al., 2015). LiDAR coverage near Birch Hill Station allows us to reinterpret the location of the Wairau Fault as being within the recent river bed (Q1a) north of the station. The eastern 13 km of this west-central portion has no LiDAR coverage. In this case, previous fault trace linework has been uploaded and reviewed using other available imagery, including an orthophoto basemap. The basemap is georeferenced and can therefore be used as a digital GIS reference. Linear geomorphic features and vegetation (change) lineaments on the basemap have been interpreted as the markers of mapped fault traces observed on other media, e.g. aerial photographs.

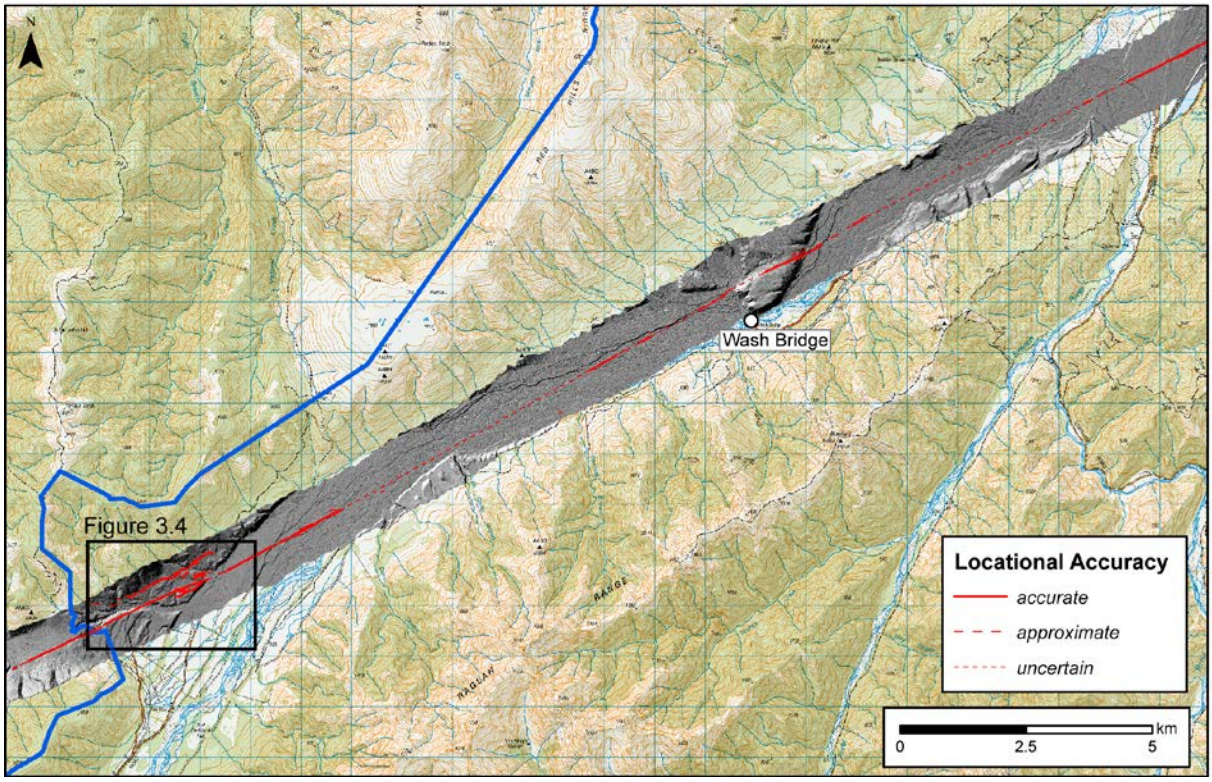

Figure 3.3 The western end of the Wairau Fault (red lines) as mapped as part of this study, from the district boundary (blue line) to Branch River.

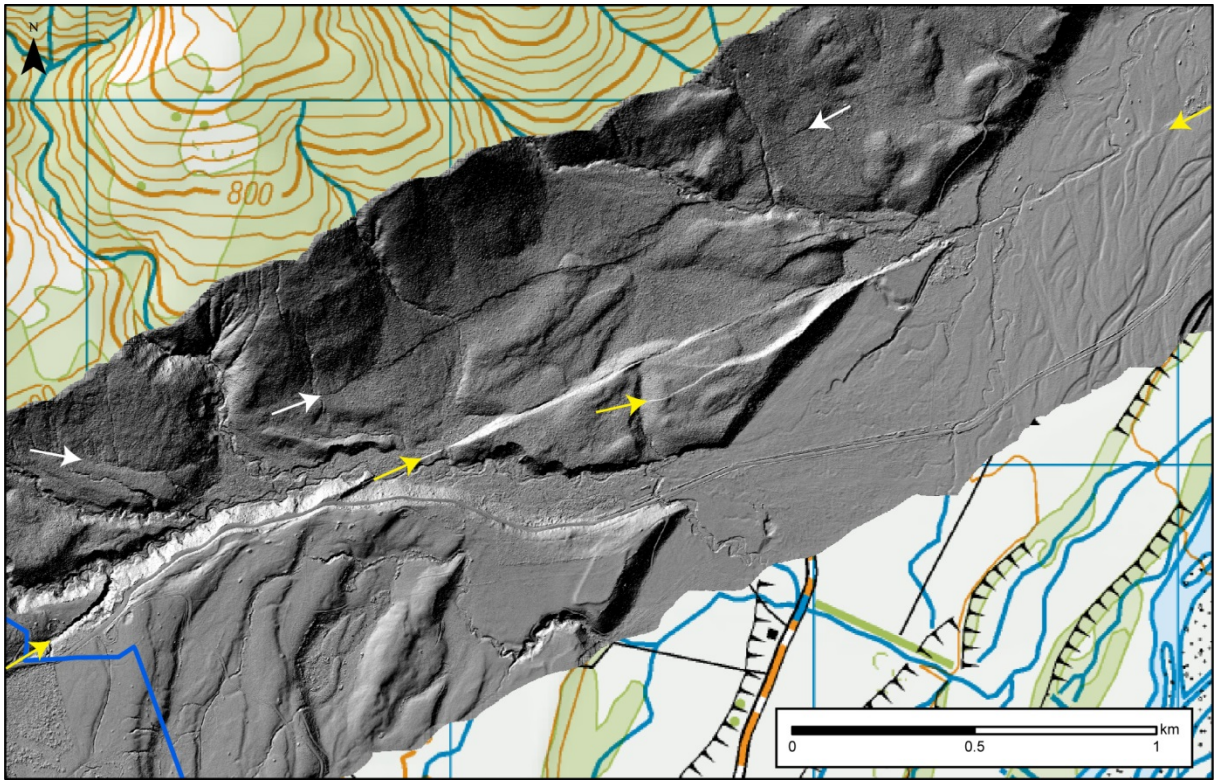

Figure 3.4 Detailed geomorphology of the western end of the Wairau Fault shown on a LiDAR hillshade model. Yellow arrows show the main dextral-slip traces of the fault zone; white arrows highlight a zone of normal faulting c. 250 m north of the main zone of faulting.

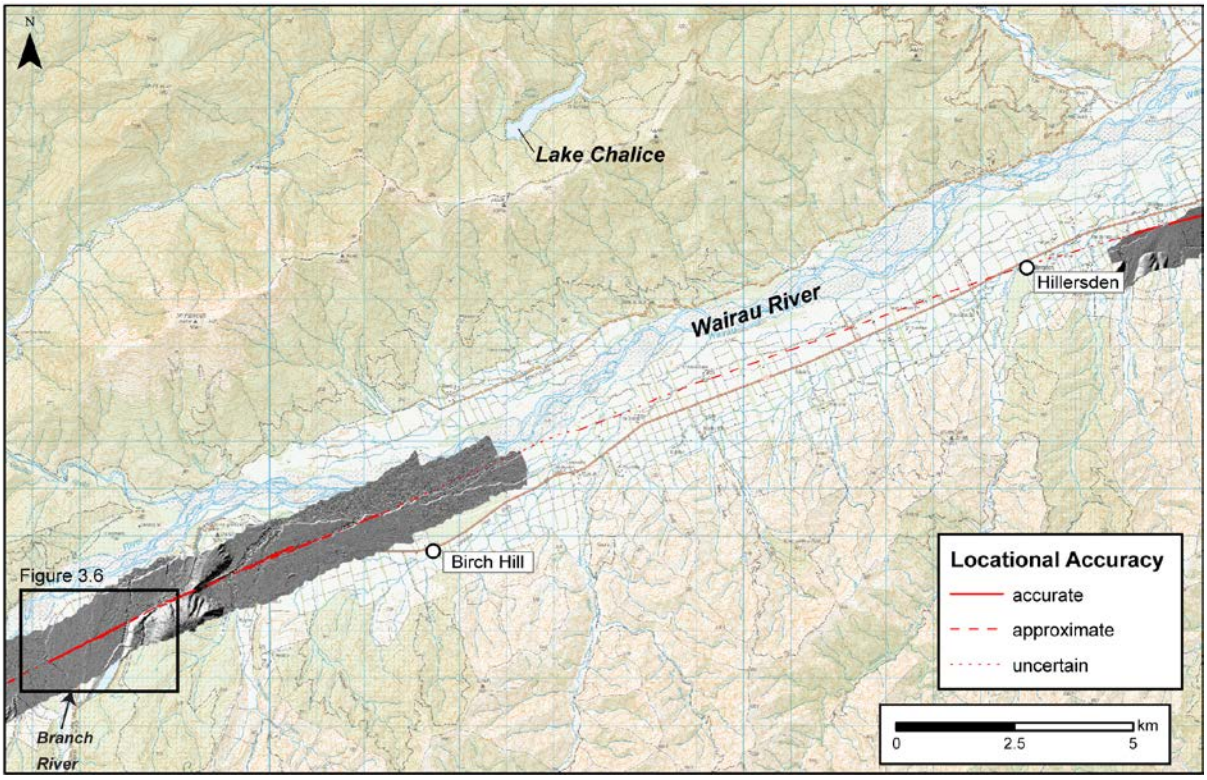

Figure 3.5 The west-central part of the Wairau Fault between Branch River and Hillersden. LiDAR was used to map the western half of this area, while a national-scale orthophotograph basemap was used where no LiDAR currently exists (between Birch Hill Station and Hillersden).

3.3.3 East-central part of the Wairau Fault

The east-central part of the Wairau Fault is defined as that part of the Wairau valley that includes the two EQC-funded LiDAR acquisitions and the area between them, i.e. the area between Stonelea Station and the Waihopai River (Figures 3.1, 3.7). This part of the Wairau Fault is characterised by a more complex pattern of faulting indicated by splitting or splaying of the fault. West of Stonelea, the fault has an average strike of 075º. Near Hillersden the fault splays into two strands that both have strikes of c. 070º (Figure 3.7). The northern strand appears to be the more active trace and was the subject of a paleoseismic study that included three excavated trenches (Zachariasen et al., 2006).

As these two strands progress to the east they cut across Q2a surfaces (c. 12,000-24,000 years) that host minor local stream drainages and ascend onto older surfaces comprised of Pliocene Hillersden gravels (Rattenbury et al., 1998). Several secondary traces have been mapped in between the two fault strands near Brothers Stream. There is no LiDAR coverage between Kiernan Creek and Marchburn Stream (Figure 3.7). Again, in this area, previous fault trace linework has been uploaded and reviewed using other available imagery, including an orthophoto basemap. In these areas, the fault trace has been remapped (shifted slightly) based on the georeferenced aerial basemap. Nevertheless, the uncertainty related to fault location is considerably greater where there is no LiDAR coverage from which to map the fault.

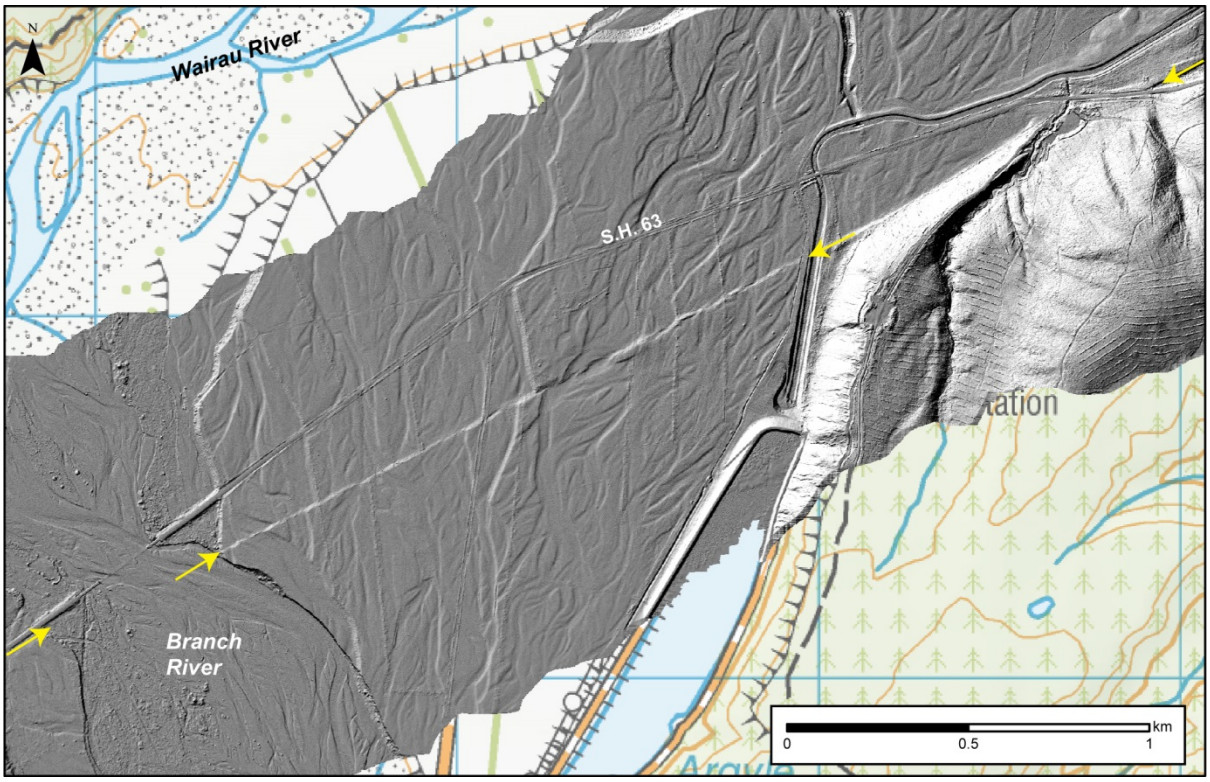

Figure 3.6 Detailed location of the Wairau Fault in the west-central area. The fault is marked by yellow arrows.

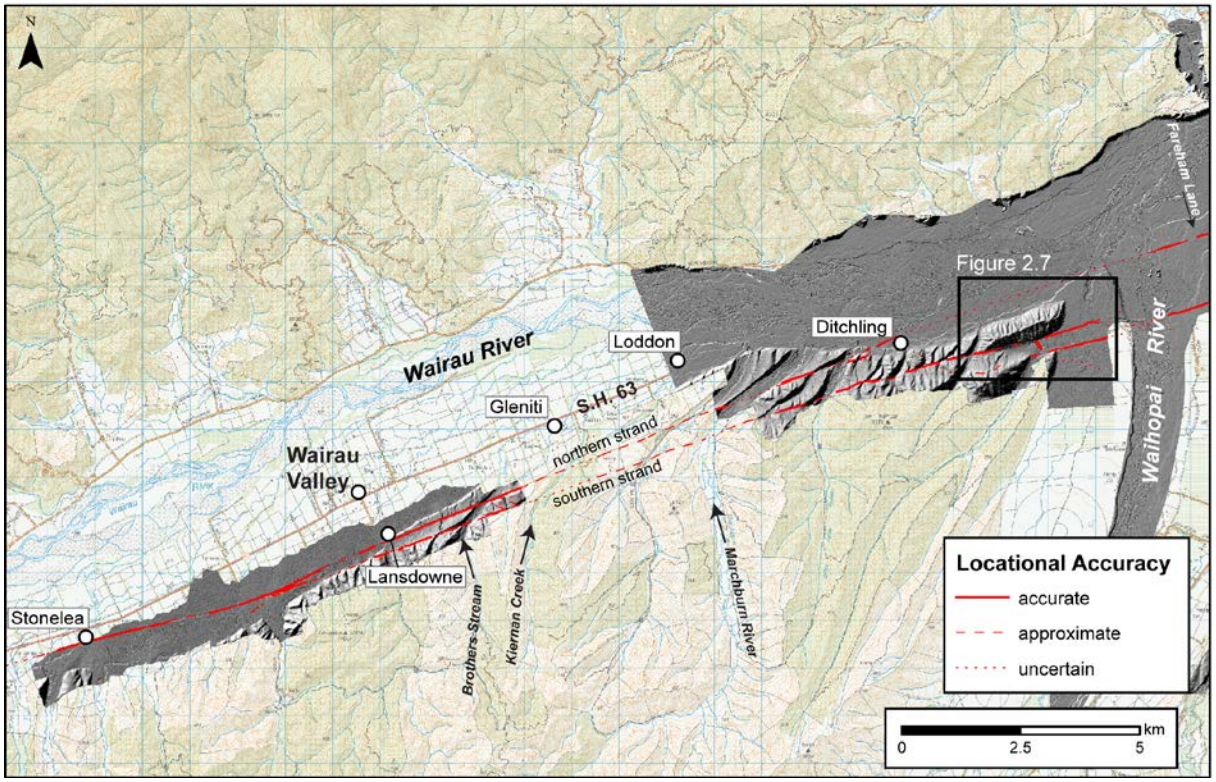

Figure 3.7 The east-central part of the Wairau Fault from Stonelea to the Waihopai River. This part of the fault includes LiDAR coverage funded by EQC and an area at centre with no LiDAR coverage.

From the Marchburn River to the Waihopai River the two strands of the fault diverge from c. 450 m to c. 1 km apart (Figure 3.7). Streams and rivers between Wairau Valley village and Bankhouse Station indicate a history of incision through upper Pleistocene Hillersden Gravel that locally forms hills. In addition, these streams and rivers are deflected right-laterally as

they cross the fault zone, indicating a significant history of dextral displacement. The northern fault strand offsets various surfaces of late Pliocene (Ph; 2? million to 1.5? million years–) and early Quaternary (eQa; <1.8 to 1.5? million) age against late Quaternary age (Q8a (245,000-303,000 years), Q6a, Q2a) in the Gleniti to Loddon stations area (Rattenbury et al., 1998, 2006). The northern strand emerges onto the Holocene floodplain of the Wairau River near Ditchling Station and is not directly observed again on the west side of the Waihopai River (Figure 3.7). In this case the fault is projected toward a trace near Fareham Lane and is attributed as *uncertain* in terms of fault location.

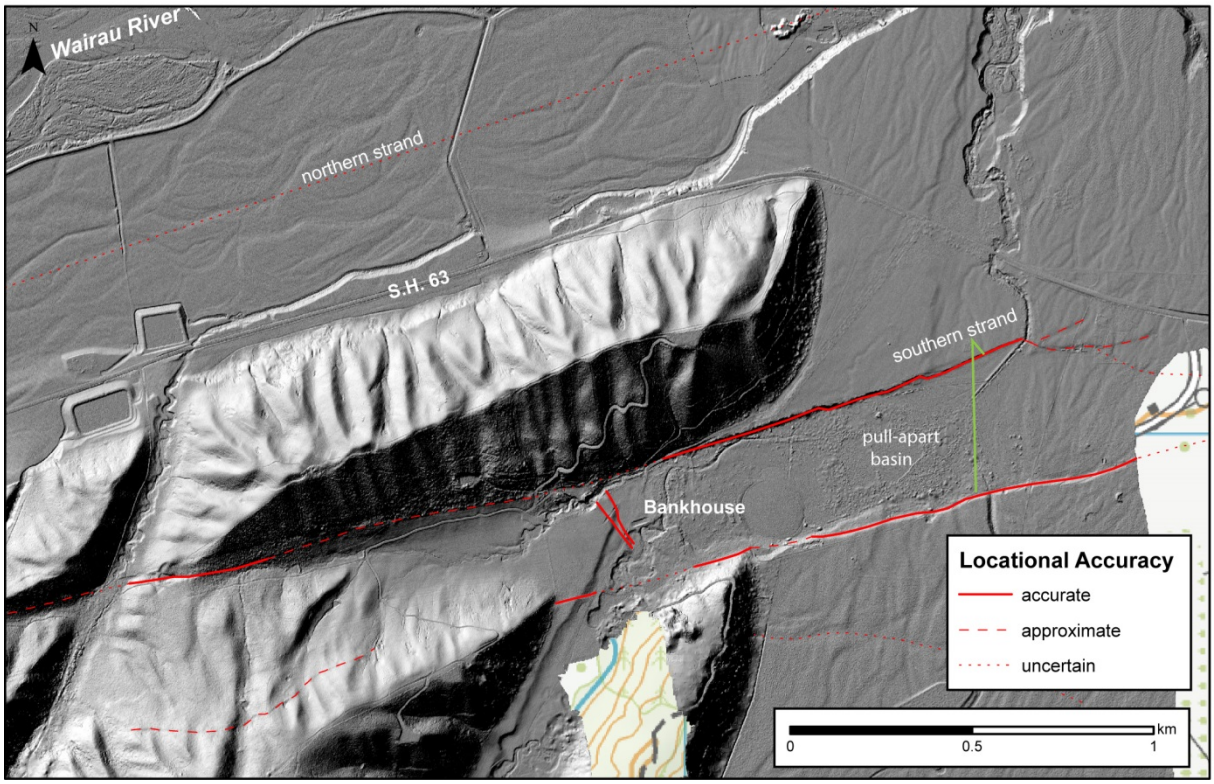

Figure 3.8 Detailed location of the Wairau Fault within the east-central area. The fault is marked by red lines of varying locational accuracy (see legend). The trace at the top is the uncertain fault location of the northern strand. In the lower part of the southern strand forms a pull-apart basin (extensional stepover) at Bankhouse Station (the green line indicates the width of the pull-apart).

The southern strand of the Wairau Fault typically cuts across uplifted Hillersden Gravel hillocks between Kiernan Creek and Bankhouse Station. The Bankhouse Station is characterised by a minor fault complexity comprising a c. 350 m wide stepover to the right that forms a rhombohedral down-droppped zone, referred to as a graben or pull-apart basin (Figure 3.8). The basin is bounded by two fault scarps that enclose it and a large pond occupies the down-droppped area (Lensen 1976). We interpret the eastern end of this pull-apart basin as being near the Waihopai River itself, after which the fault becomes a single trace again. The area of the Bankhouse Station pull-apart basin may also represent the point on the fault where the southern strand takes over from the northern strand as the major strand of the Wairau Fault.

3.3.4 Lower Wairau valley

The lower Wairau valley part of the Wairau Fault is defined as that part of the fault between the Waihopai River and the coast at Cloudy Bay (Figures 3.1, 3.9). In terms of land use, this is by far the most populated part of the Wairau Fault and the fault comes in proximity to the Renwick, Woodbourne, Spring Creek and Marshlands communities. In many ways, this is also the part of the fault where the greatest uncertainty exists regarding the continuity and location of the fault. This is highlighted by the lack of a visible surface trace between the ends of the northern, southern and coastal strands of the fault (Figure 3.9). These strands are discussed separately below, followed by a discussion of the uncertainty surrounding the fault location between Renwick and Spring Creek.

3.3.4.1 Northern strand

To the east of the Waihopai River the northern strand of the fault expressed has previously been described as the Bedford Road traces of the Wairau Fault (Lensen 1976; Yetton 2003). In this area the northern strand is c. 1.45 km north of the southern strand and is expressed as a linear 075º trending scarp across a Q2a alluvial surface. An additional arcuate splay of the northern strand has been mapped on the LiDAR to the south of it (Figure 3.9). Both of these strands drop off the Q2a terrace near Bedford Road and are not visible toward the east, i.e. they are not observed anywhere else toward the coast. For this study we have continued these two traces for a distance of 250 m further onto the Q1a surface in the same strike direction as they are observed across the Q2a surface, with an *uncertain* fault location attribute. This reflects the fact that in future ground surface faulting earthquakes, the northern strand will likely rupture farther to the east. In saying that, it is very difficult to predict its location farther east using geological and geomorphological fault mapping techniques.

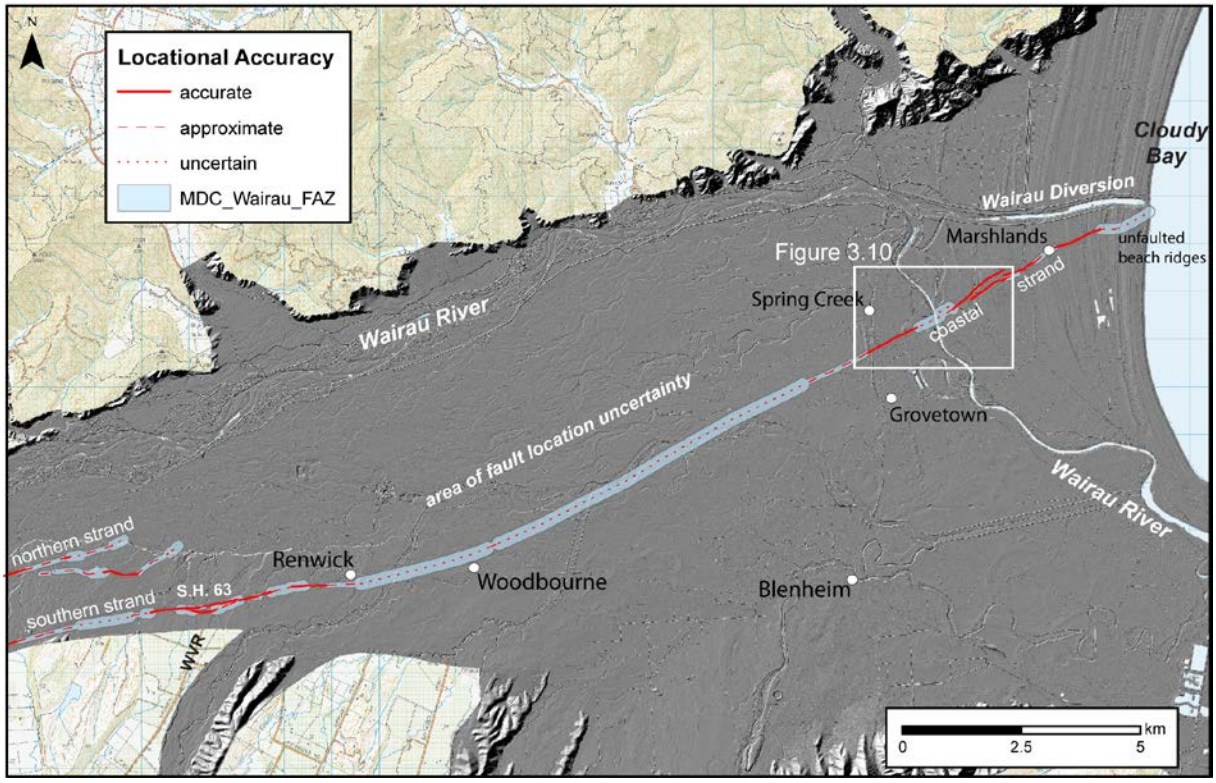

Figure 3.9 The eastern end of the Wairau Fault in the lower Wairau valley (red lines), extending to the coast at Cloudy Bay. The fault is defined by the northern, southern and coastal strands. However, the area between Renwick and near Spring Creek the fault location is mostly uncertain. WVR = Waihopai Valley Road.

3.3.4.2 Southern strand

East of the Waihopai River, the southern strand is considered to be the major strand of the Wairau Fault. The southern strand is mapped across a Q2a terrace toward the Waihopai Valley Road, where a small complexity in the fault forms a small pull-apart basin or sag, occupied by ponds and swampy ground. This strand continues on to the southern verge of the town of Renwick.

The LiDAR DEM indicates that the southern strand runs along (or close to) State Highway (S.H.) 63. The fault probably bends slightly toward the northeast between Renwick and Woodbourne village, where it probably occurs on the northern verge of Woodbourne, based on subtle changes in the slope of the floodplain. East of Woodbourne, the fault is difficult to follow across the Q1a (Holocene) floodplain surface. Previous mapping studies have consistently shown the probable location of the fault as striking to the ENE and linking up with the coastal strand. Though this is our preferred interpretation, and the uncertainty related to this interpretation is elaborated upon in section 3.3.5.

3.3.4.3 Coastal strand

A small fault scarp is observed on the LiDAR to the west of S.H. 1 near Spring Creek crossing Murrays Road (Figure 3.10). This provides positive (*accurate*) evidence of the location of the fault from which the fault location can be projected across areas where the fault location is *approximate* or *uncertain*, e.g. across the lower Opawa River floodplain where no accurate fault trace can be mapped.

The Wairau Fault crosses S.H. 1 between Grovetown and Spring Creek. Active fault trace geomorphology in the form of small scarps and grabens can be followed to the east of the Wairau River toward the coast between Spring Creek and Marshlands (Figure 3.10). One of these small scarps was investigated by Geotech Consulting Ltd. (2005) with a paleoseismic trench. To the northeast of Marshlands (Figure 3.9) the Wairau Fault crosses a series of abandoned beach ridges that relate to the progradation of the Cloudy Bay coastline. Using colour hillshading it is possible to differentiate those beach ridges that have been displaced and those younger beach ridges that are not displaced (and therefore post-date the most recent faulting event in this area). The final mapped trace of the fault is projected to the northeast across these unfaulted beach ridges to the Cloudy Bay coast using the same north-easterly strike (dashed red line on Figure 3.9 north of Marshlands). Thus, the Wairau Fault (southern strand) reaches the coast just south of the mouth of the Wairau Diversion.

Figure 3.10 Detailed location of the Wairau Fault near the eastern end of the fault. The fault is marked by red lines (demarking accurate, approximate or uncertain traces) on a colour hillshade model. Spring Creek and S.H. 1 are at left and the Wairau River is at centre.

3.3.5 Uncertainty of Wairau Fault location in the lower Wairau valley

The Wairau Fault is poorly expressed over a distance of c. 10 km between Renwick/Woodbourne and to the west of Spring Creek (Figure 3.9). The fault is concealed due to the active alluvial nature of the lower Wairau (including its tributaries) floodplain. This can be seen in the LiDAR from the sharp geomorphic expression of alluvial channels of the Wairau, Omaka and Opawa rivers in this area (Figure 3.11). During the late Holocene these rivers have flowed to the ENE until a point in the floodplain between Blenheim and Spring Creek, where they have hooked around and flow to the SE toward Big Lagoon.

The late Holocene geology of the lower Wairau valley has been described by Brown (1981a, b). Brown shows that the lower Wairau valley represents a shallow marine embayment, with a maximum mid Holocene marine highstand (c. 6600 year) that was located west of Spring Creek and coincides with the western end of the coastal strand of the Wairau Fault (Figure 3.11; Grapes and Wellman, 1986). This shoreline runs roughly north-south across the valley. Another prominent shoreline, considered to be late Holocene in age occurs outboard of the highest shoreline and runs north-south near the Wairau River close to Spring Creek. These shorelines and the intervening area have been somewhat modified by alluvial activity. However, to the east of the late Holocene shoreline, a series of less modified and prograding beach/shoreline features can be mapped to the coast at Cloudy Bay (Grapes and Wellman, 1986). These shorelines host the vast majority of the faulting observed along the coastal stand of the Wairau Fault, as shown by Brown (1981a, see his Figure 3). Thus, as sea level fell during the late Holocene, the rivers and coastline prograded to fill the space left by the retreating sea. This process did not occur in isolation from tectonic changes; but occurred during a period in which 3-4 major earthquakes occurred on the Wairau Fault. These earthquakes left their own subtle imprint on the shape and vertical levels within the valley.

The challenge is therefore to constrain the location of the Wairau Fault west of Spring Creek (and east of Renwick) where possible fault traces have been eroded and/or buried by alluvial activity, that has occurred due to the concentration of alluvial activity west of the mid Holocene highstand shoreline. Previous fault mapping studies (Geotech Consulting Ltd. 2003a; Begg and Johnston, 2000) have joined the southern and coastal strands of the fault with a smooth curve between known (*accurate, approximate*) locations of the fault near Renwick and Spring Creek.

In this study, we have attempted to resolve the uncertain location of the Wairau Fault between Woodbourne and near Spring Creek using a similar logic but also by applying a generous uncertainty to the mapped fault location (±100 or ±125 m) to areas that have an *uncertain* fault location. We have scoured the lower Wairau valley for evidence of fault traces, using profiling and colour and zoom techniques with the LiDAR hillshade and DEM. We located one *approximate* trace where the fault was not wholly buried or eroded northeast of Woodbourne. Across most of this area we show the Wairau Fault as *uncertain* projected between Woodbourne and west of Spring Creek but use this linework to develop a FAZ of up to 290 m width (Figure 3.9).

Our new revised location of the Wairau Fault across the lower Wairau valley is consistent with (though more accurate than) previous mapping efforts and with offshore mapping results (Lensen, 1976; Barnes and Pondard, 2010). In addition our new revised fault locations are consistent with subsurface data from bores and cores that outline the shape of the lower Wairau valley in the subsurface (Brown, 1981b).

Despite this, some uncertainty will still exist due to the lack of surface traces. In reality, for this area our interpretation and ensuing FAZ may span the location of the fault in total, in part (as the fault may deviate in or out of the 290 m wide FAZ), or possibly very little.

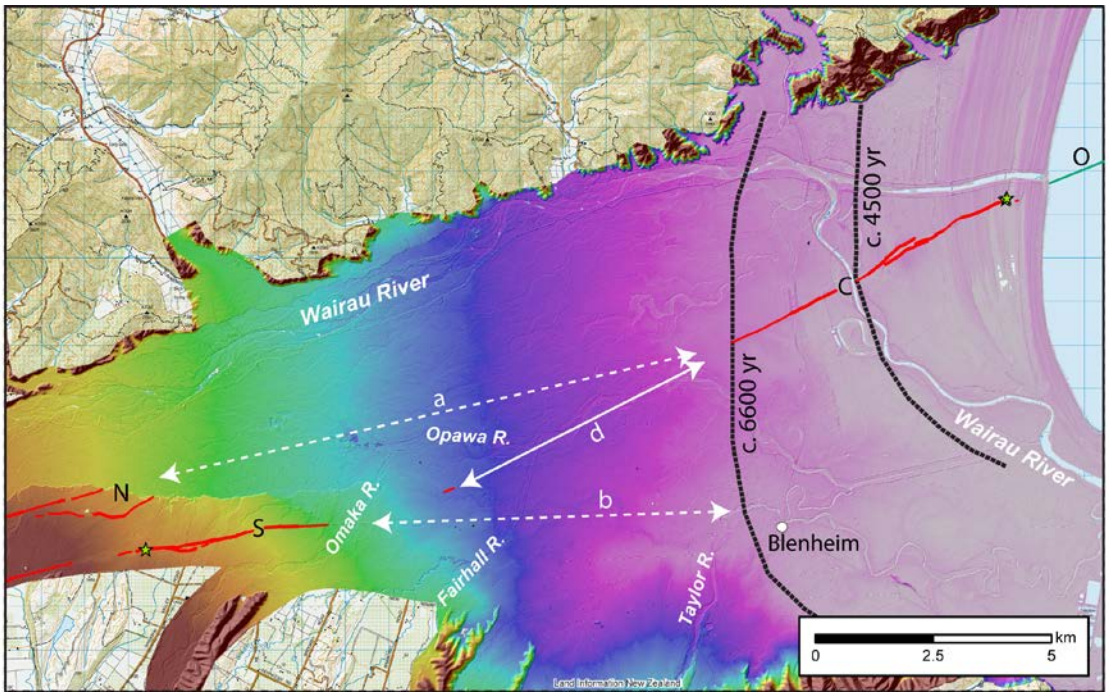

Figure 3.11 Interpretations for the location of the Wairau Fault in the lower Wairau valley. Option d is the preferred option for the fault's general location as discussed in the text. Options a and b (dashed white arrows) are possible locations. Black dashed lines mark the general location of the Cloudy Bay coast c. 6600 and 4500 years before present. The fault is well expressed where the rivers systems have not consistently eroded or deposited materials in these coastal zones. N, S, C, and O refer to the northern, southern, coastal and offshore strands of the Wairau Fault.

Other interpretations of the Wairau Fault location in the lower Wairau valley are possible, and are shown on Figure 3.11 and are as follows:

- the eroded eastern tips of the northern strand could follow the active Wairau valley toward, and link up with, the coastal trace (option a). We have found no surficial evidence with which to prove or disprove this hypothesis. We note that it is likely that the northern strands continues toward the east, but do not know its continuity in strike or length. The northern strand is eroded and/or buried beneath recent sediments of the Wairau River.
- the southern trace could continue on with an east-west strike, from its last known approximate location along the Middle Renwick Road, projecting toward the northern suburbs of Blenheim (option b). Again, due to a lack of expression we cannot confirm the continuity of such a fault trace. However, it is worth noting that there are no other active fault traces expressed across the late Holocene shorelines (besides the mapped coastal strand). It is also true that no active traces have been identified in the offshore area of Cloudy bay, to the east of Blenheim. Therefore, this option is deemed to be less likely.
- No active faults exist in an area between the northern, southern and coastal strands of the fault (option c). While this is possible, for the reasons of fault continuity along strike and the fact that the rivers have been very active across this area, it should not be surprising that there is a lack of surficial evidence for faulting. If this scenario were valid, then the coastal strand would form part of a shorter fault that includes the offshore traces of the Wairau Fault.

In simple terms, there is very little or no surficial evidence for faulting across the lower Wairau valley. Based on the paleoseismic data, this can be explained if the activity of the rivers and streams in this area have broadly reset (eroded/deposited material) the landscape during the last 2000 years or so, while other areas such as the prograding coastal strip have been little altered by alluvial erosion or sedimentation.

Our current interpretation which links the southern strand with the coastal strand (option c; Figure 3.11) is the preferred interpretation in this study. In terms of council mapping and planning activities we consider this interpretation to be the most likely of the four possible interpretations (acknowledging that the fault deformation across the lower Wairau valley is poorly constrained), and should be adopted until better datasets are available. Geophysical techniques such as shallow seismic (including Landstreamer; Polom et al., 2016) or Ground Penetrating Radar (e.g. Kaiser et al., 2009) offer some of the better prospects for identifying buried faults across the valley. Other techniques such as groundwater mapping (including the location, or absence, of springs) may also provide insights into where the fault is located (or not located) (White et al., in review).

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4.0 WAIRAU FAULT ACTIVITY

4.1 ACTIVE FAULT PARAMETERS FOR THE MFE GUIDELINES

An important parameter in terms of the hazard posed by an active fault is its recurrence interval. This term refers to the average amount of time between earthquakes large enough to rupture the Earth's surface along the fault. The MfE Guidelines define six Recurrence Interval (RI) Classes of active faults (Table 4.1; Kerr et al., 2003; Van Dissen et al., 2003). Faults with the highest activity fall into RI

Class I; these faults have an average recurrence interval of ≤2000 years. In general, the recurrence interval classes match standards correlated against hazard levels and the New Zealand Building Code, such that there are four RI classes that span the last 10,000 years (RI Classes I, II, III, and IV). The least active class of faults is RI Class VI which includes faults that have an average recurrence interval of 20,000-125,000 years. Planning restrictions developed from the MfE Guidelines typically increase with a decrease in the recurrence interval of faulting. Van Dissen et al (2003) provide a preliminary assignment of Recurrence Interval Class for the Wairau Fault (i.e. RI Class I).

The classes displayed in Table 4.1 provide a context for the discussions that follow concerning the active Wairau Fault and the application of FAZs and their associated planning recommendations.

Table 4.1 Average Recurrence Interval of Surface Rupture, RI Classes and examples of New Zealand faults that fall in each RI Class.

Recurrence Interval Class	Average RI of Ground Surface Rupture	NZ examples (faults); Marlborough District examples in bold
I	≤2000 years	Alpine, Hope, Wellington, **Awatere**, **Wairau***, **Clarence**
II	>2000 years to ≤3500 years	Ostler FZ, Ohariu, Rangipo, Ruahine, **Elliott, Fowlers**
III	>3500 years to ≤5000 years	Dunstan, Lake Heron, Poutu, Tukituki FZ, **London Hill**
IV	>5000 years to ≤10,000 years	Dalgety, Esk, Karioi, Awanui (1931), **Hog Swamp**
V	>10,000 years to ≤20,000 years	Pisa, Greendale, Martinborough, Seafield FZ
VI	>20,000 years to ≤125,000 years	ND

Notes: Faults with average recurrence intervals >125,000 years are not considered active. FZ = Fault Zone. * as stated in Van Dissen et al. (2003).

Recurrence interval values are ideally obtained as direct evidence from paleoseismic trenches, but in the lack of this information they can sometimes be derived from other fault parameters. When the timing of individual past surface rupturing earthquake events need to be defined, paleoseismic trenches are excavated at sites where the fault and its relationship with recent sediments can be exposed. These sediments offer the opportunity to separate out the evidence for, and to date, discrete past surface-rupturing earthquakes (paleoseismic events).

In the absence of paleoseismic trenching, slip rate and single-event displacement data in combination with geomorphic landscape assessment form the basis of how faults are defined

according to RI for the MfE Guidelines. Careful measurement of well-dated and displaced geomorphic features can be used to calculate a slip rate or displacement rate for a particular fault. A slip rate is the velocity of the fault measured over time, i.e. displacement divided by time. For example, the Wairau Fault has a moderate slip rate of c. 3.5 ± 0.5 mm/year (or c. 3.5 metres per thousand years). In reality, fault displacement occurs in steps during large earthquakes that shift the Earth on either side of the fault by metres at a time (Figure A2.2). When there is no data available from trenches, the RI can be defined through the combination of slip rate (SR[2]) and single-event displacement (SED[3]) data, using the equation RI=SED/SR. These latter calculations can be limited by uncertainties in the values of slip rate and or single-event displacement. Another source that can provide estimates of recurrence interval is the National Seismic Hazard Model (NSHM; Stirling et al., 2012). The NSHM also uses geologic data (SR and SED) coupled with seismic hazard parameter equations that are used to derive recurrence interval from SR and SED. We discuss RI values on the Wairau Fault based on both methods below,

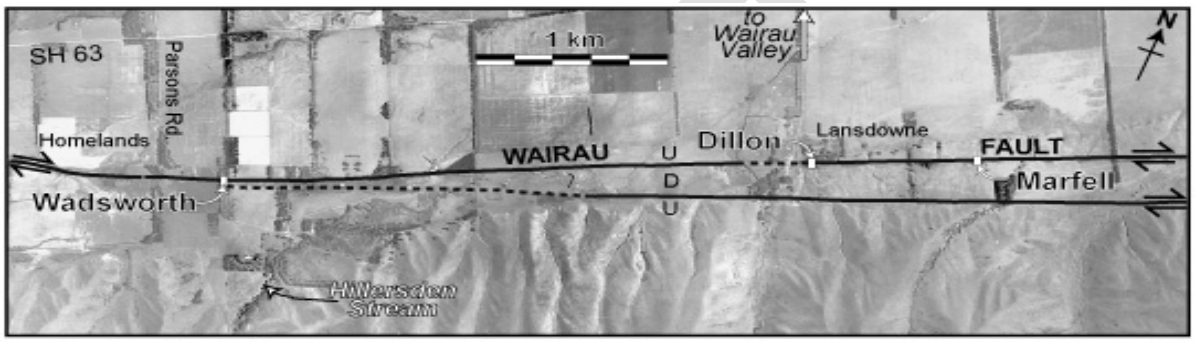

Figure 4.1 Part of the Wairau Fault near Wairau Valley town where paleoseismic trench studies were undertaken by Zachariasen et al. (2006). The fault divides into the northern and southern strands near the Wadsworth site. The two other sites on the northern strand are the Dillon and Marfell sites.

4.2 WAIRAU FAULT: RECURRENCE INTERVAL, SLIP RATE AND SINGLE-EVENT DISPLACEMENT

The recurrence interval for the Wairau Fault can be assessed from both paleoseismic data and from slip rate and displacement datasets. Results from the two methods are summarised below. We also compare this value with that used in the NSHM.

4.2.1 Paleoseismic data

Prior to 2000 there was little or no useful paleoearthquake timing data for the Wairau Fault, i.e. little geologically dated earthquake information. It was known that the recent beach ridges near the Wairau River mouth at Cloudy Bay were either unfaulted (younger than the most recent faulting event) or faulted (older than the most recent rupturing event(s)) (Grapes and Wellman, 1986). These authors infer that the minimum age of the most recent faulting event is c. 770 years ago based on estimating the rate of coastal progradation in the area. A trenching study in the Marshlands area by Geotech Consulting Ltd. (2005) confirms a minimum age for the most recent faulting event of c. 850 yr ago. They suggest that this faulting event probably occurred around 1000 AD, again based on the progradation rate of coastal beach ridges.

[2] SR refers to slip rate. Slip rate is a geological measure of how fast a fault slips averaged over an extended period of time. It is typically presented in mm/yr or m/kyr.

[3] SED refers to single-event displacement. The SED is a geological measure of how much slip or displacement occurs along a fault (at a site or on average) during a large earthquake movement (presented in m).

The first comprehensive multi-event dated paleoseismic record was published by Zachariasen et al. (2006). These authors presented two trenches from the Hillersden and Lansdowne areas (Figures 4.1, 4.2, 4.3). Together, these trenches showed up to four paleoseismic rupture events within the last 5600 years. The timing of the most recent event from trenches was somewhat ambiguous and was placed between c. 1400-2800 cal yr BP[4]. A very large landslide event that formed Lake Chalice in the ranges north of the Wairau Fault (Adams, 1981) was used as correlative evidence that very strong shaking had occurred

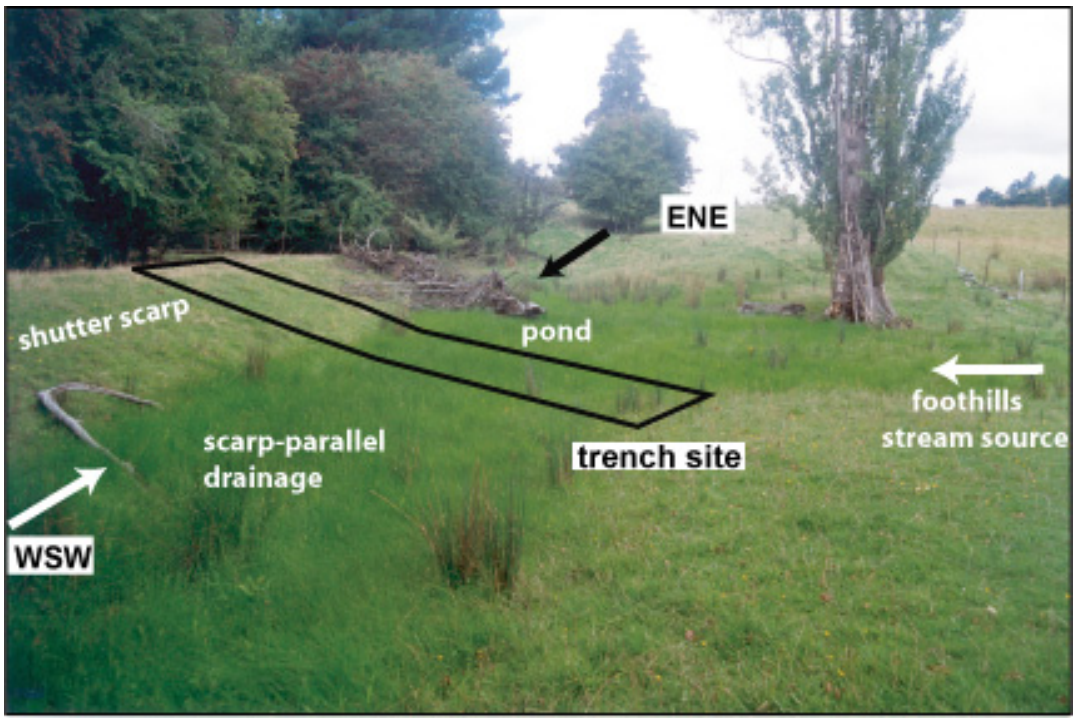

Figure 4.2 The Dillon paleoseismic site on Lansdowne Station, near Wairau Valley. The fault scarp at left ponds drainages flowing from the right, making this a good place to deposit sediments and preserve organic material.

[4] cal yr BP is used to abbreviate the term “calibrated years before present”. This refers to the correction of a radiocarbon date from a lab measurement using a calendar calibration.

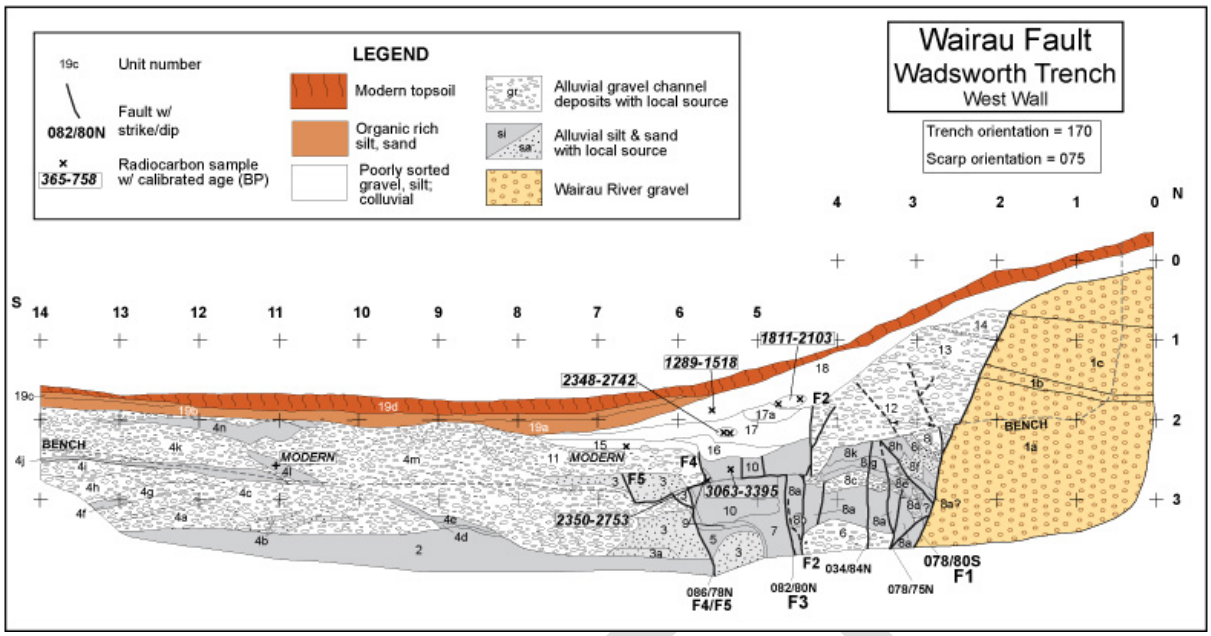

Figure 4.3 The geologic log of the Wadsworth trench, west of Wairau Valley town. The main zone of faulting is coincident with the lower edge of the fault scarp at right.

in the valley, probably as a result of a Wairau Fault earthquake (Zachariasen et al., 2006). The filling of Lake Chalice (see Figure 3.5) was well-dated (1880-2300 cal yr BP). This age overlaps with the timing of the most recent earthquake from trench data and was used by inference to define the timing of the most recent surface rupturing earthquake on the Wairau Fault.

Using the data from Zachariasen et al. (2006) the RI spanning the last four events, and also including the current interseismic period, is c. 1400 years (Figure 4.4; using the outer bounds for the 4th event back). It should be noted that other interpretations of these data (e.g. discount current interseismic period, limit the maximum age of event 4) would yield shorter recurrence intervals.

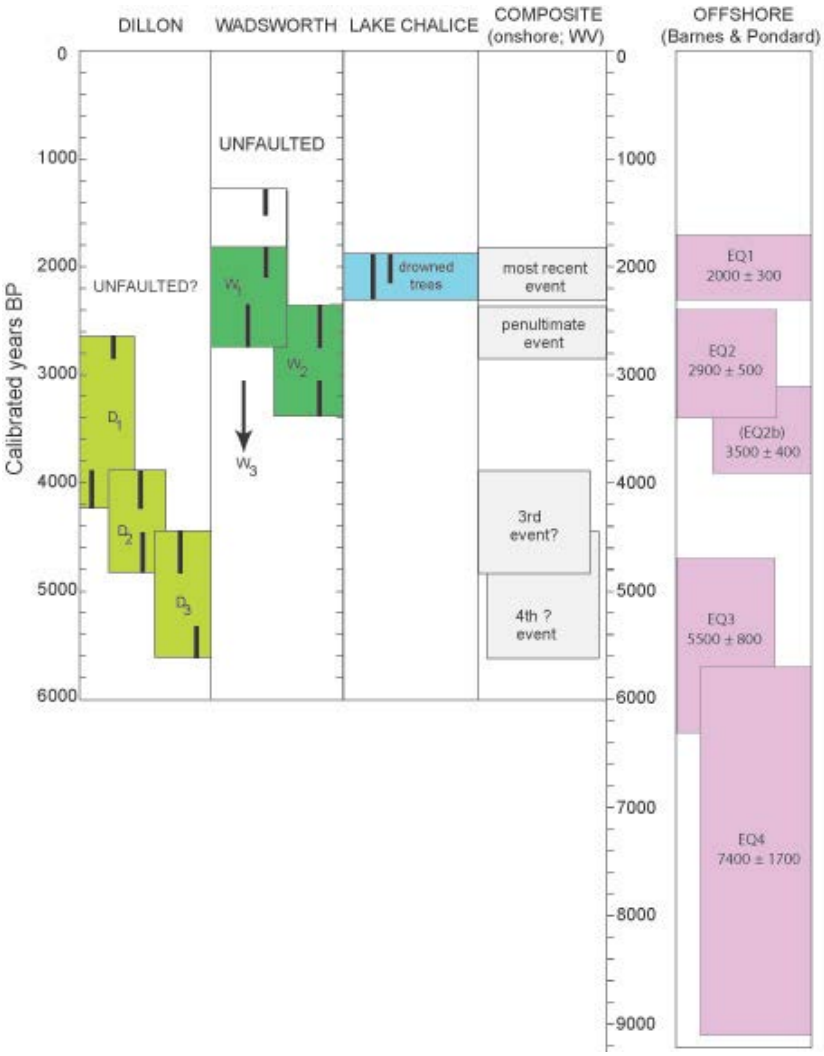

Figure 4.4 Summary of paleoseismic data from trenches onshore in the Wairau Valley area, Lake Chalice (Zachariasen et al., 2006; see Composite) and offshore from Cloudy Bay (Pondard and Barnes, 2010).

Trenching in the lower Wairau valley near Waihopai Valley Road and Marshlands indicates evidence for a young paleoseismic rupture event, that would have occurred since c. 750 cal yr B.P. (since c. 1100 yr ago) (Geotech Consulting Ltd., 2003b, 2005). This data suggests that a quite recent rupture event occurred in the lower Wairau valley; one that post-dates the youngest event near Wairau Valley township.

Another paleoseismic dataset comes from offshore within Cloudy Bay and Cook Strait along the offshore part of the Wairau Fault. Pondard and Barnes (2010) use sub-surface seismic reflection data and cores to interpret up to five paleoseismic rupture events along the offshore Wairau Fault within the last 9000 years. The four youngest events broadly correlate with the timing of the four youngest events on the Wairau Fault from the Zachariasen et al (2006) trenching study near Wairau Valley. However, Pondard and Barnes (2011) found little evidence for a very recent (c. 1100 year ago) event ascribed to the fault in the lower Wairau valley (Yetton et al., 2003b, 2005). Nevertheless, the average recurrence interval for the 5 most recent earthquake events (and including the current interseismic period) calculated from the Cloudy Bay data is at most c. 1800 years. Again, it should be noted that other interpretations of the offshore data (e.g. discount current interseismic period, limit the maximum age of event 5) would yield shorter recurrence intervals.

Collectively, the recurrence interval data from trenches and offshore data between Wairau Valley and Cloudy Bay are mutually consistent and suggest a conservative RI of 1400-1800 years for the last 4-5 surface rupturing earthquakes.

4.2.2 Slip Rate and Displacement method

In contrast, the most recent estimates of RI calculated from slip rate and single-event displacement data produce a mean value of c. 2200 years, though with a modal peak between c. 750-1250 years (Nicol et al., 2011). This result comes from Monte Carlo simulations that analyse slip rate against displacement data against one another.

Slip rate data comes from the measurement of medium-sized fault offset data (typically tens of metres), with geological dating information related to these offsets. In practice, locales such as Branch River offer both the opportunity to measure horizontally offset geomorphic features such as terraces risers and channels on surfaces, and alluvial stratigraphy with which to determine the age of several different offset surfaces. Recent studies at this site yield a Holocene dextral slip rate of 3.5 ± 0.5 mm/year (Nicol et al, 2011).

Similarly, in terms of displacement, suites of progressively abandoned and offset terrace riser and channel features can be used to assess the event-by-event displacement along a fault. Again, a locale such as Branch River offers the opportunity to visualise progressive displacement. However, this locale has an incomplete record of the last several displacement events, therefore, a wider dataset of offsets must be collated from along the fault. A full assessment of the offset data yields a single event displacement range of c. 7 ± 1 m (Nicol et al, 2011). In combination with the slip rate data, the single-event displacement data yield a recurrence interval range of 1500-2700 years, with a median value at or slightly above 2000 yr.

The NSHM uses a set of parametric equations to develop the average RI and magnitude of large surface rupturing earthquakes for more than 500 active faults in New Zealand, including the Wairau Fault (Stirling et al., 2012). The Wairau Fault is categorised as a long strike-slip fault source that extends from Cook Strait to Tophouse, having a length of 143 km (± 10%) and generating an earthquake of magnitude M_w 7.8 ± 0.1. The average, and range, of RI that are produced from magnitude-area scaling relations in the NSHM are 2490 years, and 1793-5477 years, respectively.

4.2.3 Assessment of Recurrence Interval Class for the Wairau Fault

Collectively, the data from the two techniques suggest an average RI of either less than 2000 years (from paleoseismic studies) or more than 2000 years (from slip rate + displacement). The data from paleoseismic studies provides a RI range of c. 1400-1800 years for the last 4-5 earthquakes. If the young (c. 1000 yr old) paleoearthquake event from the lower Wairau valley is included (Geotech Consulting Ltd. 2003b, 2005), then the RI is considerably less than 2000 years. Results from using a slip rate and single-event displacement approach (including the NSHM technique) produce mean RI's that are >2000 years, but also have ranges that distinctly overlap RI Class I. It should be noted that both the paleoseismic and slip rate techniques lack precision in either age control or in offset measurement control and should be open to improvement with better data.

Based on this analysis we believe that the Wairau Fault should be considered as a RI Class I fault (with an average RI ≤ 2000 years) for three reasons: (i) the available recurrence interval data is on average suitably close to, or less than 2000 years; (ii) about 176 years have already accrued since 1840 AD, which means that the next surface rupturing earthquake is probably less than 2000 years away; and (iii) the paleoseismic timing data suggests that at least 1000 years and possibly more than 2000 years have elapsed since the most recent surface rupturing earthquake. Therefore, based on these arguments we believe it is prudent to assign the Wairau Fault to RI Class I.

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5.0 BUILDING IMPORTANCE AND PLANNING CASE STUDIES

5.1 BUILDING IMPORTANCE CLASS

A component of the Resource Consent tables is the Building Importance Category (BIC). The BIC's relate directly to the NZ Building Code and are divided into BIC I (unoccupied structures) through BIC 4 (critical structures) (Table 5.1). BIC 2a and BIC 2b typically distinguish single storey homes from larger normal structures, respectively. A broader description of BIC categories is given by Kerr et al. (2003).

Table 5.1 Building Importance Categories and representative examples. For more detail see Kerr et al. (2003), and King et al. (2003).

Building Importance Category	Description	Examples
1	**Temporary structures** with low hazard to life and other property	• Structures with a floor area of <30m^2 • Farm buildings, fences • Towers in rural situations
2a	**Timber-framed** residential construction	• Timber framed single-story dwellings
2b	**Normal structures** and structures not in other categories	• Timber framed houses with area >300 m^2 • Houses ou • • tside the scope of NZS 3604 "Timber Framed Buildings" • Multi-occupancy residential, commercial, and industrial buildings accommodating <5000 people and <10,000 m^2 • Public assembly buildings, theatres and cinemas <1000 m^2 • Car parking buildings
3	**Important structures** that may contain people in crowds or contents of high value to the community or pose risks to people in crowds	• Emergency medical and other emergency facilities not designated as critical post disaster facilities • Airport terminals, principal railway stations, schools • Structures accommodating >5000 people • Public assembly buildings >1000 m^2 • Covered malls >10,000 m^2 • Museums and art galleries >1000 m^2 • Municipal buildings • Grandstands >10,000 people • Service stations • Chemical storage facilities >500m^2
4	**Critical structures** with special post disaster functions	• Major infrastructure facilities • Air traffic control installations • Designated civilian emergency centres, medical emergency facilities, emergency vehicle garages, fire and police stations

5.2 CASE STUDIES OF USING FAULT AVOIDANCE ZONES FOR PLANNING

Here we provide hypothetical examples of how a council can make sound planning decisions using the FAZs developed in this study. The purpose of these examples is to show that there is a certain amount of flexibility within the structure of the MfE Guidelines in order to make sensible, informed, risk-based planning decisions. It is worth noting however, that RI Class I faults including the Wairau Fault, are by definition the most controlled in terms of the types of planning activities that can be permitted on or adjacent to them. The examples are accompanied by a series of resource consent tables.

The following section provides examples of Resource Consent tables for various RI Class faults, Fault Complexity, Building Importance (BIC) and current land use (e.g. developed or Greenfield settings).

5.2.1 Example 1: shearing shed re-development

In the first hypothetical example, the owners of Lansdowne Station near Wairau Valley village wish to improve the already developed shearing shed (double its capacity). The shearing shed is within the FAZ for the Wairau Fault (near the northern strand of the fault there). As discussed above, the fault is RI Class I (RI ≤2000 years). However, because the building is essentially classed as a farm shed (BIC 1) and not occupied for the purposes of living in and is only rarely used intensely, the activity can be considered as 'Permitted' (Table 5.2).

Table 5.2 Examples, based on the MfE Active Fault Guidelines, of Resource Consent Category for both developed and/or already subdivided sites, and Greenfield sites along RI Class I faults. Categories account for various combinations of Building Importance Category and Fault Complexity.

Example Resource Consent categories for Class I faults (RI ≤2000 years):					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Non-Complying	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	Discretionary	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	Discretionary	*Non-Complying*	*Non-Complying*	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	Resource Consent Category				
Well Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

Notes

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

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

5.2.2 Example 2: A house development at Woodbourne

As a second example, the owners of a property near Woodbourne want to build a new house (BIC 2a structure) just north of the village within a vineyard. The house site is considered Greenfield and is also located within the FAZ for the Wairau Fault. In this area the fault location is also defined as 'Uncertain' (due to its location on a Q1a Holocene surface), so this activity would be '*Discretionary*' (note the use of *italics*; Table 5.2). In this case a council would have more flexibility around its planning solution. One option for a council would be to ask the family to provide more certainty regarding the location of the fault with respect to the house site by undertaking some surveying or geologic mapping studies, or simply to suggest that the house site be moved outside of the FAZ. In many cases, other hazards such as for example, the possibility of flooding from the Omaka or Opawa rivers should also be taken into consideration alongside the hazard posed by the Wairau Fault.

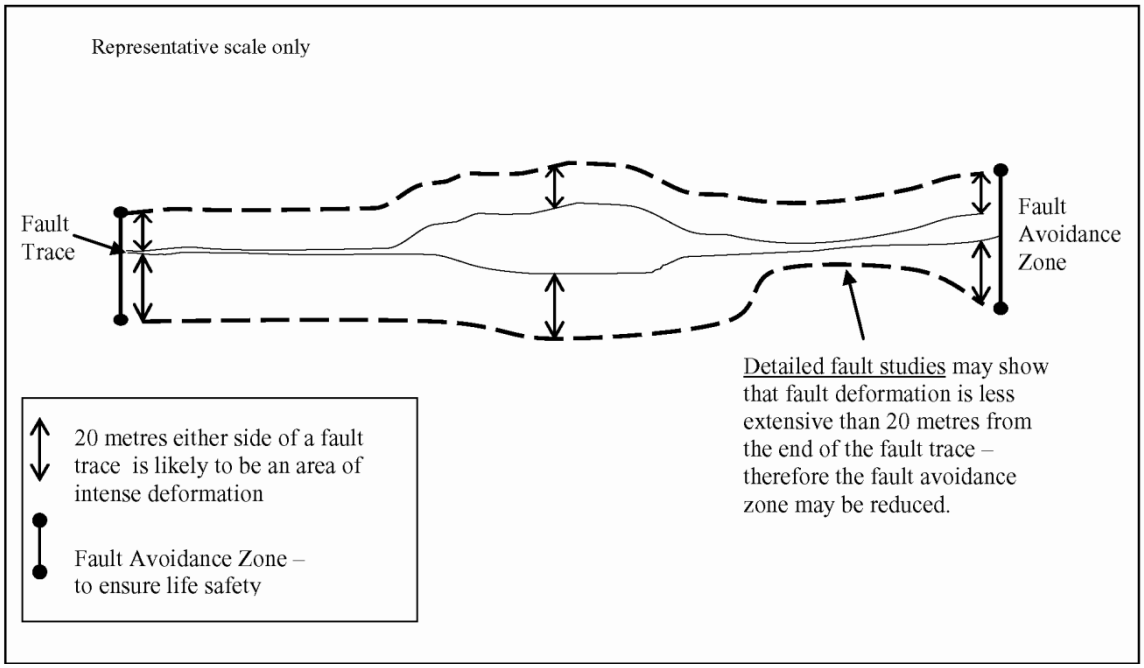

Figure 5.1 A Fault Avoidance Zone (FAZ) on a district planning map. As noted in the lower right, where detailed fault studies have been undertaken it is possible to reduce the original mapped width of a given FAZ. From Kerr et al. (2003).

5.2.3 Example 3: A community hall near Spring Creek

As a third example, the community of Spring Creek wish to build a new Community Hall in an area that is within the FAZ for the Wairau Fault, between S.H. 1 and Watsons Road. The land is 'already developed' or zoned, the fault location is 'Well-Defined' because the fault has been mapped on airborne LiDAR in this area. The BIC Category for the hall is either BIC 2b or 3. The Resource Consent Category for such a building would be '*Non-Complying'* (Table 5.).

The most practical solution would be to build the hall outside of the FAZ. In some cases, the Council can use its discretion considering the occupancy (numbers) or frequency of occupancy of persons in such a building.

Nonetheless, ground surveying, in conjunction with geological studies, can provide more certainty about the location of the fault in a cadastral or geodetic framework, thus reducing

the width of a FAZ. A good example of the benefit of surveying is where we have very wide FAZs derived from the 10-m DEM, NZAFD or QMAP linework, where the uncertainty on fault location is ±125 m. In such a case, accurate mapping or surveying could better define the actual fault location and narrow the FAZ width.

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6.0 SUMMARY

- Active traces of the strike-slip Wairau Fault have been mapped in a GIS database across Marlborough District using LiDAR digital hillshade models, an orthophotograph basemap, and with reference to pre-existing active fault trace linework. This work builds on, but supersedes, previous fault data from Geotech Consulting Ltd. (2003a). In this report, Fault Avoidance Zones (FAZs) and GIS attributes, including Locational Accuracy are presented along with the active fault trace data. Fault line data should be used to indicate the general location of active fault traces only. Planning decisions should be made on the basis of the FAZs which include the uncertainty regarding the location and width of fault deformation.
- FAZs have been defined based on the faults' location uncertainty (FAULT_LOC_UNC), which depends on the accuracy of mapping, and an additional setback zone in accordance with the MfE Guidelines. Where LiDAR is available, faults have been mapped as either *accurate* (±20 m), *approximate* (±40 m), or *uncertain* (±100 m) in terms of their fault location accuracy. Where *uncertain* traces mapped on LiDAR have been projected across distances of >1600 m, the FAULT_LOC_UNC has been increased to ±125 m from the mapped line. Where there is no LiDAR coverage pre-existing linework reviewed using a GIS-based orthophotograph basemap has been assigned an accuracy or uncertainty of ±125 m. A margin of safety (setback) buffer of +20 m is added to each side of the FAULT_LOC_UNC buffer to form a FAZ.
- FAZs range in width from 80 m for *accurate* fault traces, to 290 m for *uncertain* fault locations based on the orthophotograph basemap and fault traces projected across distances of >1600 m.
- One of the greatest uncertainties in this project is the location of the Wairau Fault across the lower Wairau valley between Renwick and Spring Creek. Our preferred interpretation is that the southern trace (as defined in this study) links with the coastal trace. Due to the considerable uncertainty related to this interpretation we have placed a FAULT_LOC_UNC of ±125 m through this area. It is still possible that the fault, or traces of the fault, exist outside of this 290 m wide FAZ. This uncertainty could be improved upon by undertaking geophysical studies that could pick up the Wairau Fault in geophysical profiles.
- We have investigated several methods to estimate the average RI and have found that the average recurrence interval is close to and probably <2000 years. Paleoseismic trenching across the fault indicates that the average RI for ground surface faulting along the Wairau Fault spanning the last four earthquakes is c. 1400 years. Studies from offshore geologic data indicate that the average recurrence interval over the last five events is c. 1800 years. Monte Carlo statistical methods suggest a mean recurrence interval of c. 2200 years (modal peak centred at 1000 years). As such, we conclude that the Wairau Fault should be considered a RI Class I fault (RI ≤2000 yr).
- Example Resource Consent Activity tables have been provided with the report to aid the council in the consent process. These tables provide guidance with respect to different land use and building types related to FAZs for the Wairau Fault.

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7.0 RECOMMENDATIONS

- We recommend that the fault trace linework and Fault Avoidance Zones (FAZs) presented as digital geospatial data be adopted by Marlborough District Council, and should supersede previous versions of active fault linework, attributes and FAZs provided by earlier reports (e.g., Geotech Consulting Ltd., 2003a).
- We recommend that the MfE Guidelines regarding active faulting should continue to be used as standard practice for planning and consenting in Marlborough District, and that these fault traces be incorporated within District Plan maps where possible, or within Council GIS databases, in order to set rules for setback distances from active faults, or require proof of consideration of active fault guidelines.
- We recommend that geophysical studies (shallow seismic, Landstreamer, Ground Penetrating Radar) be considered to refine the location of the Wairau Fault across the lower Wairau valley. Such studies could provide critical data to validate or improve upon the fault location data supplied here.
- We also recommend that active fault linework and FAZs should be updated every decade or so (or as more LiDAR data becomes available). The next practical step would be to undertake an active fault mapping and FAZ study that covers the remainder of the district in its entirety. This would be viable because LiDAR coverage exists across significant lengths of both the Awatere and Clarence faults (80 km and 43 km, respectively).

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8.0 ACKNOWLEDGEMENTS

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APPENDICES

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A1.0 GIS DATA

This study includes digital data supplied as two ESRI shapefiles, consisting of a polyline shapefile of mapped faults and a polygon shapefile of FAZs. These data and their attributes are described below. Both the fault linework and FAZ shapefiles have an identical list of attributes.

Fault line data should be used to indicate the general location of active fault traces. Planning decisions should be made on the basis of the FAZs which include the uncertainty regarding the location and width of fault deformation.

File Name: MarlboroughDC_Faultlines_CR_2016_25
Type: Polyline
Projection: NZGD 2000 New Zealand Transverse Mercator.prj

File Name: MarlboroughDC_FAZ_CR_2016_25
Type: Polygon
Projection: NZGD 2000 New Zealand Transverse Mercator.prj

Each mapped fault trace is represented as a series of features that have been attributed with the following information:

FAULT_NAME: all fault traces in this study have the name Wairau Fault.

SECTION: The name given to a fault section. In some cases a fault may be subdivided into distinct sections, where there is a geographical or structural break in the fault. A fault section will typically consist of several to many individual fault traces.

DATA_SOURCE: Refers to the source of the data used to map the fault trace. For this study the data source is limited to:

NSF2013_LiDAR: Mapped from an airborne 0.33-m LiDAR DEM and hillshade model

EQC2013_LiDAR: Mapped from an airborne 0.5-m LiDAR DEM and hillshade model

MDC_LiDAR: Mapped from an airborne 1-m LiDAR DEM and hillshade model

NZAFD_Basemap: Linework from New Zealand Active Fault Database (NZAFD) revised using a LINZ (Basemap) colour orthophotograph

SCALE: The scale at which the feature was digitised.

ACCURACY: Refers to the ability to identify and clearly map fault-related features from the available imagery and is limited to three possibilities.

Accurate: Where a fault scarp can be clearly mapped.

Approximate: Where the fault/trace is not as clearly expressed but there is clear geomorphic evidence of a surface fault rupture.

Uncertain: Where the fault is concealed (buried) or eroded away i.e. where a fault crosses an active river or floodplain.

BUFFER: Is a number value in metres with which we consider to be the maximum mapped location uncertainty for a fault line. These values are used for defining the widths of FAZs.

For this study the values used are based on the **DATA_SOURCE, SCALE** and **ACCURACY** attributes as explained in the text.

> *±100 m*: All linework from sources mapped at a scale greater than 1:10,000, i.e. regional DEM or the NZAFD. A value of ±100 m is used regardless of whether its location is considered accurate, approximate or uncertain[5].
>
> *±40 m:* Uncertain fault traces mapped from LiDAR hillshade model
>
> *±25 m:* Approximate fault traces mapped from LiDAR hillshade model
>
> *±10 m:* Accurate fault traces mapped from LiDAR hillshade model

SLIP_TYPE: Refers to the dominant sense of movement on a fault. These are as described in Chapter 2 and include:

> *Dextral* (right-lateral), *Sinistral* (left-lateral), *Reverse*, *Thrust, and Normal*

The terms *strike-slip*, *dip-slip* and <*Null*> are sometimes used when the style of movement is unclear.

DOWN_QUAD: Refers to the compass quadrant that is downthrown relative to the strike of the fault. They are limited to the following attributes:

> *N, S, E, W, NW, NE, SW, SE*

RI_CLASS: relates to the recurrence interval of faulting. The MfE Guidelines (Kerr et al., 2003) define six recurrence interval classes (RI Classes I-VI) depending on the activity of the fault. In this study in all cases, we use a RI Class I for all fault traces.

> Class I: ≤2000 yr
> Class II: >2000 to ≤3500 yr
> Class III:>3500 to ≤5000 yr
> Class IV: >5000 to ≤10,000 yr
> Class V: >10,000 to ≤20,000 yr
> Class VI: >20,000 to ≤125,000 yr

[5] We use ±100 m rather than ±125 m. The latter is used in association with QMAP (1:250,000 scale) data, however, this has not been used as the basis for fault linework locations in this study.

A2.0 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. Ground surface-rupturing earthquakes are typically of magnitude M_w >6.5. An active fault in New Zealand is generally defined as one which has deformed the ground surface within the past 125,000 years (Langridge et al., 2016).This is defined in part for practical reasons as those faults which 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 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 expressed in the landscape as linear traces displacing surficial geologic features which may include hillslopes, alluvial terraces and fans. The age of these displaced features can be used to define how active a fault is. Typically in New Zealand, alluvial terraces are associated with the contemporary river drainages, and therefore they are typically <30,000 years old. Hillslopes are mainly formed in bedrock and in New Zealand these surfaces have generally been modified by glacial or cold climate processes during the peak of the Last Glacial period (Barrell et al., 2011). This means that well-defined, linear fault traces that cut across bedrock hillslopes are probably also <30,000 years old.

Active faults are often defined by a fault scarp. A fault scarp is formed when a fault displaces or deforms a surface and produces an abrupt linear step, which smoothes out with time to form a rounded scarp (Figure A2.1). In some cases, where a fault moves purely in a horizontal sense, only a linear trace or furrow may be observed. Traditionally, faults have been mapped from aerial photographs using stereoscopy, i.e., pairs of overlapping aerial photographs that can be used to visualise the ground surface in 3-D. Airborne LiDAR and detailed Digital Elevation Models (DEM's) have greatly improved the accuracy to which active fault traces can be mapped (Meigs, 2013; Langridge et al., 2014).

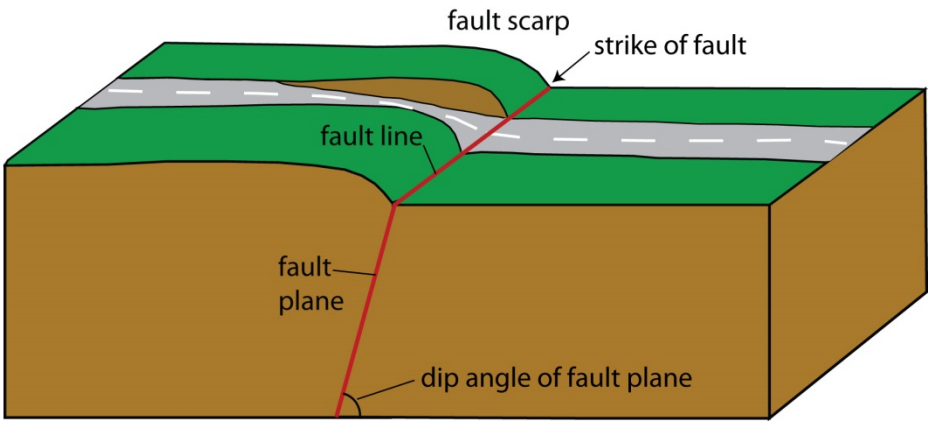

Figure A2.1 Block model of a generic active fault. Fault displacement produces a scarp along the projection of the fault plane at the Earth's surface (fault line or trace).

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 A2.2), or, left-lateral (sinistral) where the opposite side of the fault moves to the left.

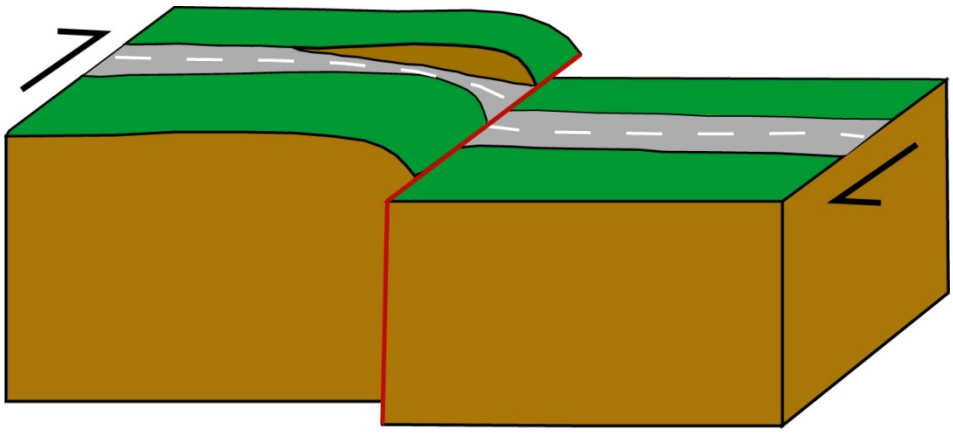

Figure A2.2 Block model of a strike-slip fault (red line). The fault is a right-lateral fault as shown by the black arrows and by the sense of movement across the two blocks and a right separation across the road.

Most strike-slip faults in New Zealand, such as the Alpine, Hope, Wairarapa and Wellington faults, have a right-lateral sense of movement (Berryman and Beanland, 1991). Right-lateral strike-slip faults predominate across Marlborough District, and include the Wairau, Clarence, Fowlers and Awatere faults (Table 4.1).

Dip-slip faults can be divided into reverse faults, formed mainly under contraction (where the hangingwall block of the fault is pushed up; Figure A2.3) and normal faults, formed under extension (where the hangingwall block of the fault drops down; Figure A2.4).

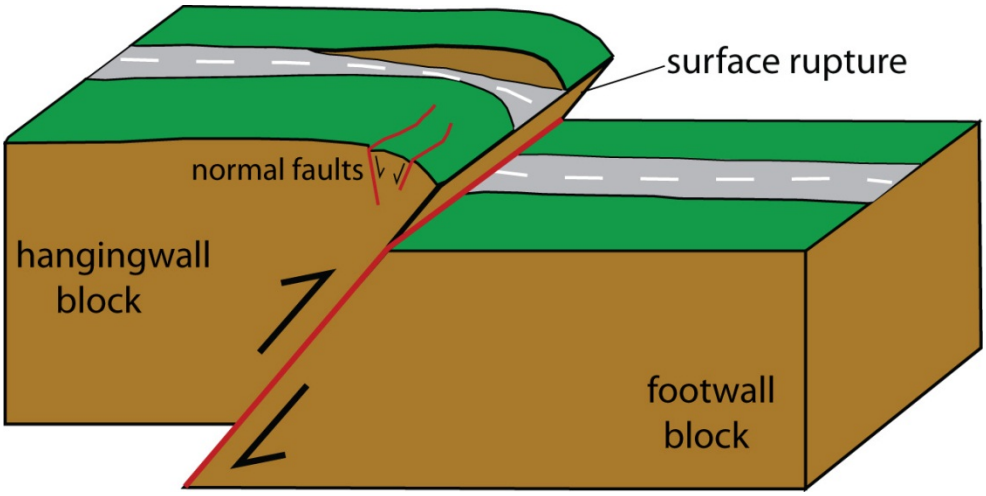

Figure A2.3 Block model of a reverse dip-slip fault that has recently ruptured. Movement of the blocks is vertical and in the dip direction of the fault plane. In this case, the hangingwall block has been pushed up over the footwall block. Folding and normal faulting are common features of deformation in the hangingwall block of reverse faults.

Reverse faults are not common within the onshore part of Marlborough District. Locally, the best example of a reverse fault is the London Hill Fault near Cape Campbell. Reverse faults have also been mapped off of the east coast of the district by NIWA (e.g. Barnes and Audru, 1999; Barnes and Pondard, 2010). An important tectonic component of deformation in the region relates to the transition from strike-slip to reverse faulting between Marlborough and the Hikurangi Subduction Zone (Wallace et al., 2012; Pondard and Barnes, 2010).

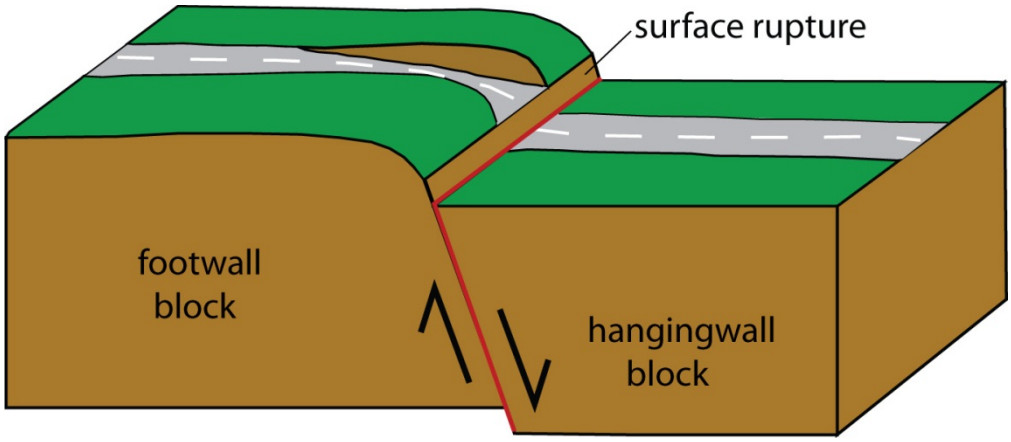

Figure A2.4 Block model of a normal dip-slip fault. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hangingwall block has dropped down, enhancing the height of the fault scarp.

Normal faults are dip-slip faults that form in the crust under conditions of extension, i.e. where the crust is pulling apart (Figure A2.4). As the active tectonics of the region are dominated by oblique compression, where active faults are typically either strike-slip or reverse in style, there were previously no known examples of active normal faults within Marlborough District. New mapping as part of this study has recognised a subsidiary zone of normal faulting related to the Wairau Fault to the east of Tophouse (see Section 3.3.1).