Updated Assessment of Active Faults in the Kaikōura District

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GNS Science Consultancy Report 2018/141
September 2019

BIBLIOGRAPHIC REFERENCE

Litchfield NJ, Morgenstern R, Van Dissen RJ, Langridge RM, Pettinga JR, Jack H, Barrell DJA, Villamor P. 2019. Updated assessment of active faults in the Kaikōura District. Lower Hutt (NZ): GNS Science. 71 p. (GNS Science consultancy report; 2018/141).

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EXECUTIVE SUMMARY

Kaikōura District Council is currently updating the Natural Hazards chapter of the Kaikōura District Plan and Environment Canterbury commissioned GNS Science to provide an update of the existing information on active geological faults in the District, including new data on the 2016 Kaikōura Earthquake fault rupture. The majority of active faults in the Kaikōura District are now also covered by high resolution laser radar (LiDAR) data, enabling higher resolution mapping of faults with particular focus on those active faults that have relatively short recurrence intervals and those that are in areas of potential future land and infrastructure development. This update included: 1) reassessing existing and generating new Fault Awareness Areas; 2) generating Fault Avoidance Zones for selected faults; 3) updating recurrence interval information; and 4) recommending how this information should be used in a planning framework.

In the Ministry for the Environment's 2003 guidelines for "*Planning for Development of Land on or Close to Active Faults*" (MfE Active Fault Guidelines), the surface rupture hazard of an active fault at a specific site is characterised by two parameters: 1) its location (i.e., the likely rupture zone, or zone where the fault is expected to break/deform the ground surface); and 2) the activity of the fault, as measured by its average recurrence interval of surface rupture (how often on average it ruptures the surface). The MfE Active Fault Guidelines suggest defining Fault Avoidance Zones that comprise the likely rupture zone, plus a 20-m-wide buffer either side of the rupture zone. The mapping scale for Fault Avoidance Zones is detailed so that it can be used at the scale of individual land parcels and prospective building platforms.

Ideally Fault Avoidance Zones would have been generated for all faults in the Kaikōura District. However, many of the faults in the District are in sparsely populated rural areas or Department of Conservation estate and are unlikely to experience development pressures in the near future. As a result, Fault Avoidance Zones have only been generated for faults with relatively short recurrence intervals and which are in areas of potential future development. For the remaining faults we have applied the concept of Fault Awareness Areas, which delineate the likely general location of an active fault. The purpose of the Fault Awareness Areas is to highlight areas where more detailed investigations could be undertaken if more information about the fault is needed such as for delineating Fault Avoidance Zones. Fault Awareness Areas were previously generated by Environment Canterbury using active fault locations defined in a 2015 GNS Science assessment of active faults in the Kaikōura District. No Fault Avoidance Zones have previously been generated for the Kaikōura District.

New Fault Awareness Areas have been generated for four previously-unmapped faults that ruptured in the Kaikōura Earthquake (the Manakau, Whites, Oaro River, and Stone Jug faults). Fault Awareness Areas have been updated for parts of, or the entire lengths of, eight other faults based on new data (the Fidget, Kekerengu, Jordan Thrust, Upper Kowhai, Stewart Creek, and Hundalee faults). The Fault Awareness Areas were generated by buffering 1:250,000 scale mapping of the faults, the buffer widths determined on a fault-by-fault basis to encompass all of the detailed traces. Most of the updated Fault Awareness Areas lie within or overlap the previously-generated Fault Awareness Areas.

New Fault Avoidance Zones, in accordance with the MfE Active Fault Guidelines, have been generated for selected high priority faults. These included parts of, or all of seven faults that ruptured in the Kaikōura Earthquake (the Tinline Downs, Kekerengu, Heaver's Creek, Papatea, Waiautoa, Corner Hill and Paparoa Point faults) and parts or all of seven faults or fault sections based on new data (the Winterholme Fault, East Lane Fault, Chaffey Link Fault, Jordan Thrust and Conway, Mt Fyffe, and Seaward sections of the Hope Fault). The Fault

Avoidance Zones were generated from buffering the deformation width of individual fault traces and adding the 20 m setback zone. Most of the Fault Avoidance Zones lie within or overlap the previously-defined Fault Awareness Areas, and in many cases, have resulted in a much narrower zone than what was previously mapped.

In the MfE Active Fault Guidelines, the recurrence interval for surface rupturing earthquakes on an active fault is a fundamental parameter used to define the hazard posed by that fault. Accordingly, recurrence interval data has been reviewed and updated for all of the mapped faults in the Kaikōura District. These updates incorporate new paleoseismic site-specific data and field observations for certain faults where such data exist. For other, major, faults the updated recurrence intervals are based on the 2010 National Seismic Hazard Model methodology which utilises fault length and slip rate information. For minor faults, the updates are assigned based on subjective comparisons with nearby major faults.

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

- Include all Fault Awareness Areas and Fault Avoidance Zones in the Kaikōura District Plan, and in any other planning or hazard information maps for Kaikōura.
- Use the recommended actions to the Fault Awareness Areas and Fault Avoidance Zones as a starting point for community consultation.
- Include Fault Awareness Area and Fault Avoidance Zone information on Land Information Memoranda and Property Information Memoranda.
- Obtain better constraints in recurrence interval class. Site-specific paleoseismic studies are currently being undertaken on some of the faults that ruptured in the Kaikōura Earthquake and it is recommended that this new information be incorporated when it becomes available. There is also potential to improve the confidence level of some other faults, particularly the Heaver's Creek, Chaffey Link, Winterholme, East Lane, Papatea, Waiautoa, and Hope (My Fyffe and Seaward sections) faults.
- Better constrain the fault zone for development sites if required. This may involve generation of Fault Avoidance Zones for faults which currently have Fault Awareness Areas or trenching to further narrow Fault Avoidance Zones.
- Investigate engineering mitigation measures for developed and already subdivided sites, and for critical lifelines that cross active faults.

1.0 INTRODUCTION

1.1 Background and Context

Beginning in the late 2000s, Environment Canterbury engaged GNS Science to provide a series of state-of-existing-knowledge compilations of the distribution and characteristics of active geological faults and folds in the various districts of the Canterbury Region, based largely on existing 1:250,000 scale geological mapping data, as summarised by Barrell et al. (2013, 2015). Subsequently, the fault[1] mapping was used by Environment Canterbury to define Fault Awareness Areas, in accordance with the *Guidelines for using regional-scale Earthquake fault information in Canterbury* (Barrell et al. 2015). The purpose of the Fault Awareness Areas is to show the general location of active faults and thereby highlight areas where a potential fault rupture hazard may be present.

The fault map compilation for the Kaikōura District (Barrell 2015), and Fault Awareness Areas generated by Environment Canterbury and provided to the Kaikōura District Council, needed updating following the 14 November 2016 M_W 7.8 Kaikōura Earthquake. In that earthquake, over 20 active faults ruptured the ground surface and/or sea bed surface (Figure 1.1), generating ground-surface fault displacements of as much as 12 m in the horizontal and 10 m in the vertical, as well as broader-scale uplift and subsidence (Clark et al. 2017; Hamling et al. 2017; Stirling et al. 2017; Kearse et al. 2018; Langridge et al. 2018; Litchfield et al. 2017, 2018; Nicol et al. 2018; Williams et al. 2018). The combined length of the surface ruptures was >220 km, of which ~105 km occurred within the Kaikōura District (Figure 1.1).

The ground-surface fault ruptures caused damage to buildings and infrastructure, including displacement and tilting of houses, displacement of nationally significant lifelines (e.g., the east coast fibre optic cable, state highways and the South Island main trunk railway), and damage to local roads, farm tracks, fences and irrigation systems (Stirling et al. 2017; Van Dissen et al. 2018, submitted). Some examples are shown in Figure 1.2.

The majority of faults that ruptured in the Kaikōura Earthquake were previously known to be active, and several had already been mapped – to some degree at least (Barrell and Townsend 2012; Barrell 2015). However, some of the faults that ruptured in the Kaikōura Earthquake were previously unknown or not considered to be active, and so were not included in the Kaikōura District fault mapping (Barrell 2015) or had Fault Awareness Areas. Another notable feature of the surface ruptures in the Kaikōura Earthquake was that some faults only partially ruptured, including only localised, minor (<1.1 m) rupture of the Hope Fault. This is potentially important because the Hope Fault is one of the most active faults in New Zealand (e.g., Langridge et al. 2003; Litchfield et al. 2014; https://data.gns.cri.nz/af/ Langridge et al. 2016).

Mapping of the surface-rupturing faults following the Kaikōura Earthquake was undertaken by a large team of scientists from multiple institutions, funded by GeoNet, the Natural Hazards Research Platform, GNS Science, NIWA and University (multiple) internal funding. The data were compiled by GNS Science into the New Zealand Active Faults database (https://data.gns.cri.nz/af/; Langridge et al. 2016) (e.g., Litchfield et al. 2017, 2018). Mapping

[1] For simplicity, the term active fault is used henceforth in this report to refer to both active fault (ground offset) and active fold (ground bending or buckling) surface deformation.

was undertaken using a range of techniques and datasets including field mapping and surveying, Light Detecting and Ranging (LiDAR, more simply called laser radar), orthophotos, and structure-from-motion Unmanned Aerial Vehicle (UAV) surveys. From the detailed mapping a simplified, 1:250,000 scale version was compiled and is available for download from the New Zealand Active Faults Database website (https://data.gns.cri.nz/af/).

Kaikōura District Council is currently updating the Natural Hazards chapter of the Kaikōura District Plan and Environment Canterbury commissioned GNS Science provide an update of the existing active fault information, which includes the 2016 Kaikōura Earthquake fault rupture information. The majority of the active faults in the Kaikōura District are now also covered by high resolution LiDAR data. The availability of such high resolution topographic data greatly facilitates the identification of active faults, and the mapping of those faults for the purpose of surface fault rupture hazard mitigation.

Ideally Fault Avoidance Zones, as defined in the Ministry for the Environment's *Planning for Development of Land on or Close to Active Faults*[2]; see also King et al. (2003) and Van Dissen et al. (2006), would be generated for all faults in the Kaikōura District. However, many of the faults in the District are in sparsely populated rural areas or Department of Conservation estate and are unlikely to experience development pressures in the near future. For this reason, and also attempting to accommodate the short time frame for the District Plan review process, Fault Avoidance Zones have only been mapped for faults with relatively short recurrence intervals and which are in areas of potential future development. For the other faults, existing Fault Awareness Areas are reviewed and if need be refined, and additional Fault Awareness Areas were added as appropriate.

The update of active fault information (i.e., Fault Awareness Areas, Fault Avoidance Zones, Recurrence Interval Classes) for the Kaikoura District is summarised in this report, and the detailed scope of the investigation and project outline are contained in the following section (1.2).

[2] The Ministry for the Environment's guidelines "Planning for development of land on or close to active faults" (Kerr et al. 2003) is available on both the Ministry for the Environment and the Quality Planning websites and throughout this report are referred to as the MfE Active Fault Guidelines.

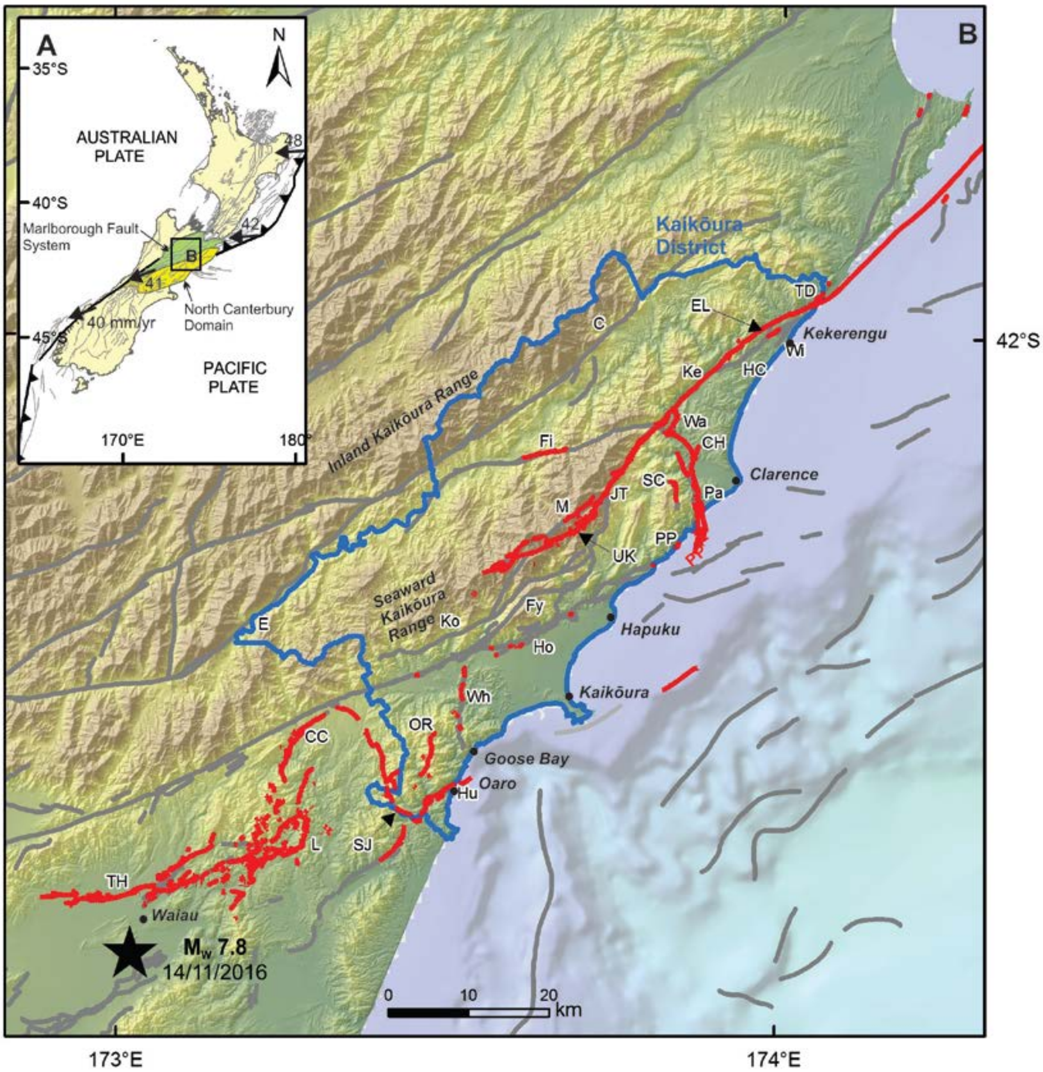


Figure 1.1 A) Tectonic setting with simplified active faults and tectonic domains. The Pacific Plate motion vectors are from Wallace et al. (2007). B) Active faults (red and grey lines) in and near the Kaikōura District. Red lines are faults that ruptured the ground surface / sea bed in the 2016 Kaikōura Earthquake, which are from this study, and the grey lines are from the New Zealand Active Faults Database https://data.gns.cri.nz/af/ (Langridge et al. 2016). C is the Clarence Fault, CC is the Conway-Charwell Fault, CH is the Corner Hill Fault, E is the Elliott Fault, EL is the East Lane Fault, Fi is the Fidget Fault, Fy is the Fyffe Fault, HC is the Heaver's Creek Fault, Ho is the Hope Fault, Hu is the Hundalee Fault, JT is the Jordan Thrust, Ke is the Kekerengu Fault, Ko is the Kowhai Fault, L is the Leader fault, M is the Manakau Fault, OR is the Oaro River Fault, Pa is the Papatea Fault, PP is the Paparoa Point Fault, SC is the Stewart Creek Fault, SJ is the Stone Jug Fault, TD is the Tinline Downs Fault, TH is The Humps Fault, UK is the Upper Kowhai Fault, Wa is the Waiautoa Fault, Wh is the Whites Fault, and Wi is the Winterholme Fault.

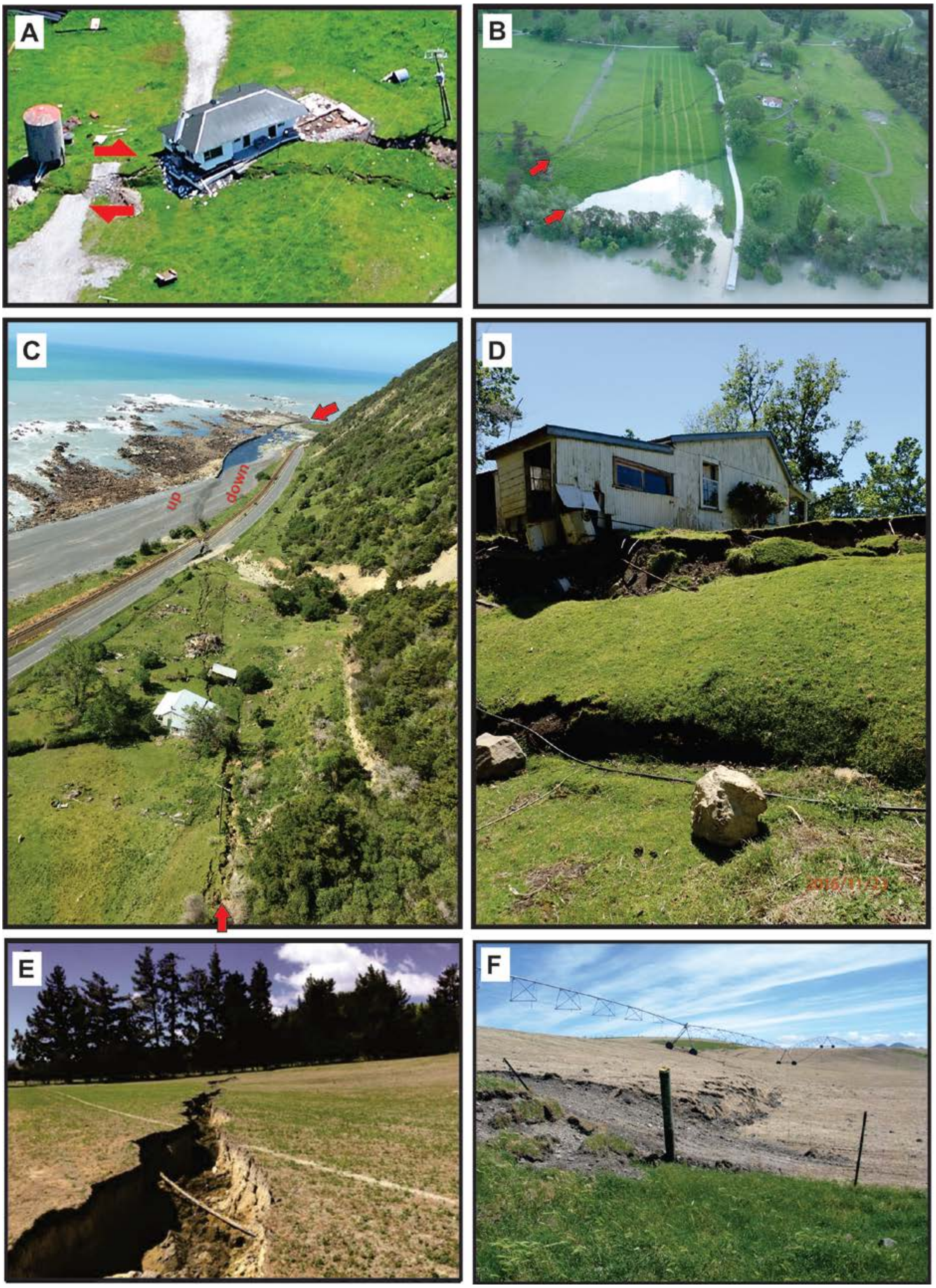


Figure 1.2 Examples of damage to houses and infrastructure from surface fault ruptures in the 2016 Kaikōura Earthquake. From Van Dissen et al. (2018, Submitted). The red arrows in A show the direction of horizontal motion of the fault in the 2016 earthquake, those in B and C point to 2016 rupture traces.

1.2 Scope and Objectives

The overall aim of this project is to update previously-defined Fault Awareness Areas (see definitions in section 1.3) based on previous active fault maps (Barrell 2015) and where appropriate to generate Fault Avoidance Zones (MfE Active Fault Guidelines) for active faults in the Kaikōura District, incorporating new information compiled following the Kaikōura Earthquake.

Tasks specified in the project brief were:

1. Create new Fault Awareness Areas for mapped 2016 fault ruptures (marked as green on Figure 1.3):
   - Fidget Fault
   - Manakau Fault and other unnamed faults in the Uwerau Fault Zone[3]
   - Upper Kowhai Fault
   - Jordan Thrust
   - Heaver's Creek Fault south of Valhalla Stream
   - Kekerengu Fault south of Valhalla Stream
   - Hundalee Fault
   - Stone Jug Fault
   - Whites Fault
2. Add these new Fault Awareness Areas to existing Fault Awareness Areas based on 1:250,000 fault dataset (marked as orange on Figure 1.3).
3. Develop detailed Fault Avoidance Zones (at 1:35,000 scale or better) for (marked as blue on Figure 1.3):
   - Kekerengu Fault north of Valhalla Stream
   - Heaver's Creek Fault and subsidiary faults north of Valhalla Stream
   - Papatea Fault and Waiautoa Fault
   - Paparoa Point Fault
   - Hope Fault (including Maungamanu Fault and southern end of Jordan Thrust to northern side of Hapuku River (near 307m hill))
4. Update any recurrence interval information with any new information since 2015.
5. Provide planning recommendations for the Fault Awareness Areas and Fault Avoidance Zones based on the recommendations in Barrell (2015) and Kerr et al. (2003) (see Section 1.3.2).

[3] The Uwerau Fault Zone was a name used in the early phases of the Kaikōura Earthquake response but was subsequently abandoned when the Manakau Fault was better defined. It is therefore not used in this report.

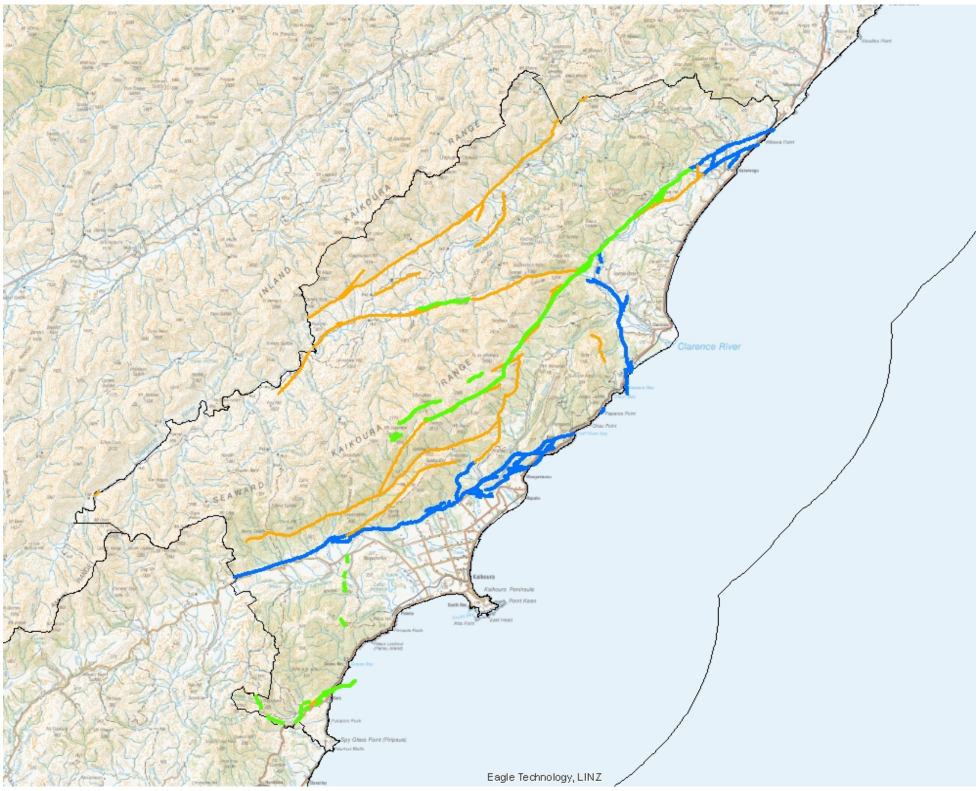


Figure 1.3 Kaikōura District active faults for which Fault Awareness Areas are to be updated (orange) or created (green), and for which Fault Avoidance Zones are to be created (blue).

1.3 Data Structure, Fault Awareness Areas and Fault Avoidance Zones

1.3.1 Data Structure

The active fault mapping compiled for the Kaikōura District by Barrell (2015) was based primarily on regional-scale geological mapping compiled in digital format as part of the GNS Science 1:250,000 QMAP (Quarter-million scale MAP) project. This is represented in the Kaikōura District by the Kaikōura QMAP (Rattenbury et al. 2006), forming part of the overall National QMAP compilation (Heron 2014).

Within a GIS environment, fault locations are typically denoted by a line. For the Canterbury region work, line datasets for faults were taken from the QMAP digital linework, and modified in location if necessary, and additional faults were added where they had been identified subsequent to the QMAP compilation. The QMAP line features representing faults were broken into segments, to allow the addition of further information (‘attributes’). This included the assignment of a name to each active fault, because not all active faults had previously been named in QMAP, and attributes for Certainty and Surface form, as described below:

- **Certainty** to indicate the level of confidence in the interpretation that the mapped landform feature is the result of fault deformation;
- **Surface form** to indicate how clearly the fault feature is expressed in the landscape, and its relation to Fault Complexity criteria of the MfE Active Fault Guidelines; the surface form information is intended to assist in the planning and targeting of any future fault investigations;

For each named fault in the GIS dataset, a recurrence interval was assigned. As defined in the MfE Active Fault Guidelines, the recurrence interval is the length of time, on average, that has elapsed between surface ruptures of any particular fault. As compiled for the Kaikōura District faults by Barrell (2015), the recurrence interval was obtained from existing geologically-based investigation data where possible. Where there were no existing data, recurrence interval estimates were calculated by dividing inferred single event displacements (2–5 m for strike-slip faults and 2 m for dip-slip faults) by slip rate.

Within a GIS environment, the locational extent of a fault is usually depicted as an area, which in technical terms is referred to as a polygon feature. Fault Awareness Areas and Fault Avoidance Zones are examples of polygon features. As these two classes of polygon feature are the focus of this report, their general character is described in the following subsection, and further details as necessary are provided later in the report.

1.3.2 Fault Awareness Areas

Fault Awareness Areas were generated by Environment Canterbury from the 1:250,000 scale GIS fault maps produced for each District within the Canterbury Region (e.g., Barrell and Townsend 2012; Barrell 2015), following the methodology described by Barrell et al. (2015). The purpose of the Fault Awareness Areas is to show the general location of active faults and thereby highlight areas where a potential fault rupture hazard may be present. Such information is intended to assist council authorities, existing and future landowners and developers, infrastructure managers and emergency managers. The fact that the surface fault rupture hazard has not been mapped precisely in some areas doesn't preclude action being taken to manage the risk.

The Fault Awareness Areas were generated by buffering[4] active faults and monocline folds by 125 m or 250 m either side of the mapped line, according to the level of certainty and surface form. That is, buffers of 125 m either side were applied to faults characterised as:

- Definite (well expressed),
- Definite (moderately expressed)
- Likely (well expressed), or
- Likely (moderately expressed).

Buffers of 250 m either side (i.e., total width 500 m) were applied to all other faults and monocline folds (i.e., those characterised as 'possible' and 'not expressed').

The existing Fault Awareness Areas constructed for the Kaikōura District based on the 1:250,000 scale fault map line work of Barrell (2015) are shown in Figure 1.4.

Description of how the Fault Awareness Areas were created or updated for this project are contained in Section 2.0. Recommendations for using the Fault Awareness Areas in a planning context are provided in Section 5.4.

[4] Buffering is a process undertaken within a GIS system, where a perimeter of a specific width is generated around a specific mapped feature.

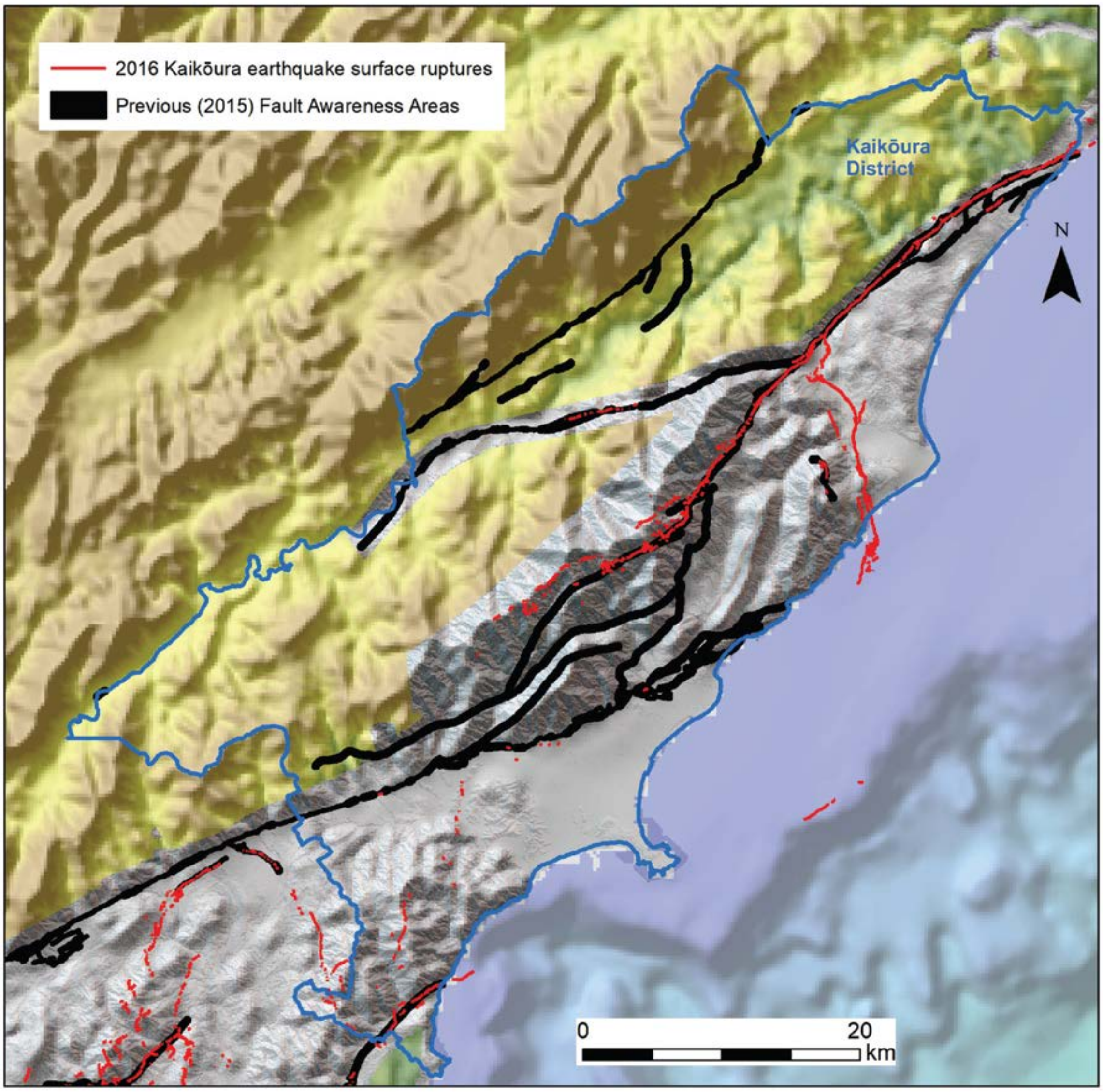


Figure 1.4 Faults that ruptured the ground surface / sea bed in the 2016 Kaikōura Earthquake overlain on the previously-defined Fault Awareness Areas generated by Environment Canterbury based on the regional-scale active fault mapping of Barrell (2015). The grey background is the 2016–2017 LiDAR data.

1.3.3 Fault Avoidance Zones

Fault Avoidance Zones are a recommended risk-based tool to mitigate surface rupture hazard for land use planning purposes, as described in the MfE Active Fault Guidelines. The aim of the MfE Active Fault Guidelines is to assist resource management planners tasked with formulating land use policy and making decisions about development of land on, or near, active faults. The MfE Active Fault Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas subject to ground-surface fault rupture hazard. In the MfE Active Fault Guidelines, the surface rupture hazard of an active fault at a specific site is characterised by two parameters:

1. location/complexity of surface rupture of the fault; and
2. activity of the fault, as measured by its average recurrence interval of surface rupture.

The MfE Active Fault Guidelines also advance a hierarchical relationship between fault recurrence interval and building importance, such that the greater the importance of a structure, with respect to life safety, the longer the avoidance recurrence interval. For example, only low occupancy structures, such as farm sheds and fences (i.e., Building Importance Category 1 structures), should be allowed to be built across active faults with average recurrence intervals of surface rupture less than 2000 years. In contrast, in a “greenfield” (i.e., undeveloped) setting, more significant structures such as schools, airport terminals, and large hotels (i.e., Building Importance Category 3 structures) should not be sited across faults with average recurrence intervals shorter than 10,000 years.

In practice, Fault Avoidance Zones are created by defining a 20 m buffer around the fault complexity zones, which defines the likely rupture zone of faults. The fault complexity zones are themselves generated from buffers placed on the detailed fault mapping linework, with the width of fault complexity zones generally determined by an expert assessment of fault location accuracy (or lack thereof).

Fault Avoidance Zones have not previously been generated for any active faults in the Kaikōura District. Description of the creation of Fault Avoidance Zones for selected faults in this project is contained in Section 3.0. Recommendations for utilising Fault Avoidance Zones in a planning and risk reduction context are provided in Section 5.3.

1.4 Tectonic Setting of the 2016 Kaikōura Earthquake and Active Faults in the Kaikōura District

The Kaikōura District is situated on the boundary zone between the Australian and Pacific Plates (Figure 1.1A). The plate boundary zone in this area is one of transition between subduction (compression and forcing downwards) of the Pacific Plate beneath the Australian Plate to the northeast, and the mainly sideways movement that occurs along the Alpine Fault to the southwest.

The active faults in this area are generally divided into two zones, the mainly reverse faults of the North Canterbury Domain to the south and the mainly strike-slip Marlborough Fault System to the north (Figure 1.1A) (e.g. Litchfield et al. 2014, 2018). The boundary between these two zones is the Hope Fault, one of the fastest-slipping faults in New Zealand (e.g., Langridge et al. 2003).

The 2016 Kaikōura Earthquake started in the North Canterbury Domain, near Waiau, and ruptured north-eastwards, crossing the Hope Fault into the Marlborough Fault System (Figure 1.1B). In general, the surface fault ruptures were shorter, less continuous, and the displacements smaller in the North Canterbury Domain, than in the Marlborough Fault System.

The rocks and landforms of the Kaikōura District are described by Barrell (2015), but broadly can be divided into basement rocks (mainly greywacke) overlain by sedimentary cover rocks (sandstones, mudstones, and limestones), and young, unconsolidated sediments (gravels and sands). The young sediments were generally formed by uplift (e.g. by earthquakes) and erosion of the ranges during fluctuating climatic conditions over the past 1 million years. The amount of deformation of these sediments are used to define the activity of the faults, such as the slip rate and recurrence interval.

2.0 NEW AND UPDATED KAIKŌURA DISTRICT FAULT AWARENESS AREAS

New Fault Awareness Areas were created for previously-unknown faults that ruptured in the 2016 Kaikōura Earthquake. Existing Fault Awareness Areas were also updated for previously-mapped faults that ruptured in 2016, or for some previously-mapped faults that didn't rupture but are now able to be much more accurately located and mapped using the newly-acquired (2016–2017) LiDAR data, or for which new field mapping data is available.

The Fault Awareness Areas were generated from the 1:250,000 scale mapping of faults, which were simplified from detailed mapping of individual traces (from field and/or LiDAR data), typically at 1:2000–1:6000 scale.

The Fault Awareness Area polygons were created from buffers of widths determined on a fault-by-fault basis to take into account both the: 1) uncertainty in location; and 2) to ensure that they encompassed all of the detailed traces. That is, we didn't follow the buffer width definitions used previously (Section 1.3.2) and instead defined the buffer widths for each fault using the above two criteria. As a result, the buffer widths range from 50 m either side of relatively straight linear main trace of the Kekerengu Fault, to 200 m either side of the southern Whites Fault where it's location is defined from InSAR data, to 250 m either side of the multiple traces of the Upper Kowhai and Manakau faults. Additional 2016 rupture traces were also buffered if they lie outside of the Fault Awareness Area defined from the 1:250,000 scale mapping (e.g., Kekerengu, Jordan Thrust, Upper Kowhai and Manakau faults).

The Fault Awareness Areas were then classified in terms of fault certainty (Definite, Likely, or Possible). For example, those faults, or parts of faults, that ruptured in the Kaikōura Earthquake were defined as "Definite", but inferred traces linking those faults (e.g., beneath rivers or landslides) were classified as "Likely" or "Possible".

The new and updated Fault Awareness Areas are shown on Figure 2.1 and are summarised for each fault below. The new and updated Fault Awareness Areas replace the previously-defined Fault Awareness Areas, which are also shown for comparison purposes. Maps without the previously-defined Fault Awareness Areas are contained in Appendix 1.0.

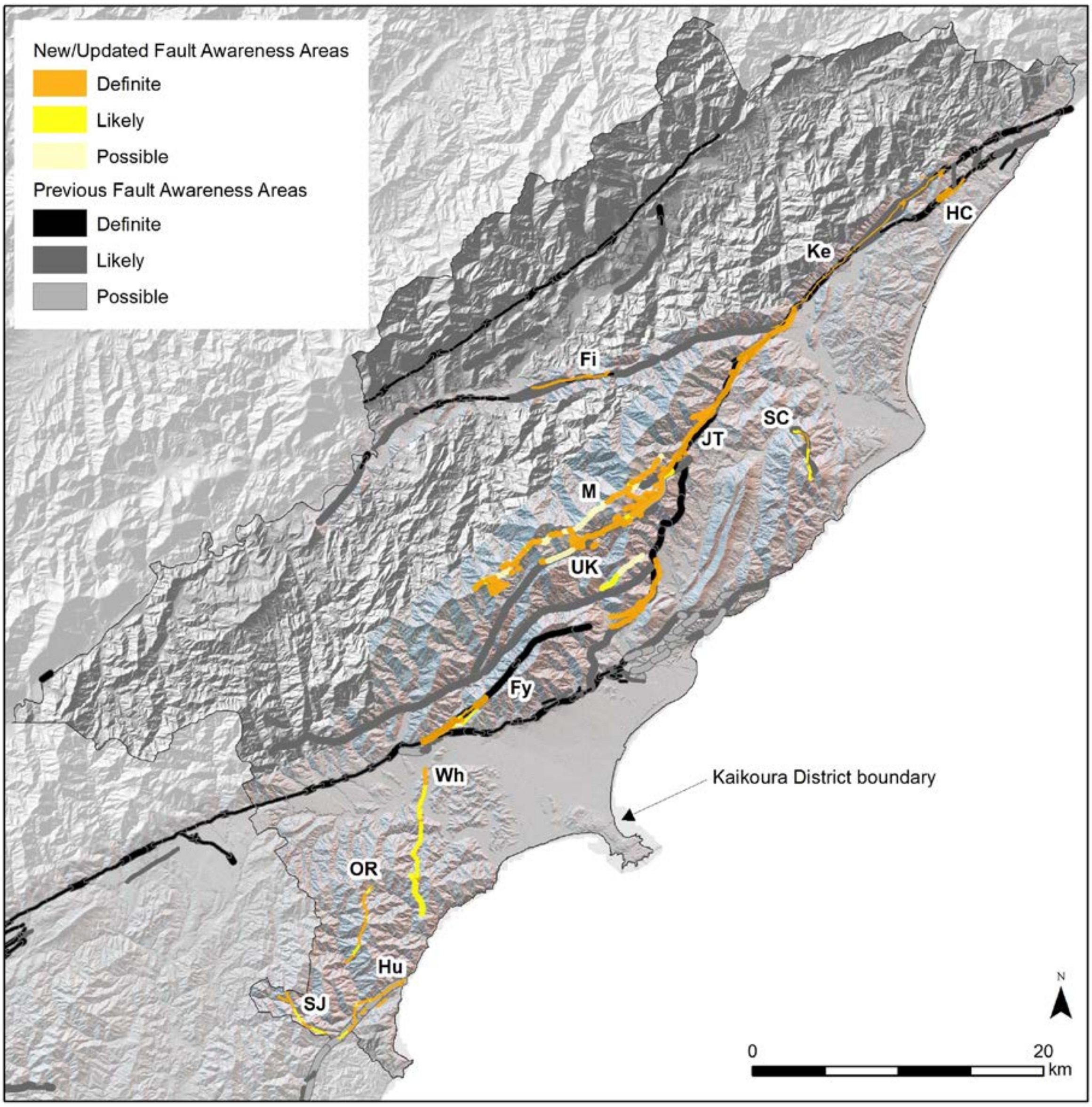


Figure 2.1 New, updated, and previously-defined (Barrell, 2015) Fault Awareness Areas in the Kaikōura District. Fi is the Fidget Fault, Fy is the Fyffe Fault, HC is the Heaver's Creek Fault, Hu is the Hundalee Fault, JT is the Jordan Thrust, Ke is the Kekerengu Fault, M is the Manakau Fault, OR is the Oaro River Fault, SC is the Stewart Creek Fault, SJ is the Stone Jug Fault, UK is the Upper Kowhai Fault and Wh is the Whites Fault.

2.1 Fidget Fault

Only a relatively short (5.4 km) portion of the central Fidget Fault ruptured in the 2016 Kaikōura Earthquake (Figure 1.1; Litchfield et al. 2018), and so the Fault Awareness Areas were updated for this portion of the Fidget Fault only (Figure 2.2).

The 2016 ground-surface fault rupture traces of the Fidget Fault are relatively linear and so Fault Awareness Areas were generated using a 100-m-wide buffer either side of the 1:250,000 scale mapped representation of the 2016 traces (Figure 2.2B). The vast majority of the 2016 rupture traces lie within the previously-defined Fault Awareness Areas, and the updated and previous Fault Awareness Areas overlap (Figure 2.2B).

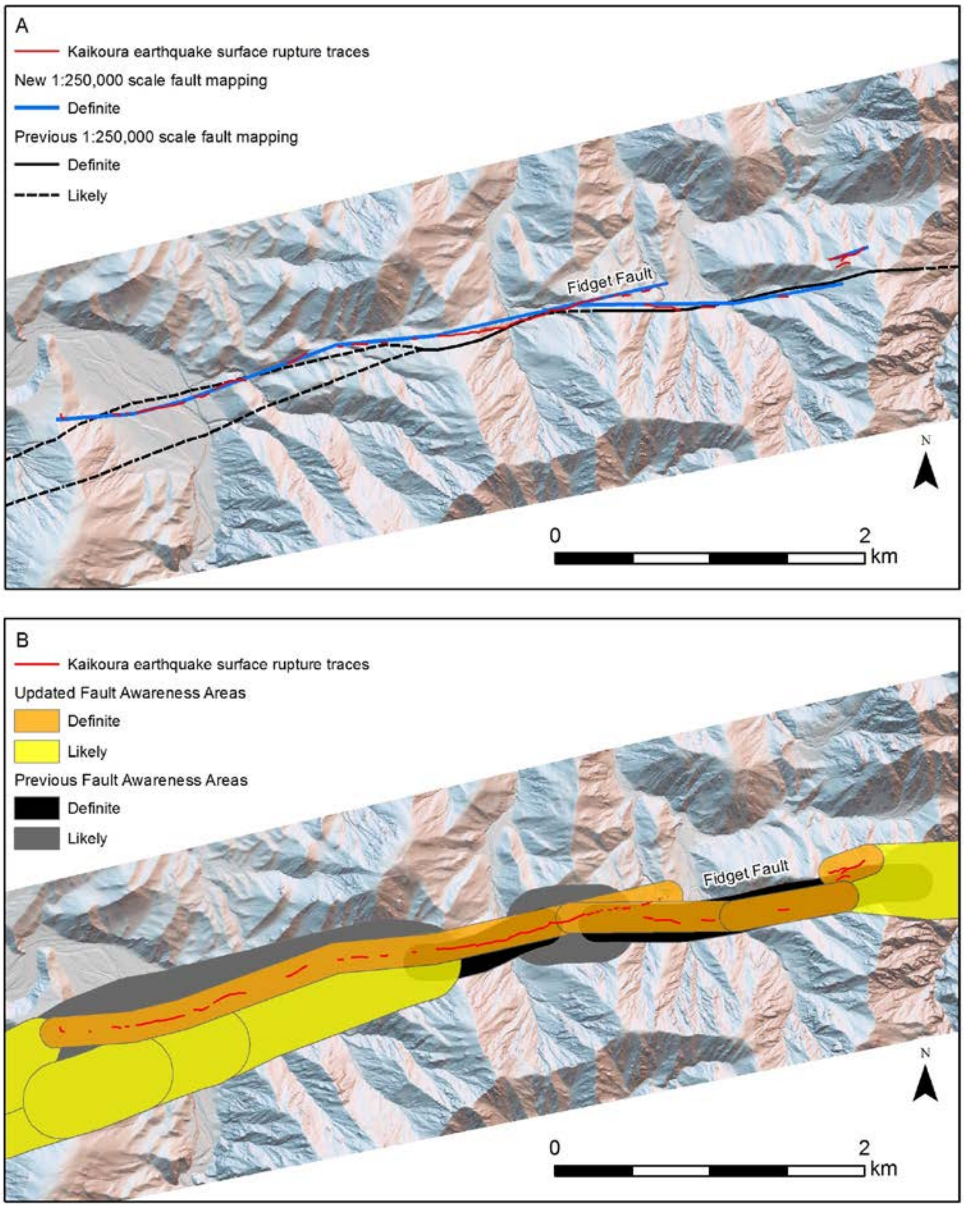


Figure 2.2 A) New and previous mapping of the Fidget Fault. B) Updated and previous Fault Awareness Areas for the Fidget Fault. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

2.2 Kekerengu Fault, South of Valhalla Stream

The entire length of the Kekerengu Fault ruptured in 2016 (Figure 1.1; Kearse et al. 2018) and Fault Awareness Areas were generated for the fault south of Valhalla Stream (Figure 2.3). The Kekerengu Fault is characterised by a main, relatively continuous trace, and in some places a series of short (≤500 m long) subsidiary traces on the hillslopes above the main trace, some of which ruptured in 2016.

Fault Awareness Areas for the main trace were generated from a 50-m-wide buffer either side of the 1:250,000 scale representation of the mapped 2016 ruptures (Figure 2.3). These all lie within the previously defined Fault Awareness Areas.

Fault Awareness Areas were generated for subsidiary traces that we are most confident are primary faults (compared with landslide scarps or ridge rents). Fault Awareness Areas for the subsidiary faults were generated from a 50-m-wide buffer on either side of selected detailed 2016 rupture traces, or 1:250,000 scale simplification of LiDAR-based mapping of faults that didn't rupture in 2016 (Figure 2.3). The majority of these lie within the previous Fault Awareness Areas.

Fault Awareness Areas have not been developed for other features visible in the LiDAR data that are of uncertain origin (Figure 2.4).

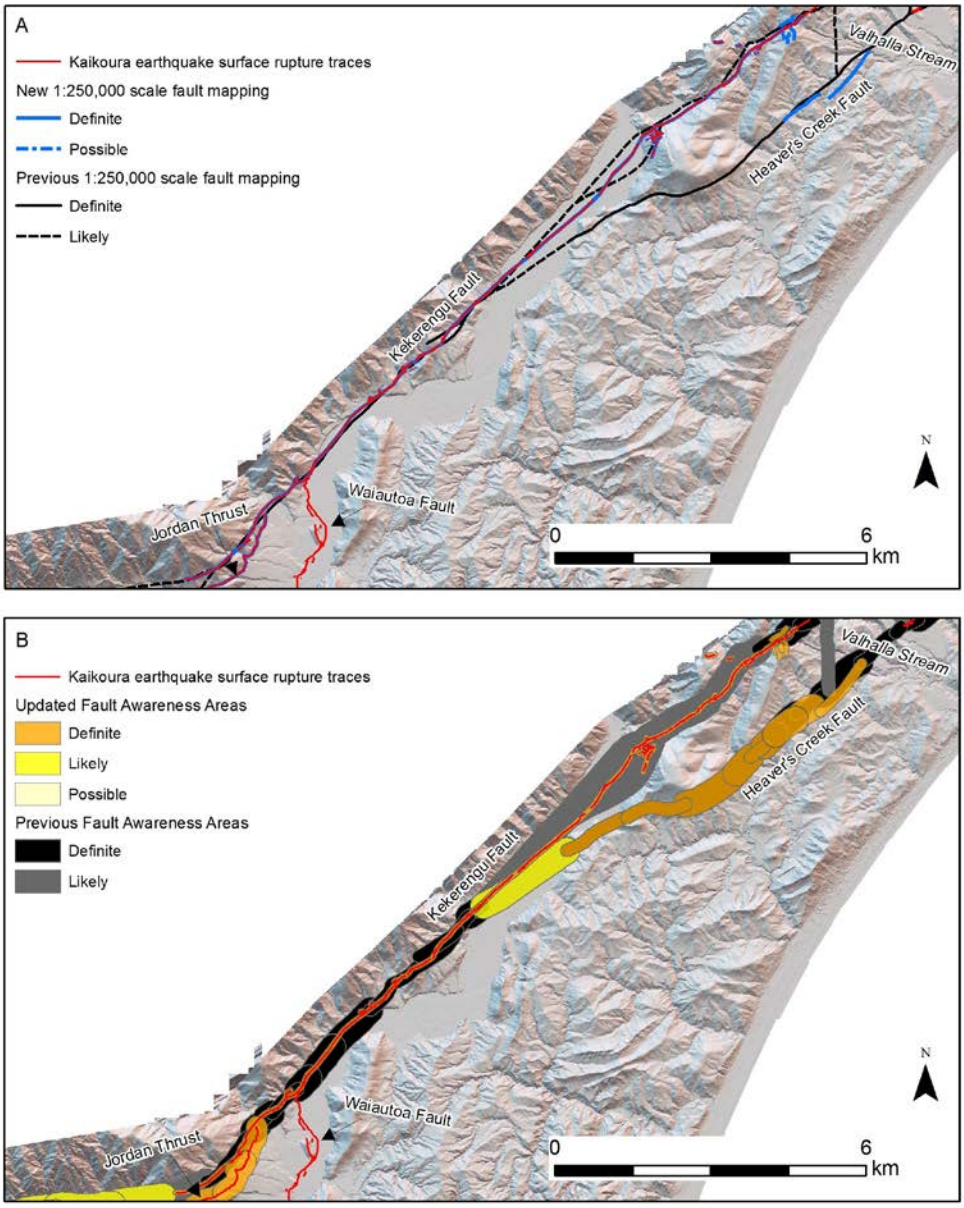
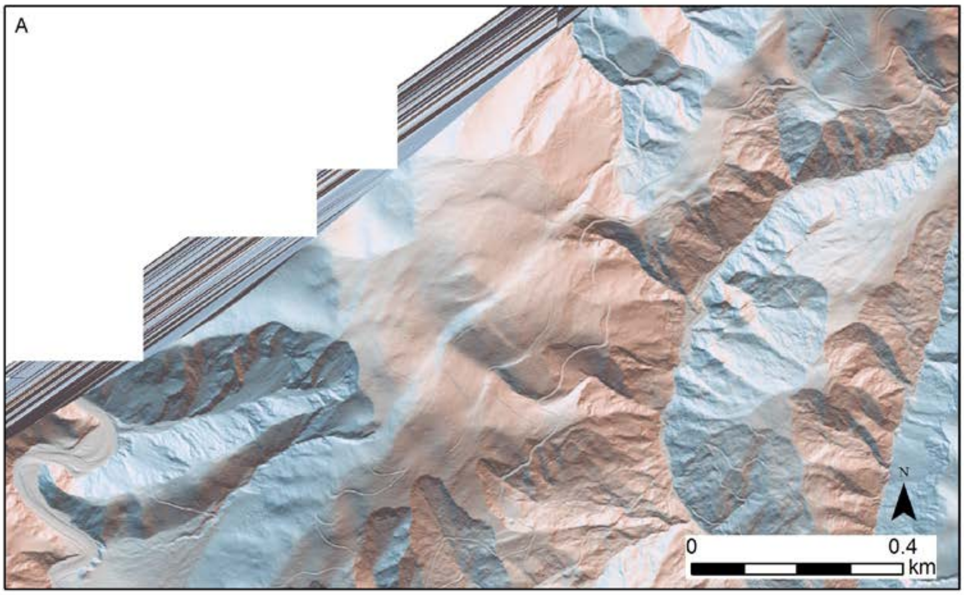


Figure 2.3 A) New and previous mapping of the Kekerengu Fault south of Valhalla Stream. B) Updated and previous Fault Awareness Areas for the Kekerengu Fault south of Valhalla Stream. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.



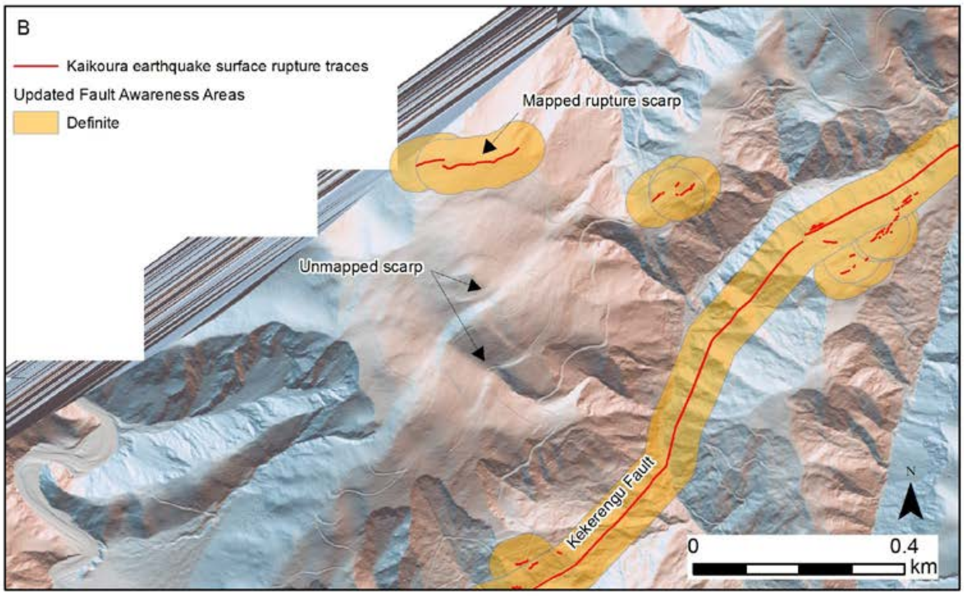


Figure 2.4 Scarps visible on the LiDAR data on the hillslopes above the Kekerengu Fault, some of which are not included in Fault Awareness Areas because their origin as a fault rather than a landslide or ridge rent (hill-crest collapse) feature is unclear.

2.3 Heaver's Creek Fault, South of Valhalla Stream

Only a short (1.5 km long) portion of the central Heaver's Creek Fault (north of Valhalla Stream) ruptured in the Kaikōura Earthquake (Figure 1.1; Litchfield et al. 2018; Kearse et al. 2018). For this portion of the fault, Fault Avoidance Zones have been generated, as described in Section 3.3. However, the entire Heaver's Creek Fault is now covered by LiDAR data and new detailed mapping is also available from Victoria University of Wellington student mapping fieldtrips. So we have updated the Fault Awareness Areas immediately south of Valhalla Stream (Figure 2.5).

As a result of this more accurate locational information, the buffer width of the trace immediately south of Valhalla Stream has been reduced from 250 m to 100 m either side of the fault trace. The new Fault Avoidance Areas overlap the previous ones.

A north-trending fault linking the Heaver's Creek and Kekerengu faults (Figure 2.5), previously called the "Heaver's Creek subsidiary faults" by Barrell (2015), has been removed as it is not visible on the LiDAR data and no evidence has been found from field mapping.

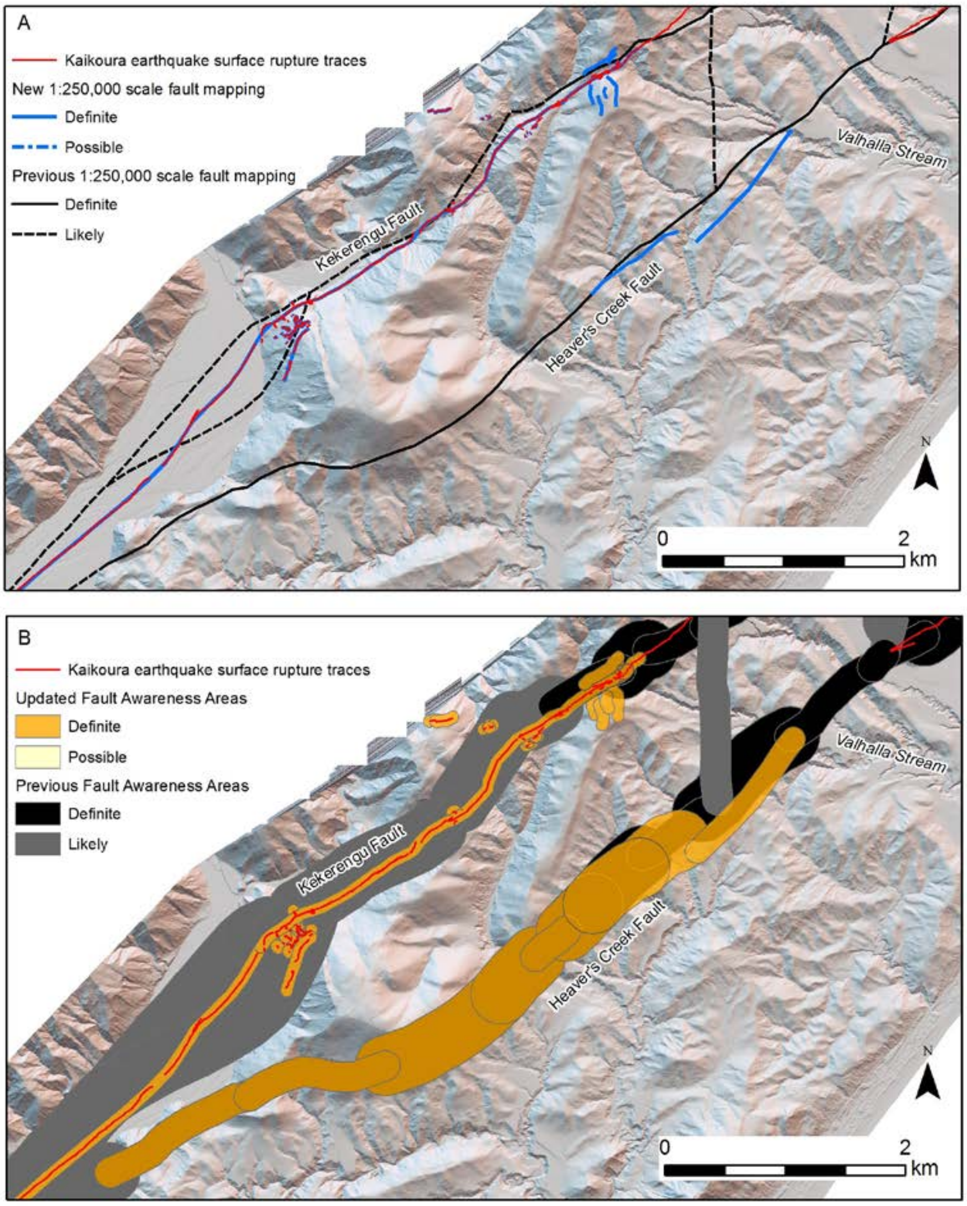


Figure 2.5 A) New and previous mapping of the Heaver's Creek Fault south of Valhalla Stream. B) Updated and previous Fault Awareness Areas for the Heaver's Creek Fault south of Valhalla Stream. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

2.4 Jordan Thrust, North of the Hapuku River

Only the northern ~15 km of the Jordan Thrust ruptured in the Kaikōura Earthquake (Figure 1.1; Kearse et al. 2018). The previous Fault Awareness Areas were updated for this portion of the fault, as well as the portion between the Kowhai Fault and the Hapuku River, from new detailed mapping using the newly-acquired LiDAR data (Figure 2.5). Although the 2016 rupture of the Jordan Thrust was primarily dextral, with a secondary, normal component, the entire fault is classified as a reverse fault (with a secondary dextral component), to reflect its long-term motion (e.g., Van Dissen and Yeats 1991).

The portion of the Jordan Thrust that ruptured in 2016 has a similar character to the Kekerengu Fault, in that it consists of a main trace and a series of subsidiary traces on the surrounding hillslopes (Figure 2.6). The Fault Awareness Areas were generated from a 200-m-wide buffer either side of the 1:250,000 scale mapping of the main trace as well as selected, detailed, subsidiary traces (Figure 2.6). The main trace Fault Awareness Areas overlap the previous ones, but some of the subsidiary Fault Awareness Areas lie outside of the previous ones.

The portion of the Jordan Thrust between the Kowhai Fault and the Hapuku River consists of one main trace (which bifurcates into two near the Hapuku River) and a sub-parallel trace to the east (Figure 2.6A). The Fault Awareness Areas were only updated for the southern, bifurcating part, and created for the eastern strand (Figure 2.6B). These were from the 1:250,000 scale mapping and with a buffer width of 200 m either side. The Fault Awareness Area for the southern trace overlaps the previous one.

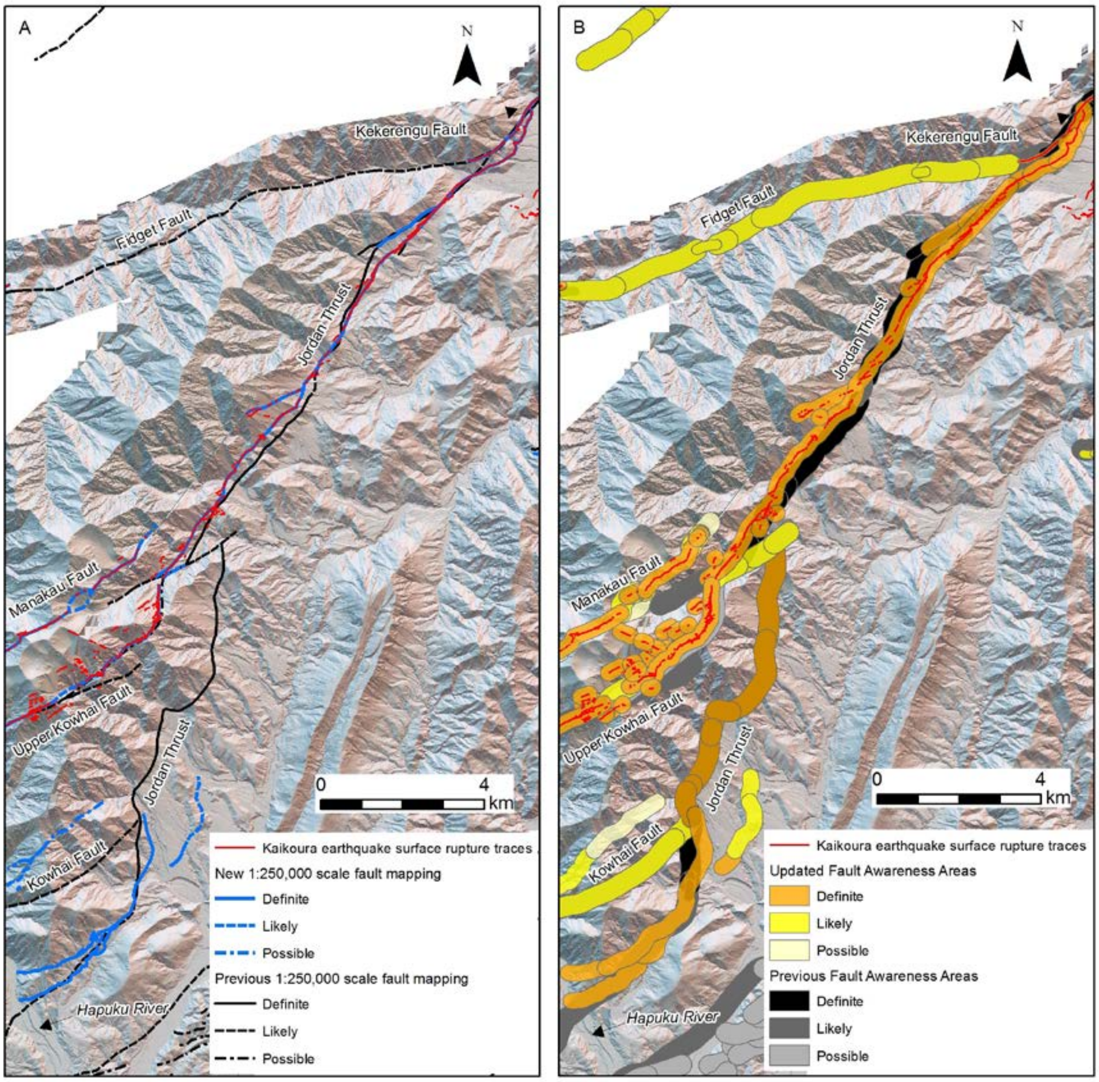


Figure 2.6 A) New and previous mapping of the Jordan Thrust north of the Hapuku River. B) Updated and previous Fault Awareness Areas for the Jordan Thrust north of the Hapuku River. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

2.5 Upper Kowhai Fault

Only the northern ~11 km of the Upper Kowhai Fault ruptured in the Kaikōura Earthquake (Figure 1.1; Kearse et al. 2018) and so Fault Awareness Areas were updated for this portion of the fault (Figure 2.7). Like the 2016 Kekerengu and Jordan Thrust ruptures, the 2016 Upper Kowhai Fault rupture is characterised by a main trace and many subsidiary traces. For some of the subsidiary traces between the Upper Kowhai and Manakau faults it is unclear which fault they belong to, but they have generally been grouped with the Upper Kowhai Fault.

Fault Awareness Areas have been generated from 200 m-wide-buffers on either side of 1:250,000 scale mapping of the main trace as well as selected, detailed, subsidiary traces (Figure 2.7). The Fault Awareness Areas for the main trace generally overlap the previous ones, but some of the subsidiary Fault Awareness Areas are outside of those previously mapped.

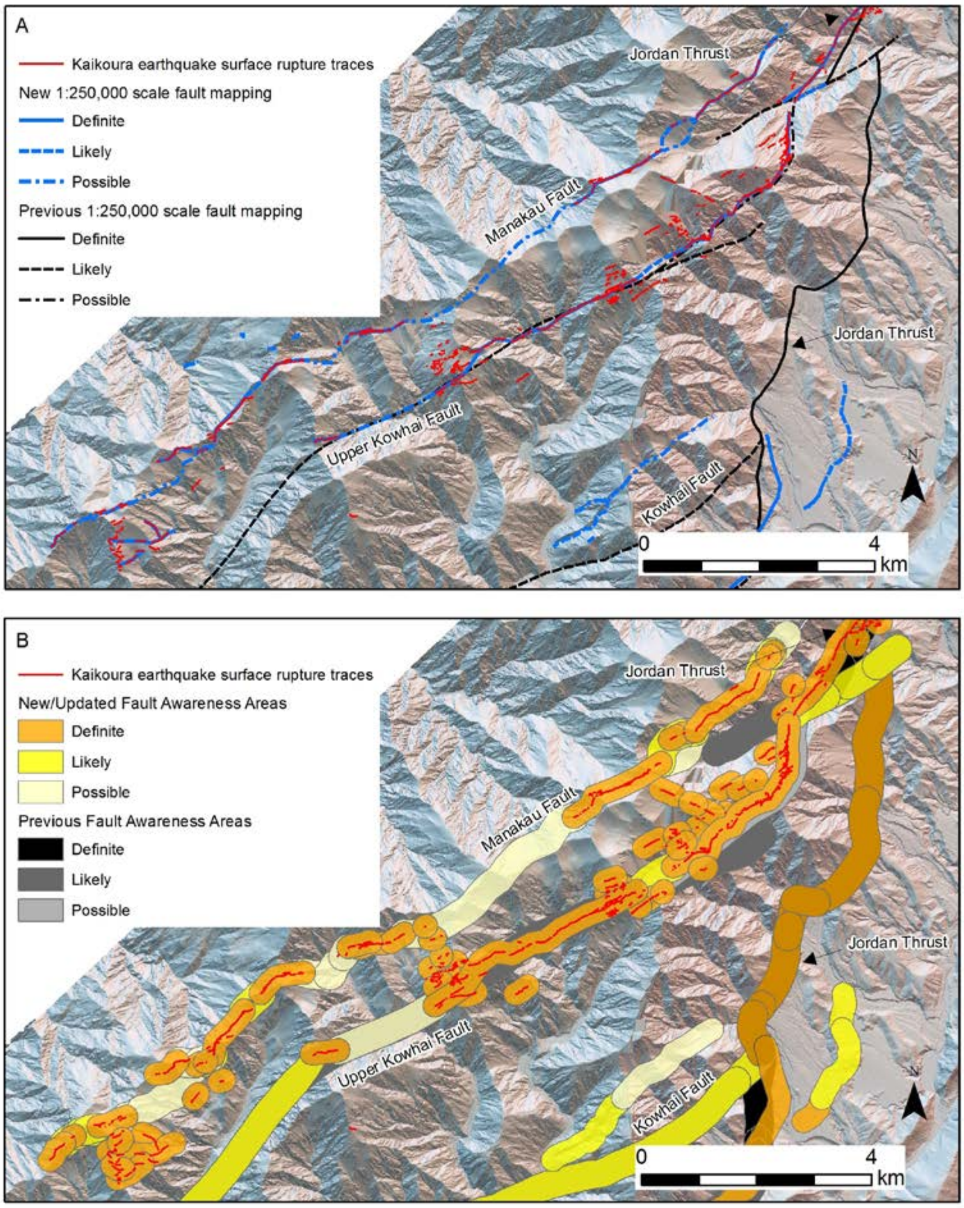


Figure 2.7 A) New and previous mapping of the Upper Kowhai and Manakau faults. B) New, updated and previous Fault Awareness Areas for the Upper Kowhai and Manakau faults. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

2.6 Manakau Fault

The Manakau Fault had not been mapped prior to the Kaikōura Earthquake and is sub-parallel to the Upper Kowhai Fault, but generally lies on the crest, or immediate northwest of, the Seaward Kaikōura Range (Figure 1.1; Kearse et al., 2018). The 2016 rupture traces of the Manakau Fault were discontinuous, but generally formed a single trace for most of its length, except for in the south, where there are subsidiary faults on its south side (Figure 2.7A). Faults inferred to connect the 2016 ruptures have been classified as “Likely” where the gap is relatively short, and “Possible” where the gap is longer and the presence of a fault is less certain (Figure 2.7A).

Fault Awareness Areas have been generated as per the Jordan Thrust and Upper Kowhai Fault — from 200 m wide buffers on either side of 1:250,000 scale mapping of the main trace as well as selected, detailed, subsidiary fault traces (Figure 2.7B).

2.7 Fyffe Fault

The Fyffe Fault did not rupture in the Kaikōura Earthquake, but a part of the southern end (north of the Kowhai River) has been re-mapped using the newly-acquired LiDAR data (Figure 2.8A). This new mapping shows that the fault consists of two main, bifurcating, traces (previously only one had been mapped) with a series of subsidiary faults in between (Figure 2.8A).

The Fault Awareness Areas have been updated from 1:250,000 scale mapping of the two main traces and selected subsidiary traces. The buffer widths are 100 m on either side of the updated fault traces, and have been classified as “Definite”, “Likely”, or “Possible” depending on their geomorphic expression in the LiDAR data (Figure 2.8B).

The Fault Awareness Area for the northern bifurcating trace lies entirely within the previous one, but the southern and subsidiary Fault Awareness Areas overlap or lie outside those mapped previously (Figure 2.8B).

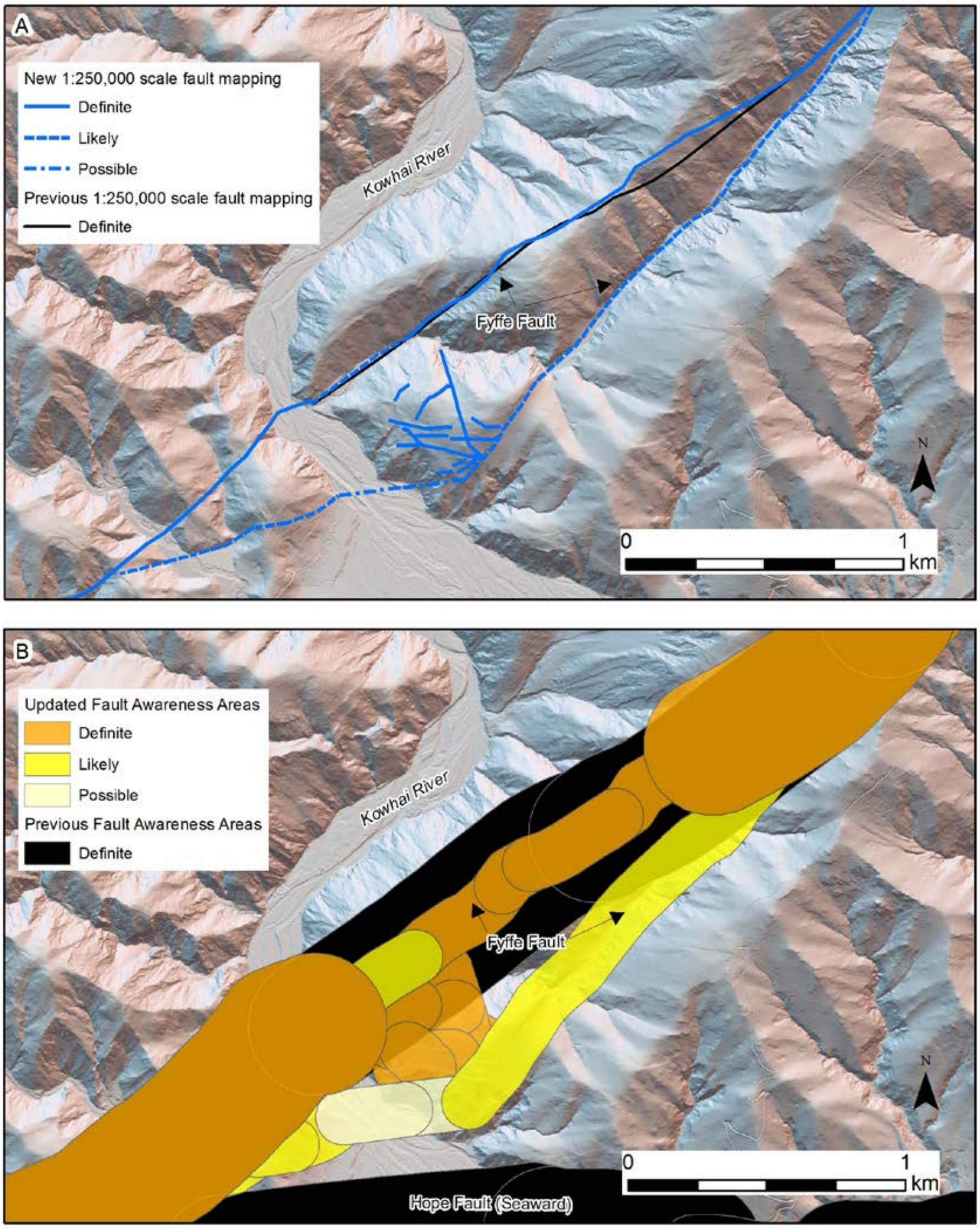


Figure 2.8 A) New and previous mapping of the south end of the Fyffe Fault. B) Updated and previous Fault Awareness Areas for the south end of the Fyffe Fault. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

2.8 Stewart Creek Fault

The Stewart Creek Fault was mapped by Barrell (2015) as a "Likely" active fault, and ~2 km of the fault ruptured in the Kaikōura Earthquake (Figure 1.1; Langridge et al. 2018). The 2016 ruptures were predominantly normal faults and formed a series of discontinuous fault traces that we infer to form one main fault trace, with two subsidiary faults (Figure 2.9A).

Fault Awareness Areas were updated from the 1:250,000 scale fault mapping and the subsidiary faults using a buffer width of 50 m on either side of the 2016 rupture traces and 100 m either side of the remaining traces (Figure 2.9B). Most of the Fault Awareness Areas fall within or overlap the previously-defined Fault Awareness Areas.

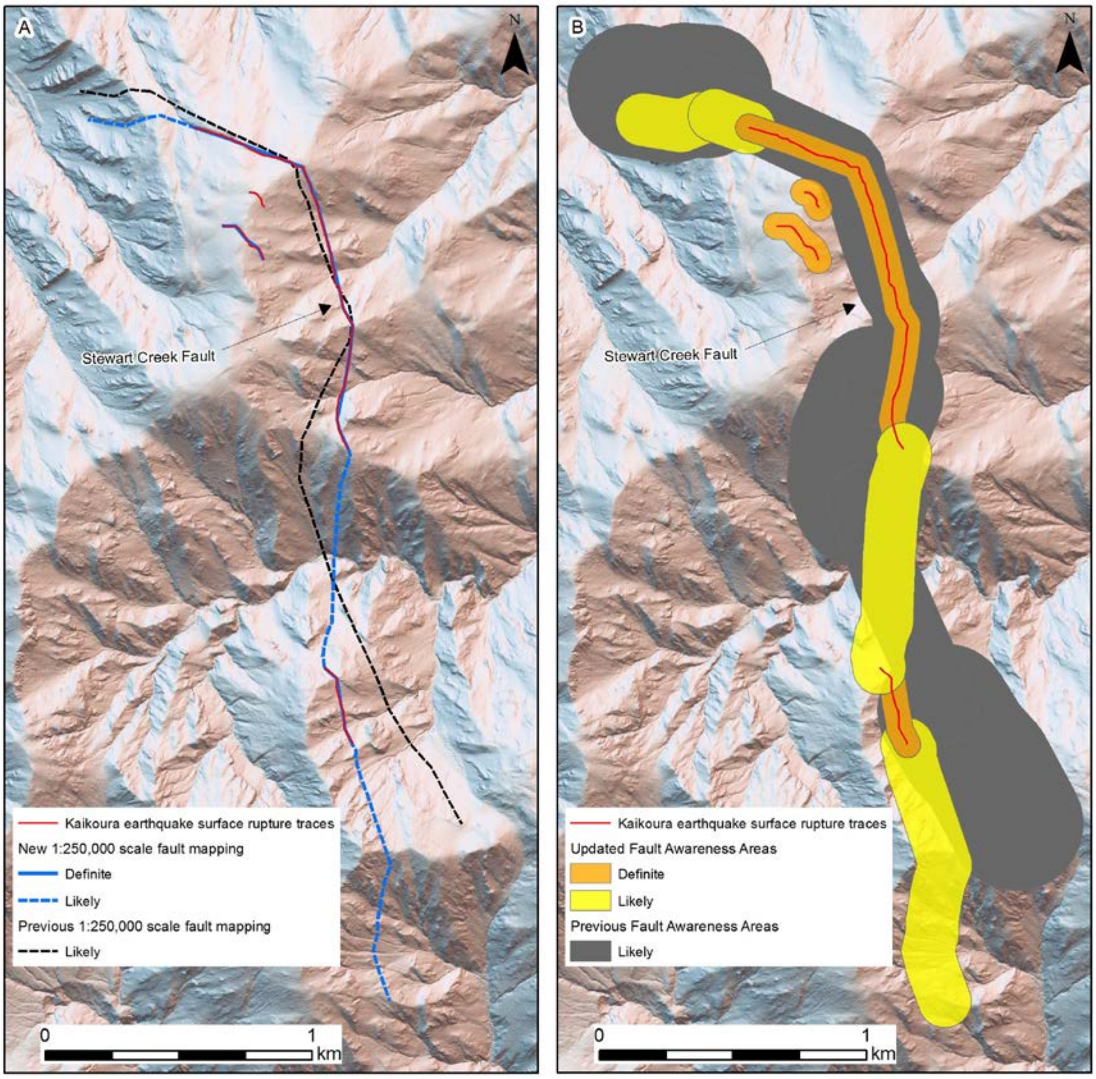


Figure 2.9 A) New and previous mapping of the Stewart Creek Fault. B) Updated and previous Fault Awareness Areas for the Stewart Creek Fault. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

2.9 Whites Fault

The Whites Fault had not been mapped prior to the Kaikōura Earthquake, and the 2016 ruptures form a series of discontinuous, but overall along-strike, traces (Figure 1.1; Litchfield et al. 2018). We infer that these form a single fault and therefore mapped "Likely" traces linking the 2016 "Definite" rupture traces (Figure 2.10A). This is consistent with the Kaikōura Earthquake InSAR data, which shows a significant elevation change across the Whites Fault, indicating a continuous fault rupture at depth (I. Hamling personal communication, 2018).

New Fault Awareness Areas were generated from a 150-m-wide buffer either side of the northern and central parts of the fault and 200-m-wide buffers either side of the southern part of the fault where the location is inferred from InSAR data mapped at 1:250,000 scale (Figure 2.10B). The relatively large width for the northern part was to encompass the 2016 traces.

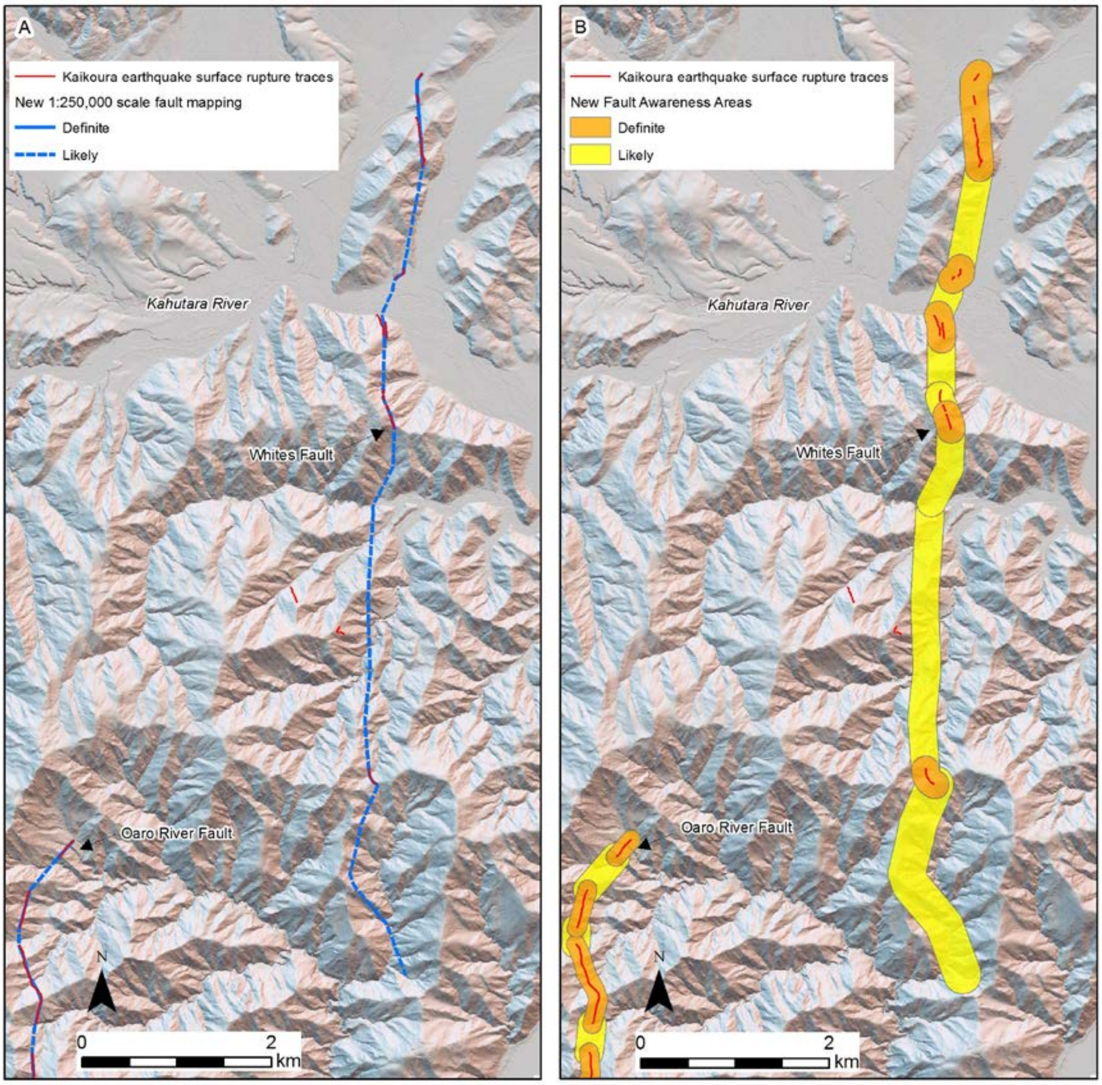


Figure 2.10 A) New mapping of the Whites Fault. B) New Fault Awareness Areas for the Whites Fault.

2.10 Oaro River Fault

The Oaro River Fault had not been mapped prior to the Kaikōura Earthquake and was only identified during the late stages of the earthquake response, and so has not been named previously (e.g., it is shown on the surface rupture map of Litchfield et al. (2018) but is not named or discussed). The 2016 ruptures were initially identified in the LiDAR data and were field verified as small (<0.5 m vertical) ruptures from helicopter, but as far as we are aware, no one has visited it on the ground. The fault traces are discontinuous, but lie along-strike from each other so, like the Whites Fault, we infer it to be a single fault and have mapped "Likely" traces linking the 2016 ruptures (Figure 2.11A).

New Fault Awareness Areas were generated from the fault traces mapped at 1:250,000 scale. The buffer width is 100-m-wide buffer either side of the "Definite" (2016) traces and 150-m-wide either side of the remaining, "Likely" traces (Figure 2.11B).

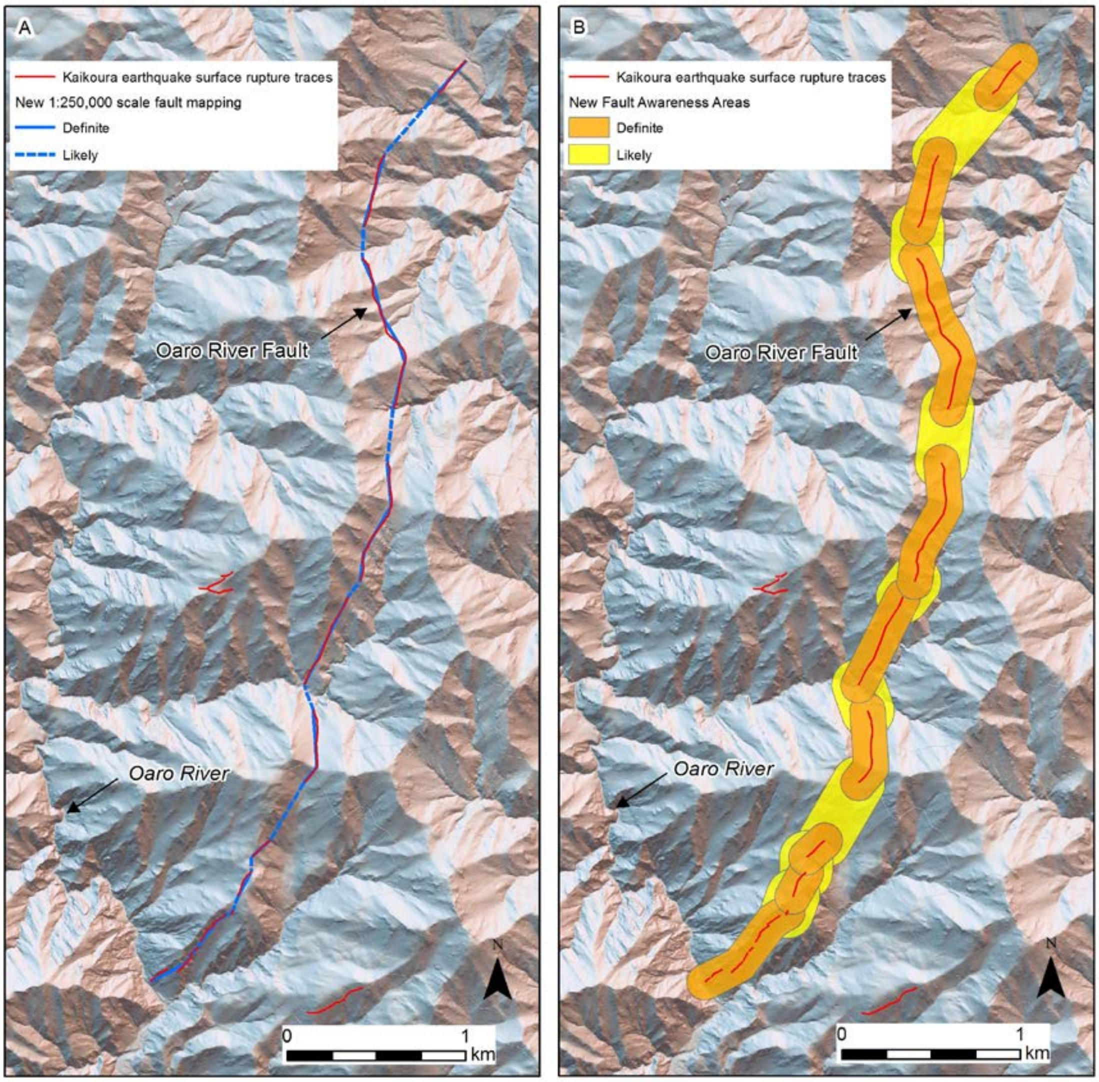


Figure 2.11 A) New mapping of the Oaro River Fault. B) New Fault Awareness Areas for the Oaro River Fault.

2.11 Stone Jug Fault

The Stone Jug Fault was previously mapped as ~4 km long (Barrell 2015), but in the Kaikōura Earthquake the total rupture length was 18–20 km (Litchfield et al. 2018; Nicol et al. 2018). The southern part crosses the southwest corner of the Kaikōura District (Figure 1.1, Figure 2.12). The 2016 rupture traces are discontinuous, but are generally along-strike from each other, so we have mapped "Likely" faults linking the 2016 ruptures (Figure 2.12A). Further detailed mapping is currently being undertaken for a University of Canterbury student project.

New Fault Awareness Areas were generated from the fault traces mapped at 1:250,000 scale. The buffer width is 100-m-wide buffer either side of the "Definite" (2016) traces and 200-m-wide either side of the remaining, "Likely" traces (Figure 2.12B).

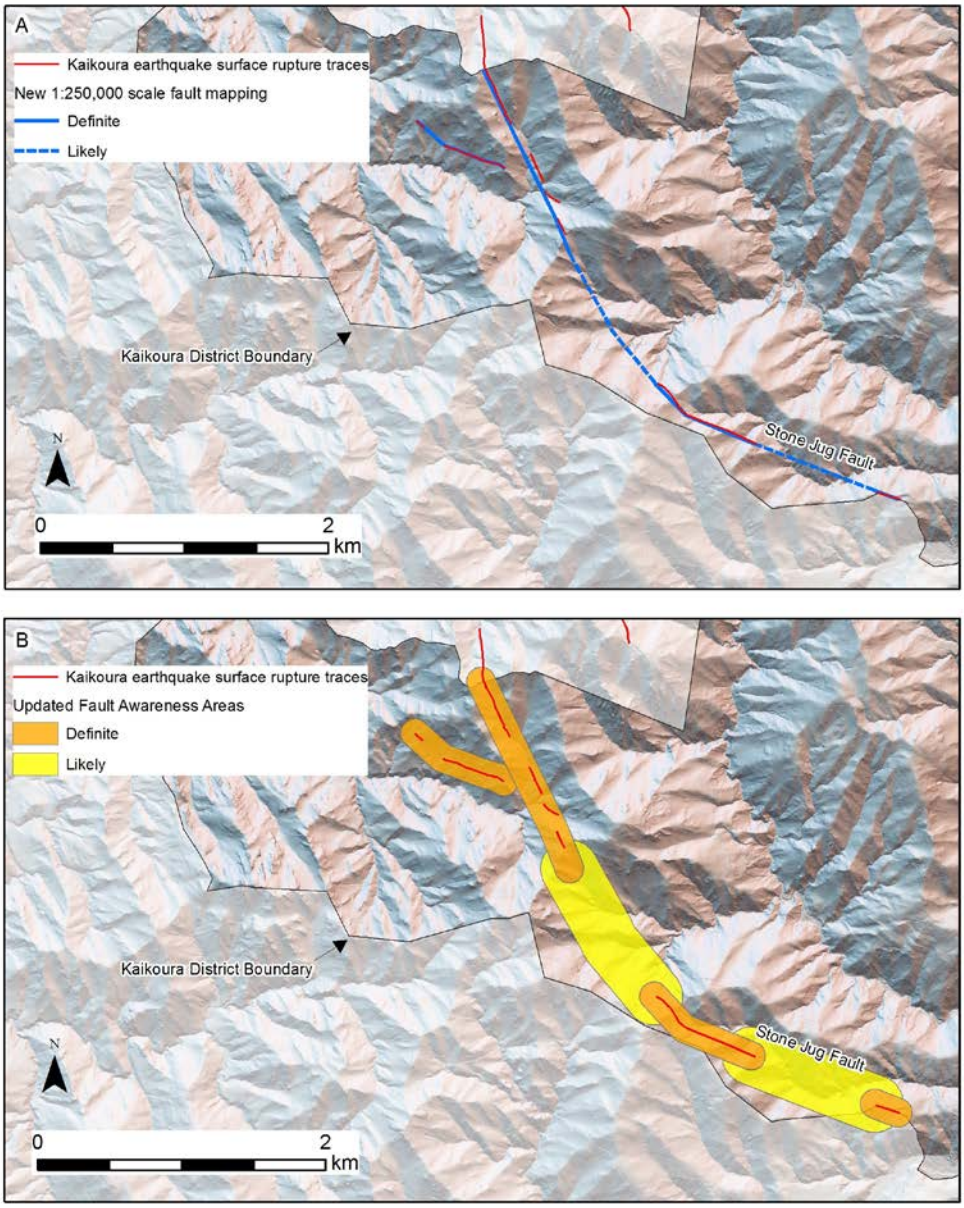


Figure 2.12 A) New mapping of the southern part of the Stone Jug Fault. B) Updated Fault Awareness Areas for the southern part of the Stone Jug Fault.

2.12 Hundalee Fault

Surface ruptures occurred along ~10 km of the previously-mapped onshore portion of the Hundalee Fault in the Kaikōura Earthquake, and sea bed mapping and InSAR data indicate that the entire rupture length may have been ~23 km (Williams et al. 2018). The surface ruptures included the entire portion of the Hundalee Fault in the Kaikōura District (Figure 1.1, Figure 2.13). The 2016 ruptures are characterised by a main trace and some subsidiary traces (Figure 2.13A).

Updated Fault Awareness Areas were generated from the fault traces mapped at 1:250,000 scale. The buffer width is 100-m-wide buffer either side of the main trace and the subsidiary faults for the portion that ruptured in 2016 (Figure 2.13B). The width of the Fault Avoidance Area immediately to the southwest is reduced to 175 m either side. Most fall within or overlap the previous Fault Awareness Areas.

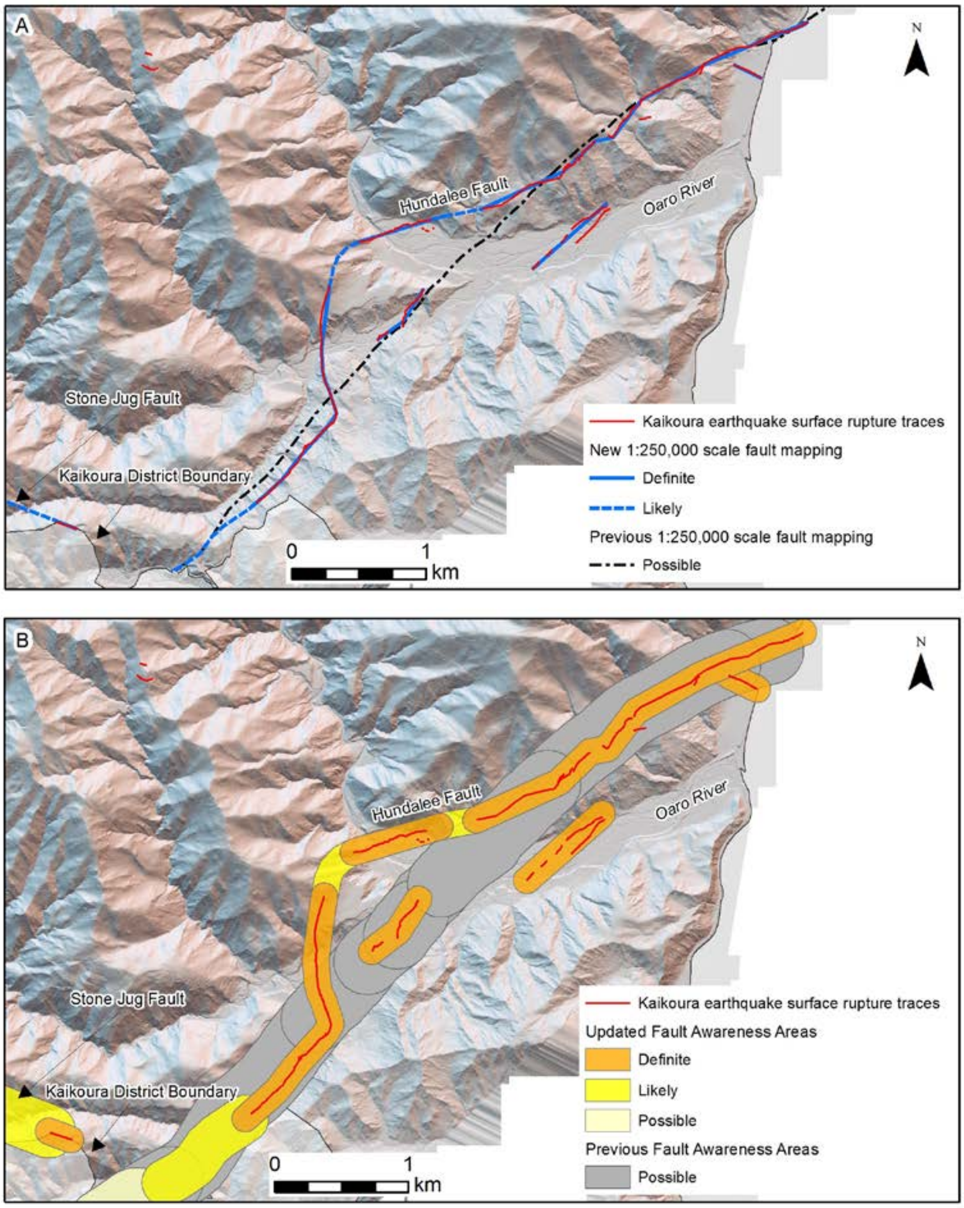


Figure 2.13 A) New and previous mapping of the Hundalee Fault. B) Updated and previous Fault Awareness Areas for the Hundalee Fault. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 1.0.

3.0 KAIKŌURA DISTRICT FAULT AVOIDANCE ZONES

New Fault Avoidance Zones were created for selected faults from the detailed fault traces mapped for the 2016 Kaikōura Earthquake ruptures (e.g., the northern Kekerengu Fault) and/or from LiDAR data (e.g., the parts of the Hope Fault that didn't rupture in 2016).

The Fault Avoidance Zones were created from the detailed fault mapping in three main steps (Figure 3.1).

1. Buffer the faults by the deformation width (light green in Figure 3.1A), to create what is referred to as the "Likely fault rupture zone" in the MfE Active Fault Guidelines. The deformation width is defined during the detailed fault mapping and generally scales with fault certainty. As a result, the buffer widths range from ≤15 m either side of the "Definite" 2016 ruptures of the Kekerengu Fault, to 150 m either wide of a "Concealed" trace of the Hope Fault.

2. Buffer these by a further 20 m (dark green in Figure 3.1A), to create what is sometimes referred to as the setback zone. This additional 20 m takes into account the intense deformation and secondary ruptures that can occur close to primary mapped fault rupture. The combined zone is the Fault Avoidance Zone (Figure 3.1B).

3. Remove overlaps and tidy junctions between Fault Avoidance Zones (Figure 3.1C). This was achieved by: (i) dissolving Fault Avoidance Zones with the same fault complexity; (ii) clipping (deleting underlying) zones according to a hierarchy of fault complexity (i.e., well-defined zones being preferentially retained over well defined – extended, uncertain – constrained, uncertain – poorly constrained and distributed); and (iii) manually trimming the rounded ends between adjacent Fault Avoidance Zones to remove artefacts (also undertaken according to the hierarchy of fault complexity outlined above).

For most faults considered in the Kaikōura District, the Fault Avoidance Zones are symmetrical about the mapped trace. However, for some predominantly dip-slip faults, such as the mainly reverse Papatea Fault and Jordan Thrust, and thrust and normal subsidiary traces of the Hope Fault, asymmetric buffers were created (prior to step 1). These are to account for the greater width of deformation on the hanging wall (the side of the fault pushed up) for reverse faults and the foot wall (the side of the fault pushed down) of normal fault. These were created by an additional first step to preferentially buffer the hanging-wall side of the specific fault (yellow in Figure 3.1A). The widths for these "half buffers" were also defined from the deformation width (so the total deformation width is 1.5 x that defined when undertaking the detailed fault mapping). The "half buffers" were then further buffered as per the steps 1 and 2 described above.

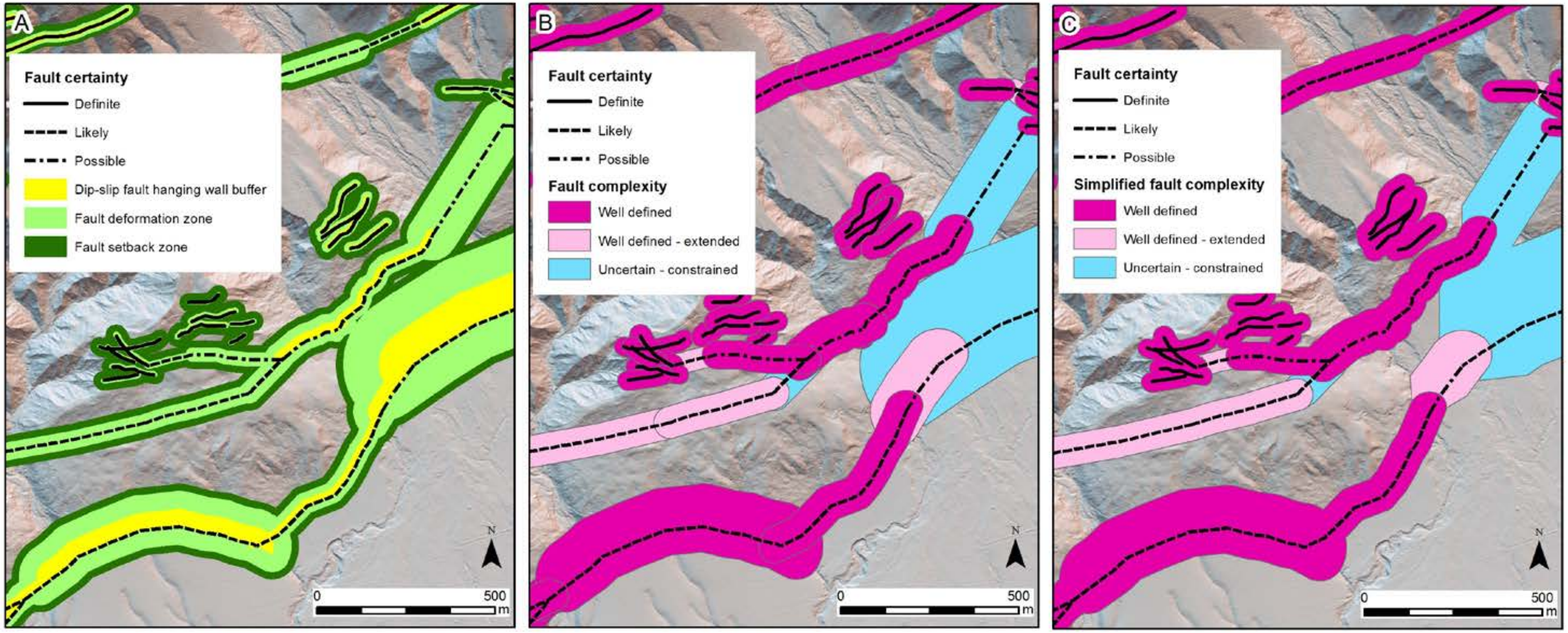


Figure 3.1 A) Individual buffer zones used to create Fault Avoidance Zones (for a part of the Hope Fault that didn't rupture in 2016). Yellow are buffers on the hanging wall of reverse faults and footwall of normal faults to account for the greater deformation width there. Light green are the deformation widths defined during the detailed fault mapping. Dark green are the 20 m setback zones. The Fault Avoidance Zones are the combination of all these buffer zones. B) The resulting Fault Avoidance Zones classified by Fault Complexity. C) Overlaps were then removed and junctions between adjacent faults tidied using a hierarchy of fault complexity as described in the text.

A few additional Fault Avoidance Zones were also created to fill gaps between multiple, short, traces (Figure 3.2). These have been defined because we considered there to be a high likelihood that future ruptures could occur there. They have been classified as "Distributed" as defined below.

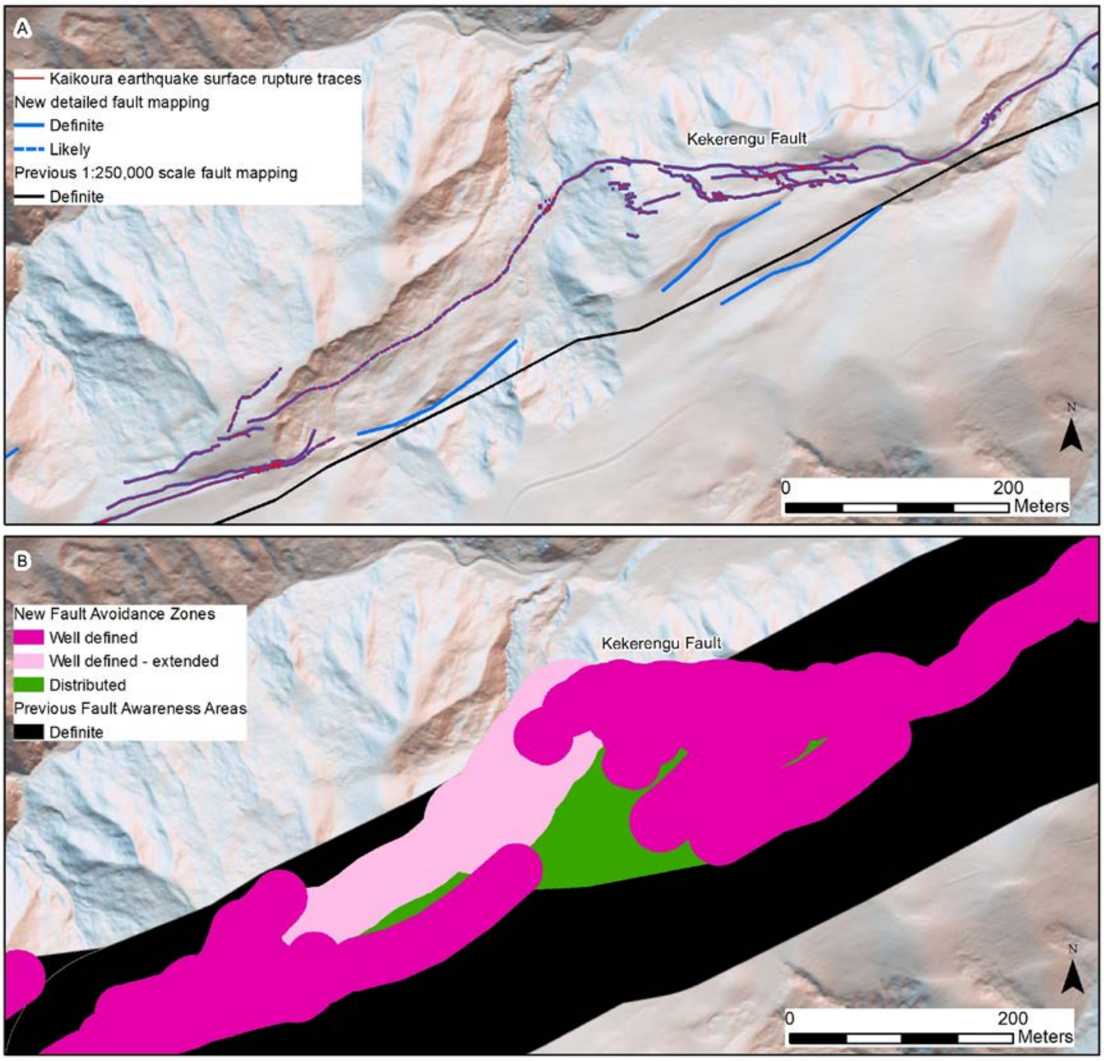


Figure 3.2 Example of Fault Avoidance Zones created for a part of the Kekerengu Fault. A) New and previous fault mapping, and the new mapping includes traces that did and didn't rupture in the 2016 Kaikōura Earthquake. B) Fault Avoidance Zones generated from the mapping in A, classified by Fault Complexity.

The Fault Avoidance Zones were then classified in terms of the Fault Complexity (Figure 3.1B, Figure 3.2). Fault Complexity refers to the width and distribution of the deformed land around a fault trace.

For this study we use the modified Fault Complexity terms used elsewhere in New Zealand (Van Dissen and Heron 2003; Van Dissen et al. 2005; Litchfield and Van Dissen 2014), whereby, as well as a "Distributed" fault complexity, "Well defined" is subdivided into "Well defined" and "Well defined – extended" and "Uncertain" is subdivided into "Uncertain – constrained" and "Uncertain – poorly constrained". These are defined as:

Well defined and **Well defined – extended:** fault rupture deformation is well defined and of limited geographic width (e.g. metres to tens of metres wide), including areas where fault rupture deformation has been either buried or eroded over short distances but its position is tightly constrained by the presence of nearby distinct fault features.

Distributed and **Uncertain – constrained:** The location of fault rupture deformation can be constrained to lie within a relatively broad geographic width (e.g. tens to hundreds of metres wide). Distributed Fault Complexity applies to areas where fault rupture deformation is distributed over a relatively broad, but defined, geographic width (e.g. tens to hundreds of metres wide), typically as multiple fault traces and/or folds. Uncertain – constrained Fault Complexity applies to areas where the location of fault rupture is uncertain because evidence has been either buried or eroded but where the location of fault rupture can be constrained to a reasonable geographic extent (≤300 m).

Uncertain – **poorly constrained:** the location of fault rupture deformation is uncertain and cannot be constrained to lie within a zone less than 300 m wide, usually because evidence of deformation has been either buried or eroded away, or the features used to define the fault's location are widely spaced and/or very broad in nature.

Examples of these Fault Avoidance Zones with different Fault Complexity classes are shown in Figure 3.1B and Figure 3.2.

The Fault Avoidance Zones are shown on Figure 3.3 and are summarised for each fault below.

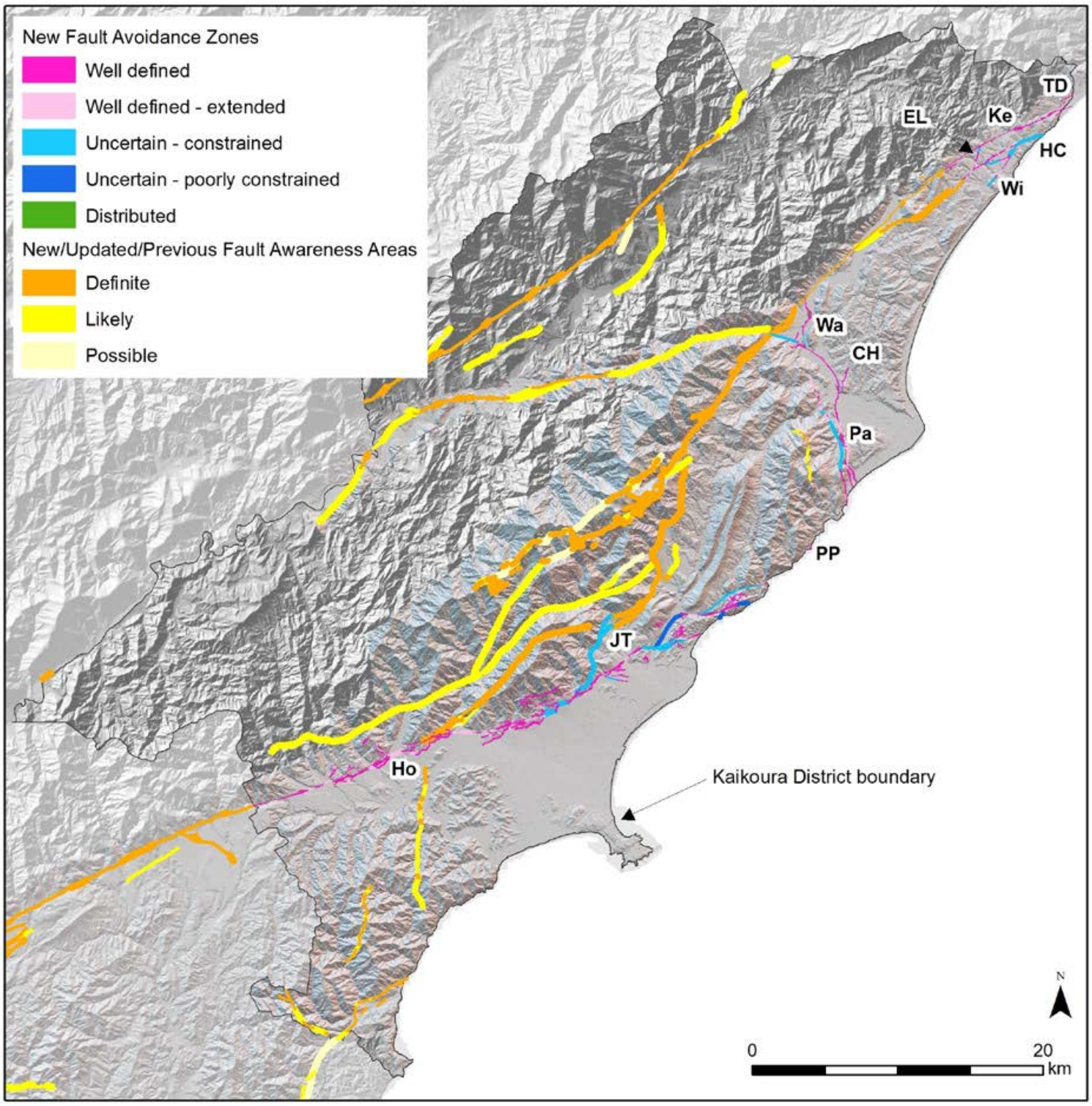


Figure 3.3 Fault Avoidance Zones created for selected faults in the Kaikōura District and classified by Fault Complexity. CH is the Corner Hill Fault, EL is the East Lane Fault, HC is the Heaver's Creek Fault, Ho is the Hope Fault, JT is the Jordan Thrust, Ke is the Kekerengu Fault, Pa is the Papatea Fault, PP is the Papatoa Point Fault, TD is the Tinline Downs Fault, Wa is the Waiutoa Fault and Wi is the Winterholme Fault.

3.1 Tinline Downs Fault

The Tinline Downs Fault had not been mapped prior to the Kaikōura Earthquake and comprises two, short (total length ~1.7 km), overlapping traces north of the Kekerengu Fault (Figure 1.1, Figure 3.4A; Litchfield et al. 2018, Kearse et al. 2018). There is no evidence in the LiDAR data for continuations of these faults to the north and south, but we have inferred two short "Likely" faults connecting the 2016 traces.

Fault Avoidance Zones have been created for the 2016 ("Definite") ruptures and the "Likely" connecting faults, which are classified as "Well defined" and "Well defined – extended", respectively (Figure 3.4B).

3.2 Kekerengu Fault, North of Valhalla Stream

As noted in section 2.2, the entire length of the Kekerengu Fault ruptured in the Kaikōura Earthquake (Figure 1.1; Kearse et al. 2018), and the ruptures comprised a main trace and some subsidiary traces (Figure 3.2, Figure 3.4A).

Fault Avoidance Zones have been created for all of the 2016 rupture traces, areas between multiple, short traces (e.g., Figure 3.2), and a few traces visible in the LiDAR data that didn't rupture in 2016 (Figure 3.4B). The Fault Avoidance Zones for the 2016 ruptures have all been classified as "Well defined" except for two traces that have been eroded by landslides, which are classified as "Well defined – extended" (Figure 3.2). As noted earlier, the areas (gaps) between multiple, short traces are classified as "Distributed".

The majority of the Fault Avoidance Zones lie within the previous Fault Awareness Areas (Figure 3.4B).

3.3 Heaver's Creek and Subsidiary Faults, North of Valhalla Stream

As noted in section 2.3, only a short (~1.5 km long) portion of the central Heaver's Creek Fault ruptured in the Kaikōura Earthquake (Figure 1.1, Figure 3.4A; Litchfield et al. 2018; Kearse et al. 2018). The 2016 ruptures consisted of a main trace and two subparallel, subsidiary, traces (Figure 3.3A). We have mapped one short "Likely" fault linking the 2016 traces.

The remainder of the Heaver's Creek fault north of Valhalla Stream, as well as three subsidiary faults, the East Lane, Chaffey Link, and Winterholme faults, have now been mapped in detail using LiDAR and field (Victoria University of Wellington student fieldtrip) data (Figure 3.4A). The Chaffey Link Fault had not been mapped by Barrell (2015), and the Winterholme Fault has been extended to the southwest.

Fault Avoidance Zones for the Heaver's Creek Fault 2016 ruptures are classified as "Well defined" or "Well defined – extended" (Figure 3.4B). Fault Avoidance Zones for the remaining Heaver's Creek Fault and the other faults are generally classified as "Well defined" and "Well defined – extended" in the centre, and "Uncertain – constrained" near the ends.

The Fault Avoidance Zones for the Heaver's Creek Fault, East Lane Fault, and northern end of the Winterholme Fault all lie entirely within the previously defined Fault Awareness Areas (Figure 3.4B).

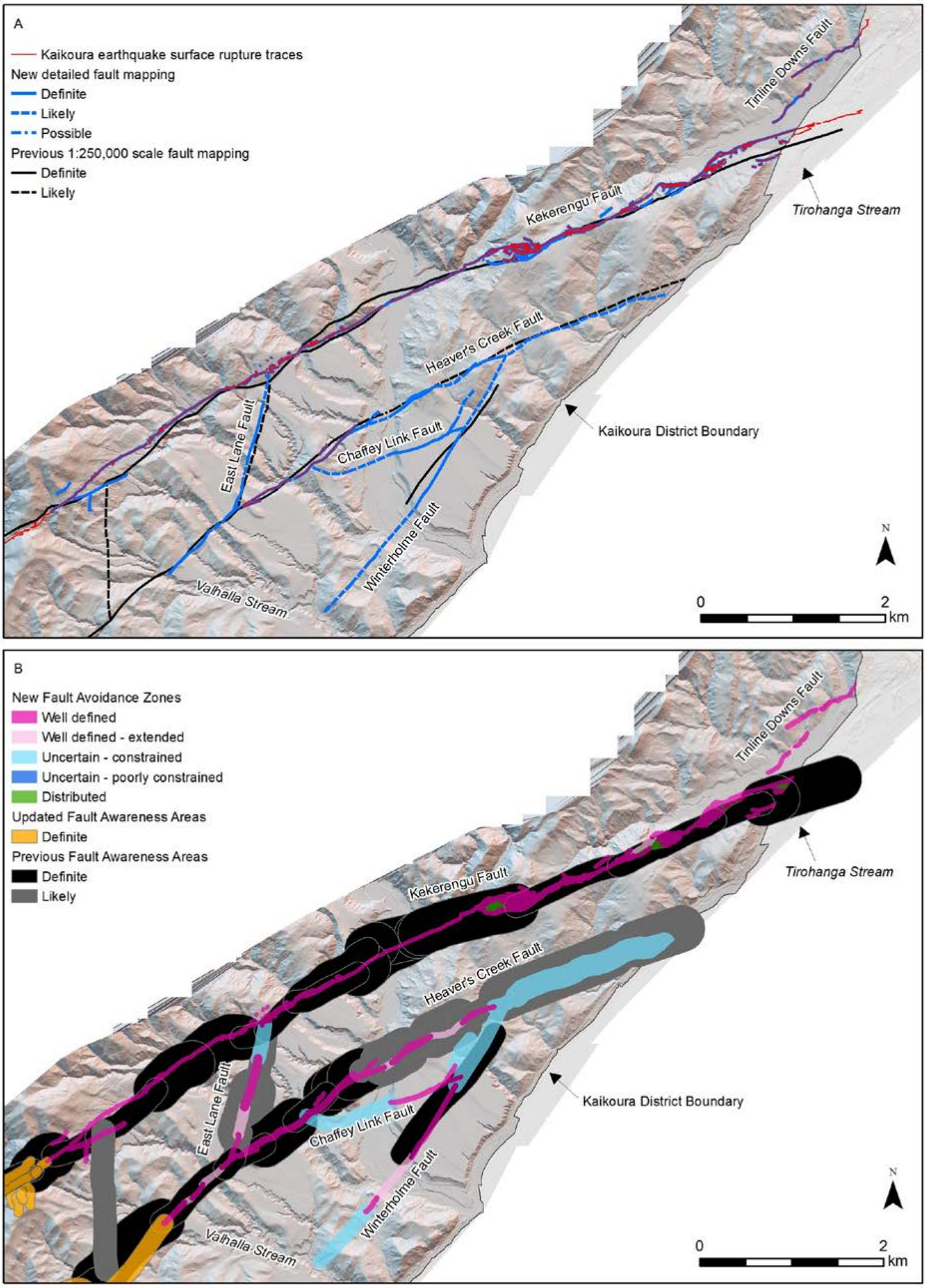


Figure 3.4 A) New and previous mapping of the Tinline Downs, Kekerengu, Heaver's Creek, East Lane, Chaffey Link, and Winterholme faults. B) Fault Avoidance Zones for the Tinline Downs, Kekerengu, Heaver's Creek, East Lane, Chaffey Link, and Winterholme faults. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 2.0.

3.4 Papatea, Waiautoa, and Corner Hill Faults

The Papatea, Waiautoa, and Corner Hill faults had not been mapped as active faults prior to the Kaikōura Earthquake. They lie east of the Stewart Creek Fault, either side and within the lower Clarence River valley (Figure 1.1; Langridge et al. 2018). The Papatea Fault consists of two main, subparallel, strands, but locally splays into several others (Figure 3.5A). The Waiautoa and Corner Hill faults splay off from the Papatea Fault at moderate to high angles. "Likely" and "Possible" faults have been mapped linking some of the 2016 traces, many of which have been eroded by landslides during the 2016 earthquake or by rivers since then (Figure 3.5A).

Fault Avoidance Zones have been created for all of the 2016 rupture traces, the "Likely" and "Possible" linking faults, and a few small areas (gaps) between multiple, short traces (Figure 3.5B). The zones for the 2016 ruptures are classified as "Well defined" and "Well defined – extended" (e.g., where they have been eroded by rivers or landslides). Fault Avoidance Zones for inferred faults linking ruptures of the western strand of the Papatea Fault and the southern Waiautoa Fault and the inferred western end of the Papatea Fault have been classified as "Uncertain – constrained".

3.5 Paparoa Point Fault

The Paparoa Point Fault had not been mapped prior to the Kaikōura Earthquake and was identified from the differential LiDAR data model crossing Paparoa Point (Figure 1.1, Figure 3.5A; Clark et al. 2017, Langridge et al. 2018). The ruptures consist of three short traces and there is no evidence on the LiDAR data for their continuation farther along the coast to the north or south.

Fault Avoidance Zones have been created for these three traces, and all have been classified as "Well defined" (Figure 3.5B).

3.6 Jordan Thrust to the Northern Side of the Hapuku River

The southern end of the Jordan Thrust didn't rupture in the Kaikōura Earthquake, but the portion between the Hope Fault and the Hapuku River has been re-mapped using the new LiDAR data (Figure 3.6).

Traces are only clearly visible in the LiDAR data in two places, adjacent to the Hope Fault and in the Hapuku River, and so in those cases the Fault Avoidance Zones have been classified as "Well defined" (Figure 3.6B). The location of the remainder of the fault is broadly constrained from bedrock mapping and geomorphically along the base of the range front and splits into two strands near the Hapuku River. This part of the fault has been classified as "Uncertain – constrained" (Figure 3.6B). The Fault Avoidance Zones for the main trace overlap the previous Fault Awareness Areas but diverge at the northern and southern ends (Figure 3.6B)

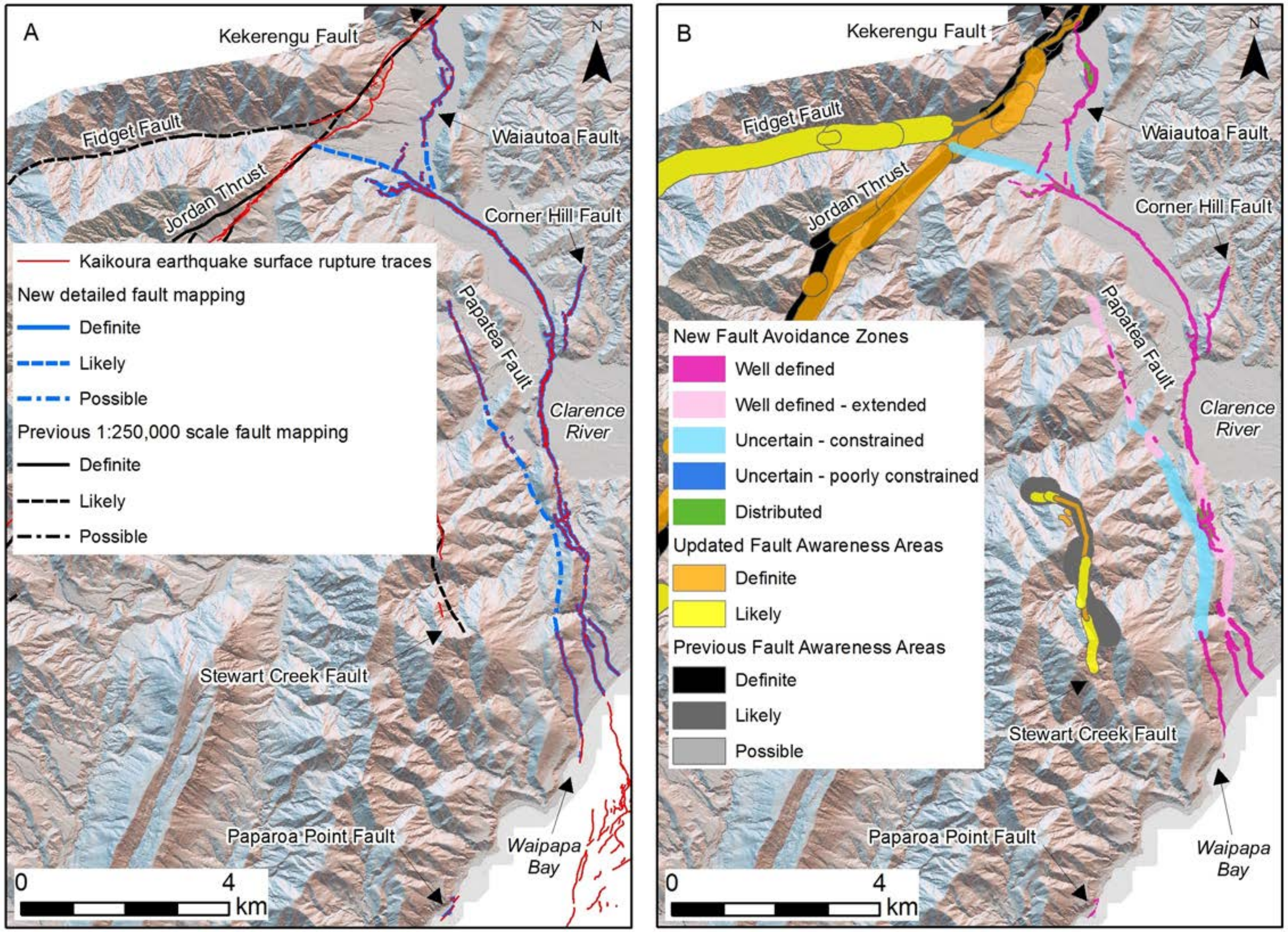


Figure 3.5 A) New and previous mapping of the Papatea, Waiautoa, Corner Hill, and Paparoa Point faults. B) Fault Avoidance Zones for the Papatea, Waiautoa, Corner Hill, and Paparoa Point faults. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 2.0.

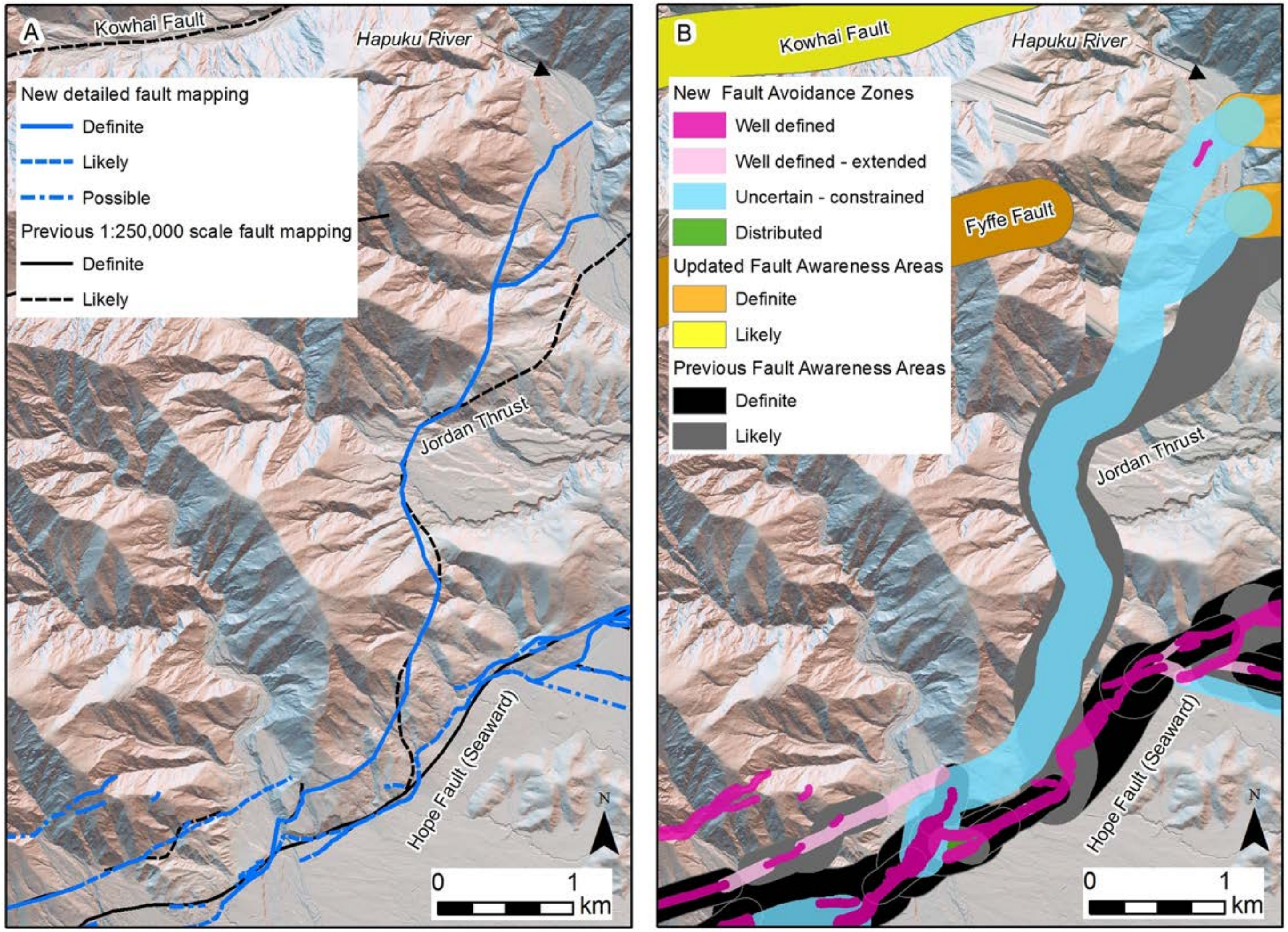


Figure 3.6 A) New and previous mapping of the southern end of the Jordan Thrust. B) Fault Avoidance Zones for the southern end of the Jordan Thrust.A version of this figure without the previous Fault Awareness Areas is contained in Appendix 2.0.

3.7 Hope Fault

Only a handful of short (≤200 m long) ruptures occurred on the Hope Fault in the Kaikōura Earthquake (Figure 1.1; Litchfield et al., 2018). Most of the Hope Fault between approximately Mt Fyffe and the coast had been mapped for University of Canterbury research projects (e.g., Coulter 2007; J. Pettinga unpublished data summarised by Barnes and Pettinga (2018)). Detailed fault mapping using LiDAR data undertaken for the project summarised by Barnes and Pettinga (2018) was used as the basis for this study.

The Hope Fault in the Kaikōura District is highly complex, but based on changes in geomorphic expression and slip rate across major faults, we follow the three-section classification of Van Dissen (1989) and Coulter (2007):

- Conway Section – west of the Fyffe Fault, characterised by a single main dextral strike-slip (mostly horizontal motion) fault (Figure 3.7A);
- Mt Fyffe Section – between the Fyffe Fault and Jordan Thrust – characterised by a partitioned dextral strike-slip and reverse frontal thrust system (some parts have mostly horizontal motion and others have mostly vertical motion) (Figure 3.8A);
- Seaward Section – between the Jordan Thrust and the coast – characterised by anastomosing, mainly dextral strike-slip (mostly horizontal motion) faults (Figure 3.9A).

The Conway and Mt Fyffe sections correspond to the Eastern Section of Barrell (2015), and the Seaward Section includes Barrell's Seaward Segment, and Hapuku and Mangamaunu faults.

In addition to the main traces, there are multiple subsidiary dextral, reverse, and normal faults. We have mapped those that we are most confident are primary fault traces, but like the Kekerengu and Jordan Thrust, there are many scarps of ambiguous origin visible in the LiDAR data within the ranges that we have not mapped (e.g., Figure 3.10), as their primary active fault origin (compared with a landslide or ridge rent) is not clear.

Fault Avoidance Zones have been generated for all of the mapped traces, as well as a few areas (gaps) between multiple short traces as was done for the Kekerengu and Papatea faults.

The Fault Avoidance Zones for the Conway Section are classified as "Well defined", "Well defined – extended" (for inferred concealed or eroded faults between traces), or "Distributed" (gaps between multiple traces) (Figure 3.7B). The Fault Avoidance Zones for the main trace lie within the previous Fault Awareness Areas, but many of the subsidiary faults lie outside of these.

The Fault Avoidance Zones for the Mt Fyffe Section are classified as "Well defined", "Well defined – extended" (for inferred concealed or eroded faults between traces), or "Uncertain – constrained" (for inferred faults between larger gaps in traces) (Figure 3.8B). It is unknown if frontal reverse faults on the true left bank of the Kowhai River extend farther west beneath young alluvium (marked by "?" in Figure 3.8A). As a result, we have not generated Fault Avoidance Zones beneath the young alluvium, but we cannot rule out the potential for future fault rupture there. The Fault Avoidance Zones for the main dextral strand generally lie within the previous Fault Awareness Areas, but those for the frontal reverse faults and many of the subsidiary faults do not.

The Fault Avoidance Zones for the Seaward Section are classified as “Well defined”, “Well defined – extended” (for inferred concealed or eroded faults between traces), “Uncertain – constrained” (for inferred faults between larger gaps in traces), “Uncertain – poorly constrained” (for the northeast ends of two of the strands and a possible fault along the Puhi Puhi River), or “Distributed” (gaps between multiple traces) (Figure 3.9B). It is unknown if frontal reverse faults on the true right bank of the Hapuku River extend farther east beneath young alluvium (marked by “?” in Figure 3.9A). So, as for the Mt Fyffe section, Fault Avoidance Zones have not been generated in the area of the young alluvium, but we cannot rule out the possibility of future fault rupture there. Many of the Fault Avoidance Zones lie within the previous Fault Awareness Areas, but those for some of the subsidiary faults do not. There is no evidence in the LiDAR data for the previously mapped Fault Awareness Areas crossing the Hapuku River, and so we have shortened what was previously called the Hapuku Fault and considered them to be short splays of the main trace of the Seaward Section.

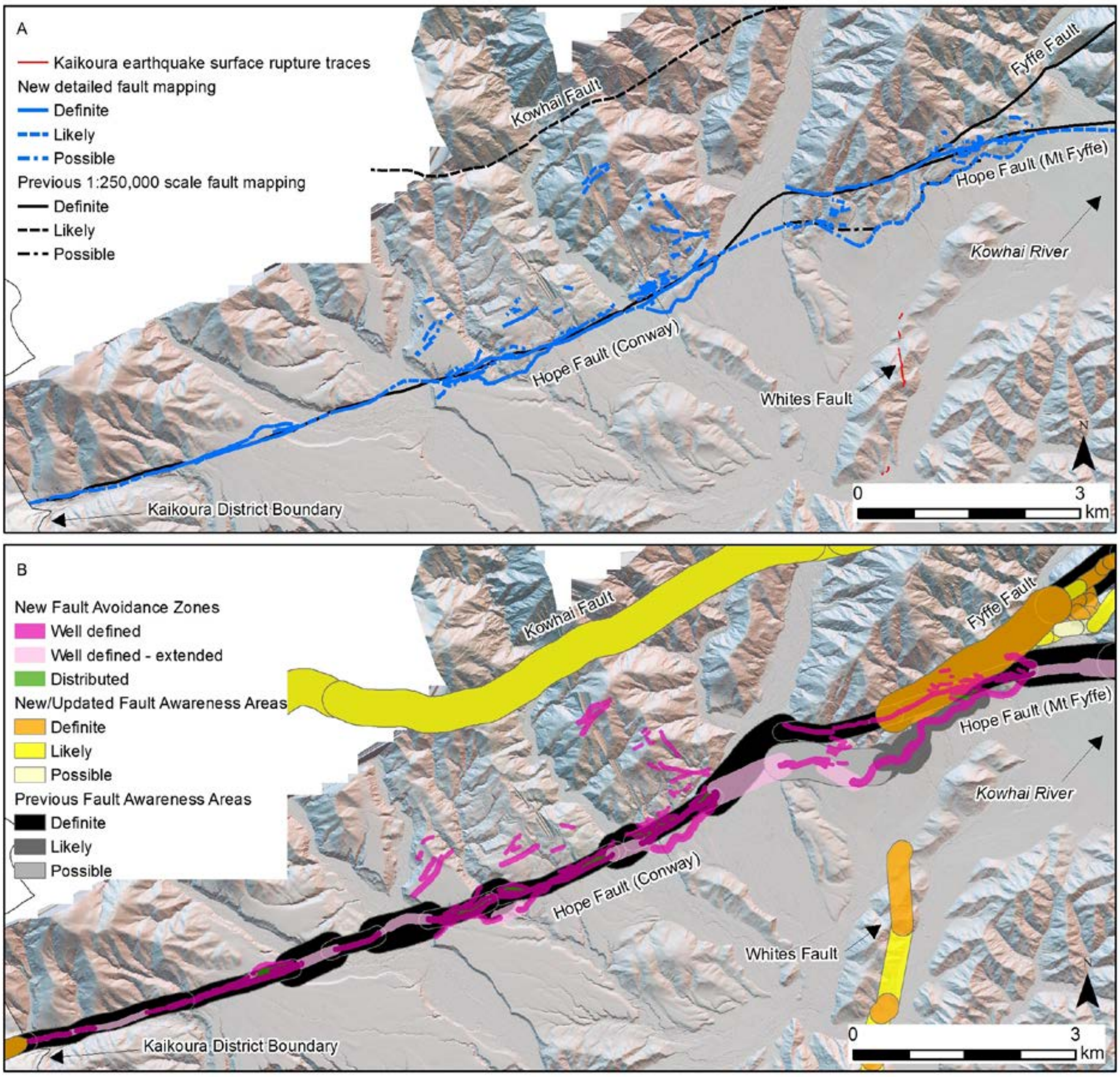


Figure 3.7 A) New and previous mapping of the Conway Section of the Hope Fault. B) Fault Avoidance Zones for the Conway Section. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 2.0.

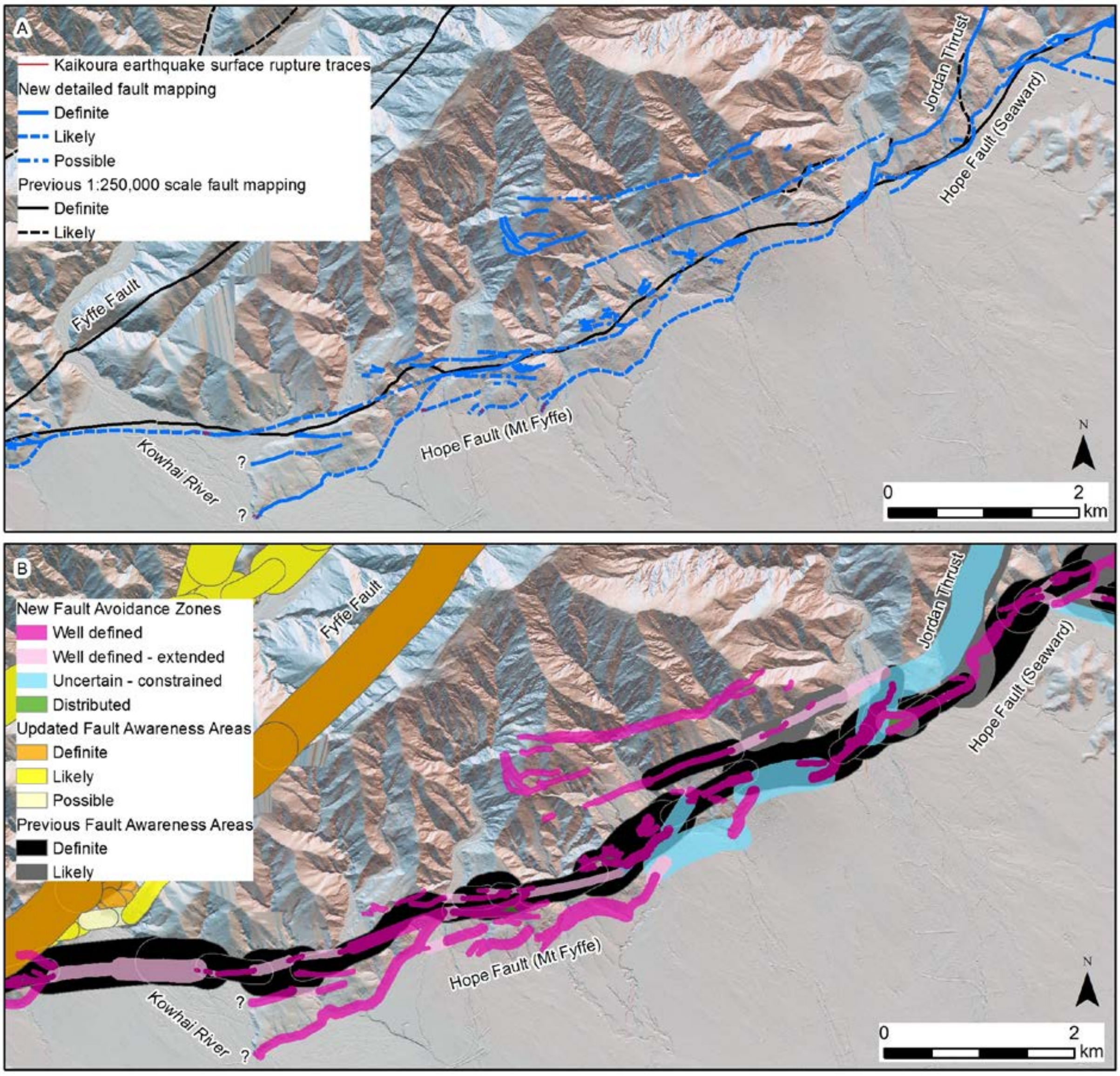


Figure 3.8 A) New and previous mapping of the Mt Fyffe Section of the Hope Fault. B) Fault Avoidance Zones for the Mt Fyffe Section. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 2.0.

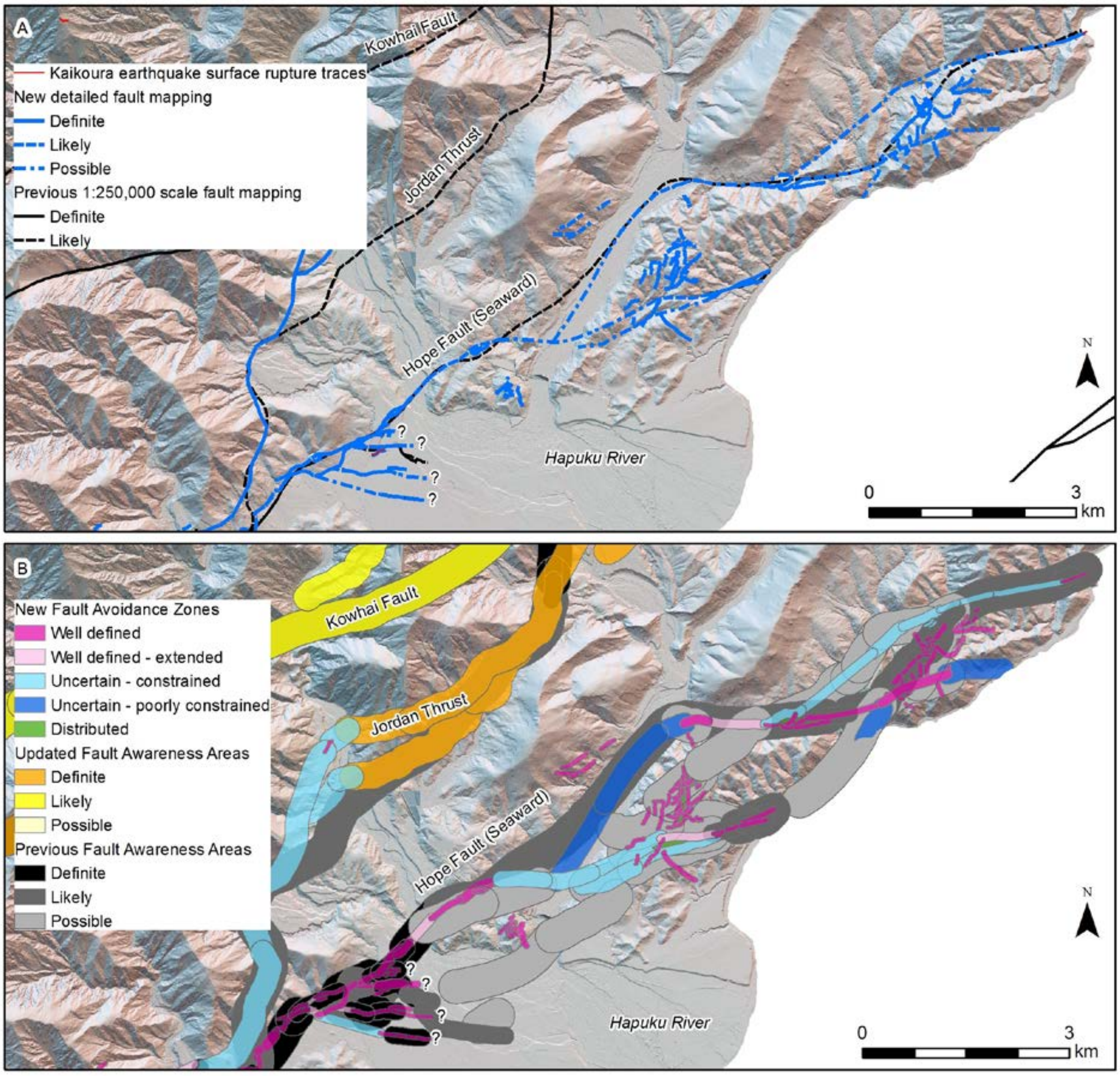


Figure 3.9 A) New and previous mapping of the Seaward Section of the Hope Fault. B) Fault Avoidance Zones for the Seaward Section. A version of this figure without the previous Fault Awareness Areas is contained in Appendix 2.0.

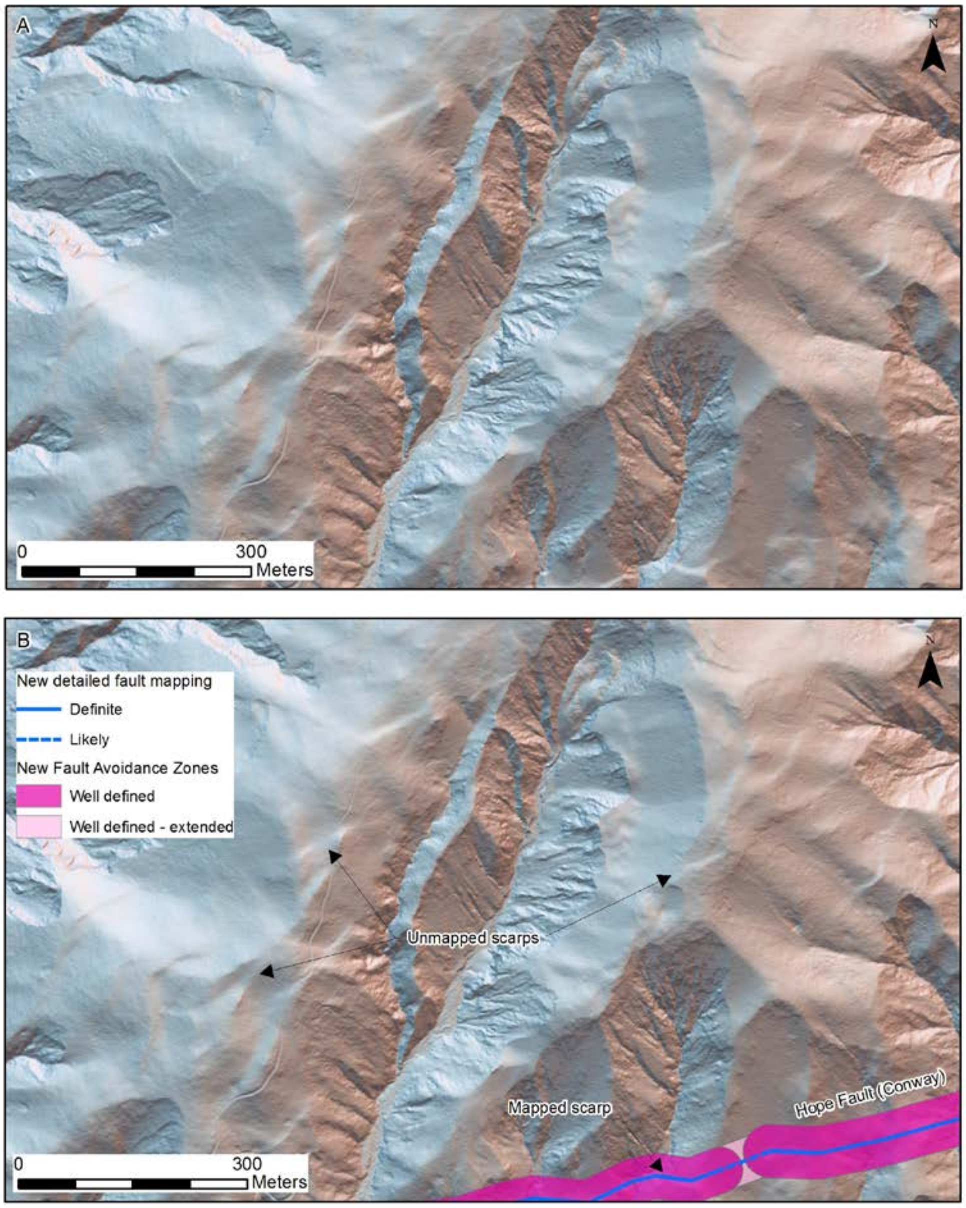


Figure 3.10 Scarps visible on the LiDAR data on the hillslopes above the Hope Fault, some of which are not included in Fault Avoidance Zones because their origin as a fault rather than a landslide feature is unclear.

4.0 UPDATED RECURRENCE INTERVALS

The currently-available recurrence interval data for all of the mapped faults in the Kaikōura District have been reviewed and updated, as summarised in Table 4.1. Below we make some overview comments on the data sources, uncertainties, and methods of calculation.

Site-specific paleoseismic (trenching) data is currently only available for four faults in the Kaikōura District – the Clarence and Kekerengu faults, and the Conway and Mt Fyffe sections of the Hope Fault (Table 4.1). Of these, only the Kekerengu Fault trenching data (Little et al. 2018) is new since the previous compilation (Barrell 2015), and there is no overall change to the recurrence interval class for any of these faults.

Paleoseismic or geomorphological field observations have been collected for a few other faults, most notably the Jordan Thrust, Papatea, and Stone Jug faults. The observations for the Papatea and Stone Jug faults have been made during fieldwork following the Kaikōura Earthquake and are currently being updated with site-specific (trenching) work. Site-specific (trenching) work is also currently being undertaken for the Hundalee Fault. Additional work on the Jordan Thrust is planned over the next several years.

For some of the major faults (Fidget and Hundalee faults) we have adopted the values from the 2010 National Seismic Hazard Model (2010 NSHM; Stirling et al. 2012). For other major faults not in the 2010 NSHM (Heaver's Creek, Upper Kowhai, Kowhai, and Fyffe faults) we have used the same methodology as used in the 2010 NSHM to calculate recurrence intervals. Briefly, the methodology is to calculate recurrence interval from single event displacement divided by slip rate, and the single event displacement is calculated from magnitude-scaling relationships based ultimately on fault length (see Stirling et al. 2012 for more details). For these calculations we have relied on the slip rate values from Barrell (2015) and updated fault lengths.

For the minor faults that ruptured in the Kaikōura Earthquake (Tinline Downs, Waiautoa, Corner Hill, Stewart Creek, Paparoa Point, Manakau, Whites, and Oaro River faults) the recurrence intervals are assigned to be the same, or longer than nearby major faults that ruptured. This is done under the assumption that these faults are most likely secondary faults that only rupture with the major faults. Assigning the recurrence interval from nearby major faults is also used for the Chaffey Link, Winterholme, and East Lane faults.

The faults have then been assigned to a single recurrence interval class based on the preferred recurrence interval from the field data, or from the preferred calculated value (e.g., using the methodology applied in the 2010 NSHM), or for the central value for an estimated range (e.g., the Papatea Fault and associated subsidiary faults). These are accompanied by a confidence level as defined in the MfE Active Fault Guidelines (see the table footnote for definitions). For those values close to a recurrence interval class boundary (e.g., 2100 years for the Kowhai Fault) we have followed the MfE Active Fault Guidelines recommendation to include such faults in the lower (more restrictive) recurrence interval class (e.g., <2000 years for the Kowhai Fault).

Table 4.1 Previous (Barrell 2015) and updated recurrence interval information for Kaikōura District active faults. RI is recurrence interval.

Fault name	Barrell (2015)			Updates			Single RI class			
	RI (years)	RI class	Data	RI (years)	RI class	Data / update	Preferred RI (years)	RI class	RI class (years)	Confidence level§
Clarence	1700	I	Paleoseismic studies (Van Dissen and Nicol 2009)	1650–1730	I	Paleoseismic studies (Van Dissen and Nicol 2009) – same data, but calculated more precisely.	1700	I	≤2000	High
Fidget	700–5000	I–III	Calculated from a slip rate of 2 ± 1 mm/yr and 2–5 m horizontal displacement per event	715–2610	I–II	Calculated in 2010 NSHM (Stirling et al. 2012).	1200	I	≤2000	Low
Elliott	2000–3500	II	Assigned by Van Dissen et al. (2003)	1650–1730	I	Assigned to be the same as the Clarence Fault.	1700	I	≤2000	Medium
Tinline Downs	-	-	-	350–1700	I	Assigned to be the same as the Heaver's Creek Fault.	1300	I	≤2000	Medium
Kekerengu	100–500	I	Calculated from a slip rate of 10–20 mm/yr and 2–5 m horizontal displacement per event	350–410	I	Trenching (Little et al. 2018).	375	I	≤2000	High
Heaver's Creek	2400–6000	I–IV	Calculated from a slip rate of 0.8 mm/yr and 2–5 m horizontal displacement per event	350–1700	I	Minimum is the minimum Kekerengu Fault RI. Maximum and preferred are calculated from a slip rate of 0.8 mm/yr, rupture lengths of 20 and 15 km, and the scaling relationship used in the 2010 NSHM (Stirling et al. 2012).	1300	I	≤2000	Medium
Chaffey Link	-	-	-	350–1700	I	Assigned to be the same as the Heaver's Creek Fault.	1300	I	≤2000	Medium
Winterholme	-	-	-	350–1700	I	Assigned to be the same as the Heaver's Creek Fault.	1300	I	≤2000	Medium
East Lane	-	-	-	350–1700	I	Assigned to be the same as the Heaver's Creek Fault.	1300	I	≤2000	Medium
Jordan Thrust	≤1200	I	Calculated from at least 3 rupture events in the past ~3500 years (Van Dissen 1989)			Consistent with last event <1730–1630 cal. yr BP (Van Dissen et al. 2006).	1150	I	≤2000	High
Manakau	-	-	-	1200–6100	I–V	Assigned to be the same as the Upper Kowhai Fault.	2800	II	>2000 to ≤3500	Low
Upper Kowhai	4000–10,000	II–V	Calculated from a slip rate of 0.5 mm/yr and 2–5 m horizontal displacement per event	1200–6100	I–IV	Calculated from a slip rate of 0.5 (0.25–1) mm/yr, a length of 15 km, and the scaling relationship used in the 2010 NSHM (Stirling et al. 2012).	2800	II	>2000 to ≤3500	Low
Kowhai	2000–5000	II–III	Calculated from a slip rate of 1 mm/yr and 2–5 m horizontal displacement per event	940–4600	I–III	Calculated from a slip rate of 1 (0.5–2) mm/yr, a length of 30 km, and the scaling relationship used in the 2010 NSHM (Stirling et al. 2012).	2100	I	≤2000	Low
Fyffe	1000–2500	I–II	Calculated from a slip rate of 2 mm/yr and 2–5 m horizontal displacement per event	310–1150	I	Calculated from a slip rate of 2 (1–3) mm/yr, a length of 15 km, and the scaling relationship used in the 2010 NSHM (Stirling et al. 2012).	520	I	≤2000	Medium
Papatea	-	-	-	5000–12,000	IV–V	Estimated based on geomorphic field evidence (Langridge et al. 2018).	8500	IV	>5000 to ≤10,000	Medium
Waiautoa	-	-	-	5000–12,000	IV–V	Assigned to be the same as the Papatea Fault.	8500	IV	>5000 to ≤10,000	Medium
Corner Hill				5000–12,000	IV–V	Assigned to be the same as the Papatea Fault.	8500	IV	>5000 to ≤10,000	Medium
Stewart Creek	10,000–20,000	V	Inferred	5000–12,000	IV–V	Assigned to be the same as the Papatea Fault.	8500	IV	>5000 to ≤10,000	Medium
Paparoa Point	-	-	-	5000–12,000	IV–V	Assigned to be the same as the Papatea Fault.	8500	IV	>5000 to ≤10,000	Low
Hope (Conway)*	200–300	I	Trenching (Langridge et al. 2003)	180–310	I	Trenching (Langridge et al. 2003) – same data but calculated more precisely.	245	I	≤2000	High

Fault name	Barrell (2015)			Updates			Single RI class			
	RI (years)	**RI class**	**Data**	**RI (years)**	**RI class**	**Data / update**	**Preferred RI (years)**	**RI class**	**RI class (years)**	**Confidence level§**
Hope (Mt Fyffe)*	200–300	I	Trenching (Langridge et al. 2003)	<2000	I	Trenching data indicates 1 event since 660 AD, and at least 1 between 1410 and 1640 AD (Coulter 2007).		I	≤2000	High
Hope (Seaward)	1700	I	Modelled by Robinson et al. (2011)	<2000	I	Inferred from the other sections.		I	≤2000	High
Whites	-	-	-	5000–20,000	IV–V	Inferred to be longer than The Humps Fault in the Hurunui District and the Papatea Fault.	12,500	V	>10,000 to ≤20,000	Low
Oaro River	-	-	-	5000–20,000	IV–V	Inferred to be longer than The Humps Fault in the Hurunui District and the Papatea Fault.	12,500	V	>10,000 to ≤20,000	Low
Stone Jug#	≥6000 yrs	III–IV	Assigned from the Lottery River faults (Hancox et al. 2006)	2500–10,000	II–IV	Calculated from a slip rate of 0.1–0.4 mm/yr and displacement of >1 m (Barrell and Townsend 2012; Nicol et al. 2018).	4000	III	>3500 to ≤5000	Low
Hundalee	>5000–10,000	IV or more	Assigned	1450–10,200	I–V	Calculated in the 2010 NSHM (Stirling et al. 2012).	3100	II	>2000 to ≤35000	Low

* Part of the Hope (Eastern) of Barrell (2015).

Part of the Conway-Charwell faults mapped by Barrell and Townsend (2012).

§ Following the definitions in the MfE Active Fault Guidelines (Kerr et al. 2003); High = well constrained RI (usually based on fault-specific data) that is well within a specific RI class, or has such a high slip rate that it can be confidently placed within the 2000 year RI class; Medium = uncertainty embraces a significant portion (> ~25%) of two RI classes; the mean of the uncertainty range typically determines into which class the fault is placed; Low = uncertainty embraces a significant portion of three or more RI classes, or there are no fault-specific data (i.e., RI class is assigned based on only subjective comparison with other faults).

5.0 PLANNING RECOMMENDATIONS

This section provides recommended actions for both the Fault Avoidance Zones and Fault Awareness Areas generated in this report, based on the MfE Active Fault Guidelines (Kerr et al. 2003) and *Guidelines for using regional-scale Earthquake fault information in Canterbury* (Barrell et al. 2015).

Both guidelines promote a risk-based approach where the recommended action is based on:

- how active the fault is over a long-time period (the recurrence interval)
- the fault complexity, or how well it can be located at the ground surface
- the proposed activity or structure (Building Importance Category).

The recommended planning provisions provide a starting point for community consultation and the final planning provisions may be more or less restrictive as deemed appropriate by the community and the Council.

5.1 Building Importance Category

In the event of fault rupture, buildings constructed on a fault that ruptures will be subject to distortion and can suffer extensive damage, and possibly collapse. Buildings adjacent or near (i.e., within tens of metres of) a fault may also be damaged when subject to fault rupture induced ground deformation. The risk of damage from fault rupture at a site is therefore a function not only of the location and activity of a fault, but also on the type of structure/building that may be impacted by rupture of that fault. The MfE Active Fault Guidelines define five Building Importance Categories (Table 5.1) based on accepted risk levels for building performance considering building type, use and occupancy. This categorisation is weighted towards life safety, but also allows for the operational continuity of critical structures whose post-Earthquake function is required to be maintained.

Table 5.1 Building Importance Categories and representative examples. From the MfE Active Fault Guidelines (Kerr et al. 2003).

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

5.2 Relationship between Fault Recurrence Interval Class and Building Importance Category

A key parameter used in the MfE Active Fault Guidelines to characterise surface rupture hazard is the average recurrence interval of surface rupture faulting. The average recurrence interval of surface rupture is the average number of years between successive surface rupture earthquakes along a specific section/length of fault. Typically, the longer the average recurrence interval of surface rupture of a fault, the less likely the fault is to rupture in the near future (i.e., over the intended design life of a building that may be sited on or close to the fault). Likelihood of rupture is probably also a function of other variables such as elapsed time since the last rupture of the fault, and the size, style and timing of large earthquakes on other nearby faults; however, these variables are not used to define rupture hazard in the MfE Active Fault Guidelines. Notwithstanding, a fault with a long recurrence interval typically poses less of a hazard than one with a short recurrence interval. In the MfE Active Fault Guidelines, active faults are grouped according to Recurrence Interval Class (Table 5.2), such that the most hazardous faults, i.e., those with the shortest recurrence intervals, are grouped within Recurrence Interval Class I. The next most active group of faults are those within Recurrence Interval Class II, and so on.

The MfE Active Fault Guidelines advocate a risk-based approach to dealing with development of land on, or close to active faults. At a particular site the risk of collapse posed by fault rupture is a function not only of the location and activity of a fault, but also the resilience of the structure/building that may be impacted by rupture of the fault. For sites on, or immediately adjacent to, active faults, the hazard (risk) is higher for faults that have shorter recurrence intervals. Also, society's expectation of building performance in an earthquake increases as Building Importance Category increases. Therefore, to maintain a consistent level of acceptable risk, it appears reasonable to impose more restrictions on the development of sites located on, or immediately adjacent to highly active faults, compared to sites located on, or immediately adjacent to low activity faults.

This hierarchical relation between fault activity (Recurrence Interval Class) and building type (Building Importance Category) is presented in Table 5.2. The MfE Active Fault Guidelines also make a pragmatic distinction between previously subdivided and/or developed sites, and undeveloped "greenfield" sites, and allows for different conditions to apply to these two types of sites of differing development status. The rationale for this is that in the subdivision/development of a "greenfield" area, a change of land usage is usually being sought, and it is much easier, for example, to require a building setback distance from an active fault, or to plan subdivision of land to avoid encroaching on an active fault. However, in existing built-up areas, buildings may have been established without knowledge of the existence or location of an active fault, and members of the community may have an expectation to continue to live there, despite the potential danger.

Table 5.2 Relationships between Recurrence Interval Class and Building Importance Category From the MfE Active Fault Guidelines (Kerr et al. 2003).

Recurrence interval class	**Average recurrence interval of surface rupture**	**Building Importance Category (BIC) limitations (allowable buildings)**	
		Previously subdivided or developed sites	**'Greenfield' sites**
I	≤2000 years	BIC 1 Temporary buildings only	BIC 1 temporary buildings only
II	>2000 years to ≤3500 years	BIC 1 and 2a Temporary and residential timber-framed buildings only	
III	>3500 years to ≤5000 years	BIC 1, 2a, and 2b Temporary, residential timber-framed and normal structures	BIC 1 and 2a temporary and residential timber-framed buildings only
IV	>5000 years to ≤10,000 years	BIC 1, 2a, 2b and 3 Temporary, residential timber-framed, normal and important structures (but not critical post-disaster facilities)	BIC 1, 2a, and 2b temporary, residential timber-framed and normal structures
V	>10,000 years to ≤20,000 years		BIC 1, 2a, 2b and 3 temporary, residential timber-framed, normal and important structures (but not critical post-disaster facilities)
VI	>20,000 years to ≤125,000 years	BIC 1, 2a, 2b, 3 and 4 Critical post-disaster facilities cannot be built across an active fault with a recurrence interval ≤20,000 years	
Note: Faults with average recurrence intervals >125,000 years are not considered active			

5.3 Fault Avoidance Zones

Fault Avoidance Zones, based on detailed fault mapping, have been generated for the:

- Tinline Downs Fault
- Kekerengu Fault north of Valhalla Stream
- Heaver's Creek Fault north of Valhalla Stream
- East Lane, Winterholme, and Chaffey Link faults
- Papatea, Waiautoa, and Corner Hill faults
- Paparoa Point Fault
- Jordan Thrust to the northern side of the Hapuku River (near 307 m hill)
- Hope Fault (Conway, Mt Fyffe, and Seaward sections)

These are faults with relatively short recurrence intervals and/or are in areas where future development is likely or in areas of particular interest to Kaikōura District Council.

Taking a risk-based approach using the MfE Active Fault Guidelines, recommended resource consent categories for activities within the fault avoidance zones for these faults are given in Tables 5.3 and 5.4.

Table 5.3 Recommended resource consent categories for Greenfield sites in relation to fault complexity for the Fault Avoidance Zones generated in this study.

Greenfield sites						
Building Importance Category		**1**	**2a**	**2b**	**3**	**4**
RI Class	**Fault complexity**	**Resource consent category**				
Tinline Downs Fault, Kekerengu Fault, Heaver's Creek Fault, Chaffey Link Fault, Winterholme Fault, East Lane Fault, Jordan Thrust, Hope Fault (Conway Section), Hope Fault (Mt Fyffe Section), Hope Fault (Seaward Section)						
I <2,000 years	Well defined Distributed Uncertain	Permitted Permitted Permitted	*Non-complying* *Discretionary* *Discretionary*	*Non-complying* *Non-complying* *Non-complying*	*Non-complying* *Non-complying* *Non-complying*	Prohibited Non-complying Non-complying
Papatea Fault, Waiautoa Fault, Corner Hill Fault, Paparoa Point Fault						
IV **5000-10000 years**	Well defined Distributed Uncertain	Permitted Permitted Permitted	Permitted* Permitted Permitted	Permitted* Permitted Permitted	*Non-complying* *Discretionary* *Discretionary*	Non-complying Non-complying Non-complying
* The recommended resource consent category is permitted, but could be controlled or discretionary given that the fault location is well-defined. ** Although the activity status is permitted, care should be taken in locating BIC 4 structures on or near known active faults. Controlled or discretionary activity status may be more suitable. *Italics* show that the activity status is more flexible. For example, where *discretionary* is indicated, controlled activity status may be considered more suitable.						

Table 5.4 Recommended resource consent categories for developed and already subdivided sites in relation to fault complexity for the fault avoidance zones generated in this study.

Developed and already subdivided sites						
Building Importance Category		**1**	**2a**	**2b**	**3**	**4**
RI Class	**Fault complexity**	**Resource consent category**				
Tinline Downs Fault, Kekerengu Fault, Heaver's Creek Fault, Chaffey Link Fault, Winterholme Fault, East Lane Fault, Jordan Thrust, Hope Fault (Conway Section), Hope Fault (Mt Fyffe Section), Hope Fault (Seaward Section)						
I <2,000 years	Well defined	Permitted	*Non-complying*	*Non-complying*	*Non-complying*	Non-complying
	Distributed	Permitted	*Discretionary*	*Non-complying*	*Non-complying*	Non-complying
	Uncertain	Permitted	*Discretionary*	*Non-complying*	*Non-complying*	Non-complying
Papatea Fault, Waiautoa Fault, Corner Hill Fault, Paparoa Point Fault						
IV 5000-10000 years	Well defined	Permitted	Permitted*	Permitted*	Permitted*	Non-complying
	Distributed	Permitted	Permitted	Permitted	Permitted	Non-complying
	Uncertain	Permitted	Permitted	Permitted	Permitted	Non-complying

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

** Although the activity status is permitted, care should be taken in locating BIC 4 structures on or near known active faults. Controlled or discretionary activity status may be more suitable.

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

Permitted activities are allowed 'as of right' subject to complying with any conditions set out in the District Plan. A resource consent is not required (although a building consent is required for a building).

Discretionary means that the Council can grant or decline an application for the activity or building. If granted, it can impose conditions in relation to any matter that helps to control any of the activity's potential adverse effects.

Non-complying means that the Council can only grant an application for the activity or building if its adverse effects are minor, or if it is consistent with the District Plan's objectives and policies. If it grants consent, the council can impose conditions in relation to any matter that helps to control the activity's potential adverse effects.

Prohibited means that a resource consent cannot be applied for or granted for the activity.

5.4 Fault Awareness Areas

Fault Awareness Areas, based on new or existing 1:250,000 fault mapping, have been supplied for the:

- Clarence Fault (including subsidiary faults)
- Elliott Fault
- Fidget Fault
- Kekerengu Fault south of Valhalla Stream
- Heaver's Creek Fault south of Valhalla Stream
- Jordan Thrust north of Hapuku River
- Upper Kowhai Fault
- Kowhai Fault
- Manakau Fault
- Fyffe Fault
- Stewart Creek Fault
- Whites Fault
- Oaro River Fault
- Stone Jug Fault
- Hundalee Fault

These are faults in areas where future intensive development is unlikely.

Taking a risk-based approach using the *Guidelines for using regional-scale Earthquake fault information in Canterbury* (Barrell et al. 2015) recommended actions for activities within the Fault Awareness Areas for these faults are given in Table 5.5.

Table 5.5 Recommended actions for the Fault Awareness Areas generated in this study.

<table>
<tr><th rowspan="2">Proposed Activity</th><th colspan="3">Recommended Actions</th></tr>
<tr><td>For FAA categories:
definite (well expressed)
definite (mod expressed)
likely (well expressed)
likely (mod expressed)
with RI Class I, II or III</td><td>For FAA categories:
definite (well expressed)
definite (mod expressed)
likely (well expressed)
likely (mod expressed)
with RI Class IV, V or VI</td><td>For all other FAA categories:
definite (not expressed)
likely (not expressed)
possible</td></tr>
<tr><td>Single residential dwelling
(BIC 2a and 2b in part)</td><td colspan="3">Permitted activity.</td></tr>
<tr><td>Normal structures and structures not in other categories (BIC 2b, apart from single dwellings)</td><td colspan="2">Consideration of the surface fault rupture hazard should be a specific assessment matter if resource consent for a new structure is required for some other reason.
Site-specific investigation including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures for the accurately mapped fault (e.g. set back or engineering measures).</td><td>Permitted activity.</td></tr>
<tr><td>Important or critical structures
(BIC 3 and 4)</td><td colspan="3">Consideration of the surface fault rupture hazard should be a specific assessment matter if resource consent for a new structure is required for some other reason.
Site-specific investigation including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures determined for the accurately mapped fault (e.g. set back or engineering measures).</td></tr>
<tr><td>New subdivision (excluding minor boundary adjustments)</td><td colspan="2">Consideration of the surface fault rupture hazard should be a specific assessment matter.
Site-specific investigation including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures for the accurately mapped fault (e.g. set back or engineering measures).</td><td>Permitted activity.</td></tr>
<tr><td>Plan Changes</td><td colspan="3">Consideration of the surface fault rupture hazard should be a specific assessment matter.
Site-specific investigation including detailed fault mapping at 1:35,000 or better and appropriate mitigation measures for the accurately mapped fault (e.g. set back or engineering measures.</td></tr>
</table>

5.5 District Plan Maps

All Fault Avoidance Zones and Fault Awareness Areas should be shown in the Kaikōura District Plan, and any other planning or hazard information maps for Kaikōura.

5.6 Land Information Memoranda (LIMs) and Property Information Memoranda (PIMs)

Guidance for including information on Fault Awareness Areas based on 1:250,000 fault information on Land Information Memoranda (LIMs) and Project Information Memoranda (PIMs) is provided in *Guidelines for using regional-scale Earthquake fault information in Canterbury* (Barrell et al. 2015). This guidance, with some minor modifications, can also be used for Fault Avoidance Zones which are based on more detailed mapping.

6.0 SUMMARY AND CONCLUSIONS

This report describes updates to existing active fault information for the Kaikōura District with the information from the 2016 Kaikōura Earthquake and new mapping derived from high-resolution LiDAR data and some new field data.

New Fault Awareness Areas have been generated for previously-unmapped faults that ruptured in the Kaikōura Earthquake – the Manakau, Whites, Oaro River, and Stone Jug faults. Fault Awareness Areas were updated using Kaikōura Earthquake data for the Fidget, Kekerengu (part), Jordan Thrust (part), Upper Kowhai, Stewart Creek, and Hundalee faults. Fault Awareness Areas have also been updated for parts of the Heaver's Creek and Fyffe Faults. The Fault Awareness Areas were generated by buffering 1:250,000 scale mapping of the faults; the buffer widths were determined on a fault-by-fault basis to take into account the location uncertainty and to encompass all of the detailed traces. Most of the updated Fault Awareness Areas lie within or overlap the previous Fault Awareness Areas.

New Fault Avoidance Zones have been generated for faults that ruptured in the Kaikōura Earthquake – the Tinline Downs, Kekerengu (part), Heaver's Creek (part), Papatea, Waiautoa, Corner Hill and Paparoa Point faults. New Fault Avoidance Zones have also been generated for the Winterholme, East Lane, Chaffey Link, Jordan Thrust (part) and Hope (Conway, Mt Fyffe, and Seaward sections) faults based on the LiDAR data. The Fault Avoidance Zones were generated from buffering the detailed rupture or LiDAR fault mapping following the methodology outlined in the MfE Active Fault Guidelines, with the additional modifications of using asymmetrical buffers for dip-slip faults, and an expanded list of fault complexity terms. Faults that ruptured in the Kaikōura Earthquake have been classified as "Well defined", with gaps and inferred extensions classified as "Well defined – extended", "Uncertain – constrained", "Uncertain – poorly constrained" or "Distributed". Most of the Fault Avoidance Zones lie within or overlap the previous Fault Awareness Areas.

Recurrence interval data has been reviewed and updated for all the mapped faults in the Kaikōura District. The updates include some new paleoseismic site-specific data and field observations, the use of the 2010 NSHM methodology for major faults, and assigning recurrence intervals for the minor faults from nearby major faults.

Recommended consent categories for activities within the Fault Avoidance Zones have been made based on Recurrence Interval Class and Building Importance Category, as per the MfE Active Fault Guidelines. Two sets of recommendations are made – for "Greenfield" and "Developed and already subdivided" sites.

Recommended actions for the Fault Awareness Areas have been made based on fault certainty and recurrence interval, and Building Importance Category, as outlined by Barrell et al. (2015).

7.0 RECOMMENDATIONS

Based on the findings in this report, GNS Science recommends that Environment Canterbury and Kaikōura District Council:

- Include all Fault Awareness Areas and Fault Avoidance Zones in the Kaikōura District Plan, and in any other planning or hazard information maps for Kaikōura.
- Use the recommended actions to the Fault Awareness Areas and Fault Avoidance Zones as outlined in Sections 5.2 and 5.3 as a starting point for community consultation.
- Include Fault Awareness Area and Fault Avoidance Zone information on Land Information Memoranda and Property Information Memoranda.
- Obtain better constraints in recurrence interval class. Site-specific paleoseismic studies are currently being undertaken on some of the faults that ruptured in the Kaikōura Earthquake and it is recommended that this new information be incorporated when it becomes available. There is also potential to improve the confidence level of some other faults, particularly the Heaver’s Creek, Chaffey Link, Winterholme, East Lane, Papatea, Waiautoa, and Hope (Mt Fyffe and Seaward sections) faults.
- Better constrain the fault zone for development sites if required. This may involve generation of Fault Avoidance Zones for faults which currently have Fault Awareness Areas, or trenching to further narrow Fault Avoidance Zones.
- Investigate engineering mitigation measures for developed and already subdivided sites, and for critical lifelines that cross active faults.

8.0 ACKNOWLEDGMENTS

The Kaikōura Earthquake surface rupture mapping was undertaken by a large team of people from multiple universities and organisations (see Stirling et al. 2017 and Litchfield et al. 2018). We'd also like to thank the land owners for unlimited access to map the faults following the 2016 Kaikōura Earthquake. The draft report benefited from peer review by Tim McMorran at Golder Associates Ltd. Some of the issues raised in the peer review about implementing the MfE Active Fault Guidelines can be dealt with during the development of the District Plan provisions.

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APPENDICES

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APPENDIX 1 FAULT AWARENESS AREA MAPS WITHOUT THE PREVIOUSLY-DEFINED FAULT AWARENESS AREAS

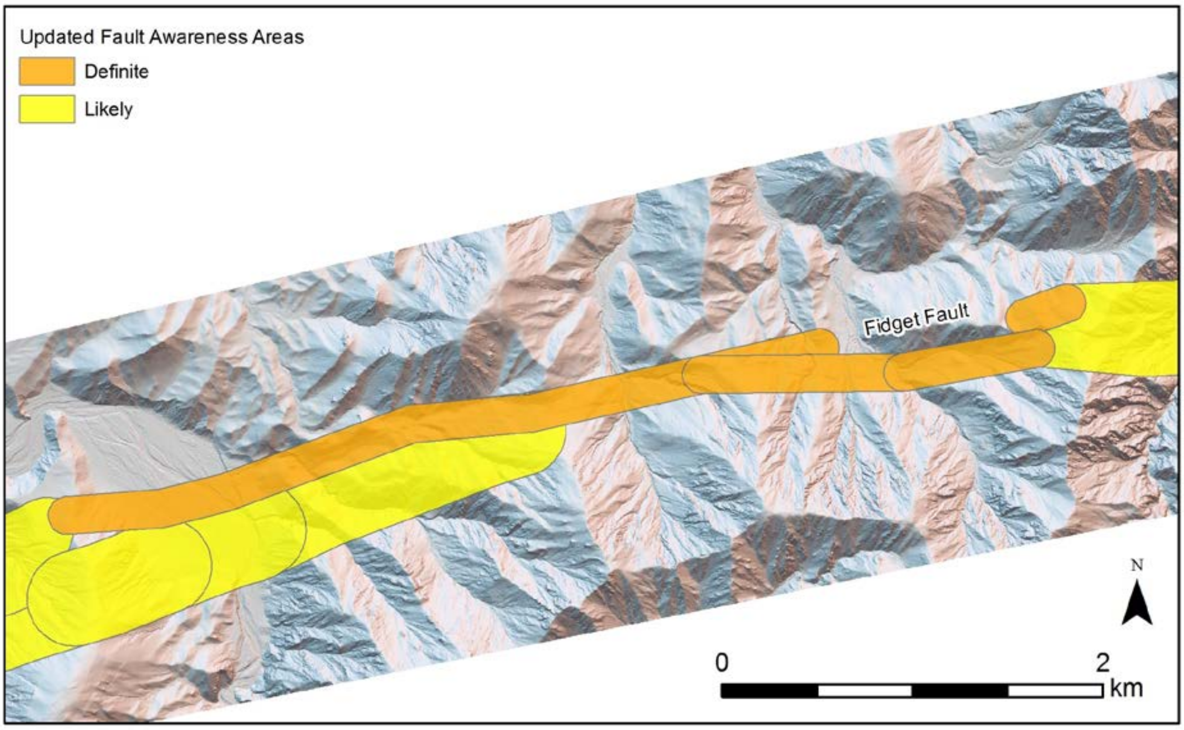

Figure A1.1 Updated Fault Awareness Areas for the Fidget Fault.

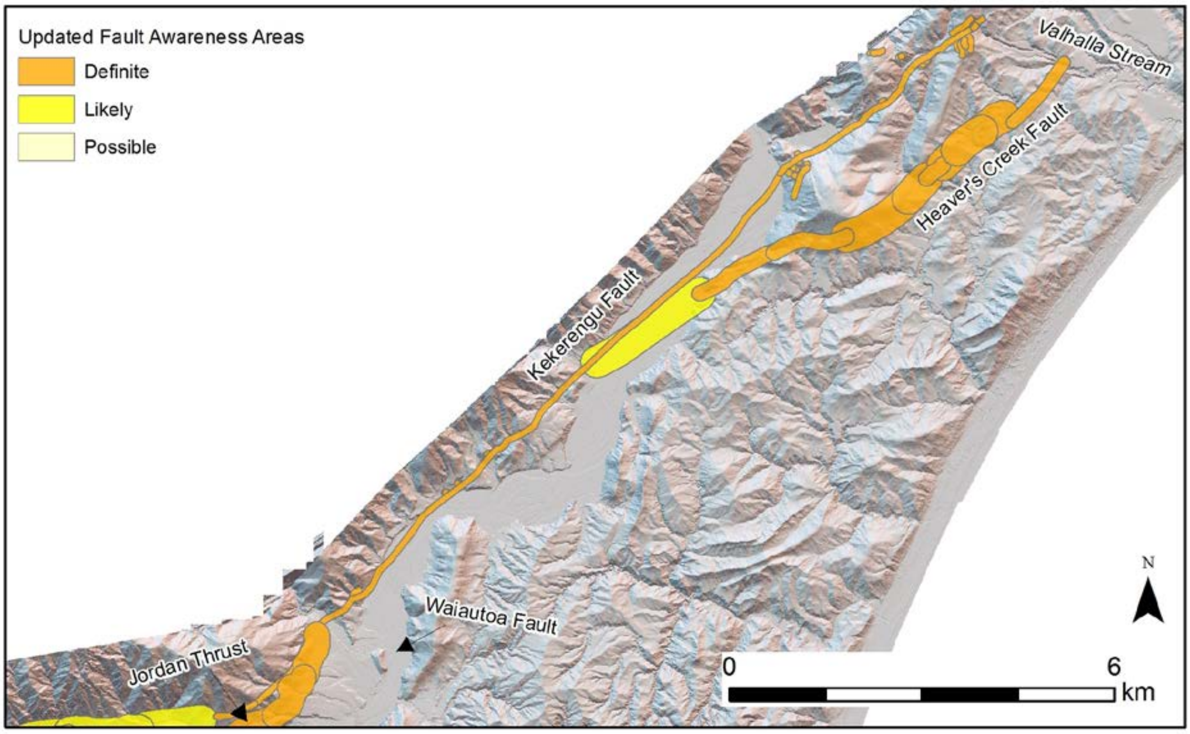

Figure A1.2 Updated Fault Awareness Areas for the Kekerengu Fault south of Valhalla Stream.

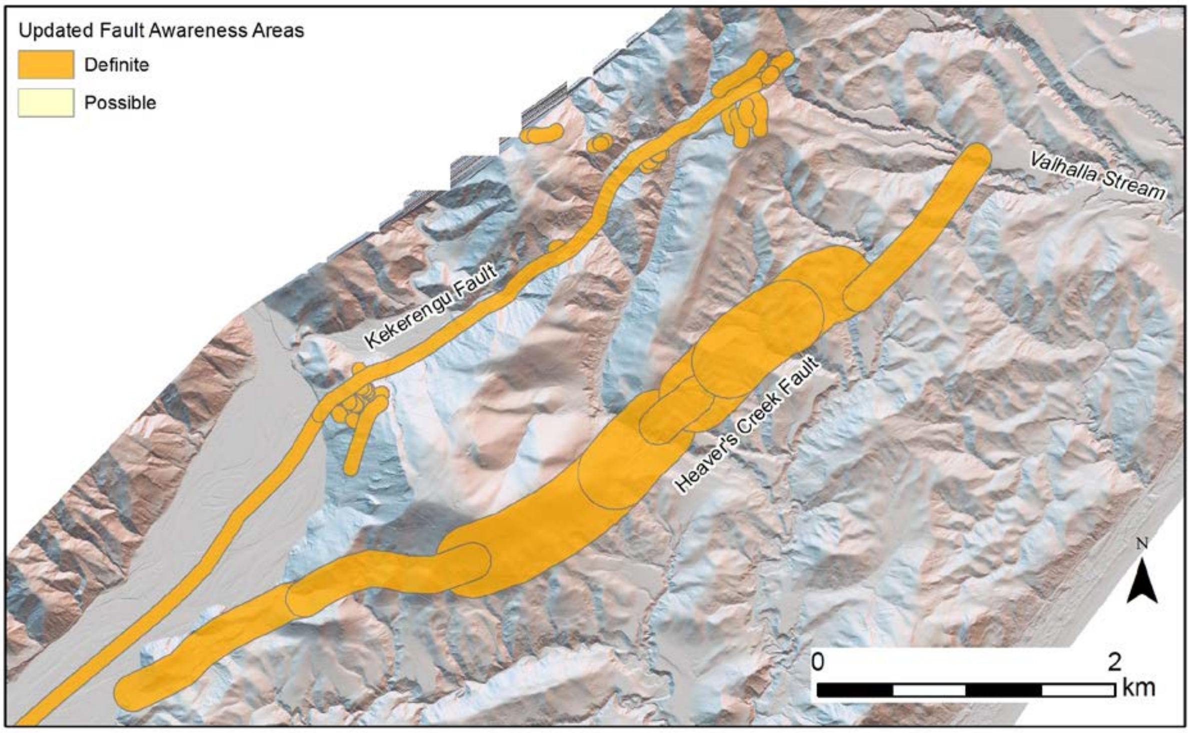

Figure A1.3 Updated Fault Awareness Areas for the Heaver's Creek Fault south of Valhalla Stream.

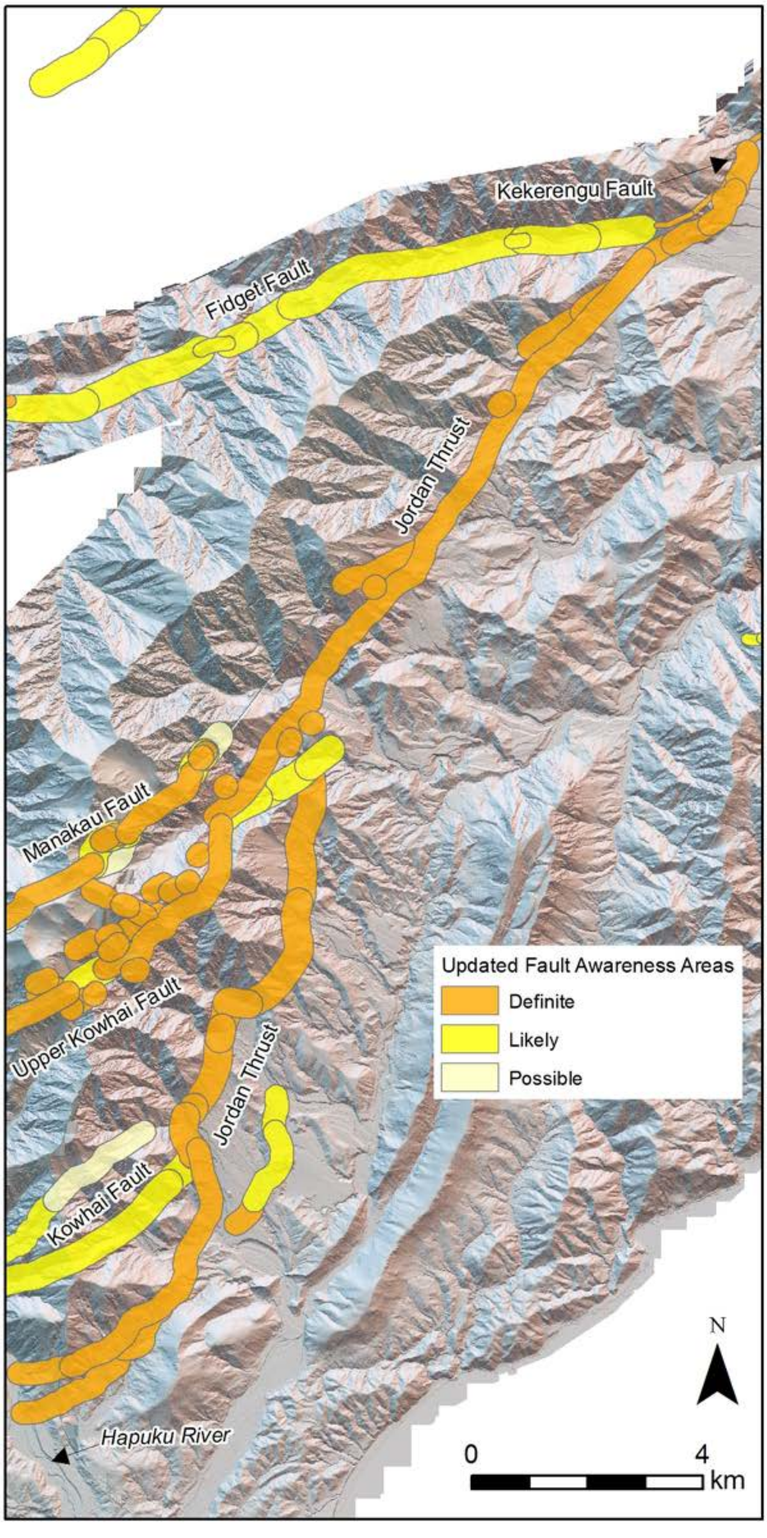

Figure A1.4 Updated Fault Awareness Areas for the Jordan Thrust north of the Hapuku River.

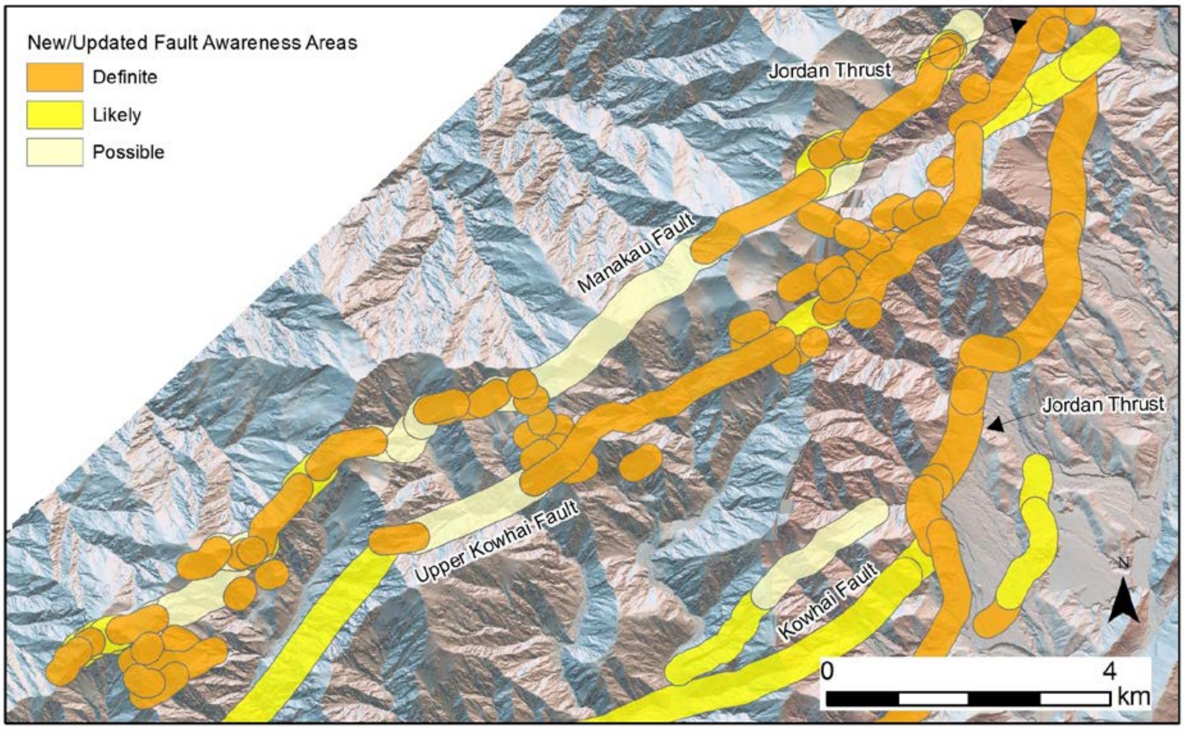

Figure A1.5 New and updated Fault Awareness Areas for the Upper Kowhai and Manakau Faults.

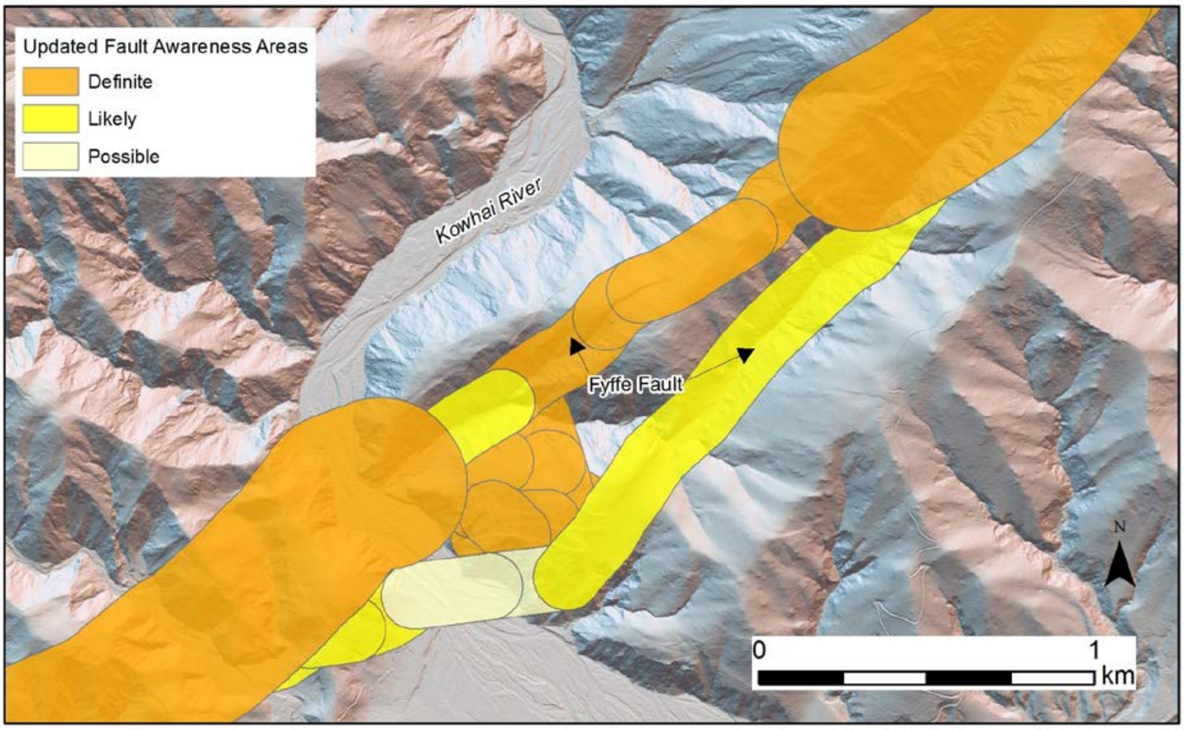

Figure A1.6 Updated Fault Awareness Areas for the south end of the Fyffe Fault.

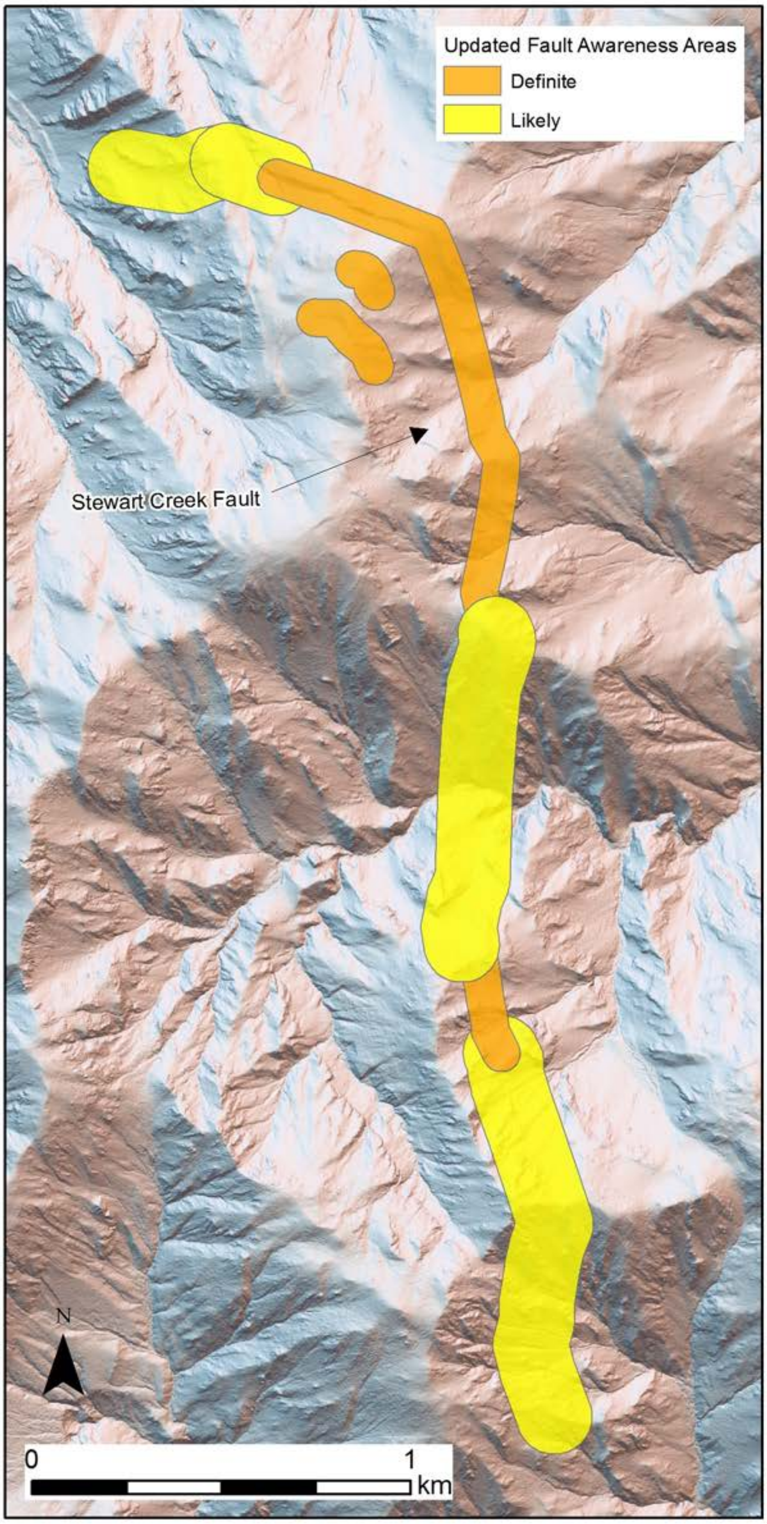

Figure A1.7 Updated Fault Awareness Areas for the Stewart Creek Fault.

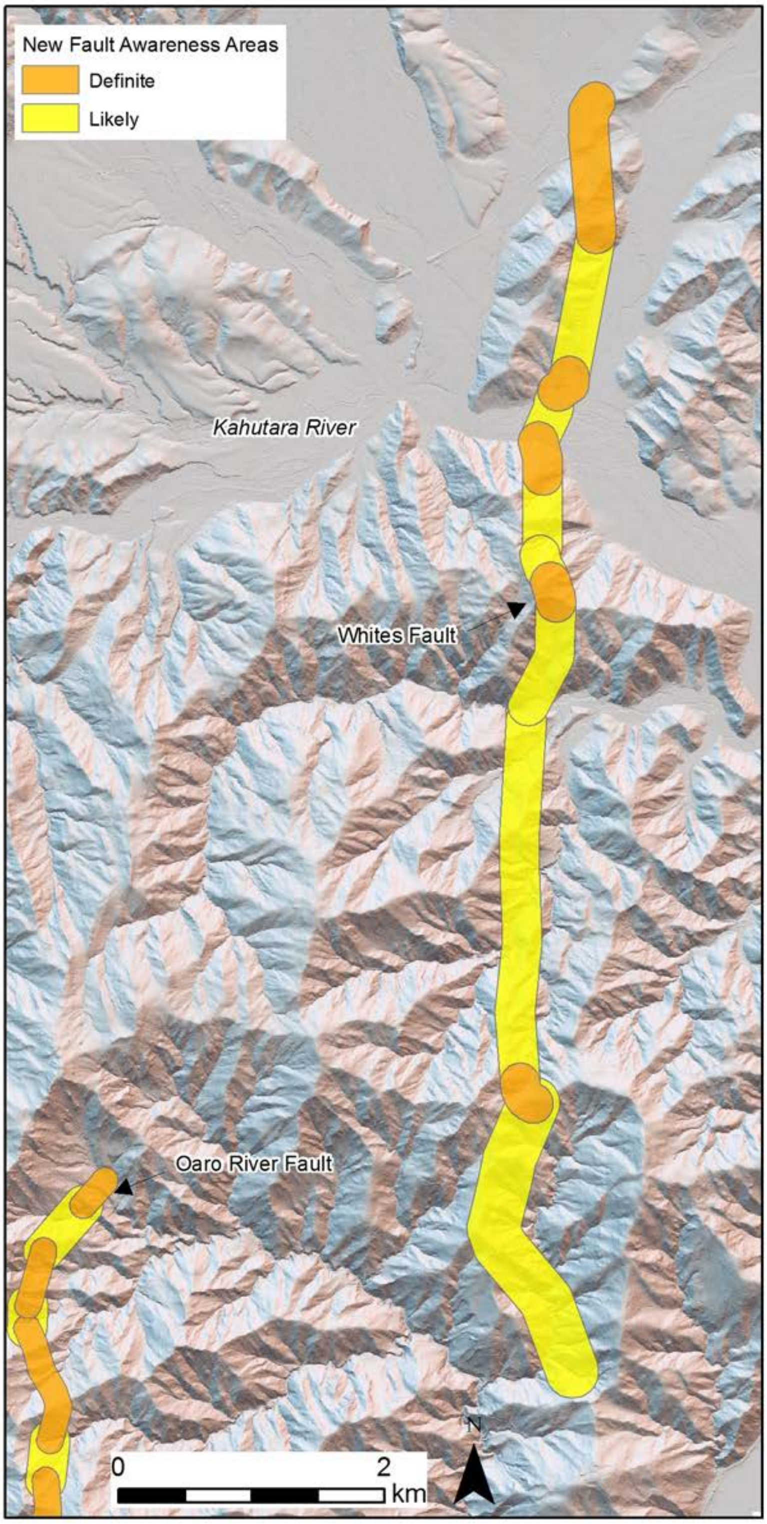

Figure A1.8 New Fault Awareness Areas for the Whites Fault.

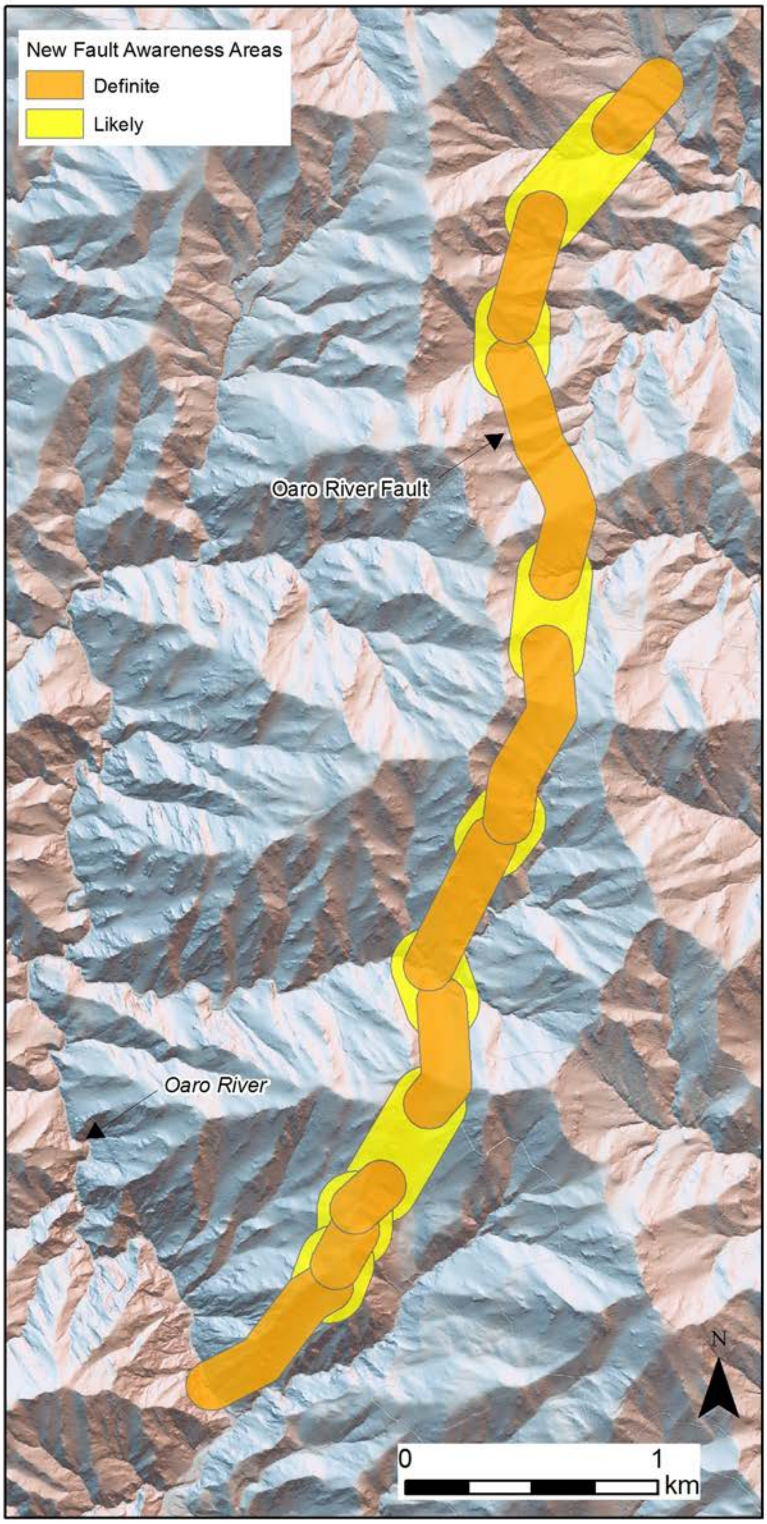

Figure A1.9 New Fault Awareness Areas for the Oaro River Fault.

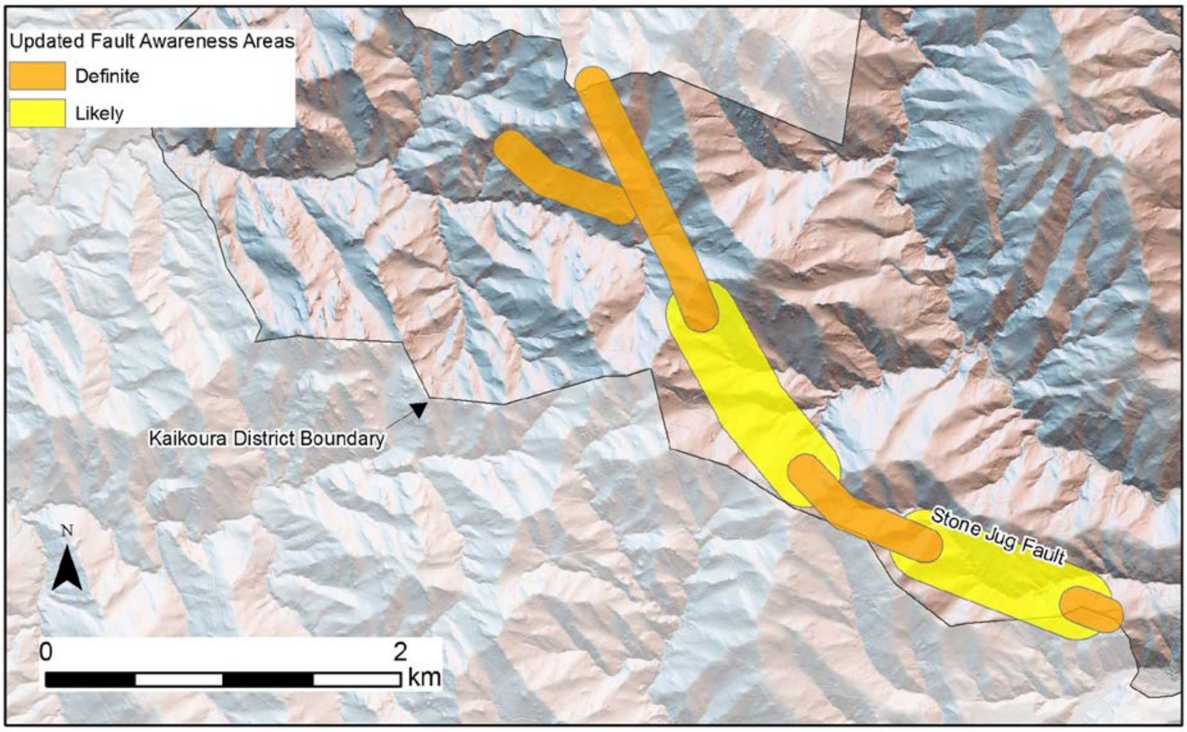

Figure A1.10 Updated Fault Awareness Areas for the Stone Jug Fault.

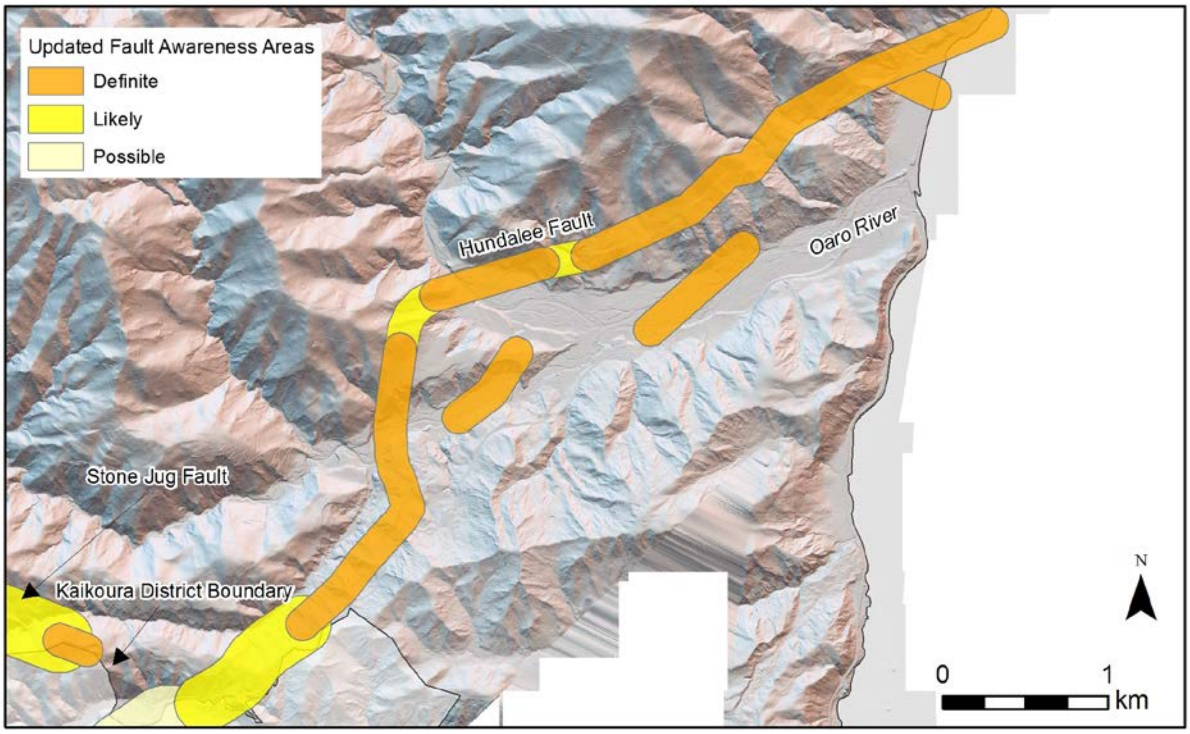

Figure A1.11 Updated Fault Awareness Areas for the Hundalee Fault.

APPENDIX 2 FAULT AVOIDANCE ZONE MAPS WITHOUT THE PREVIOUSLY-DEFINED FAULT AWARENESS AREAS

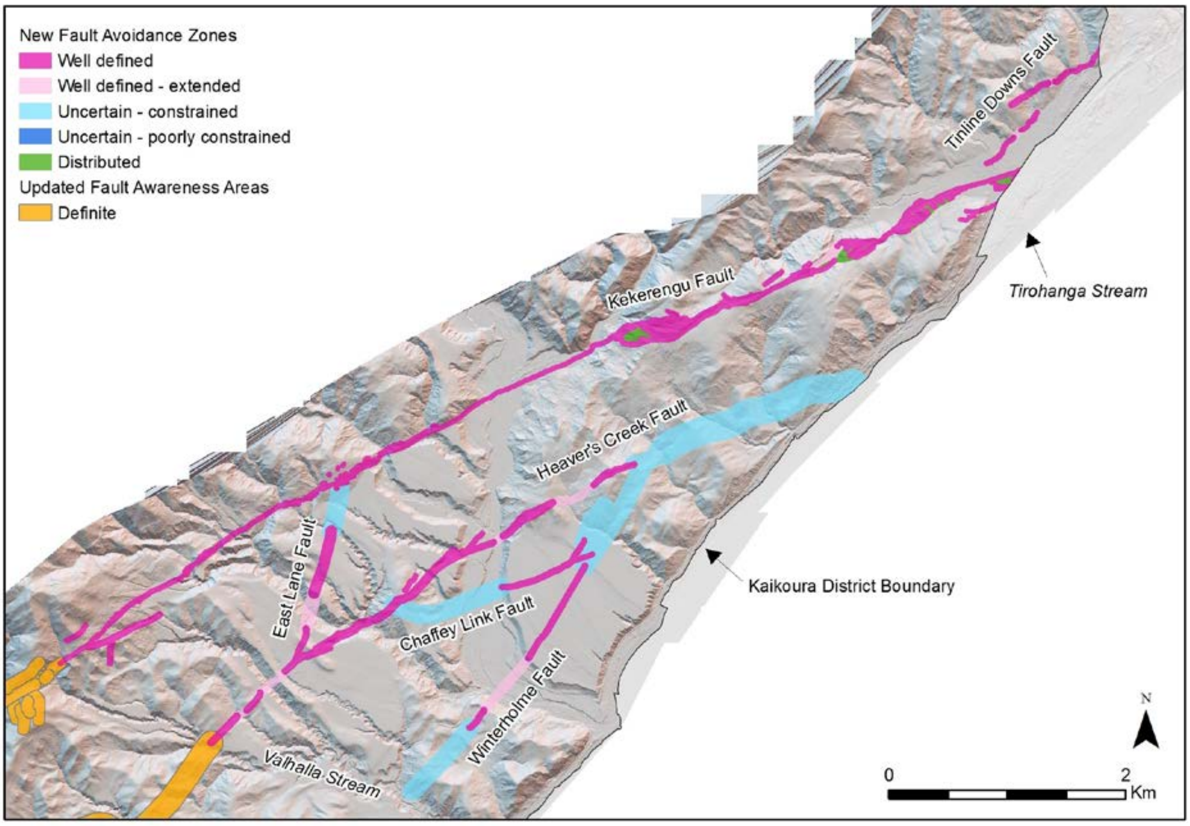

Figure A2.1 New Fault Avoidance Zones and updated Fault Awareness Areas for the Tinline Downs, Kekerengu, Heaver's Creek, East Lane, Chaffey Link, and Winterholme Faults.

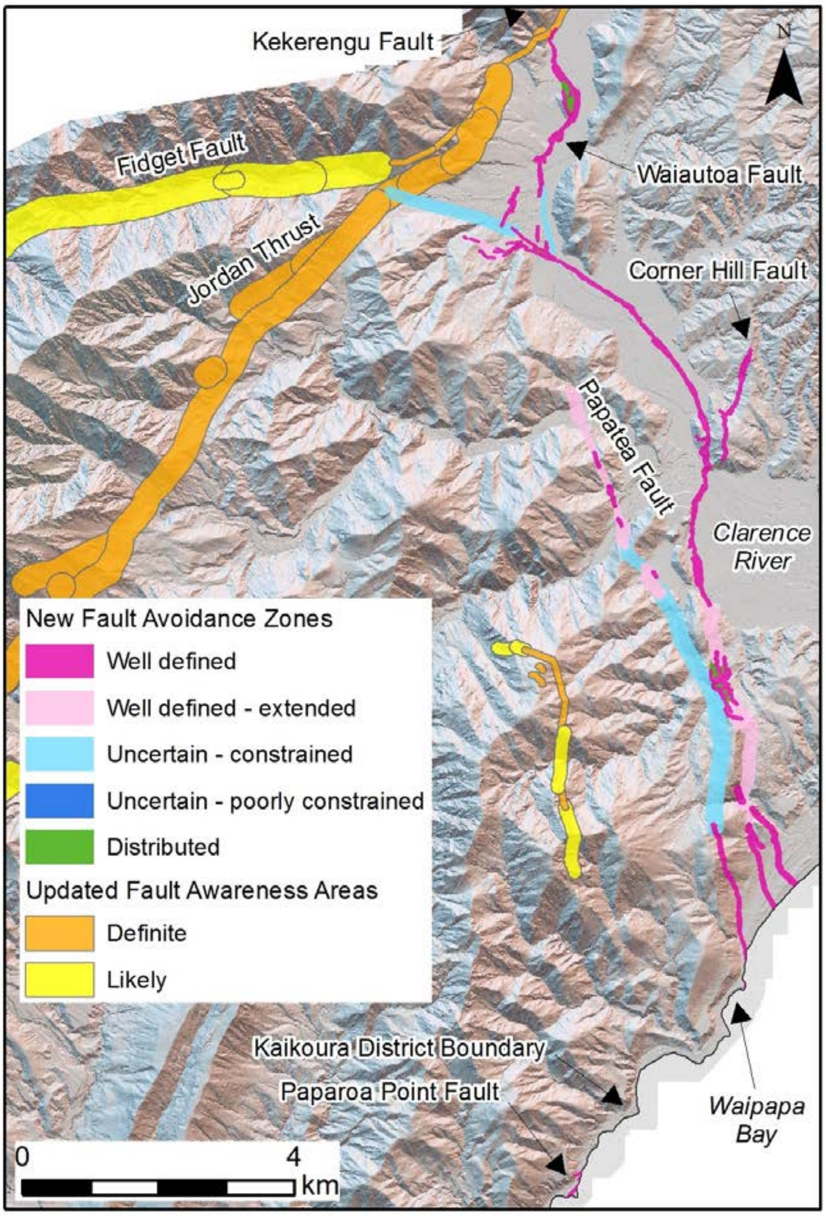

Figure A2.2 New Fault Avoidance Zones and updated Fault Awareness Areas for the Papatea, Waiautoa, Corner Hill, and Paparoa Point Faults.

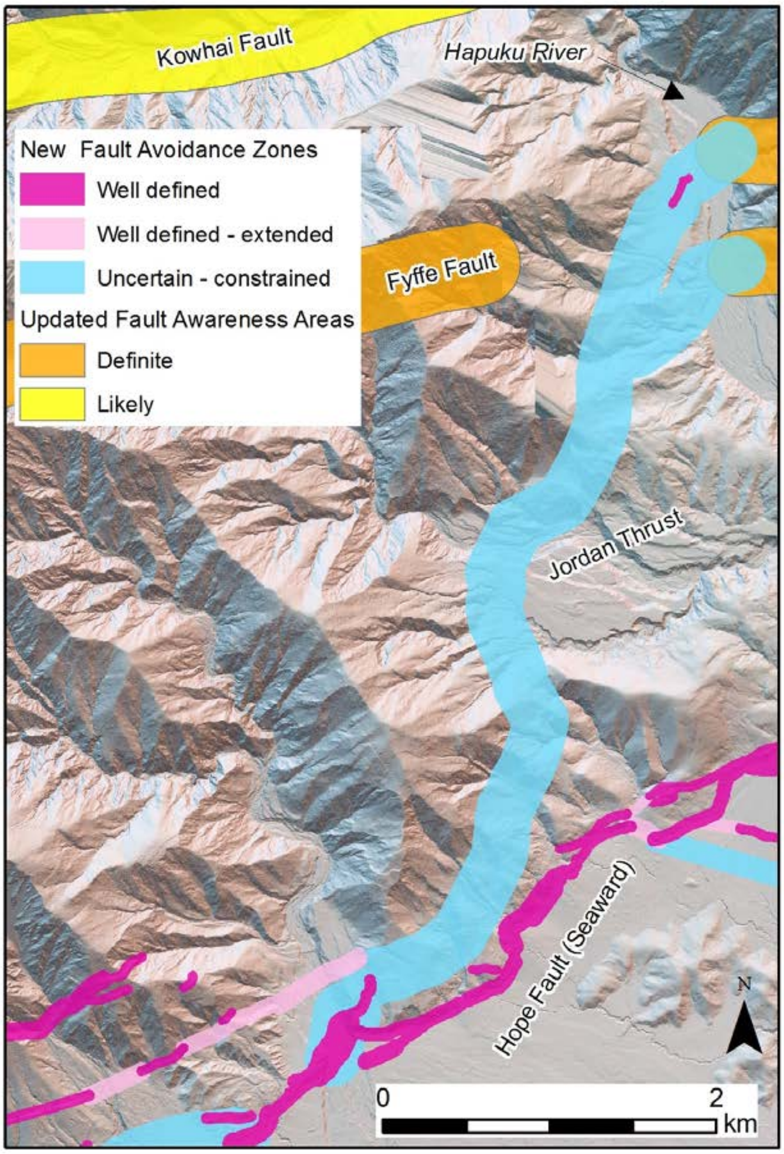

Figure A2.3 New Fault Avoidance Zones and updated Fault Awareness Areas for the southern end of the Jordan Thrust.

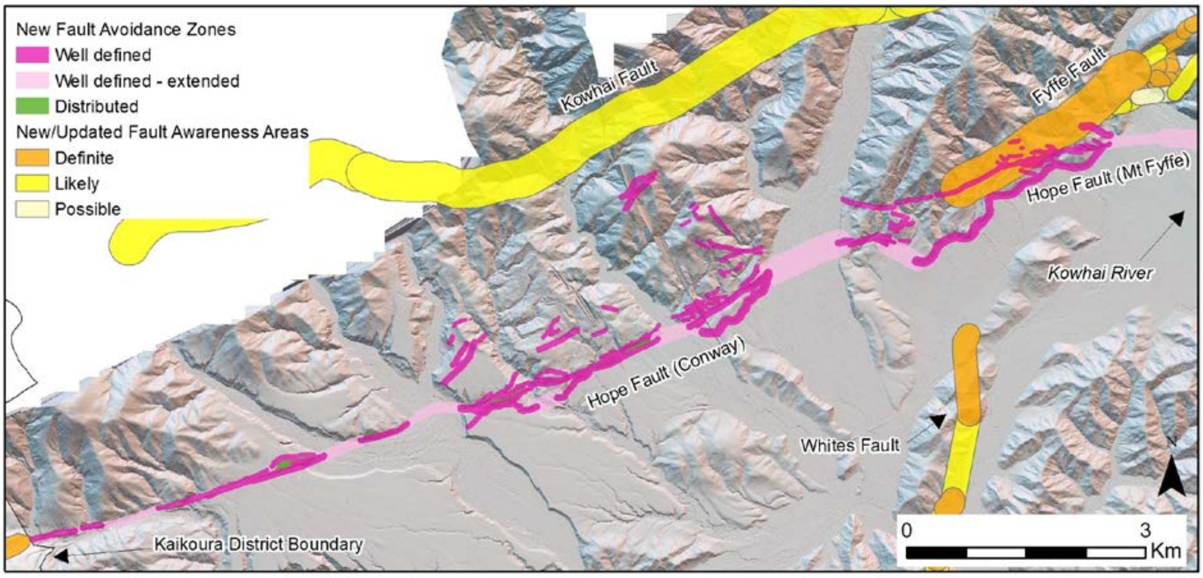

Figure A2.4 New Fault Avoidance Zones and new and updated Fault Awareness Areas for the Conway Section of the Hope Fault.

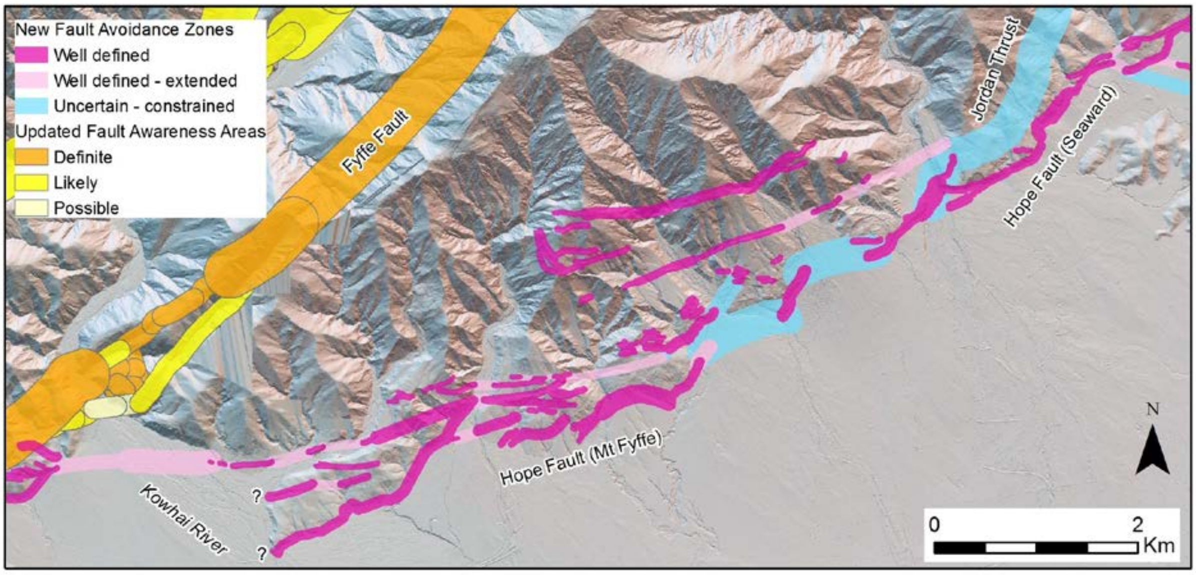

Figure A2.5 New Fault Avoidance Zones and updated Fault Awareness Areas for the Mt Fyffe Section of the Hope Fault.

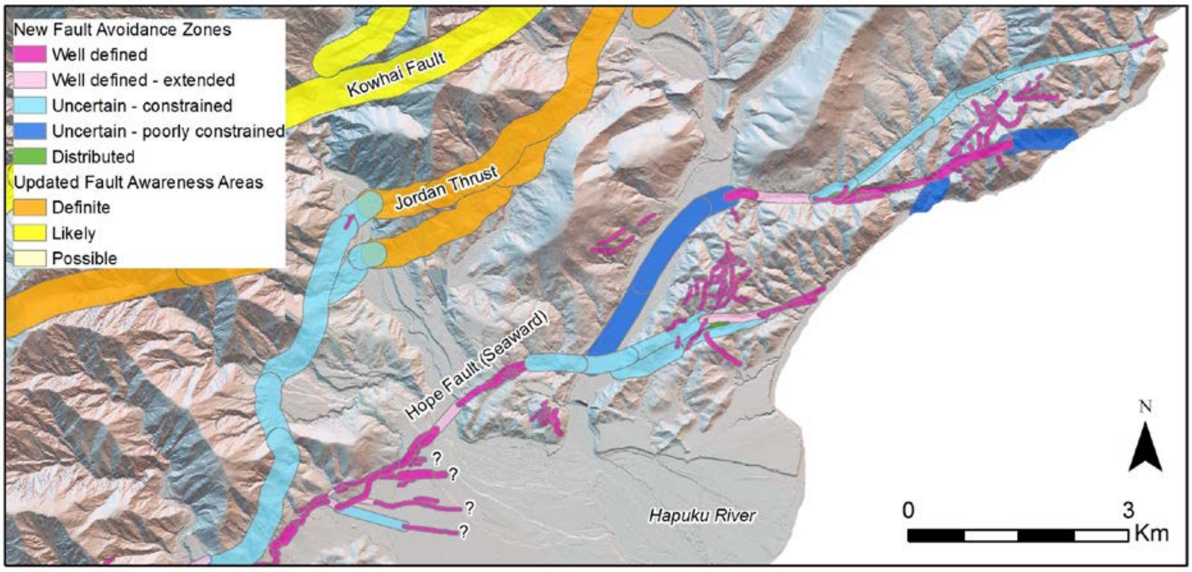

Figure A2.6 New Fault Avoidance Zones and updated Fault Awareness Areas for the Seaward Section of the Hope Fault.

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