NHRP Contestable Research Project

Pre-historic ruptures on 2016 Kaikōura earthquake faults and implications for seismic hazard

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ABSTRACT

The 14 November 2016 M_w 7.8 Kaikōura Earthquake was one of the largest and most complex on-land earthquakes ever observed globally and ruptured at least 14 faults with displacements of >1.5 m. The earthquake ruptured faults progressively from near the epicentre in the southwest on The Humps Fault in the North Canterbury (NCD) domain, northeast into the Marlborough Fault System (MFS) and on to Cape Campbell, including rupture of submarine faults and extensive uplift of the Marlborough coast.

NHRP- and EQC-funded research into the paleoseismicity of NCD faults has indicated that in general these faults, e.g. The Humps, Leader, Stone Jug, Conway-Charwell and Hundalee faults, each have had multiple Holocene earthquake ruptures with an average recurrence interval of 2500–4000 years (where long enough records exist). Slip rates of 0.5 mm/yr have been estimated for The Humps Fault.

This work has significantly advanced our understanding of the activity of faults in the NCD region. Results indicate that these faults may operate together in multi-fault earthquake ruptures, or rupture in a sequence over relatively short time periods (years to centuries) in a cluster of seismic release. The results also highlight that the NCD region that includes these faults was under-represented in the national seismic hazard model (NSHM-2012).

Paleoseismic studies undertaken on the Papatea Fault indicate that it is an important active plate boundary fault that has had at least three earthquake ruptures during the past 1000 years. The main and western strands of the Papatea Fault can rupture at the same time (and sometimes with the Corner Hill Fault as seen in 2016), and the timing of Papatea Fault earthquakes is also similar to the last few paleo-earthquakes on the Kekerengu Fault. The average recurrence interval of earthquakes on faults in the south-eastern part of the MFS, including the Hope, Jordan, Kekerengu and Papatea faults is 300–500 years, which is consistent with the high slip rates of these faults. Our results offer the possibility that this group of faults can rupture all together, as they did in 2016, or as a sequence of events spaced closely in time. Ongoing studies of the Hope Fault, and landscape impacts in the Clarence River valley may help elucidate when multi-fault or multi-segment ruptures versus single-segment/fault earthquakes have occurred in the past.

In summary, the recurrence interval of MFS and NCD faults is an order of magnitude different. Earthquakes occur on the main MFS faults approximately 10 times more often than they occur on the NCD faults. Multi-fault earthquakes have probably occurred in the past in both the NCD and MFS regions (individually). However, the occurrence of fault ruptures across both domains in the 2016 Kaikōura earthquake was a highly unusual event. Multi-fault ruptures spanning the NCD-MFS domains are being incorporated into the next generation of seismic hazard models, along with the other important outcomes of this research.

Preliminary results from this project have been communicated to stakeholders including NCTIR, the district councils and the public through several presentations

KEYWORDS

2016 Kaikōura Earthquake, paleoseismicity, Papatea Fault, The Humps Fault, Clarence River

KEY MESSAGES FOR MEDIA

- A substantial amount of new paleo-seismological research funded by the Natural Hazards Research Platform (NHRP) and EQC has been undertaken on faults that ruptured in the 14 November 2016 M_w 7.8 Kaikōura Earthquake to understand their past activity and rupture histories
- Faults in the North Canterbury Domain (NCD) south of the Hope Fault have had repeated earthquake ruptures during the Holocene and have an average recurrence time of 2500–4000 years.
- The ages of past earthquakes on the NCD faults (The Humps, Leader, Stone Jug, Conway-Charwell, and Hundalee) indicates that multi-fault ruptures (or sequences of ruptures) could have occurred in the past
- Faults in the Marlborough Fault System (MFS) north of, and including the Hope Fault, have had repeated earthquake ruptures during the last 1000 years or so.
- The ages of past earthquakes on the MFS faults (Hope, Papatea, and Kekerengu) indicates that multi-fault ruptures (or sequences of ruptures) could have occurred on these faults in the past
- However, a complex multi-fault rupture as seen in 2016, is a very uncommon event as the recurrence intervals are c. 10 times different between the MFS (shorter) and NCD (loner) regions.
- Results from this research are being used to update the national seismic hazard model which assesses the probability of strong ground motions across New Zealand.

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1.0 INTRODUCTION

Impact Statement 1

"Deriving and communicating new earthquake geology results for Kaikōura region faults."

> *To derive new geologic slip rate and paleoseismic data for four of the faults involved in the 2016 Kaikōura Earthquake: the Papatea, Hundalee, Humps and Hope (Seaward) faults. Communicating the science effectively to stakeholders and end-users.*

The 14 November 2016 M_W 7.8 Kaikōura Earthquake was one of the largest and most complex on-land earthquakes observed globally and ruptured at least 14 faults with surface displacements of >1.5 m (Figure 1.1; Hamling et al. 2017; Litchfield et al 2018). The epicentre of the earthquake was near Waiau in North Canterbury (Kaiser et al. 2017). The fault rupture progressed from the southwest to the northeast along onshore faults of the North Canterbury Domain (NCD) into the Marlborough Fault System (MFS) terminating around Cape Campbell (Stirling et al. 2017; Litchfield et al. 2018). The 2016 earthquake also included rupture of offshore faults and extensive uplift of the Marlborough coast (Clark et al. 2017a). The subduction-termination setting of this earthquake has led researchers to model the potential role of slip (seismic release) on the subduction interface in this event (Cesca et al. 2017; Mouslopoulou et al. 2019).

The rupture process of the 2016 earthquake was similar to some of the earthquake scenarios in the New Zealand national seismic hazard model (NSHM; Stirling et al. 2012). For example, rupture of the Jordan, Kekerengu and Needles faults was a multi-fault rupture option within the NSHM. However, there were also significant differences between the 2016 earthquake and the modelled rupture scenarios in the NSHM, e.g., the rupture of several faults in the NCD and northward propagation onto major faults of the MFS. It was previously assumed that the different styles and recurrence intervals of fault north and south of the Hope fault would preclude them rupturing in the same earthquake.

Distinctive aspects of the 2016 M_W 7.8 Kaikōura Earthquake rupture process included:

- Initiation of the rupture within the NCD on The Humps Fault (or fault zone) (Nicol et al. 2018);
- Propagation of rupture from The Humps Fault to the Leader, Conway-Charwell, Stone Jug, Hundalee and Whites faults etc., to the south of the Hope Fault (Nicol et al. 2018; Williams et al. 2018);
- The minor involvement (in terms of surface rupture) of the Hope Fault (Litchfield et al. 2018);
- Propagation of faulting offshore from the Hundalee Fault, possibly toward the Point Kean Fault (Clark et al. 2017a; Klinger et al. 2018);
- Propagation of faulting across the Hope Fault into the Seaward Kaikōura Range, and on to the Jordan Thrust fault (Kearse et al, 2018; Howell et al. in review);
- progressive rupture of the Kekerengu, Needles, Fidget and Papatea faults, with minor rupture of faults near Cape Campbell (Kearse et al. 2018; Langridge et al. 2018; Litchfield et al. 2018); and
- Possible rupture of a mid-crustal detachment fault, or of the plate interface beneath Marlborough (Bai et al. 2017; Cesca et al. 2017).

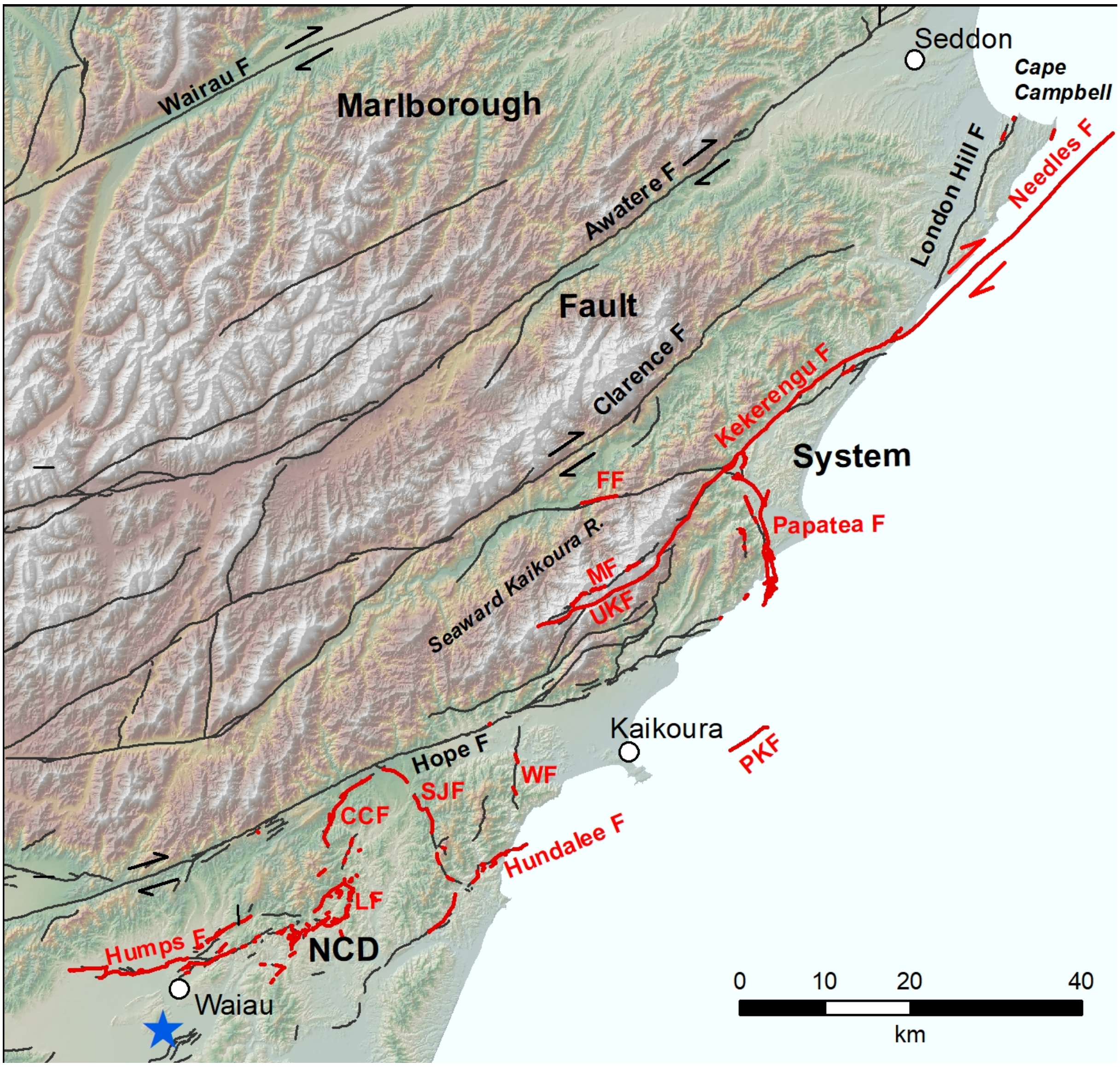

Figure 1.1 The 2016 Kaikōura Earthquake rupture zone. Epicentre shown as blue star; active faults that ruptured during the earthquake shown in red.Other active faults are shown as black lines (from Langridge et al. 2016). Abbreviations are: LF, Leader Fault; CCF, Conway-Charwell Fault; SJF, Stone Jug Fault; WF, Whites fault; PKF, Point Kean Fault; MF, Manakau Fault; UKF, Upper Kowhai Fault; FF, Fidget Fault; NCD, North Canterbury Domain.

The size and complexity of the Kaikōura earthquake carries global insights for tectonics and implications for seismic hazard. It also demands that we re-think our geological and seismic hazard models for how crustal environments, such as a subduction-termination setting operates (Mouslopoulou et al. 2019). As geologists, one response is to dig deeper into the paleo-earthquake record of faults involved in the 2016 Kaikōura earthquake. A significant hypothesis that required testing was “was the 2016 Kaikōura earthquake and rupture sequence the norm, OR, was this event one out-of-the box? In other words, looking into the past, was this event a repeatable one in the geologic record?

The major goal of this NHRP Contestable project was to collect data on the paleo-earthquake history (paleoseismicity and recurrence interval) and longer-term activity (slip rate) of faults involved in the Kaikōura earthquake. Results inform us about the role of these faults in the medium to long-term regional tectonic strain budget and provide an understanding of how faults behave and interact from earthquake cycle to cycle.

In this project there are four key field tasks built around four of the major faults (or fault sets) that ruptured in 2016. These are as follows, with Task Leaders in brackets:

1. Paleoseismicity and slip rate of The Humps Fault, and other faults in the epicentral region of the Kaikōura earthquake [Andy Nicol, Tim Stahl];
2. Paleoseismicity and slip rate of the Hundalee Fault [Mark Stirling, David Barrell];
3. Paleoseismicity and slip rate of the Seaward section of the Hope Fault [Russ Van Dissen, Jarg Pettinga]; and
4. Paleoseismicity and slip rate of the Papatea Fault and landscape change in the Waiautoa/ Clarence valley [Rob Langridge, Peter Almond].

These faults were highlighted as important targets in light of the earthquake because they were all tractable and representative faults that could be studied in the field, onshore and inboard of the coastal environment, and in generally low-lying, accessible environments.

This NHRP Contestable project integrates with other post-Kaikōura scientific projects including an NHRP Contestable project awarded to Kate Clark on paleo-coastal uplift and earthquakes; an EQC-funded project awarded to Andy Nicol to investigate fault ruptures within the NCD, and two EQC-funded projects awarded to Tim Little (VUW) that looked to trench the Kekerengu Fault, both before and following the 2016 earthquake. Together these allow a regional perspective, fault-by-fault characterisation and correlation of records.

The other major goals of the project revolve around developing and maintaining a team ethos, communicating and engaging with stakeholders including councils, civil defence, Iwi and the general public.

Chapters in this report are laid out according to the key Research Aims of the project, beginning with the development of team ethos (Chapter 2), collection and results of paleoseismic and slip rate data (Chapter 3), and outreach and engagement (Chapter 4). Chapter 5 contains a discussion of the science outcomes of the project.

2.0 RESEARCH AIM 1.1: DEVELOP A TEAM ETHOS

“To develop a Working Group philosophy amongst the four task teams and to enhance stakeholder, end-user and Iwi engagement”.

2.1 Introduction

One of the powerful scientific legacies of the 2016 M_W 7.8 Kaikōura Earthquake was the cooperation and collaboration of a large team of geoscientists in response to what was a huge and complex event (Berryman et al. 2018). The Kaikōura earthquake rupture zone was long (c. 180 km; Figure 1.1), extending both onshore and offshore and extending into high elevation environments without road access. In addition, access to the town of Kaikōura was blocked by landsliding to the north and south of it (Massey et al. 2018), effectively dividing the earthquake rupture zone into three parts.

The wider fault rupture response team consisted of scientists from GNS Science, NIWA, and the universities of Canterbury, Victoria, Auckland, Otago and Massey, along with many colleagues from overseas institutions and universities. It was quickly realised that a collaborative and cooperative response to mapping these three parts of the fault rupture zone was required.

A large team of scientists and students from the University of Canterbury naturally led rupture mapping efforts in North Canterbury, based out of Waiau (see Nicol et al. 2018). At the same time a collaborative effort between GNS Science and University of Otago mapped the Hundalee Fault as the highway network was re-established in coastal North Canterbury (see Williams et al. 2018). GNS Science (Wellington) led mapping of the northern fault ruptures, collaborating with the universities of Victoria and Auckland and with many visiting scientists, based out of Blenheim (see Litchfield et al. 2018). NIWA diverted significant resources to investigate offshore fault ruptures off the east coast of South Island (see Clark et al. 2017a; Kearse et al. 2018).

Following on from the earthquake response and response publication phase, continuing cooperation was desirable to carry into these identified post-earthquake paleoseismic projects. In essence those teams that were familiar with the nature and distribution of faulting in any given area were best placed to consider paleoseismic and slip rate sites. Thus, the NHRP task teams were largely formed around the original response teams in each area/fault.

One year after the earthquake and still one month before S.H. 1 re-opened the teams got together to run an international conference focused on the Kaikōura earthquake and northern South Island tectonics (Clark et al. 2017b; Langridge and Howarth 2018). The 8th International PATA Days conference was a huge success and continued to foster the special collaborative nature of the wider team. Field trips were run to visit the northern fault ruptures and coastal deformation (north of Kaikōura) and the southern fault ruptures (in the Waiau area) as access was still not possible via Kaikōura itself (Upton et al. 2017a, b).

Within this NHRP Contestable project a major goal was to continue our team ethos by holding research workshops amongst the four task teams and to enhance stakeholder, end-user and Iwi engagement.

2.2 Project Workshops

Two workshops were held as part of this NHRP project; at the project midpoint in November 2018 and near the project end in August 2019.

Workshop 1 was field-based and was designed to bring together project and task leaders from both the NHRP and EQC projects and students working on theses focused on the Kaikōura earthquake. The re-opening of S.H. 1 facilitated an unbroken 2-day field workshop from Blenheim to Waiau ending in Christchurch (Figure 2.1 and Figure 2.2). The key components and attendees of the Field Workshop are described in Appendix 1.

Workshop 2 was held at the University of Canterbury on August 30th, 2019. The objective of this 1-day workshop was to bring together the wider team to present science results from the NHRP and EQC projects spanning the last three years. The format consisted of 15–20-minute talks. Stakeholders from Environment Canterbury, and Hurunui and Kaikōura District Councils were invited to attend. The structure and attendees of Workshop 2 are described in Appendix 1.

Workshop 2 wrapped up with a big picture discussion of the results and how paleo-earthquake timings and fault interactions may be viewed across the NCD and the MFS and spanning across the two domains. The original research hypotheses were discussed and answered by the end of the workshop.

The two workshops enabled the wider team to share results and research challenges and plot a path forward for disseminating the science results.

Figure 2.1 Professor Mark Stirling discussing the role of the Hundalee Fault and upcoming field visit, Kaikōura. 5–10 minute ‘speed talks’ were a feature of Workshop 1.

Figure 2.2 Professor Jarg Pettinga discussing the tectonics of the Seaward section of the Hope Fault, northwest of Kaikōura. Workshops included an even balance of students and senior researchers.

2.3 Direct Stakeholder and Iwi Engagement

Part of Research Aim 1.1 (i.e. *…and to enhance stakeholder, end-user and Iwi engagement"),* overlaps strongly with Research Aim 1.3 and it is discussed further in Chapter 5 of this report.

3.0 COLLECTION OF ON-FAULT PALEOSEISMIC AND SLIP RATE RECORDS (NCD FAULTS)

3.1 Introduction

Research Aim 1.2 states that we will undertake:

> *"Geologic studies that determine slip rate, paleoearthquake age and recurrence data for the Humps Fault Zone, Hundalee, (and other MFS) faults. Studies involve excavation combined with geologic dating, and geophysical studies (where warranted)".*

This chapter summarises paleoseismic studies undertaken on faults of the NCD region that ruptured in the 2016 M_W 7.8 Kaikōura Earthquake (Figure 1.1). These are described from west to east, following the direction of progressive fault failure during the earthquake (Kaiser et al. 2017; Litchfield et al. 2018).

3.2 The Humps, Leader, Conway-Charwell and Stone Jug Faults

The Humps, Leader, Conway-Charwell and Stone Jug faults ruptured in the epicentral area of the Kaikōura earthquake (Litchfield et al. 2018; Nicol et al. 2018). Paleoseismic studies of these faults were led by the University of Canterbury with significant student involvement. Student projects, supervised by Andy Nicol, Jarg Pettinga, Tim Stahl and Russ Van Dissen, were developed for each of the faults (see Brough 2019; Bushell 2019; Hyland-Brook 2018; Scott 2019). The collective goal of these projects was to develop new paleoseismic and slip rate data for this set of faults, with particular focus on The Humps Fault (Zone) which covers about half of the length of ruptured faults in the NCD.

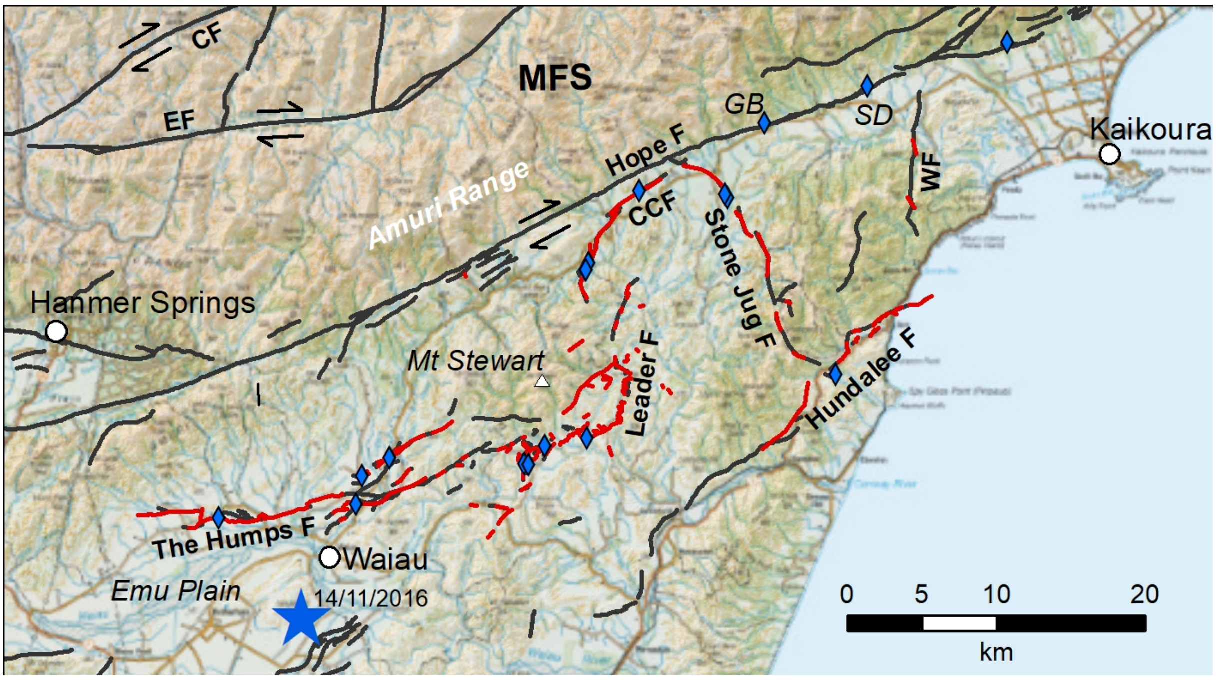

Figure 3.1 Fault ruptures (red lines) and paleoseismic sites (blue diamonds) in the North Canterbury (NCD) domain. Kaikōura Earthquake epicentre near Waiau shown as blue star. Other active faults are shown as black lines (from Langridge et al., 2016). Abbreviations are: CCF, Conway-Charwell Fault; WF, Whites fault; CF, Clarence Fault; EF, Elliott Fault; MFS, Marlborough Fault System; GB, Breen Burn; SD Sawyers Downs.

3.2.1 The Humps Fault Zone

The M_W 7.8 Kaikōura Earthquake nucleated on The Humps Fault at a depth of about 14 km and propagated northwards for about 180 km (Figure 3.1; Nicol et al. 2018). The fault is ~36 km in length from a free tip in the west to its intersection with the Leader Fault in the east. The Humps and Leader faults form a complicated network of faults, many of which ruptured in the 2016 earthquake.

The Humps Fault crosses the Emu Plain, an area of extensive Late Quaternary alluvial fans, before continuing into the Mt Stewart Range (Figures 3.1 and 3.2). Up to ~40% of the fault was previously mapped as active (or likely active) by Barrell and Townsend (2012), although prior to this study the earthquake history of the fault was unconstrained. During the course of this project fault trenching of The Humps Fault and extensive dating of displaced landforms were conducted to determine the paleoseismic history and slip rates of the fault over the last ~60,000 years. These studies were primarily undertaken on the Emu Plain and included the completion of one MSc thesis (Brough 2019).

The Humps Fault forms a segmented array of faults that range in average strike from ~090° in the west to ~050° in the east. The fault has been divided into two main sections which, based on changes in its strike and dip, have been referred to as The Humps West and The Humps East (Nicol et al. 2018). The Humps West is the focus of this study and is restricted to the western ~25 km of the fault where it crosses the alluvial Emu Plain, where it generally strikes east to east-northeast and mainly dips steeply (80–90°) to the south (Nicol et al. 2018; Lanza et al. 2019) (Figure 3.2). During the Kaikōura earthquake, The Humps Fault on the Emu Plain primarily accommodated right-lateral strike-slip (maximum ~4 m and average ~2 m) with minor (<1 m) up-to-the-south displacement (Nicol et al. 2018). The highest vertical displacements were recorded in pop-up and pull-apart basins on the plains, consistent with the fault being mainly strike slip.

The Humps Fault on the Emu Plain is segmented on a range of scales (Figure 3.2). In the west the fault comprises one main fault trace (on a regional scale), while on the plains the eastern part of the fault comprises two primary traces (Figure 3.2). For this project we have trenched each of the main traces, determined the age of the alluvial surfaces displaced by the fault and measured displacements of channels offset by the fault. We excavated three trenches across the fault that are here referred to as McLean-1, Dalmer-1 and Chaffey-1 (see Table 3.1 for details and Figure 3.2 for locations). In each case the trenches were excavated across (and normal to) fault traces that ruptured during the 2016 Kaikōura Earthquake displacing different age surfaces, with the McLean-1 trench on the western strand of the fault proving most productive for paleoseismic information (Figures 3.3 and 3.4). The ages of past earthquakes and the faulted alluvial surfaces were constrained using a combination of 18 Optically Stimulated Luminescence (OSL) dates and five radiocarbon samples of mainly charcoal preserved in silt beds. For further information on the data from the McLean-1 trench refer to Brough (2019).

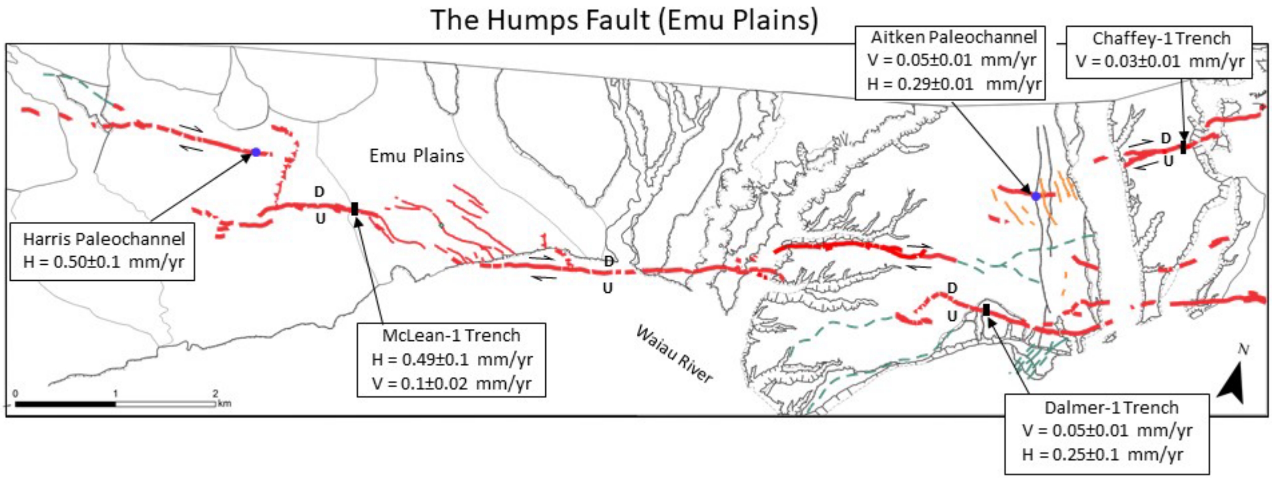

Figure 3.2 Map of The Humps Fault in the Emu Plain area. Red lines show faults that ruptured in 2016 with right-lateral strike slip.Orange lines show 2016 fault traces with left-lateral strike slip. Green lines indicate paleo-scarps for faults that did not rupture in 2016. Numbers in boxes indicate fault slip rates determined from displaced landforms or trench stratigraphy (H= horizontal slip rate, V= vertical slip rate). Up- and down-throw directions are indicated by U/D, respectively. Modified from Brough (2019).

To constrain the timing of paleoseismic events dated faulted Quaternary stratigraphy exposed in the trench walls was logged. The trench logs are not presented in detail here and primarily provide information on Holocene paleo-earthquakes. In Table 3.1 we have summarised the preferred timing of paleo-earthquakes from the McLean-1 and Chaffey-1 trenches. Data from the Dalmer-1 trench across the southern strand of the fault provides no paleoseismic data, in part due to erosion of the hanging-wall of the fault. Data from the Dalmer-1 trench were used to estimate vertical slip rates only (we have used a displaced channel edge 50m west of the trench to estimate the right lateral slip rate at this site; see Figure 3.2 for slip rates).

The trench stratigraphy and dating reveal at least five paleo-earthquakes in the McLean-1 trench over as much as ~17,000 years (Figures 3.3 and 3.4). The youngest two of these events are the best constrained, although they could have occurred at any time during windows of ~1500 and 4200 yrs. Despite these large uncertainties, which arise due to errors and inconsistencies in the dating, it is clear from the trench stratigraphy that the western part of The Humps Fault has accommodated at least three events in the Holocene (including the Kaikōura Earthquake). Based on data from the McLean-1 trench we estimate that the average recurrence interval on the western section of The Humps Fault is approximately 3 ± 1 kyr.

Table 3.1 Information on the trenches excavated across The Humps Fault on the Emu Plain between January 2018 and October 2019 (see Figure 3.2 for locations).

Trench Name	Location (Lat. Long.)	Trench Dimensions (m)	Surface Age (kyr^)	Fault Orientation	Number of Dates	Number of Events*
McLean-1	Lat 42°37’56.94”S Long 172°51’15.78”E	16x3x4	<18	090/80N	8 (OSL) 3 (RC)	≥5
Dalmer-1	Lat 42°37’25.69”S Long 173°04’02.48”E	15x2.5x2.5	~30	105/50S	3 (OSL) 1 (RC)	≥2
Chaffey-1	Lat 42°35’44.85”S Long 173°05’40.76”E	18x3x3	~60	075/75N	3(OSL) 1 (RC)	≥3

*Including the 2016 Kaikōura Earthquake. ^kyr = thousands of years ago

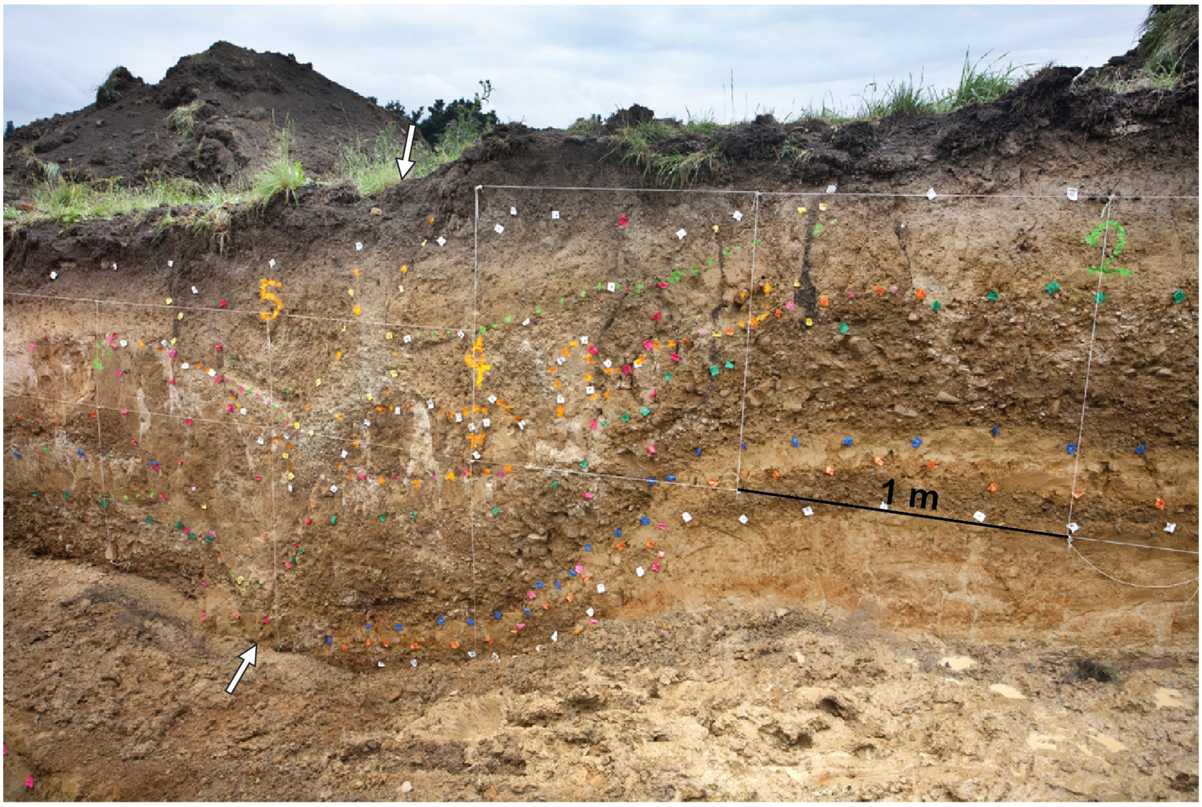

Figure 3.3 Detail of the east wall of the McLean-1 trench excavated across The Humps Fault (metres-2 to -6 upper batter).White arrows mark the 2016 surface rupture trace and scarp, and the main fault at the bench in the trench. The scale is shown by the grid and a 1 m scale bar (black line).

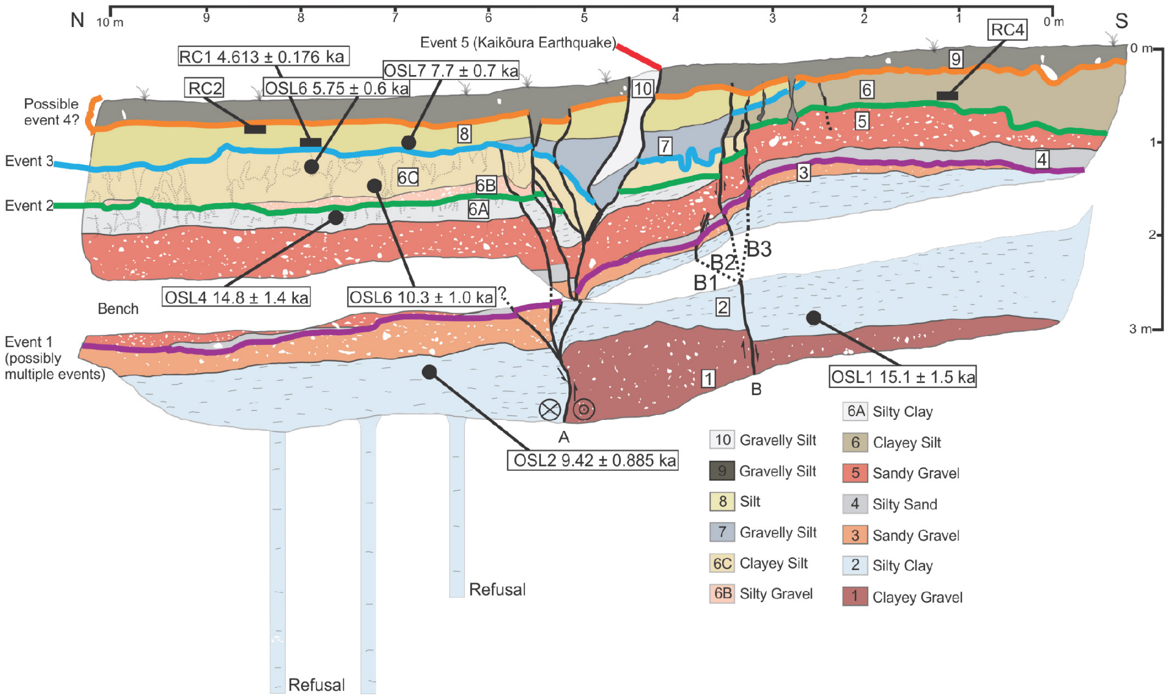

Figure 3.4 Log of the east wall of the McLeans-1 trench including auger hole stratigraphy (blue bars beneath log).The main faults (red and black lines) occur in the middle of the trench. OSL (black dots) and radiocarbon (black rectangles) samples are marked on the log. See Brough (2019) for further detail.

There are insufficient data from the Chaffey-1 trench to calculate a recurrence interval, although the trench provides evidence for multiple Holocene events on the northern strand of the fault close to the eastern edge of the plains (Figure 3.2). At the present time there is insufficient data to determine if both strands of the fault in the eastern Emu Plain generally rupture together. However, because some Holocene fault traces did not rupture in 2016 it is clear that not all fault traces along The Humps Fault rupture during every surface-rupturing earthquake.

Table 3.2 Summary of event histories for the McLean-1 and Chaffey-1 trenches.

Trench	Event #	Max. Age (yr BP)	Min. Age (yr BP)	Summary
McLean-1	1	2016 AD	2016 AD	5 events in ~15–10 kyr, mean recurrence interval ~2–4 kyr
	2	4450	180	
	3	6170	4460	
	4	14600	5200	
	5	17600	6100	
Chaffey-1	1	2016 AD	2016 AD	2 or more events in last ~6 kyr mean recurrence <6 kyr
	2	5700	180	

In addition to the timing of paleo-earthquakes we have estimated slip rates at four sites using the displaced margins of paleochannels as piercing points and OSL dates from silts infilling the channels. Assuming that the dates provide estimates of the timing of channel formation we calculate horizontal slip rates of 0.50 ± 0.1 mm/yr and 0.49 ± 0.1 mm/yr on the western sections of the fault and a combined slip rate of 0.54 ± 0.1 mm/yr for both strands of the fault at its eastern end on the plains (see Figure 3.2). Based on these data we estimate that the average slip rate for the fault is 0.5 ± 0.1 mm/yr. By comparison, the vertical slip rate on the fault is estimated to be about 0.1 ± 0.05 mm/yr. The vertical slip rate determined here is marginally lower than the ~0.2 mm/yr proposed by Barrell and Townsend (2012). For a slip rate 0.5 mm/yr and an average single event displacement of 2 m (as occurred in the 2016 earthquake), the average recurrence interval for The Humps Fault would be c. 4000 years, which is comparable to 3 ± 1 kyr estimated from the trench data.

3.2.2 The Leader, Conway-Charwell, and Stone Jug Faults

Study of The Humps Fault has been conducted in parallel with paleoseismic studies of the Leader, Conway-Charwell and Stone Jug faults east of the present study and funded by EQC. Seven trenches across these faults suggest that they too likely ruptured multiple times during the latest Pleistocene to Holocene. In particular, the Stone Jug Fault appears to have ruptured the ground surface three times in the last c. 7000 years (including the 2016 earthquake). Dating of a deformed paleosol interpreted to have fallen into a fissure formed during the youngest paleo-earthquake on the Stone Jug Fault suggests that this event occurred about 3500 years ago (Scott 2019). Given the available data it remains possible that past Holocene earthquakes in the North Canterbury region also ruptured several of the faults that moved during the Kaikōura Earthquake.

Further details on these studies can be found in MSc theses by Scott (2019), Bushell (2019) and Hyland-Brook (2018).

3.3 Hundalee Fault Investigations

The Hundalee Fault is a major northeast-striking structure in the southern Kaikoura District of North Canterbury (Figure 3.1). As defined from bedrock stratigraphic offset, the Hundalee Fault is about 30 km long and has a vertical component of Late Cenozoic displacement of >1 km (Warren 1995; Rattenbury et al. 2006; Williams et al. 2018). The net amount, if any, of Late Cenozoic lateral displacement is unknown. The Hundalee Fault ruptured along at least 23 km of its length during the 2016 Kaikōura Earthquake (Figure 3.5), expressed as measurable surface offsets along a 14 km long north-eastern sector of the fault (Litchfield et al. 2018), and by differential ground-shift interpreted from InSAR data, but without recognisable surface displacement features, along a 9 km sector of the fault southwest of the mapped surface traces (Hamling et al. 2017; Williams et al. 2018).

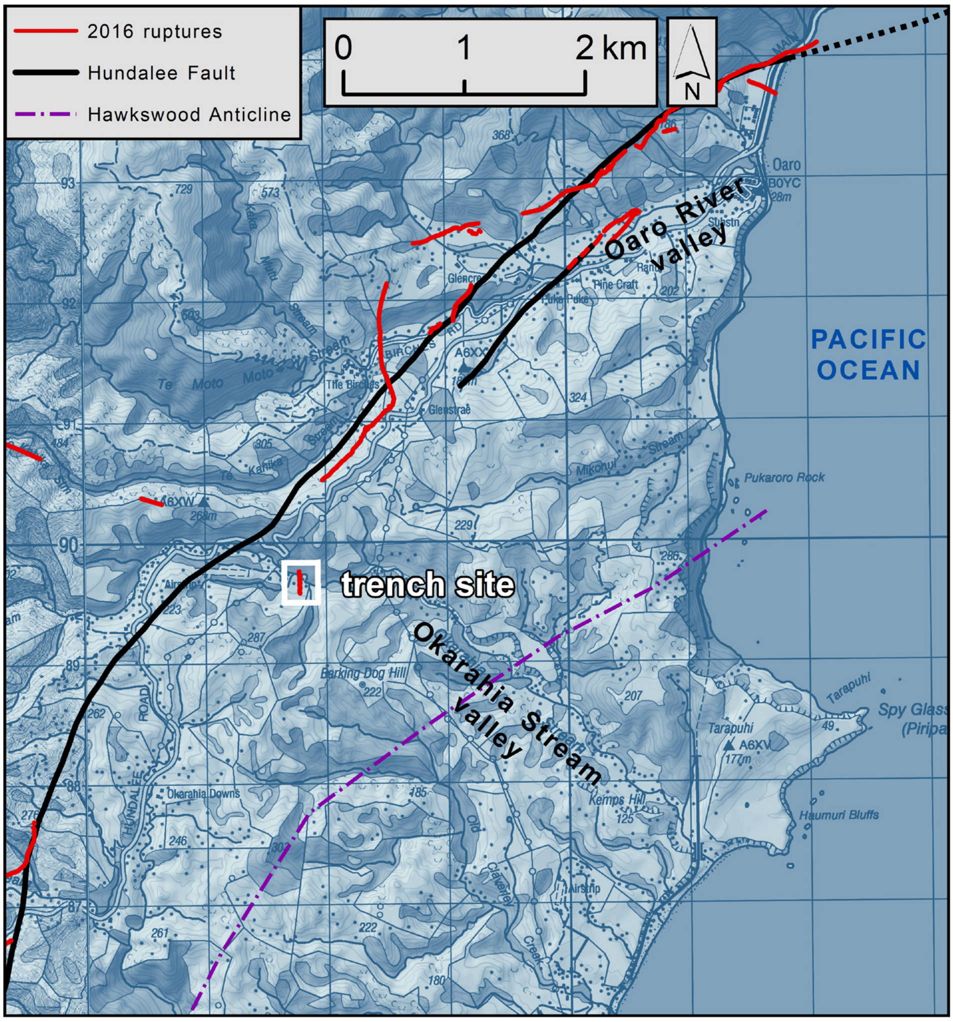

Figure 3.5 Detailed location map of 2016 Kaikōura earthquake ruptures on the Hundalee Fault near Oaro, showing the location of the Okarahia trench site.

The 2016 surface ruptures were surprisingly diffuse and discontinuous for such a major fault, with rupture strands as much as 0.8 km off the line of the bedrock fault. The 2016 movement sense was oblique reverse-dextral on east-northeast-striking strands of the fault, and reverse-sinistral on north-northeast striking strands, consistent with the regional principal strain axes (Williams et al. 2018). Although not mapped as such prior to the earthquake, post-quake field examination revealed pre-existing surface rupture traces in several locations, mostly on relatively youthful steep hillslope terrain.

Figure 3.6 Fault scarp and surface ruptures of the Hundalee Fault at Okarahia during Workshop 1. Fresh surface rupture (between white arrows), highlighted by turf roll at the left of the photo still existed in November 2018. The fault scarp is constructed from at least 2 faulting events. The trench was sited to the left of the photographer.

Paleoseismic investigations of the Hundalee Fault were jointly led by GNS Science and the University of Otago. Following consideration of field mapping data collected after the earthquake, documented by Williams at al. (2018), additional field inspection was undertaken to identify a suitable location for trenching a pre-existing scarp that also experienced 2016 rupture, to obtain age control on at least one pre-2016 surface rupture on the Hundalee Fault. Key criteria for trench-site selection were safe and reasonably easy access for people and an excavation machine, as well as being free of interpretive complications that may arise at localities on landslide terrain (due to the challenge of distinguishing gravitational from tectonic displacement). Only one prospective trenching site was identified, at Okarahia Stream (Figures 3.6 to 3.8). Initial identification and mapping of the fault scarp was done in November 2016 and the trench excavation was undertaken in February 2018. This fault strand lies ~0.8 km away from the main (bedrock) strand of the Hundalee Fault.

The trench exposure (Figures 3.7 and 3.8) provides robust evidence for at least one rupture of the fault prior to the 2016 rupture. Radiocarbon dating of charcoal fragments in the stream sediments exposed in the trench (Figure 3.7) returned an age of ~3500 calendar years before present. This is a maximum age for the previous surface rupture(s) on the strand of the fault at this location. The relative sizes of the 2016 rupture and previous rupture(s) are difficult to determine from the trench data. However, a vertical component of 0.5 ± 0.1 m is ascribed to the 2016 earthquake (Williams et al. 2018). Thus, the present scarp height implies an aggregate vertical throw of ~2.5 m for at least the last two ruptures at this site.

A manuscript for journal publication on the Hundalee paleo-seismological investigation is at an advanced stage of drafting at the timing of writing.

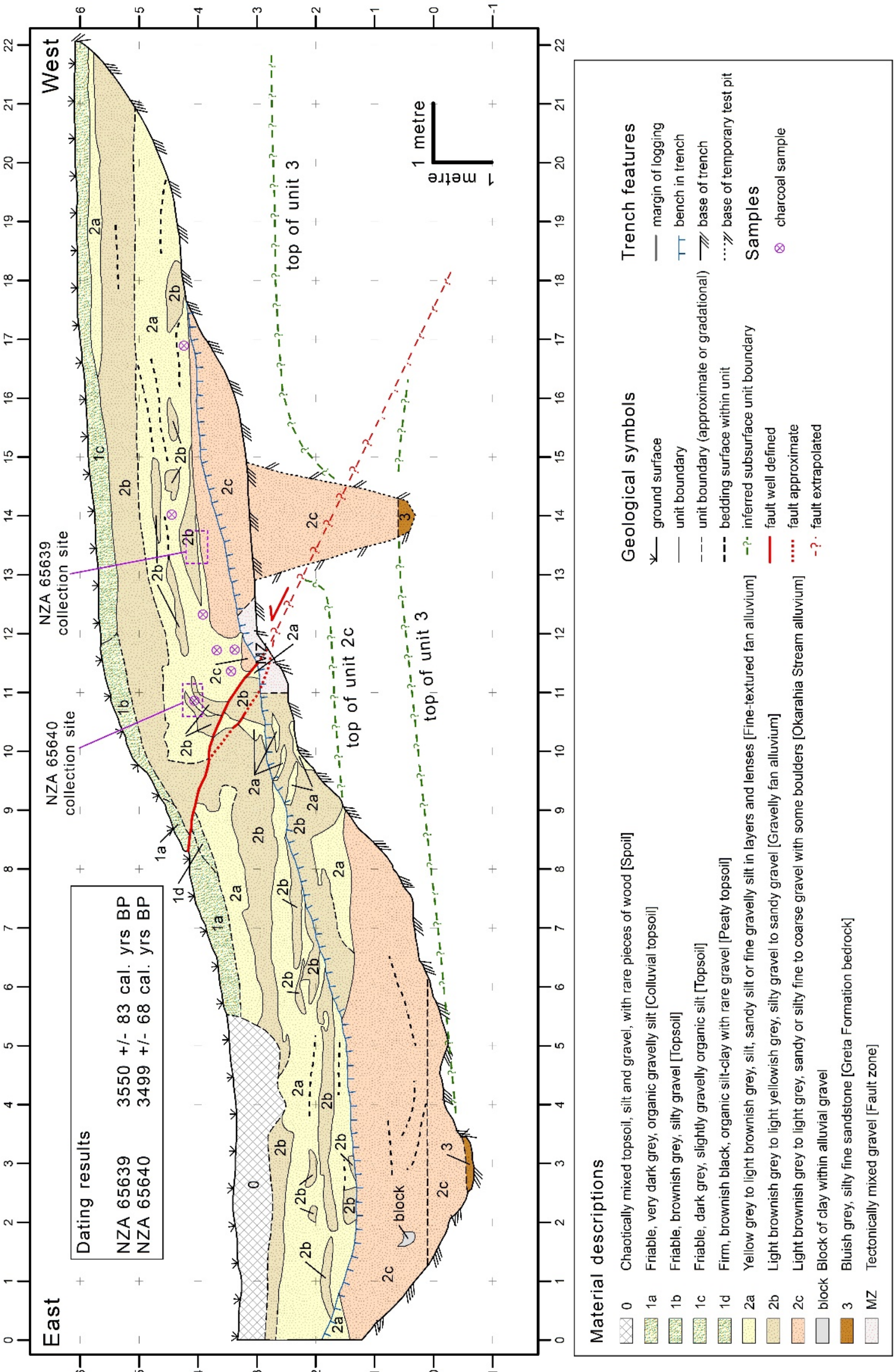

Figure 3.7 Trench log, south wall of the Okarahia trench on the Hundalee Fault.

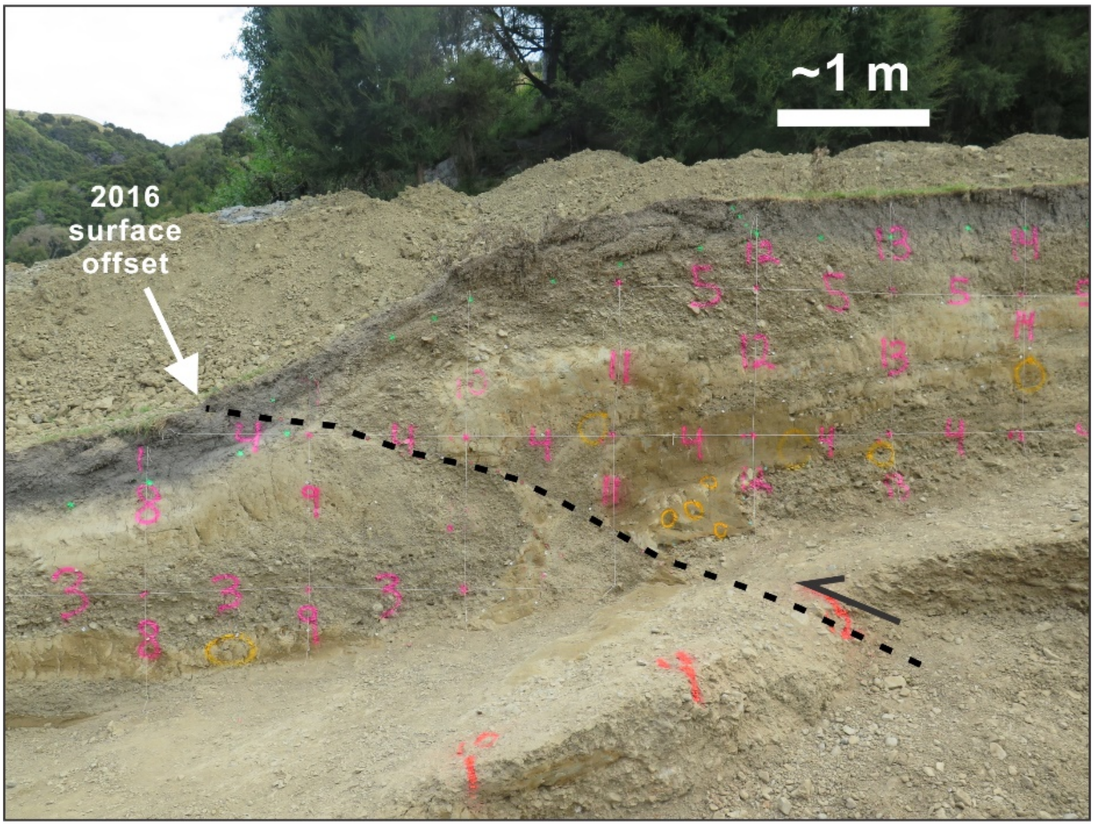

Figure 3.8 Photograph of the south wall of the trench. Dashed black line marks the fault location through the stream sediment sequence.

3.4 Summary of the Paleoseismicity of NCD faults

Thirteen trenches and slip rate sites on five major faults have been investigated across the NCD region following the 2016 Kaikoura earthquake on five major faults (Figure 3.1). Results from The Humps Fault, Leader Fault, Conway-Charwell Fault, Stone Jug fault and Hundalee Fault indicate that all of these faults have ruptured twice during the late Holocene (last 5000 years), including in 2016, and where longer record are available, these faults have all experienced multiple surface-rupturing earthquakes throughout the Holocene and extending back to c. 15,000 years BP (Figure 3.9).

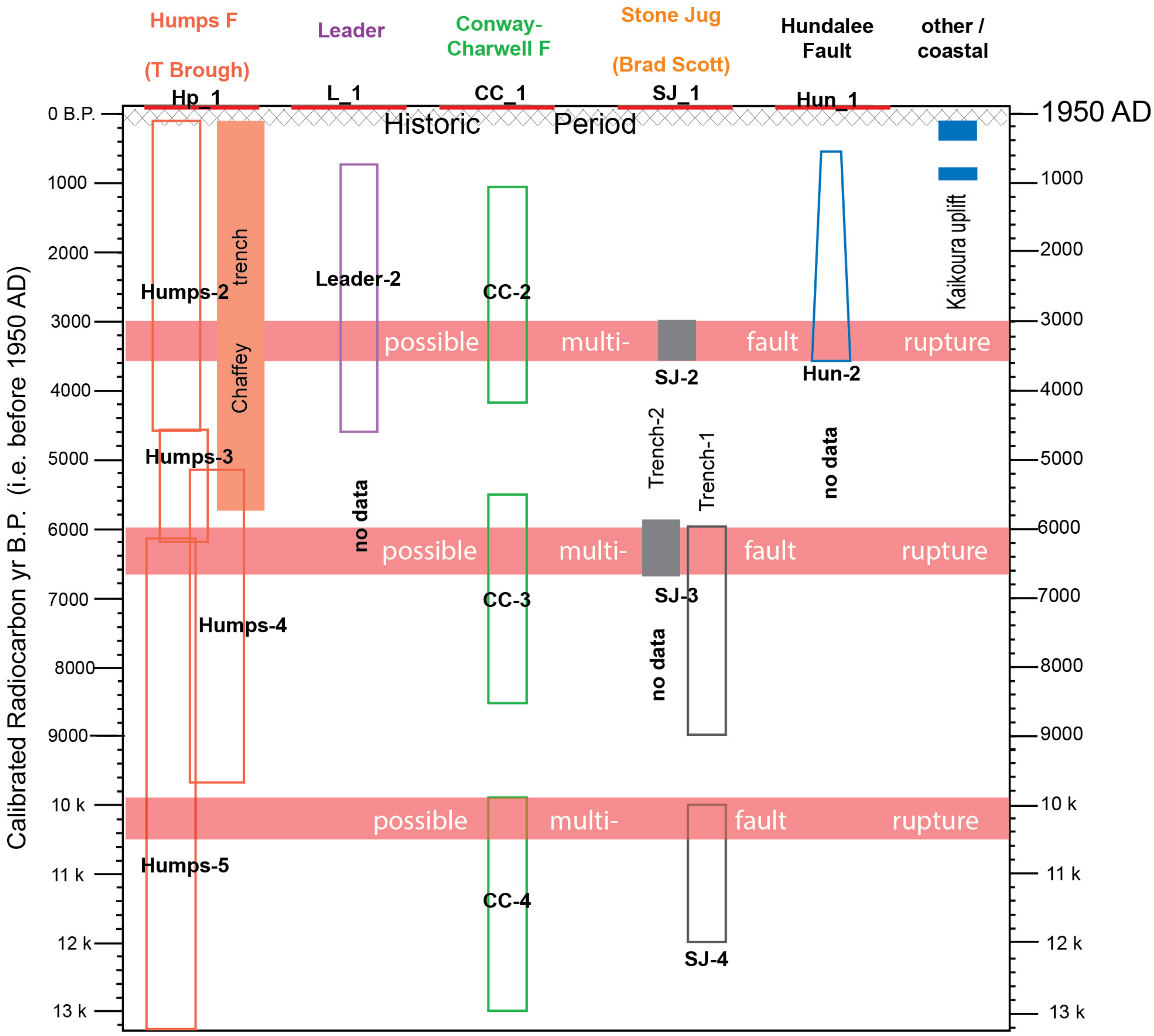

Figure 3.9 Summary of the timing of past earthquakes on the five active faults studied across the NCD.

Based on results from the McLean and Chaffey trenches, The Humps Fault has experienced five surface-rupturing earthquakes during the last 10–15 kyr and has an average recurrence interval of 2500–4000 years (Table 3.2; Brough 2019). The Leader Fault, which ruptured in 2016, had a penultimate faulting event during the late Holocene (Figure 5.1; Bushell 2019). Four faulting events have been documented from the Conway-Charwell fault during the last 10–13 kyr, yielding a recurrence interval of 3300–4000 years (Figure 5.1). Based on results from two trenches, the Stone Jug Fault has experienced at least four distinct earthquake ruptures during the last 10–12 kyr, which yields an average recurrence interval of 3300–4000 years. Hundalee Fault studies at Okarahia provide evidence for a penultimate faulting event that post-dates c. 3500 years BP.

Collectively, these results are intriguing for the following reasons:

1. The faults have similar recurrence interval ranges (2500–4000 years) with each having ruptured twice during the late Holocene;
2. For the NCD faults that ruptured in 2016, only the Hundalee Fault was recognised as an earthquake fault source in the current NSHM (Stirling et al. 2012). In the NSHM the Hundalee Fault has a calculated average recurrence interval of 3076 years, which is consistent with the results from the Okarahia trench site

3. While the uncertainties are large, the possibility exists from the data (Figure 5.1), that several of these faults have ruptured at the same time (or roughly closely in time), e.g., the event timing windows for all five faults overlap for their penultimate faulting events. This could indicate that multi-fault ruptures have occurred in the past, or that these faults rupture in a sequence or cluster of events closely spaced in time.

These results all indicate that the seismic hazard of the NCD region has been underestimated in the current NSHM, because:

1. There are more active faults ad individual earthquake sources than have previously been accounted for;
2. The average recurrence intervals of these faults are probably shorter than previously considered (because they were unmapped or not in the NSHM); and
3. These faults may operate together in multi-fault earthquake ruptures or rupture in a sequence over relatively short time periods (years to centuries) in a cluster of seismic release.

Such considerations have been included in the NSHM update for NCTIR (Goded et al. 2018) and will be included in future iterations of the NSHM (Gerstenberger et al. 2018).

4.0 COLLECTION OF ON-FAULT PALEOSEISMIC AND SLIP RATE RECORDS (MFS FAULTS)

4.1 Introduction

Research Aim 1.2 states we will undertake:

> *"Geologic studies that determine slip rate, paleoearthquake age and recurrence data for the Hope (Seaward) Fault and Papatea Fault (as well as NCD faults). Studies involve excavation combined with geologic dating, and geophysical studies (where warranted)".*

This chapter summarises paleoseismic studies undertaken on faults of the MFS region that were involved in the 2016 Kaikōura Earthquake (Figure 4.1), beginning with the Hope Fault.

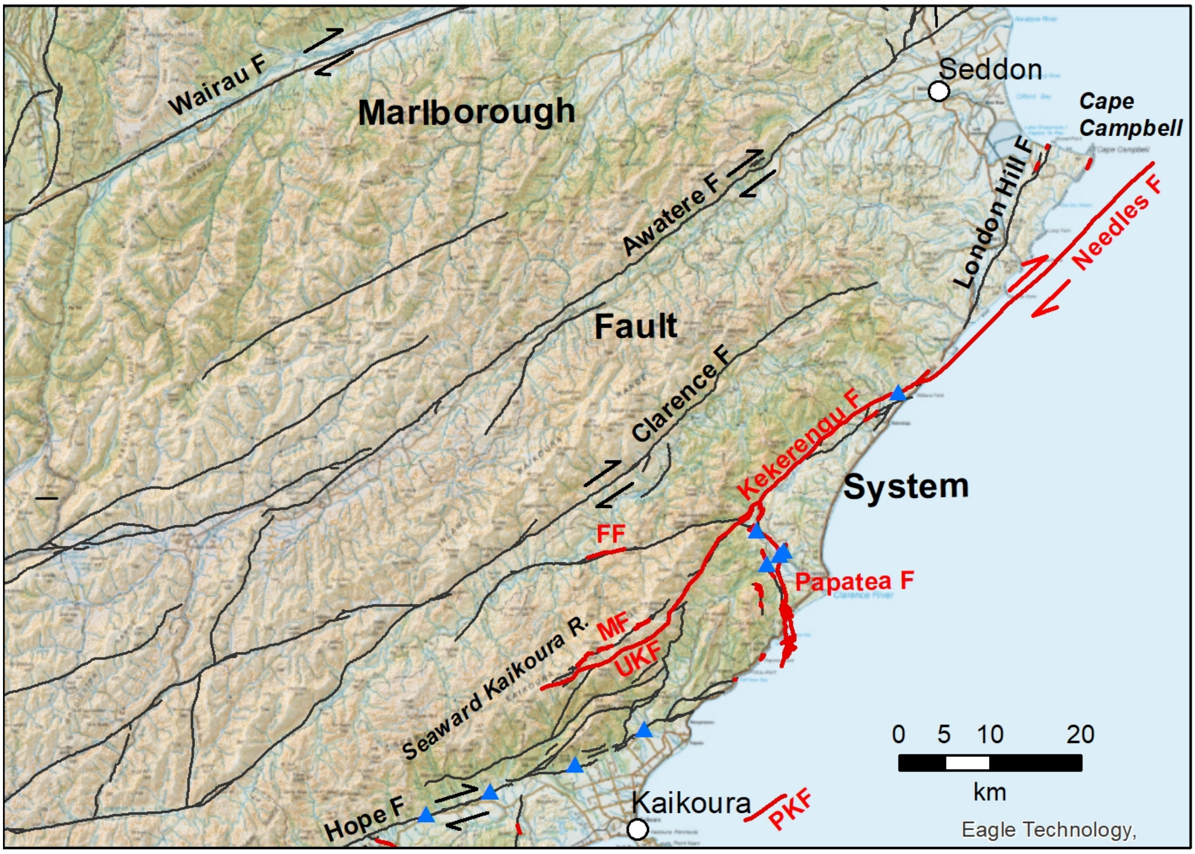

Figure 4.1 The 2016 Kaikōura Earthquake rupture zone and paleoseismic sites (blue triangles) within the Marlborough Fault System (MFS); active faults that ruptured shown in red.Other active faults are shown as black lines (from Langridge et al. 2016). Abbreviations are: PKF, Point Kean Fault; MF, Manakau Fault; UKF, Upper Kowhai Fault; FF, Fidget Fault.

4.2 Hope Fault

4.2.1 Introduction

The role of the Hope Fault has been one of the outstanding questions regarding the tectonics of the 2016 Kaikōura Earthquake. Aerial reconnaissance of the range front of the Hope Fault did not identify multi-meter surface ruptures that were apparent along many of the other faults (Litchfield et al. 2018). However, initial reconnaissance identified minor surface rupture along the Seaward section of the Hope Fault at Half Moon Bay, across S.H. 1 and within the rail tunnel there.

As access improved, minor surface rupture (<1 m) was identified along the Seaward section of the Hope Fault near Hapuku, and along the Mt Fyffe section of the Hope Fault between Rockwood Station and the Kowhai River below the Hinau Track (Figure 4.2). Surface ruptures along these parts of the Hope Fault are mainly characterised by reverse and low-angle reverse (thrust) ruptures identified from ground cracks and warping.

Environment Canterbury (Marion Schoenfeld) requested that a paleoseismic study be undertaken on the Seaward and/or Mt Fyffe sections of the Hope Fault as the risk of another earthquake following the 2016 Kaikōura Earthquake was perceived to be high, and there was little paleoseismic data along this portion of the Hope Fault. A limited amount of new work was undertaken on the Hope Fault during the course of this project. Therefore, this discussion focuses on some past and future progress on this part of the fault.

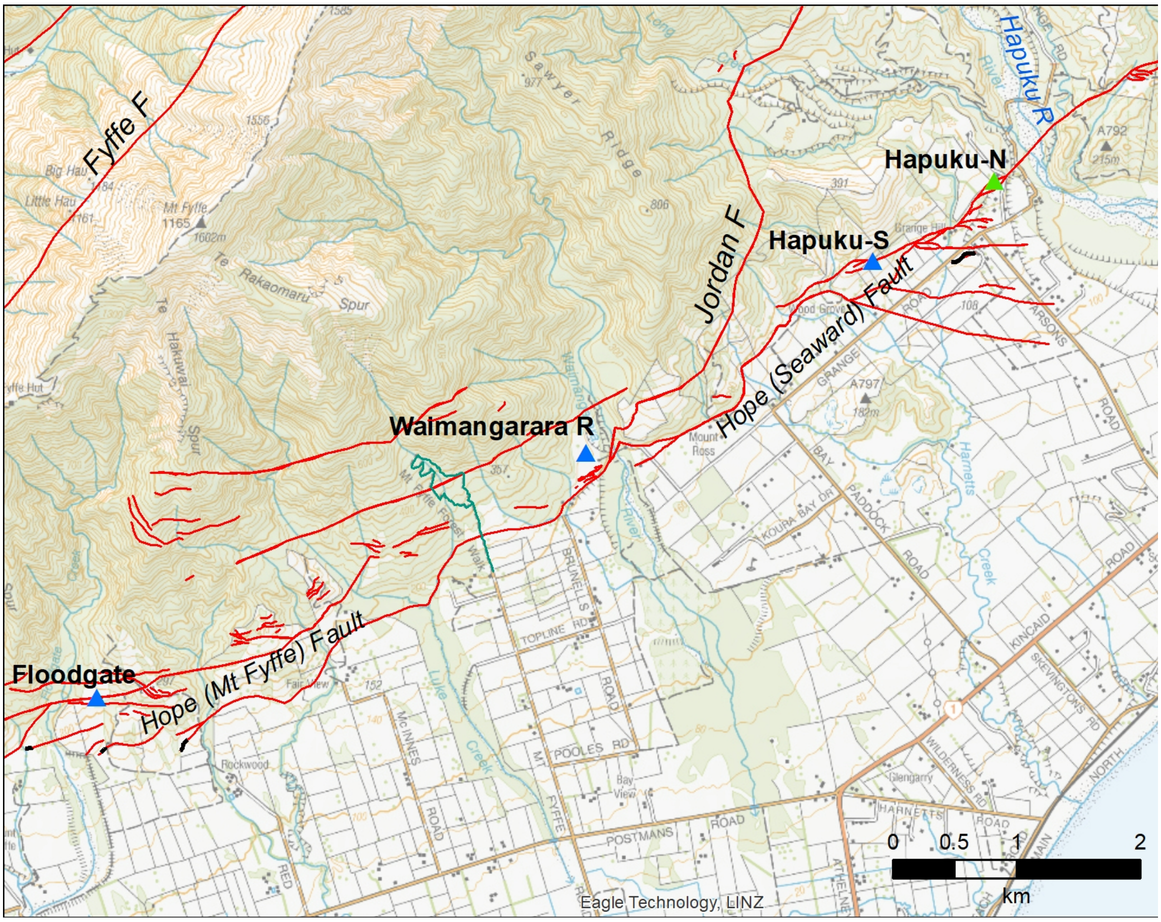

Figure 4.2 Active fault map of the Hope Fault range front along the Seaward Kaikōura Range. The change from the Mt Fyffe to Seaward section of the fault occurs at the junction with the Jordan thrust fault. Named trench and slip rate sites are shown by triangles. 2016 Kaikōura earthquake surface ruptures are shown by short black lines near Floodgate and Hapuku.

4.2.2 Pre-Existing Paleoseismic Datasets

A University of Canterbury MSc project focusing on two paleoseismic sites had been undertaken along the Mt Fyffe and Seaward sections of the Hope Fault, prior to the Kaikōura earthquake (Coulter, 2007). A single trench was opened at Floodgate Creek on the Mt Fyffe section (Figures 4.2 and 4.3). The Floodgate trench provides evidence for at least two paleo-earthquakes. There are two radiocarbon dates from this trench; a young date (138 ± 35 yr BP) that may pre-date the most recent faulting event; and an older date (1320 ± 37 yr BP) that probably pre-dates the penultimate faulting event.

The second trench excavated by Coulter (2007) was at the Hapuku South site. At this location a shallow trench was excavated prior to the digger breaking. The results from the Hapuku trench are limited but provide evidence for a most recent faulting event that is constrained by two maximum radiocarbon dates (373 ± 41; 464 ± 41 yr BP).

The results of these two trenches highlight the occurrence of a recent pre-historic rupture on both the Mt Fyffe and Seaward sections of the Hope Fault, with the likelihood of a penultimate faulting event having also occurred within the last 1400 years or so.

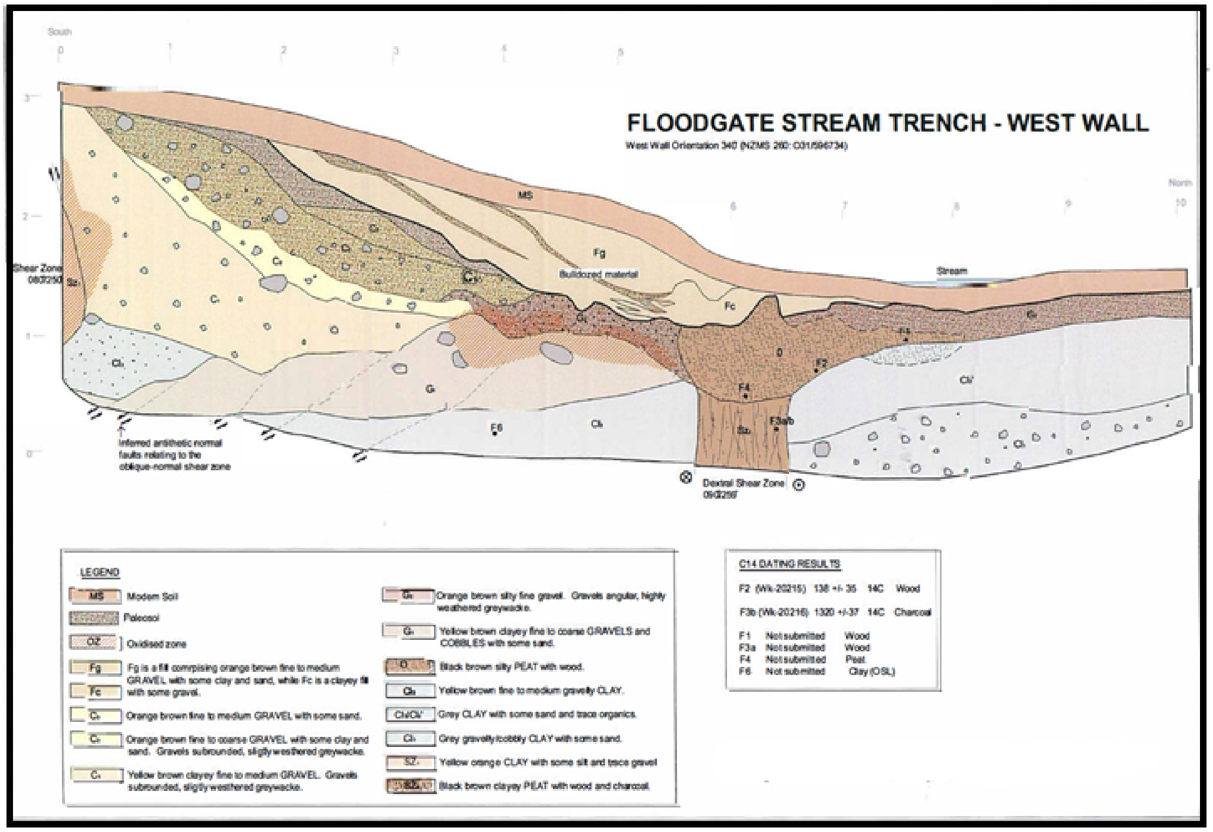

Figure 4.3 Log of the west wall of the Floodgate Stream trench across the Hope Fault, north of Kaikōura. For further details and a log of the Hapuku trench see Coulter (2007).

4.2.3 New NHRP Studies

New sites were considered along the Seaward and Mt Fyffe sections of the Hope Fault (Figure 3.9). These were at the Hapuku River (Hapuku-N), Waimangarara River and with some thought given to reinvestigating the Floodgate Creek and Hapuku sites of Coulter (2007) described above. Late in 2019, one other site was considered (at Sawyers Downs station; Figure 3.1) where convincing 2016 surface ruptures were identified. The following briefly describes the progress made along the Hope Fault. Landowner access and permission was advanced at the Hapuku River site of Van Dissen (1989). At this location a Late Pleistocene to Holocene slip rate could be established from offset stream terraces risers. Terraces and risers of Hapuku River are right-laterally offset by the Hope Fault at this site. An archaeological site notice exists on part of the highest terrace on the upthrown side of the fault. We are continuing to develop a relationship with the Rūnanga o Kaikōura so that in future it would be possible to undertake work at this site.

A similar situation exists for the Waimangarara River site, 3 km to the west of the Hapuku River at the Seward-Mt Fyffe section junction (Figure 3.9). While this site has potential for both paleoseismic event timings and slip rate results, there is a registered archaeological site in the area of interest.

The site at Sawyers Downs is c. 14 km west of Kaikōura on the Conway segment of the Hope Fault (Figure 3.1). At this locality, an array of curving normal or gravitational faults occurs in the hanging-wall of the Hope fault. Surface rupture or cracking was confirmed on at least two of these faults. The most prominent of these has an uphill-facing scarp that holds an ephemeral pond, and uphill-facing rupture traces from the 2016 earthquake. Such a site has potential to yield a paleo-earthquake record from ponded, dateable sediments.

Figure 4.4 Surface rupture within the hanging-wall of the Hope Fault at Sawyers Downs Station. Left: Fresh surface rupture (between white arrows) located from a UAV image. Right: surface rupture, marked by arrows at the edge of a ponded uphill-facing bog. Road marker sits in an open fissure still visible in 2019.

4.3 Papatea Fault

4.3.1 Introduction

Rupture of the 19-km long sinistral reverse Papatea Fault and the southward escape of the Papatea Block were among the exceptional features of deformation related to the 2016 M_W 7.8 Kaikōura Earthquake (Figure 3.1; Hamling et al. 2017; Langridge et al. 2018). Prior to the Kaikōura earthquake the Papatea Fault was not included within the New Zealand active faults database (NZAFD, Langridge et al. 2016) but like other ~N-striking faults that ruptured in 2016, it was an important component of the rupture process during the earthquake (Litchfield et al. 2018; Nicol et al. 2018). The maximum up-to-the-west throw on the main strand was ~9.5 ± 0.5 m and the mean throw across the fault was ~4.5 ± 0.3 m. The maximum horizontal (left-lateral) offset was ~6.1 ± 0.5 m. From these data and considering fault dip, the maximum net slip for the Papatea Fault is 11.5 ± 2 m (average net slip ~6.4 ± 0.2 m) (Diederichs et al. 2019; Langridge et al. 2018), which is comparable to the largest measured surface displacements on the Kekerengu Fault in 2016 (Kearse et al. 2018; Litchfield et al. 2018).

The Papatea Fault is best characterised as a fault zone with 2–3 parallel strands (Figure 3.12; main, western, Edgecombe). This fault zone is associated with extensive co-seismic deformation of a tectonic sliver between the main and western strands, which was particularly evident at the coast and in the lower Clarence valley (Clark et al. 2017). In addition to these strands, other minor faults (Corner Hill, Waiautoa, and Stewart Creek faults) local to the Papatea Fault ruptured in 2016 (Langridge et al. 2018).

Because it was previously unmapped (as being active) and yet had impressive displacements in 2016, it was important to understand the past record of earthquake movements and tectonic role of the Papatea Fault. In addition, there were significant landscape impacts caused by rupture of the Papatea Fault and its ground motions, particularly very large landslides and avulsion of the *Waiautoa*/ Clarence River. For this project, the immediate challenges with undertaking paleoseismic studies were to locate sites that: 1) had a pre-existing fault trace that could be mapped; 2) were not impacted/buried by landsliding; 3) were not impacted by active alluvial avulsion and erosion; and critically 4) had the potential to yield a paleo-earthquake record from stratigraphy, despite the very large co-seismic vertical and horizontal displacements that occurred in 2016.

Following reconnaissance, three sites were chosen for paleoseismic trenching. These were on the main and western strands of the Papatea Fault, and Corner Hill Fault (Figure 3.12). A fourth location (Jackies Gully) became relevant as an active gully near the northern end of the fault exposed more stratigraphy from 2017 to 2019. In addition, stratigraphic and soil studies undertaken in the lower Clarence valley added important constraints on the Late Holocene landscape development and change in the valley. These studies were important to characterise the relative slip rate of the Papatea Fault and of the scale of past earthquake events in the landscape, compared to 2016. The following sections describe the main results of this work, beginning with the record from the Corner Hill trench.

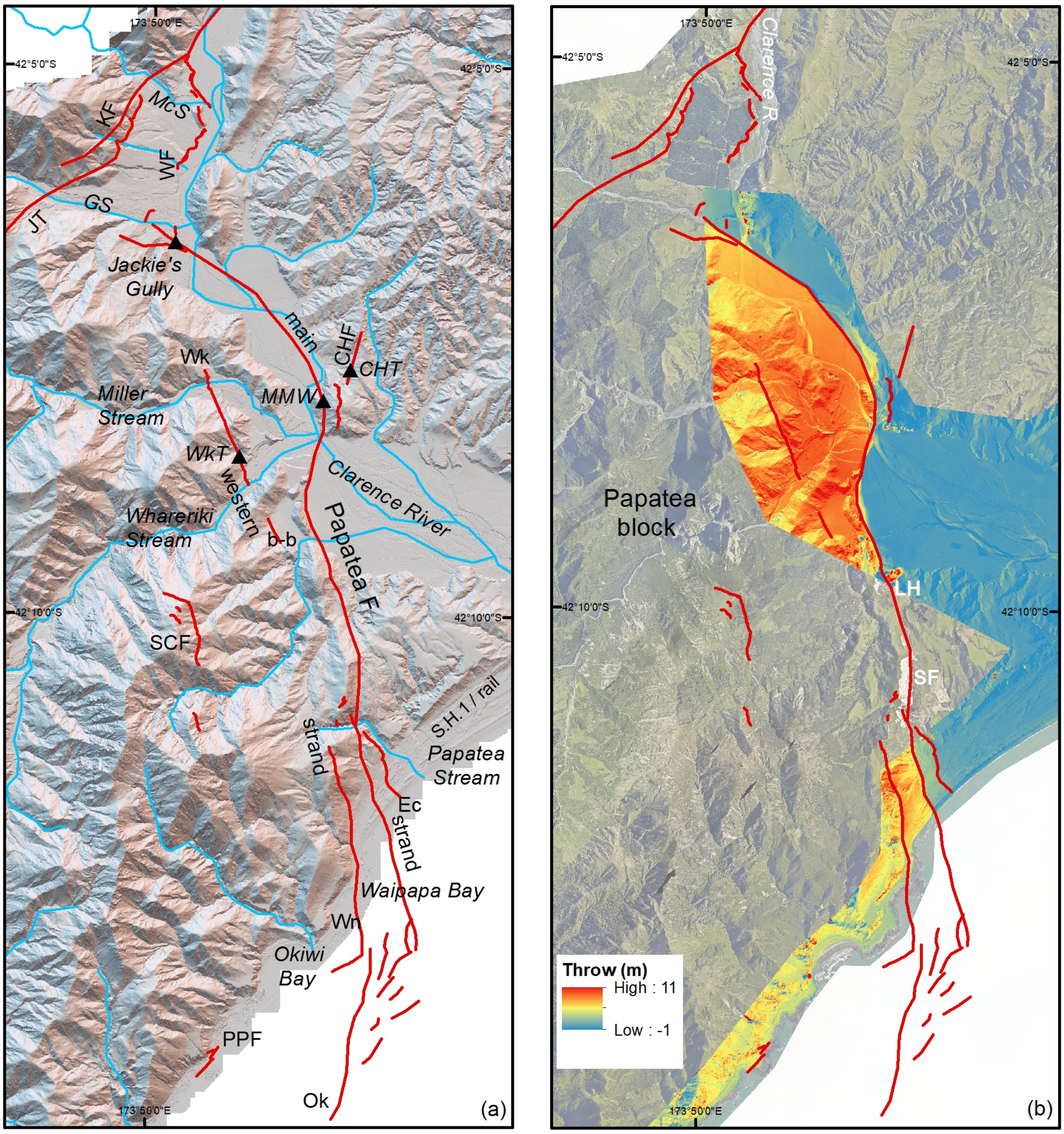

Figure 4.5 The Papatea Fault and other local faults that ruptured in the 2016 Kaikōura earthquake (after Langridge et al. 2018). (a) post-earthquake LiDAR hill-shade model indicating the major geographic features and rupture strands. Abbreviations: Ok, Okiwi; Wn, Wainui, b-b, back-basin, Wk, Wharekiri and Ec, Edgecombe traces of the Papatea Fault; PPF, Paparoa Point; SCF, Stewart Creek; KF, Kekerengu faults and JT, Jordan thrust; GS, George, and McS, McLean streams. Black triangles indicate paleoseismic sites discussed in this report: MMW, Murray mega-wall; WkT, Wharekiri trench; and CHT, Corner Hill trench. (b) post-earthquake colour orthophoto mosaic overlain by the area of differential LiDAR coverage along the coast and in the lower Clarence valley. Scale shows the magnitude of vertical throw from D-LiDAR across the Papatea Fault, shown in m above pre-earthquake LiDAR dataset.

4.3.2 Corner Hill Trench

Co-seismic rupture of the Corner Hill Fault was mapped in association with a pre-existing fault trace on the footwall (north) side of the Papatea Fault (Figure 4.5; Langridge et al. 2018). While the displacements in 2016 were minor (10’s cm of vertical) it was decided to trench the fault, because it had a pre-existing fault scarp and a good site was located with potential to recognise and date past earthquakes, that could potentially be correlated to the paleoseismic record of the Papatea Fault (Figure 4.6).

Figure 4.6 The Corner Hill Fault (CHF) and trench. Left: Pre-existing trace and surface rupture on the CHF from left to right in picture and on the edge of the small bog, marked by arrows. Right: The Corner Hill trench. Small scarp, rupture trace and fault zone in the south wall located to the left of the worker.

The Corner Hill trench was sited across a rupture trace where a small swamp, characterised by an organic-rich soil and reedy vegetation, was ponded against a small fault scarp. The trench revealed a fault zone related to the 2016 earthquake and past earthquake events centred on the fault scarp geomorphology. Evidence in the trench walls for surface displacement in 2016 was consistent with offset of the uppermost units in the trench: a soil and subsoil (Figure 4.7). In addition, the main fault zone marked a major contrast in stratigraphy from the east end of the trench (characterised by relatively impervious fine-grained deposits capped by a peaty soil) to the west end (characterised by typically coarse-grained deposits capped by a soil). The depth of the peaty bog stratigraphy was limited to up to 0.5 m on the downthrown side of the fault. Age control within the stratigraphy was limited. Organic samples were collected for radiocarbon dating and sediment samples were collected for luminescence dating. At this time, a single radiocarbon sample (CH-05; 662 ± 19 yr BP) has been dated (Figure 4.7). This date gives an indication of when the drainage across the fault scarp changed, allowing for the accumulation of peaty material. One IRSL (luminescence; CH-01) date from the UCLA Luminescence Lab is pending. The main purpose of this date is to characterise the age of the deposits on the west side of the fault zone.

Currently, there is little evidence for past earthquakes expressed by the presence of upward-terminating fault relations or colluvial wedge deposits (Figure 4.7). Perhaps the most compelling evidence for past fault ruptures are: the pre-existing fault scarp, and the change in stratigraphy to peaty soils on the east side of the fault zone. Based on these inferences, the penultimate faulting event may pre-date the formation of the peaty bog characterised by sample CH-05, i.e. prior to AD 1302–1397.

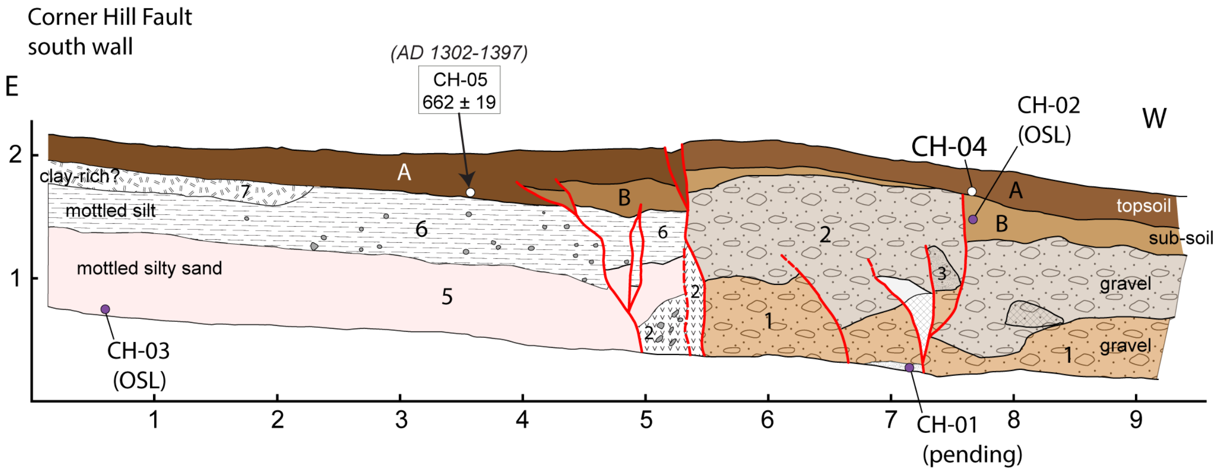

Figure 4.7 Simplified log of the south wall of the Corner Hill trench

4.3.3 Main Strand Papatea Fault Exposure

Mapping of the main strand of the Papatea Fault during the 2016 earthquake response highlighted the difficulties in locating a site where a pre-existing fault trace or even a small sedimentary trap may exist along the fault. Later reconnaissance focused on an area in the lower Clarence valley near Corner Hill where the fault strand was not in the floor of the Clarence valley cutting across the youngest alluvial terraces but was above the valley cutting across landscapes formed in Tertiary bedrock (Figure 4.5).

A site was chosen, c. 700 m southwest of the Corner Hill trench, where a pre-existing farm road obliquely crossed the fault zone and was offset in the 2016 earthquake (Figure 4.8). At this location the vertical component of motion in 2016 was assessed from differential (D-LiDAR) LiDAR to be c. 6–7 m up-to-the-west. The pre-existing road was enhanced by the excavator to create a road cut exposure, dubbed the Murray Mega-wall, that was 35 m long and up to 4 m high (Figure 4.9). Prior to excavation, points were surveyed in to attempt to relocate the original pre-earthquake geometry of the road, which had been fixed by the farmer after the earthquake. A reconstruction of the road using these points and LiDAR datasets confirmed c. 6–7 m of vertical displacement occurred across a c. 20-m wide zone of deformation.

The Murray Mega-wall exposed Tertiary bedrock and Holocene deposits and soils. The main features of the stratigraphy of the Murray Mega-wall are:

1. Weathered and sheared white Amuri Limestone exposed largely on the western (upthrown) side of the fault exposure;
2. Limestone ‘residuum’ soils formed into ‘1’ containing scattered charcoal;
3. A range of Tertiary bedrock facies in fault contact slivers east of the main exposure of Amuri Limestone, including green mudstone, massive grey mudstone, and minor oxidised and coloured mudstone and sandstone, some of which contain clasts of volcanic? origin;
4. A single package of weathered Amuri Limestone overlying this package of Tertiary mudstones, interpreted as a debris flow/landslide deposit comprised of limestone, transported from west to east;
5. Soils formed on ‘3’ and ‘4’;
6. A suite of young (late Holocene?) slope wash deposits and soils, including paleosols exposed to the east of the main zone of faulting

Figure 4.8 Field view of the Murray Mega-wall exposure across the main strand of the Papatea Fault near Corner Hill. The main faults that ruptured in 2016 are shown in red along with the surface trace of the frontal thrust (white line) and the rupture free face (at right). Movement across the fault zone is sinistral reverse — the scrub-covered ridge, that the road cuts across, has been transported up and to the left relative to the vehicle.

The Murray Mega-wall was excavated in February 2019 and logged in detail from UAV-captured photomosaic imagery (Figures 4.8 and 4.9). Faults mapped in the wall are consistent with reverse and thrust faulting. Strike-slip faulting is difficult to document, however, the juxtaposition of units in the wall and the translation of a flat pedestal (considered to be a remnant of the original farm road) are consistent with a component of sinistral strike-slip motion. The details of the wall stratigraphy will not be described in detail here, but the wall preserves evidence of three past earthquakes and all radiocarbon ages from the wall are <1000 years BP; indicating at least three surface-rupturing earthquakes on the main strand of the Papatea Fault in the past 1000 years.

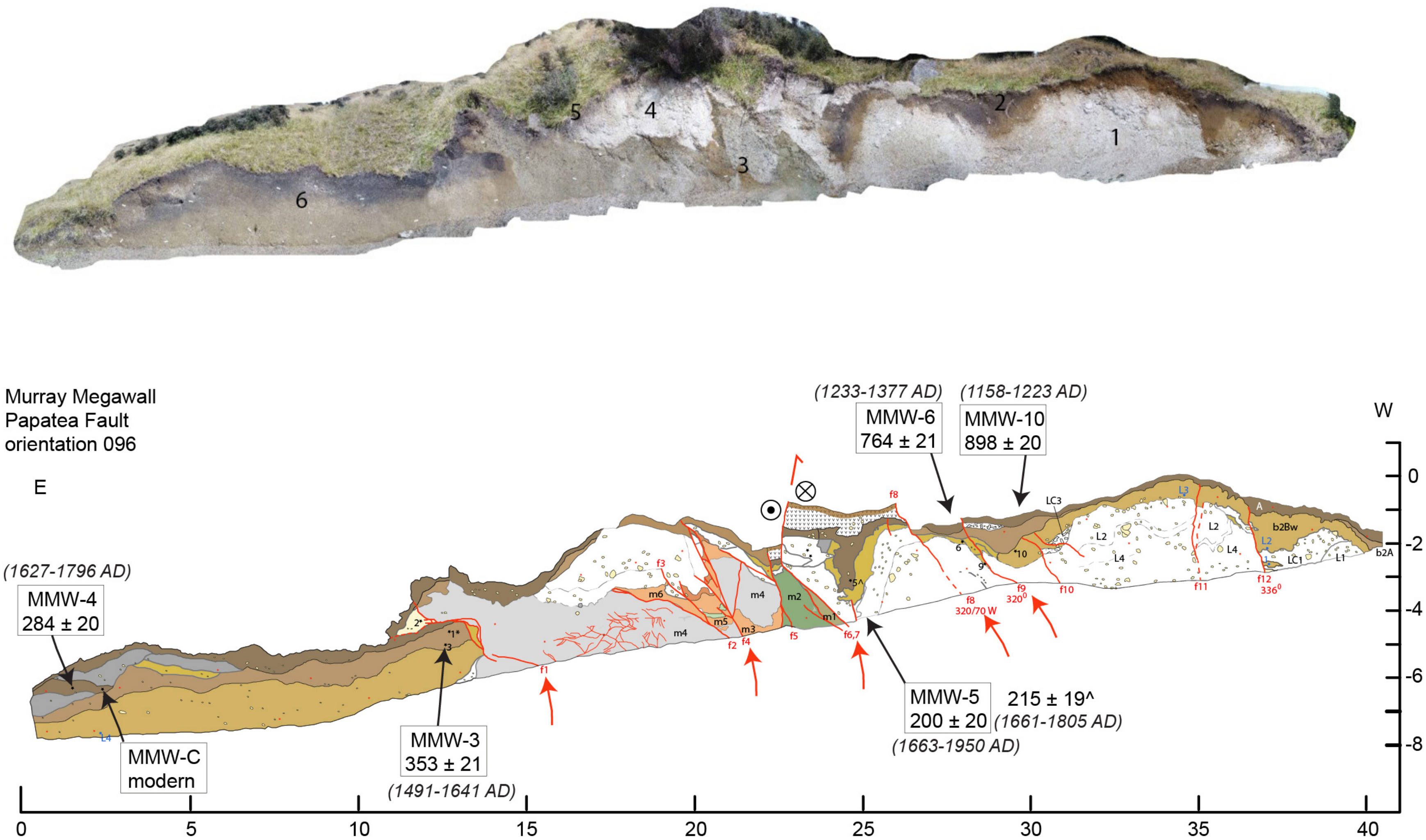

Figure 4.9 The Murray Mega-wall exposure across the main strand of the Papatea Fault, including scale. Left: photomosaic of the wall. The numbers refer to the 6 broad unit packages exposed in the wall (described above). Right: detailed log including faults and radiocarbon dates from the exposure.

4.3.4 Western Strand Papatea Fault Trench

A third trench was sited across the Wharekiri trace (western strand) of the Papatea Fault (Figure 4.5a). The Wharekiri trace is an NNW-striking fault that ruptured in 2016, located between the Wharekiri and Miller streams on Middle Hill Station. It was first recognised from D-LiDAR images (Figure 4.5b) that indicated a down-to-the-west vertical height change across a lineament in that area. Field checking in 2018 confirmed the presence of surface rupture along the Wharekiri trace. D-LiDAR studies suggest that motion on the Wharekiri trace was both sinistral and vertical (dip-direction uncertain) in 2016 (Diederichs et al. 2019; Langridge et al. 2018).

A site was identified where a small (<0.5 m high) uphill-facing scarp was located in association with a ponded bog and left-stepping tension gashes from the 2016 earthquake. The Wharekiri trench was excavated in April 2019 and logged in detail from UAV-captured photomosaic imagery (Figure 4.10). The stratigraphy of the scarp and the lower part of the bog comprised weathered and oxidised poorly-sorted coarse debris flow or slope deposits. The upper bog stratigraphy comprised thin, poorly sorted fine-grained debris flow or slope deposits (units 0, b2B) into which soils (bA, b2A) were developed. Charcoal was present within these upper deposits and several samples were submitted for radiocarbon dating.

Evidence for at least 2 deformation events in the Wharekiri trench has been documented. All radiocarbon dates from the trench were <1000 radiocarbon yr BP, suggesting that there have been at least 2 deformation events on the western strand of the Papatea Fault during the last 1000 years or so.

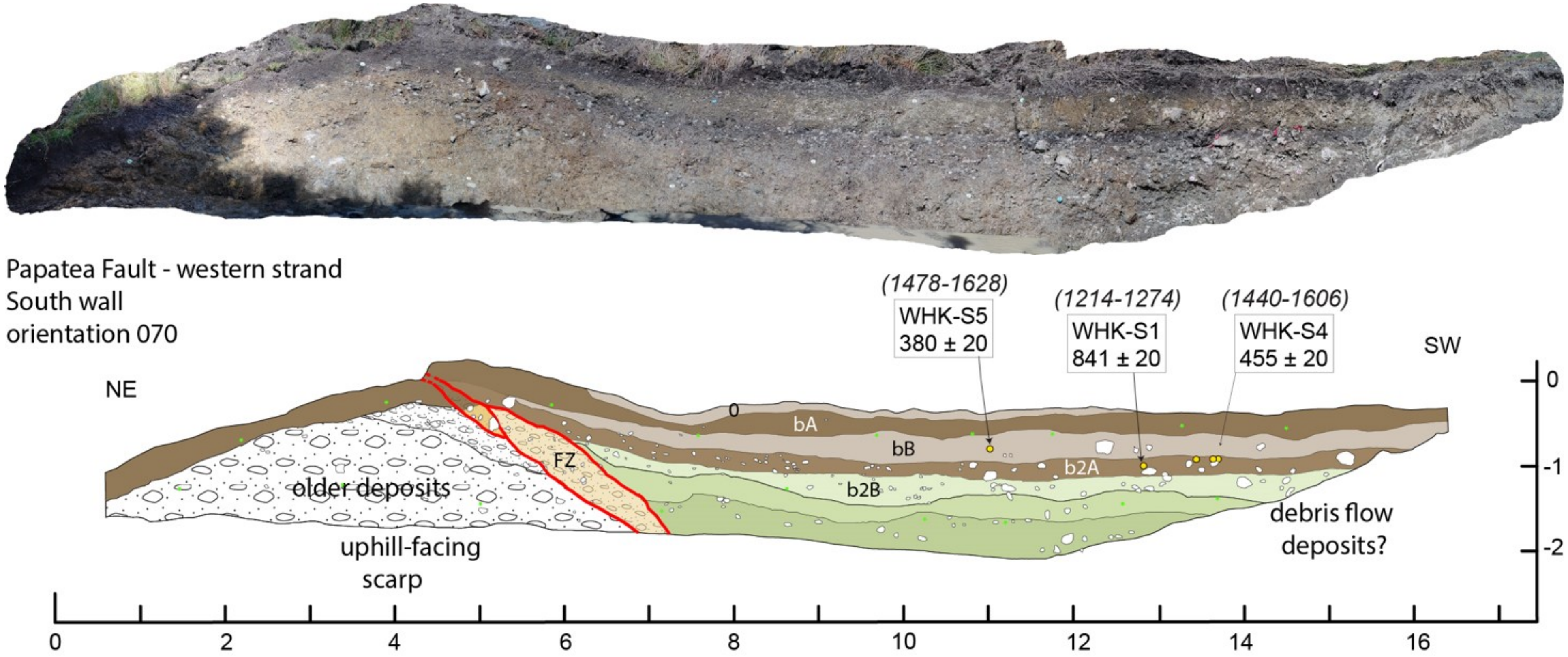

Figure 4.10 The south wall of the Wharekiri trench across the western strand of the Papatea Fault. Left: Photomosaic of the wall. Buried A-horizons have a pronounced dark brown colour. Right: detailed log including faults and radiocarbon dates. The labels refer to the soil unit packages exposed in the wall (described above).

4.3.5 Stratigraphy and Deformation Exposed in Jackie's Gully

During the earthquake reconnaissance and response, the impacts of the Papatea Fault rupture were evident in the tiny Glen Alton community through loss of the Glen Alton bridge and surface faulting that damaged houses and displaced roads (Langridge et al. 2018; Van Dissen et al. 2019). A large vertical scarp formed across Jackie Hamilton's property, the scarp has been progressively cut into by an active spring and gully (Figure 4.5a).

A soil section through the gully wall was logged in 2018 and several charcoal samples were collected from it for radiocarbon dating (Figure 4.11). The stratigraphy within the gully walls was consistent with an alluvial fan/stream that emanates from the hills local to Glen Alton. By 2019, downcutting through the fault scarp had exposed a sequence through the gully and across the main fault trace. Radiocarbon dates within this section are all <1000 yr BP. Dates from above and within a buried soil near the top of this sequence are typically <200 radiocarbon yr BP. This buried soil is deformed across the fault scarp (by the 2016 earthquake) and appears to preserve evidence for an earlier deformation event, i.e. the buried A-horizon is broken and boudined. Such a young penultimate faulting event is consistent with evidence from the Murray Mega-wall and Wharekiri trench. Deeper buried soils have been recognised within the gully walls and a single IRSL luminescence date from near the base of this section is still pending.

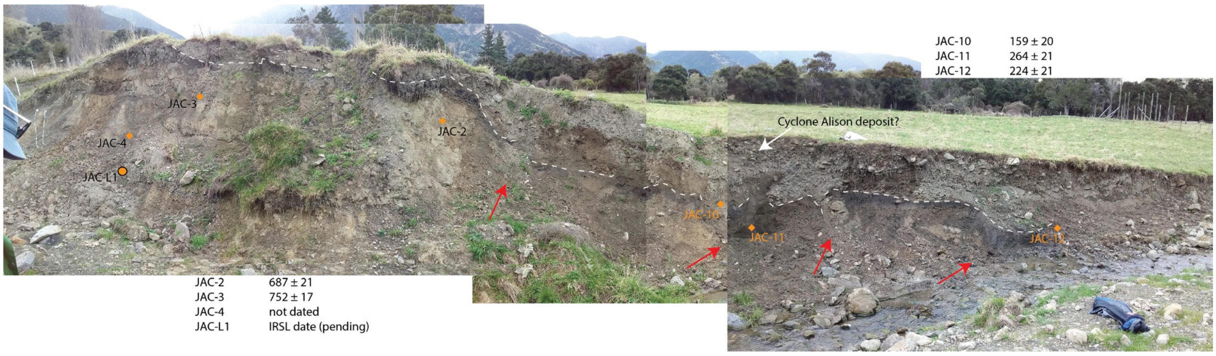

Figure 4.11 Photomosaic of the northwest wall of 'Jackie's Gully' in August 2019, an exposure through the main strand of the Papatea Fault at Glen Alton. The white dashed line indicates the top of a buried soil. Red arrows show the possible locations of faults in relation to the exposure: Radiocarbon samples are shown by orange diamonds. JAC-10 to -12 were sampled and dated in 2019. JAC-2 to -4 were sampled in 2018. JAC-L1 is an IRSL sample.

4.3.6 Summary of Papatea Fault and Clarence Valley Paleoseismicity

The results of paleoseismic trenches and exposures studied in the Clarence valley is summarised in Table 4.1. These preliminary results highlight that the Papatea Fault has probably ruptured three or more times during the last 1000 years or so. These are important observations because as stated it was not mapped as an active fault until after it ruptured in 2016. In addition, Langridge et al. (2018) suggested, based on landscape modification observations, that the Papatea Fault should have a recurrence interval of 5000–10,000 years.

Table 4.1 Information on the trenches and exposures across the Papatea and Corner Hill faults in the Clarence valley (see Figure 3.12 for locations).

Trench/ exposure name	Fault/ strand	Location (NZ Metric)	Number of Dates	Number of Events*	Timing of Events
Murray mega-wall	Papatea main strand	1671767 N 5334963 E	7 (C-14)	≥3	2016 AD 1742–1858 AD 1279–1579 >AD 909–1249
Jackie's Gully	Papatea main strand	1669264 N 5337638 E	1 (IRSL) 5 (C-14)	≥2	2016 AD 1672–1845 ? >AD 999–1391
Wharekiri	Papatea western strand	1670347 N 5334024 E	6 (C-14)	≥3	2016 AD 1701–1858 AD 1453–1601 >AD 1117–1493
Corner Hill	Corner Hill Fault	1672237 N 5335479 E	1 (C-14) 1 (IRSL)	≥2	2016 >1392 AD

*Including the 2016 Kaikōura Earthquake. ^

4.3.7 Slip Rate of the Papatea Fault

A secondary goal to studying the paleoseismicity of the Papatea Fault was to estimate slip rates for the fault. Langridge et al. (2018) estimated a preliminary uplift rate for the Papatea block of ~1–2 mm/yr, based on comparisons with uplift rates for the Seaward Kaikōura and North Canterbury ranges and locally to other fault slip rates. Such an uplift rate corresponds to a dip-slip rate of 1.5–2.5 mm/yr, and an oblique-slip rate of ~2–3 mm/yr. This equates to uplift of 1–2 m/1000 years or oblique slip of 2–3 m/1000 years. At face value, these rates are low compared to the evidence described above for 2–3 Late Holocene movements on the Papatea Fault, or conversely, the slip recorded in 2016 was exceptionally large compared to other deformation events recorded in trenches. Thus, it was important to attempt to calibrate the medium- to long-term slip rate of the fault through an analysis of the geomorphology and age of deformed surfaces within the Clarence valley.

In the Middle Hill Station area, alluvial terraces of the *Waiautoa*/ Clarence River and the Wharekiri and Miller streams were uplifted c. 8–10 m in 2016 (Langridge et al. 2018). Flights of three distinct terraces (T1–T3) were preserved on either side of the Wharekiri and Miller stream (and between them) (Figure 4.12). Terraces T1–T3 were considered to represent the same terrace flights uplifted within the fault sliver between the main and western strands of the Papatea Fault. Regional geological maps published before the 2016 Kaikōura earthquake (Rattenbury et al. 2006), indicate that T1 and T2 near the Middle Hill homestead were formed during the Late Pleistocene MIS Stage 4 (Q4a alluvium; 59,000–71,000 years BP), while terraces on the downthrown side of the (now-recognised) fault are from MIS Stage 2 (Q2a alluvium; 12,000–24,000 years BP). Inset terraces near the Clarence River were mapped as Q1a alluvium (i.e. <12,000 years BP).

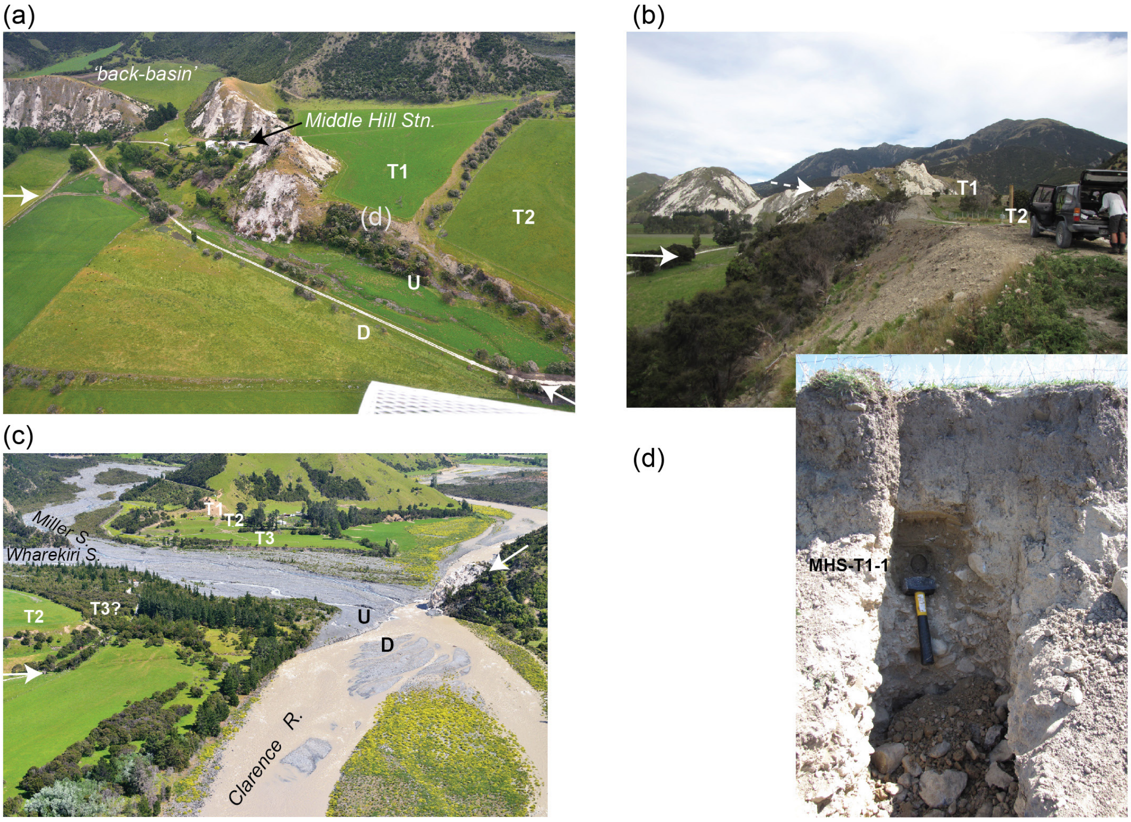

Figure 4.12 Photographs from the Middle Hill Station (MHS) portion of the Papatea Fault. (a) oblique aerial view of the northern extension of Waipapa Road at MHS. White arrows mark the sinuous, frontal reverse fault scarp. T1 and T2 are uplifted and preserved alluvial surfaces. (b) T1 and T2 sample site locations along a new road cut along the scarp of the Papatea Fault. (c) Oblique aerial view of the confluence of Miller and Wharekiri streams with the Clarence River. The streams catchments were uplifted ~8 m on the northwest side of the fault forming an abrupt scarp (between white arrows and U, D) (d) Sample location of IRSL sample at the top of T1 (see 'a' for location).

Several radiocarbon and luminescence samples have been collected and dated (some are pending at this time) from sediments upon the terraces. In addition, soil chronostratigraphic studies provide relative age dating of these surfaces. Preliminary results indicate that the terrace sequence is 5–10 times younger than previously thought, which is consistent with their preservation in an actively uplifting fault zone.

Preliminary results are derived from the following:

1. An IRSL date from a sandy bed near the top of T2 (sample T2-L1) provided an age of 10.59 ± 1.24 kyr. An IRSL date from near the top of T1 is rejected at this time because it gave an age of 3.60 ± 0.64 kyr, which is significantly younger than the age for T2.
2. Soil development on T3 may be equivalent to a Late Holocene 'Eyre' soil, a soil with a characteristic age and development in North Canterbury settings
3. A radiocarbon date from terraces on the downthrown side of the fault is 1258 ± 22 yr BP, which is considerably younger than the Q2a terrace age (12,000–24,000 yr) assigned to it by QMAP (Rattenbury et al. 2006)

Currently, there is not enough age or structural data to determine a slip rate for the Papatea Fault from these alluvial terraces. However, the uplift of the Middle Hill Station terraces is consistent with a moderate to high slip rate fault comparable to the other main faults of the MFS (e.g. Little et al. 2018). This supports the inference that the Papatea Fault is an important structural player in the transition from the Hope Fault to the Hikurangi subduction system.

4.4 Summary of MFS Paleoseismic Studies

In this NHRP project, paleoseismic studies in the MFS have focused on the Hope and Papatea faults. While paleo-earthquake records are rich for much of the MFS (e.g. Awatere, Wairau, and Clarence faults), several of the faults that ruptured in the 2016 Kaikōura Earthquake (e.g. Fidget, Jordan and London Hills faults) have little or no paleoseismic data associated with them. However, in the discussion that follows we include recently published results for the Kekerengu Fault (Little et al. 2018).

A summary of data from the Mt Fyffe and Seaward sections of the Hope Fault (Coulter 2007) indicates that there have been 1–2 ruptures of the fault during the last 1300 years or so. A recent paper by Hatem et al. (2019) suggests there have been 5–6 rupture events during the last 2000 years at Green Burn on the Conway segment of the Hope Fault Neither of these three sites experienced surface rupture in 2016. Nonetheless, these results confirm that the recurrence interval for the Hope Fault is significantly shorter than those presented for the NCD faults and is consistent with a recurrence interval range of 180–310 years (Langridge et al. 2003; Hatem et al. 2019).

Paleoseismic studies on the Papatea Fault indicate that there have been at least three ruptures of the fault during the last 1000 years (Figure 4.13). Trenches across the main strand (Murray Mega-wall) and western strand (Wharekiri) provide evidence for a coincident penultimate faulting event (at both sites) at around AD 1720–1855. The timing of this event is coincident with the penultimate faulting event on the Kekerengu Fault (Little et al. 2018).

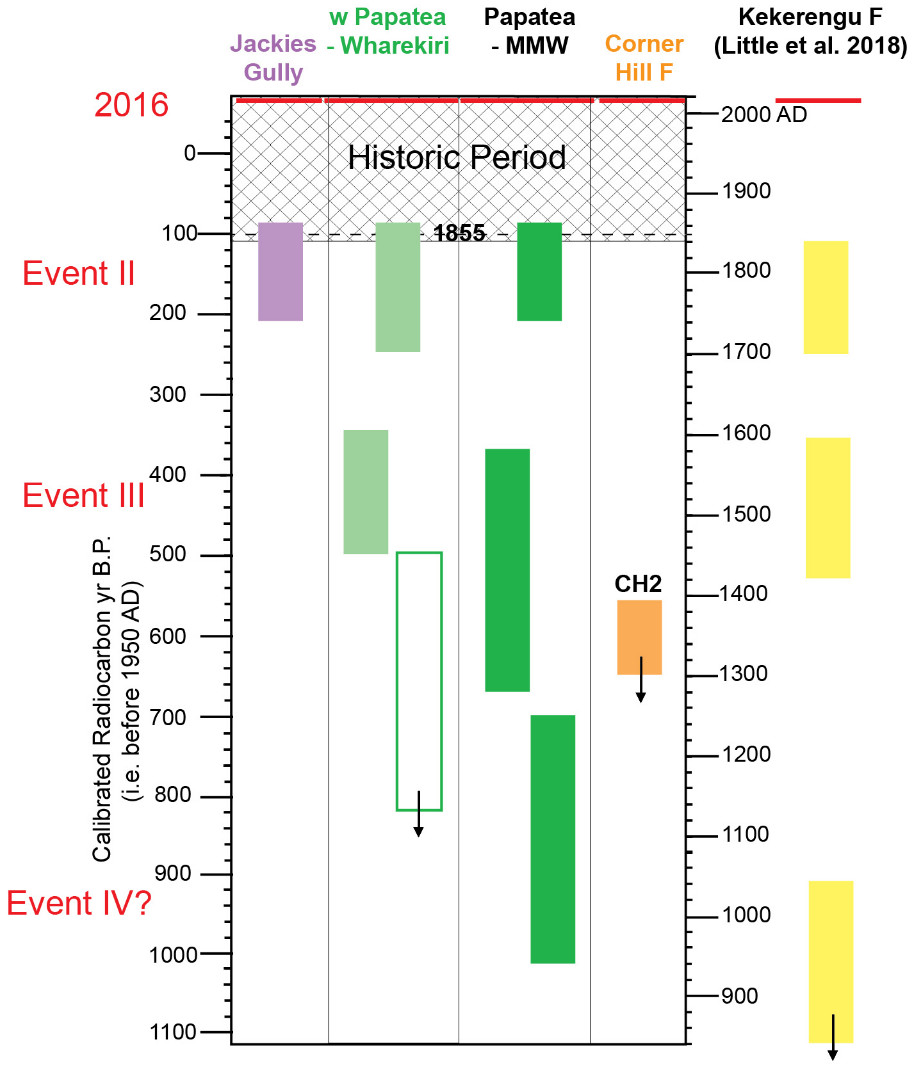

Figure 4.13 Ages of past earthquakes on the Papatea fault network.

The age range of the penultimate Papatea Fault rupture could have occurred as recently as AD 1855, which has been emphasised by the model we used with OxCal. Event III on the Papatea Fault could be coincident at both sites and have a timing of c. AD 1450–1600. Event IV in these trenches may correlate with the penultimate faulting event observed in the Corner Hill trench.

Results from the Kekerengu Fault indicate four earthquake ruptures during the last 1000 years or so, and an average recurrence interval of 376 ± 32 years (Little et al. 2018). This result is consistent with the high slip rate of the Kekerengu Fault and large single-event displacements experienced in 2016 (Kearse et al. 2018). The paleo-earthquake records of the Papatea and Kekerengu faults are roughly coincident over this time period. This may imply that, as in 2016, these two faults rupture together, or are closely spaced in time. The recurrence intervals of these two faults are similar to that for the Hope Fault, and although there is limited paleoseismic and slip rate data for the Jordan thrust fault, these results consistently show that the main corridor of the plate boundary along the Hope-Jordan-Kekerengu faults is one of high slip rate and short recurrence interval.

The role of the Papatea Fault in this part of the plate boundary requires further consideration, particularly to reconcile its role in the 2016 Kaikoura earthquake versus previous displacement events. It is probably not sustainable for such a short fault to have very large displacements (c. 10 m) every 300 years or so.

5.0 RESEARCH AIM 1.3: ENGAGEMENT AND OUTREACH

"To develop strong stakeholder, Iwi and end-user engagement through activities including a Science talk tour".

5.1 Introduction

Stakeholder engagement, scientific reporting and presentation, and outreach formed an important part of this project. We summarise the work in these areas comprising:

1. Stakeholder and iwi engagement
2. Public talks and outreach
3. Presentation of scientific papers at conferences
4. Publication of scientific papers
5. Media engagement

5.2 Stakeholder and Iwi Engagement

The NHRP project wrapped up in November 2019 with a major stakeholder engagement meeting in Kaikōura, hosted by Kaikōura District Council (KDC). Rob Langridge spoke to members of the NCTIR (North Canterbury Transport Infrastructure Recovery) RLG on November 29th on the results of this NHRP and allied EQC projects.

The NCTIR RLG (Restoration Liaison Group) comprises members from: New Zealand Transport Agency (NZTA), KiwiRail Holdings Limited, KDC, Environment Canterbury, Marlborough District Council, Hurunui District Council, Department of Conservation (DoC), Heritage New Zealand, Te Rūnanga o Ngāi Tahu, Kaikōura Marine Guardians, and Te Rūnanga o Kaikōura. Kate Clark presented to this RLG at the beginning of 2018 as part of another NHRP study.

In some cases, this is our first and most significant engagement with stakeholders in this project. In particular, engagement with Te Rūnanga o Kaikōura has been difficult because of the many pressures placed on local *Iwi* since the Kaikōura earthquake. We have an ongoing commitment to engage with Te Rūnanga o Kaikōura and the RLG meeting at the end of November has helped to open doors for future collaboration with NCTIR agencies and *Iwi.*

5.3 Public Talks and Outreach

In the wake of the 2016 Kaikōura Earthquake many talks were presented to the public across a range of forums. This was an opportunity to summarise science on the Kaikōura Earthquake and present on other near-time hazards, such as the hazard posed by an Alpine Fault earthquake.

These talks include:

- 29 August 2018 — public talk in Blenheim preceding the 2018 Annual South Island Civil Defence conference (speakers: Rob Langridge, Chris Massey, Caroline Holden, Russ Van Dissen, Caroline Orchiston). Speakers covered a range of topic related to the Kaikōura earthquake, and the It's Our Fault and AF8 projects.

- 3 April 2019 — public talk in Greymouth as part of the AF8 program. Speaker: Rob Langridge, who spoke on the relationship of “multi-hazard cascades” in the 2016 Kaikōura earthquake and similar impacts that could be expected from an Alpine Fault (AF8) scenario event.
- 4 April 2019 — public talk in Westport as part of the AF8 program. Speaker: Rob Langridge, who spoke on the relationship of “multi-hazard cascades” in the 2016 Kaikōura earthquake and similar impacts that could be expected from an Alpine Fault (AF8) scenario event.
- 5 April 2019 — public talk in Reefton as part of the AF8 program. Speaker: Rob Langridge, who spoke on the relationship of “multi-hazard cascades” in the 2016 Kaikōura earthquake and similar impacts that could be expected from an Alpine Fault (AF8) scenario event.
- 11 June 2019 — public talk in Franz Josef as part of the AF8 program. Speakers: Caroline Orchiston, Rob Langridge. Topics include preparedness for an AF8 earthquake and “multi-hazard cascades” observed in the Kaikōura earthquake vs. an Alpine Fault scenario event.
- 12 June 2019 — public talk in Hokitika as part of the AF8 program. Speakers: Caroline Orchiston, Rob Langridge. Topics include preparedness for an AF8 earthquake and “multi-hazard cascades” observed in the Kaikōura earthquake vs. an Alpine Fault scenario event.

Figure 5.1 Public outreach talks. Left: Russ Van Dissen addresses the audience at a public meeting in Blenheim on the topic of ground motions. Right: Rob Langridge addresses the audience at an AF8 public meeting in Greymouth.

We plan to deliver more talks in future following on from the NCTIR RLG meeting in November 2019. For example, we hope to deliver NHRP talks to the public in Amberley and Kaikōura, the seats of Hurunui and Kaikoura districts. In addition, in 2020 Project AF8 plans to deliver more public outreach talks throughout the Canterbury region, and this is an opportunity to inject science from the Kaikoura Earthquake and NHRP projects.

5.4 Conference Papers and Presentations

The following abstracts have been presented at conferences as talks or posters.

Geoscience Society of New Zealand Annual Meeting 2018, Napier:

Barrell, D, Stirling, M., Williams, J., Sauer, K., van den Berg, E. 2018. Kaikōura earthquake: Hundalee Fault paleoseismology. In: Sagar, M.W.; Prebble, J.G. (eds.) Geosciences 2018, 27–30 November 2018, Napier: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 151A, p. 19 (poster).

Brough, T.; Pettinga, J.; Van Dissen, R.J.; Nicol, A.; Stahl, T.; Khajavi, N.; Clark, D.; Pedley, K.; Langridge, R.M. 2018 Tectonic geomorphology and paleoseismology of the Humps fault which initiated the Mw 7.8 Kaikoura earthquake. In: Sagar, M.W.; Prebble, J.G. (eds.) Geosciences 2018, 27–30 November 2018, Napier: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 151A, p. 35.

Bushell, T., Nicol, A.; Khajavi, N.; Pettinga, J., Stahl, T. 2018. Fault rupture patterns, complexity and slip transfer during the M_W 7.8 2016 Kaikōura Earthquake in North Canterbury, New Zealand. p. 37 IN: Sagar, M.W.; Prebble, J.G. (eds.) Geosciences 2018, 27–30 November 2018, Napier: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 151A, p. 37.

Langridge, R.M.; Van Dissen, R.J.; Nicol, A.; Pettinga, J.; Stirling, M.W.; Barrell, D.J.A.; Almond, P.; Williams, J.; Stahl, T.; Pedley, K.; Brough, T. 2018. Paleoseismicity of 2016 MW 7.8 Kaikoura earthquake faults: was this event the norm or one "out of the park"? IN: Sagar, M.W.; Prebble, J.G. (eds.) Geosciences 2018, 27–30 November 2018, Napier: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 151A, p. 158.

Scott, B., Nicol, A., Pettinga, J., Stahl, T. 2018. The Stone Jug Fault: Facilitating sinistral displacement transfer during the M_W 7.8 Kaikōura earthquake. IN: Sagar, M.W.; Prebble, J.G. (eds.) Geosciences 2018, 27–30 November 2018, Napier: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 151A, p. 242.

GSA Cordilleran Section meeting, Portland, USA:

Langridge R.M.; Nicol, A.; Van Dissen, R.J.; Pettinga, J.; Stirling, M.W.; Barrell, D.J.A.; Clark, K.J.; Little, T.; Williams, J.; Stahl, T.; Pedley, K.; Kearse, J.; Litchfield, N.J.; Gerstenberger, M.C.; Goded, T. 2019. Paleoseismicity of 2016 Mw 7.8 Kaikoura Earthquake faults: what have we learnt and implications for the New Zealand seismic Hazard model? In: 2019 GSA Cordilleran Section 115th Annual Meeting, 15–17 May 2019, Portland, Oregon USA. Boulder, Colo.: Geological Society of America. Abstracts with programs / Geological Society of America 51(4). (poster)

Invited talk:

Langridge R.M.; Clark, K.J.; Kearse, J.; et al. 2019. Paleoseismicity of the Papatea Fault 2016 Mw 7.8 Kaikoura Earthquake faults: in: 2019 GSA Cordilleran Section 115th Annual Meeting, 15–17 May 2019, Portland, Oregon USA. Boulder, Colo.: Geological Society of America. Abstracts with programs / Geological Society of America 51(4).

Geoscience Society of New Zealand Annual Meeting 2019, Hamilton:

Bushell, T., Nicol, A.; Khajavi, N.; Pettinga, J., Stahl, T. 2019. Fault rupture patterns, complexity and slip transfer Models of subsurface rupture of the humps-leader fault system during the Kaikōura earthquake. In: Kamp, PJJ and Pittari, A eds. Geosciences 2019, 24–27 November 2019, Hamilton: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 154A. p. 30.

Morris, P., Little, T.A., Hill, M., Van Dissen, R., Kearse J., Petherick, L., Hemphill-Haley, M., Norton, K., Manousakis, J., Zekkos, D. 2019. Three-dimensional co-seismic accommodation of ~9 m of displacement through a “mole-track” structure in a strike-slip earthquake. In: Kamp, PJJ and Pittari, A eds. Geosciences 2019, 24–27 November 2019, Hamilton: abstract volume. Wellington, N.Z.: Geoscience Society of New Zealand. Geoscience Society of New Zealand miscellaneous publication 154A. p. 140.

5.5 Student Theses

Brough, T., 2019. Tectonic Geomorphology and Paleoseismology of The Humps Fault Zone, North Culverden Basin. MSc thesis, University of Canterbury, 93 p

Bushell, T 2019. Tectonic geomorphology and paleoseismology of The Leader Fault Zone, North Canterbury. MSc thesis, University of Canterbury, 93 p

Hyland-Brook, N. 2018. Geometry and kinematics of the South Leader Fault: insights from the 2016 MW 7.8 Kaikoura earthquake. MSc thesis, University of Canterbury, 112 p.

Scott, B., 2019. The Stone Jug Fault: facilitating sinistral displacement transfer during the M_W 7.8 Kaikōura Earthquake. MSc thesis, University of Canterbury, 112 p.

5.6 Scientific Papers

The following scientific papers have been published or are in review in scientific journals during this project:

Diederichs, A., Nissen, E.K., Lajoie, L.J., Langridge, R.M., Malireddi, S.R, Clark, K.J., Hamling, I.J., Tagliasacchi, A. 2019. Unusual kinematics of the Papatea fault (2016 Kaikōura earthquake) suggest anelastic rupture. Science Advances, doi: 10.1126/sciadv.aax5703.

Hatem, A.E., Dolan, J.F., Zinke, R.W., Van Dissen. R.J., McGuire, C.M., Rhodes, E.J. 2019. A 2000 yr paleoearthquake record along the Conway segment of the Hope Fault: Implications for patterns of earthquake occurrence in northern South Island and southern North Island, New Zealand. Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120180313.

Howell, A., Nissen, E., Stahl, T., Clark, K., Kearse, J., Van Dissen, R., Villamor, P., Langridge, R.M., Jones, K, (in review 2019). 3D surface displacements during the 2016 MW 7.8 Kaikōura earthquake (New Zealand) from photogrammetry-derived point clouds. For: Journal of Geophysical Research — Solid Earth.

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

A further five papers were published in the Bulletin of the Seismological Society of America, Special volume on the 2016 Kaikōura Earthquake in 2018, on the topic of the surface rupture of faults (see Volume 108, Number 3B).

5.7 Media Engagement and GNS Outreach

An important component of this project was to communicate our results to the general public through media engagement. The following is a list of direct media engagement and material produced through GNS Science.

New Zealand Herald coverage of the Papatea Fault:

https://www.nzherald.co.nz/national-video/news/video.cfm?c_id=1503075&gal_cid=1503075&gallery_id=200598

https://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=12273002

The Papatea Fault is also highlighted in this NIWA video:

https://vimeo.com/205492748

Julian Thomson of GNS Science was used throughout the Kaikōura earthquake response and subsequent NHRP-funded science to collect still frame, drone and interview coverage for his GNS blog. This material is summarised at:

https://www.youtube.com/watch?v=L3CrEiWo7fY — this video features Kate Clark talking about the Papatea Fault at the coast

https://www.youtube.com/watch?v=tzh0_CibQzY — this video features Rob Langridge talking about the Papatea Fault along its length

This is a GNS Science article written for the third anniversary of the Kaikōura quake:

https://www.gns.cri.nz/Home/News-and-Events/Media-Releases/Scientists-explain-unusual-behaviour-of-Papatea-Fault-03-10-2019

Stuff media coverage of the Papatea Fault:

https://www.stuff.co.nz/environment/116279892/kaikura-quake-unusual-papatea-fault-produced-a-19km-surface-rupture-raising-land-8m

6.0 DISCUSSION

This work has significantly advanced our understanding of the activity of faults in the North Canterbury (NCD) region. NHRP- and EQC-funded research into the paleoseismicity of NCD faults versus Marlborough (MFS) faults indicated that in general the NCD faults, e.g. The Humps, Leader, Stone Jug, Hundalee faults, each have multiple Holocene earthquake ruptures with an average recurrence interval of 2500–4000 years (where long enough records exist). This is similar to the three earthquake fault sources identified in the North Canterbury region (in Figure 6.1) prior to these studies, i.e. for fault sources within the national seismic hazard model (NSHM). For instance, the Hundalee, Lowry and Kaiwara N earthquake fault sources have derived average recurrence intervals of 3000–3200 years (Stirling et al. 2012). Nonetheless, the results of this work indicate that the area that includes the Humps, Leader, Conway-Charwell and Stone Jug faults was previously under-represented in the NSHM (Figure 6.1). This is particularly evident in that slip rates of c. 0.5 mm/yr have been calculated for The Humps Fault in this study. Results from this study indicate that these faults may operate together in multi-fault earthquake ruptures or rupture in a sequence over relatively short time periods (years to centuries) in a cluster of seismic release.

In contrast, the average recurrence interval for faults in the south-eastern part of the MFS, including the Hope, Jordan, Kekerengu and Papatea faults is on the order of 300–500 years (Langridge et al. 2003; Little et al. 2018; Hatem et al. 2019). Importantly, new results from this project indicate that the Papatea Fault has had at least three earthquake ruptures during the past 1000 years.

The starting hypothesis of this project was "do these (2016 Kaikōura Earthquake) faults operate together in every earthquake or earthquake cycle", and we were able to reach a consensus on this based on results from paleo-earthquake studies. The recurrence interval of MFS faults in the core of the plate boundary zone is about one tenth of those in the NCD region. This suggests that the occurrence of the 2016 Kaikōura earthquake, in rupturing more than 20 faults across both the NCD and MFS regions was an unlikely event to occur. Multi-fault ruptures such as the 2016 earthquake have been incorporated into the next generation of seismic hazard models (Goded et al. 2018), however, it has been assigned a low level of probability of occurrence. Other combinations of fault sources, especially ones that involve a smaller number of faults sources, e.g. the Jordan-Kekerengu-Needles ‘earthquake fault source’ (Figure 6.1), have a higher probability of occurrence and this is consistent with our paleoseismic studies that show multi-fault ruptures within the NCD and the MFS have possibly occurred in the past.

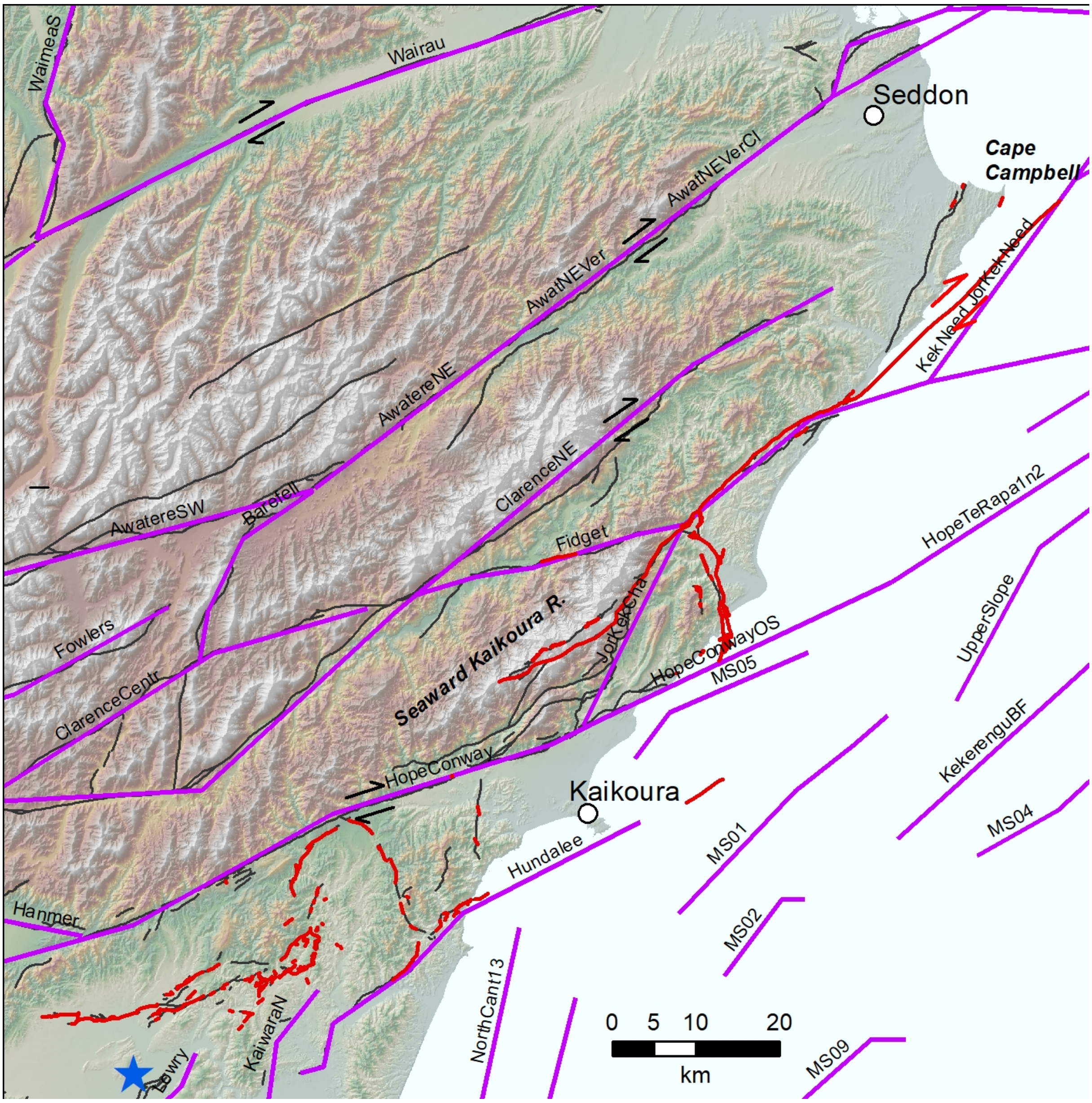

Figure 6.1 Earthquake fault sources of the national seismic hazard model (NSHM; purple) and 2016 fault ruptures (red). The faults of the epicentral area, north of the blue star, is an area of under-represented seismic hazard in the NSHM (2012). This version of the NSHM has been updated by Goded et al. (2018).

7.0 ACKNOWLEDGEMENTS

We wish to thank the many landowners for access to land, especially to the Murray and King families in the Clarence valley. We also thank Regine Morgenstern, Colin Amos, Stephane Baize, Jack Williams, Jesse Kearse, Lisa Dowling, Andy Howell, Julian Garcia-Mayordomo, Kirsten Deuss, Ed Nissen, Ian Hamling, Élyse Gaudreau, Anna Diederichs and many from the University of Canterbury team for help in the field. We also thank Margaret Norris, Jenny Dahl and Jocelyn Turnbull at the Rafter Radiocarbon Lab for their assistance and advice on radiocarbon dating. This report was reviewed by Pilar Villamor and Nicola Litchfield and we thank them for their interest and comments

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Clark KJ, Nissen E, Howarth JD, Hamling I, Mountjoy J, Ries W, Jones K, Goldstien S, Cochran U, Villamor P, et al. 2017. Highly variable coastal deformation in the 2016 MW7.8 Kaikōura earthquake reflects rupture complexity along a transpressional plate boundary. *Earth and Planetary Science Letters*.474:334–344. doi:10.1016/j.epsl.2017.06.048.

Clark KJ, Upton P, Langridge RM, Kelly K, Hammond KAT, editors. c2017. Proceedings of the 8th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology: handbook and programme. 2017 Nov 13-16; Blenheim, New Zealand. Lower Hutt (NZ): GNS Science. 445 p. (GNS Science miscellaneous series; 110).

Coulter RF. 2007. Tectonic geomorphology and seismic hazard of the Mt Fyffe section of the Hope Fault [MSc thesis]. Christchurch (NZ): University of Canterbury. 211 p. + map.

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

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APPENDICES

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APPENDIX 1 WORKSHOP AGENDAS

A1.1 Workshop 1

The key components of the Field Workshop were:

1. An opening dinner in Blenheim and evening ‘speed talks‘.

Speed talks were designed to provide 5–10-minute snapshots introducing the group to each of the forthcoming field trip stops. This was also an opportunity for students to give presentations in front of peers describing areas that could not always be visited on the field trip.

Day 1

1. Description of pre- and post-earthquake trenching across the Kekerengu Fault (led by Russ Van Dissen and Jesse Kearse).
2. Introduction to Papatea Fault trench sites and challenges, and landscape change in the lower Clarence valley (led by Rob Langridge and Peter Almond).
3. A walk-through coastal terrace uplift in the Papatea fault zone at Waipapa Bay (led by Kate Clark).
4. Description of surface faulting and trench sites along the Seaward section of the Hope Fault (led by Jarg Pettinga).
5. Dinner in Kaikōura and speed talks for Day 2.

Day 2

6. Discussion of a trench study on the Hundalee Fault (led by Mark Stirling).
7. Drive through to Waiau for lunch, stopping at surface rupture localities.
8. Discussion of trenching studies on The Humps Fault (led by Tom Brough and Andy Nicol).

Field trip attendees were:

- Rob Langridge, Kate Clark, Nicola Litchfield, Russ Van Dissen (GNS Science)
- Jesse Kearse, Andy Howell (Victoria University of Wellington)
- Andy Nicol, Jarg Pettinga, Kate Pedley, Tom Brough, Tabitha Bushell, Bradley Scott (University of Canterbury)
- Mark Stirling, Samantha Allan, Ella van den Berg (University of Otago)
- Peter Almond (Lincoln University) and
- Caleb Gasston (University of Auckland).

A1.2 Workshop 2

The morning session was dedicated to talks on regional deformation (Andy Howell, Tim Stahl), North Canterbury aftershocks (Kate Pedley), the paleoseismicity of NCD faults (Andy Nicol, Tabitha Bushell), and research into Kaikoura landslides (Caleb Gasston).

The afternoon session was dedicated to Marlborough Fault System (MFS) faulting with talks on the Hope Fault (Jarg Pettinga), coastal uplift and deformation (Kate Clark), the Papatea Fault (Rob Langridge), and Kekerengu Fault studies (Philippa Morris).

Workshop attendees were:

- Rob Langridge, Kate Clark, Nicola Litchfield, David Barrell, Jesse Kearse (GNS Science)
- Tim Little, Philippa Morris (Victoria University of Wellington)
- Andy Nicol, Jarg Pettinga, Kate Pedley, Tabitha Bushell, Andy Howell (University of Canterbury) and
- Caleb Gasston (University of Auckland.

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