**Repeating Earthquake Detection and
Characterisation in New Zealand:
A Catalogue for the Raukumara Peninsula,
Northern Hikurangi Subduction Margin**

By

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Abstract

Repeating earthquakes provide a novel way of monitoring how stresses load faults between large earthquakes. In this thesis, we develop a method and composite criterion for identifying repeating earthquakes in New Zealand and present New Zealand's first long-duration repeating earthquake catalogue. This thesis addresses three primary objectives: (1) develop a method and composite criterion for identifying repeating earthquakes; (2) build a long-duration catalogue of repeating earthquakes for the Raukumara Peninsula; and (3) apply the method and composite criterion in different tectonic settings to investigate whether it can be applied more broadly elsewhere in New Zealand. The systematic identification of repeating earthquakes in New Zealand provides the first step in being able to monitor the state of stresses of New Zealand's active faults in situ throughout the earthquake cycle.

Studies elsewhere, particularly in Japan and California, have developed case-specific criteria for identifying repeating earthquakes. Building on these studies, we develop a method and composite criterion for identifying repeating earthquakes in New Zealand, focusing on seismicity around the Raukumara Peninsula. Our composite criterion states that for events to be identified as repeating earthquakes, two or more events must have a normalised cross-correlation of at least 0.95 at two or more seismic stations, when calculated for 75% of the earthquake coda. Sensitivity to correlation window length, filtering frequency-band and correlation threshold were tested during the development of the composite criterion. These tests indicated that small perturbations to the parameter thresholds did not affect our ability to detect repeating earthquakes using the composite criterion.

By applying our composite criterion to seismicity around the Raukumara Peninsula, we identified 62 repeating earthquake families occurring between 2003 and 2018, consisting of 160 individual earthquakes. These families have a magnitude range of M_W 1.5–4.5, and have recurrence intervals and family durations of <1–12 years. High-precision absolute and relative locations were calculated using manual phase picks and cross-

correlation re-picking. Focal mechanisms for 56 of the families were also determined, using P-wave first motions, revealing predominantly strike-slip and normal faulting at shallow depths, low-angle reverse faulting along the subduction interface, and normal faulting in the subducting plate. We compared the timing of the repeating earthquakes to slow-slip events previously identified using geodetic measurements around the Raukumara Peninsula and observed that repeating earthquakes occurred during 26 of the 31 identified periods of slow-slip. We also compared the seismic moment–recurrence interval relationship of the Raukumara Peninsula repeating earthquakes to that of earthquakes near Parkfield, California, identified by Nadeau and Johnson (1998), and observed a similar functional relationship. Slip-rates of the Raukumara Peninsula repeating earthquake families were also calculated using a slip-rate–moment relationship and were found to vary from <10 mm/yr to ~ 80 mm/yr.

We applied the method and composite criterion developed for the Raukumara Peninsula to two other locations to ensure it could be applied successfully in other New Zealand regions with different seismotectonic characteristics. Using our workflow, we successfully identified four families in Marlborough, and three families around Fiordland. These families differ from those identified around the Raukumara Peninsula in that they had relatively short recurrence intervals and family durations, of 2 minutes–15 months. The ability of the composite criterion to identify these families confirms its suitability for further studies of repeating earthquakes throughout New Zealand.

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Chapter 1

Introduction

How stress loads faults in the run-up to large earthquakes, and what impact this has on earthquake nucleation and dynamics, remains a significant challenge in understanding earthquake physics (Kanamori and Brodsky, 2001). Repeating earthquakes, which are earthquakes that re-rupture the same fault patch at different times, provide one way of monitoring these processes (Uchida et al., 2003). In New Zealand, little attention has been paid to repeating earthquakes, despite long-duration seismic data. In this thesis, we develop a method and composite criterion for detecting repeating earthquakes and construct the first decadal-scale catalogue of tectonic repeating earthquakes anywhere in New Zealand. We¹ focus on the Raukumara Peninsula region, which hosts various seismic and aseismic phenomena, and construct a catalogue spanning the years 2003 to 2018.

The first part of this chapter addresses the motivations and objectives of this research (Sections 1.1 and 1.2). This is followed by an overview of the tectonic and geological settings of the Raukumara Peninsula (Section 1.3). Finally, this chapter will cover the remaining layout of the thesis (Section 1.4).

¹This thesis documents original research conducted by me, Laura Hughes, under the supervision of Calum Chamberlain and John Townend. To reflect standard scientific practice and my supervisors' input throughout the project, and in anticipation of publishing these findings as a peer-reviewed manuscript, the thesis is written in the first person plural (“we”).

1.1 Motivation

Understanding the continuum of seismic and aseismic phenomena associated with faulting is crucial for understanding the physics of earthquakes (Kanamori and Brodsky, 2001; Peng and Gomberg, 2010). Specifically, observing how faults are loaded towards eventual failure in large earthquakes may be key to understanding how earthquakes start (Mavrommatis et al., 2015). New Zealand provides an ideal natural laboratory for understanding these processes due to the range of tectonic settings. This is due to New Zealand being located on a geometrically and tectonically complicated plate boundary, with the Hikurangi Margin lying to the east (Bassett et al., 2014; Williams et al., 2013), the Alpine and Marlborough Fault Systems through the South Island (Langridge et al., 2010), and the Puysegur Subduction Zone to the south west (Figure 1.1; Lamarche and Lebrun, 2000, Reyners et al., 2002).

Figure 1.1: Map of New Zealand showing the Australian-Pacific Plate boundary. The red box shows the location where this study was focused, and the blue boxes show where the final repeating earthquake identification composite criterion was tested.

At the Puysegur Subduction Zone, the Australian Plate obliquely subducts beneath the Pacific Plate (Boese et al., 2013; Hayes and Furlong, 2010; Lamarche and Lebrun, 2000; Reyners et al., 2002; Sutherland et al., 2006). Further north, the plate boundary transitions to a transpressive faulting regime which accommodates oblique strike-slip motion along the Alpine Fault (Norris and Toy, 2014). The plate boundary transitions, through the Marlborough Fault System, to the Hikurangi Margin, which extends the length of the North Island (Barnes and Audru, 1999; Clark et al., 2019). Here, the Pacific Plate is obliquely subducting beneath the Australian Plate at rates varying from 27 mm/yr in the south to 57 mm/yr in the north (Wallace et al., 2004, 2009; Wallace and Beavan, 2010). Due to the complexity of the plate boundary system through New Zealand, the prospect of large-magnitude earthquakes occurring has been extensively studied (e.g. Berryman et al., 2012; Boulton et al., 2018; Clark et al., 2015, 2019; Howarth et al., 2018; Kaneko et al., 2018; Sutherland et al., 2007; Wallace et al., 2014). Along the Hikurangi Margin, the interplay between seismic and aseismic phenomena has also been investigated, and is discussed further in Section 1.3.3 (e.g. Douglas et al., 2005; Todd and Schwartz, 2016; Wallace et al., 2016, 2018; Warren-Smith et al., 2018).

Repeating earthquakes are one group of seismic events in New Zealand that remain relatively unstudied. Repeating earthquakes have been the subject of extensive research at other plate boundary zones, notably the Japan Trench (e.g. Geller and Mueller, 1980; Hatakeyama et al., 2017; Kimura et al., 2006; Mavrommatis et al., 2015; Uchida et al., 2003, 2010, 2015; Yamanaka and Kikuchi, 2004) and the San Andreas Fault system (e.g. Chen and Lapusta, 2009; Igarashi, 2010; Nadeau et al., 1994, 1995; Nadeau and Johnson, 1998; Schaff and Beroza, 2004; Thomas et al., 2009; Williams et al., 2019), as well as China (e.g. Schaff and Richards, 2004, 2011), Taiwan (e.g. Chen et al., 2008; Rau et al., 2007) and the Tonga–Kermadec Trench (e.g. Yu (2013); Figure 1.2). Repeating earthquakes can provide information on the stresses that are loading faulting and the magnitude of those stresses (e.g. Lui and Lapusta, 2018; Marone et al., 1995). Moreover, repeating earthquakes can provide a novel way of monitoring fault slip-rates at depth (e.g. Igarashi et al., 2003; Uchida and Matsuzawa, 2013).

The underlying motivation behind this study is to construct the first long-duration catalogue of tectonic repeating earthquakes in New Zealand. In order to complete this, we need to develop and validate a method and criterion for identifying repeating earthquakes in New Zealand. This will provide the basis for future repeating earthquake catalogues in New Zealand to be created. The creation of a long-duration repeating earthquake catalogue for New Zealand will enable future research into how faults are moving at depth, or being loaded by background slip, and how seismic and aseismic phenomena interact. In addition, the catalogue will enable comparisons between

the New Zealand repeating earthquakes, and global repeating earthquake studies (e.g. Nadeau and Johnson, 1998; Uchida et al., 2003).

Figure 1.2: World map highlighting the locations of repeating earthquake studies. Locations have been adapted from Uchida and Bürgmann (2019) Supplemental Table 1.

1.2 Primary objectives

The primary goal of this research is to construct a robust method and composite criterion for identifying repeating earthquakes throughout New Zealand. We address this via three objectives;

1. Develop a method and composite criterion for identifying repeating earthquakes using the seismicity around the Raukumara Peninsula. This involves taking the GeoNet clustered catalogue, created by Chamberlain et al. (2019), and developing a method for extracting repeating events based on waveform similarity and/or location similarity. The Raukumara Peninsula was chosen as the case study area to form the initial catalogue due to the high levels of seismicity around the region and a number of already documented complex interactions between seismic and aseismic phenomena (Wallace, 2020);
2. Using the method and composite criterion developed in Objective 1, construct a catalogue of repeating earthquakes that occurred around the Raukumara Peninsula between 2003 and 2018;

3. Apply the methods and composite criterion used to identify repeating earthquakes around the Raukumara Peninsula to two different tectonic settings in New Zealand, to investigate whether it can be applied more broadly around New Zealand. These two locations are Marlborough and Fiordland.

1.3 Study location: Raukumara Peninsula

The Raukumara Peninsula is situated on the northeast corner of the North Island, New Zealand (Figure 1.1). The regional tectonic and geological settings are discussed in the following sections, along with the seismic and aseismic phenomena that have been documented around the region in recent years.

1.3.1 Regional tectonic setting

Subduction along the Hikurangi Margin commenced $\sim 24\text{--}30$ Ma, with the majority of this motion being accommodated along the subduction thrust (Nicol and Wallace, 2007). Upper plate reverse and strike-slip faulting helped to accommodate the remainder of this motion (Nicol and Wallace, 2007). Rapid uplift occurs within the Raukumara Ranges, with the central portion of the ranges experiencing the highest uplift rates (Litchfield and Berryman, 2006). Uplift is suggested to be controlled by sediment subduction and underplating beneath the Raukumara Ranges, as the sediments impinge on a shallow, mantle backstop (Litchfield et al., 2007; Reyners et al., 1999). Seamount subduction may also contribute to uplift on the east coast of the Raukumara Peninsula (Litchfield et al., 2007). Additionally, normal faulting around the Raukumara Peninsula helps accommodate the extension resulting from this rapid uplift (Clark et al., 2010).

The present tectonic setting is dominated by the Hikurangi Margin, which lies to the east, and below, the Raukumara Peninsula. Here, the Pacific Plate is subducting beneath the Australian Plate at a rate of $50\text{--}60$ mm/yr (Wallace et al., 2004). Rapid clockwise rotation of the eastern North Island forearc results in back-arc rifting to the west of the Raukumara Peninsula in the Taupō Volcanic Zone (Wallace et al., 2004; Wilson et al., 1995). Beneath the East Coast, the plate interface is located at $\sim 12\text{--}15$ km, and progressively deepens to ~ 50 km depth beneath the western side of the Raukumara Peninsula (Williams et al., 2013). Faults in the North Island Dextral Fault Belt to the west of the Raukumara Peninsula accommodate much of the right-

lateral strike-slip component of the Australia-Pacific relative plate motion (Beanland, 1995; Nicol and Wallace, 2007; Wallace et al., 2004). Additionally, reverse faults have been imaged offshore of the Raukumara Peninsula, and further help accomodate the relative plate motion (Figure 1.3; Barnes et al., 2010, Litchfield et al., 2020, Mountjoy and Barnes, 2011)

Figure 1.3: Map of the Raukumara Peninsula showing both the onshore and offshore faults (red lines; adapted from Litchfield et al., 2020), the subduction interface (black contours; adapted from Williams et al., 2013), and the generalised geology; Pahau Terrane (PA), the East Coast Allochthon (ECA) and Neogene strata (adapted from Eberhart-Phillips et al., 2017a and Reyners and McGinty, 1999). S1 and S2 are subducting seamounts, adapted from Bell et al. (2010). Black arrows represent the convergence rates at the trench, adapted from Wallace et al. (2012a).

1.3.2 Regional geology

The regional geology of the Raukumara Peninsula can be structurally divided into three main units; (1) the Pahau Terrane, (2) the East Coast Allochthon, (3) the Neogene marine sedimentary rocks (Mortimer, 2004; Reyners and McGinty, 1999).

The first unit is the Late Jurassic Pahau Terrane, which flanks the western edge of the Raukumara Peninsula (Figure 1.3; Adams et al., 2009, Mortimer, 2004). This terrane is predominantly inter-bedded sandstones and mudstones, which are the oldest basement rocks in the region (Adams et al., 2009). Early Cretaceous limestones and cherts are also included within these sandstone-mudstone layers (Mortimer, 2004).

The East Coast Allochthon is a belt of Late Cretaceous and Early Tertiary rocks, which were thrust over the Pahau Terrane during the Early Miocene (Figure 1.3; Moore, 1988 and Reyners et al., 1999). The Matakaoa Volcanics are the oldest rocks within the allochthon, and contain highly imbricated and deformed basalts and pillow lavas (Rait, 1992). Also included within the East Coast Allochthon are the allochthonous Cretaceous to Paleogene stratum (Thornley, 1996). These strata consists of alternating sandstone and mudstone, which transition into calcareous and smectitic mudstones, along with minor sandstone and limestone (Thornley, 1996)

The final unit is the Neogene marine sedimentary strata (Figure 1.3; Reyners et al., 1999, Stoneley, 1968). These strata have been faulted against the East Coast Allochthon (Thornley, 1996). Normal faulting, and folds, extend throughout the strata (Reyners and McGinty, 1999). The Neogene strata has also been intruded by dikes, and widespread mud volcanism continues today (Barnes et al., 2010; Reyners et al., 1999).

1.3.3 Seismic and aseismic phenomena observed

The interplay between the tectonic components discussed above results in a wide range of observable transient seismic phenomena throughout the region (Wallace et al., 2009). These include moderate to large magnitude earthquakes (Francois-Holden et al., 2008; Koulali et al., 2017; Warren-Smith et al., 2018), repeated episodes of slow-slip (e.g. Delahaye et al., 2009; Douglas et al., 2005; Wallace and Beavan, 2010; Wallace et al., 2012b, 2016, 2018; Wallace, 2020), tremor (Todd and Schwartz, 2016; Todd et al., 2018) and recently documented burst-type repeating earthquakes (Warren-Smith et al., 2018, Shaddox and Schwartz, 2019; Figure 1.4).

Figure 1.4: Map of the North Island and top of the South Island, New Zealand, showing the seismicity in 2019 catalogued by GeoNet². Circles represent the seismicity and are coloured by depth and scaled by magnitude. Red stars represent the earthquakes above magnitude 6.0 that have been recorded by GeoNet since 2001³. The orange box represents the region where burst-type repeating earthquakes have been identified (Shaddox and Schwartz, 2019), and the red box denotes the site of this research.

²<https://quakesearch.geonet.org.nz/csv?bbox=172,-43,180,-35&startdate=2019-01-01T0:00:00&enddate=2019-12-30T23:00:00>, last accessed 21/05/2020

³<https://quakesearch.geonet.org.nz/csv?bbox=172,-43,180,-35&minmag=6.0&startdate=2001-12-01T0:00:00&enddate=2019-12-30T23:00:00>, last accessed 21/05/2020

Several large earthquakes have occurred across the region in the last century. These include:

- Two M_W 7.2 tsunami earthquakes that occurred in March and May 1947, offshore of Gisborne and Tokomaru Bay (Bell et al., 2014; Doser and Webb, 2003). Tsunami earthquakes are earthquakes that result in larger tsunamis than would be expected by earthquakes of that magnitude (Pelayo and Wiens, 1992);
- A normal-faulting intraslab M_W 6.6 event offshore Gisborne in December 2007 (Francois-Holden et al., 2008);
- The M_W 7.1 Te Araroa earthquake that occurred in September 2016 (Koulali et al., 2017; Warren-Smith et al., 2018).

These larger events rarely occur in isolation, and often involve interactions with other seismic phenomena including those mentioned below.

Repeated slow-slip is a common occurrence along the eastern edge of the Raukumara Peninsula (Wallace, 2020). Slow-slip events (SSEs) involve earthquake-like slip on a fault at rates faster than the background plate motion, but below seismic speeds (Dragert et al., 2001). At the northern end of the Hikurangi Margin, SSEs typically occur every 18 to 24 months, but can have recurrence intervals of greater than two years, and durations of days to years (e.g. Douglas et al., 2005; Wallace and Beavan, 2010; Wallace et al., 2016). The equivalent moment release of these SSEs ranges from M_W 6.3 to 7.2, and they typically occur at depths of less than 15 km (Koulali et al., 2017; Wallace and Beavan, 2010). SSEs along the Hikurangi Margin have also been triggered by the 2016 M_W 7.8 Kaikōura in the weeks to months following the earthquake (Wallace et al., 2018).

There are complex spatiotemporal relationships between SSEs and other types of seismicity around the Raukumara Peninsula. Delahaye et al. (2009), Kim et al. (2011) and Todd et al. (2018), for example, examined the relationship between SSEs and tectonic tremor in the region. Northern Hikurangi SSEs tend to be accompanied by tremor, which typically occurs downdip of the geodetically determined slip patch, and towards the end of the SSE and continuing afterwards (Todd and Schwartz, 2016; Todd et al., 2018). While most common during the larger-magnitude SSEs around the Gisborne area, tremor has still been documented in smaller SSEs further north around the Tolaga Bay and Puketiti regions, but is often difficult to detect in offshore regions using New Zealand’s entirely land-based National Seismic Network (Todd and Schwartz, 2016; Todd et al., 2018). Additionally, close associations between SSEs and microseismicity

around the Northern Hikurangi Margin have also been documented (Delahaye et al., 2009).

Recently, repeating earthquakes have been identified around the Raukumara Peninsula. In the Te Araroa sequence, 113 distinct groups of repeating earthquakes were identified, with most events occurring within a day of each other (Warren-Smith et al., 2018). Repeating earthquakes have also been identified following the 2014 Gisborne SSE, in which they also coincide with tremor (Shaddox and Schwartz, 2019). These repeating earthquakes were inferred to occur on an upper-plate fracture network above a subducting seamount, and only occurred for a short time period (approximately seven weeks; Shaddox and Schwartz, 2019). However, no studies of long duration tectonic repeating earthquakes have been undertaken around the Raukumara Peninsula or New Zealand.

1.4 Thesis structure

This thesis consists of five chapters, including this Introduction, and is structured as follows.

Chapter two: Background

The first section of this chapter covers the general seismological theory that underpins the research undertaken. The focus of the chapters then turns to repeating earthquakes, including how they have been identified in previous studies elsewhere, and the theory behind their occurrence. Key definitions used throughout the thesis have been included in each of the sections.

Chapter three: Methods

This chapter outlines the processes undertaken to develop the composite criterion for detecting repeating earthquakes in New Zealand. It also documents the specific methods used to construct the catalogue of repeating earthquakes identified around the Raukumara Peninsula, including the methods used to obtain absolute and relative earthquake locations and calculations made using the final catalogue.

Chapter four: Results

This chapter is divided into four key sections. The first section covers the development of the components which combine to form the final composite criterion. The

second section provides detailed results of the Raukumara Peninsula repeating earthquake catalogue. The third section covers the repeating earthquakes identified around Marlborough and Fiordland. The final section of the chapter is a summary of the key results of this research.

Chapter five: Discussion and Conclusions

The first section of this chapter compares the repeating earthquake identification composite criterion identified for New Zealand with other studies' criteria, and discusses the reasoning behind the final parameters' choices and their ramifications. Analysis of the final catalogue, the repeating earthquakes locations, and comparisons to other repeating earthquake studies' previously established relationships follows. The final section of this chapter contains the key conclusions of this thesis, and potential future research.

Appendices:

Appendix A contains a set of tables outlining other studies that have identified and analysed repeating earthquakes. Appendix B provides further details of the iterations run to obtain the absolute and relative locations. Appendix C contains the final catalogue of repeating earthquakes identified around the Raukumara Peninsula, as well as details of the repeating earthquakes identified around Marlborough and Fiordland. Appendix D contains further details of the focal mechanisms calculated.

A reference for the acronyms used throughout this thesis is included in Table 1.1.

Table 1.1: List of acronyms used in thesis

Acronym	Definition
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
M_L	Local Magnitude
M_W	Moment Magnitude
M_0	Seismic Moment
SSE	Slow-slip event

Chapter 2

Background

In this chapter, we firstly outline the background general seismological theory that underpins this research (Section 2.1). We next cover how repeating earthquakes are identified and the theory that underpins repeating earthquake studies, and the analysis in later chapters (Sections 2.2–2.3). Definitions of some of the key terms used throughout this thesis are included at the start of each section.

2.1 General seismological theory

2.1.1 Seismic waveforms

The seismogram recorded at a particular sensor in response to an earthquake, $u(t)$, is composed of components detailing the earthquake source signal, or source time function, $x(t)$, the effects of the earth’s structure, $e(t)$ and $q(t)$, and the instrument response of the seismometer, $i(t)$ (Stein and Wysession, 2009);

$$u(t) = x(t) * e(t) * q(t) * i(t) \tag{2.1}$$

where $*$ indicates the convolution of each of these elements (Hartzell, 1978). Here, $x(t)$ is determined by the type of faulting and rupture process, as well as the size of the earthquakes (Aki, 1972; Hartzell, 1978). As repeating earthquakes are assumed to rupture the same fault patch, and have similar magnitudes, this term should be the same for all the repeating earthquakes. $e(t)$ describes the effect of reflections and conversions of the seismic waves at different interfaces along the source to receiver path, as well as how the velocity structure affects the geometric spreading of the seismic

rays (Lay and Wallace, 1995; Stein and Wyssession, 2009). $q(t)$ describes the anelastic attenuation of the waves (Lay and Wallace, 1995; Stein and Wyssession, 2009). The path from the source of the earthquake to the receiver should be similar, assuming negligible changes in the velocity structure through time, resulting in the same $e(t)$ and $q(t)$ components making up the seismogram. However, small changes in the path will decrease the waveform similarity for otherwise repeating earthquakes. Finally, provided event waveforms are always compared on the same station, $i(t)$ will be the same for all events. If instrumentation changes, an instrument correction must be applied to remove any variations with time. All of the above components allow the waveforms to be used as a way of identifying repeating earthquakes due to their assumed similarities.

2.1.2 Absolute earthquake locations

Absolute locations are earthquake locations in absolute space and time, and can be calculated using single-stations, networks or arrays (Aki and Richards, 1980). It is one of the oldest inverse problems in seismology (Aki and Richards, 1980). A number of factors influence absolute locations, which can result in significant errors associated with the final locations. These factors include arrival-time reading accuracy, network geometry, and knowledge of the underlying velocity structure (Waldhauser and Ellsworth, 2000).

Although other methods are available (e.g. back-propagation or migration; Langet et al., 2014 and Yao et al., 2012), the inversion of arrival-time data is well suited to our network geometry, and provides good comparison with other earthquake locations in the New Zealand national catalogue. This method requires the time of the P- and S-wave first arrivals (Guo and Zhang, 2017). For a homogeneous half-space model, the timing of the body wave first arrivals (t) can be related to the hypocentre parameters (X, Y, Z), which are in Cartesian co-ordinates, and origin time (T), using Equation 2.2, where subscript i denotes the values at the i^{th} station, and v is the velocity of the homogeneous half-space (Stein and Wyssession, 2009).

$$t_i = T + \frac{1}{v} \sqrt{(X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2} \quad (2.2)$$

From Equation 2.2, the best hypocentre location is identified by minimising the residuals (r_i), between the calculated and observed travel times, at each of the seismic stations (Equation 2.3; Chamberlain, 2016).

$$r_i = t_i^{calc} - t_i^{obs} \quad (2.3)$$

The forward problem outlined above can be solved through an inverse approach by using the method derived by Geiger (1910), to locate local earthquakes, which relies on the expansion of the first-order Taylor series (Equation 2.4; Thurber, 1985) and the first-order partial derivatives.

$$r_i = \frac{\delta t_i}{\delta X} \Delta X + \frac{\delta t_i}{\delta Y} \Delta Y + \frac{\delta t_i}{\delta Z} \Delta Z + \Delta t_0 \quad (2.4)$$

$$\frac{\delta t_i}{\delta X} = \frac{X - x_i}{vS} \quad \frac{\delta t_i}{\delta Y} = \frac{Y - y_i}{vS} \quad \frac{\delta t_i}{\delta Z} = \frac{Z - z_i}{vS} \quad (2.5)$$

Here, t_0 is the origin time, the terms before Δ are adjustments that are made to the model hypocentre, and the path length term S is added.

For each of the events being located, the timing of at least four first arrivals must be identified before locations can be obtained (Stein and Wyssession, 2009). Locations are found by minimising the residuals between the predicted and observed arrival times of the P- and S-wave first arrivals by iterative inversion algorithms (Grigoli et al., 2013). However, there are two key factors that can influence the accuracy of the locations found using this method. Firstly, an inaccurate background velocity structure used in the travel time calculations (Guo and Zhang, 2017). Secondly, insufficient network geometry will also influence the accuracy of the locations (Guo and Zhang, 2017).

Arrival time reading accuracy is an important factor that can introduce error into absolute earthquake locations. Slunga et al. (1995) state that an error of 0.1 seconds in the identification of the P-wave first arrival corresponds to a distance of 650 m. The errors associated with the S-wave first arrivals tend to be larger than the P-wave first arrivals due to difficulties identifying when the S-wave is occurring due to the overlap of other waves which are arriving at a similar time, as well as fewer physical constraints on the arrivals (Slunga et al., 1995). These errors are dependent on the velocity structure that is used in the location process (Slunga et al., 1995). In general, pick uncertainties can result in location errors in the range of 500-700 m in the horizontal coordinate system and approximately 1000 m in the vertical (Slunga et al., 1995). To reduce these errors the majority of location algorithms minimise a weighted square sum of the arrival time residuals (Slunga et al., 1995).

Network geometry and coverage can heavily influence the accuracy and stability of earthquake hypocentre calculations (Ellsworth and Roecker, 1981; James and Sacks, 1969). In order to achieve accurate and stable hypocentral locations, the network should ideally have a large number of stations that provide good azimuth and range distribution relative to the epicentre of the earthquake (Ellsworth and Roecker, 1981).

This allows for a wide distribution of ray take-off angles and azimuths from source to stations (James and Sacks, 1969). The term azimuthal gap refers to the largest open azimuth between recording stations, with errors associated with the absolute location decreasing with decreasing azimuthal gap (Bai et al., 2006). In general, if events occur along the outer boundary or outside of the network aperture, then the location solution is likely to be unstable, whereas those events which are located within the network are more likely to be stable (James and Sacks, 1969). When a network contains many stations that provide good coverage of the earthquake location, uncertainties can still arise due to a trade-off between focal depth and origin-time of the event, with the degree of sensitivity in the location increasing with increasing focal depth of the event (Nordquist, 1962). Overall, the network geometry, coverage and density all provide controls on the final earthquake hypocentre locations and the associated uncertainties.

Lack of knowledge of the velocity structure of the region can significantly impact the final locations. One dimensional (1D) and three dimensional (3D) velocity models of the subsurface can be used in the location process, depending on the location algorithm and software used. While using a three dimensional velocity model can significantly improve earthquake locations, if the model does not accurately reflect the structure of the region, then the earthquake locations can be severely impacted (Boese et al., 2012). If the 3D velocity model does not accurately reflect the horizontal velocity changes, then the errors associated with the absolute location may be larger than if a 1D velocity model had been used (Theunissen et al., 2017). This is dependent on how well each of the models fit the underlying structure.

2.1.3 Relative earthquake locations

Unlike absolute earthquake locations, relative locations are usually found by analysing multiple closely-spaced earthquakes simultaneously, and relocating the events relative to one another (Waldhauser and Ellsworth, 2000). One benefit of using relative locations over absolute locations is that velocity model errors can be minimised, increasing the precision of the locations (Waldhauser and Ellsworth, 2000).

The most commonly used method to obtain relative earthquake locations is double-difference. Similar to the absolute location methods, an earthquake's relative location is found by minimising the double difference residual (dr_k^{ij}) between a pair of earthquakes, i and j (Equation 2.6; Waldhauser and Ellsworth, 2000).

$$dr_k^{ij} = (t_k^i - t_k^j)^{calc} - (t_k^i - t_k^j)^{obs} \quad (2.6)$$

Equation 2.6 relies on the assumption that the travel path for both of the events between the source and the receiver is constant, which requires events to be sufficiently close together. By expanding Equation 2.6 with the origin times and travel path, Waldhauser and Ellsworth (2000) arrived at Equation 2.7.

$$dr_k^{ij} = \frac{\delta t_k^i}{\delta x} \Delta x^i + \frac{\delta t_k^i}{\delta y} \Delta y^i + \frac{\delta t_k^i}{\delta z} \Delta z^i + \Delta \tau^i - \frac{\delta t_k^j}{\delta x} \Delta x^j - \frac{\delta t_k^j}{\delta y} \Delta y^j - \frac{\delta t_k^j}{\delta z} \Delta z^j - \Delta \tau^j \quad (2.7)$$

where t is the vector of the travel times, x, y, z is the locations coordinates and τ is the origin time (Waldhauser and Ellsworth, 2000). In Equation 2.7, Δx , Δy , Δz and $\Delta \tau$ are the changes required in the hypocentral parameters, to obtain the best fit of the model to the data (Waldhauser and Ellsworth, 2000). The iterative changes to the parameters required to obtain the best fitting model are computed by a least squares inversion for all the stations and all the hypocentral pairs (Waldhauser and Ellsworth, 2000). This allows for the location errors to be minimised due to uncertainties in the velocity structure that is being used in the relocation (Waldhauser and Ellsworth, 2000). In order to obtain relative hypocentre location in HypoDD, a combination of catalogue-derived travel-time differences between events, and cross-correlation data, an a priori weighted by the squared coherency, is added to the P- and S-wave travel times of the events (Figure 2.1).

Figure 2.1: Illustration of the HypoDD relocation algorithm adapted from Waldhauser and Ellsworth (2000). Here, events i and j are being relocated relative to each other, from their original hypocentral locations (open blue circles). By iteratively altering the hypocentre location (black circles) the event locations which best fit the model and the data are obtained. The orange arrows indicate the final relocation vector for events i and j.

2.1.4 Earthquake magnitude scales

Earthquake magnitude is a single number that quantifies the size of an earthquake (Lee et al., 1981). Originally developed for earthquakes occurring in southern California, local magnitudes (M_L) are calculated using Equation 2.8, where A is the maximum amplitude on a Wood-Anderson seismometer in millimetres, Δ is epicentral distance, and A_0 is the maximum trace amplitude of the zero-magnitude earthquake (e.g. Duda and Nuttli, 1974; Gutenberg and Richter, 1942; Lee et al., 1981):

$$M_L = \log_{10} A(\Delta) - \log_{10} A_0(\Delta) \quad (2.8)$$

The zero-magnitude earthquake was arbitrarily defined by Richter (Richter, 1935) to be an earthquake which has a maximum trace amplitude of $1 \mu\text{m}$ at a distance of 100 km (Duda and Nuttli, 1974). The fall-off of amplitude with epicentral distance, as specified by the zero-magnitude earthquake, only applies to southern California, resulting in the relationship having to be uniquely scaled to different regions in order to cover global earthquakes (e.g. Boese et al., 2012; Duda and Nuttli, 1974; Gutenberg and Richter, 1942; Lee et al., 1981; Michailos et al., 2019).

The moment magnitude (M_W) scale was formed to provide a way of directly linking seismologically observable magnitudes to the source processes of an earthquake (Stein and Wyssession, 2009). To calculate M_W (Equation 2.9; Hanks and Kanamori, 1979), seismic moment (M_0) needs to be calculated (Equation 2.10; Madariaga, 1977), where μ is the rigidity of the elastic medium surrounding the fault, $\bar{D}$ is the average slip, or dislocation, on the fault with area S .

$$M_W = \frac{3}{2} \log M_0 - 16.1 \quad (2.9)$$

$$M_0 = \mu \bar{D} S \quad (2.10)$$

The magnitude scales discussed above do not stand in isolation, as magnitudes from different scales can be converted in order to compare earthquake sizes. For example, M_L can be scaled so that it is related to M_W (Michailos et al., 2019; Ristau, 2009). However, due to the magnitude saturation and depth constraints, care needs to be taken to only convert within the bounds of the scale.

2.1.5 Gutenberg-Richter relationship

Also known as the frequency-magnitude relationship, the Gutenberg-Richter relationship quantifies the relationship between the number of earthquakes of a given magnitude in a set period of time and their magnitudes (Gutenberg and Richter, 1944). The relationship is expressed below, where N is the number of earthquakes with magnitude greater than M occurring in a given time, and a and b are constants (Gutenberg and Richter, 1944);

$$\log N = a - bM \quad (2.11)$$

In Equation 2.11, the value of a is dependent on the seismicity rate and region sampled (Olsson, 1999). The value of b is related to the properties of the focal material and varies regionally, and with depth, but generally falls around one (Olsson, 1999). However, when calculated for earthquake swarms the b value can near 2.5 (Stein and Wysession, 2009). The relationship can provide insight into variations in frictional properties along the fault, and the potential controls on the recurrence of large earthquakes and the moment that is released by them (Stein and Wysession, 2009).

Figure 2.2: Frequency-magnitude histogram and cumulative density plot for all earthquakes in the GeoNet catalogue in 2019 that occurred around the North Island, New Zealand¹. The location of the seismicity used in the graph is plotted in Figure 1.4.

¹<https://quakesearch.geonet.org.nz/csv?bbox=172,-43,180,-35&startdate=2019-01-01T00:00:00&enddate=2019-12-30T23:00:00>, last accessed 21/05/2020

When this relationship is plotted alongside a $b = 0.96$, line deviations from this line are observed at both the lower and upper magnitudes (Figure 2.2; Stein and Wyssession, 2009). This is the result of the incompleteness of the seismic catalogue at the lower end of the magnitude scale, due to events not being catalogued, and saturation of magnitude at the higher end of the scale, or insufficient sampling duration (Stein and Wyssession, 2009). While there are some deviations from the expected line, this relationship is important for earthquake statistics as a way of quantifying the expected number of events of a given magnitude in time, which is critical to seismic hazard models (Stein and Wyssession, 2009).

2.1.6 Relationship between earthquake magnitude and source dimensions

An asperity is a strong patch on a fault plane (Aki, 1984). Slip is resisted on these strong patches, while the surrounding weaker fault plane continually creeps in response to the loading of tectonic stresses (Johnson, 2010). This results in a slip deficit, both on the asperity and in the shadow region created by the asperity (Figure 2.3; Johnson, 2010). The asperity will ultimately fail, resulting in an earthquake, when the stress on the asperity reaches a critical value, alleviating the slip deficit of both the asperity and the shadow (Johnson, 2010). Asperities vary in size, with large asperities resulting in larger earthquakes compared to smaller ones. Small asperities tend to surround larger asperities, especially at subduction zones (Johnson, 2010). It is assumed that these smaller surrounding asperities tend to host repeating earthquakes (Yamashita et al., 2012). Models of repeating earthquakes are centred around the idea of asperities, and are explained in detail in Section 2.3.

Figure 2.3: Model of an asperity on a plate boundary. No movement is observed on the asperities (black), resulting in a slip deficit in the slip shadows (grey). Adapted from Uchida et al. (2003).

Further to this, stress drop is the magnitude of stress released by an earthquake (Figure 2.4; Stein and Wyssession, 2009).

Figure 2.4: Stress cycle for an idealised earthquake cycle. Adapted from Stein and Wyssession (2009).

The magnitude of this stress release can be linked to the relationship between slip, fault dimensions and seismic moment of the earthquake (Stein and Wyssession, 2009). The average stress drop over a fault is approximated by Equation 2.12, where $\bar{D}$ is the slip that occurs on a fault with characteristic dimension L , and μ is the rigidity of the elastic medium (Stein and Wyssession, 2009).

$$\Delta\sigma = \mu\bar{D}/L \quad (2.12)$$

There are also a number of other methods that can be used to calculate stress drop, but each of the methods requires the estimation of the fault parameters (e.g. Abercrombie et al., 2016; Cotton et al., 2013). The calculated stress drop provides insight into the physics of the earthquake, for example how energetic the earthquake was (Brune, 1970). As a result the greater the amount of slip over the same source dimensions, the higher the stress drop will be, and vice versa (Brune, 1970; Kaneko and Shearer, 2015).

The magnitude of an earthquake can be directly related to the source dimensions of the asperity that ruptured, and the stress drop, if a circular source geometry is assumed. For a circular fault patch;

$$R = \left(\frac{7M_0}{16\Delta\sigma} \right)^{\frac{1}{3}} \quad (2.13)$$

where R is the radius of the fault patch, M_0 is the moment of the earthquake and $\Delta\sigma$ is the stress drop (Stein and Wyssession, 2009). This is based on a Brune earthquake source model (Brune, 1970). The Brune model is a semi-empirical and semi-theoretical model, belonging to suite of circular-shear dislocation models, and explains the rupture mechanics based on stress (Liu and Liu, 2012). There are two assumptions with this model; first is that at the moment of rupture, a stress is applied on the entire dislo-

cation circle, and is of the same magnitude as the released stress, but in the opposite direction (Liu and Liu, 2012). The second is that 80% of the total seismic-wave energy is taken up with the S-wave energy (Liu and Liu, 2012).

Equation 2.13 implies that larger earthquakes rupture larger asperities. When calculating source areas for repeating earthquakes a uniform stress drop is often assumed (Chen et al., 2007; Hatakeyama et al., 2017; Igarashi et al., 2003; Peng et al., 2005; Rubinstein and Ellsworth, 2010; Uchida, 2019). The assumed stress drop tends to vary between these studies ranging from 1 MPa to 20 MPa (e.g. Yu, 2013; Materna et al., 2018, respectively), but extremely high stress drops greater than 100 MPa have also been estimated (e.g. Matsuzawa et al., 2002). This is discussed further in Section 5.1.

2.2 Repeating earthquake identification

2.2.1 Definition of a repeating earthquake

Repeating earthquakes are identified first and foremost on the basis of highly similar waveforms, observed at multiple stations, which imply similar hypocentres and focal mechanisms (e.g. Nadeau et al., 1994; Nadeau and Johnson, 1998; Uchida et al., 2003; Zhang et al., 2008; Chen et al., 2013; Naoi et al., 2015; Li et al., 2018; Senobari and Funning, 2019). Due to their similarities, it is hypothesised that they represent the repeated rupture of the same strong asperity or fault patch (e.g. Ellsworth, 1995; Marone et al., 1995; Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999; Uchida et al., 2003; Vidale et al., 1994).

Repeating earthquakes have been documented most frequently on plate boundary faults, but also occur in a wide range of other settings including volcanoes, glaciers and landslides (Uchida and Bürgmann, 2019, and references therein). The occurrence of repeating earthquakes in non-tectonic settings can represent a wider range of mechanisms, rather the repeated rupture of the same fault patch (Uchida and Bürgmann, 2019, and references therein). For example, volcanic repeating earthquake can represent the movement of fluid in the region (Uchida and Bürgmann, 2019, and references therein). As discussed further in Section 2.3.1, repeating earthquakes can also be classified as either burst-type or continual-type.

2.2.2 Using waveform cross-correlation as an identification criterion

Waveform cross-correlation is the most commonly used method for identifying repeating earthquakes. The cross-correlation coefficient is a measure of the similarity of two time-series as a function of lag time, as shown in Equation 2.14;

$$C(\tau) = \frac{1}{N} \sum_{t=1}^N f_x(t) f_y(t + \tau) \quad (2.14)$$

Here f_x and f_y are two time-series with N discrete samples and τ is the lag time (Uchida and Bürgmann, 2019). An alternative that is used in repeating earthquake identification is normalised cross-correlation (e.g. Chen et al., 2008). Normalised cross-correlation allows for two different time series to be compared together, and there are a number of different techniques which allow it to be calculated. The most direct method involves dividing each inner product by the square root of the energy of the template and the time series to which it is being compared (Martin and Crowley, 1995). In this method, the template can be normalised before starting the correlation calculations (Martin and Crowley, 1995). Zero mean normalised cross-correlation is another method, whereby the mean is subtracted from both signals before computing the inner product of the energy of the signal being compared (Martin and Crowley, 1995). This must be completed unless the magnitude of the earthquake, and the noise, is assumed to be irrelevant. In this thesis we use normalised cross-correlation as implemented in EQcorrscan using the Equation 2.15:

$$c(\tau) = \frac{\sum_y (a_y - \bar{a})(b_{t+y} - \bar{b}_t)}{\sqrt{\sum_y (a_y - \bar{a})^2 \sum_y (b_{t+y} - \bar{b}_t)^2}} \quad (2.15)$$

where $c(\tau)$ is the normalised cross-correlation at time t , a is the template window which has length y , b is the continuous data, $\bar{a}$ is the mean of the template, and $\bar{b}_t$ is the local mean of the continuous data.

If cross-correlation or normalised cross-correlation is used in the identification process, it tends to only be calculated for event pairs that are within a given hypocentral distance, in order to reduce the computation power required (Igarashi et al., 2003; Uchida et al., 2003). In order for earthquakes to be classed as repeating, a normalised cross-correlation of at least 0.9 between the waveforms of the earthquakes, at multiple stations, is required (e.g. Nadeau et al., 1995; Nomura et al., 2017). Depending on the recorded signals, some studies use a normalised cross-correlation threshold of as low

as 0.8 to identify repeating earthquakes (e.g. Schaff and Richards, 2011). Table A.1 lists the different normalised cross-correlation thresholds used in studies to identify repeating earthquakes, as the determined threshold is study dependent.

Filtering of the waveforms is important in order to remove some of the noise, which is likely to reduce the normalised cross-correlation. However, it is important to retain the entire frequency bandwidth of the P- and S-waves (Bohnhoff et al., 2017; Igarashi et al., 2003; Uchida et al., 2003; Schaff and Richards, 2011). Additionally, determining the length of the waveforms that are being correlated is critical, in order to include the S-wave in the coda (Igarashi et al., 2003; Schaff and Richards, 2011). Higher frequencies provide greater constraints on subtle differences in source-time function than low frequencies, and coda-waves include information on scattered arrivals, which provide further constraints on earthquake location similarity (Ammon et al., 1990).

2.2.3 Using waveform coherence as an identification criterion

Waveform coherence, like cross-correlation, is a measure of the similarity of two time-series, however, it is a function of frequency rather than time. The coherence formula is shown in Equation 2.16, where $S_{xy}(\omega)$ is the cross spectrum between earthquakes x and y calculated from the Fourier transform of the original waveforms (Poupinet et al., 1984; Uchida and Bürgmann, 2019; Uchida, 2019).

$$\text{coh}(\omega) = \sqrt{\frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega)S_{yy}(\omega)}} \quad (2.16)$$

As with correlation, coherence is only calculated for event pairs within a specified hypocentral separation (Uchida et al., 2006, 2009; Uchida, 2019). For studies that use coherence to identify repeating earthquakes, the average coherence over a specified frequency band is usually used (Lengliné and Marsan, 2009; Materna et al., 2018; Taira et al., 2014; Uchida et al., 2006, 2009; Uchida and Bürgmann, 2019; Uchida, 2019). Each study that uses coherence as an identifier of repeating earthquakes has developed a bespoke criterion for both the frequency range over which the mean coherence is calculated, as well as the acceptance threshold (Table A.2). However, the frequency range which the mean coherence is calculated over is commonly 1–8 Hz. The threshold of repeating earthquake identification tends to be higher for coherence than correlation, with a minimum coherence of at least 0.95 being preferred, rather than a minimum of 0.9 (Uchida and Bürgmann, 2019; Uchida, 2019).

Unlike cross-correlation, coherence tends to be calculated on the raw waveforms. In addition to the frequency range, the length of the waveform used needs to be determined, to ensure that both the P-wave and S-wave arrivals are included. If event pairs have high coherence, then the S-P time is similar, resulting in the events possibly having highly similar or the same location (Lengliné and Marsan, 2009; Uchida et al., 2006, 2009). When the signal to noise ratio of an event waveform is low, the frequency band over which the waveform coherence is calculated is reduced (Materna et al., 2018). This is completed in order to remove noise from the waveforms, resulting in higher accuracy and more representative coherence being calculated (Materna et al., 2018). However, due to the small window the coherence that is calculated is less robust compared to that obtained using the larger windows (Materna et al., 2018).

2.2.4 Using earthquake hypocentre locations as an identification criterion

As repeating earthquakes are thought to represent repeated rupturing of the same fault patch, one way to identify these earthquakes is through hypocentre locations (e.g. Bohnhoff et al., 2017; Lee et al., 2018; Nadeau and Johnson, 1998; Vidale et al., 1994). In order to use hypocentral location to identify repeating earthquakes, precise relative earthquake locations are required. Individual studies define different criterion for identifying repeating earthquakes based on location. In the study conducted by Naoi et al. (2015), repeating earthquakes were identified if the event-separation distance, D , was less than a particular length;

$$D < 0.5r_{lg} \quad (2.17)$$

Here, r_{lg} is the rupture radius evaluated from the scalar moment of the larger of the pair, assuming a stress drop of 16 MPa, which was determined as the logarithmic average of stress drops for events in their study. Other studies state that the rupture areas need to overlap by a given percentage, for example 50% (Peng et al., 2005; Rubinstein and Ellsworth, 2010). This is because if there is an overlap of the effective area of the asperity, in both location and size, then it is likely that the same asperity ruptures for each repeating earthquake. Appendix A summaries studies which have identified repeating earthquakes, using location as a criterion. Due to uncertainties associated with location of earthquakes, hypocentral separation is never used in isolation to identify repeating earthquakes.

2.2.5 Using the time between repeating earthquakes as an identification criterion

Some studies have used the timings between events as a way of distinguishing repeating earthquakes from other seismic events. Uchida et al. (2005) stated that activity of the events needed to last longer than a month in order for events to be classed as repeating. This would help remove activity that was occurring as swarms. Similarly, Bohnhoff et al. (2017) used the criterion that the time difference between repeating events had to be at least 30 days. Again, this allowed for repeating earthquakes to be identified that were not part of swarm events. However, most studies do not define a time range over which the events are occurring, and instead distinguish between burst- and continual-type repeating earthquakes (discussed further in Section 2.3.1; Mesimeri and Karakostas, 2018 and Yamashita et al., 2012).

2.2.6 Challenges and uncertainties associated with identifying repeating earthquakes

There are a number of challenges and uncertainties when searching for and identifying repeating earthquakes. The rate of occurrence of false positive detections, events that are incorrectly identified as repeating, and false negatives, events that are not detected, need to be minimised in order to build a reliable and complete catalogue of repeating events (Senobari and Funning, 2019). This involves improving the methods in the identification process in order to reduce the number of false negative identifications.

It is often difficult to obtain high-accuracy earthquake locations, due to limited station coverage, timing accuracy, and unmodelled velocity variation (Trugman and Shearer, 2017). When developing a distance criterion for what classifies a repeating earthquake in a particular region, multiple factors need to be considered. If a catalogue is very poorly located then the distance criterion needs to be relaxed in order to account for the amplified errors, whereas a well-located catalogue can have a stricter distance criterion due to the minimisation of errors. Using precisely relatively relocated events is the current best-practice for repeating earthquake studies (Uchida, 2019; Yao et al., 2017).

Different studies have developed unique criteria to work around the challenges associated with analysing seismic waveforms. Making the normalised cross-correlation criterion too strict results in potential repeating earthquakes being excluded; conversely if the criterion are too weak then earthquakes are included in the study which are

not applicable. Testing different time window lengths, and filtering frequency bands, allows for a suitable criterion to be determined (Uchida and Bürgmann, 2019; Materna et al., 2018). In regions with high noise levels, the cross-correlation threshold would be lowered to account for the noise, whereas the value maybe stricter for higher signal to noise ratio regions. Similar approaches are used when determining a criterion for coherence.

Each repeating earthquake study has developed a unique criterion, allowing for local/regional uncertainties, so cannot be applied to other regions without testing their suitability. These prior studies will provide the starting point developing a criterion for identifying repeating earthquakes in New Zealand.

2.3 Repeating earthquake source processes

2.3.1 Nomenclature

Repeating Earthquake Family

A repeating earthquake family is the set of earthquakes that have met the specified criterion used for identifying repeating earthquakes; e.g. all events in a family have highly similar waveforms and locations and are inferred to represent the same seismic source. The events that make up the family have the properties outlined in Section 2.2.1. The term “family” is used throughout this thesis in preference to the term “cluster” or “sequence”, which are terms that are often used in repeating earthquake studies but which are also applied to non-repeating earthquakes (e.g Chen et al., 2010; Nomura et al., 2017; Shaddox and Schwartz, 2019; Uchida and Bürgmann, 2019; Wu et al., 2014, and references therein). Other studies have also used the terms “doublet”, for a pair of repeating events, or “multiplet”, for multiple events (e.g. Lee et al., 2018; Li et al., 2011a; Nadeau et al., 1995; Poupinet et al., 1984). For simplicity in this first New Zealand study, the term “family” will be used to define unique groups of repeating events, no matter how many events are included.

Family duration

Family duration is defined as the length of time over which the repeating family occurred. It is the difference in time between the youngest detected earthquake, which

is the most recent, and the oldest earthquake, which is the first event recorded, of each family (Figure 2.5). When calculated for families in an earthquake catalogue, the stated duration is specific to that catalogue, and is influenced in particular by the duration of the catalogue analysed and the magnitude of completeness. This is because some repeating earthquakes may have occurred outside of the timing of the catalogue, or not been detected due to their small magnitude, and are therefore not included in the catalogue. In other words, the family duration is a minimum duration.

Figure 2.5: Differences between family duration and repeating earthquake recurrence interval. Individual earthquakes in the repeating earthquake family are represented as red circles.

Repeating earthquake recurrence interval

We define recurrence interval as the average time between consecutive earthquakes in the same repeating earthquake family (Figure 2.5). For example, a family which contains three events that occurred in 2011, 2013 and 2015 would have a recurrence interval of ~ 2 years. As with family duration, if events in a family are missing from the catalogue, then this can distort the recurrence interval for the family, making the calculated value longer than the true value. When the average recurrence interval is stated, it is the family duration divided by the number of events within the family minus one.

Burst-type repeating earthquakes

Burst-type repeating earthquake families are concentrated in time, with durations of often less than one year (Mesimeri and Karakostas, 2018), and tend to have extremely short recurrence intervals, on the scale of hours to days (e.g. Igarashi et al., 2003; Templeton et al., 2008). Burst-type repeating earthquake families tend to occur within earthquake swarms or aftershock sequences (e.g. Igarashi et al., 2003; Kimura et al., 2006; Shaddock and Schwartz, 2019). However, the time threshold that distinguished

burst-type families from continual-type repeating earthquake families changes depending on the study. For example, Yamashita et al. (2012) defined the events that had a duration of less than three years, in their 17 year study period, to be burst-type, whereas Mesimeri and Karakostas (2018) defined repeating earthquakes that have a duration of less than one year, in their 6 year study period, to be burst-type.

Slip-rates, calculated by estimating the cumulative amount of slip which has occurred for the family and dividing it by the family duration (Igarashi et al., 2003), for burst-type repeating earthquake families tend to be significantly higher than those calculated using continual-type repeating earthquake families (Mesimeri and Karakostas, 2018). For example, in a study conducted in the western Gulf of Corinth by Mesimeri and Karakostas (2018), mean annual slip rates calculated using burst-type repeating earthquake were estimated to be ~ 671 mm/yr, where as the mean annual slip rates calculated using continual-type repeating earthquakes, and were estimated to be ~ 26 mm/yr. Burst-type repeating earthquakes families tend to be removed when investigating interplate quasi-static slip-rates, as they do not reflect the background slip-rate of a fault, and can distort the estimated slip-rates (Chen et al., 2013; Yamashita et al., 2012).

Continual-type repeating earthquakes

Continual-type repeating earthquake families have significantly longer family durations compared to burst-type repeating earthquake families, with the time distinction between the two being study-dependent, as previously stated (e.g. Igarashi et al., 2003; Igarashi, 2010; Mesimeri and Karakostas, 2018; Nadeau and McEvilly, 1999; Shaddox and Schwartz, 2019).

Studies at plate-boundary transform faults and subduction zones have used the frequent and periodic occurrence of repeating earthquakes to estimate fault slips-rates at depth (Nadeau and McEvilly, 1999; Igarashi et al., 2003; Uchida et al., 2004). Further discussion on these calculations is included in Section 5.5. Slip-rates calculated from these events tends to be much slower than those calculated by burst-type repeating earthquakes better reflecting the overall slip-rates for a region, but this is often an underestimation of the rate (Mesimeri and Karakostas, 2018; Templeton et al., 2008). For example, the slip-rate calculated by Templeton et al. (2008), using continual-type repeating earthquakes on the San Andreas Fault, was found to be 11.6 mm/yr, which is consistent with the geodetically determined creep rate of 11 mm/yr, found by Kelson et al. (1992), but not the long term slip-rate of 22 mm/yr.

2.3.2 Asperity models of repeating earthquakes

The leading model for the occurrence of repeating earthquakes is the periodic rupture of a frictionally strong fault patch, or single asperity, which is embedded in an aseismically sliding region (Figure 2.6; e.g. Ellsworth, 1995, Marone et al., 1995, Nadeau and Johnson, 1998, Nadeau and McEvilly, 1999, Uchida et al., 2003, Vidale et al., 1994). This model has been used and adapted by different studies to explain the occurrence of a repeating earthquake families, including Beeler et al. (2001), who applied it to a fixed-area fault patch that is allowed to continually creep and strain harden until reaching a failure threshold of stress. An alternative model has been suggested that involves an asperity that is surrounded by a creeping region, all of which is within a locked fault plane (Figure 2.6; Anooshehpour and Brune, 2001, Mesimeri and Karakostas, 2018).

Figure 2.6: Asperity models for repeating earthquakes. Left: Model for a repeating earthquake on an asperity embedded in an aseismically sliding region, adapted from Uchida et al. (2003). Right: Model for a repeating earthquake on an asperity surrounded by a creeping region which is within a locked fault plane.

Repeating earthquake families are typically concentrated in the transition zone between locked and creeping regions of faults in the crust (Uchida and Bürgmann, 2019, and references therein). Based on the models above, repeating earthquake families represent the cyclical build-up and release of stress on the isolated asperity where the earthquake is occurring (Beeler et al., 2001; Schaff et al., 2002). This sequence allows repeating earthquake families to be modelled as a renewal process in statistics and interplate slip rates to be determined from repeating earthquake recurrence intervals (Nomura et al., 2014, 2017).

Igarashi et al. (2003) distinguished between the rupture processes of continual- and burst-type repeating earthquakes occurring on the plate boundary off Sanriku, north-eastern Japan. Continual repeating earthquakes were identified along the coupled

sections of the plate boundary, as it provides the necessary conditions to allow stress to become concentrated on an asperity (Igarashi et al., 2003). Uchida et al. (2003) also investigated repeating events in northeastern Japan, and stated that if coupling is strong only on the sparsely distributed asperities, the occurrence of repeating earthquakes will be governed by the surrounding aseismic slip rate. Igarashi et al. (2003) also identified burst-type repeating earthquakes along the boundary, however, the processes leading to their occurrence differed slightly. Large interplate earthquakes occur on large asperities, and the resulting slip changes the stress regime on surrounding asperities (Igarashi et al., 2003). Igarashi et al. (2003) attributed the burst-type repeating earthquakes they found to the stress changes on these surrounding asperities, from the large nearby event.

2.3.3 Alternative source models of repeating earthquakes

In situations where the models described in Section 2.3.2 do not hold, alternative models have been used to explain the occurrence of repeating earthquakes. Burst-type repeating earthquake families have been observed in locations where there is little or no resolvable tectonic strain (Uchida and Bürgmann, 2019). As loading rates alone cannot account for the stress accumulation required to produce repeating earthquakes, alternative methods such as loading from large nearby earthquakes or high pore fluid pressures are required to explain the repeating earthquake occurrence (Uchida and Bürgmann, 2019, and references therein). Due to the small number of studies which have identified intermediate to deep intraslab earthquakes (Prieto et al., 2012; Zhang et al., 2008), the causes of repeating earthquakes in these settings remains unknown. However, the causes maybe linked to the mechanisms of earthquakes of similar depth events which include, thermal shear instability of plastic deformation, and dehydration embrittlement (Hasegawa and Nakajima, 2017, and references therein). However, the mechanism for all intermediate to deep intraslab seismicity remain highly debated (Uchida and Bürgmann, 2019). The alternative models mentioned previously are for tectonic repeating earthquakes. Further models have been hypothesised for non-tectonic repeating earthquakes, however, the focus for this study is tectonic repeating earthquakes so these have not been included (Uchida and Bürgmann, 2019, and references therein).

2.3.4 Magnitude characteristics of repeating earthquakes

Microearthquakes tend to be defined as earthquakes that have a magnitude less than three, whereas great earthquakes have a magnitude of eight or larger (Lee et al., 1981). Many repeating earthquake studies have focused on repeating microearthquakes as these events occur more frequently than large events, as described by the Gutenberg-Richter relationship (Section 2.1.5), so more repeats can be analysed (e.g. Nadeau and McEvilly, 1999; Naoi et al., 2015; Yao et al., 2017; Zhang et al., 2008). Moderate-sized repeating earthquakes, magnitude 3–5, have also been extensively studied as they provide insights into larger scale processes (e.g. Ellsworth et al., 1999; Matsuzawa et al., 2002; Uchida et al., 2005; Zhang et al., 2008). Analysis of large-magnitude repeating earthquakes, greater than magnitude 6, is only possible when long duration seismic records are available. During a study to create an asperity map along the northeastern Japan subduction zone, undertaken by Yamanaka and Kikuchi (2004), large earthquakes were classified as repeating as they occur within the same source area. Estimates of large magnitude, and long duration, repeating earthquakes can also come from paleoseismic evidence (Schwartz and Coppersmith, 1984). However, due to the long intervals between events, the methods that are used to identify smaller repeating earthquakes cannot be employed for these events. In these studies, repeating earthquake identification is reliant solely on event location (Yamanaka and Kikuchi, 2004).

2.3.5 Repeating earthquake seismic moment–recurrence interval relationship

In the asperity model described in Section 2.3.2, the stress build up on the asperity is driven by the relative plate motion, or motion on the fault, surrounding the asperity (Beeler et al., 2001; Nomura et al., 2017). Nadeau and Johnson (1998) derived the following relationship between repeating earthquake recurrence interval and seismic moment, based on this asperity model for a set of 62 repeating earthquake families occurring near Parkfield, California (Equation 2.18);

$$T_r \propto M_0^{\frac{1}{6}} \quad (2.18)$$

Here, T_r is the repeating earthquake recurrence interval, and M_0 is the repeating earthquake seismic moment. Based on Equation 2.18, longer repeating earthquake recurrence intervals are expected for larger magnitude events. This relationship has been

found to hold in many different study regions (Parkfield, Taiwan, the Japan subduction zone, and the Tonga-Kermadec-Vanauatu subduction zones; Chen et al., 2007, Nadeau and Johnson, 1998, and Yu, 2013), and its application to New Zealand is discussed in Section 5.4.2.

While these relationships can be applied to investigate a general rule, for repeating earthquakes in aftershock sequences, systematic variations in recurrence interval and seismic moment have been observed, which do not follow Equation 2.18 (Chen et al., 2010; Peng et al., 2005). In a study conducted by Chen et al. (2010), recurrence intervals were observed to shorten and seismic moments increase immediately following a M 4.5 earthquake in Parkfield (Chen et al., 2010). They also observed these changes systematically returning to pre-quake levels through time (Chen et al., 2010). Peng et al. (2005) and Schaff et al. (1998) have also investigated this change in the relationship following the 1984 M 6.2 Morgan Hill and 1989 Loma Prieta earthquake, respectively. Variations in repeating earthquake recurrence intervals and seismic moment following a large earthquake also differ with the depth of the repeating earthquake family. Shallower repeating earthquake families are influenced more than deeper repeating earthquake families following a significant event, with these differences being explained due to decreases in fault-healing rates with depth, due to increases in temperature (Peng et al., 2005).

2.3.6 Triggering and interactions between repeating earthquake families

Another important concept which has been investigated using repeating earthquakes, is the ability of earthquakes to interact with each other. This can result in the triggering of a repeating earthquake family. Triggering can involve one repeating earthquake family triggering another repeating earthquake family, with sequences being considered interacting if the events in one sequence occur within a short time of the next (Lui and Lapusta, 2016). It can also involve a larger event, not associated with the repeating earthquake family, triggering the next event in the repeating earthquake family (Chen et al., 2010, 2013; Wu et al., 2014). Triggering of repeating earthquake families can provide crucial insights into fault properties and the overall stress field (e.g. Chen et al., 2013; Nadeau et al., 1995; Lui and Lapusta, 2016; Wu et al., 2014). This is because repeating earthquake recurrence intervals have been shown to respond, either shorten or lengthen, in response to nearby stress changes (e.g. Chen et al., 2013; Nadeau et al., 1995; Lui and Lapusta, 2016; Wu et al., 2014).

The concept of one repeating earthquake family triggering another repeating earthquake family was investigated by Nadeau et al. (1995), along the San Andreas Fault. Shallow repeating earthquakes (< 5 km depths) were found to interact over a spatial range of 100 m to 200 m, on a timescale of several minutes. Interaction was less common with deeper clusters (> 5 km), but where observed it occurred over similar spatial scales, and over longer time periods of hours to days (Nadeau et al., 1995). Two mechanisms were proposed to explain how one cluster can trigger another at ranges less than 200 m. One mechanism involves rapid aseismic slip on the fault surface, whereas the other mechanism requires stress field perturbations to be sufficiently large to induce slip. Nadeau et al. (1995) also did not discount the role of fault zone fluids allowing for the communication.

Lui and Lapusta (2016) also investigated the concept of repeating earthquake family interaction, through numerical simulations of small repeating earthquakes, based on rate and state fault models. However, their interpretation was that the interaction between sequences was dominated by static stress changes due to postseismic slip. Their models suggested further that the distances over which triggering can occur is significantly larger than previously observed, approximately four to seven rupture diameters, due to the propagating stress front.

Triggering of repeating earthquakes in a family can be caused by larger events not associated with the sequence, resulting in a reduction of the recurrence interval of the repeating earthquakes (Chen et al., 2010, 2013; Wu et al., 2014). All of the studies discussed below investigated repeating earthquakes in the Parkfield area. Chen et al. (2010) looked into how the recurrence interval between repeating earthquakes changed following nearby magnitude four to five earthquakes. The cause of the reduction in recurrence interval was determined to be the result of static coseismic stress changes of 0.6–26.6 kPa, within distances of approximately 5 km from the larger magnitude event (Chen et al., 2010). Small repeating earthquakes would only be triggered when they were already approaching critical conditions for rupture, late in their earthquake cycle (Chen et al., 2010). This study was later extended to investigate triggering by magnitude one to four events by Chen et al. (2013). For these events, repeating earthquake families tended to be triggered only in the short-term, less than a day, or when the static stress changes caused by the neighbouring events were high enough, (> 30 kPa; Chen et al., 2013). The role of dynamic stress changes resulting in triggering were not discounted, but static stress changes remained the predominant cause (Chen et al., 2013). Alongside this, the distances that triggering occurred over varied with the size of the event, with the hypocentral distances of the triggered events remaining under 5 km (Chen et al., 2013). This study also investigated the probability of the

triggering event being part of the repeating earthquake family, rather than a distinct event. However, the likelihood of this was found to be extremely small for events in the Parkfield area, occurring less than one percent of the time (Chen et al., 2013). Instead of static stress changes resulting in triggering, Wu et al. (2014) investigated the likelihood of triggering due to dynamic stress changes. For dynamic stress changes similar to those static changes inferred by Chen et al. (2013), approximately 20 kPa, a weak correlation was observed with shorter recurrence intervals (Wu et al., 2014). When looking at dynamic stress changes as the mechanism of triggering, hypocentral separation did not alter the correlations (Wu et al., 2014).

Chapter 3

Methods

After reviewing previous repeating earthquake studies (see Appendix A), we tested the suitability of different detection methods for identifying repeating earthquakes around the Raukumara Peninsula. To understand how repeating earthquakes relate to aseismic processes occurring around the Raukumara Peninsula, we undertook the following key steps:

- Determine a suitable detection method and workflow;
- Pick phase arrivals and precisely relocate earthquakes;
- Estimate the seismic moment and construct focal mechanism of the repeating earthquakes.

Each of these key steps are outlined in detail in the following sections.

3.1 Raukumara Peninsula seismicity catalogue

Initial clustering of the GeoNet seismicity catalogue between 1987 and 2018, was undertaken by Chamberlain et al. (2019) to remove dissimilar events, thereby generating a smaller dataset with which to test repeating earthquake detection thresholds. The GeoNet catalogue was clustered based on inter-event distance (hypocentral separation < 30 km) and normalised cross-correlation averaged across multiple stations. This identified a number of earthquake clusters around the Raukumara Peninsula. The density of possible repeating earthquakes in the region, and previously studied seismic and

aseismic phenomena (see Section 1.3.3) led us to focus our study here. Figure 3.1 provides a general overview of the detection and analysis undertaken.

Figure 3.1: Process undertaken for identifying repeating earthquakes in New Zealand. The red box was completed by Chamberlain et al. (2019), the yellow boxes show the development of the repeating earthquake composite criterion for New Zealand. The blue boxes represent the formation of the repeating earthquake catalogue for the Raukumara Peninsula, and testing of the composite criterion in Fiordland and Central New Zealand. The purple box is the final stage analysis of the Raukumara Peninsula catalogue.

3.2 Initial repeating earthquake family identification

Chamberlain et al. (2019) initially clustered the GeoNet earthquake catalogue using the following composite criterion; waveforms have to have a cross-correlation of ≥ 0.7 and the events have to have hypocentral separations of < 30 km. Repeating earthquake identification began using the clustered catalogue formed by Chamberlain et al. (2019), and 8 s waveforms. To calculate the waveform correlation, the horizontal components for each of the earthquakes in a cluster, recorded on common stations were isolated, and the traces aligned to the P-wave arrival. In order to accurately align the traces, the traces were allowed to shift up to 0.9 s. A fourth-order bandpass filter between 1 and 20 Hz was applied to all the waveforms. We computed the normalised cross-correlation of these waveforms relative to the stack of all the waveforms in that cluster. Events that had a normalised cross-correlation greater than the correlation threshold were retained as repeating. We used a correlation threshold of 0.96, as this removed events with visibly different first motion arrivals and delayed timing of the later phases, while aligning with the events that were retained when coherence was calculated. Other detection methods were also investigated, which involved calculating the normalised cross-correlation and coherence between pairs of earthquakes. However, the method outlined previously provided the best set of preliminary results with which to complete further testing of the detection criterion.

Overall, 145 clusters had at least two events retained on two or more GeoNet stations, and formed the preliminary repeating earthquake family catalogue for the Raukumara Peninsula. From this point, what was previously referred to as a cluster are now referred to as a family.

3.3 First arrival and polarity analysis for the youngest event in each family

The next phase of the analysis was conducted using 120 s of waveform data, downloaded from the GeoNet stations in Figure 3.2. Data was downloaded for all the events in the 145 families, including events that were initially rejected due to having cross-correlations that were lower than the 0.96 correlation threshold. Because there was a notable increase in seismometer coverage across the Raukumara Peninsula from 2003 (Petersen et al., 2011), we only consider events occurring after 2003. This pro-

vided the longest time frame with enough continually running stations to conduct the analysis on. This resulted in the removal of six families from the initial catalogue because all the events in each of the families occurred before 2003. We isolated the youngest event from each of the 139 remaining families, and manually picked the first arrivals and the polarities of the first motion using SEISAN (Havskov and Ottemoller, 1999). Picks were made manually to ensure accuracy and consistency, as they were to be used for correcting the GeoNet picks of the remaining events in the family (Section 3.4). This also allowed for S-picks to be added on stations that had not been identified previously by GeoNet.

Figure 3.2: GeoNet broadband and short period seismometers and GNSS stations used. Red circles represent broadband seismometers, pink circles represent short-period seismometers, and blue triangles represents the GeoNet GNSS stations.

P-wave arrivals were always identified on the vertical component of the seismogram, and S-wave arrivals identified on either the north or east horizontal component, depending on which showed the arrival more clearly (Figure 3.2). To facilitate the later calculation of focal mechanisms, we manually picked P-wave polarities.

Noise was the most significant problem encountered as it obscured some of the phase arrivals (Figure 3.3), preventing them from being accurately identified. In total, we made 1159 P-picks and 939 S-picks. Note that fewer S-picks than P-picks were made due to strong P-coda obscuring the S-arrival, at short epicentral distances.

Figure 3.3: Earthquake 2228041 waveforms with first P- and S-wave first arrivals identified. Blue lines mark the P-wave arrivals identified and the red line marks the S-wave arrival identified. Waveforms have had a fourth-order bandpass filter from 1 to 20 Hz applied. Only three stations are shown here, to show the variation in the waveform quality. First arrivals were identified on four stations for this earthquake.

3.4 Correction of the phase-arrival picks for the remaining events in the family

To improve the accuracy of the remaining events' phase-arrival picks, without having to manually pick every event, cross-correlation pick correction was used for the remaining events in each of the families. The remaining events phase-arrivals were corrected relative to the youngest events in the family, as this event had the best station coverage. The process is outlined in Figure 3.4.

Figure 3.4: Process for correcting the GeoNet first arrival picks. The GeoNet first arrival picks for each of the events in a family were corrected based on the manual picks of the youngest event to improve the accuracy.

For cross-correlation pick correction to be run, the picks that required correcting needed to be on the same component as those manually picked. In order to correct the picks for the remaining event in a family, all the GeoNet picks needed to be on the same component as the SEISAN picks. If the components did not match, the GeoNet picks were copied to the component that matched the SEISAN pick component. Similarly, if an event had picks missing on a station that was manually picked, a temporary pick was made based on the move-out of the manual pick.

Two methods were trialled to obtain corrections to the GeoNet picks. The first implemented the ObsPy function `xcorr_pick_correction()` (Beyreuther et al., 2010). This function uses the method identified by Deichmann and Garcia-Fernandez (1992), which calculates a correction for the differential pick time. This correction is determined by cross-correlating narrow windows of the waveforms around the pick times (Deichmann and Garcia-Fernandez, 1992). In this function, one window length around both the P- and the S-pick had to be set. This resulted in a good fit for the P-arrivals (Figure 3.5: A) but the S-arrivals were not accurately corrected as the window was too small (Figure 3.5: B).

Figure 3.5: Correction of the P- and S-wave GeoNet picks for earthquake 3079134 in family NU01 using `xcorr_pick_correction()`. Trace 1 is the trace of the picked event (earthquake 3606233), Trace 2 is the trace of the picked event being corrected (earthquake 3079134). **A:** Correction of the P-wave pick on the vertical component of GeoNet broadband station MWZ. **B:** Correction of the S-wave pick on the horizontal component of GeoNet broadband station MWZ. Note the poor alignment of the S-pick arising from the use of a small time window.

We decided to use the function `xcorr_pick_family()` in `EQcorrscan` to correct the picks (Chamberlain et al., 2018). There are two key differences between this function and the `ObsPy` function previously mentioned. The first is that it allowed us to implement different window lengths around the P- and S-arrivals, and the second is that if a pick cannot be corrected then the event pick is skipped and the next pick is corrected.

This enables us to run the pick correction through all the events in the family, and identify which picks could not be corrected, without the function stopping prematurely. As can be seen in Figure 3.6, it allowed for the precise correction of both the P- and S-arrival picks, for all the events in the initial families identified.

Figure 3.6: Correction of the P- and S-wave GeoNet picks for earthquake 3079134, using the manual picks made for earthquake 3606233 in family NU01 using `xcorr_pick_family()`. P-pick corrections are completed on the vertical components and S-pick corrections are completed on the horizontal components. Note the better fit between the template and the waveform for the S-picks.

3.5 Earthquake locations

3.5.1 Raukumara Peninsula repeating earthquake absolute locations

We used NonLinLoc (Lomax et al., 2000) and SIMUL (Thurber and Eberhart-Phillips, 1999) to obtain absolute earthquake locations.

NonLinLoc (Lomax et al., 2000) solves the second-order travel-time equations using non-linear grid search methods. In doing so, a probability density function is created and the most-likely location found (Lomax et al., 2000). This probability density function captures both the uncertainty size, and geometry (Lomax et al., 2000). Previous

studies in New Zealand have used NonLinLoc successfully (e.g. Michailos et al., 2019; Warren-Smith et al., 2018) using both 1D and 3D velocity models. We decided to use the NZ3D2.1 velocity model created by Eberhart-Phillips et al. (2017b) in preference to a 1D model, as it provides a more realistic interpretation of the velocity structure of the area. However, the velocity model that was used does not contain a recently identified large, low velocity sedimentary wedge to the east of the Raukumara Peninsula, which will further influence the locations found (Kaneko et al., 2019). We used the 134 youngest event to refine the key parameters, as these provided a smaller dataset to run multiple location attempts on.

We attempted to locate these events, using parameters previously found to work both in other regions of New Zealand (e.g. GeoNet), and for a region north of the Raukumara Peninsula (e.g. Warren-Smith et al., 2018). Locations were unstable between tested parameter sets, with multiple events locating at the top of the velocity grid (e.g. above ground). A summary of the parameters tested is included in Appendix B. Alongside this, NonLinLoc was unable to compute arrival times that matched the pick time (Figure 3.7). Lanza et al. (2019) found a similar issue for the Kaikōura Region using the same velocity model. We therefore chose to use SIMUL to compute the initial locations.

Figure 3.7: Misfit between the picked arrivals (P-pick and S-pick) and the modelled arrivals (P-arrival and S-arrival) computed using NonLinLoc for earthquake 2474118.

SIMUL2014 is an extension of `simulps12` and `simul2000` (Eberhart-Phillips and Reyners, 2012; Eberhart-Phillips and Bannister, 2015; Evans et al., 1994; Thurber and Eberhart-Phillips, 1999). It is based on a linearised earthquake method and uses a 3D velocity model to calculate absolute earthquake locations (Lanza et al., 2019). To obtain the locations of the repeating events in SIMUL2014, we used the same 3D velocity model as was used with NonLinLoc.

We tested location parameters using the 139 manually picked youngest events for each of the families (see Appendix B). 134 events were located, and the computed arrivals matched the pick times more closely than those obtained in NonLinLoc (Figure 3.8). However, as can be seen in Figure 3.8, there is still a slight misfit between the S-pick and the S-arrival at some of the stations.

We then located the remaining events in each of the families, and obtained a further 220 earthquake locations using SIMUL2014. The events that were not located had fewer than four first arrivals identified due to a combination of station continuity and waveform quality.

Figure 3.8: Misfit between the picked arrivals (P-pick and S-pick) and the modelled arrivals (P-arrival and S-arrival) computed using SIMUL2014 for earthquake 2474118.

3.5.2 Raukumara Peninsula repeating earthquake relative locations

We used HypoDD2.1 (Waldhauser and Ellsworth, 2000) with the same 3D velocity model as used with both NonLinLoc and SIMUL2014. We computed differential times and cross-correlation differential times using the `catalog_to_dd` functions in EQcorrscan (Chamberlain et al., 2018). Events were linked if they were within 20 km and shared picks on at least two stations.

After testing the most suitable parameters (See Appendix B), we computed two sets of locations. The first used all individual events for the repeating earthquakes as starting locations. The second used the youngest event location as the starting location for all events in a family. We did this due to the separation in the locations of the events in each of the families found using SIMUL2014, and because repeating earthquakes should be co-located (Uchida and Bürgmann, 2019, and references therein). We expect this to demonstrate whether events could be co-located despite varying network quality. When the events in each of the family were set to the location of the youngest events, 337 of the original 354 events were located using HypoDD2.1.

3.6 Raukumara Peninsula repeating earthquake catalogue analysis

To allow us to use previously calculated seismic moment–recurrence interval relations (e.g. Nadeau and Johnson, 1998), we estimated seismic moments for all repeating earthquakes in the final catalogue. Equation 3.1 was used to convert moment magnitude to seismic moment (Hanks and Kanamori, 1979, and references therein);

$$\log(M_0) = 16.1 + 1.5M_W \quad (3.1)$$

where M_0 is the estimated seismic moment, in dyne-cm, M_W is the moment magnitude. The calculated seismic moments were used in three key sets of calculations in the Discussion. In Section 5.1, seismic moment was used to calculate the source area. For these calculations the seismic moment was converted to Nm by multiplying M_0 by 10^{-7} . For the calculations in Section 5.4.2 and 5.5, moment was kept in dyne-cm to align with the calculations made by Nadeau and Johnson (1998).

In this thesis we use, and state, the GeoNet preferred magnitude of the earthquake (Ristau, 2009). For each of the repeating earthquakes identified, we convert the preferred magnitude to moment using Equation 3.1, using the assumption that the moment magnitude in the equation is equal to the GeoNet preferred magnitude.

We constructed a focal mechanisms of the youngest event in each family, using first arrival polarities identified in Section 3.3 and FPFIT (Reasenber, 1985) in SEISAN (Havskov and Ottemoller, 1999). The event locations were fixed to the SIMUL2014 locations. The small differences between the HypoDD2.1 and SIMUL2014 locations meant that the differences in take-off angles and resulting focal mechanisms would be minimal. Of the final 62 families, 56 had focal mechanism constructed. Focal mechanisms could not be calculated for six of the events, because there were too few first arrival polarities identified.

Chapter 4

Results

This chapter summarises the key results of this research. Section 4.1 addresses the identification method and composite criterion developed. Section 4.2 provides details of the repeating earthquake families identified around the Raukumara Peninsula, and Section 4.3 provides details of the families identified in two alternative tectonic settings, Marlborough and Fiordland. The chapter concludes with a summary of the key results (Section 4.4).

4.1 Raukumara Peninsula repeating earthquake identification composite criterion

The overarching aim of the research was to develop a composite criterion to identify repeating earthquakes around New Zealand. We have developed a method and composite criterion for identifying repeating earthquakes around the Raukumara Peninsula which involved determining the following parameters;

- The cross-correlation window length;
- The filtering parameters required to reduce noise in the waveforms;
- The correlation threshold which distinguishes repeating earthquakes from other seismicity;
- The distance separation threshold between events for them to be classed as repeating.

4.1.1 Cross-correlation window length

A window of 40 s, encompassing both P- and S-arrivals, has commonly been used (e.g. Uchida et al., 2003, 2004; Yamashita et al., 2012). We tested the sensitivity of the correlations to varying waveform lengths, to try to determine an appropriate waveform length (Figure 4.1).

Because the event-station path length varies between <1 km and ~ 180 km, coda durations also varied strongly between events and stations. We therefore chose to use a waveform length dependent on coda-duration. To ensure that this was not unfairly biasing short waveforms, we investigated the impact of varying waveform length and found that, although correlation decreases with increasing waveform length, we were unable to determine a window length spanning both the P- and S-arrivals that could be applied to all the families consistently. Figure 4.1 shows how the calculated normalised cross-correlation varies with increasing waveform length for one family (TT27). For this family, a window length of 30–35 s resulted in the maximum normalised cross-correlation being calculated.

Figure 4.1: Graph of family TT27 used to investigate how the calculated normalised cross-correlation changes with increasing length of the waveforms. Multiple points at the same station represent the different events within the family. Correlations are calculated with respect to the stack of the waveforms in the potential repeating family. All waveforms had a fourth-order bandpass filter between 1 and 20 Hz applied before normalised cross-correlations were calculated. A line is drawn at 0.95 which is the minimum correlation threshold for events to be identified as repeating.

We calculated the signal to noise ratio for each of the waveforms to determine the end of the coda, and computed normalised cross-correlations for varying percentages of the coda duration. We identified a 5 s noise window before the P-pick, which was used to calculate the root-mean-square amplitude of the noise. The signal window was set to the same length as the noise window (5 s), and for each step of the signal window the root-mean-square amplitude was calculated. The signal to noise ratio was calculated by dividing the signal window by the noise window, with the end of the coda being identified when the ratio returned to one. When investigating the values identified as the end of the waveform coda, the majority of the events had coda lengths of less than 30 s, confirming that calculating the cross-correlation over 40 s waveforms, which is commonly used in studies, would not be suitable for the events recorded around the Raukumara Peninsula. Using the end of the coda, we varied the percentage of the coda used to calculate the normalised cross-correlation, to investigate if there was an optimal percentage to use. Figure 4.2 shows how the normalised cross-correlation changes as the percentage of coda is increased.

Figure 4.2: Graph of family TT27 used to investigate how the calculated normalised cross-correlation changes with increases in the percentage of waveform coda used in the calculation. Multiple points at the same station represent the different events within the family. Correlations are calculated with respect to the stack of the waveforms in the potential repeating family. All waveforms had a fourth-order bandpass filter between 1 and 20 Hz applied before calculations were completed. A line is drawn at 0.95 which is the minimum correlation threshold for events to be identified as repeating.

We decided that 75% of the coda length was appropriate to calculate the normalised

cross-correlation, as it allowed for both the P- and S-arrivals to be included, as well as resulting in the maximum normalised cross-correlation. If the end of the coda was not identified, due to the level of noise in the waveform, the waveform length used to calculate the normalised cross-correlation was set to 25 s, starting 1 s before the identified P-arrival. This was chosen because when we plotted the P travel-time against the S-P time (ie. a Wadati Plot), the S-P times were all less than 25 s (Figure 4.3). This allowed for the both the P and S arrivals to be included in the window that normalised cross-correlation was being calculated over.

Figure 4.3: Raukumara Peninsula potential repeating earthquakes Wadati plot of P travel-time, in seconds, plotted against the S-P time, in seconds.

4.1.2 Filtering parameters

Before calculating correlations, we decided to apply a fourth-order bandpass filter between 1 and 20 Hz. This removed the low-frequency noise that dominated the signal at some of the stations, especially URZ and MXZ. We tested the response of the calculated normalised cross-correlation to increases in the frequency band which the waveforms were filtered over, always keeping the low frequency limit at 1 Hz. As the calculated normalised cross-correlation showed little response to changes in the frequency band upper limit, we decided on 20 Hz as it retained a wide range of frequencies but limited the high-frequency noise in the waveforms.

4.1.3 Correlation threshold

We found no reason to vary the correlation threshold, of 0.95 at two or more stations, that has been used by other global studies to identify repeating earthquakes (Uchida and Bürgmann, 2019, and reference therein). To test this however, we calculated how many families would be retained for the correlation thresholds ranging from 0.90 to 0.99, at intervals of 0.01. The number of families that were rejected as repeating, as well as the number of events in each family, varied more when the correlation was set to less than 0.95 compared to when it was larger than 0.95. When the correlation was set to greater than 0.95, families were found to be rejected due to small differences in the background noise of the waveform rather than significant differences in first arrivals.

4.1.4 Distance threshold

Some studies, (e.g. Bohnhoff et al., 2017; Marone et al., 1995; Schaff et al., 1998), use the spatial separation between potential repeating events as an indicator of whether the events are repeating or not. Similarly, overlapping source areas are sometimes added to the identification composite criterion (e.g. Naoi et al., 2015; Rubinstein and Ellsworth, 2010; Yu, 2013). We investigated the potential of including an event separation threshold in our repeating earthquake identification criterion, as discussed further in Section 5.1. However, our final identification criterion did not include a distance threshold due to location uncertainties arising from varying network geometry throughout our study period.

4.1.5 Overall composite criterion

The composite criterion we developed for identifying repeating earthquakes in New Zealand is as follows, and Section 5.1 discusses why our composite criterion did not include elements based on factors such as distance or magnitude:

1. Waveforms should be processed using a fourth-order bandpass filter between 1 and 20 Hz;
2. Cross-correlation should be calculated for 75% of the earthquake coda, or 25 s if the end of the coda could not be identified;
3. After processing, events need to have a cross-correlation of at least 0.95 on two or more stations.

4.2 Raukumara Peninsula repeating earthquakes

4.2.1 Summary of detections

We identified 62 repeating families, from 145 original candidates, between 2003 and 2018, using the composite criterion in Section 4.1.5 (summarised in Table 4.1). The families we identified are distinguished using a geographical name (Figure 4.4), as well as a two-digit number. Geographic names were given to families based on their proximity to local towns around the Raukumara Peninsula, and the numbers are given within each set of locations based on the relative order of the first recorded event in the family. For example, TT01 is a family that is located near Tokomaru Bay and Tolaga Bay and the first event in the family was recorded in 2003, earlier than all the other Tokomaru–Tolaga families.

Figure 4.4: Naming convention for Raukumara Peninsula repeating earthquake families. Boxes represent the geographical bounds, with the names attached. Blue circles represent the location of each of the families.

Table 4.1: Summary of the repeating earthquake families identified around the Raukumara Peninsula in this study. Each geographic area has two letter code which is used to identify families within the group. N is the number of events in a family. T is the repeating earthquake recurrence interval. Magnitudes, $M_{\min}$ and $M_{\max}$, are the minimum and maximum preferred magnitudes calculated by GeoNet for the family. Focal mechanisms are denoted as SS (strike-slip), OSS (oblique strike-slip), N (normal), ON (oblique normal), R (reverse), OR (oblique reverse) or PC (poorly constrained). Plate is where the family was located, either the Australian (AUS) or Pacific (PAC) Plate or along the subduction interface (INTER).

Geographic area	Name	N	T (yr)	Earliest	Latest	$M_{\min}$	$M_{\max}$	Mechanism	Plate
Waihau (WA)	WA01	2	12.3	2004-10-01	2017-03-09	4.5	4.5	PC	AUS
Te Araroa (TA)	TA01	2	6.6	2005-01-04	2011-09-27	2.7	2.7	OR	PAC
Ruatōria (RA)	RA01	4	1.9	2004-06-15	2010-05-11	2.4	2.7	OSS	AUS
	RA02	3	2.0	2011-08-05	2015-09-25	2.1	2.4	OR	INTER
Te Puia (TP)	TP01	3	1.8	2004-12-14	2008-08-28	2.5	2.6	NA ¹	PAC
	TP02	2	10.3	2006-03-21	2016-09-09	3.2	3.5	N	AUS
	TP03	2	1.7	2011-04-22	2013-01-06	2.5	2.8	PC	AUS
	TP04	2	0.0	2011-10-07	2011-10-07	2.5	2.5	PC	PAC
Tokomaru–Tolaga (TT)	TT01	3	5.5	2003-12-02	2015-02-28	3.1	3.5	OSS	AUS
	TT02	3	1.5	2004-05-09	2007-04-24	3.3	3.4	NA ¹	AUS
	TT03	2	2.9	2004-05-10	2007-04-25	3.4	3.4	R	INTER
	TT04	3	3.0	2004-05-10	2010-07-15	2.3	3.3	ON	AUS
	TT05	2	2.4	2004-11-03	2007-04-25	1.9	1.9	NA ¹	AUS
	TT06	3	5.9	2005-08-08	2017-08-08	2.2	2.8	R	INTER
	TT07	2	3.2	2005-08-08	2008-11-14	2.3	2.4	NA ¹	AUS
	TT08	2	11.8	2005-10-17	2017-09-25	2.8	3.3	NA ¹	AUS
	TT09	3	5.7	2006-03-27	2017-09-25	2.8	3.4	SS	AUS
	TT10	4	3.4	2007-04-25	2017-09-25	1.9	2.7	OR	AUS
	TT11	2	11.1	2007-04-25	2018-08-01	2.9	3.1	ON	AUS

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Geographic area	Name	N	T (yr)	Earliest	Latest	M _{min}	M _{max}	Mechanism	Plate
	TT12	3	4.4	2008-11-14	2017-09-25	3.2	3.6	SS	AUS
	TT13	2	2.4	2009-03-22	2011-09-04	2.7	2.9	PC	AUS
	TT14	2	9.0	2009-05-22	2018-07-31	2.2	2.5	SS	AUS
	TT15	2	0.0	2010-01-20	2010-01-30	2.3	2.4	OSS	AUS
	TT16	3	2.7	2010-02-05	2015-06-25	2.4	2.7	R	INTER
	TT17	4	2.7	2010-05-16	2018-08-12	1.5	2.1	OR	AUS
	TT18	5	1.3	2010-06-09	2015-08-08	2	2.4	SS	AUS
	TT19	2	3.0	2010-07-14	2013-07-17	2.4	2.5	R	INTER
	TT20	3	3.3	2010-07-14	2017-03-30	3.5	3.6	R	INTER
	TT21	3	3.9	2010-07-15	2018-06-14	2.5	2.8	R	INTER
	TT22	2	4.9	2010-07-16	2015-06-26	2.1	2.5	R	INTER
	TT23	2	6.3	2011-03-07	2017-08-07	1.7	2.4	N	AUS
	TT24	2	1.8	2011-09-03	2013-07-17	2.2	2.4	R	INTER
	TT25	3	3.0	2011-09-03	2017-09-24	2.4	2.7	R	INTER
	TT26	3	2.4	2010-07-14	2015-06-25	2	3.4	OR	PAC
	TT27	3	3.0	2011-09-04	2017-09-27	2.2	2.6	R	INTER
	TT28	2	0.9	2012-08-10	2013-07-18	1.6	1.8	R	INTER
	TT29	3	1.8	2012-12-24	2016-08-28	1.9	2.3	R	INTER
	TT30	2	3.6	2014-02-14	2017-09-27	2.1	2.3	SS	AUS
	TT31	2	0.0	2015-01-10	2015-01-10	1.5	2.4	OR	AUS
	TT32	2	1.8	2015-01-10	2016-11-17	2.2	2.3	SS	AUS
	TT33	2	0.5	2015-01-10	2015-06-25	1.7	1.8	N	AUS
	TT34	2	0.1	2017-08-08	2017-09-25	2.6	2.9	OSS	PAC
Whatatutu (WH)	WH01	3	4.4	2009-08-12	2018-08-03	1.8	2.2	N	AUS

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Geographic area	Name	N	T (yr)	Earliest	Latest	M_{min}	M_{max}	Mechanism	Plate
Tolaga–South(TS)	TS01	4	2.0	2011-09-04	2017-10-16	2.1	2.4	ON	PAC
Te Karaka (TK)	TK01	3	3.8	2003-09-08	2011-05-29	3.4	3.6	OSS	PAC
	TK02	2	5.0	2004-07-31	2009-08-07	2.4	2.5	R	INTER
	TK03	2	8.0	2008-04-04	2016-05-07	2	2.3	N	AUS
	TK04	2	2.2	2008-08-09	2010-10-29	3	3.1	PC	AUS
	TK05	3	3.1	2011-12-12	2018-04-08	1.9	2.2	SS	AUS
	TK06	3	2.3	2012-12-19	2017-07-14	2.8	2.9	N	AUS
	TK07	2	2.5	2014-05-11	2016-11-13	3.2	3.5	OSS	AUS
Pouawa (PO)	PO01	2	7.8	2005-08-08	2013-07-10	2.8	2.8	N	PAC
	PO02	3	4.4	2007-12-30	2016-12-03	2.8	3	N	PAC
	PO03	3	2.1	2010-02-03	2014-05-07	2.2	2.5	OR	PAC
	PO04	2	3.2	2010-04-05	2013-07-06	2.5	2.6	ON	PAC
	PO05	3	2.1	2013-07-05	2017-10-14	2.2	2.4	PC	PAC
Māhia (MA)	MA01	2	1.7	2004-11-01	2006-07-13	2.8	2.9	NA ¹	AUS
	MA02	3	6.1	2005-11-06	2018-03-15	2.1	2.6	PC	PAC
	MA03	2	3.6	2010-02-05	2013-09-30	2.3	2.4	ON	PAC
	MA04	3	2.3	2010-03-17	2014-10-09	2.2	2.4	N	AUS
Nūhaka (NU)	NU01	3	1.8	2008-03-21	2011-11-06	2.1	2.3	OSS	AUS
	NU02	2	1.3	2012-05-26	2013-10-02	1.9	1.9	PC	AUS

¹Focal mechanism not calculated due insufficient of first arrival polarities.

4.2.2 Raukumara Peninsula repeating earthquake locations

Of the 160 earthquakes in the final catalogue, we obtained 147 absolute locations using SIMUL2014 (Eberhart-Phillips and Reyners, 2012; Eberhart-Phillips and Bannister, 2015; Thurber and Eberhart-Phillips, 1999). Table 4.2 contains a summary of the root-mean-square residual errors associated with the locations obtained using SIMUL2014.

Table 4.2: Summary of the errors associated with the locations obtained using SIMUL2014. RMSRES is the root-mean-square residual errors. Errors are the weighted travel-time differences in seconds.

	Minimum	Maximum	Average
RMSRES	0.06	1.7	0.47

HypoDD2.1 was used to try to minimise the error associated with the final locations for the repeating events in each of the families. 147 of the final 160 repeating earthquakes had relative locations calculated using HypoDD2.1 (Waldhauser and Ellsworth, 2000). Appendix C contains the final repeating earthquake catalogue, which includes the final HypoDD2.1 locations. Table 4.3 contains a summary of the errors associated with the final HypoDD2.1 locations. The errors given are the least-squares error estimate computed by HypoDD2.1, using the singular value decomposition (SVD) solver. They represent the variance of each parameter, multiplied by a common factor calculated from weighted residuals.

Table 4.3: Summary of the errors associated with the relative locations obtained using HypoDD2.1. All errors given are in metres. Errors were calculated using singular value decomposition (SVD).

		X	Y	Z
	Minimum	0.0	0.0	0.0
SVD	Maximum	6830.6	4999.8	1734.0
	Average	350.96	374.29	284.94

Uncertainties in the locations obtained in both SIMUL2014 and HypoDD2.1 precluded use of an event separation criterion in the final composite repeating earthquake identification criterion outlined in Section 4.1.5. This is discussed further in Section 5.1. However, as can be seen in Figures 4.5–4.6, the relative locations obtained result in a tighter distribution of events within a family, as well as a clearer separation between families.

Figure 4.5: Maps comparing the absolute and relative hypocentre locations for the earthquakes in the final repeating earthquake families identified around the Raukumara Peninsula. The repeating earthquakes are coloured by depth and scaled by their GeoNet preferred magnitude. Locations of the cross-sections in Figure 4.6 are denoted by the red lines and letters. Depth to the subduction interface model created by Williams et al. (2013) are represented by the black contours. Black inverted triangles represent the GeoNet seismic stations used to calculate the hypocentre locations.

Figure 4.6: Cross-sections comparing absolute (red circles) and relative (blue circles) hypocentre locations obtained for the earthquakes in the final repeating earthquake families identified around the Raukumara Peninsula. The black line through the cross sections represents the model of the subduction interface developed by Williams et al. (2013). Distances along the bottom of each of the cross-sections represent the length of the cross-section across the map area. The swath width for each of the cross-sections extends 10km either side of the cross-section line. Locations of the cross-section lines are denoted by the red lines and letters in Figure 4.5. Note the variable vertical exaggeration of each of the cross-sections.

A comparison of the separation between events in four of the families is included in Figure 4.7. The separation between the events calculated for the GeoNet and HypoDD2.1 are compared to SIMUL2014, as it allows the comparison of the absolute location methods and the SIMUL2014 locations were used as a starting point for the HypoDD2.1 calculations.

Figure 4.7: Graphs of the separation between the repeating earthquakes in four of the families, RA02, WH01, TS01 and TK01. **Left:** Separation between the repeating earthquakes GeoNet locations compared to the SIMUL2014 calculated locations. **Right:** Separation between the repeating earthquakes SIMUL2014 calculated locations, and the location calculated using HypoDD2.1.

As can be seen in Figure 4.7, the range of the separation between the events HypoDD2.1 locations is significantly smaller than for both the GeoNet and SIMUL2014 locations. For the four families that are plotted, all the HypoDD2.1 separations are less than 4.0 km (and most are less than 500 m), whereas the GeoNet and SIMUL2014 location separations are up to 9 km.

4.2.3 Focal mechanisms for the Raukumara Peninsula repeating earthquakes

We calculated focal mechanisms for the youngest event in 56 of the 62 families (Figure 4.8). The focal mechanisms obtained were used to divide the families based on whether the event was located to be occurring on the subduction interface, in the overlying Australian Plate or in the subducting Pacific Plate. Further discussion of this is included in Section 5.3. Uncertainties of the focal mechanism solution were calculated

for the strike, dip and rake, within FPFIT (Reasenber, 1985) in SEISAN (Havskov and Ottemoller, 1999), and are summarised in Table 4.4. These uncertainties are minimum uncertainties, as we have not fully propagated the location uncertainty through to the focal mechanism solution. Appendix D contains a table of the best solution for strike, dip and rake for each of the focal mechanisms calculated for the youngest event in each of the repeating earthquake families. Additionally, to investigate how well constrained the focal mechanism are, for each of the regional groups, a selection of the focal mechanisms obtained are shown with all the possible solutions calculated using FPFIT are included in Appendix D. While 56 focal mechanisms were calculated, for some of the events, specifically WA01, MA02 and NU02, are not well constrained.

Figure 4.8: Map of the focal mechanisms calculated for the youngest event in each of the repeating earthquake families coloured by the events HypoDD2.1 depth. Focal mechanisms were calculated using FPFIT in SEISAN. Focal mechanisms are coloured by the depth of the event, and scaled by the magnitude of the event.

Table 4.4: Summary of the minimum errors associated with the calculated focal mechanisms, in degrees.

	Strike	Dip	Rake
Minimum	1.0	1.0	1.0
Maximum	34.0	30.0	54.0
Average	7.06	8.67	14.53

4.2.4 Raukumara Peninsula repeating earthquake regional groups

Details of families in each of the geographic locations are provided under each of the following headings. This includes a summary of the regional group, as well as the vertical component seismograms for each of the families in the group. Focal mechanisms have also been included, if they were calculated. All magnitudes that are stated for each of the regional groups are the GeoNet preferred magnitudes of the earthquakes.

Waihou Group: WA01 is the only repeating family that is located to the northwest of the Raukumara Peninsula, in the northeastern Bay of Plenty. The family consists of two earthquakes (Figure 4.9), which have a recurrence interval of ~ 12 years. These earthquakes are the largest in the final catalogue (M_W 4.5). While a focal mechanism was calculated for WA01, it is not included due to it being poorly constrained (see Appendix D).

Figure 4.9: Seismic waveforms for the repeating earthquakes in WA01. Waveforms are from the vertical component of the station, stated in the bottom right hand corner. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Te Araroa Group: TA01 is the furthest offshore repeating earthquake family identified in the catalogue and is made up of two events, which occurred ~ 6 yrs apart (Figure 4.10). The focal mechanism obtained indicates oblique reverse faulting.

Figure 4.10: Seismic waveforms for the repeating earthquakes in TA01. Waveforms are from the vertical component of the station, stated in the bottom right hand corner. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Figure 4.11: Seismic waveforms for the repeating earthquakes in the Ruatōria Group. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Ruatōria Group: The Ruatōria Group contains two families that are distinctly separated in time (Figure 4.11). RA01 spans 2004 to 2010, while RA02 spans 2011 to 2015. These families also have similar focal mechanisms, that indicate a combination of strike-slip and normal faulting. They also have similar epicentral locations, but RA02 occurs at a greater depth.

Te Puia Group: Of the four families that form the Te Puia group, TP02 differs from the others (Figure 4.12). TP02 has a magnitude of M_W 3.5 while the other families have magnitudes of $\sim M_W$ 2.5. The other families also occurred deeper in the crust. The focal mechanism produced for TP02 is normal. TP03 and TP04 also had focal mechanism constructed but these mechanisms were poorly constrained. No focal mechanism was formed for TP01, due to insufficient first arrival polarities.

Figure 4.12: Seismic waveforms for the repeating earthquakes in the Te Puia Group. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Tokomaru–Tolaga Group: The Tokomaru–Tolaga Group consists of 34 families, which have a broad range of magnitudes (M_W 1.5 to M_W 3.6), and depths (4 km to 30 km) and cover all faulting types. The number of events in each family ranges from two to five, with the majority of the families containing two or three events. TT18 is the largest family, not only in this group but in the entire catalogue, containing five events of $\sim M_W$ 2.2. The waveforms and focal mechanism for five of the families is included in Figure 4.13.

Figure 4.13: Seismic waveforms for the repeating earthquakes in five of the largest Tokomaru–Tolaga Group families. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20 Hz has been applied.

Whatatutu Group: WH01 (Figure 4.14), consists of three events of $\sim M_W 2.0$. The focal mechanism calculated indicates normal faulting. The recurrence interval for the family is ~ 4 yrs.

Figure 4.14: Seismic waveforms for the repeating earthquakes in WH01. Waveforms are from the vertical component of the station, stated in the bottom right hand corner. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Tolaga-South Group: The Tolaga-South Group is made up of one family, TS01 (Figure 4.15). There are four repeating earthquakes within this family, which have a magnitude range of $M_W 2.1 - 2.4$, and oblique normal faulting is indicated by the focal mechanism.

Figure 4.15: Seismic waveforms for the repeating earthquakes in TS01. Waveforms are from the vertical component of the station, stated in the bottom right hand corner. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Te Karaka Group: The Te Karaka Group is made up of seven families, with each family containing 2–3 earthquakes. As can be seen in Figure 4.16, a range of faulting types is observed. The magnitude range of the families also varies from M_W 1.9 – 3.6. TK01 contains the oldest earthquake in the final catalogue.

Figure 4.16: Seismic waveforms for the repeating earthquakes in the Te Karaka Group families. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Pouawa Group: Of the five families that form the Pouawa Group (Figure 4.17), PO02 has the longest family duration, spanning ~ 9 yrs. Oblique strike-slip, normal and reverse faulting all occur within the group. Recurrence intervals in this group also vary from ~ 2.1 – ~ 4.4 yrs.

Figure 4.17: Seismic waveforms for the repeating earthquakes in the Pouawa Group families. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Māhia Group: Four families form the Māhia Group (Figure 4.18). Similar magnitudes are observed for each of the families (M_L 2.1 – 2.9), but the recurrence intervals vary significantly within the group, as they range from ~ 1.7 to ~ 6 yrs.

Figure 4.18: Seismic waveforms for the repeating earthquakes in the Māhia Group families. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

Nūhaka Group: Similar to the Ruatōria Group, the Nūhaka Group is comprised of two groups that are separated by time (Figure 4.19). NU01 occurred between 2008 and 2011, and at a depth of ~ 6 km. This was followed by NU02, which occurred between 2012 and 2013, and at a slightly deeper depth of ~ 12 km. The focal mechanisms change from NU01 indicates strike-slip motion, but the focal mechanism for NU02 is poorly constrained.

Figure 4.19: Seismic waveforms for the repeating earthquakes in the Nūhaka Group families. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

4.3 Application of composite criterion to other tectonic settings in New Zealand

To test the applicability of the established composite criterion to other tectonic settings in New Zealand, we ran the methods established for identifying repeating earthquakes around the Raukumara Peninsula, on subsections of the clustered earthquake catalogue located around Marlborough and Fiordland (Chamberlain et al., 2019). The only difference that was implemented was that the correlation threshold during the initial family identification (Section 3.2), was altered to 0.95 from 0.96. This was due to the initial correlation values used to cluster the seismicity being significantly lower than the correlation values observed around the Raukumara Peninsula.

We identified three families around Fiordland and four families around Marlborough. As this was conducted to see if the composite criterion could be applicable to other regions, the youngest events in each of the families were picked, to ensure the accuracy of the alignment of the traces. However, absolute and relative earthquake locations were not calculated. The repeating earthquake families identified are summarised in Table 4.5, and a catalogue of all the events is included in Tables C.2–C.3.

Table 4.5: Summary of the repeating earthquake families identified in Marlborough (Clarence and Clifford Bays) and Fiordland (Te Anau and Milford Sound). Each geographic area has a two-letter code which is used to identify families within the group. **N** is the number of events in a family. **T** is the recurrence interval of the events in the family. Magnitudes, $M_{\min}$ and $M_{\max}$, stated are local magnitudes calculated by GeoNet.

Geographic area	Name	N	T	Earliest	Latest	$M_{\min}$	$M_{\max}$
Clifford Bay (CB)	CB01	2	2 minutes	2005-11-01T21:37:50	2005-11-01T21:40:02	2.6	2.9
	CB02	2	4 weeks	2005-11-22T11:21:22	2005-12-18T03:58:25	2.1	2.7
	CB03	3	9 hours	2011-07-04T03:43:10	2011-07-04T12:56:58	2.2	2.5
Clarence (CL)	CL01	3	48 minutes	2010-08-03T21:38:23	2010-08-03T22:26:59	1.8	2.6
Milford Sound (MS)	MS01	4	6 months	2009-01-27T07:17:07	2010-10-08T09:16:47	2.7	3
	MS02	4	9 months	2009-05-03T14:48:22	2011-10-03T06:43:42	2.5	2.9
Te Anau (TU)	TU01	2	15 months	2003-10-14T17:35:41	2005-02-25T01:11:25	2.4	2.8

4.3.1 Marlborough repeating earthquakes

Applying the New Zealand repeating earthquake composite criterion to the seismicity clusters identified by Chamberlain et al. (2019) around Marlborough, we identified four repeating earthquake families, from an initial 51 possible families (summarised in Table 4.5 and C.2). As with the Raukumara Peninsula, we focused the search between 2003 and 2018. The youngest event in the initial seismicity clusters occurred in 2016, and was rejected when the final composite criterion was applied, with no repeating events after 2011 being identified. Figure 4.20 shows the locations of the four families identified.

Figure 4.20: Map of the repeating earthquake identified around Marlborough. Filled circles represent the youngest event identified in each of the families and the open circles represent the remaining events in the family, which are coloured by family. Black inverted triangles represent the GeoNet seismic stations.

These families differ from those identified around the Raukumara Peninsula, as the family durations are significantly shorter, on the scale of days to weeks rather than years. However, this may be an artefact of the GeoNet catalogue's completeness (see Section 5.2). Conducting an extensive matched-filter search using the youngest event in each of the families could find any potentially missing events and correct the issue of completeness. The waveforms of the identified families are shown in Figure 4.21.

Figure 4.21: Seismic waveforms for the repeating earthquakes in the families that were identified around Marlborough. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

4.3.2 Fiordland repeating earthquakes

We also ran the identification methods and composite criterion on seismicity clusters around Fiordland. Three families met the final criterion of the six initial families we identified, with no events occurring before 2003. The summary of the families identified is included in Table 4.5 and C.3. At all the stages of identification no events before 2003 meet the criterion we developed. However, this could be an artefact of the level of completeness of the GeoNet seismicity catalogue. Similar to Marlborough, an extensive matched-filter search using the youngest event in each of the families could solve completeness issues with the GeoNet catalogue. Figure 4.22 shows the locations of the three families identified, and Figure 4.23 shows the waveforms of all the families identified.

Figure 4.22: Map of the repeating earthquake identified around Fiordland. Filled circles represent the youngest event identified in each of the families and the open circles represent the remaining events in the family, which are coloured by family.

Figure 4.23: Seismic waveforms for the repeating earthquakes in the families that were identified around Fiordland. Waveforms are from the vertical component of the station, stated in the bottom right hand corner of each family. A fourth-order bandpass filter between 1 and 20Hz has been applied.

4.4 Results Summary

The key results presented in this chapter are:

1. We developed a method and composite criterion suitable for detecting repeating earthquakes around the Raukumara Peninsula. This method and composite criterion is:
 - Waveforms should be processed with using a fourth-order bandpass filter between 1 and 20 Hz;
 - Cross-correlation should be calculated for 75% of the earthquake coda;
 - After processing, events need to have a cross-correlation of at least 0.95 on two or more stations.
2. We applied this composite criterion to seismicity occurring around the Raukumara Peninsula and found 62 repeating earthquake families, made up of 160 earthquakes, spanning the years 2003–2018
3. Repeating earthquakes around the Raukumara Peninsula have a range of focal mechanisms consistent with both plate interface faulting and intraplate faulting.
4. We tested our repeating earthquake composite criterion in two different tectonic regions and found it was able to successfully identify repeating earthquake families in both regions:
 - Four families identified around Marlborough;
 - Three families identified around Fiordland.

Chapter 5

Discussion and Conclusions

This chapter begins with a discussion of the final composite criterion for identifying repeating earthquakes in New Zealand, and the completeness of the final catalogue (Sections 5.1–5.2). Following this we investigate the locations of the repeating earthquakes (Section 5.3), and compare the seismic moment and slip-rate relationship for our Raukumara Peninsula families to previously established relations (Sections 5.4–5.5). The chapter concludes with a summary of our final conclusions and possible extensions to the research undertaken (Section 5.6–5.7).

5.1 Comparison of repeating earthquake identification criteria

One of the initial studies of repeating earthquakes was undertaken by Geller and Mueller (1980), with four similar earthquakes being identified in Central California. In this study four earthquake were identified by their near identical waveforms and locations, but a criteria was not stated. Poupinet et al. (1984) formed one of the first definitive criteria for identifying repeating earthquake studies, which stated earthquakes are repeating if the coherence of the waveforms is greater than 0.95. Since these initial studies, the criteria that have been used to identify repeating earthquakes around the world has remained extremely similar (see Appendix A). Only minor adjustments have been made to allow for changes such as noise levels in the waveforms, and station coverage (Uchida and Bürgmann, 2019, and references therein). The composite criterion we developed follows this trend and is discussed below.

We use normalised cross-correlation to distinguish between repeating earthquakes and other types of seismicity in New Zealand, an approach consistent with most of the repeating earthquake criteria described in Appendix A ($\sim 80\%$). Similar to these studies, a correlation of 0.95 is required on at least two stations. The key difference between our study and previous ones was that we decided to calculate the waveform correlation for 75% of the earthquake coda rather than a fixed time window around the P- and S-arrivals. We developed this criterion using the seismicity around the Raukumara Peninsula, but also tested it in two other tectonic regions with varying station coverage, to assess if it could be applied uniformly throughout New Zealand. Similar to the Raukumara Peninsula, the search for repeating earthquakes was restricted to earthquakes which occurred after 2003, due to the changes in GeoNet station coverage (Petersen et al., 2011). While the composite criterion did identify repeating earthquakes around Fiordland and Marlborough, we advise care to confirm that other events that should be classified as repeating are not missing from those families identified. Small changes to the criterion may be required in regions with sparse network coverage, such as Fiordland. For example, a correlation of 0.95 may be required on only one station instead of two, as it is difficult to obtain all the events in the family on multiple stations.

Of the previous studies in Table A.1, $\sim 37\%$ include hypocentral separation between events, or overlapping source areas, as a method for identifying repeating earthquakes. We calculated the separation between the events in the final catalogue of repeating earthquake families around the Raukumara Peninsula, using the final HypoDD2.1 locations and plotted it against the calculated normalised cross-correlation (Figure 5.1).

Figure 5.1: Distance between repeating earthquakes HypoDD2.1 locations verse calculated normalised cross-correlation between each of the events. No pattern between the separation between events and the calculated correlation is observed. Note, only events with a normalised cross-correlation above 0.95 appear in our final catalogue.

As can be seen in Figure 5.1, there is no clear relationship between the normalised cross-correlation and the distance between the events. Due to no obvious pattern between the separation between the events and correlation, and the wide range of uncertainties in the relative earthquake locations, due to varying network coverage and identified first arrivals (Table 4.3), we did not determine a distance criterion for New Zealand.

We also investigated whether the events in a family have overlapping source areas, and if it could be used as a criterion. In order to estimate the source area, some studies assume a stress drop (e.g. Schaff et al., 2002; Hatakeyama et al., 2017), where as others calculate the stress drop for individual events (e.g. Dreger et al., 2007; Materna et al., 2018). Additionally, a fault model has to be assumed. The commonly assumed stress drops for repeating earthquakes are 3 MPa and 10 MPa, with a circular crack model (Chen et al., 2007; Peng et al., 2005; Schaff et al., 2002). Using these two stress drops, and a circular crack model, we calculated the source radii for each of the repeating earthquakes in the final catalogue (using Equation (2.13)). When a stress drop of 3 MPa was used, radii varied from ~ 32 m to $\sim 1,010$ m, and decreased to ~ 21 m to ~ 680 m when 10 MPa was used (Figure 5.2). Figure 5.3 shows the source areas calculated for three repeating earthquake families. Taking location uncertainties and plausible values of stress drop into account, the two youngest events in each of the families display overlapping source areas when comparing the north-south and east-west locations, as well as comparing the east-west and depth locations. For each of the three families in Figure 5.3, it is the oldest event in each of the families which displays a separation from the remaining events in the family. This could be an artefact from calculating the event locations, as the oldest events tend to have fewer picks than the other events in the family, due to changes in station coverage. For events with similar station coverage, events within our repeating earthquake families have overlapping source areas. We suspect that non-overlapping source areas are an artefact of station coverage and therefore to provide the longest duration catalogue possible we do not use overlapping source area as a criterion.

We did not investigate or develop a magnitude criterion for identifying repeating earthquakes. This was due to the small number of studies that add a magnitude criterion alongside correlation ($\sim 25\%$), and observations of variable magnitudes with repeating earthquake families. For example, studies have shown that following large magnitude earthquakes, repeating earthquake families which are located in regions of large postseismic slip, show increases in the magnitude of the individual repeating earthquakes (e.g. Chen et al., 2010; Peng et al., 2005; Schaff et al., 1998; Uchida et al., 2015). Despite not using magnitude as a criterion, events with our repeating earthquakes vary on average by less than 0.3 magnitude units.

Figure 5.2: Histogram of the source radii calculated using 3 MPa and 10 MPa. In both data sets, WA01 has been removed due to the size of the event masking the distribution of the remaining events.

Figure 5.3: Calculated event source areas for families RA02, TT10 and PO02, assuming a 3 MPa stress drop and a circular crack fault model. For families RA02 and PO02, all events in the family are displayed. For TT10 the oldest event in the family is not shown as it was not relocated in HypoDD2.1. Events are plotted relative to the youngest events location (black circles) in the family, red is the oldest event and blue is the middle event. HypoDD2.1 location errors for each of the events are included as black bars. Top: Difference in the north-south and east-west directions between the events. Bottom: Difference in the east-west and depth between the events.

Coherence has also been used to identify repeating earthquakes around the world, however, it was only used by $\sim 19\%$ of studies we looked at (Appendix A). Using coherence as an identification criterion was tested during the initial phase of composite criterion development, and gave similar results to correlation. We decided to use correlation as it is more widely used, and requires fewer variables. To develop a coherence criterion the waveform filtering frequency, the range of frequencies coherence is calculated over, and the threshold all need to be determined.

5.2 Completeness of the final repeating earthquake catalogue

There are two key factors which govern the completeness of the final repeating earthquake catalogue for the Raukumara Peninsula. The first is the completeness of the GeoNet seismicity catalogue through time. Lack of completeness would not only result in events being missed within families, affecting the family duration and recurrence interval, but also result in small magnitude families not being identified. As can be seen in Figure 5.4, the range of magnitudes which form the repeating earthquake families changes after 2011.

Before 2008, very few events smaller than magnitude 2.5 were observed in the Raukumara Peninsula repeating earthquake catalogue (Figure 5.4). Following this from 2008–2011 very few events less than magnitude 2.0 are documented. Finally, after 2011 we see a larger number of events smaller than magnitude 2.0 included in the families. It is likely that this represents a change in completeness of the GeoNet catalogue rather than reflecting changes in the families identified.

We calculated the completeness of the GeoNet catalogue around the Raukumara region using the maximum curvature method (Figure 5.5; Wiemer and Wyss, 2000). The magnitude of completeness decreases from ~ 2.7 to ~ 1.7 through our study period. This follows a similar trend to the magnitudes of the repeating earthquakes identified.

The second is the length of time that we were searching for repeating events. Due to changes in the GeoNet seismic network, with new stations coming online and old stations being removed or upgraded, we limited our search for repeating earthquakes around the Raukumara Peninsula to after 2003. This provided us with the longest duration of continually operating broadband and short-period stations around the region. However, it also limited the number of long recurrence interval families which could be

identified.

Figure 5.4: Graph showing the how the magnitude of the repeating earthquakes changes through time. The magnitude 4.5 events, from WA01, have been removed, in order to observe any patterns in the lower-magnitude earthquakes.

Figure 5.5: Graph of the calculated magnitude of completeness of the GeoNet catalogue around the Raukumara region, from 1992 to 2019. We calculated completeness using the maximum curvature method (Wiemer and Wyss, 2000) for groups of 2000 events.

For example, WA01 is a family that has only two events in the final catalogue, and a recurrence interval of ~ 12.3 years, with the first event occurring in 2004. It is possible that there are other events in the family, potentially occurring around 1992, but this catalogue does not identify them. Similarly, larger magnitude events which have longer recurrence intervals (e.g. longer than ~ 15 yrs), may only have one event occurring in this study's time frame and would thus be missing.

In order to resolve issues around the completeness of the catalogue, an extensive matched-filter search, using both the families identified as templates, and other events in the GeoNet catalogue could be run. This would not only help identify events that were not in the GeoNet catalogue due to their small magnitude, but would also enable the catalogue to be extended both before 2003, and after 2018, when our analysis ends.

5.3 Repeating earthquake locations

We investigated the relationship of the repeating earthquake families to the plate boundary beneath the Raukumara Peninsula, based on the focal mechanism and location of each family. Families with low-angle reverse focal mechanisms were assumed to be occurring on the plate interface. Due to uncertainties in the earthquake locations, we determined the interface families based on the focal mechanisms rather than depth to the interface model determined by Williams et al. (2013). When the family's depths are directly compared to the plate interface, families with focal mechanism not consistent with interface faulting were located on the interface. As a result, we decided to go with the focal mechanisms as the determining factor, over depth. The other events were assigned to have occurred in the overlying Australian Plate or the subducting Pacific Plate based on the associated HypoDD2.1 resolved depth, in comparison to the interface families. However, we only observe interface families at three distinct locations, the Ruatōria, Tokomaru–Tolaga and Te Karaka Groups. To assign locations to the families in groups away from the interface families, we interpolated the interface following the subduction interface model developed by Williams et al. (2013). Figure 5.6 shows the focal mechanism for each of the families coloured by where they have been assumed to be occurring, while Figures 4.5 and 4.6 show the hypocentre locations for each of the repeating earthquakes. While the families have been assigned to the Australian or Pacific Plates or the interface, uncertainties in the depths can result in ambiguity of where the families are occurring. For example, for families who are located close to the plate interface, may occur in either the Australian or Pacific Plate. In Sections 5.3.2–5.3.3, we split the families based on their location, and discuss

their proximity to other previously documented structures, such as seamounts, SSE patches, and resistivity changes.

Figure 5.6: Top: Map of the youngest events in each family, which have had focal mechanisms calculated using FPFIT in SEISAN. Focal mechanisms are coloured based on where the families have been assumed to be occurring; blue is the Australian Plate, orange is along the interface, and green is the Pacific Plate. Black contours represent the model of the depth to the plate interface, constructed by Williams et al. (2013). Red line represents the location of the cross-section. Bottom: Cross-section of the focal mechanisms along the red line.

5.3.1 Australian Plate repeating earthquakes

34 of the 62 repeating earthquake families identified around the Raukumara Peninsula appear to be located in the Australian Plate. 20 of the Tokomaru–Tolaga Group

families have depths which range from ~ 3 – 13 km. Five of the seven Te Karaka Group families (southwest of Tokomaru–Tolaga) occur in the Australian Plate at depths of ~ 11 – 21 km (Figure 4.4). WA01 is the deepest family occurring in the Australian Plate, to the northwest of the Raukumara Peninsula, at a depth of ~ 49 km. Around the Māhia Peninsula we place two families from the Māhia Group, and two from the Nūhaka group in the Australian Plate at a depth of ~ 13 km (Figure 4.4). Some of the families have the same depths as the subduction interface families discussed below in Section 5.3.2, however, the focal mechanisms are not compatible with interface slip. While these families were assumed to be occurring in the Australian Plate, due to the close depth proximity to the modelled plate interface and uncertainties in the earthquakes locations, these families could be occurring close to the subduction interface, or in the top of the subducting Pacific Plate.

When comparing the location of the repeating earthquake families to the Gisborne SSE slip-model documented by Wallace and Beavan (2010), the Tokomaru–Tolaga and Te Karaka Groups occur down-dip of the SSE (Figures 5.7 and 4.4).

Figure 5.7: Map of the interface locking model adapted from Wallace et al. (2012b). Red regions indicate the interface is locked, and blue regions indicate the interface is stably sliding. The black contours represent the modelled SSE slip contours, in mm for the 2014 SSE event (adapted from Wallace et al., 2016). Black dots indicate the repeating earthquakes identified in this study, and are scaled by the magnitude of each of the earthquakes.

The Māhia and Nūhaka Groups are co-located with the southern edge of the SSE modelled slip patch (Wallace et al., 2016). Further discussion of the relationship between SSEs which occur around the Raukumara Peninsula and the repeating earthquake families is included in Section 5.4.1. Additionally, Jacobs et al. (2016) quantified seismicity associated with SSEs along the Hikurangi Margin, with three of the largest sequences occurring in 2007, 2009 and 2010 approximately 20 km to the east of the Raukumara Peninsula. An increase in the number of repeating earthquakes occurring in the Australian Plate is observed around the occurrence of both the 2009 and the 2010 sequences but not the 2008 sequence.

Comparisons of the repeating earthquake locations to resistivity and geodetically-derived area strain rate data, showed that the Māhia Group occurs above a region where the interface has low resistivity (Figures 5.8 and 4.4; Heise et al., 2017).

Figure 5.8: Resistivity of the plate interface from Heise et al. (2017) (rainbow colour scale). Superimposed is the area strain rate calculated by Dimitrova et al. (2016) (red/blue coloured contours). Black dots represent the repeating earthquakes identified in this study, and are scaled by the magnitude of each of the earthquakes.

MA01 is located in a region of positive area strain (dilatation), whereas MA04, NU01 and NU02, are located along the transition from positive to negative (contractional) area strain (Dimitrova et al., 2016). The Tokomaru–Tolaga Group Australian Plate families, are occurring above the interface, which has a resistivity of $\sim 20 \Omega\text{m}$, and where the areal strain is positive. In contrast, the Te Karaka group occurs above the interface which showed high resistivity ($\sim 200 \Omega\text{m}$) and a negative areal strain rate (Dimitrova et al., 2016; Heise et al., 2017).

5.3.2 Subduction interface repeating earthquakes

Based on the focal mechanisms, 14 families have focal mechanisms consistent with low-angle subduction on the plate interface. These families are from three regional groups. One family is part of the Ruatōria Group (RA02) at ~ 11 km depth, and another is part of the Te Karaka Group (TK02) at ~ 22 km (Figure 4.4). The remaining families are from the Tokomaru–Tolaga Group, and have a range of depths from ~ 5 – 14 km, with a median depth of the interface occurring at ~ 11 km at this group. In comparison, Williams et al. (2013) model the interface at this location at 15 – 20 km depth. As a result of the discrepancy between the repeating earthquake depths and the plate interface model, it is possible that some of the shallower earthquakes that have focal mechanisms consistent with subduction interface faulting, are occurring in the Australian Plate.

As with the families occurring in the Australian Plate, the interface families, excluding RA02, occur along the down-dip limit of the Gisborne SSE patch (Figures 5.7 and 4.4; Wallace and Beavan, 2010). This is similar to findings by Delahaye et al. (2009), who identified high-frequency microearthquakes, occurring either on the subduction interface, or just below, that were triggered down-dip of a slow-slip event in October–November 2004. The repeating earthquakes families are also occurring in very similar locations to the microseismicity identified by Yarce et al. (2019), with no potential interface repeating earthquake families occurring in the seismicity gap that has been identified. Moreover, work done by Bassett et al. (2014), to try and explain the occurrence of slow-slip in the region, identified slower wavespeeds and the possibility of near-lithostatic fluid pressures on the interface, which may also have an effect on the repeating earthquakes. Additionally, all of the interface families locate along sections of the interface which has been previously modelled as stably sliding (Wallace and Beavan, 2010). This could indicate that the repeating earthquakes represent the repeated rupture of asperities which are embedded in a the creeping matrix. However,

the Tokomaru–Tolaga families are occurring adjacent to a locked patch on the interface that has been identified geodetically by Wallace and Beavan (2010). When comparing it to the earthquake sequences identified by Jacobs et al. (2016) following slow slip, no changes in the rate of occurrence of repeating earthquakes that are estimated to be occurring along the subduction interface are not observed during the three largest sequences that occurred to the east of the Raukumara Peninsula. The interface families located along the coast align with regions of relatively low resistivity, while the inland TK02 family occurs in a patch of higher resistivity (Figures 5.8 and 4.4). Heise et al. (2017) interpreted this resistive patch as a region of the interface shear zone that has either reduced fluid or sediment content.

5.3.3 Pacific Plate repeating earthquakes

We identified 14 families as occurring in the Pacific Plate. These families are located at depths of 13–32 km, and along the length of the Raukumara Peninsula. All of the families in the Pouawa and Te Araroa groups are located in the Pacific Plate, as well as two of the Māhia Group families which locate around the Māhia Peninsula (Figure 4.4). Similar to the families in the Australian Plate, the families represent a range of faulting styles, but with a slight predominance of normal faulting.

When the model of interface locking is laid over the distribution of repeating earthquakes (Figure 5.7), the Pouawa, Te Puia and Te Araroa Groups, which have families occurring in the Pacific Plate, all lie along the transition between the locked and sliding regions of the interface (Wallace and Beavan, 2010). Specifically, the distribution of the Pouawa Group families closely follows the small indentation of locking to the north-east of Gisborne, as well as transecting the Gisborne SSE patch (Wallace and Beavan, 2010). Further discussion of the potential relationships between the repeating earthquakes and SSEs is included in Section 5.4.1. Three earthquake sequences have been identified to be associated with SSEs in 2007, 2009 and 2010 by Jacobs et al. (2016), however, the rate of occurrence of the Pacific Plate repeating earthquakes increases in response to the 2010 sequence, but not the other two. Additionally, when the location of the repeating earthquake families is compared to the microseismicity identified by Yancey et al. (2019), the families are occurring in a very similar location. However one family, TS01, is located with the seismicity gap that was identified. Comparing the repeating earthquake family’s locations to seismic reflection data analysed by Bell et al. (2010), reveals that the Pouawa Group families and one of the Te Puia Group families occur down-dip of two subducting seamounts, and along high-amplitude reflective

layers adjacent to the plate interface (Figures 5.9 and 4.4).

Figure 5.9: Map of the seamount location, and regions which show high- and low-amplitude reflections, identified by Bell et al. (2010). Stars represent burst-type repeating earthquake families identified by Shaddock and Schwartz (2019). Black dots represent the repeating earthquakes identified in this study, and are scaled by the magnitude of each of the earthquakes.

As previously interpreted in Section 5.3.1, the Māhia families locate below regions of low resistivity, whereas TK01 locates below a region of high resistivity (Figure 5.8) (Heise et al., 2017). The resistivity and areal strain rate data, from Heise et al. (2017) and Dimitrova et al. (2016) respectively, do not extend offshore, so comparisons to the Pouawa, Te Puia and Te Araroa Groups could not be made.

5.4 Seismic moment relationships

In the following sections we investigate two key repeating earthquake seismic moment relationships. The first is the relationship between seismic and aseismic phenomena and repeating earthquakes around the Raukumara Peninsula. The second, focuses on a comparison between the seismic moment–recurrence interval relationship determined

for the Raukumara Peninsula, and the model developed by Nadeau and Johnson (1998) for Parkfield repeating earthquakes.

5.4.1 Raukumara Peninsula repeating earthquake cumulative moment relationships

Connections between repeating earthquakes and slow-slip events have been extensively documented at Japan’s subduction zones (e.g. Gardonio et al., 2018; Kato et al., 2012; Igarashi et al., 2003; Uchida et al., 2004, 2006; Uchida and Matsuzawa, 2013; Uchida et al., 2016). These studies combine GNSS time series and long duration seismic catalogues, to investigate interactions between slow-slip, repeating earthquakes and large-magnitude earthquakes. To investigate possible triggering relationships between the Raukumara Peninsula repeating earthquakes and slow-slip, we compared the cumulative moment release of the repeating earthquakes to time-series’ of GNSS measured displacement and periods of slow-slip previously identified (e.g. Koulali et al., 2017; Todd and Schwartz, 2016; Wallace and Beavan, 2010; Wallace et al., 2012b; Wallace and Eberhart-Phillips, 2013; Wallace et al., 2016).

We exclude family WA01 from our analysis, as the events which make up the family have a magnitude of M_W 4.5 that masks the signal of the remaining events in the catalogue. Moreover, WA01 is located to the northwest of the Raukumara Peninsula, away from the potential influence of slow-slip sources. Figures 5.10 and 5.11 shows the normalised cumulative moment of each of the families, alongside periods of previously identified slow-slip, a GNSS displacement time-series from GeoNet station GISB (Figure 3.2), and nearby large earthquakes. We display the displacement of GISB as it provides a general reference for the motion around the Raukumara Peninsula and has been operating since 2002. The M_W 7.8 Kaikōura earthquake has also been included in this plot, as this earthquake triggered slow-slip off the coast of Gisborne in the following months, and we wanted to investigate if it also resulted in triggering or changes in the repeating earthquake families identified (Wallace et al., 2018). A summary of the repeating earthquake families response in relation to geodetically detected SSEs is included in Table 5.1.

In Figure 5.12, we compare the Tokomaru–Tolaga, Te Puia and Ruatōria Groups events, to the Puketiti SSEs and the GNSS displacement of GeoNet stations PUKE and ANAU (Figure 3.2). This was completed to see if we can observe steps in the cumulative moment that correspond to displacements observed on these two stations, but not observed at GISB. Only the three groups were compared, as in Table 5.1 these

are the only groups that show a response to the Puketiti SSEs. While PUKE has been operational since February 2004, ANAU has only been operating since October 2010.

Table 5.1: Summary of the interactions between identified periods of slow-slip, and large earthquakes, and whether there is a step in the cumulative moment for the repeating earthquakes regional groups. Event is the timing of the SSE or large earthquake, and event location is where it occurred. M_W is the estimated moment magnitude. Group is the regional groups where steps in the cumulative moment were observed during or shortly following the event.

Event	Event Location	M_W	Group	Reference
Nov 2004	Gisborne	6.7	MA, TT	Wallace and Beavan (2010)
Dec 2004	Tolaga Bay	6.3	TP	Wallace and Beavan (2010)
Jul 2006	Gisborne	6.6	MA	Wallace and Beavan (2010)
Dec 2007	North of Gisborne	6.5	PO	Wallace and Beavan (2010)
Gisborne	Offshore Gisborne	6.6	PO	Francois-Holden et al. (2008)
Mar 2008	Māhia	6.7	NU, TK	Wallace and Beavan (2010)
Aug 2008	Tolaga Bay	6.4	TP, TK, RA	Wallace and Beavan (2010)
Feb 2010	Tolaga Bay + Mahia	6.7	PO, TT, MA	Wallace and Beavan (2010)
Mar 2010	Gisborne	6.7	PO, MA	Wallace and Beavan (2010)
Jun-Jul 2010	Puketiti		TT, RA	Todd and Schwartz (2016)
Aug 2010	Māhia			Todd and Schwartz (2016)
Apr-May 2011	Puketiti + Tolaga Bay		TP, TK	Todd and Schwartz (2016)
Aug-Sep 2011	Māhia		TT, RA	Wallace et al. (2012b)
Sep-Oct 2011	Tolaga Bay		TP	Wallace et al. (2012b)
Dec 2011	Gisborne			Wallace et al. (2012b)
Mar 2012	Puketiti		TT	Todd and Schwartz (2016)
Aug 2012	Tolaga Bay		TT	Todd and Schwartz (2016)
Dec- Jan 2012/13	Puketiti		TP, TK	Todd and Schwartz (2016)
Jun-Jul 2013	Gisborne		PO, TT	Todd and Schwartz (2016)
Jul-Aug 2013	Tolaga Bay			Todd and Schwartz (2016)
Sep-Oct 2013	Māhia		MA, NU	Todd and Schwartz (2016)
Dec 2013	Puketiti		RA	Todd and Schwartz (2016)
May-Jun 2014	Tolaga Bay		TK, PO	Todd and Schwartz (2016)
Sep-Oct 2014	Gisborne	6.8	PO, MA	Wallace et al. (2016)
Sep- Jan 2014/15	Tolaga Bay		TK, TT	Todd and Schwartz (2016)
Dec- Jan 2014/15	Māhia			Todd and Schwartz (2016)
Jan-Feb 2015	Puketiti		TT	Todd and Schwartz (2016)
Feb 2015	Gisborne		TT	Todd and Schwartz (2016)
Jun 2015	Tolaga Bay- Tokomaru Bay		TT	Koulali et al. (2017)
May 2016	Tokomaru Bay		TK	Koulali et al. (2017)
Jun 2016	Pouawa-Tologa Bay			Koulali et al. (2017)
Aug 2016	Pouawa-Ruatōria	6.7	TP	Koulali et al. (2017)
Te Araroa	Offshore Te Araroa	7.1	TP	Koulali et al. (2017)
Kaikōura	Kaikōura	7.8	PO, TT	Wallace et al. (2016)

Of the 31 SSEs identified to the north of Māhia Peninsula, five did not coincide with a step in the cumulative moment of the repeating earthquake (Figure 5.10 and Table 5.1). Similarly, we also observe a step in the cumulative moment following the large magnitude Gisborne, Te Araroa and the Kaikōura earthquakes. Of all the regional groups, the Pouawa and Ruatōria Group families show the clearest correlation between steps in their cumulative moments and the occurrence of SSEs (Figure 5.10).

Four of the seven events in the Ruatōria Group families occur during the approximate timing of the SSEs that occurred after 2008 (Figure 5.10). These events account for $\sim 45\%$ of the total moment of this group. Two of these four SSEs occur around Puketiti, ~ 10 km south of the Ruatōria Group. One of the SSEs is located close to Tolaga Bay (~ 60 km south), with an estimated moment magnitude of 6.4 (Wallace and Beavan, 2010), and one SSE is located near the Māhia Peninsula (~ 130 km south). The repeating earthquakes in the Te Puia Group show a similar trend to the Ruatōria Group, except they appear to only respond to SSEs near Tolaga Bay and Puketiti. As can be seen in Figure 5.10, a $M_W 3.5$ repeating earthquake in this group occurs seven days following the Te Araroa Earthquake. This is the only group which shows a possible step in cumulative moment following this earthquake. When comparing the Te Puia Group repeating earthquakes to the GPS displacement of ANAU and PUKE (Figure 5.12), we observe steps in the normalised cumulative moment and the ANAU and PUKE GPS displacement in 2011, 2013, and 2016.

The Tokomaru–Tolaga Group contains 35 families, and the events that make up this group show a step in cumulative moment during 11 of the 31 SSEs. These SSEs predominantly occurred offshore of Gisborne and Tolaga Bay, however, this group also shows a step in cumulative moment to SSEs which are occurring as far south as Māhia (~ 100 km away), as well as to the north including one Puketiti SSE (~ 30 km away). We also see a step in cumulative moment of a repeating earthquake three days following the Kaikōura earthquake, but there is no change following the Te Araroa earthquake. When comparing the normalised cumulative moment of the Tokomaru–Tolaga Group to ANAU and PUKE (Figure 5.12), it is harder to see a correlation than when comparing the Te Puia Group repeating earthquakes. However, there is a slight step in cumulative moment and the GPS displacement in 2015, and following the Kaikōura earthquake.

The Te Karaka Group is the furthest inland group compared to the SSEs. We see the occurrence of a repeating earthquake during seven SSEs, which are located from Māhia to the south, to Tokomaru Bay in the north. In Figure 5.10 there is a step in the cumulative moment just before the Kaikōura earthquake, as the repeating earthquake occurred ~ 3 hours before Kaikōura.

Figure 5.10: Normalised cumulative moment through time for all the identified repeating earthquakes, split based on geographic region. Regions with only one family have been excluded. Displacement is shown for GeoNet GNSS station GISB. Black vertical lines indicate the occurrence of large magnitude events, from left to right; Gisborne (M_w 6.6), Te Araroa (M_w 7.1), Kaikōura (M_w 7.8). Grey bars represent periods when slow-slip was occurring, as identified by Koulali et al. (2017), Todd and Schwartz (2016), Wallace and Beavan (2010), Wallace et al. (2012b), Wallace and Eberhart-Phillips (2013) and Wallace et al. (2016).

Figure 5.11: Normalised cumulative moment through time for all the identified repeating earthquakes, split based on location relative to the Hikurangi subduction zone. Displacement is shown for GeoNet GNSS station GISB. Black vertical lines indicate the occurrence of large magnitude events, from left to right; Gisborne ($M_w 6.6$), Te Araroa ($M_w 7.1$), Kaikōura ($M_w 7.8$). Grey bars represent periods when slow slip was occurring, that have been identified by Koulali et al. (2017), Todd and Schwartz (2016), Wallace and Beavan (2010), Wallace et al. (2012b), Wallace and Eberhart-Phillips (2013) and Wallace et al. (2016).

Figure 5.12: Normalised cumulative moment through time for all the identified repeating earthquakes, of the northern Raukumara Peninsula families. Displacement is shown for GeoNet GNSS stations Puke and ANAU. Black vertical lines indicate the occurrence of large magnitude events, from left to right; Gisborne (Mw 6.6), Te Araroa (Mw 7.1), Kaikōura (Mw 7.8). Grey bars represent periods when slow slip was occurring, near Puketiti that have been identified by Koulali et al. (2017) and Todd and Schwartz (2016)

Six repeating earthquakes in the Pouawa Group correspond to the occurrence of a SSE (Figure 5.10). As can be seen in Table 5.1, the step in cumulative moment of the Pouawa Group corresponds predominantly to the Gisborne SSEs (four SSEs), but also responds to SSEs around Māhia and Tolaga Bay. This could be a result of the Pouawa Group transecting the one of the predominant Gisborne SSE patches (Figure 5.7, Wallace and Beavan, 2010). The Pouawa Group is the only group that shows a possible step in cumulative moment 10 days after the M_W 6.6 Gisborne earthquake, as well as 19 days after the Kaikōura earthquake.

The two most southern groups, Māhia and Nūhaka, also show a step in cumulative moment during some of the documented SSEs. Only two of the five Nūhaka Group earthquakes occur during SSEs, and both of these SSEs are located near the Māhia Peninsula. Similarly, the Māhia Group earthquakes show a step in cumulative moment during six SSEs, which are located around the Māhia Peninsula and Gisborne. This accounts for $\sim 60\%$ of the total moment of the Māhia Group. However, the events in these two groups do not show a step in cumulative moment during the same SSEs.

We have also split the repeating earthquakes based on whether they are occurring in the Australian or Pacific Plates or along the interface (Figure 5.11). For the interface repeating earthquakes, we see a step in cumulative moment during nine SSEs, and none of the repeating earthquakes show a step in cumulative moment following the large regional earthquakes plotted. For the repeating earthquakes in the Pacific Plate families, we observe a response to 12 SSE, as well as to the Gisborne and Kaikōura earthquakes. This is very similar to the Australian Plate repeating earthquakes, with a step in cumulative moment during or after 15 SSEs being observed. Additionally, repeating earthquakes occurring in the Australian Plate show steps in cumulative moment following both the Te Araroa and Kaikōura earthquakes, while the Pacific Plate repeating earthquakes show a step in cumulative moment following the Gisborne and Kaikōura earthquakes. The Pacific Plate repeating earthquake occurs 19 days after the Kaikōura earthquake, whereas the Australian Plate repeating earthquake occurs three days after.

Overall, we observe that while some of the repeating earthquakes in the Raukumara Peninsula region show a step in cumulative moment during the occurrence of SSEs others do not. Moreover, the repeating earthquakes tend to occur down-dip of the SSE patch when the SSE is occurring in a similar geographic region. For example, the Ruatōria Group earthquakes occur down-dip of the Puketiti SSEs, and the Tokomaru–Tolaga Group earthquake occur down-dip of the Gisborne SSEs. Similar patterns have been observed by Delahaye et al. (2009) with high-frequency microearthquakes

triggered by SSEs, and tectonic tremor identified by Todd et al. (2018).

Of the 31 SSEs that we compare to the repeating earthquakes, we only have the exact date of occurrence for one of the events, the December 2011 SSE (12–24 of December 2011; Wallace et al., 2012b). However, this is one of the events for which we do not observe a step in cumulative moment. In order to further investigate the relationship between the SSEs and the repeating earthquakes, more precise timings of the SSEs are required, and investigation of the statistical significance of the repeating earthquake timing, as well as a larger catalogue of repeating earthquakes. The SSEs could stop repeating earthquakes from occurring, by releasing stress on the asperity. This is discussed in Section 5.7.

5.4.2 Seismic moment–recurrence interval relationship

Based on the model that repeating earthquakes reflect cyclic loading and release of stress on the same fault patch, their magnitudes and recurrence interval times should scale together (Nadeau and Johnson, 1998). As discussed in Section 2.3.5, as seismic moment increases the recurrence interval should also increase, which has been verified in other regions (Chen et al., 2007; Chen and Lapusta, 2009; Dominguez et al., 2016; Johnson, 2010; Lengliné and Marsan, 2009; Marone et al., 1995; Mavrommatis et al., 2015; Mesimeri and Karakostas, 2018; Nadeau and Johnson, 1998; Peng et al., 2005; Schaff and Richards, 2011; Uchida, 2019; Yu, 2013). Nadeau and Johnson (1998) initially constructed a seismic moment–recurrence interval relationship for repeating earthquake families occurring around Parkfield of:

$$\log(T) = 4.85 + 0.17 \log(M_O) \quad (5.1)$$

where T is the recurrence interval in seconds, and M_0 is the seismic moment in dyne-cm. This relationship has since been the point of reference for other repeating earthquake studies. Comparisons have been made between the Parkfield families, and families in central Taiwan, northeast Japan, Tonga–Kermadec and Mexico, which all show similar trends (Uchida, 2019). Slight variations in the relationship have been observed between different regions, as well as changes occurring before and after nearby large earthquakes (e.g. Schaff and Richards, 2011; Yu, 2013). Schaff and Richards (2011) and Yu (2013), for example, noted that the recurrence intervals of their respective repeating earthquakes families, tend to be shorter than those identified by Nadeau and Johnson (1998), for the same magnitude.

To investigate this relationship in the New Zealand context, we calculated the average recurrence interval for each of the families, and the moment for the youngest event in the family. The magnitude of the youngest event was taken to represent the magnitude of the entire family, rather than averaging the magnitudes of all the events in a family, for two reasons. The first was that the magnitudes of each of the families were extremely similar (see Table 4.1). The second was that the GeoNet preferred magnitudes were used to calculate the moment, and it was assumed that the youngest event in the family had the most well constrained magnitude and lowest associated error. Further to this, we plot the logarithm of each of these variables in Figure 5.13. We split the families based on whether they were occurring in the Australian or Pacific Plates, or along the interface, to see if there were any differences between the locations. We fitted a linear relationship to the logarithms of each of the variables by minimising the L1 norm.

Figure 5.13: Raukumara Peninsula repeating earthquake families recurrence interval (T) plotted against seismic moment (M_0), with outlier families, TP04, TT31, TT15 and TT34, and WA01 removed. Repeating earthquake families are split based on where the families are located, and regression lines fitted. The black dashed line represents the relationship identified by Nadeau and Johnson (1998) using Parkfield repeating earthquake families. Bottom left: All the data.

Table 5.2: Summary seismic moment – recurrence interval relationship identified for the Raukumara Peninsula repeating earthquakes compared to the Nadeau and Johnson (1998) model. Regression lines were fitted once the outlier points had been removed. 95% confidence intervals for the gradient and intercept are included in the brackets

Location	Intercept	Gradient
Australian Plate	6.27 (2.68–9.86)	0.085 (–0.094–0.264)
Interface	6.03 (2.05–10.00)	0.097 (–0.103–0.298)
Pacific Plate	7.71 (3.29–12.14)	0.017 (–0.203–0.238)
Nadeau and Johnson (1998): Parkfield	4.85 ± 0.16	0.17 ± 0.009

In the insert of Figure 5.13, four families were identified as outliers. These families were, TP04, TT15, TT32 and TT34. To highlight the significant differences between these four families, and the largest families in the catalogue, the magnitude of the events in the repeating earthquake families were plotted through time (Figure 5.14).

Figure 5.14: Repeating earthquake families recurrence interval plots. Top: Largest repeating earthquakes through which are occurring in the Australian or Pacific Plates, or along the interface. Bottom: Repeating earthquake families with extremely short family durations. Above each of the plots is the name of the family.

Figure 5.14, clearly highlights the difference in recurrence interval between these families, despite all the events in each of the families having similar magnitudes. Due to the extremely short recurrence intervals of the four outlier families, these were removed and the regression line recalculated. This allowed for the long duration repeating earth-

quake families identified around the Raukumara Peninsula, to be compared to Parkfield repeating earthquake families. WA01 was also excluded due to the magnitude difference between this family and the remaining families ($\log(M_0) = 23$ compared to $\log(M_0) < 22$).

As can be seen in Figure 5.13 and Table 5.2, the relationship between seismic moment and recurrence interval for the Raukumara Peninsula repeating earthquake families is weaker than the relationship identified by Nadeau and Johnson (1998). However, the 95% confidence intervals for both the gradient and the intercept include the values for the Parkfield repeating earthquakes. Due to the scatter in the data for all the plate locations and the small magnitude range the relationships are calculated over, the confidence intervals are extremely wide, and prevent us from determining a reliable relationship.

Overall, while we found that the Raukumara Peninsula repeating earthquake families' relationship between recurrence interval and seismic moment followed a very weakly positive trend, as identified by previous global repeating earthquake studies, the error associated with these trends is very large. This places uncertainty on using other relationships established by Nadeau and Johnson (1998), with the Raukumara Peninsula repeating earthquakes. This is discussed further in Section 5.5.

5.5 Slip-rate relationships

Using 53 repeating earthquake families, from the Parkfield segment of the San Andreas fault, and 8 repeating earthquake families from the Stone Canyon section, Nadeau and Johnson (1998) derived a formula which relates the average seismic moment to the average amount of slip of a repeating earthquake family (Equation 5.2). The Parkfield segment families had a magnitude range of $M_W -0.7$ – 1.4 , while the Stone Canyon families were added to the analysis to extend the magnitude range to $M_W 3.7$ – 6.0 . Nadeau and Johnson (1998) derived the relationship:

$$\log(d) = -2.36(\pm 0.16) + 0.17(\pm 0.009) \log(M_0) \quad (5.2)$$

where d is the average amount of slip for a repeating earthquake family in cm, and M_0 is the average seismic moment of the repeating earthquake family, in dyne-cm.

This relationship has also been applied to other tectonic settings and studies, including Japan, to determine the slip of identified repeating earthquake families (e.g. Uchida

et al., 2003). Based on the magnitude range the relationship was derived over, and that it has been universally applied to different settings, we applied the relationship to the Raukumara Peninsula repeating earthquake families. Once the average slip had been calculated using Equation 5.2, we divided the calculated slip by the family duration in order to estimate the slip-rate of each of the families. Figure 5.15 shows the calculated slip-rate for each of the families, which has been converted to mm/yr.

Figure 5.15: Slip-rates calculated from the slip-seismic moment relationship derived by Nadeau and Johnson (1998). Families are coloured by the slip-rate, and the white circles are the families with slip-rates greater than 80 mm/yr. Black inverted triangles represent the GeoNet seismic stations that were used in the analysis, and the black contours represent the model of the depth to the plate interface, constructed by Williams et al. (2013).

Slip-rates calculated for the Raukumara Peninsula repeating earthquake families range from < 10 mm/yr up to ~ 80 mm/yr, when the families with extremely short family durations are excluded. Family durations are typically 2–4 yrs and 10 families have durations which are longer than 6 yrs. Generally, the shorter the family duration the faster the slip-rate will be. For example, MA02 has a family duration of 12.4 yrs and an estimated slip-rate of ~ 8 mm/yr, where as TT34 has a family duration of 0.5 yrs

and an estimated slip-rate of ~ 178 mm/yr. This trend follows previously established relationships established for Parkfield and Japan, with burst-type repeating earthquake families having slip-rates which are significantly higher than the tectonic loading rate, compared to continual-type repeating earthquake families. In the Raukumara Peninsula repeating earthquake catalogue, six of the 62 families identified would be classed as burst-type as they have family durations less than year. This was determined following the distinction between continual- and burst-type repeating earthquake families outlined by Mesimeri and Karakostas (2018). As Nadeau and Johnson (1998) formed the relationship using repeating earthquake families with at least three events, this relationship may not hold for the Raukumara Peninsula families, as half of the families only have two repeats. Additionally, the seismic moment–recurrence interval for the Raukumara Peninsula repeating earthquake shows a slightly different trend to the Parkfield repeating earthquakes, which may also affect the use of the Nadeau and Johnson (1998) slip-rate model on the repeating earthquake we identified.

In order to compare similar families we isolated TT18 and TS01, which are the two largest families in the catalogue. TT18 is located in the Australian Plate, has a family duration of ~ 5.1 yrs and average moment of $\sim 5 \times 10^{12}$ Nm. Based on the Nadeau and Johnson (1998) model, the estimated slip-rate for this family is ~ 19 mm/yr. TS01 is further south and is located in the Pacific Plate. It has a similar family duration of ~ 6.1 yrs, but a slightly smaller average moment of $\sim 3.5 \times 10^{12}$ Nm, and a slip rate of ~ 15 mm/yr. These two families have slip-rates that are lower than the plate convergence rate of 45 mm/yr, but comparing the slip-rates of families that are not occurring on the subduction interface to the plate convergence rate is difficult. Additionally, when comparing the slip-rates of some of the interface families to the plate convergence rate, only one, TT24, has a slip rate which matches at ~ 45 mm/yr. NU02 is the only other family which has a slip-rate similar to the plate convergence rate. This family is located in the Australian Plate rather than along the interface due to the family focal mechanism, but it is occurring at the same depth as estimated for the interface. Both of these families only have two repeats and have moments of $\sim 8.9 \times 10^{11}$ Nm.

The slip-rates for the Raukumara Peninsula repeating earthquake families, were calculated assuming stationary slip-rates, and may not accurately reflect the slip on the fault patches where these events are occurring. Instead of using a stationary model, Mavrommatis et al. (2015) and Nomura et al. (2017) used variable slip-rate models to show changes in the amount and rate of slip on the fault patches where repeating earthquakes are occurring. Future modelling of the Raukumara Peninsula repeating earthquake family’s slip, which accounts for variable slip on the fault patch, may reflect a closer relationship to the plate convergence rate.

5.6 Conclusions

This thesis provides the first comprehensive analysis of repeating earthquakes on a decadal timescale in New Zealand. The key conclusions obtained are summarised below.

1. **Identifying repeating earthquakes in New Zealand:** We developed a method and composite criterion for identifying repeating earthquakes in New Zealand, using the seismicity around the Raukumara Peninsula. For events to be identified as repeating they must meet the following:
 - Waveforms should be processed using a fourth-order bandpass filter between 1 and 20 Hz;
 - Cross-correlation should be calculated for 75% of the earthquake coda;
 - After processing, events need to have a normalised cross-correlation of at least 0.95 on two or more stations.
2. **Formation of the Raukumara Peninsula repeating earthquake catalogue:** Using the composite criterion outlined under (1), we investigated the seismicity around the Raukumara Peninsula to identify repeating earthquake families. The following is a summary of the key features of the catalogue.
 - 62 repeating earthquake families were identified, containing 160 earthquakes which occurred between 2003 and 2018;
 - Focal mechanisms were calculated for 56 of the families, which show a range of faulting styles;
 - The families are occurring not only along the interface but in the overlying and subducting plates;
 - The magnitude of the repeating earthquakes identified ranges from 1.5 to 4.5.
3. **Relationship of repeating earthquakes to episodic loading around the Raukumara Peninsula:** Of the 62 repeating families identified, 34 were located in the Australian Plate, 14 along the subduction interface, and 14 in the Pacific Plate. The repeating earthquake families' locations were compared to models of plate interface locking, SSEs, resistivity, areal strain and subducting seamounts. We observed that the repeating earthquake families are concentrated along the down-dip extent of the Gisborne SSE. The offshore repeating earthquake families

occurring in the Pacific Plate align with the modelled transition from locked to creeping regions of the interface, and are located down-dip of the subducting seamounts. We also observe that the repeating earthquake families which are occurring along the eastern coast of the Raukumara Peninsula, occur around patches of low resistivity, whereas the inland repeating earthquake families occur around regions of high resistivity.

4. **Comparison of Raukumara Peninsula repeating earthquake families to previously established relationships:** We compared the Raukumara Peninsula repeating earthquakes to seismic moment–recurrence interval relationships, and calculated slip-rates using relationships previously established by Nadeau and Johnson (1998). The seismic moment–recurrence interval relationships showed similar trends to those of the Parkfield repeating earthquakes, but due to the narrow magnitude range in our catalogue, the calculated relationships have large uncertainties. The slip-rate relationships revealed varying slip-rates with no obvious geographic connection between the repeating earthquakes location and the estimated slip-rate. Using the relationship established by Nadeau and Johnson (1998) only one interface family was found to have an estimated slip-rate that matched the plate convergence rate. Due to the lack of consistency between the slip-rates of the repeating earthquake families and the plate motion rates, it may be problematic to use the families as creepmeters until further modelling has been completed and a slip relationship has been determined for the Raukumara Peninsula.
5. **Application of the process and criterion to other tectonic regions in New Zealand:** To test whether the process and composite criterion could detect repeating earthquakes elsewhere in New Zealand, we applied it to seismicity in Fiordland and Marlborough. The key conclusions are summarised below.

- Four repeating earthquake families were identified around Marlborough, and three were identified around Fiordland.
- Families identified in these two regions differed from those around the Raukumara Peninsula, as they had shorter recurrence intervals and durations, on average.
- We concluded that the process and criterion identified could be applied elsewhere in New Zealand. However, small changes to the filtering frequency band and the number of stations the correlations need to be recorded on may be required due to changes in noise levels and station availability.

5.7 Future research recommendations

In this thesis we have provided the framework for identifying repeating earthquakes in New Zealand, along with the first detailed catalogue of repeating earthquakes around the Raukumara Peninsula. This final section provides recommendations for further research surrounding repeating earthquakes, which will provide the opportunity to extend the final catalogue and conclusions we identified here.

- **Application of composite criterion to the rest of New Zealand:** We have shown that the composite criterion established can be applied to other tectonic settings throughout New Zealand. Using the clustered GeoNet seismicity catalogue, already completed by Chamberlain et al. (2019), the method and composite criterion can be used to establish a repeating earthquake catalogue for the entirety of New Zealand. However, we recommend caution when applying the criterion, as conditions around filtering or the number of stations required to identify a repeating earthquake family may need to be adjusted. Extensive matched-filter search using the identified families as templates could resolve completeness issues in the GeoNet seismicity catalogue (Chamberlain et al., 2018), by identifying missing events in a family. We know that the established composite criterion can be applied to a range of tectonic setting (Section 4.3), however, it has not been tested in volcanic settings in New Zealand. Whether the composite criterion can be applied, as well as the adaptations that maybe needed, requires further investigation.
- **Repeating earthquake interactions:** The catalogue we identified provides a starting point for investigating repeating earthquake interactions. There are two key types of interactions that could be analysed. The first is the triggering relationships between repeating earthquake families, similar to those studies addressed by Nadeau et al. (1995) and Lui and Lapusta (2016), for example. Secondly, the triggering of repeating earthquake families due to other phenomena, such as large magnitude earthquakes or slow slip events, comparable to studies completed by Chen et al. (2010, 2013) and Uchida et al. (2004), for example, should be investigated. In this research we have begun to document the occurrence of repeating earthquakes during SSEs. However, the lack of documented timings of the SSEs, and time constraints, has limited this analysis. Ongoing work by geodetic scientists to develop a complete catalogue of SSEs along the Hikurangi Margin, will greatly aid in further analysis of potential connections between SSEs and repeating earthquakes.

- **Repeating earthquake slip modelling:** We briefly investigated slip-rate relationships using the Raukumara Peninsula repeating earthquake catalogue and the relationship derived by Nadeau and Johnson (1998). However, a relationship for New Zealand was not determined, and investigations into if the repeating earthquakes could be used as deep slip-meters for major faults was not undertaken. Studies conducted by Uchida et al. (2016) and Nomura et al. (2017) use repeating earthquakes as slip-meters at depth and provide crucial information into the stresses on the fault over the earthquake cycle. This could provide key information about the stresses which load large plate-boundary faults in New Zealand, and the potential hazards that they pose.

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Appendix A

Repeating Earthquake Studies

Appendix A contains a series of tables that outline the composite criterion used in previous studies to identify repeating earthquakes. Table A.1 summarises the studies which use correlation, Table A.2 summarises the studies that use coherence, Table A.3 summarises the studies that use an alternative to correlation and coherence, and Table A.4 summarises the studies that use repeating earthquakes but do not specify the composite criterion used, or used a previously identified repeating earthquake catalogue.

In Tables A.1–A.4, “**Reference**” is the reference for the paper where the information was taken from and “**Location**” is where the study took place. In Tables A.1–A.3, “**Magnitude**” is the magnitude threshold and “**Separation**” is the hypocentral separation threshold, that is used by the study, and “**Comment**” includes any other components included in the composite criterion, key ideas from the study, or similarities to other studies. In Table A.1, “**Correlation**” is the normalised cross-correlation threshold used by the study. Similarly, in Table A.2 “**Coherence**” is the coherence threshold used by the study, and in Table A.3, “**Time**” is the time between earthquakes which have been used to determine if events are repeating. Finally, in Table A.4, “**Notes**” provides a brief summary of the study undertaken, and if stated which repeating earthquake catalogue that was used.

Table A.1: Repeating earthquake studies which use correlation as the main identification parameter.

Reference	Location	Correlation	Magnitude	Separation	Comment
Geller and Mueller (1980)	Central California	High degree of correlation			Highly similar waveforms and near identical locations
Nadeau et al. (1994)	Parkfield	≥ 0.9 to frequency of 50 to 100 Hz		Nearly identical hypocentres	
Marone et al. (1995)	Calaveras fault	Nearly identical P - wave coda		Relative centroid locations are within ± 10 m	Using similar correlation criteria of Ellsworth (1995)
Nadeau et al. (1995)	Parkfield				Highly similar waveforms over the full 100 Hz bandwidth of the data, used equivalency class algorithm to determine similarity
Nadeau and Johnson (1998)	Parkfield	≥ 0.98	± 0.1 magnitude units	Identical at a 5 - 10 m resolution	Virtual collocation investigate changes not identified by CCC
Schaff et al. (1998)	San Andreas			Within ± 7 m	Same criteria as Beroza et al. (1995) using temporal variation in coda - Q
Nadeau and McEvilly (1999)	Parkfield	≥ 0.98			
Rubin et al. (1999)	San Andreas		Essentially the same magnitude	Same location	
Matsuzawa et al. (2002)	Japan	Same waveforms	Difference of 0.1		Amplitude fluctuations are within 20 %
Rubin (2002)	California		Similar magnitudes		Clear separation from other earthquake sources and the absence of foreshock - aftershock relationships. Relocation of events occurred required waveform similarities of only 75 %
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Reference	Location	Correlation	Magnitude	Separation	Comment
Igarashi et al. (2003)	Japan	≥ 0.95 at ≥ 2 stations		Hypocentre separations of $< 30\text{km}$	
Okada et al. (2003)	NE Japan		$M 4.8 \pm 0.1$	Same hypocentre locations	Similar waveforms, used to investigate whether asperities are persistent features
Uchida et al. (2003)	Japan	≥ 0.95 for a 40 s window containing the P and S waves		Hypocentre separations of $< 30\text{km}$	
Schaff and Richards (2004)	China	≥ 0.80 for a window of 5 s before the P-wave arrival to 40 s after the Lg - wave			CCC needed at one station
Schaff and Beroza (2004)	California				Near identical waveforms, rupture the same fault patch
Uchida et al. (2004)	Japan	≥ 0.95 for a 40 s window containing both the P- and S- waves			Same process as Igarashi et al. (2003) and Uchida et al. (2003) applied to different regions and magnitude ranges
Matsubara et al. (2005)	Japan	≥ 0.95 at ≥ 3 stations for a window starting 1 s before the P-wave till 40 s after if a S-wave pick was not available else a window 1 s before the P-wave to 5 s after the S-wave			Waveforms bandpass-filtered between 1 and 8 Hz
Peng et al. (2005)	California		Differences $< 1.5 M$	Near complete overlapping source areas ($> 50\%$)	Visual inspection of similarity, as well as using clusters identified by Rubin (2002)

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Reference	Location	Correlation	Magnitude	Separation	Comment
Uchida et al. (2005)	Japan	≥ 0.95 for a 40 s window containing the P and S waves			Bandpass filter of 1 - 4 Hz applied. Activity duration was longer than one month
Kimura et al. (2006)	Central Japan	≥ 0.95 at ≥ 2 stations, for a window 2 s before the P arrival to 5 s after the S arrival	≤ 0.5 difference		Filtered with a passband of 1 - 20 Hz
Li et al. (2007)	China	≥ 0.85			Average recurrence interval > 100 days, and conditions of the travel time picks were also added to the criteria
Rau et al. (2007)	Taiwan	Determined for a 10.5 s window beginning 0.5 s before the P arrival			2 - 18 Hz bandpass filtered applied to waveforms
Mochizuki et al. (2008)	Japan		Constant size ($M \sim 7$)		Recurrence interval of ~ 20 years, repeating earthquakes occurring near subducting seamounts
Templeton et al. (2008)	California	≥ 0.95			Amplitude and phase coherence is ≥ 0.85 is also required
Zhang et al. (2008)	South Sandwich Islands Region	≥ 0.9 for a 30 s window starting 5 s before the predicted P-arrival			Visual inspection to see whether they are truly highly similar to be name doublets. Also searched in the Aleutian Islands, Kuril Islands and Tonga, Fiji and Solomon Islands
Chen et al. (2010)	Parkfield				Updated the High Resolution Seismic Network Repeating earthquake sequence catalogue
Igarashi (2010)	Japan				Same criteria as that used by Igarashi et al. (2003)
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Reference	Location	Correlation	Magnitude	Separation	Comment
Johnson (2010)	Central San Andreas	≥ 0.98		Centroid locations within 3 m	Used moment rate function instead of seismograms
Rubinstein and Ellsworth (2010)	Parkfield	≥ 0.98 on ≥ 5 stations OR ≥ 0.95 on ≥ 5 stations and has a standard deviation of < 0.002 s	Within ± 0.3 magnitude units	Overlap at least 50 % OR could overlap at least 50 % given 2σ SVD errors from hypoDD	
Schaff and Richards (2010)	China	≥ 0.8 computed for window 5 s before P-wave to 40 s after Lg-wave			Waveforms filtered from 0.5–5 Hz, extending on the catalogue create by Schaff and Richards (2004)
Li et al. (2011a)	China	≥ 0.80 computed for window 1 s before P - wave to 5 s after S - wave			Distinguish repeating earthquakes from aftershocks / swarms by their spatial distribution
Li et al. (2011b)	China	≥ 0.80 at ≥ 3 stations for the whole waveform			Waveforms had a 0.5 - 5 Hz bandpass filtered applied
Schaff and Richards (2011)	China	≥ 0.8 for the time window of 5 s before the P arrival to 40 s after the Lg arrival		Hypocentres separated by no more than 1 km	Filtered 0.5 - 5 Hz
Rubinstein et al. (2012)	Parkfield	≥ 0.98 at ≥ 5 stations		Event hypocentres have a $\geq 50\%$ overlap	Subset of the the sequences initially defined by Rubinstein and Ellsworth (2010)
	Taiwan	(1) 75 % of the data has a maximum CCC greater than 0.75, (2) 50% of the data maximum CCC greater 0.85			10.5 s waveforms filtered between 2 and 8Hz
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Reference	Location	Correlation	Magnitude	Separation	Comment
Yamashita et al. (2012)	Japan	≥ 0.95 on ≥ 2 stations for a 40 s time window		CCC calculated for event pairs with epicenter distances < 50 km	Bandpass filter 2-8 Hz on the vertical component which corresponds to the dominant frequency and a quarter wavelength of the S- wave which is equal to the source size
Zechar and Nadeau (2012)	Parkfield				Maximum cross-correlation of raw seismic waveforms averaged across all available stations then divided into groups before being visually inspected
Chen et al. (2013)	Parkfield		± 0.1 magnitude units		Waveform similarity assessed using maximum cross-correlation and phase and amplitude spectral coherence
Yu (2013)	Tonga-Kermadec-Vanuatu subduction zones	> 0.8 for a 30 s window after the P arrival		Overlapping source areas	Similar seismic moments, bandpass filtered 0.8 - 2.0 Hz
Yu et al. (2013)	Sumatra	$\geq 0.8-0.95$, varies depending on the station correlation is being calculated on			Waveforms 0.5-2 Hz bandpass filtered, varies between stations.
Abercrombie (2014)	Parkfield	≥ 0.8 after low-pass filtering to 20 Hz			
Khoshmanesh et al. (2015)	Central San Andreas Fault	≥ 0.98	$\pm 0.1 M_W$		
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Reference	Location	Correlation	Magnitude	Separation	Comment
Naoi et al. (2015)	South Africa	≥ 0.90 at ≥ 2 stations		Distance D $< 0.5r_{lg}$ where r_{lg} is the rupture radius evaluated from M_0	
Chen et al. (2016)	Taiwan				Same method as used by Chen et al. (2008)
Dominguez et al. (2016)	Mexico		Similar magnitudes	Hypocentre resolution of a few tens of meters	Near identical waveforms
Hatakeyama et al. (2016)	Japan				updated repeating earthquake catalogue formed by Uchida and Matsuzawa (2013), based on waveform similarity in 1-8 Hz or lower frequency bands
Schmittbuhl et al. (2016)	Marmara Fault	≥ 0.90 for a 15 s window starting 1s before the P-arrival for both the vertical and horizontal components			Waveforms filtered between 1 and 10 Hz
Bohnhoff et al. (2017)	Marmara Sea - Turkey	≥ 0.90 at ≥ 2 stations	± 0.2 magnitude units	Within 5 km epicentral distance	≥ 30 days between events
Hatakeyama et al. (2017)	Japan				Same method as used by Uchida and Matsuzawa (2013)
Hayward and Bostock (2017)	Queen Charlotte Plate Boundary	> 0.95 for waveforms with a passband of 1-8 Hz			

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Reference	Location	Correlation	Magnitude	Separation	Comment
Yao et al. (2017)	Costa Rica	> 0.9		Identical intracluster event locations	
Lee et al. (2018)	Taiwan	≥ 0.8 for waveform recordings from 1 s prior to the P arrival to 4 s after the S arrival		Within < 30 m	Template matching to search for potentially repeating earthquakes based on normalised CCC. Detected if 24 times the median absolute deviation of the averaged normalised CCC of the day.
Li et al. (2018)	Afghanistan	≥ 0.95 for a 16 s time window starting 1 s before the P arrival on the vertical component AND ≥ 0.9 around the S arrival on the horizontal components, on ≥ 3 stations			Recurrence times range from 2 - 15 days
Mesimeri and Karakostas (2018)	Greece	≥ 0.95 at ≥ 2 stations		Interevent distances less than a quarter wavelength	Bandpass filtered 2.0 - 10 Hz, investigated waveform similarities for longer waveform windows
Warren-Smith et al. (2018)	New Zealand	≥ 0.95 at ≥ 4 stations			CCC calculated on unfiltered waveforms
Shaddox and Schwartz (2019)	New Zealand		varies within families		“Burst-type” repeating earthquake families identified in a subducting seamount and within a slow-slip event
Senobari and Funning (2019)	San Francisco Bay Area	≥ 0.9 for a 10 s window around the catalogue P-wave pick time			
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Reference	Location	Correlation	Magnitude	Separation	Comment
Deng et al. (2020) ¹	Northeastern Tibet	≥ 0.9 for a 20 s window starting 2 s before the P arrival on ≥ 2 stations			Applied a 2-16 Hz bandpass filter on the data.

¹This article has not been peer reviewed as of the submission of this thesis

Table A.2: Repeating earthquake studies which use coherence as the main identification parameter.

Reference	Location	Coherence	Magnitude	Separation	Comment
Poupinet et al. (1984)	California	≥ 0.95			Near identical waveforms indicating identical source processes and medium properties, coherence calculated from spectral methods
Uchida et al. (2006)	Japan	Averaged coherences at 1-8 Hz were ≥ 0.95 at ≥ 2 stations			Used a time window of 0-40 s from the P-wave arrivals
Lengliné and Marsan (2009)	Parkfield	Mean coherence in the 1.5-18 Hz band is $\geq 90\%$	≤ 0.2 M		Source overlap is $> 70\%$ in the horizontal direction and $> 35\%$ in the vertical
Uchida et al. (2009)	Japan	Average of the coherences at 1, 2, 3, 4, 5, 6, 7 and 8 Hz is ≥ 0.95 at ≥ 2 stations		Epicentral separations of < 30 km	Used a time window of 0-40 s from the P-wave arrivals, ensuring that events with high coherence have the same S-P time
Uchida et al. (2010)	Japan	Average of the coherences at 1, 2, 3, 4, 5, 6, 7 and 8 Hz is ≥ 0.95 at ≥ 2 stations for a 40 s time window			Same method as Uchida et al. (2009)
Rubinstein et al. (2012)	Japan	≥ 0.95 at ≥ 2 stations for the frequencies between 1 and 8 Hz			40 s seismograms
Uchida and Matsuzawa (2013)	Japan	Averaged coherences at 1-8 Hz ≥ 0.95 for a 40 s window from the P-wave arrival		Epicentral separations are < 30 km in order for coherence to be calculated	Same procedure as Uchida et al. (2009)
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Reference	Location	Coherence	Magnitude	Separation	Comment
Wu et al. (2014)	Parkfield				Employed the same catalogue as Lengliné and Marsan (2009) which identifies repeating earthquakes based on identical rupture sizes, recorded waveforms, and overlapping sources
Uchida et al. (2015)	Japan	Averaged coherence in the 1 - 8 Hz passband > 0.95 for M 2.5 to M 4.0 events OR the average coherence at half to double the corner frequency must be > 0.8 for earthquakes larger than M 4.0, using a 40 s window			Used the repeating earthquake catalogue formed by Uchida and Matsuzawa (2013)
Taira et al. (2014)	San Juan Bautista Region	$\geq 0.95 \geq 2$ stations	< 0.5 M		To maximise the signal to noise ratio bandpass filters were applied. Frequency ranges were selected to be 8 - 24 Hz and 1 - 8 Hz band dependent on the data set
Mavrommatis et al. (2015)	Japan	Based off criteria outline by Uchida and Matsuzawa (2013)			Isolated repeating earthquakes that occurred in the upper surface of the Pacific Plate and those that had focal mechanism similar to the Tohoku-oki earthquake
Pacheco et al. (2017)	Japan	> 0.8 for both P and S waves at > 100 stations			Coherence calculated for both P and S waves for the frequency range of 1 to 4 Hz
Materna et al. (2018)	Mendocino Triple Junction	> 0.97 at ≥ 2 stations		< 30 km apart	Frequency band 5 - 15 Hz

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Reference	Location	Coherence	Magnitude	Separation	Comment
Uchida et al. (2019)	North Anatolian Fault	> 0.95 for the 2-10 Hz band for a 40 s window starting 2 s before the P arrival on 1 station			Calculated for all event pairs with horizontal separation of < 20 km

Table A.3: Repeating earthquake studies which use an alternative criterion

Reference	Location	Time	Magnitude	Separation	Comment
Gibowicz and Lasocki (2007)	Fiji-Tonga-Kermadec	Within 200, 300, 450 days, for magnitude 5.0-5.4, 5,5-5.9 and ≥ 6.0 events respectively	≤ 0.25 units	≤ 40 km, ≤ 60 km, and ≤ 90 km for magnitude 5.0-5.4, 5,5-5.9 and ≥ 6.0 events respectively	

Table A.4: Studies which use repeating earthquakes but do not specifying an identification criterion.

Reference	Location	Notes
Poupinet et al. (2000)	South Sandwich Islands and Tonga	Use the identification of teleseismic doublets to investigate the existence of an inner core super-rotation
Anooshehpour and Brune (2001)	Parkfield	Developed model for repeating earthquakes - inner asperity surrounded by a larger creeping zone, which is surrounded by a still larger locked zone
Beeler et al. (2001)	Parkfield	Developed model for repeating earthquakes - fixed area fault patch that continuously creep and strain harden until reaching a failure threshold stress
Sammis and Rice (2001)		Investigating an alternative model for repeating earthquakes - repeating events occur at the border between locked and creeping fault patches
Wiens and Snider (2001)	Tonga	Using repeating deep earthquakes, identified by the overlap of source locations, to investigate the potential of fault reactivation at depth
Johnson and Nadeau (2002)	San Andreas Fault	Developed an earthquake asperity model to explain the empirical scaling relationships for repeating earthquakes, based on the static problem
Nadeau and McEvilly (2004)	Central San Andreas	Investigating deep fault slip rates on fault segments from characteristically repeating earthquakes
Waldhauser et al. (2004)	Parkfield	Investigation of the spatio-temporal behaviour of the seismicity around Parkfield, including the occurrence of repeating earthquakes
Yamanaka and Kikuchi (2004)	Japan	Discusses Igarashi et al. (2003) investigation of small repeating earthquakes in relation to the slip rate distribution on the plate boundary, when investigating seismic coupling
Johnson and Nadeau (2005)	San Andreas Fault	Developed an earthquake asperity model to explain the empirical scaling relationships for repeating earthquakes, based on the dynamic problem
Zhang et al. (2005)	South Sandwich Islands region	Using doublets to investigate inner core differential motions
Chen et al. (2007)		Development of a universal recurrence interval scaling rule for global repeating earthquakes
Dreger et al. (2007)	Parkfield	Using repeating earthquake finite source models to investigate strong asperities on the San Andreas Fault

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Reference	Location	Notes
Uchida et al. (2007)	Japan	Calculation of high precision relative locations, source dimensions and stress drops for repeating earthquakes that surround a M 4.9 earthquake rupture
Baisch et al. (2008)		Testing the $\lambda/4$ criterion for identifying repeating earthquakes and the further constraints that need to be applied if it is used
Chen and Lapusta (2009)	Parkfield	Scaling of small repeating earthquakes based on a model of a small fault patch governed by steady state velocity-weakening friction which is surrounded by a much larger velocity-strengthening region
Goltz et al. (2009)	California and Japan	Investigating how rescaled earthquake recurrence time statistic statistics can be applied to repeating earthquakes
Thomas et al. (2009)	San Andreas	Catalogue of repeating earthquakes added to a larger dataset to investigate tremor - tide correlations and near - lithostatic pore pressure
Shimamura et al. (2011)	Japan	Investigation of the similarities and difference in the rupture properties of a sequence of M 4.8 repeating earthquakes
Bisrat et al. (2012)	New Madrid Seismic Zone	Investigate the differences between swarm clusters and repeating earthquake clusters
Hayashi and Hiramatsu (2013)	Japan	Search for similar aftershocks following a large inland earthquake - distributed in the northern section of the source fault but few in the southern section
Kanu et al. (2013)		Used repeating earthquakes that had slightly different locations and source mechanisms to estimate velocity changes in different locations
McLaskey and Kilgore (2013)		Use laboratory based measurements to explain the observations in repeating earthquake sequences, including increases in the seismic moment of the repeating earthquakes immediately following large nearby earthquakes
Turner et al. (2013)	San Andreas	Extension of Nadeau and McEvilly (2004) existing catalogue for the central section of the San Andreas fault system to the Loma Prieta aftershock zone
Jiang et al. (2014)	China	Used repeating earthquakes it investigate the location errors in the China National Seismograph Network, identified earthquakes as repeating if they had correlations greater than 0.8, and used a similar criteria to Schaff and Richards (2004)

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Reference	Location	Notes
Nomura et al. (2014)	Parkfield	Use simulated repeating earthquake catalogues to validate space time models, and analyse recurrence intervals
Chen et al. (2015)	Taiwan	Analysis of repeating earthquakes to investigate changes in waveform propagation in the near-surface versus the fault zone damage
Sawazaki et al. (2015)	Japan	Used repeating earthquakes to investigate a depth-dependence of a seismic velocity changes associated with the 2011 Tohoku earthquake
Yagoda-Biran et al. (2015)	California and Japan	Investigation of the differences between large ($M > 6$) earthquakes to improve national hazard maps in Southern California
Frank et al. (2016)	Mexico	Repeating earthquakes distinct from others studies due to locations not occurring along the plate boundary, and that seismicity rates observed are an order of magnitude faster
Kim et al. (2016)	Parkfield	Using waveform empirical Green's functions finite-source inversion to investigate the changes slip behaviour of a M_W 2.1 repeating earthquake following the M 6 Parkfield main shock
Lui and Lapusta (2016)	Parkfield	Simulating interactions between repeating earthquakes during periods of postseismic slip
Nomura et al. (2017)	Japan	Modelled a repeating earthquake sequence to investigate the space-time distribution of interplate slip rates from the recurrence interval of the repeating earthquakes, then applied method to a complete set of repeating earthquakes used by Uchida and Matsuzawa (2011, 2013)
Corbi et al. (2017)		Analysing model behaviour using repeating earthquakes
Kaneko et al. (2017)	San Andreas Fault	Using previously identified M 2 repeating earthquakes, investigated with nucleation process of the events
Kawamura and Chen (2017)	California and Taiwan	Investigating what influences the location of repeating earthquakes using a and b imaging
Valoroso et al. (2017)	Italy	Used repeating earthquakes to investigate mixed-mode slip behaviour on low-angle normal fault systems
Dublanchet (2018)		Repeating earthquakes not identify but modelled to investigate slip rates (synthetic earthquake catalogue produced)
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Reference	Location	Notes
Lui and Lapusta (2018)	Parkfield	Model two well studied earthquake sequences identified by Nadeau and McEvilly (2004); Zoback et al. (2011) to investigate a suitable model for repeating earthquakes in the region
Cattania and Segall (2019)		Based on numerical simulation found that crack models can be used to predict observed moment-recurrence scaling relationships for repeating earthquakes. Used similar techniques to Chen and Lapusta (2009).
Chen and Lapusta (2019)		Using repeating earthquakes on a fault governed by rate- and state-friction, investigate the behaviour and scaling of the repeating earthquakes to gain a theoretical understanding of the interaction between the repeating earthquakes and the fault properties
Dublanche (2019)		Using a fault model and the synthetic earthquake catalogues produced by Dublanche (2018), to statistically investigate how repeating earthquakes sequences are generated when there are interacting sources on a slowly sliding fault plane
Uchida (2019)		Review of the methods for identifying repeating earthquakes and how slow fault slip can be estimated using repeating earthquakes
Uchida and Bürgmann (2019)		Review of repeating earthquakes, what they are, how they are detected, global observations, mechanics of repeating earthquakes and the uses of repeating earthquake datasets
Williams et al. (2019)	Parkfield	Used Lengliné and Marsan (2009) catalogue of repeating earthquakes, and identified co-located events in catalogues produced by Waldhauser (2009) and Waldhauser and Schaff (2008) based on the criteria that events are located within one radius and within 0.3 magnitude units

Appendix B

Earthquake Location Procedures

Appendix B contains the iterations and/or the files that were run to obtain absolute and relative locations for the repeating earthquakes around the Raukumara Peninsula.

B.1 NonLinLoc

Table B.1 summarises the iterations that were tested to try and obtain absolute earthquake locations for all the events in the preliminary repeating earthquake catalogue using NonLinLoc (Lomax et al., 2000). The two key parameters which were altered during these iterations were **LOCSEARCH** and **LOCMETH**.

In NonLinLoc, **LOCSEARCH** can be set to one of three search methods: (1) the oct-tree importance sampling algorithm, **OCT**, the grid-search algorithm, **GRID**, or the Metropolis-Gibbs sampling algorithm, **MET** (Lomax et al., 2000). When **GRID** is specified in Table B.1, the number of grids trialled is included in the brackets.

As with **LOCSEARCH**, **LOCMETH** can be set to one of three location methods: (1) **GAU_ANALYTIC** is based on the inversion approach of Tarantola and Valette (1982), and assumes all calculated errors are Gaussian, (2) **EDT_OT_WT** which is based on the equal differential time likelihood function and (3) **EDT_OT_WT_ML** which is also based on the equal differential time likelihood function but weights the locations based on a maximum-likelihood estimate of the origin time (Lomax et al., 2000).

Table B.1: Iterations run in NonLinLoc to calculate relative locations for all the potential repeating earthquakes identified around the Raukumara Peninsula.

Iteration	LOCSEARCH	LOCMETH
One	OCT	EDT_OT_WT
Two	GRID (5)	EDT_OT_WT
Three	GRID (10)	EDT_OT_WT
Four	OCT	GAU_ANALYTIC
Five	OCT	EDT_OT_WT_ML
Six	MET	EDT_OT_WT

B.2 SIMUL2014

This section contains the parameter file which was used to run SIMUL2014 (Thurber and Eberhart-Phillips, 1999) to obtain the absolute locations for the youngest events in each of the families which were in the preliminary repeating earthquake catalogue. The only parameter that was altered to run SIMUL2014, was **neqs**, which relates to the number of earthquakes that will be located. The same file was used to calculate the absolute locations of the remaining events in each of the families, with the **neqs** parameter being altered to 220. Before the remaining events in the families were located, events which had less than three corrected first arrival picks were removed.

```

134 000 000 1.00 4 1 0 neqs,nshot,nblast,wtsht,kout,kout2,kout3
000 1.0 4 02.0 06.0 10.0 ntel,wtel,ntobmin,reste1,reste2,reste3
0 50.0 1.5 1 2.0 0.80 iuserdt,edisrdt,facrayr,mxiqdd,wtrdtsht,res4
0 500 20.0 2.0 1 8 0.2 0.40 75.0 iuseclu,nclu,edisedt,facraye,
mxiqedt,nstaepair,wtepdw,wrmscex,gminedt0
01 0.62 .0005 0.03 -0.35 1.00 0.10 0.001 nitloc,wtsp,eigtol,rmscut(hyp
),zmin,dxmax,rderr,ercof
05 0.20 0.010 8.95 1.50 nhitct,dvpmx,dvpvsmx,corrvmx,corrvmmin
0 0400.0 0400.0 400.0 9500.0 2.00 idmp,vpdamp,vpvsdamp,stadamp,
telpad_damp,step1
0 3 0 0.03 0 0.08 0 ires,i3d,nitmax,snrmct,ihomo,rmstop,ifix1
075.00 400.00 0.60 2.00 08.00 delt1,delt2,res1,res2,res3
9 3 1.50 2.00 ndip,iskip,scale1,scale2
1.4 0.004 15 30 xfax,tlim,nitpb(1),nitpb(2)
2 1 1 0 0 kttfor,iuseP,iuseS,invdelay,iuse2t
0 050.0 0.07 1800.0 12.0 iuseQ dqmax qdamp qmax

```

Listing B.1: SIMUL2014 input file

B.3 HypoDD2.1

Table B.2 contains a summary of the key iterations that were trialled in the calculation of the relative earthquake locations for the earthquakes that were in the final repeating earthquake catalogue for the Raukumara Peninsula using HypoDD2.1 (Waldhauser and Ellsworth, 2000). In Table B.2, “**Events Relocated**” details the catalogue of events that were used in the relocation process, “**Starting Locations**” outlined the starting locations assigned to each of the events that were being relocated, “**OBSECT**” is the minimum number of catalogue links for each event pair to form a continuous cluster, and “**Correlation Used**” indicates if correlation was used to refine the final locations. Iteration six is the final set of parameters that were used to calculate the relative earthquake location.

Table B.2: Iterations run in HypoDD2.1 to calculate relative locations for all the potential repeating earthquakes identified around the Raukumara Peninsula.

Iteration	Events Relocated	Starting Locations	OBSECT	Correlation Used
One	Preliminary repeating earthquake catalogue (347 events)	Individual SIMUL2014 locations	0	No
Two	Preliminary repeating earthquake catalogue (347 events)	Individual SIMUL2014 locations	5	No
Three	Preliminary repeating earthquake catalogue (347 events)	Individual SIMUL2014 locations	8	No
Four	Preliminary repeating earthquake catalogue (347 events)	Individual SIMUL2014 locations	8	Yes
Five	Final repeating earthquake catalogue (160 events)	Events in each family set to the location of the youngest event	8	Yes
Six	Preliminary repeating earthquake catalogue (347 events)	Events in each final family set to the location of the youngest event, SIMUL2014 locations for the remaining events	8	Yes

Appendix C

Repeating Earthquake Families Catalogue

Appendix C contains a summary of the Raukumara Peninsula repeating earthquake catalogue. Table C.1 contains the name of the family, which correspond to the family names outlined in Section 4.2.1, the GeoNet ID number for each of the events in the family, the magnitude of the event, and the latitude, longitude and depth of the relative earthquake location obtained using HypoDD. Further details for each of the events is provided in the QUAKEML file in the electronic appendix. This includes, the manual or revised picks, the absolute and relative locations obtained using SIMUL2014 and HypoDD2.1 respectively, and the calculated focal mechanisms.

Table C.1: Raukumara Peninsula repeating earthquake catalogue. Name corresponds to the names in Table 4.1, assigned based on geographic location and age of the oldest event. GeoNet Id is the earthquake identifier given by GeoNet. M is the GeoNet magnitude of the event and is either the local magnitude (ML) or moment magnitude (MW). Latitude, longitude and depth refer to the relative location obtained using HypoDD2.1. Where these values are not stated, relative locations were not obtained.

Name	GeoNet ID	M	Latitude	Longitude	Depth (km)
WA01	2301968	MW4.5	-37.33	177.74	49.19
	2017p181223	MW4.5	-37.33	177.74	49.21
TA01	2347169	ML2.7			
	3585977	ML2.7	-37.69	179.26	13.00
RA01	2248130	ML2.7	-37.91	178.61	6.06
	2682530	ML2.6			
	2941476	ML2.6			
	3304889	ML2.4	-37.91	178.61	5.94
RA02	3559924	ML2.4	-37.85	178.45	11.19

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Name	GeoNet ID	M	Latitude	Longitude	Depth (km)
	2014p026984	MW2.1	-37.85	178.45	11.37
	2015p723848	MW2.2	-37.85	178.45	11.36
TP01	2338634	ML2.6			
	2542295	ML2.5			
	2960418	ML2.6	-38.03	178.81	23.89
TP02	2542384	ML3.5	-38.12	178.94	12.82
	2016p683453	MW3.2	-38.12	178.94	13.19
TP03	3500901	ML2.8	-38.07	178.93	6.02
	2013p015325	MW2.5	-38.07	178.93	5.98
TP04	3591169	ML2.5	-38.28	178.94	32.08
	3591216	MW2.5	-38.28	178.94	31.98
TT01	2153386	ML3.5			
	2012p252782	MW3.5	-38.26	178.65	6.20
	2015p158899	MW3.1	-38.27	178.65	6.20
TT02	2227664	ML3.3	-38.20	178.31	11.70
	2473919	ML3.4			
	2729629	ML3.3			
TT03	2227875	ML3.4	-38.17	178.38	13.49
	2729976	ML3.4	-38.16	178.36	14.09
TT04	2228098	ML3.2			
	2729717	ML3.3			
	3339782	ML2.3	-38.22	178.52	13.55
TT05	2316798	ML2.9	-38.28	178.38	5.50
	2729758	ML2.9	-38.28	178.38	5.37
TT06	2443660	ML2.8	-38.25	178.39	7.44
	2013p419231	MW2.7	-38.25	178.39	6.85
	2017p593450	MW2.2	-38.25	178.39	6.86
TT07	2443690	ML2.4	-37.91	178.61	6.06
	2999590	ML2.3	-38.19	178.31	11.83
TT08	2474158	ML3.3	-38.29	178.38	3.45
	2017p722257	MW2.8	-38.28	178.38	3.32
TT09	2545347	ML3.4			
	2014p267308	MW3.1	-38.31	178.47	4.02
	2017p724207	MW2.8	-38.31	178.47	4.25
TT10	2729757	ML2.7			
	2012p048502	MW1.9	-38.20	178.29	11.86
	2015p473371	MW2.2	-38.20	178.28	11.80
	2017p723914	MW2.3	-38.20	178.29	11.76
TT11	2730059	ML3.1	-38.37	178.39	3.99
	2018p573260	MW2.9	-38.38	178.39	4.01
TT12	2999580	ML3.2	-38.20	178.35	11.24
	3573568	ML3.6	-38.19	178.36	12.67
	2017p724099	MW3.2	-38.19	178.35	12.61
TT13	3068446	ML2.7	-38.19	178.34	12.49
	3573457	ML2.9	-38.19	178.34	12.23
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Name	GeoNet ID	M	Latitude	Longitude	Depth (km)
TT14	3095479	ML2.5	-38.22	178.22	5.69
	2018p571231	MW2.2	-38.22	178.22	5.81
TT15	3244765	ML2.3	-38.32	178.22	4.36
	3249326	ML2.4	-38.32	178.22	4.45
TT16	3252637	ML2.7	-38.20	178.30	12.56
	2012p602010	MW2.4	-38.20	178.28	11.88
	2015p473961	MW2.5	-38.20	178.28	11.86
TT17	3307988	ML2.1	-38.18	178.32	11.99
	2015p082267	MW1.5	-38.18	178.33	12.85
	2017p683469	MW1.6	-38.17	178.30	12.97
	2018p603011	MW1.5	-38.18	178.32	12.42
TT18	3320369	ML2.4	-38.19	178.39	5.04
	2012p261267	MW2.2	-38.19	178.39	5.08
	2013p341393	MW2.2	-38.19	178.39	4.99
	2014p966635	MW2	-38.19	178.39	5.09
	2015p594162	MW2.4	-38.19	178.39	5.48
TT19	3339186	ML2.5	-38.20	178.28	11.64
	2013p534453	MW2.4	-38.20	178.27	11.45
TT20	3339412	ML3.6	-38.27	178.40	4.86
	2015p024195	MW3.5	-38.27	178.40	5.07
	2017p238427	ML3.5	-38.27	178.40	5.02
TT21	3339720	ML2.5	-38.19	178.32	10.76
	2013p419255	MW2.7	-38.18	178.34	12.22
	2018p444706	ML2.8	-38.19	178.33	11.63
TT22	3340269	ML2.5	-38.25	178.26	10.98
	2015p477536	MW2.1	-38.25	178.26	11.02
TT23	3474987	ML2.4	-38.22	178.47	13.86
	2017p591204	MW1.7	-38.22	178.47	13.87
TT24	3573095	ML2.4	-38.21	178.28	11.37
	2013p534039	MW2.2	-38.20	178.32	12.97
TT25	3573268	ML2.7	-38.20	178.29	11.32
	2015p024059	MW2.4	-38.20	178.28	11.45
	2017p721599	MW2.4	-38.20	178.28	11.46
TT26	3339193	ML3.4	-38.20	178.36	15.99
	2015p025917	MW2	-38.20	178.34	15.90
	2015p473385	MW3.3			
TT27	3573621	ML2.6	-38.16	178.33	12.62
	2014p120414	MW2.4	-38.16	178.32	12.66
	2017p727385	MW2.2	-38.16	178.32	12.60
TT28	2012p602104	MW1.8	-38.18	178.30	12.94
	2013p536056	MW1.6	-38.18	178.28	12.73
TT29	2012p968306	MW2.3	-38.34	178.20	8.53
	2015p487528	MW2	-38.34	178.20	8.43
	2016p649538	MW1.9	-38.34	178.20	8.35
TT30	2014p119415	MW2.1	-38.18	178.35	12.04

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Name	GeoNet ID	M	Latitude	Longitude	Depth (km)
	2017p727319	MW2.3	-38.17	178.34	12.17
TT31	2015p025508	MW1.5	-38.19	178.32	11.27
	2015p025818	ML2.4	-38.19	178.32	11.15
TT32	2015p025691	MW2.2	-38.19	178.32	12.04
	2016p867621	ML3.2	-38.19	178.32	12.00
TT33	2015p025711	MW1.7	-38.19	178.27	11.24
	2015p474292	MW1.8	-38.19	178.27	11.04
TT34	2017p593707	MW2.6	-38.19	178.38	27.15
	2017p724160	MW2.9	-38.19	178.38	27.19
WH01	3138199	ML2.2	-38.41	177.91	22.94
	2014p804341	MW1.8	-38.41	177.91	22.97
	2018p578506	MW1.9	-38.41	177.91	22.86
TS01	3573797	ML2.3	-38.54	178.31	25.33
	2012p814437	MW2.1	-38.55	178.31	24.16
	2015p518891	MW2.4	-38.54	178.30	25.59
	2017p778729	MW2.3	-38.54	178.30	25.69
TK01	2112696	ML3.4	-38.54	177.89	25.91
	2506531	ML3.5	-38.54	177.88	22.27
	3520839	ML3.6	-38.54	177.88	22.44
TK02	2272779	ML2.4	-38.57	177.87	22.70
	3143653	ML2.5	-38.57	177.87	22.54
TK03	2889487	ML2.3	-38.60	177.95	11.03
	2016p344723	MW2	-38.60	177.96	10.97
TK04	2950801	ML3	-38.53	177.88	21.43
	3399092	ML3.1	-38.53	177.88	21.49
TK05	3625621	ML2.2	-38.54	177.86	18.29
	2016p134238	MW2.1	-38.54	177.86	20.86
	2018p263987	MW1.9	-38.54	177.86	20.84
TK06	2012p956389	MW2.9	-38.54	177.88	21.47
	2014p950198	MW2.9	-38.54	177.88	21.45
	2017p526750	MW2.8	-38.54	177.88	21.48
TK07	2014p354029	MW3.5	-38.54	177.87	21.90
	2016p857673	MW3.2	-38.54	177.87	21.85
PO01	2443718	ML2.8	-38.68	178.50	21.53
	2013p515567	MW2.8	-38.68	178.51	22.56
PO02	2844171	ML2.9	-38.67	178.53	24.12
	3470170	ML3	-38.68	178.53	23.93
	2016p912302	MW2.8	-38.68	178.53	23.85
PO03	3251291	ML2.5	-38.68	178.50	23.61
	3281309	ML2.4	-38.67	178.50	24.47
	2014p341201	MW2.2	-38.67	178.50	24.53
PO04	3286195	ML2.6	-38.68	178.60	31.66
	2013p505181	MW2.5	-38.68	178.60	31.85
PO05	2013p501682	MW2.4	-38.71	178.50	32.25
	2014p766762	MW2.3	-38.71	178.50	32.20
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Name	GeoNet ID	M	Latitude	Longitude	Depth (km)
	2017p775429	MW2.2	-38.71	178.50	31.72
MA01	2315765	ML2.9	-39.13	177.96	13.01
	2595570	ML2.8	-39.14	177.96	12.99
MA02	2482897	ML2.6			
	3606431	ML2.4	-39.11	178.00	23.00
	2018p198988	MW2.1	-39.11	178.00	22.91
MA03	3263102	ML2.4	-39.12	178.04	20.54
	2013p737584	MW2.3	-39.12	178.04	20.56
MA04	3276555	ML2.4	-38.96	177.91	12.88
	3469945	ML2.4	-38.96	177.91	13.05
	2014p760995	MW2.2	-38.96	177.91	13.05
NU01	2883152	ML2.2	-39.03	177.77	12.03
	3079134	ML2.3	-39.03	177.77	11.75
	3606233	ML2.1	-39.03	177.77	11.85
NU02	2012p397296	MW1.9	-39.06	177.72	12.88
	2013p741866	ML1.9	-39.06	177.72	12.86

Table C.2: Marlborough repeating earthquake catalogue. Name corresponds to the names in Table 4.5, and were given based on geographic location and age of the oldest event. GeoNet Id is the earthquake identifier given by GeoNet. M_L is the GeoNet local magnitude of the event. Latitude, longitude and depth is the GeoNet location.

Name	GeoNet ID	M_L	Latitude	Longitude	Depth (km)
CB01	2480975	2.6	-41.67	-174.21	5
	2480976	2.9	-41.66	174.2	8
CB02	2490155	2.1	-41.69	174.23	10
	2501319	2.7	-41.66	174.2	5
CB03	3540218	2.4	-41.6	174.15	17
	3540219	2.5	-41.58	174.14	19
	3540402	2.2	-41.59	174.15	17
CL01	3350087	2.2	-41.93	173.97	14
	3350101	1.8	-41.93	173.96	13
	3350108	2.6	-41.94	173.99	15

Table C.3: Fiordland repeating earthquake catalogue. Name corresponds to the names in Table 4.5, and were given based on geographic location and age of the oldest event. GeoNet Id is the earthquake identifier given by GeoNet. M_L is the GeoNet local magnitude of the event. Latitude, longitude and depth is the GeoNet location.

Name	GeoNet ID	M_L	Latitude	Longitude	Depth (km)
MS01	3036439	2.9	-44.75	167.86	95
	3120890	3.0	-44.73	167.85	97
	3289477	3.0	-44.72	167.88	99
	3384647	2.7	-44.81	167.96	92
MS02	3085449	2.5	-44.73	167.91	98
	3215313	2.9	-44.72	167.91	97
	3245704	2.9	-44.72	167.84	100
	3588936	2.6	-44.74	168.06	90
TU01	2128623	2.8	-45.61	167.02	13
	2369392	2.4	-45.57	166.99	9

Appendix D

Focal Mechanism Information

Appendix D contains further information for the focal mechanisms calculated. The potential focal mechanism solutions identified using FPFIT, for two families in each of the regional groups is included in Figures D.1–D.9. When the regional group only have one family, then the FPFIT for that family is shown. Table D.1 contains the earthquake GeoNet ID, and the strike, dip and rake of the final focal mechanism solution.

Figure D.1: WA01 and TA01 FPFIT focal mechanism possible solutions

Figure D.2: RA01 and RA02 FPFIT focal mechanism possible solutions

Figure D.3: TP02 and TP03 FPFIT focal mechanism possible solutions

Figure D.4: TT01 and TT25 FPFIT focal mechanism possible solutions

WH01

TS01

Figure D.5: WH01 and TS01 FPFIT focal mechanism possible solutions

TK01

TK05

Figure D.6: TK01 and TK05 FPFIT focal mechanism possible solutions

PO01

PO05

Figure D.7: PO01 and PO05 FPFIT focal mechanism possible solutions

Figure D.8: MA02 and MA04 FPFIT focal mechanism possible solutions

Figure D.9: NU01 and NU02 FPFIT focal mechanism possible solutions

Table D.1: GeoNet Id, strike, dip and rake of the focal mechanisms calculated for each of the families. Further details of the focal mechanisms including the errors and the first arrival polarities are included in the electronic appendix.

GeoNet ID	Strike	Dip	Rake	GeoNet ID	Strike	Dip	Rake
2729976	14	0	77	2015p723848	11.3	114	68
3143653	22.2	48	48	2016p344723	10.9	140	76
3249326	4.5	18	30	2016p649538	8.3	28	58
3304889	6	85	58	2016p683453	13.1	136	45
3339782	13	114	18	2016p857673	21.8	71	47
3399092	21.4	25	7	2016p867621	11.9	160	58
3520839	24.7	86	55	2016p912302	23.8	80	33
3573457	22.4	80	89	2017p181223	49.3	6	88
3585977	13	136	38	2017p238427	5	4	34
3591216	32	62	18	2017p526750	21.4	156	77
3606233	6	12	48	2017p591204	13.8	24	19
2013p015325	5.9	50	90	2017p593450	6.8	64	68
2013p505181	31.8	149	31	2017p721599	11.4	44	62
2013p515567	22.5	16	32	2017p723914	11.7	75	48
2013p534039	12.9	10.1	78	2017p724099	12.6	11	88
2013p534453	11.4	37	47	2017p724160	27.1	158	58
2013p536056	12.7	59	50	2017p724207	4.2	2	77
2013p737584	20.5	8	18	2017p727319	11.7	10	68
2013p741866	12.8	92	80	2017p727385	12.5	60	56
2014p341201	24.5	160	76	2017p775429	31.7	80	58
2014p760995	13	82	50	2017p778729	25.6	10	38
2015p025818	11.1	158	80	2018p198988	22.9	70	90
2015p158899	6.1	90	48	2018p263987	20.8	121	88
2015p473385	15.9	146	40	2018p444706	11.6	31	59
2015p473961	11.8	2	76	2018p571231	5.8	49	88
2015p474292	11	0	18	2018p573260	4	142.2	81.7
2015p477536	11	68	38	2018p578506	22.8	148	34
2015p594162	5.4	38	76	2018p603011	12	105	60