A Repeating Earthquake Catalog from 2003 to 2018 for the Raukumara Peninsula, Northern Hikurangi Subduction Margin, New Zealand

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Key Points:

- 62 repeating earthquakes families were identified between 2003 and 2018 around the Raukumara Peninsula
- Family focal mechanisms are consistent with both intra- and inter-plate faulting
- Timing of the repeating events coincide with previously identified slow-slip events and locate at the edges of slow-slip patches

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Abstract

Repeating earthquakes provide a novel way of monitoring how stresses load faults between large earthquakes. To date, however, and despite the availability of long-duration, high-quality seismological datasets, little attention has been paid to tectonic repeating earthquakes in New Zealand. We develop a workflow and composite criterion for identifying repeating earthquakes in New Zealand, using data from the GeoNet permanent seismic network, and present New Zealand's first decadal-scale repeating earthquake catalog. For events to be identified as repeating in this study, two or more events must have a normalized cross-correlation of at least 0.95 at two or more seismic stations, when calculated for 75% of the earthquake coda. By applying our composite criterion to seismicity around the Raukumara Peninsula, northern Hikurangi subduction margin, we have 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 recurrence intervals of $<$1–12 years. The repeating earthquake families identified in this study coincide with the location and timing of previously identified slow-slip events and tremor. However, the responses shown to slow-slip are not consistent within families or within regional groups.

Plain Language Summary

Repeating earthquakes are earthquakes that re-rupture the same fault patch thereby producing highly similar seismograms, and occur sporadically and in some cases periodically through time. In this study, we developed a methodological workflow and a criterion for identifying repeating earthquakes in New Zealand, using data from the GeoNet permanent seismic network. The criterion is similar to that used in previous repeating earthquake studies at plate boundary zones elsewhere, but is customized to the available data and earthquake sources of interest. We identified 62 repeating earthquake families, consisting of 160 individual earthquakes, which occurred between 2003 and 2018 around the Raukumara Peninsula, northeastern North Island. The location and timing of the repeating earthquake families coincide with those of previously identified slow-slip and tremor.

1 Introduction

Monitoring and interpreting how stresses load faults in the run-up to large earthquakes, and what impact this has on nucleation and rupture processes, remains a significant challenge in earthquake physics (e.g. Passelègue et al., 2020). Repeating earthquakes provide one means of monitoring these processes within the seismogenic portions of faults (Uchida et al., 2003). In New Zealand, little attention has been paid to repeating earthquakes, despite the availability of high-quality, long-duration seismological datasets. In this paper, we describe the construction and analysis of the first long-duration catalog of repeating earthquakes of tectonic origin in New Zealand.

1.1 Repeating earthquakes

Repeating earthquakes are identified primarily on the basis of their highly similar waveforms, observed at multiple stations, which imply similar hypocenters and focal mechanisms (e.g. Nadeau et al., 1994; Nadeau & Johnson, 1998; Uchida et al., 2003; Zhang et al., 2008; K. H. Chen et al., 2013; Naoi et al., 2015; Li et al., 2018; Senobari & Funning, 2019). Due to their similarities, it is hypothesized that repeating earthquakes represent the repeated rupture of the same strong asperity or fault patch (e.g. Nadeau & McEvilly, 1999; Uchida et al., 2003). Repeating earthquakes have been the subject of extensive research at several plate boundary zones, notably the Japan Trench (e.g. Hatakeyama et al., 2017; Uchida et al., 2003) and the San Andreas fault system (e.g.

Nadeau et al., 1994; Thomas et al., 2016; J. R. Williams et al., 2019; Abercrombie, Rachel E. and Chen, Xiaowei and Zhang, Jiewen, 2020), as well as China (e.g. Schaff & Richards, 2004), Taiwan (e.g. K. H. Chen et al., 2008), Costa Rica (e.g. Chaves et al., 2020; Yao et al., 2017), Greece (e.g. Mesimeri & Karakostas, 2018) and the Tonga–Kermadec Trench (e.g. Yu, 2013).

If, as hypothesized, repeating earthquakes represent repeated failure of the same fault patch, due to successive phases of loading and slip, then their magnitudes — or equivalently their stress-drops, assuming the same rupture area — and inter-event times will be interpretable in terms of stressing-rate. Furthermore, the interaction between repeating earthquakes within a family, between different families, and with nearby and distal seismic and aseismic phenomena may provide insights into fault properties (e.g. Marone et al., 1995) and changes in the surrounding stress field (e.g. Nadeau et al., 1995; Lui & Lapusta, 2016). The interaction between large earthquakes nearby and repeating earthquake families can also provide information about how stresses are loading the small asperities on which repeating earthquakes are assumed to be occurring (K. H. Chen et al., 2010, 2013; Wu et al., 2014). Repeating earthquakes have also been recorded during episodes of slow slip (Kato et al., 2012; Shaddox & Schwartz, 2019), and have been used as a proxy to monitor aseismic creep prior to large earthquakes (e.g. Mavrommatis et al., 2015; Kato et al., 2012).

Fault slip-rates can be estimated from repeating earthquake observations using either the recurrence interval and seismic moments of the repeating earthquakes (e.g. Mavrommatis et al., 2015; Nomura et al., 2017) or the average seismic moment of the family (e.g. Nadeau & Johnson, 1998; Uchida et al., 2003). Slip-rates can then be determined by dividing the estimated slip by the repeating earthquake family duration. An extension of this allows variable slip-rates to be modeled to show changes in the amount and rate of slip on the fault patches where repeating earthquakes are occurring (Mavrommatis et al., 2015; Nadeau & Johnson, 1998; Nomura et al., 2017). Changes in slip-rate recorded by repeating earthquake families have been observed in the lead up to, and/or following, large earthquakes (Mavrommatis et al., 2015; Nomura et al., 2017). Hence, our work provides the first step to potentially monitoring changes in slip-rates around the plate boundaries of New Zealand.

1.2 Tectonic setting

The Hikurangi Subduction Margin accommodates convergence of the Australian and Pacific Plates and runs the length of the North Island of New Zealand (Clark et al., 2019), posing the largest seismic hazard for New Zealand (Clark et al., 2019). Due to the risk of great earthquakes ($M \geq 8$) occurring along this margin, extensive research has been undertaken to examine and quantify the associated hazard and risks (Clark et al., 2019, and references therein). Convergence rates vary from 32 mm/yr in the south, to 54 mm/yr in the north. Interface coupling also varies along the margin, with the interface locked to ∼35 km depth in the south but only to ∼10 km depth in the north (Wallace et al., 2009; Wallace, 2020).

The Raukumara Peninsula lies above the northern Hikurangi Subduction Margin in the northeast of New Zealand's North Island (Figure 1). Here the Pacific Plate is subducting beneath the Australian Plate with convergence rates at the trench ranging from ∼47 mm/yr at the southern extent of the Peninsula, to ∼57 mm/yr to the north (Figure 1) (Wallace et al., 2012). Beneath the eastern edge of the Raukumara Peninsula, the plate interface is inferred to lie at ∼12–15 km and it progressively deepens to ∼50 km beneath the western edge (C. A. Williams et al., 2013). Upper plate faults in the North Island Dextral Fault Belt in the overriding Australian Plate accommodate much of of the right-lateral strike-slip component of the Australia-Pacific relative plate motion (Figure 1) (Beanland, 1995; Wallace et al., 2004; Nicol & Wal-

lace, 2007). Reverse faults have been imaged offshore from the Raukumara Peninsula and accommodate part of the convergent component of relative plate motion (Barnes et al., 2010; Mountjoy & Barnes, 2011; Litchfield et al., 2020).

These tectonic components exhibit a wide range of transient seismic phenomena throughout the Raukumara Peninsula and surrounding region (Wallace et al., 2009), including moderate- to large-magnitude earthquakes (M≤7.2) (Francois-Holden et al., 2008; Koulali et al., 2017; Warren-Smith et al., 2018), repeated episodes of shallow and deep slow-slip (e.g. Douglas et al., 2005; Wallace & Beavan, 2010; Wallace et al., 2012, 2016, 2018; Wallace, 2020), tectonic tremor (Todd & Schwartz, 2016; Todd et al., 2018), triggered seismicity (Delahaye et al., 2009), and recently documented burst-type repeating earthquakes (Shaddox & Schwartz, 2019) (Figure 1). Several large earthquakes have occurred across the region in the last century. Of particular note are two M_W 7.2 tsunamigenic earthquakes that occurred in March and May of 1947 off the coast of Gisborne and Tokomaru Bay (Bell et al., 2014; Doser & Webb, 2003), a normal-faulting intraslab M_W 6.6 event offshore from Gisborne in December 2007 (Francois-Holden et al., 2008), and the M_W 7.1 Te Araroa earthquake of September 2016 (Koulali et al., 2017; Warren-Smith et al., 2018). These larger events appear to often involve interactions with other seismic phenomena: for instance, the Te Araroa earthquake was preceeded by slow-slip events (Koulali et al., 2017; Warren-Smith et al., 2018).

Repeated slow-slip is a common occurrence along the eastern edge of the Raukumara Peninsula (Wallace, 2020). At the northern end of the Hikurangi Subduction Margin, slow-slip events (SSEs) have typical recurrence intervals of 18 to 24 months (e.g. Douglas et al., 2005; Wallace & Beavan, 2010; Wallace et al., 2016). The equivalent moment magnitudes of these SSEs are M_W 6.3 to 7.2, and they typically occur at depths of less than 15 km (Koulali et al., 2017; Wallace & Beavan, 2010). SSEs along most of the the Hikurangi Subduction Margin were triggered by the 2016 M_W 7.8 Kaikōura earthquake in the weeks to months that followed (Wallace et al., 2018).

SSEs have been observed simultaneously with both tremor (e.g. Todd & Schwartz, 2016; Todd et al., 2018) and distinctive microseismicity (Delahaye et al., 2009), at the northern Hikurangi Subduction Margin. Todd and Schwartz (2016) and Todd et al. (2018) concluded that the northern Hikurangi SSEs tend to be accompanied by tremor, which typically occurs down-dip of the geodetically determined slip patch, and typically occur towards the end of the SSE and afterwards. Tremor has been most commonly observed during the larger-magnitude SSEs around the Gisborne area, but has also been documented during smaller SSEs further north in the vicinity of Tolaga Bay and Puketiti. However, tremor associated with offshore SSEs is often difficult to detect using New Zealand's entirely land-based national seismic network (Delahaye et al., 2009; Todd & Schwartz, 2016; Todd et al., 2018), complicating interpretation of its relationship to SSEs.

Recently, "burst-type" repeating earthquakes have been identified near the Raukumara Peninsula following the 2014 Gisborne SSE (Figure 1; Shaddox & Schwartz, 2019). These repeating earthquakes were inferred to occur on an upper-plate fracture network above a subducting seamount, and were only observed to be active for a short time period (approximately seven weeks; Shaddox & Schwartz, 2019). We note that such "burst-type" repeating earthquakes were detected using less stringent waveform similarity criteria than employed in most other repeating earthquake studies referred to above (cf. Uchida & Bürgmann, 2019), and may not represent repeated slip of exactly the same asperity. Other than the study by Shaddox and Schwartz (2019) of burst-type repeating earthquakes accompanying the 2014 Gisborne SSE, no long-duration analyses of tectonic repeating earthquakes have been undertaken around the Raukumara Peninsula.

1.3 Repeating earthquake identification around the Raukumara Peninsula

In this paper, we describe the construction and interpretation of the first long-duration tectonic repeating earthquake catalog in New Zealand. We have focused our search for repeating earthquakes on the Raukumara Peninsula, due to the high levels of seismicity observed in the region and the large number of previously documented interactions between seismic and aseismic deformation phenomena occurring in the northern Hikurangi Subduction Margin (Wallace, 2020).

The first step in our analysis has been to develop and test a workflow and composite detection criterion for identifying repeating earthquakes in the New Zealand context using data from the GeoNet network. Waveform cross-correlation is the most commonly used method for identifying repeating earthquakes (Nadeau et al., 1994; Senobari & Funning, 2019; Uchida & Bürgmann, 2019). Cross-correlations are calculated for candidate pairs of earthquakes that are within a given hypocentral distance of one another, with the events being identified as repeating if they have a normalized cross-correlation exceeding some threshold (commonly 0.90 to 0.95) at multiple seismic stations (e.g. Nadeau et al., 1995; Nomura et al., 2017). While the majority of studies follow this general approach, each study has adapted components of the detection criteria to local conditions and requirements, including the length of the waveforms used to calculate the cross-correlation, the number of stations required, the filtering applied to the waveforms, and the threshold imposed to cope with particular geometries and data quality (e.g. Nadeau & Johnson, 1998; Bohnhoff et al., 2017).

2 Methods

2.1 Dataset and initial clustering

We constructed our catalog of repeating earthquakes starting with the GeoNet seismicity catalog from 1 January 1987 to 26 July 2019 (as downloaded from the GeoNet International Federation of Digital Seismograph Networks (FDSN) service (https://www.geonet.org.nz/data/tools/FDSN) on 26 July 2019). We downloaded waveform data from the GeoNet FDSN service using ObsPy (Krischer et al., 2015) for all broadband and short-period stations and channels represented by the cataloged picks. We first clustered the entire GeoNet catalog of 570,671 earthquakes throughout New Zealand based on inter-event separation and multi-station averaged inter-event cross-correlation. This initial clustering was conducted with a low cross-correlation threshold (0.75) and relatively large inter-event separation (30 km) to allow for location uncertainties. Note that throughout this paper the term "cross-correlation" refers to fully normalised cross-correlation.

In this initial step, cross-correlations were computed on the vertical channels of 2–15 Hz instrument-response-corrected bandpassed data resampled to 50 Hz beginning 2 s before the P-pick and of 6 s duration. Single-station correlations were allowed to shift by ±1.5 s to allow for pick uncertainty, and the maximum cross-correlations for each station were averaged to generate a mean inter-event cross-correlation. Cross-correlations were only computed for pairs of events with hypocentral separations of less than 30 km to reduce computational demands. To cope with multiple possible groupings, we used a hierarchical clustering approach, as implemented in SciPy (Virtanen et al., 2020) and applied using EQcorrscan (Chamberlain et al., 2018) to assign earthquakes to clusters of potentially repeating events (herein termed "families").

The purpose of this initial clustering step was to reduce the size of the dataset and allow efficient testing of the parameters used to define repeating earthquakes in the Raukumara Peninsula study region. Based on this initial clustering, we extracted earthquakes within the region between –37.2 and –39.2 degrees latitude and 177.2

and 179.7 degrees longitude for further analysis. This region contained 133 possible repeating earthquake families. For each of these 133 possible families, we conducted manual phase-picking of P and S arrivals for the youngest event in the family to ensure consistent phase pick quality for the later analysis.

2.2 Repeating earthquakes detection

The core of our detection criterion is a threshold based on the cross-correlation of different events recorded at different stations. We assessed the sensitivity of the repeating earthquake catalog to variations in the length of the cross-correlation window, waveform filtering parameters, and the specific correlation threshold employed. We also compared our cross-correlation-derived catalog with one constructed using coherence as a measure of similarity (as used by some studies, e.g. Materna et al. (2018)). We chose not to use coherence as our detection metric because it introduced additional parameters, namely the frequency band over which coherence was assessed, without significantly changing our results.

A cross-correlation window-length of 40 s, encompassing both P- and S-arrivals, has commonly been used in studies elsewhere to detect repeating earthquakes (Uchida et al., 2003, 2004; Yamashita et al., 2012). However, because the event-to-station path-length in our study area varies between <10 km and ∼180 km, S–P times and coda durations also varied strongly between different events and different stations. We therefore chose to use a waveform length dependent on coda-duration to compute robust cross-correlations that captured similar amounts of signal for different event-station paths. We found that using 75% of the coda duration (defined herein as when the signal to noise ratio first dropped below unity) was appropriate for calculating the normalized cross-correlation, as it includes both P- and S-arrivals and most of the coda and resulted in the maximum normalized cross-correlation for visibly similar events. When the cross-correlation window length was less than 50% or greater than 100% of the coda length, the resulting cross-correlation between earthquakes in the prospective families was found to be distinctly lower. If we could not identify the end of the coda, due to the level of noise in the waveform, a window-length of 25 s was imposed. In all cases, our cross-correlation windows started 1 s before the identified P-arrival. Cross-correlations were computed after aligning the waveforms on the P-arrivals, with each waveform allowed to shift by as much as 1 s in order to achieve optimal alignment and thereby allow the maximum cross-correlation to be calculated.

Prior to computing cross-correlations, we detrended the data and applied a fourth-order bandpass filter between 1 and 20 Hz. The lowcut of this filter was chosen to remove low-frequency noise found to dominate the signal at some of the broadband stations. We tested the response of the calculated normalised cross-correlation to changes in the highcut parameter but observed no strong variations and opted for a 20 Hz highcut as this retains a wide range of frequencies while ameliorating high-frequency noise.

Finally, to test the sensitivity of our catalog to changes in cross-correlation threshold, we determined which earthquakes would be retained as the correlation threshold was increased from 0.90 to 0.99 at intervals of 0.01. We required this threshold to be exceeded on at least two stations. We found that the number of families that were rejected as repeating and the number of events in each family varied more when the threshold was set to less than 0.95, compared to when it was larger than 0.95. When the threshold was set to greater than 0.95, families were rejected due to small differences in the background noise of the waveform rather than significant differences in the signal. We therefore chose to use a threshold of 0.95, as used in multiple other repeating earthquake studies (e.g. Uchida & Bürgmann, 2019, and references therein). We were unable to require high cross-correlation on more than two stations due to station

continuity: nearby stations generally provide the highest cross-correlation values due to higher signal-to-noise ratios, but prior to 2003 there only two permanent broadband seismometers and seven permanent short period seismometers within 120 km of the main clusters of repeating earthquakes. This station continuity limits our analysis to times after 2003.

2.3 Location procedure

We undertook absolute location and relative relocation of all possible repeating earthquakes to verify that events identified with the correlation-based detection criterion are indeed closely spaced. The phase picks in the original GeoNet catalog vary in quality, having been made using both automatic and manual methods, so we conducted additional phase picking for all events in our repeating earthquake catalog to ensure consistency. We manually picked P- and S-wave first arrivals for the youngest event in each family, which is commonly the best-recorded event due to the general increase with time of the number of stations, and identified P-wave polarities for later focal mechanism analysis. This yielded a total of 1,159 P-picks and 939 S-picks for the 133 possible families, resulting in an average of 9 P-picks and 7 S-picks for each of the youngest events. Fewer S-picks than P-picks were made due to the P-coda obscuring the S-arrival at short epicentral distances. Since all events in a particular family are, by definition, well-correlated we were able to compute accurate (sub-sample) relative pick times for all the other events using the EQcorrscan cross-correlation pick correction function `xcorr_pick_family()` (Chamberlain et al., 2018). This function follows the approach of Deichmann and Garcia-Fernandez (1992) and computes a moving window cross-correlation that is represented at each epoch by a parabolic function fit to the five samples around the maximum correlation. The peak of this parabola is taken as the time-shift of the pick. This workflow not only provides accurate and consistent phase arrivals but also provides 572 additional phase picks compared to the GeoNet catalog from which we started.

All the events in our catalog have hypocenters computed by GeoNet but the location algorithms and velocity models with which they have been determined have changed throughout the catalog period. To generate consistent locations, and to take advantage of our additional phase-picks, we computed absolute locations for all events using the NonLinLoc location software (Lomax et al., 2000) and the New Zealand-wide 3D velocity model (version 2.1) (Eberhart-Phillips et al., 2017; Eberhart-Phillips & Bannister, 2015). We also computed absolute locations using the SIMUL2014 software (Eberhart-Phillips et al., 2015), but found that this gave poorer fits to our picks compared to the NonLinLoc locations.

To test whether the earthquakes we identified as repeating based on correlation criteria truly overlap in source area, we also undertook relative relocation of all events. Due to the number and positions of seismometers in the network changing and generally improving with time, the absolute locations of older earthquakes are generally of poorer quality than the more recent earthquakes. To cope with this variable quality, and to test whether earthquakes within each family overlap, we used the absolute location of the youngest event in each family as the starting location for the relocation of all other events within the family. Using this starting location allows us to verify whether the earthquakes within a family can be well-fit by overlapping locations, rather than necessarily providing highly accurate relative locations between families. For this relocation we used the GrowClust software of Trugman and Shearer (2017) with the onshore 1D velocity model from Yarce et al. (2019).

2.4 Focal Mechanisms

We constructed focal mechanisms for the youngest event in each family, using the manually picked P-wave first-motion polarities in the `FPFIT` (Reasenberg, 1985) routine implemented in SEISAN (Havskov & Ottemoller, 1999). The event locations were fixed to the locations obtained using GrowClust, no relative weightings were applied to the polarities and a 2° increment was used to search for the best fit solution.

2.5 Magnitudes

Alongside variations in location procedure throughout the cataloged period, the magnitudes procedures used by GeoNet have also varied. To generate consistent magnitudes we recomputed the local magnitudes of the youngest event in each family, and computed relative magnitudes for all other events within a family. To compute the magnitudes of the youngest events in each family we first generated automatic amplitude picks for the horizontal components of each station picked. Automatic amplitude picks were made on data that were filtered between 1 and 20 Hz, then instrument corrected and convolved with the response of a Wood Anderson seismometer. The response of the pre-filter was subsequently corrected for in the resulting amplitude picks. The resulting amplitude picks were used to compute a consistent set of station correction and attenuation terms based on the GeoNet-computed local magnitudes for these events. The magnitudes for all other events within families were computed using a correlation-weighted average of the relative-amplitudes, following the method of Schaff and Richards (2014).

3 Results

We identified 62 repeating earthquake families active between 2003 and 2018, which collectively contained 160 individual earthquakes. The 62 families are clustered into more active regions around the Raukumara Peninsula (Figure 2). To facilitate further description, we assigned each family to one of eleven regional groups, which were named based on their proximity to local population centers (see Figure 2). Within each of the regional groups, families were assigned a two letter geographic code and a two-digit number, based on the relative order of the first recorded repeating event in the family. The number of families within each of the regional groups ranges from one to 34 (Figure 2 and Table 1).

The repeating earthquake families identified have a magnitude range of M_L0.6 to M_L5.3, and the recurrence intervals range between <1 yr and ∼12 yrs (Table 1). The number of repeating events in each of the families ranges from two to five, with only five families containing more than three events. In Figure 3, the waveforms of the repeating events in four region groups are depicted, highlighting the visual similarities between the events in each of the families. In Figure 3, WA01 is the largest magnitude family in the catalog and is the only family located to the northwest of the Raukumara Peninsula, TA01 is the furthest offshore family (∼30 km), TS01 locates ∼10 km offshore just south of Tolaga Bay and NU01 and NU02 locate onshore to the west of the Māhia Peninsula.

Focal mechanism for 56 of the 62 families were constructed, with the remaining six families not having focal mechanism created due to a lack to first arrival polarities being identified during manual picking. The focal mechanisms of the repeating earthquake families are consistent with both upper and lower intra-plate faulting, as well as faulting along the subduction interface. Due to the location of the families with respect to the GeoNet seismic network, many of the focal mechanisms are poorly constrained, with maximum one sigma errors for the strike, dip and rake being 34.0°, 30.0° and 54.0°

respectively. The average one sigma error in the strike, dip and rake of the focal mechanisms are 7.06°, 8.67° and 14.53° respectively.

The repeating earthquake catalog we have constructed is intrinsically no-more complete than the GeoNet catalog. However, the magnitude of completeness of the GeoNet catalog around the Raukumara region varied from ∼M 3 in 2003 to ∼M 2 in 2019 (Figure 4 a). In the Raukumara repeating earthquake catalog, only nine of the 160 identified repeating earthquakes have calculated local magnitudes which are less than M_L 2 (Figure 4 b). As the catalog was formed using the GeoNet catalog, if smaller magnitude events were not identified in the GeoNet catalog, then they would not be included in this repeating earthquake catalog.

4 Discussion

4.1 Spatial and temporal relationships to other subduction phenomena

Based on the location of the youngest event and focal mechanism of each family, we categorized the repeating earthquakes as occurring on the subduction interface, within the Australian plate, or within the Pacific plate. Families which had a low-angle reverse focal mechanism and were within ∼5 km of the C. A. Williams et al. (2013) interface model were assumed to be occurring on the interface, or associated faults, and the remaining families were assigned to the over-riding or down-going plate based on their location relative to those events. As a result, 40 families are concluded to occur within the over-riding Australian Plate, exhibiting a range of faulting types, 15 occur along the subduction interface, and 7 are in the down-going Pacific Plate and exhibit predominantly strike-slip and normal faulting focal mechanisms. However, 35 of the families not concluded to occur on the plate interface, due to the type of faulting are located within ±5 km of the interface (Figure 5). While the focal mechanism of WA01 is consistent with interface faulting, the mean depth (58 km) of the family is slightly shallower than the interface model, so is not consistent with being on the interface.

All of the repeating earthquake families inferred, on the basis of their hypocenters and focal mechanisms, to occur on the subduction interface lie within regions identified by (Wallace et al., 2012) to have low-coupling (Figure 5). The spatial relationship of the intraplate families to interface locking is less clear, with only the Pouawa and Tolaga-South families located above, and below, the locked–sliding transition.

Heise et al. (2017) recently investigated the relationship between geodetically observed locking of the subduction interface (Wallace et al., 2012; Dimitrova et al., 2016) and the physical properties of the interface inferred from electrical resistivity observations. They argued that areas in which the interface is locked and the upper plate is undergoing areal contraction are electrically resistive, notably between the Māhia Peninsula and Tolaga Bay, and concluded that the frictional coupling of the interface is governed by low fluid or sediment volumes.

We observe that repeating earthquake families occurring on the subduction interface and in the over-riding plate in the Te Karaka group coincide with an area of distinctively high resistivity on and above the interface (200–600 Ωm) identified by Heise et al. (2017); the single family in Whatatutu group, which occurs in the Pacific plate, lies beneath this zone of high resistivity. However, repeating earthquakes occurring on the interface or in the upper plate in the the Māhia and Nūhaka groups in the south of the Peninsula and the Tolaga Bay and Tokamaru Bay groups further north occur within zones of relatively low interface resistivity (≤20 Ωm; cf. Figure 2 of Heise et al., 2017). Moreover, no clear spatial relationship is evident between the epicenters of repeating earthquakes and areal strain rates (Figure 4 of Dimitrova et al., 2016).

Active-source seismic imaging has revealed two seamounts subducting offshore between the Māhia Peninsula and Tokomaru Bay (Figure 5, after Bell et al., 2010). Additionally, high-amplitude reflections have been observed adjacent to the plate interface, down-dip of the subducting seamounts (Bell et al., 2010). Bell et al. (2010) interpreted these high-amplitude reflections as fluid-rich sediments, entrained by the subducting seamount. The Pouawa group families (offshore to the southeast of Tolaga Bay) are located down-dip of the southern seamount, coincident with the high-amplitude reflectors mapped by Bell et al. (2010) and down-dip of the "burst–type" repeating earthquakes identified by Shaddox and Schwartz (2019), but no repeating earthquakes have been detected in the vicinity of the northern seamount.

When the location of the repeating earthquakes are compared to the location of previously identified slow slip, the Te Karaka, Whatatutu, Tokomaru-Tolaga and Te Puia groups locate along the down-dip periphery of the identified cumulative slow-slip patch (Figure 2; Wallace & Beavan, 2010; Wallace et al., 2016; Koulali et al., 2017). In comparison, the Nūhaka and Māhia repeating earthquakes transect the southern extent of the modeled slow-slip patch (Wallace & Beavan, 2010; Wallace et al., 2016). Furthermore, the Pouawa and Tolaga-South group families lie along the boundary between two persistent patches of slow-slip which occur to the northeast and southwest of the families locations (Wallace & Beavan, 2010; Wallace et al., 2016).

We next consider the temporal relationships between the repeating earthquakes and previously described slow slip. Such relationships have been extensively documented throughout the Japan subduction zone (Gardonio et al., 2018; Kato et al., 2012; Igarashi et al., 2003; Uchida et al., 2004, 2006; Uchida & Matsuzawa, 2013; Uchida et al., 2016) and we similarly compare the timing of individual repeating earthquakes and their cumulative moment release to time-series of geodetically measured displacement and recognized episodes of slow slip (Figure 6). For the purposes of comparison with measured deformation, we focus on the displacement time-series from GeoNet's global navigation satellite system station near Gisborne ("GISB") as it provides a general reference for motion in the region of interest and has been operating continuously since 2002. We compute the moment of each repeating earthquake by converting the calculated local magnitudes using the following scaling relationship in Aki (1972).

$$\log(M_0) = 1.4 \log(M_L) + 17.0 \tag{1}$$

We observe some episodes of slow slip to be accompanied by repeating earthquake activity in some families, such as in 2004 (TA and TP groups) and in 2011 (TA and TP groups again) (Figure 6). However, this is not consistent for all slow-slip events or regional repeating earthquake groups. Of the 31 slow-slip events previously identified to the north of Māhia Peninsula, five are not clearly associated with a step in the cumulative moment curve of any repeating earthquake groups. The Ruatōria and Pouawa Groups show the clearest correlation between the occurrence of the repeating earthquakes and the occurrence of a slow-slip event (Figure 6, e and f respectively). For the Ruatōria Group, four of the seven repeating earthquakes occur during the approximate timing of the slow-slip events that occurred after 2008, with the slow-slip events occurring from the Māhia Peninsula to Puketiti (Figure 6e). These earthquakes account for ∼45% of the total moment of the group. Moreover, six events in the Pouawa Group correspond to the occurrence of slow-slip events, with four of these slow-slip events occurring around Gisborne.

Overall, the repeating earthquakes show little consistent response to any of the three large earthquakes that have occurred in the time spanned by this study. However, the 2008 Gisborne earthquake was followed 10 days later by a repeating earthquake in the Pouawa group (Figure 6f), and the 2016 Kaikōura earthquake was similarly followed, 19 days later, by the next event in that same family. Similarly, both the Te

Araroa and Kaikōura earthqukes were followed within days by repeating earthquakes in the Tokomaru-Tolaga area(Figure 6i).

Distinguishing the repeating earthquakes on the basis of tectonic position (Figure 6m) reveals marked steps in the cumulative moment release of earthquakes occurring on the subduction interface at the time of slow slip in early 2010. The early 2010 episode of slow slip occurred between Tolaga Bay and Māhia (Wallace & Beavan, 2010). The two largest increments of moment release associated with Pacific Plate repeating earthquakes occurred in late 2005 and early 2011 and neither is associated with recognized slow slip. Australian Plate repeating earthquakes exhibit a generally constant rate of moment release with the largest increments showing no clear relationship to episodes of slow slip.

Jacobs et al. (2016) analyzed seismicity associated with slow-slip events along the length of the Hikurangi Subduction Margin and found that three of the largest sequences occurred in 2007, 2009 and 2010 approximately 20 km to the east of the Raukumara Peninsula. We observe increases in the number of repeating earthquakes occurring in the Australian Plate at the times of both the 2009 and 2010 sequences but not the 2007 sequence. Similar patterns are observed with the Pacific Plate families, with the rate of repeating earthquakes increasing in response to the 2010 sequence but not the 2007 or 2009 sequences. However, no response to any of these sequences is observed for the repeating earthquakes inferred to occur on the subduction interface. The patterns we have observed are consistent with the findings of Delahaye et al. (2009), who identified 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 also occur in similar locations to the microseismicity identified by Yarce et al. (2019), with only one repeating earthquake family (TS01) occurring in a seismicity gap identified in that study. 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, alongside inferred fluid-pressure cycling related to SSE occurrence (Warren-Smith et al., 2019).

We also compared the timing of three large earthquakes to the timing of the occurrence of repeating earthquakes. Two of these earthquakes occurred within the area of interest around the Raukumara Peninsula. The first was the M_W6.6 Gisborne earthquake, which occurred on the 20^{th} of December 2007 UTC, 64 km from Gisborne at a depth of 40 km, in the subducting Pacific Plate (Francois-Holden et al., 2008). The second was the M_W7.1 Te Araroa earthquake 1^{st} of September 2016 UTC, at a depth of 19 km, also in the subducting Pacific Plate (Warren-Smith et al., 2018). The timing of the 2016 M_W7.8 Kaikōura earthquake was also compared to the timing of repeating earthquakes despite not occurring within the study area. This is due to the Kaikōura earthquake triggering slow-slip in the study region following the earthquake (Wallace et al., 2018). We observe a step in the cumulative moment in three of the regional groups following the three large earthquakes previously mentioned. The Pouawa Group is the only regional group where steps in the cumulative moment is observed following to the Gisborne M_W6.6 earthquake, occurring five months following the event, as well as a step 19 days after the Kaikōura earthquake (Figure 6f). Three days following Kaikōura earthquake, a step in the Tokomara-Tolaga Group is also observed (Figure 6i). Moreover, the Te Puia Group is the only regional group which showed a step in the cumulative moment following the Te Araroa earthquake (Figure 6f). We see no evidence for direct triggering of repeating earthquakes following these large earthquakes.

4.2 Scaling relationships for the the Raukumara Peninsula repeating earthquakes

Nadeau and Johnson (1998) proposed that the magnitudes of repeating earthquakes should scale as a function of recurrence interval, based on the cyclic loading and stress release model. They demonstrated this to be the case near Parkfield, California, obtaining the relationship

$$\log(T) = 4.85 + 0.17 \log(M_O) \tag{2}$$

where T is the recurrence interval in seconds and M_O is the seismic moment in dyne-cm. This scaling of moment with recurrence interval has since been examined and verified in other many other locations (K. H. Chen et al., 2007; T. Chen & Lapusta, 2009; Dominguez et al., 2016; Johnson, 2010; Lengliné & Marsan, 2009; Marone et al., 1995; Mavrommatis et al., 2015; Mesimeri & Karakostas, 2018; Nadeau & Johnson, 1998; Peng et al., 2005; Schaff & Richards, 2011; Uchida, 2019; Yu, 2013). Slight variations in the relationship have been observed between different regions, as have changes in scaling before and after nearby large earthquakes (Schaff & Richards, 2011; Yu, 2013; Chaves et al., 2020).

To investigate this relationship in the New Zealand context, we used the average recurrence interval for each of the repeating earthquake families and the moment of the youngest event in the family (Figure 7). The magnitude of the youngest event was taken to represent each family as a whole, rather than averaging the values of all the events in a family, for two reasons: first, the magnitudes of each of the families were extremely similar; and second, it was assumed that the youngest event in each family had the best-constrained magnitude and lowest associated error due to overall improvements in network coverage and geometry.

In Figure 7, families with durations shorter than six months were removed before the relationships were calculated, as the relationship identified by Nadeau and Johnson (1998) was for long duration repeating earthquake families, and we wanted to compare similar families. Furthermore, these short duration families masked any identifiable relationship between recurrence interval and seismic moment. As can be seen in Figure 7, 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, 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, consistent with the findings of repeating earthquake studies elsewhere, the uncertainty associated with these trends is very large. This places uncertainty on applying other relationships established by Nadeau and Johnson (1998) to the Raukumara Peninsula repeating earthquakes. We speculate that the scatter we observe may be due to the influence of variable slip-rates associated with nearby slow-slip episodes.

4.2.1 Calculating the slip-rate of the repeating earthquake families

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 3). 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:

$$\log(d) = -2.36 + 0.17 \log(M_O) \tag{3}$$

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 setting and studies, including Japan, to determine the slip of identified repeating earthquake families (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, to calculate the slip-rate.

Preliminary slip-rates calculated for the Raukumara Peninsula repeating earthquake families range from < 10 mm/yr up to $\sim$80 mm/yr, when the families with extremely short family durations (less than 1 year) are excluded. Generally, the shorter the family duration the faster the slip-rate will be. This trend follows previously established relationships for Parkfield and Japan, with short duration families having slip-rates which are significantly higher than the tectonic loading rate, compared to long-duration families. TT19 is the only interface family that has a calculated slip-rate close to the plate convergence rate (31 mm/yr compared to 45 mm/yr). However, due to the differences observed in the seismic moment–recurrence interval relationship previously mentioned, applying the Parkfield repeating earthquake slip model to the Raukumara Peninsula families, may not be appropriate.

We close this section by noting that in this first New Zealand study of earthquakes we made no attempt to detect events not otherwise listed in the original GeoNet catalog. Future work using matched-filter methods to detect lower-magnitude events is likely to greatly expand the number of repeating earthquakes detected, and provide a more robust basis for investigating scaling relationships and the use of repeating earthquakes to quantify slip rates.

5 Conclusions

We have identified 62 repeating earthquake families containing a total of 160 earthquakes that occurred between 2003 and 2018 in the vicinity of the Raukumara Peninsula, on the northern Hikurangi Subduction Margin. These families represent a range of faulting types and occur along the subduction interface and in the overlying and subducting plates. We observe steps in the cumulative moment of the repeating earthquakes coinciding with 26 of 31 previously identified slow-slip events. We also compared the Raukumara Peninsula families to families and repeating earthquake relationships previously identified around Parkfield, California. When comparing recurrence interval–seismic moment relationships, we identified a similar trend between the two locations, and when calculating the slip-rate of the families, only one was found to have an estimated slip-rate that matched the plate convergence rate.

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Table 1. Summary of the repeating earthquake families identified in each of the regions. Geographic areas are identified in Figure 2, and abbreviations how each of the families are identified. T_{min} and T_{max} are the minimum and maximum recurrence intervals respectively for each of the regional groups. M_{min} and M_{max} are the minimum and maximum local magnitudes respectively for each of the regional groups.

Geographic area	Abbreviation	Number of families	T_{min}	T_{max}	M_{min}	M_{max}
Waihau	WA	1	12.3	12.3	5.2	5.3
Te Araroa	TA	1	6.6	6.6	2.3	2.5
Ruatōria	RA	2	1.9	2.0	2.3	2.6
Te Puia	TP	4	0.0	10.3	2.3	3.5
Tokomaru-Tolaga	TT	34	0.0	11.8	0.6	4.5
Whatatutu	WH	1	4.4	4.4	2.3	2.4
Tolaga South	TS	1	2.0	2.0	2.2	2.5
Te Karaka	TK	7	2.2	8.0	2.0	4.1
Pouawa	PO	5	2.1	7.8	2.1	3.4
Māhia	MA	4	1.7	6.1	2.1	2.6
Nūhaka	NU	2	1.3	1.8	1.6	2.3

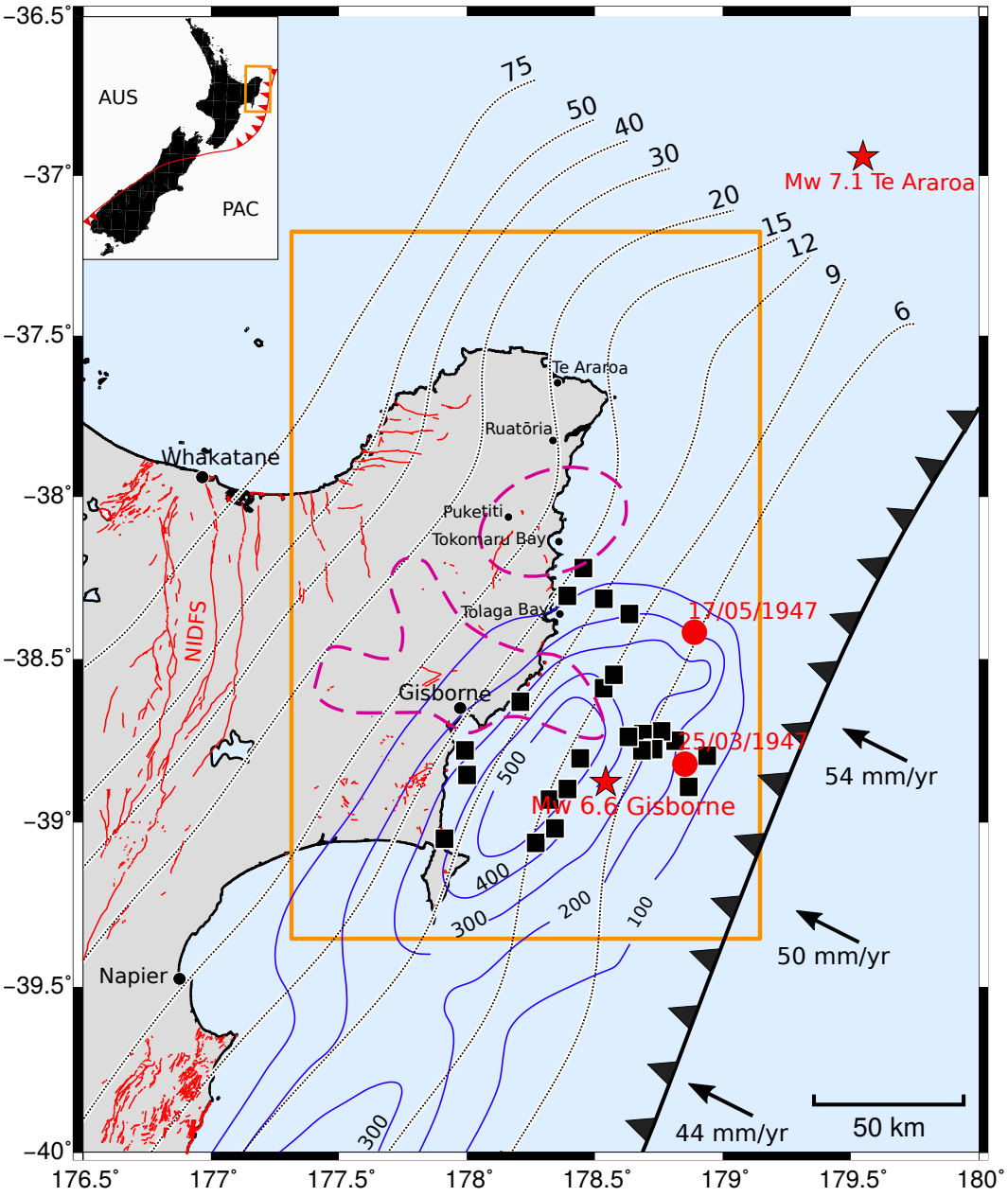


Figure 1. Seismic and aseismic phenomena recorded around the Raukumara Peninsula. Black arrows represent the convergence rates at the trench (Wallace et al., 2012) and black dotted lines represent the depth (labeled in km) to the plate interface (C. A. Williams et al., 2013). Red stars mark the locations of the M_W6.6 Gisborne earthquake of 2007 and the M_W7.1 Te Araroa earthquake of 2016. Red circles represent the location of two tsunami-generating earthquakes that occurred in 1947 (Bell et al., 2010). Filled black boxes mark the locations of burst-type repeating earthquakes between May 2014 and July 2015 that were reported by Shaddox and Schwartz (2019). Purple dashed contours demarcate locations of tremor between 2010 and 2015 identified by Todd and Schwartz (2016). Blue contours represent the cumulative slow slip, in mm, that occurred between 2002 and 2014, as described by Wallace (2020). The orange box in the main panel indicates the focus area of this study. Red lines represent active faults from the New Zealand Active Fault Database (Langridge et al., 2016), including the North Island Dextral Fault System (NIDFS). Inset: Map of New Zealand showing the study area in a larger context.

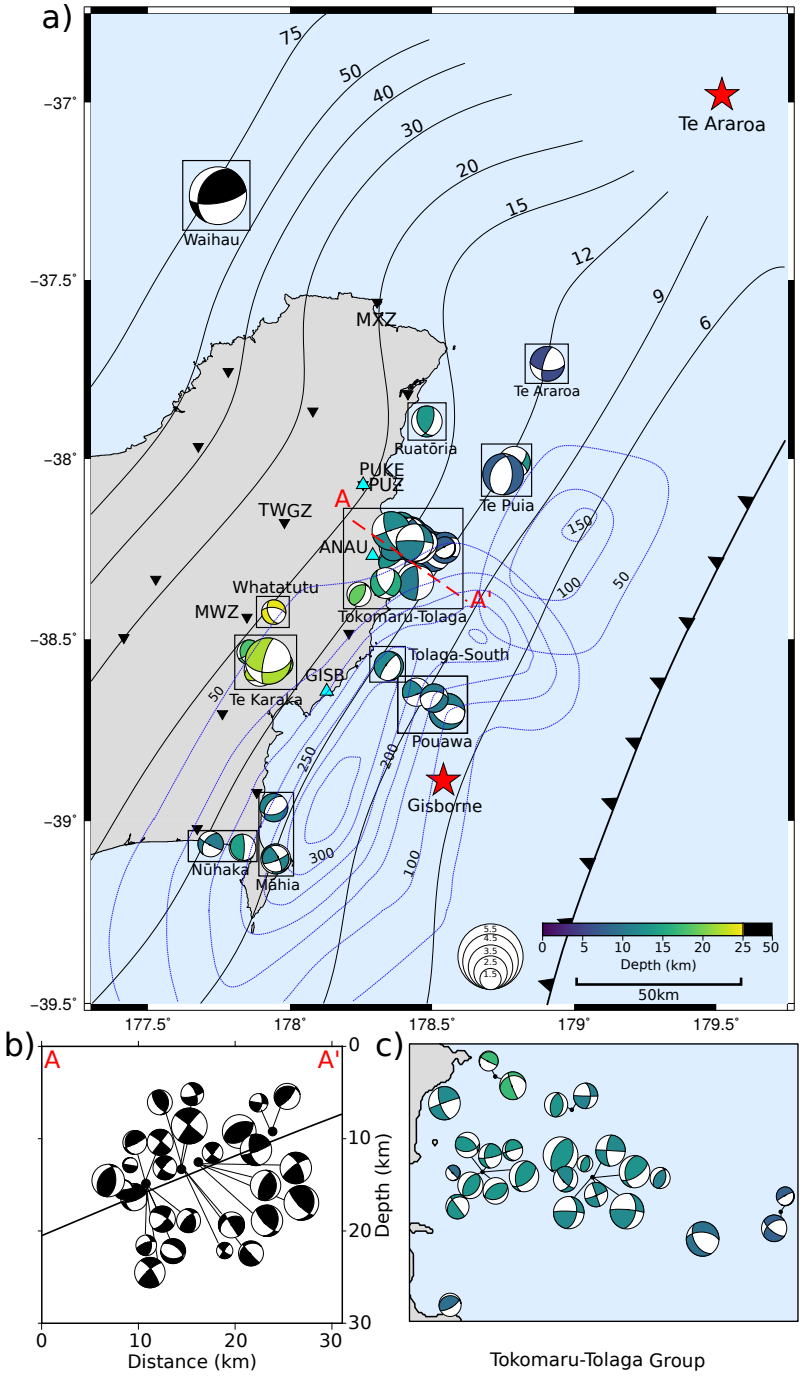


Figure 2. Maps (panels a and c) and cross-section (panel b) of repeating earthquake focal mechanisms. a) The repeating earthquakes are colored by depth and scaled by the calculated magnitudes. The red dashed line labeled A–A' represents the location of the cross-section in b). Contours mark the depth to the subduction interface modeled by C. A. Williams et al. (2013). Black inverted triangles mark the GeoNet seismic stations used to calculate the hypocenter locations. Data from the labeled stations are plotted in Figure 3. Blue contours demarcate slow-slip patches identified by Wallace and Beavan (2010) and Koulali et al. (2017) and are labeled in mm. Red stars mark the locations of the Gisborne M_W6.6 earthquake and the Te Araroa M_W7.1 earthquake. b) Cross-section of the line A-A', displaying seismicity with a ±10 km swath. c) Expanded view of the Tokomaru-Tolaga group families focal mechanism locations. Note: the maps in a) and c) shows lower hemisphere projections and the cross-section in b) shows back hemisphere projections.

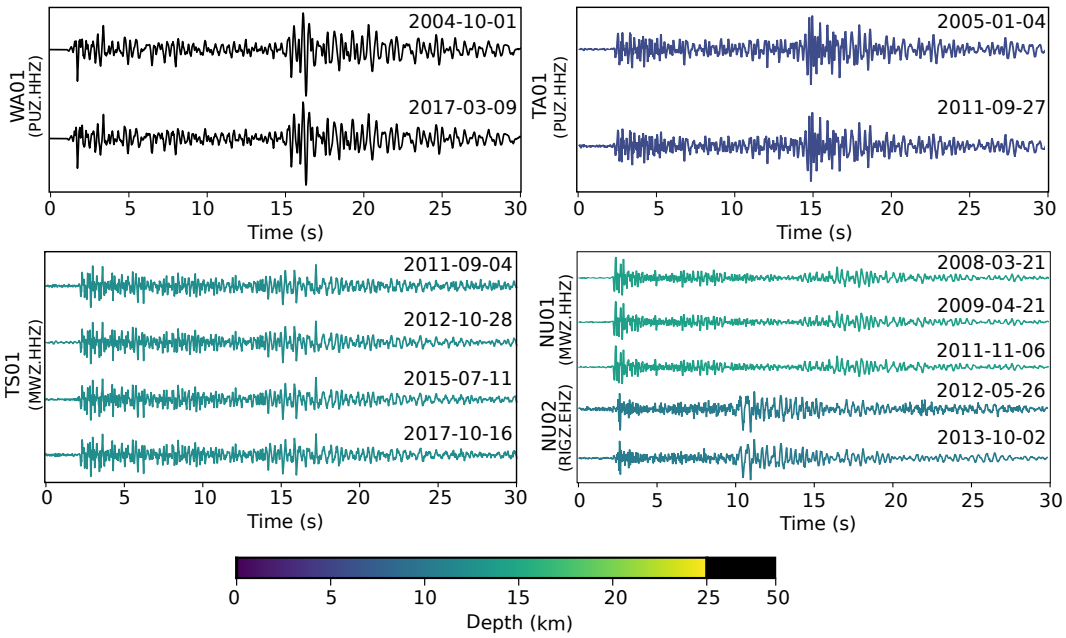


Figure 3. Representative repeating earthquake waveforms from four regional groups. All waveforms have had a fourth-order bandpass filter between 1 and 20 Hz applied. The GeoNet stations and channels that the waveforms were recorded on are included in the brackets under the family names. Waveforms are colored by earthquake depth. Top left: Waihau (WA) group family. Te Puia (TP) group families. Top right: Te Araroa (TA) group family. Bottom left: Tolaga-South (TS) group family. Bottom right: Nūhaka (NU) group families.

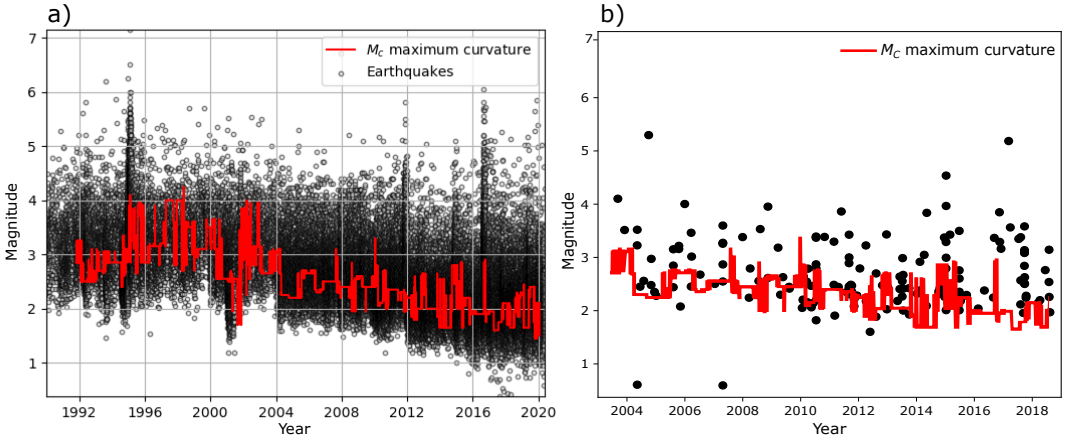


Figure 4. Magnitude of completeness for the repeating earthquake catalog. a) Calculated magnitude of completeness of the GeoNet catalog around the Raukumara region, from 1992 to 2019. We calculated completeness using the maximum curvature method (Wiemer & Wyss, 2000) for groups of 2000 events. b) Calculated local magnitude of the repeating earthquakes identified in this catalog through time. Note the shortened time scale in panel b).

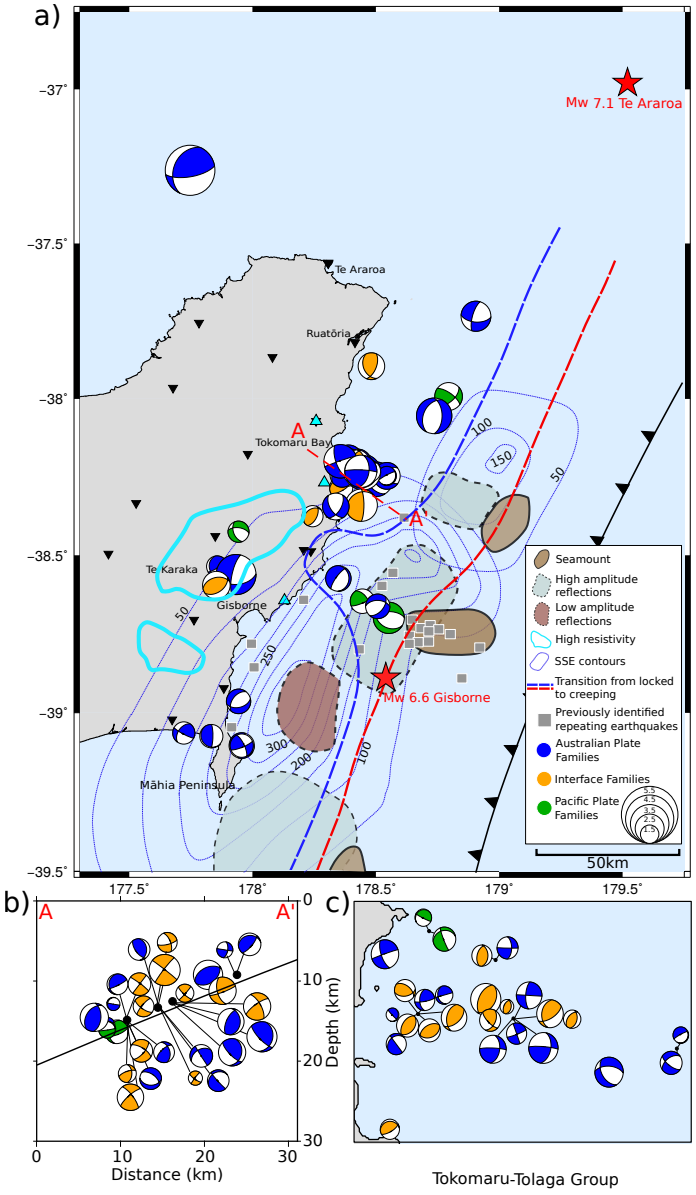


Figure 5. Maps (panels a and c) and cross-section (panel b) of repeating earthquake tectonic locations. a) Locations of the Raukumara Peninsula repeating earthquake families colored according to whether an event is occurring in the Australian Plate, along the interface or within the Pacific Plate, and scaled by calculated magnitude. The red dashed line labeled A–A' represents the location of the cross-section in b). Blue contours demarcate slow-slip patches identified by Wallace and Beavan (2010) and Koulali et al. (2017) and are labeled in mm. Blue and red dashed lines identify the transition from locked to creeping regions of the geodetic locking model of Wallace et al. (2012). The interface is locked to the right of the red line and creeping to the left of the blue line. Seamount locations and high- and low-amplitude reflections are adapted from Bell et al. (2010), and the regions of the interface which have a high resistivity (200–600 Ωm) are illustrated after Heise et al. (2017). "Burst-type" repeating earthquakes identified by Shaddox and Schwartz (2019) are shown in gray squares. Red stars mark the locations of the Gisborne M_W6.6 earthquake and the Te Araroa M_W7.1 earthquake. b) Cross-section of the line A-A', displaying seismicity with a ±10 km swath. c) Expanded view of the Tokomaru-Tolaga group families focal mechanism locations. Note: the maps in a) and c) shows lower hemisphere projections and the cross-section in b) shows back hemisphere projections.

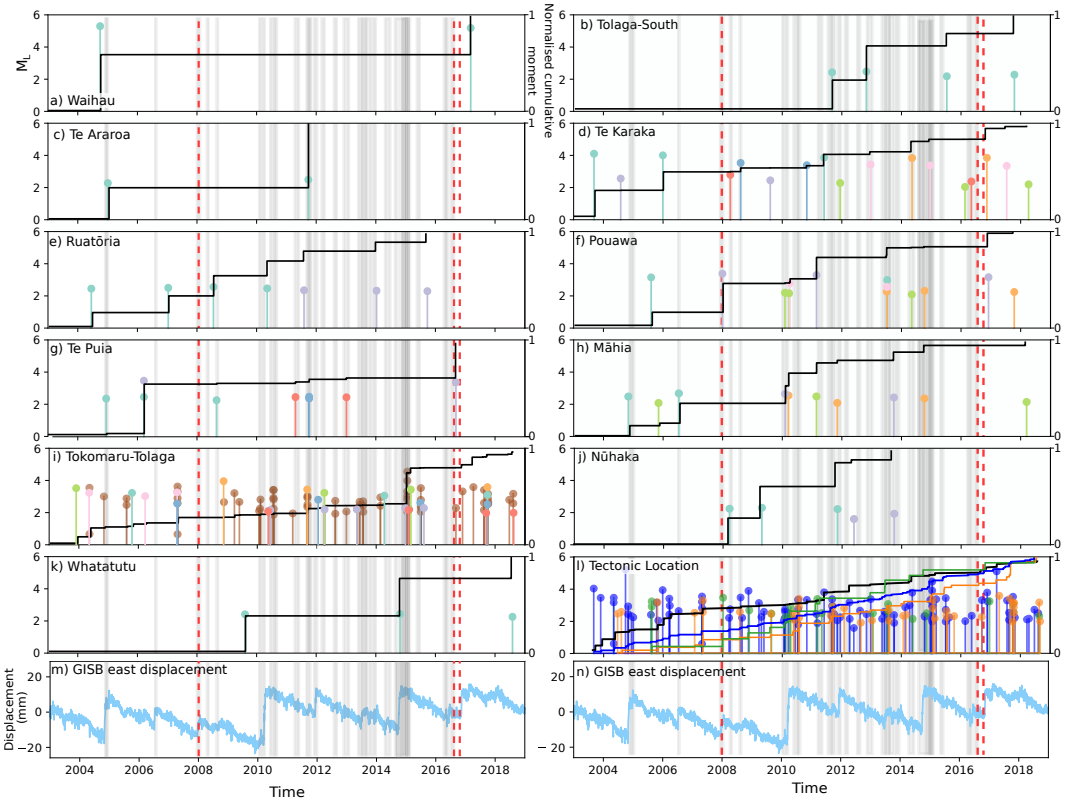
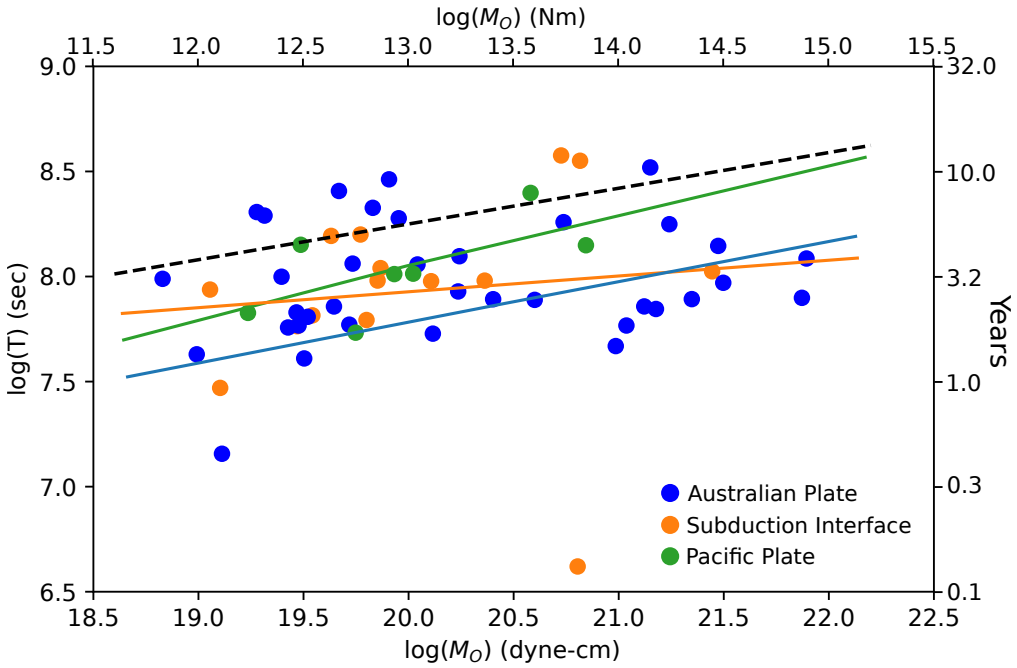


Figure 6. Chronology of repeating earthquakes and cumulative moment release within each geographic area. The lollipop symbols indicate the timing and magnitude of each repeating earthquake and are colored by family. Panel l) depicts the timing of every repeating earthquake colored by their tectonic location (blue is Australian Plate, orange is interface and green is Pacific Plate) and the respective cumulative moment release, while the black line represents the total cumulative moment release. Episodes of slow slip periods (Koulali et al., 2017; Todd & Schwartz, 2016; Wallace & Beavan, 2010; Wallace et al., 2012; Wallace & Eberhart-Phillips, 2013; Wallace et al., 2016) are shown in gray and large earthquakes are marked in red. Note that the slow-slip catalog completeness is not consistent in time. The panels m) and n) show the east-component from the GISB (Gisborne) GNSS site operated by GeoNet and are repeated to aid visual comparisons. The cumulative moment curves are normalized to unity for comparison between different regional groups.



Location	Intercept	Gradient
Australian Plate	3.92 (0.31 - 7.51)	0.19 (0.01 - 0.37)
Interface	6.47 (2.47 - 10.47)	0.07 (-0.13 - 0.27)
Pacific Plate	3.11 (-0.89 - 7.11)	0.25 (0.03 - 0.47)
Nadeau and Johnson (1998): Parkfield	4.85 ± 0.16	0.17± 0.009

Figure 7. Repeating earthquake recurrence interval–seismic moment relationship. Top: Raukumara Peninsula repeating earthquake families' average recurrence interval plotted against seismic moment and colored according to occurrence in the overlying Australian Plate, on the subduction interface or in the subducting Pacific Plate. Shown in the black dashed line is the relationship obtained for repeating earthquakes near Parkfield, California, by Nadeau and Johnson (1998). Linear relationships of the logarithms of each of the variables were fitted by minimizing the L2 norm, after families with durations shorter than six months had been removed. Bottom: Intercept and gradient values, including the 95% confidence intervals for the recurrence interval seismic moment relationships plotted above. The relationship identified by Nadeau and Johnson (1998) has been included for comparison.