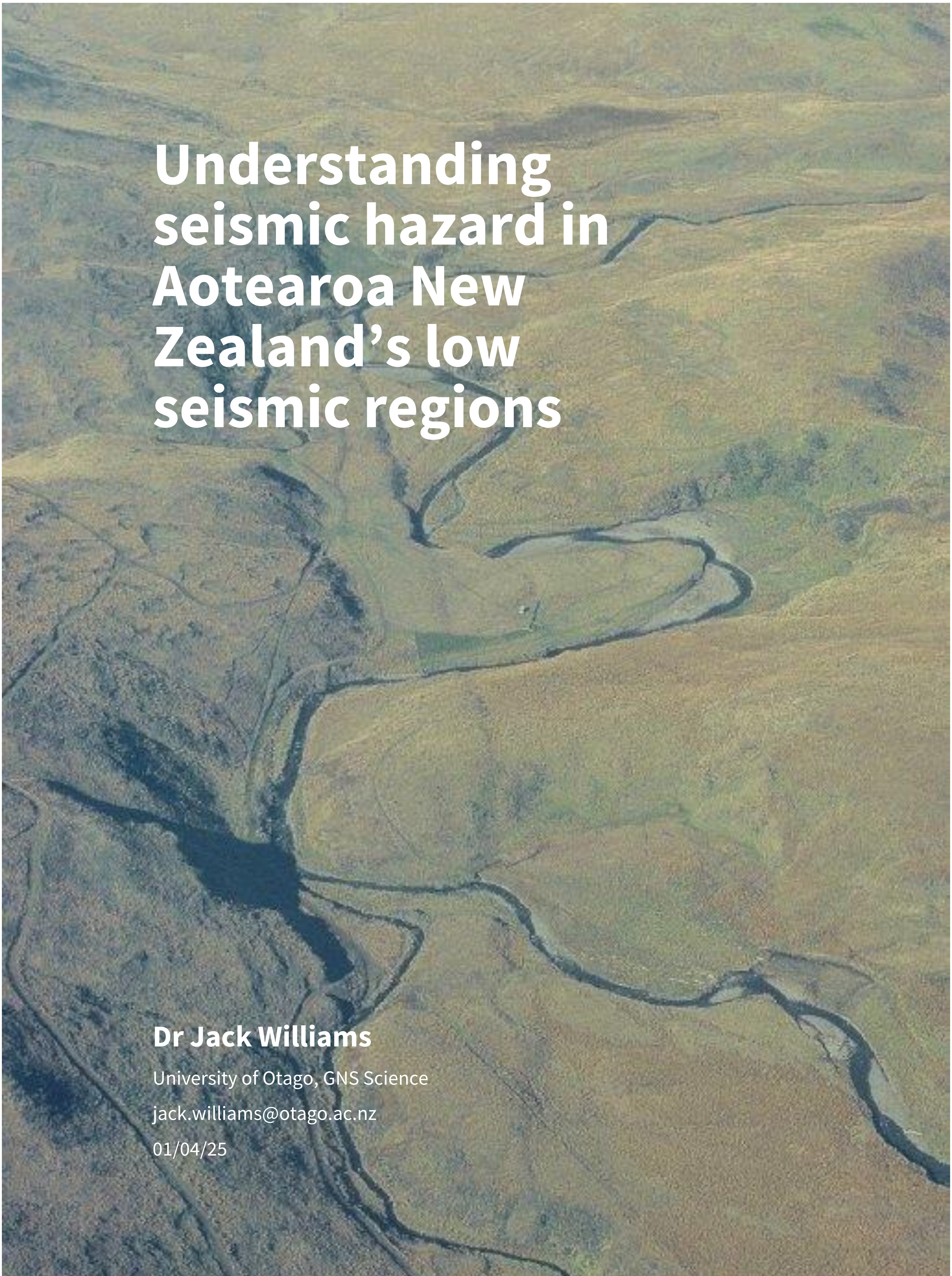
As of 1 July 2024, our name changed from the Earthquake Commission to the Natural Hazards Commission Toka Tū Ake. Find out more about our organisation and insurance scheme on www.naturalhazards.govt.nz.



Understanding seismic hazard in Aotearoa New Zealand's low seismic regions

Dr Jack Williams

University of Otago, GNS Science

jack.williams@otago.ac.nz

01/04/25

Acknowledgements

This project was funded by Natural Hazards Commission (NHC) Toka Tū Ake Research Funding, Project no, 4039. Additional funding was provided through the Aotearoa New Zealand National Seismic Hazard Model project, which is funded by the Ministry of Business, Innovation and Employment (MBIE) through contract C05X2301. I am incredibly grateful to Mark Stirling (University of Otago), who along with Caroline Orchiston (University of Otago), initiated the research described in this report through a 2020-2023 NHC University Research Program project (RCP023), and has supported my career for many years. I also thank the many colleagues at GNS Science who have supported this research; in particular: Donna Eberhart-Phillips, David Barrell, Sandra Bourguignon and Matt Gerstenberger.

Executive Summary

There are large swathes of Aotearoa New Zealand lie away from the Australian-Pacific plate-bounding faults, but where large damaging earthquakes can still occur. Accurately characterising earthquakes hazard in these “low seismicity regions” remains a key challenge as: (1) there is less data to constrain when and where future earthquakes will occur, and (2) the lack of felt earthquakes means that awareness to seismic risk in these regions is often relatively low. It is in this context that I undertook a multidisciplinary research program into the seismic hazard of the low seismicity southern South Island. Key outcomes of this research are: (1) new constraints on a ‘reservoir’ of earthquake prone crust at depths 15-35 km below Southland, (2) justification of changes to the statistical model used to forecast earthquake rates in Otago in the 2022 National Seismic Hazard Model update, and (3) advances to our understanding of where prehistoric earthquakes have occurred, and will likely do so again in future, in Southland. These results will be of use in future national and regional-level earthquake hazard assessments and should motivate the collection of more data to constrain seismic hazard in Aotearoa New Zealand’s other low seismicity regions.

Technical Abstract

It is inherent that low seismicity regions have relatively low seismic hazard levels. However, (1) data scarcity means that their hazard estimates have high uncertainties, and (2) earthquakes in low seismicity regions tend to result in relatively high losses. Hence, there is a continuing need to collect new data to constrain these region's seismic hazard. In this report, I describe work carried out in 2024 to address knowledge gaps in seismic hazard assessment of the low seismicity southern South Island. This research builds on work conducted through the Natural Hazards Commission Toka Tū Ake 2020-2023 University Research Program "Seismic hazard of the southern South Island: the neglected provinces" (RCP023). From locating earthquakes recorded by a temporary deployment of seismometers in Southland, we highlight a sharp transition from ~30-35 km thick seismogenic crust in Southland to ~15 km thick in Otago, and evaluate the crustal stresses within this region. Increased seismic hazard estimates for these regions in the 2022 New Zealand National Seismic Hazard Model (NZ NSHM 2022) reflect the adoption of a negative non-binomial model to forecast "distributed" earthquakes. Nevertheless, our comparisons with "on-fault" earthquakes rates in Otago indicate that the new distributed earthquake rates are justified. Through a literature review and analysis of recently released lidar data, we have revised the extent of several previously identified active faults in Southland, and propose downgrading the activity of the Hillfoot and Hauroko faults. The outputs of this research have been designed so that they can be easily implemented into future updates to the NZ NSHM 2022, New Zealand Active Faults Database, and for use by local councils. Furthermore, the multidisciplinary research undertaken for this research project can serve as a template for examining seismic hazard in other low seismicity regions in Aotearoa New Zealand and elsewhere.

Keywords

Earthquake, quantifying hazards and risk, smarter land use, low seismicity regions, seismic hazard, seismology, active faults

Introduction

Characterising seismic hazard in “low” seismicity regions remains a key challenge in earthquake science. The probability of a future damaging earthquake occurring in these regions is of course less than in their high seismicity counterparts. Nevertheless, there are aspects of the earthquake itself (e.g., ground motion attenuation, stress drop), and with society’s preparedness (e.g., awareness of seismic risk, quality of building stock) that mean that earthquakes in low seismicity regions can be particularly damaging (England and Jackson, 2011; Reyners, 2011; Johnston et al., 2017). In addition, earthquake forecasts in these regions often have larger uncertainties as: (1) there are fewer recorded earthquakes to help constrain the frequency and location of future events, and (2) earthquake recurrence in these regions may be temporally clustered (Christophersen et al., 2017; Griffin et al., 2020; Iturrieta et al., 2022).

In the context of Aotearoa New Zealand, assessing seismic hazard and risk in low seismicity regions is important as there are large swathes of the motu, such as Auckland, Waikato, eastern Canterbury, Otago, and Southland, that lie away from the major Australian-Pacific plate boundary faults, and so are considered to be low seismicity regions (Figure 1). However, a tendency for earthquake research to focus on high seismicity regions has led to data scarcity for how to constrain earthquake rates and prepare communities for future earthquakes in these regions (Johnston et al., 2017; Villamor et al., 2018). Using Otago and Southland as a case study, the NHC 2020-2023 University Research Program “Seismic hazard of the southern South Island: the neglected provinces” (henceforth referred to as RCP023) has started to address this knowledge gap. Highlights of RCP023 include:

- Collection of paleoseismic records for the Nevis-Cardrona and Settlement Faults. Both faults represent significant sources of seismic hazard in the southern South Island, and the new data will lead to revisions for how these faults are treated as earthquake sources in future seismic hazard models.
- The design and establishment of the Southland-Otago Seismic Array (SOSA), a 19-station 12-month seismic array, which provides the first detailed examination of microseismicity in the southern South Island.
- A literature review of active faults in Southland.

RCP023 formally concluded on 31 May 2024. However, due to a secondment by this project’s postdoctoral scholar (Jack Williams - JW) at GNS Science for the 2023-2024 Financial Year through the New Zealand National Seismic Hazard Model (NSHM) Te Tauira Matapae Pūmata Rū program, there was unspent funding at the end of this project. This funding was therefore allocated to support JW through a separate NHC research project “Understanding seismic hazard in Aotearoa New Zealand’s low seismicity regions” (Project no, 4039); the results of which are described herein. Specific goals of this project are:

1. Formally analyse the seismicity data collected by SOSA. This includes a combination of auto and manual picking of earthquake arrivals from the SOSA data, earthquake relocation in a 3-D velocity model, and deriving P-wave first motion focal mechanisms for events recorded by SOSA.
2. Using Otago as a case study, evaluate and test the negative non-binomial model used in the NZ NSHM 2022 update to describe earthquake recurrence in low seismicity regions (Iturrieta et al., 2022; Gerstenberger et al., 2024a). This goal coincides with ongoing work conducted by JW through the NSHM.
3. Developing new active fault databases for Southland's from a literature review and analysis of newly released 1 m^2 lidar digital elevation models across this region. This database to be incorporated into future updates of the New Zealand Active Faults Database and Environment Southland Natural Hazards Portal.
4. Completion of scientific articles describing the paleoseismic data collected on the Nevis-Cardrona and Settlement faults for RCP023.

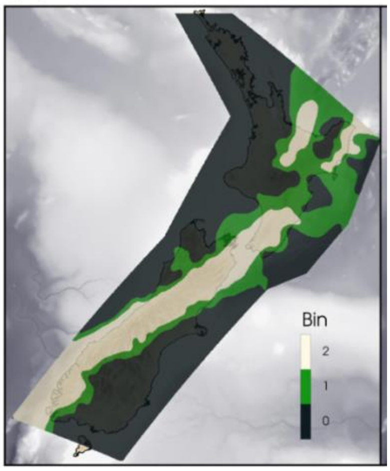


Figure 1: A three bin discretisation of strain rate map for New Zealand (Iturrieta et al., 2022). Anywhere within the dark grey '0' bin can be considered a low seismicity region.

By combining geologic, seismologic, and numerical approaches, these research objectives maximise the scare available data for understanding southern New Zealand's seismic hazard, and can serve as a template for assessing seismic hazard in other low seismicity regions. These research objectives also align with NHC 2021-2023 research investment priorities statements #3 (Smarter land use) and #5 (Quantifying hazards and impacts), and leverage ongoing research opportunities with the NSHM and Resilience to Nature Challenges (RNC) programs. In the context that a probabilistic seismic hazard model can essentially be divided into two components : (1) an earthquake source model or forecast, and (2) a ground motion model (Gerstenberger et al., 2020), we note here that the research conducted here considers only the earthquake source component.

Discussion

I discuss the results from this project in the context of its four goals as listed above.

1. Formal analysis of data from the Southland Otago Seismic Array (SOSA)

A key knowledge gap for understanding southern South Island's seismic hazard is the lack of instrumentally detected earthquakes with well-constrained locations. This reflects: (1) the region's *inherently* low seismicity rates, and (2) the *artificially* sparse coverage provided by the GeoNet network of seismometers in this region (Eberhart-Phillips and Reyners, 2023; Warren-Smith et al., 2024). These factors motivated the establishment of the Southland Otago Seismic Array, a temporary deployment of 19 seismometers between western Catlins and eastern Fiordland from October 2022-2023. An overview of the SOSA data acquisition and data processing can be found in Williams et al., (*in review-1*), Williams et al., (*in prep-1*), and the RCP023 Final Report. Below, I summarise the key implications of these data for characterising Southland's seismic hazard.

In total, I located 85 M_{Lv} 0.2-3.1 earthquakes that occurred in and around Southland using the SOSA data. A striking aspect of the events recorded by SOSA is their focal depth. In continental crust close to plate boundaries, earthquakes typically do not nucleate at depths >15-20 km (Chen and Molnar, 1983). In Southland, however, SOSA recorded focal depths of up to 40 km (Figure 2). This is an important finding as: (1) the depth of an earthquake influences surface ground motions, and (2) in the New Zealand Community Fault Model (NZ CFM; Seebeck et al., 2024) and NZ NSHM 2022 update, the maximum depth of earthquakes was used to constrain the down-dip extent of faults (Ellis et al., 2024), and which in turn, is proportional to a fault's moment rate. Our finding of deep earthquakes in Southland had been inferred previously, and so the NZ CFM already indicates that faults in this region extend down to depths of ~35 km. However, because of the lack of well-located earthquakes in the southern South Island, the spatial extent of this thick "seismogenic" crust had a large uncertainty with Ellis et al. (2024) indicated that it gradually thinned to the north in Otago. From considering earthquake depths in Otago recorded by temporary seismic arrays similar to SOSA (Reyners et al., 2017; Warren-Smith et al., 2017b), we propose that there is a sharp transition between ~35 km thick seismogenic crust in Southland and ~15 km thick seismogenic crust in Otago (Figure 2). This finding is consistent with the presence of mafic minerals in Southland's mid-lower crust, and we recommend that future updates to the NZ CFM should revise the down-dip extent of faults in Otago (Williams et al., *in review-1*).

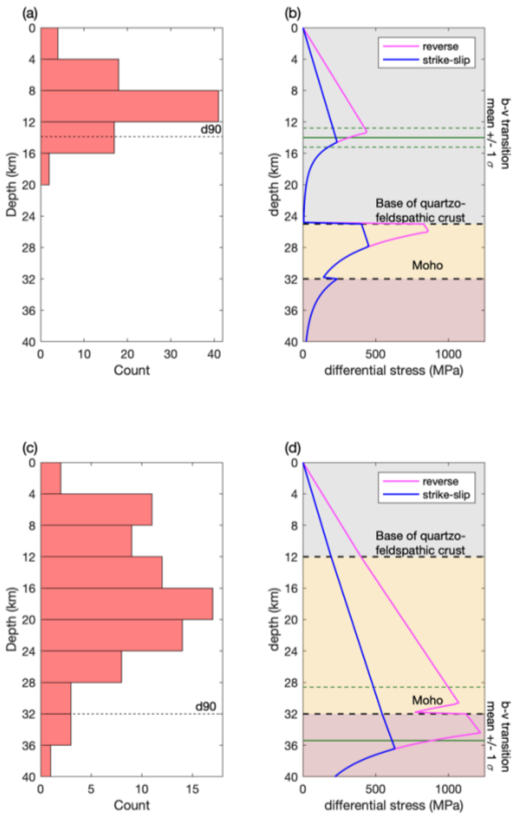


Figure 2: Comparison of focal depths and lithospheric strength in Otago and Southland. (a) Histograms for earthquake depths in Otago (4 km wide bins) for events recorded by the Central Otago Seismic Array and Otago arrays, and relocated by Eberhart-Phillips et al., (2022). (b) 1-D lithospheric strength profiles for Otago where the base of the quartzofeldspathic is considered to be at ~24 km depth. (c)&d Equivalent to (a&b), but for Southland earthquakes recorded by SOSA, and where the quartzofeldspathic crust is ~12 km thick. For further information on this figure, see Williams et al., (*in review-1*)

In ongoing work with the SOSA data, and supplemented by data from a previous temporary seismic array in Otago (Reyners et al., 2017), we are conducting the first study to systematically derive and asses P-wave first motion earthquake focal mechanisms in the southeastern South Island (Figure 3, Williams et al. in *prep-1*). Focal mechanisms provide information about the orientation and slip sense of a fault during an earthquake and, in turn can be used to constrain crustal stress orientations. Initial results indicate a combination of strike-slip and reverse fault earthquakes occurring in an overall strike slip stress state with an ESE trending maximum principal compressive stress (Figure 3). This result is consistent with previous studies elsewhere in the South Island (Balfour et al., 2005; Warren-Smith et al., 2017a), and will be useful for constraining fault mechanics, and developing ‘Distributed Seismicity Model’ (DSM) earthquake sources for this region in future seismic hazard models (Thingbaijam et al., 2024). The SOSA deployment and results also attracted considerable media attention (see the Media Engagement section below).

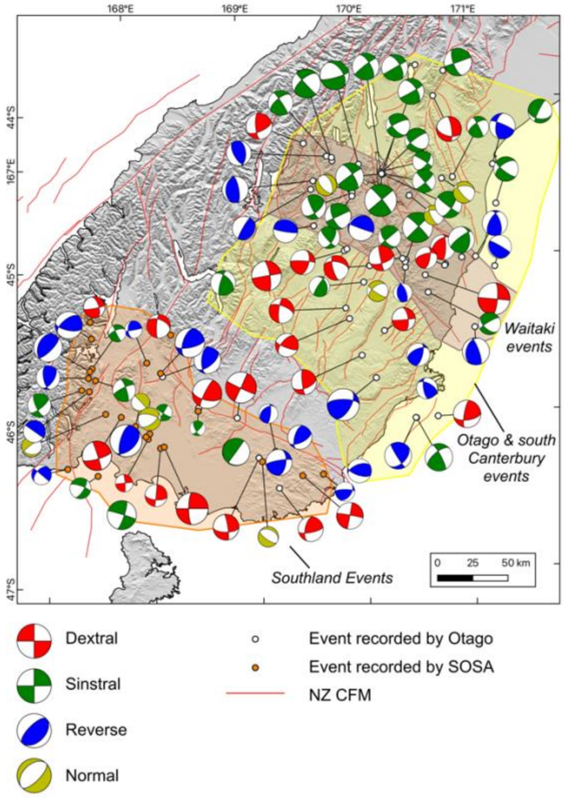


Figure 3: 'Beachball' plots representing focal mechanisms for earthquakes recorded by the Otago and SOSA deployments in the southeastern South Island. The color of the plots, and the orientation of the bounding lines (or 'nodal planes') indicate the earthquake's slip sense and fault planes respectively.

2. Evaluating seismic hazard models in low seismicity regions: a case study from Otago

A notable outcome from the NZ NSHM 2022update was the large increases in seismic hazard estimates for New Zealand's low seismicity regions (Gerstenberger et al., 2024a). In Dunedin, for example the 2010 NZ NSHM estimates there is a 10% probability of exceeding (PoE) 0.1 g ground motion in the next 50 years (Stirling et al., 2012). In the NZ NSHM 2022, the estimate is for a 10% PoE 0.25 g in the next 50 years (Figure 4). This increase can be partly explained by updates to the ground motion models used in the 2010 and 2022 NSHM's (Gerstenberger et al., 2024a). However, changes to how the 2010 and 2022 NSHM DSM forecast earthquakes rates also contributed to this increase. Evaluating these changes to the DSM was the subject of a NSHM subcontract awarded to JW for the 2023-2024 Financial Year through GNS, and finalising the results of this work was within the scope of Project no, 4039. The results of this study are currently in review with the Bulletin of the Seismological Society of America (Williams et al *in review-2*) and are summarised below.

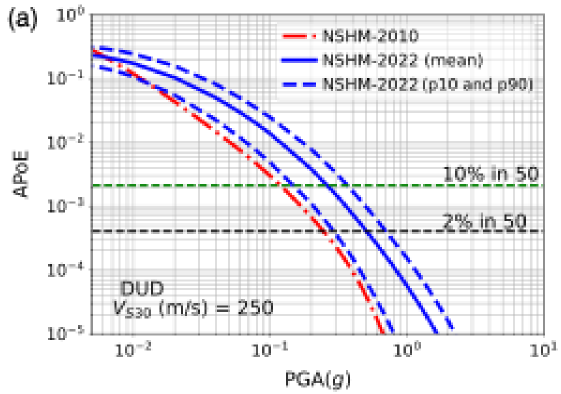


Figure 4: Seismic hazard curve for Dunedin for the 2010 and 2022 NZ NSHM. The curves indicates the annual probability of exceeding (APOE) various ground motions (PGA – Peak Ground Motion in gravitational acceleration, *g*) in Dunedin, as constrained by both the 2010 and 2022 NSHM's

The NZ NSHM 2010 followed the conventional 'Poisson' statistical model to develop its DSM. In this framework, the earthquake rate is time-independent, so that its forecasted rate in the next 50-100 years is broadly equivalent to the observed rate during the previous 50-100 years. From examining earthquake catalogues in New Zealand, Japan, California, and Italy, Iturrieta et al., (2022) observed that the Poisson model was a poor fit for forecasting seismicity rates in regions where the number of recorded earthquakes was small (i.e., in low seismicity regions). This result is consistent with other studies, which indicate temporally clustered seismicity in low seismicity regions from earthquake catalogues (Stevens and Avouac, 2021) and paleoseismic data (Griffin et al., 2020).

Instead, Iturrieta et al., (2022) proposed that low seismicity regions should use a negative binomial statistical model to forecast the rate of future earthquakes. However, the probability distribution of this forecast inherently has a positive skew in regions with few recorded earthquakes (i.e., 'training events'), and since, the NZ NSHM 2022 only ingests the distribution's 'mean', the model's earthquake rate is deviated up from the observed rate. For example, we find that the NZ NSHM 2022 DSM forecasts (on average) 4.5 $M_W \geq 5$ earthquakes in Otago in the next 50 years, even though a $M_W \geq 5$ earthquake has not been observed in this region for at least 70 years (Figure 5).

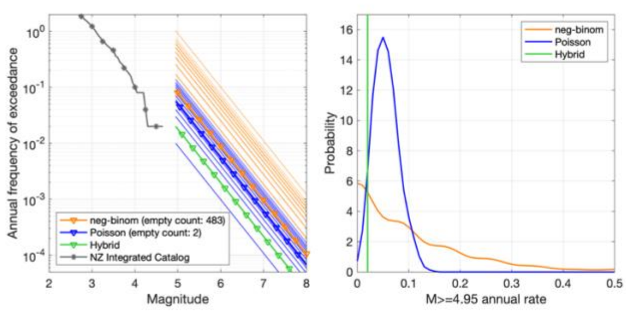


Figure 5: (left panel) The observed magnitude frequency distribution of earthquakes in Otago (grey line) compared to 50-years forecasts for $M_W \geq 5$ in Otago using a Poisson model, a hybrid model (which incorporates various constraints on earthquake rates; Rastin et al., 2024), and the negative binomial model. The thinner blue and orange lines indicate stochastic exploration of the uncertainty in the Poisson and negative binomial forecasts. (right panel) The distribution for the mean annual rate of $M_W \geq 5$ in Otago in the next 50 years for the three forecasts.

To test these NZ NSHM 2022 DSM forecasts further, we consider Otago as there is abundant data on earthquake rates that is independent of instrumental catalogues: the NZ CFM, geodetic data, and paleoseismic data. Overall we find that the NZ NSHM 2022 DSM forecast rate for earthquake rates in Otago in the next 50 years is high relative to data contained within the NZ CFM, but it is within the 'random' variability of the NZCFM's earthquake rates (Figure 6). Interestingly, we also find that the fault slip rates obtained from the NZ NSHM 2022 geodetic model (Johnson et al., 2024) are likely an overestimate as they imply that a $M_W \geq 5$ earthquake should have occurred in Otago in the last 50 years.

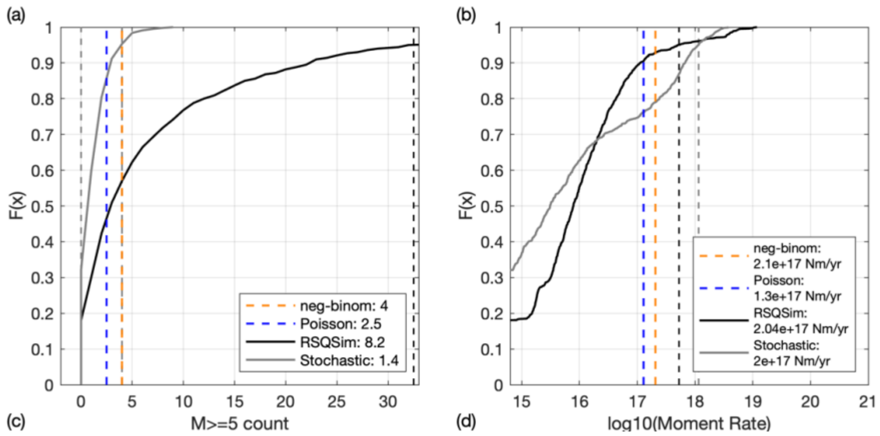


Figure 6: Comparison between the NZ NSHM 2022 DSM negative binomial and Poisson forecasts for the annual rate of $M_W \geq 5$ earthquakes in Otago in the next 50 years (Iturrieta et al., 2022), and 1,000 50-year samples of Otago seismicity as realised by the incorporation of NZ CFM data into: (1) the RSQSim earthquake simulator and (2) a 'stochastic' event catalogue, which is generated using a priori assumptions of on-fault magnitude frequency distribution and renewal process (Williams et al. *in review-2*). (a) Empirical cumulative distribution function and 5% and 95% bounds for the number of earthquakes in the NZ CFM-based 50-year catalogue samples compared to the mean number of $M_W \geq 5$ earthquake in the DSM 50-year forecasts. (b) Equivalent to (a) but comparing the catalogues in terms of their moment rate.

A variety of methods are now available for incorporating fault data (i.e., fault slip rates and geometries) into seismic hazard models (e.g., Shaw et al., 2018; Field, 2019). The NZ NSHM 2022 adopted an "inversion-based" approach that attempts to satisfy various constraints from paleoseismology, a fault's slip rate and geometry, and instrumental catalogues to forecast a fault's earthquake magnitude-frequency distribution (Gerstenberger et al., 2024b). An alternative approach is a "physics-based" approach, in which a synthetic earthquake catalogue is generated using our understanding of earthquake mechanics and a region's fault network; for example, in Aotearoa New Zealand, the Rate and State Earthquake Simulator (RSQSim) has proven useful in tsunami hazard assessment (Hughes et al., 2023). Hence, an additional goal of this research was to use Otago as case study for comparing physics- and inversion-based seismic hazard modelling approaches in a low seismicity region (Williams et al *in review*-2).

Our analysis of these methods indicate significant differences in how an inversion-based approach forecasts on-fault earthquake in Otago relative to a RSQSim catalogue. Namely, the RSQSim catalogue suggests Otago's faults host relatively frequent 'single'-fault M_W 7.0-7.4 earthquakes relative to rare but large (M_W 7.5-8.0) 'multifault' earthquakes in the inversion-based approach (Figure 7). We currently do not have the empirical data to evaluate which of these approaches is a better indicator of on-fault seismicity in Otago. Nevertheless, since these different realisations of on-fault earthquake magnitude-frequency distributions can bias seismic hazard level estimates (Valentini et al., 2020), we recommend that Otago, and other low seismicity regions, should carefully consider how on-fault seismicity is evaluated (Williams et al. in in *review-2).*

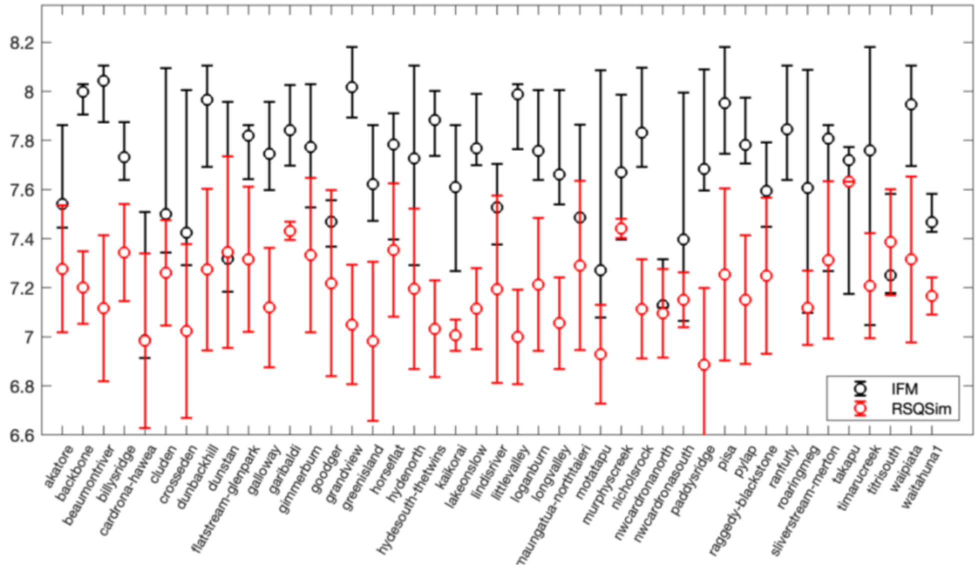


Figure 7: Comparison of magnitudes in the NZ NSHM 2022 Inversion Fault Model (IFM) and an RSQSim catalog for Otago faults. For the IFM, the central point and errors of represents the fault's weighted average and magnitude range.

3. New active faults databases for Southland

As described in the Final Report for RCP023, there is a need to revise active fault datasets for Southland. Such datasets are a foundational component of many seismic hazard assessments, yet active fault compilations for Southland haven't been updated for ~20 years (Turnbull and Allibone, 2003). In addition, the recent release of near complete lidar data, across Southland (https://data.linz.govt.nz/layer/113172-southland-lidar-1m-dem-2020-2024/), has provided us with new data to help constrain the location of fault scarps.

Following on from fault mapping conducted within RCP023, I have continued to refine fault maps for Southland in Project No, 4039. In particular the recent release of the New Zealand Active Fault Database (NZAFD) High Resolution Dataset v 2.0 (Morgenstern et al., 2024) has motivated us to conduct the mapping at a range of scales. In ongoing work funded by the NSHM, we are using the lidar data to identify hitherto unknown active fault scarps in Southland with the ultimate aim of: (1) describing the new fault mapping in a scientific article (Williams et al., in *prep-2*), (2) ensuring these new active fault data are included in future NZAFD updates, and (3) collaborate with Environment Southland so that the new active fault mapping is included in their natural hazards portal as fault avoidance zones/fault awareness regions. With respect to aim (3), preliminary meetings were held with Environment Southland on 06/09/24 with the view that we would submit a proposal to them to undertake this work in the 2025/26 financial year. JW has also been in contact with the NZAFD developers (meeting held 26/02/25) to facilitate the eventual uptake of these datasets into the NZAFD.

4. Finalisation of Nevis-Cardrona and Settlement fault paleoseismic records

A major goal of RCP023 was to collect new paleoseismic records in the southern South Island, which could then be used to update earthquake sources in this region. Following site prioritisation, paleoseismic excavations were conducted on the Nevis-Cardrona Fault in March 2022 and the Settlement Fault in February 2023. Further description of these excavations are provided in RCP023's Final Report. At the time of this project's completion, the interpretation and write-up of these paleoseismic excavations was incomplete. Hence, we note here that the project described Project No, 4039 facilitated the finalisation of describing and interpreting these paleseismic data, and that following peer reviews, articles describing the Nevis-Cardrona and Settlement Fault trenches have now been published Open Access in *Seismica* (Williams et al., 2024) and the *New Zealand Journal of Geology and Geophysics* respectively (Williams et al., 2025). Through a press release issued by the University of Otago, several news articles highlighted the publication of the Nevis-Cardrona Fault study (see Media engagement section below).

Conclusions

Summary of key results

Herein, I describe a multidisciplinary work program undertaken during 2024, which uses the southern South Island of Aotearoa New Zealand as a case study for examining the challenges and opportunities with characterising seismic hazard in Aotearoa New Zealand's low seismicity regions. This research extends work undertaken for the 2021-2023 Natural Hazards. Commission (NHC) Toka Tū Ake University Research Program RCP023. From analysis of seismic waveform data collected through the Southland Otago Seismic Array during RCP023 and analysis of previous temporary seismic deployments in Otago (Reyners et al., 2017; Warren-Smith et al., 2017b), we propose that there is a sharp transition from ~35 km to ~15 km thick seismogenic crust that coincides with the boundary between Southland and Otago. This contrasts with the gradual transition from ~35 to ~25 km thick seismogenic crust between these regions that was implemented for the 2022 New Zealand National Seismic Hazard Model (NZ NSHM 2022) update (Ellis et al., 2024; Gerstenberger et al., 2024a). In ongoing work, we are investigating the stress state and fault kinematics in this region, which will help with characterising seismicity on unknown faults in this region.

In work that was co-funded by a subcontract from the NSHM, I have examined modelling decisions that resulted in higher seismic hazard estimates for New Zealand's low seismicity regions during the NZ NSHM 2022 update (Iturrieta et al., 2022). Specifically, I find that the negative non-binomial model used to forecast earthquake rates is consistent with independent data on earthquake rates in Otago. However, the geodetically-derived slip rate estimates for Otago's faults (Johnson et al., 2024) are likely too high as they imply a M_W >5 earthquake should have been observed in this region in the last 70 years. We also highlight how an "inversion-based" and "physics-based" method to incorporate fault data into seismic hazard models lead to different suggestions for whether a faults in Otago host relatively frequent segmented M_W 7-7.4 ruptures, or rarer but longer multi-fault M_W 7.5.-8.0 ruptures.

Through this project, I am continuing the first update to active fault maps for Southland in 20 years. This update is motivated by: (1) new widespread lidar coverage for this region, which can illuminate the extent of fault scarps and (2) continuing changes to how we define "active" faults (Nicol et al., 2016). Thus far, we have revised the extent and position of several faults in Southland, and have suggested that some faults previously thought to be active should be downgraded to 'possibly active.' This new mapping will be incorporated in the national-level New Zealand Active Fault Database and we are engaging with Environment Southland so that is considered in their regional-level Natural Hazards Portal.

Recommendations

A major challenge highlighted by this research is the lack of available data to constrain seismic hazard in low seismicity regions, and for which there are both inherent (the lack of recorded earthquakes) and artificial (a tendency to focus research on higher seismicity regions) reasons. Obviously, we cannot the address former, but the research described herein demonstrates how we can close knowledge gaps for the latter case. From a source modelling perspective, we recommend:

1. The permanent network of GeoNet seismometers is densified in low seismicity region and/or targeting of these regions by dense temporary seismic arrays.
2. The use of statistical models that specifically incorporate the earthquake rate uncertainty in low seismicity regions into seismic hazard models.
3. Leverage the ever-expanding coverage of open-access lidar coverage in Aotearoa New Zealand (https://www.linz.govt.nz/products-services/data/types-linz-data/elevation-data) to revise active fault datasets in low seismicity regions.

We note too, the potential value of a risk-based approach for this research, and that regions where the seismic hazard is low, but the vulnerability is high, should be prioritised. A study conducted by Villamor et al. (2018) to investigate active faults and seismic hazard for Dunedin provides a template for this research.

The results of this project also has specific implications for developing earthquake sources for seismic hazard modelling in the southern South Island. In principle, our suggestion that the seismogenic crust thickness and geodetic slip rates used for Otago in the NZ NSHM 2022 are overestimates will lead to lower seismic hazard values for this region in future NSHM updates. In addition, new paleoseismic data collected from the Nevis-Cardrona Fault indicate it's slip rate should be revised down (van den Berg et al., 2024; Williams et al., 2024); and this implies lower seismic hazard estimates for the rapidly developing Queenstown-Wānaka-Cromwell region. Nevertheless, the tragic consequences of the Canterbury Earthquake Sequence demonstrates that this ostensibly welcome news should not be used as a pretence for neglecting continued research into Aotearoa New Zealand's low seismicity regions.

Publications and Communications

Publications

Published [including publications associated with RCP023]

- Williams, J., Stirling, M., Langridge, R., Niroula, G., Vause, A., Stewart, J., ... & Wang, N. (2024). Along-strike extent of earthquakes on multi-segment reverse faults; insights from the Nevis-Cardrona Fault, Aotearoa New Zealand. *Seismica*, 3(2).
- Williams, J. N., Stirling, M. W., Barrell, D. J., Niroula, G., & Wavelet, E. (2025). Insights into temporal earthquake clustering from the Settlement Fault, southeastern Otago, Aotearoa New Zealand. *New Zealand Journal of Geology and Geophysics,* 1-26.

In review

- Williams, J. N., Eberhart-Phillips, D., Bourguignon, S., Stirling, M. W., & Oliver, W. (*in review-1).* Deep and clustered microseismicity at the edge of southern New Zealand's transpressive plate boundary. *In review with Journal of Geophysical Research Solid Earth*. Preprint available via ESS Open Archive at: https://doi.org/10.22541/essoar.172770788.83492166/v1
- Williams, J.N., Stirling, M.W., Howell, A., McGrath, J., Gerstenberger, M.. Coffey, G., Griffin, J., Van Dissen, R., Penney, C., Chamberlain C. (*in review-2*). Evaluating and comparing seismicity models in the low strain rate Otago region, Aotearoa New Zealand. *In review with Bulletin of the Seismological Society of America*

In draft

- Williams, J. N., Eberhart-Phillips, D., Bourguignon, S., Stirling, M. W., & Reyners M., (*in prep-1).* Focal mechanisms in the southeastern South Island of New Zealand indicate scale dependent release of transpressional strain
- Williams, J.N., Stirling, M.W., Barrell, D. J-A (*in prep-2*). A review of active faulting in Southland, New Zealand

Conference Presentations

- Williams, J.N., Eberhart-Phillips, D., Bourguignon, S., Stirling, M.W., Oliver (2024): Deep and clustered microseismicity at the peripheral edge of a transpressive plate boundary: results from the Southland Otago Seismic Array (SOSA). *Presented at the 2024 Annual Conference of the Geoscience Society New Zealand, Dunedin, New Zealand*

List of engagement events and science presentations

[see URP RCP023 Final Report for engagement events and presentations between 2022-2023].

Media engagement

- Interviewed for article in the Otago Daily Times about commemorating 50th anniversary of the 1974 Dunedin Earthquake: https://www.odt.co.nz/news/dunedin/information-event-commemorate-earthquake
- 03/07/2024: Appearance on the Otago Access Radio 'Left from Nowhere' to discuss natural hazards in Aotearoa: https://oar.org.nz/left-from-nowhere/ (episode 03).
- NHC press release on results from the Southland-Otago Seismic Array (https://www.naturalhazards.govt.nz/news/scientists-discover-deep-earthquakes-under-southland/#:~:text=New%20research%20from%20the%20University,country's%20least%20seismically%20active%20regions.) led to the following articles:
    - 1News feature on deep earthquakes in Southland (aired 30/11/24)
    - Radio New Zealand: https://www.rnz.co.nz/news/national/534455/southland-s-hidden-reservoir-of-quake-prone-crust-revealed
    - Southland Times: https://readnow.isentia.com/Temp/177947-1134657138/1030063551_20250221.pdf
    - Otago Daily Times: https://www.odt.co.nz/southland/southland-express/depth-earthquakes-strikes-scientists
    - Stuff: https://www.stuff.co.nz/nz-news/360494709/earthquakes-discovered-deep-under-southland
    - The Press: https://www.thepress.co.nz/nz-news/360494709/earthquakes-discovered-deep-under-southland
    - What on Invers: https://whatsoninvers.nz/hidden-faults-found-deep-in-southland/
- University of Otago press release on publication of Nevis-Cardrona Fault paleoseismology results (https://www.otago.ac.nz/news/newsroom/new-research-updates-old-earthquake-theory) led to the following articles/radio items:
    - Crux: https://crux.org.nz/crux-news/nevis-cardrona-fault-quake-chances-lower-than-thought/
    - Lakes Weekly: https://lwb.co.nz/content/earthquake-risk-lower-than-previously-thought/
    - Otago Daily Times: https://www.odt.co.nz/news/dunedin/campus/study-revises-likelihood-earthquakes
    - Newstalk ZB

Outreach events/Talks

- 01/03/2024: U3A presentation, Invercargill, 'Active faults and seismic hazard in Southland
- 11/04/2024: Presentation to the National Seismic Hazard Model (NSHM) Seismicity Rate Model Working Group on testing earthquake rate forecasts in Otago
- 26/03/2024: 'Thirst for Knowledge' presentation, Dunedin: 'Are we on shaky ground? Dunedin and its earthquake hazards'
- 09/04/2024: Sat on public forum commemorating the 1974 Dunedin Earthquake, Otago Museum, Tūhara (see also URP RCP-023 Final Report).
- 17/09/2024: Geoscience Society of New Zealand (GSNZ) Otago Branch talk: ‘Earthquakes in the south: when, where, and why?”
- 10/10/2024: GNS Science Seminar Series “Deep and clustered microseismicity at the peripheral edge of southern New Zealand’s plate boundary: results from the Southland Otago Seismic Array”
- 13/11/2024: Developed and led workshop that introduced ~30 students from Otago Girls High Schools to earthquake science.

References

Balfour, N.J., Savage, M.K., and Townend, J., 2005, Stress and crustal anisotropy in Marlborough, New Zealand: Evidence for low fault strength and structure-controlled anisotropy: Geophysical Journal International, v. 163, p. 1073–1086, doi:10.1111/j.1365-246X.2005.02783.x.

Chen, W.-P., and Molnar, P., 1983, Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere.: Journal of Geophysical Research, v. 88, p. 4183–4214, doi:10.1029/jb088ib05p04183.

Christophersen, A., Rhoades, D.A., and Colella, H. V., 2017, Precursory seismicity in regions of low strain rate: Insights from a physics-based earthquake simulator: Geophysical Journal International, v. 209, p. 1513–1525, doi:10.1093/gji/ggx104.

Eberhart-Phillips, D., and Reyners, M., 2023, Catalogue of 2001–2011 New Zealand earthquakes relocated with 3-D seismic velocity model and comparison to 2019–2020 auto-detected earthquakes in the sparsely instrumented southern South Island: New Zealand Journal of Geology and Geophysics, v. 66, p. 646–653, doi:10.1080/00288306.2022.2089171.

Eberhart-Phillips, D., Upton, P., Reyners, M., Barrell, D.J.A., Fry, B., Bourguignon, S., and Warren-Smith, E., 2022, The Influence of Basement Terranes on Tectonic Deformation: Joint Earthquake Travel-Time and Ambient Noise Tomography of the Southern South Island, New Zealand: Tectonics, v. 41, p. e2021TC007006, doi:10.1029/2021TC007006.

Ellis, S. et al., 2024, New Zealand Fault-Rupture Depth Model v.1.0: A Provisional Estimate of the Maximum Depth of Seismic Rupture on New Zealand's Active Faults: Bulletin of the Seismological Society of America, v. 114, p. 78–94, doi:10.1785/0120230166.

England, P., and Jackson, J., 2011, Uncharted seismic risk: Nature Geoscience, v. 4, p. 348–349, doi:10.1038/ngeo1168.

Field, E.H., 2019, How physics-based earthquake simulators might help improve earthquake forecasts: Seismological Research Letters, v. 90, p. 467–472, doi:10.1785/0220180299.

Gerstenberger, M.C. et al., 2020, Probabilistic Seismic Hazard Analysis at Regional and National Scales: State of the Art and Future Challenges: Reviews of Geophysics, v. 58, p. e2019RG000653, doi:10.1029/2019RG000653.

Gerstenberger, M.C. et al., 2024a, The 2022 Aotearoa New Zealand National Seismic Hazard Model: Process, Overview, and Results: Bulletin of the Seismological Society of America, v. 114, p. 7–36, doi:10.1785/0120230182.

Gerstenberger, M.C. et al., 2024b, The Seismicity Rate Model for the 2022 Aotearoa New Zealand National Seismic Hazard Model: Bulletin of the Seismological Society of America, v. 114, p. 182–216, doi:10.1785/0120230165.

Griffin, J.D., Stirling, M.W., and Wang, T., 2020, Periodicity and Clustering in the Long-Term Earthquake Record: Geophysical Research Letters, v. 47, p. e2020GL089272, https://doi.org/10.1029/2020GL089272.

Hughes, L., Power, W., Lane, E.M., Savage, M.K., Arnold, R., Howell, A., Shaw, B., Fry, B., and Nicol, A., 2023, A Novel Method to Determine Probabilistic Tsunami Hazard Using a Physics-Based Synthetic Earthquake Catalog: A New Zealand Case Study: Journal of Geophysical Research: Solid Earth, v. 128, doi:10.1029/2023JB027207.

Iturrieta, P., Gerstenberger, M.C., Rollins, C., van Dissen, R.J., Wang, T., and Schorlemmer, D., 2022, Accounting for earthquake rates' temporal and spatial variability through least-information Uniform Rate Zone forecasts:, doi:doi:10.21420/HYDZ-8W17.

Johnson, K.M., Wallace, L.M., Maurer, J., Hamling, I., Williams, C., Rollins, C., Gerstenberger, M., and Van Dissen, R., 2024, Inverting Geodetic Strain Rates for Slip Deficit Rate in Complex Deforming Zones: An Application to the New Zealand Plate Boundary: Journal of Geophysical Research: Solid Earth, v. 129, p. e2023JB027565, doi:10.1029/2023JB027565.

Johnston, D.M., Becker, J., Orchiston, C., Egbelakin, T., and Coomer, M.A., 2017, Earthquake Awareness and Preparedness in Dunedin and Oamaru: A 2016 Survey: Data Report: GNS Science report ; 2017/12., doi:https://doi.org/10.21420/G21C7V.

Morgenstern, R. et al., 2024, New Zealand Active Faults Database: the high-resolution dataset v2.0: New Zealand Journal of Geology and Geophysics, p. 1–16, doi:10.1080/00288306.2024.2427396.

Nicol, A., Van Dissen, R.J., Stirling, M.W., and Gerstenberger, M.C., 2016, Completeness of the Paleoseismic Active-Fault Record in New Zealand: Seismological Research Letters, v. 87, p. 1299–1310, doi:10.1785/0220160088.

Rastin, S.J., Rhoades, D.A., Rollins, C., Gerstenberger, M.C., Christophersen, A., and Thingbaijam, K.K.S., 2024, Spatial Distribution of Earthquake Occurrence for the New Zealand National Seismic Hazard Model 2022: Bulletin of the Seismological Society of America, p. 1–22, doi:10.1785/0120230173.

Reyners, M., 2011, Lessons from the destructive Mw 6.3 Christchurch, New Zealand, earthquake: Seismological Research Letters, v. 82, p. 371–372, doi:10.1785/gssrl.82.3.371.

Reyners, M., Eberhart-Phillips, D., Upton, P., and Gubbins, D., 2017, Three-dimensional imaging of impact of a large igneous province with a subduction zone: Earth and Planetary Science Letters, v. 460, p. 143–151, doi:10.1016/j.epsl.2016.12.025.

Seebeck, H. et al., 2024, The New Zealand Community Fault Model–version 1.0: an improved geological foundation for seismic hazard modelling: New Zealand Journal of Geology and Geophysics, v. 67, p. 209–229, doi:10.1080/00288306.2023.2181362.

Shaw, B.E., Milner, K.R., Field, E.H., Richards-Dinger, K., Gilchrist, J.J., Dieterich, J.H., and Jordan, T.H., 2018, A physics-based earthquake simulator replicates seismic hazard statistics across California: Science Advances, v. 4, p. 1–10, doi:10.1126/sciadv.aau0688.

Stevens, V.L., and Avouac, J.P., 2021, On the relationship between strain rate and seismicity in the India-Asia collision zone: Implications for probabilistic seismic hazard: Geophysical Journal International, v. 226, p. 220–245, doi:10.1093/gji/ggab098.

Stirling, M. et al., 2012, National seismic hazard model for New Zealand: 2010 update: Bulletin of the Seismological Society of America, v. 102, p. 1514–1542, doi:10.1785/0120110170.

Thingbaijam, K.K.S., Rattenbury, M.S., Van Dissen, R.J., Gerstenberger, M.C., Ristau, J., and Fitzenz, D.D., 2024, Characterization of Focal Mechanisms for Upper Crustal Distributed Seismicity in Aotearoa New Zealand: Seismological Research Letters, v. 95, p. 150–158, doi:10.1785/0220230196.

Turnbull, I.M., and Allibone, A.H., 2003, Geology of the Murihiku area: Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 20.

Valentini, A., DuRoss, C.B., Field, E.H., Gold, R.D., Briggs, R.W., Visini, F., and Pace, B., 2020, Relaxing Segmentation on the Wasatch Fault Zone: Impact on Seismic Hazard: Bulletin of the Seismological Society of America, v. 110, p. 83–109, doi:10.1785/0120190088.

Villamor, P. et al., 2018, Unknown faults under cities:, doi:doi:10.21420/G2PW7X.

Warren-Smith, E., Jacobs, K., Rollins, C., Chamberlain, C.J., Eberhart-Phillips, D., and Williams, C., 2024, A quantitative assessment of GeoNet earthquake location quality in Aotearoa New Zealand: New Zealand Journal of Geology and Geophysics, p. 1–14, doi:10.1080/00288306.2024.2421309.

Warren-Smith, E., Lamb, S., and Stern, T.A., 2017a, Stress field and kinematics for diffuse microseismicity in a zone of continental transpression, South Island, New Zealand: Journal of Geophysical Research: Solid Earth, v. 122, p. 2798–2811, doi:10.1002/2017JB013942.

Warren-Smith, E., Lamb, S., Stern, T.A., and Smith, E., 2017b, Microseismicity in Southern South Island, New Zealand: Implications for the Mechanism of Crustal Deformation Adjacent to a Major Continental Transform: Journal of Geophysical Research: Solid Earth, v. 122, p. 9208–9227, doi:10.1002/2017JB014732.

Appendices

For further descriptions of research methods associated with this project, please refer to the publications listed in the 'Publications and Communcations' section.