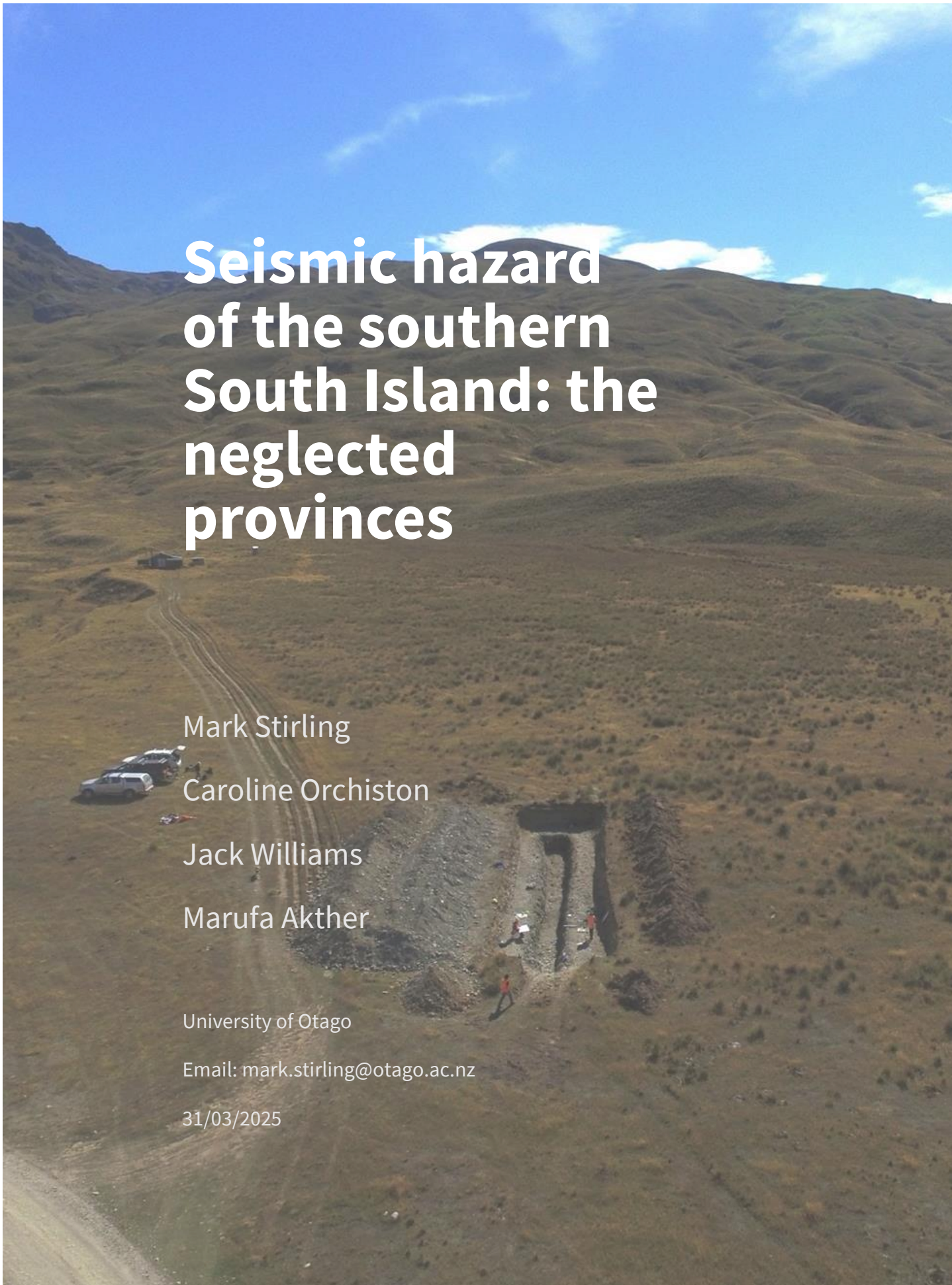
Natural Hazards Commission
Toka Tū Ake

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.



Seismic hazard of the southern South Island: the neglected provinces

Mark Stirling

Caroline Orchiston

Jack Williams

Marufa Akther

University of Otago

Email: mark.stirling@otago.ac.nz

31/03/2025

Acknowledgements

At the University of Otago Department of Geology, we acknowledge the assistance of postgraduate students for their field support during this project: Govinda Niroula, William Oliver, Luce Lacoua, Solen Chanony, Emeline Wavelet, Grace Duke, and Ashleigh Vause. We also thank Hamish Bowman and Steve Read for their technical support. Donna Eberhart-Phillips, David Barrell, Sandra Bourguignon, Robert Langridge (all GNS Science) and Andy Nicol (University of Canterbury) are thanked for their invaluable assistance during this project. Michele Salmon and Robert Pickle at the Australian National Research Facility for Earth Sounding (ANSIR) are acknowledged for loaning the equipment used for the Southland Otago Seismic Array. We are also grateful to the many landowners who kindly granted us permission to deploy seismometers or excavate fault trenches on their properties. The team at the Centre for Sustainability wishes to acknowledge the support of many students (Ashleigh Vause, Seth Whittington, Rhys Latton, Josh Stewart and Sonja Mueller at Otago) and colleagues at Emergency Management Otago (Erica Andrews and Paula Cathie), Massey University (Prof. David Johnston and Dr. Lauren Vinnell), and GNS Science (Simon Cox, David Barrell, and Tatiana Goded).

Executive Summary

We hereby provide our final report for this URP, which had the goals of: (1) understanding the location and activity of earthquake sources in low seismicity regions located away from the plate boundary of New Zealand; and (2) assessing the current understanding of earthquake resilience legislation by key stakeholders, and the progress being made to improve preparedness and reduce risk in these regions. Southland was chosen as the focus for the study, as it is one of New Zealand's low seismicity regions, and one that has received minimal focus in previous years in comparison to the attention given to the more active plate boundary areas. We took this as an opportunity to work in an area of the country that has had limited attention, and sought to establish whether the region's low hazard in the 2012 national seismic hazard model was due to the lack of knowledge of earthquake sources, or because of a real absence of sources. Our activities and achievements over the course of this URP have occurred across the topic areas of earthquake source identification, and earthquake resilience.

There was a six-month delay to research initiation due to Postdoctoral and Doctoral student recruitment timelines. Jack Williams (Postdoc) began in mid-2021, and Marufa Akther (PhD student) started in March 2021.

This report describes what has been achieved across two workstreams. Key achievements include: (1) determination of the prehistoric earthquake activity of the Nevis and Settlement faults, adjacent to northern and eastern Southland, respectively; (2) recording of the locations and depths of small earthquakes across Southland by establishment of the Southland Otago Seismic Array (SOSA) for the period October 2022 to September 2023. The study revealed several areas of enhanced earthquake activity in the region, and the depth of seismicity to be much deeper than originally thought, and much deeper than in neighbouring Otago; (3) An examination of the extant literature on lower seismic hazard zones, including analysis of relevant policies and plans designed to guide decision-

making for disaster risk reduction; 4) ethical approval to undertake a qualitative research approach, including stakeholder mapping to identify expert knowledge holders; 5) An examination of the implementation and effective of earthquake resilience policies in low seismic risk areas, focusing on Dunedin and Oamaru; and (6) publication of research papers and dissemination of results at conferences and via public engagement across (1)-(5).

Prior Work

This URP represents a continuation of NHC-funded work on seismic source characterisation in Otago over the period 2016-19. At that time NHC provided operational funding support to assist with startup of the Chair of Earthquake Science at Otago. The funding specifically co-funded paleoseismic studies of the Akatore, NW Cardrona and Hyde faults, associated seismic source characterisations, and participation in development of the national seismic hazard model (NSHM) update programme. The URP has also paralleled Resilience to Nature's Challenges (RNC) funded efforts to further the development earthquake rupture simulation models, and in particular, testing and evaluation of the models. Workstream 2 leverages past research and engagement activity undertaken through QuakeCoRE's Disciplinary Theme 4, and the RNC-Rural programme, and disaster risk reduction, public education and community resilience efforts by the AF8 programme.

Keywords

Earthquake, seismic network, paleoseismology, quantifying hazards and impacts, public education, earthquake commemoration, low seismic risk, policies **.**

Research Team

Professor Mark Stirling, Chair of Earthquake Science, University of Otago (URP leader).

Associate Professor Caroline Orchiston, Director, Centre for Sustainability, University of Otago (URP leader).

Dr Jack Williams, Postdoctoral Fellow, University of Otago (Key researcher).

Marufa Akther, Doctoral student

Introduction

Our URP had the goals of: (1) providing a better understanding of the location and activity of earthquake sources in low seismicity regions located away from the plate boundary of New Zealand; and (2) investigating the awareness and understanding of earthquake resilience legislation and its implementation towards reducing earthquake risk in these regions. These goals were addressed by focusing on the Southland region as a case study for low seismicity regions in New Zealand. These regions show low seismic hazard relative to surrounding region (Stirling et al. 2012), but it was unknown as to whether these differences were due to a lack of knowledge of earthquake sources, or an actual lack of earthquake sources.

Work on the source identification and characterisation (Workstream 1) was largely carried out by Jack Williams (JW), with leadership and assistance from Mark Stirling (MS). The work involved geological studies of previously unstudied or poorly understood faults, and through establishment of a temporary (12 month) seismic network across Southland to constrain the location and depth of small earthquakes not recorded by GeoNet. Workstream 2 supported one doctoral and several summer scholarship students, supervised by Caroline Orchiston (CO).

The URP has contributed to developing research capabilities surrounding the identification of earthquake sources of long recurrence intervals from both seismological and geological datasets. Local government policy makers, engineers and building owners' perspectives on reducing risk to buildings in low seismic risk areas have been explored, revealing significant barriers to the effective and timely implementation of policies designed to reduce risk to life in vulnerable buildings.

Collaboration and Stakeholder Engagement

Throughout this URP, MS and JW have been closely engaged with the NSHM/Te Tauira Matapae Pūmata Rū program. This will ensure that revisions to earthquake sources in the southern South Island will be implemented in future NSHM updates. MS and JW have also been closely involved within the Resilience to Nature's Challenges (RNC) Earthquake & Tsunami program through their supervision of RNC-funded student Govinda Niroula. In particular, the familiarity we have gained with the Rate and State Earthquake Simulator (RSQSim) through this supervision has fed into further analysis of RSQSim in NHC Project 4039.

For the Nevis-Cardrona Fault trench, we collaborated with Robert Langridge (GNS Science), Andy Nicol (University of Canterbury), Ningsheng Wang (Victoria University of Wellington), and James Stewart (GeoSolve). In addition, we hosted visitors from Contact Energy, owners of the nearby Clyde Dam, to view the trenches and learn about our research into the region's seismic hazard.

The Settlement Fault and Southland fault mapping involved collaboration with David Barrell (GNS Science). This work has kick-started the development of a Southland fault dataset for inclusion in future updates to the New Zealand Active Fault Database (hosted by GNS Science). We are currently developing a collaborative arrangement with Environment Southland (Karen Wilson) to include this dataset on their natural hazards portal.

Donna Eberhart-Phillips and Sandra Bourguignon (both GNS Science) provided support for the Southland Otago Seismic Array (SOSA) through the Ministry of Business, Innovation & Employment Strategic Science Investment Fund, contract C05X1702. Equipment for this deployment was loaned to us by the Australian National Research Facility for Earth Sounding (ANSIR). Indeed, the partnership that formed between the University of Otago and ANSIR was an unanticipated benefit of the SOSA deployment, with ANSIR allowing the university to host the equipment necessary to deploy similar seismic arrays and/or to rapidly deploy seismometers around a future moderate-large magnitude earthquake in southern New Zealand.

This research has benefited from strong alignment and collaboration with Massey University research on low seismic risk areas, in the Auckland-Northland context. Dr. Lauren Vinnell's NHC funding explores the influences on earthquake resilience in Auckland-Northland. We have had regular discussions, and offered feedback on Lauren's survey and interview schedules. We have collaborated on co-authored conference abstracts and publications from this work.

Early phases of workstream 2 also involved communication and engagement with Resilient Organisations to understand how this project complemented their existing building resilience research. In August 2024, ResOrgs hosted Caroline and Marufa for a discussion about the project and its progress to date.

Existing relationships with Emergency Management Southland (EMS) led to another collaboration aligned this project, on tsunami hazard related to the Puysegur Trench. CO's interactions with EMS through AF8 led to discussions about local earthquake risk and other science needs in Southland. The desire for a review of the state of knowledge about tsunami hazard was expressed by EMS. In response, we recruited a summer scholarship student (Ash Vause) from the Otago Earthquake Science team to complete a literature review and draft a journal article on tsunami hazard science for southern Aotearoa. We were joined by Dr. Ursula Cochran during the latter stages of paper drafting, and it was subsequently published in NZJGG. Since then, Environment Southland has used this document, and the media interest that stemmed from its publication, to drive action on tsunami inundation research and public education in Southland.

In September 2021, the team ran a Lower Seismic Hazard workshop at the QuakeCoRE Annual meeting (co-hosted by MS and CO), which included presentations from Matt Gerstenberger, David Johnston and Lauren Vinnell, to explore research synergies and collaboration for lower seismic zones, including Otago/Southland and Auckland/Northland.

The team collaborated closely with GNS Science, Emergency Management Otago, the Dunedin City Council and Massey University to support several public events related to the 50th anniversary of the 1974 Dunedin earthquake. Most notably, a public commemoration event was held at Tūhura Otago Museum on the 9th April (50 years since the earthquake). MS also presented a Geoscience Society of New Zealand Otago Branch talk on this earthquake on April 8th, while JW gave a talk about this event as part of the series of "Thirst for Knowledge" talks at Ombrellos bar in Dunedin (26th March 2024). We discuss these events further in the Discussion section for Workstream 2.

A list of media articles about our research and community outreach talks associated with this URP is provided below. See also the Project 4039 Final Report for media engagement and outreach presentations by JW during 2024.

Media engagement

- NHC press release on the Nevis-Cardrona Fault paleoseismic trench excavation (https://www.naturalhazards.govt.nz/news/new-research-confirms-major-seismic-events-in-west-otago/) led to the following articles:
- Radio New Zealand article and episode on "Our Changing World": https://www.rnz.co.nz/national/programmes/ourchangingworld/audio/2018844820/digging-into-the-past-of-sleeping-giant-faults
- Stuff/Southland Times: https://www.stuff.co.nz/national/128157543/new-research-confirms-nevis-fault-could-cause-major-quake
- Otago Daily Times: https://www.odt.co.nz/regions/queenstown/finding-seismic-fault-data
- NHC press release on the Southland Otago Seismic Array Deployment (https://www.naturalhazards.govt.nz/news/new-seismometer-network-fills-knowledge-gap-in-southlandpost/) led to the following articles:
- Stuff/Southland Times: https://www.stuff.co.nz/national/130123385/previously-undetectable-earthquakes-to-be-recorded-in-southland?rm=a
- New Zealand Herald: https://www.nzherald.co.nz/nz/what-were-learning-about-nzs-biggest-quake-maker/RT5YGOB32CMNQTUFXPGAGYXFDI/
- NHC press release on the Settlement Fault paleoseismic trench excavation (https://www.naturalhazards.govt.nz/news/scientists-fill-knowledge-gap-for-catlins-fault-hazards/) led to the following article:
- https://www.odt.co.nz/regions/south-otago/fault-assessment-project-adds-hazard-risk-knowledge
- Otago Daily Times, 9th April 2024: Information event to commemorate the 50th anniversary of the 1974 Dunedin Earthquake: https://www.odt.co.nz/news/dunedin/information-event-commemorate-earthquake
- The Herald (Jamie Morton), November 14th Tsunami hazard in Southland. https://www.nzherald.co.nz/nz/nz-region-at-risk-of-12m-high-tsunamis-will-have-only-one-to-two-hours-notice/NCEHTBYUH5HQVHCT77EINITGFM/ (Similar stories in the Otago Daily Times, RNZ and Stuff)

Outreach events/talks

- 12/11/22 (and repeated June 16th) Waikouaiti Community Hall (East Otago), public community resilience day – presentation about earthquake hazards in Otago and community preparedness.
- 20-21/03/23: [JW] Presentations on "Earthquake faults & hazards in the south" for the 2023 AF8 Roadshow in Te Anau and Winton
- 08/04/24 [MS]: Geoscience Society of New Zealand Otago Branch talk on "Dunedin earthquake hazards, 50 years since the last big shake," University of Otago
- 09/04/2024 [CO & JW}: Commemoration event on the 1974 Dunedin Earthquake, Tūhura Otago Museum
- 11/07/24. Panelist for the New Zealand International Science Festival: Disaster resilience in Aotearoa New Zealand, hosted by Aaron Hawkins.
- In 2024 - Local presentations to community groups, including the Dunedin Club, Queenstown U3A, St Kilda Bowling Club, Taieri Emergency Response Group, Waikouaiti Community Response Group (2022 & 2024) and Palmerston Community response group

- 12/2024 – Keynote presentations on seismic hazard and risk for both the FENZ Volunteer Conference (May 2023) and the Āpopo Conference (2024, hosted by Otago Polytechnic).
- -02/2025: Invited presentation to NEMA's Emergency Management Leadership Group, on tourism and emergency management research, including Southland/Milford Sound.

Programme Overview and Objectives

The following milestones were set at the time of project commencement, so provide a useful framework to describe what we set out to do and what was subsequently achieved. As is typical of multi-year projects, there were some necessary departures from the exact milestone definitions, but a substantial delivery was achieved by the time of project end.

The project was divided into three annualised milestones, and represent both workstreams. The milestone definitions are given, and then followed by the relevant achievements.

Milestone 1: *(1) Documentation of the state of knowledge of earthquake hazard in the province; (2) preparation of a journal article outlining the key societal issues related to low seismic hazard zones in NZ; and (3) completion of a stakeholder mapping exercise to identify key research participants. (1) will be produced as an online report (as yet unspecified).*

Workstream 1: JW has developed a database of known active fault sources in Southland, and has made a significant contribution to the state of knowledge, including the interpretation of new LIDAR data (now available for the entirety of Southland), and paleoseismic investigations of the Nevis and Settlement faults. JW will be producing a publication documenting his active fault database of Southland in association with Environment Southland, much in the same way that has been done for Otago Regional Council in recent years by GNS Science.

Workstream 2: The doctoral research project involved stakeholder mapping for the Dunedin and Oamaru case studies. The qualitative methodological approach involved interviews with expert knowledge holders, and deductive explorations of key themes and code development. The dataset brought together perspectives from local government, practicing engineers, building owners and other relevant stakeholders.

Milestone 2: *Documentation of: (1) paleoseismic investigations of three priority sites by preparation of a draft journal article; and (2) Completion of the qualitative data collection, and development of an earthquake scenario.*

Workstream 1: Paleoseismic studies of two sites on the Nevis Fault and one site on the Settlement Fault were carried out, and two journal articles were prepared. A major additional activity was the deployment of the SOSA temporary seismic network across Southland for the period of one year. Regular (c. 6 week) maintenance fieldwork was required during the duration of deployment.

Workstream 2: The data collection involved 30 interviews with expert knowledge holders across multiple stakeholder groups. Some delays in progress occurred due to the Covid pandemic, such that Marufa needed to take a deferral for a family health emergency in Bangladesh. She contracted Covid on her return which further delayed her progress due to health issues. The use of an earthquake

scenario was not progressed as a result, and instead the research focussed on a thorough examination of the qualitative data to address the research questions.

Milestone 3: *Documentation of: (1) paleoseismic investigations for a second group of three priority sites by finalising the draft manuscript prepared in Milestone 2, and the method in which results are being incorporated into NSHM and RNC projects; and (2) End user engagement continues with a planning exercise based on an earthquake scenario, towards developing policy briefs and a journal article summarising all key findings and policy implications.*

Workstream 1: Journal articles on the Nevis and Settlement fault studies were published. Additional activities were the analysis of SOSA data, and preparation of a journal publication detailing the SOSA study and results. Efforts to incorporate the SOSA data into the NSHM, and rupture simulation modelling of Otago faults are covered in the reporting of the aligned NHC project 4039 by JW.

Workstream 2: Due to delays in progress, the doctoral research has an amended submission date of June 2025. Marufa will then have a publishing bursary for three months, and she will be drafting a journal article based on her results.

The URP workstream 1 activities, and aligned NHC project 4039 activities, have ably addressed the cross-cutting theme of the Otago Earthquake Science Group/Chair of Earthquake Science, to quantify the recurrence behaviour of earthquake sources in low seismicity southern New Zealand. The group has now conducted studies of no less than 10 active or potentially active fault sources in the south since establishment of the Chair of Earthquake Science (MS's position) in early 2016. MS's Core leadership role in the current NSHM work programme, and JW's reseaercher role in the programme have also ensured that the results of the URP have been immediately available for implementation. While the doctoral research has been progressing, significant additionality has been generated through exploring low seismic hazard and risk issues in Auckland and Northland, and collaborations related to: (1) the 1974 Dunedin earthquake commemoration, as a tool to engage the Dunedin public on seismic risk and preparedness; and (2) a review of tsunami hazard for southern NZ at the request of colleagues at Environment Southland (Orchiston et al. 2024), and the subsequent collaboration with AF8 to present tsunami hazard information to Southland communities as part of the AF8 Roadshow in April 2025. CO has been in regular contact with CDEM Group Controller (Aly Curd) and Lucy Hicks (General Manager Environment Southland) on tsunami hazard and risk research needs. CO is presenting at a GNS Science Puysegur Trench research workshop in early April to share local government hazard science needs for Southland region. Caroline also attends the quarterly TsurGE meetings, which have recently restarted, providing another opportunity to advocate for increased research focus on the hazards of southern NZ.

Student Abstracts

Please refer to the Appendices

Discussion

Workstream 1

Seismic hazard assessment of low seismicity regions is frequently complicated by the lack of available data (i.e., instrumental seismicity and active fault data) to help forecast where and when future earthquakes might occur (England and Jackson, 2011). The southern South Island is no different in this regard, and from a literature review of previous seismic hazard research in this region, we identified the following knowledge gaps:

1. Influences on the timing and along-strike extent of earthquakes
2. Sparse instrumental coverage from the GeoNet network of permanent seismometers
3. Uncertainty on the thickness of the seismogenic crust
4. Completeness of active fault mapping

Below we discuss the attempts made to address these knowledge gaps.

Paleoseismic trench investigations on the Nevis-Cardrona and Settlement Fault

Following a literature review and field reconnaissance, we prioritised the Nevis-Cardrona and Settlement faults as paleoseismic investigation targets. For the Nevis-Cardrona Fault, we identified two sites on its southern segment in the Nevis Valley as: (1) it would allow along-strike comparisons of event timings to trenches excavated on this fault in the 1980s and 2018 (Beanland and Barrow-Hurlbert, 1988; van den Berg, 2020); and (2) the Nevis-Cardrona Fault is the most proximal known active fault to the Queenstown-Wanaka-Cromwell region, and so a future earthquake on the fault would impact one of the fastest developing regions in Aotearoa New Zealand.

Trenches were excavated in March 2022 (see also a NHC press release), and revealed evidence for two surface rupturing events on the southern Nevis-Cardrona Fault 12.8 ± 4.9 and $28.9^{+12.9}_{-9.1}$ ka (Figure 1). By comparison, the central and northern part of this fault hosted surface rupturing events $20.5^{+12.9}_{-9.1}$ and $6.5^{+4.3}_{-3.7}$ ka (Figure 1, n.b., these event timings follow reinterpretation of these trenches conducted by JW and described in van den Berg et al., 2024) In combination with new active fault mapping in the Nevis Valley, we interpret that instead of hosting 'whole fault' M_W ~7.5 ruptures, the Nevis-Cardrona Fault has hosted shorter discrete 'segmented' M_W ~7.0 ruptures during the late Quaternary. In addition, we revise down slip rate estimates for the southern Nevis-Cardrona Fault from 0.4 ± 0.2 mm/yr to $0.07^{+0.11}_{-0.04}$ mm/yr. These results are described in Williams et al., (2024), and were also publicised through a University of Otago media release (see also the Project 4039 Final Report).

The Settlement Fault was selected for further analysis as: (1) a previous study indicated ambiguous evidence for it hosting temporally clustered earthquakes (Hayward et al., 2007); (2) the availability of new lidar data (https://data.linz.govt.nz/layer/109627-otago-coastal-catchments-lidar-1m-dem-2021/) has allowed us to re-evaluate the fault's surface expression and select an optimal trench site;

and (3) the Settlement Fault extends offshore, and so it is a hitherto unknown tsunami hazard for the southern South Island (cf. Orchiston et al., 2024).

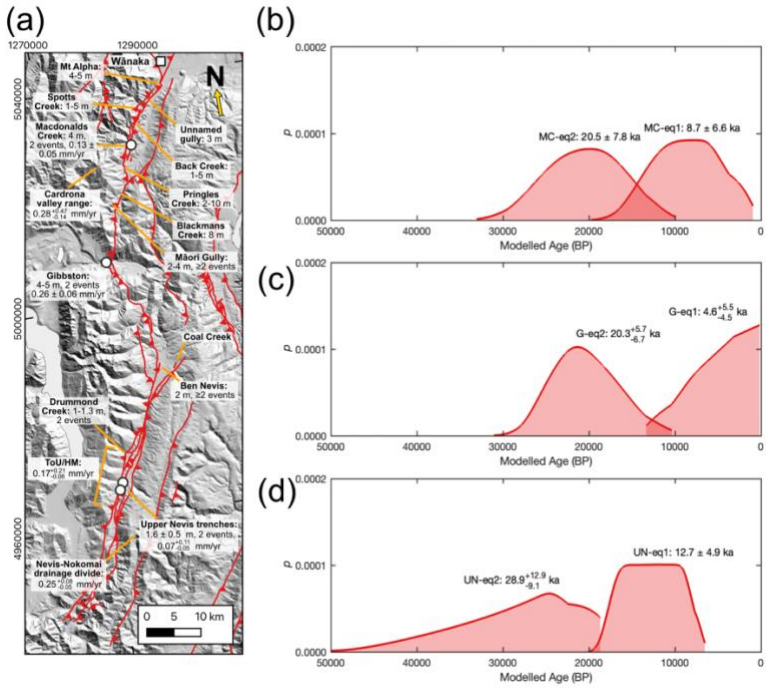


Figure 1: (a) Map of paleoseismic trenches along the Nevis-Cardrona Fault, and a collation of vertical separation of geomorphic surfaces and slip rate estimates along the fault. Rupture timing probability distributions for (b) the MacDonalds Creek (van den Berg et al., 2024), (c) the Gibbston (Beanland and Barrow-Hurlbert 1988), and (d) the Upper Nevis trenches (which were the ones excavated in March 2022).

A trench was excavated across the Settlement Fault in February 2023 close to Owaka township (see the associated NHC press release). The trench revealed a package of ~20 ka uniformly folded alluvial sediments. Given the uniformity of folding, we cannot discern the number of surface rupturing earthquakes that the Settlement Fault has hosted since~20 ka. However, from evidence elsewhere along the fault, we consider it likely that there have been at least 2 events. Moreover, we re-evaluated an interglacial estuarine-marine terrace adjacent to Catlins Lake (first identified by Hayward et al., 2007), which indicates only 0-4 m uplift since ~125 ka. Given that our paleoseismic trench indicates 2.5 ± 0.2 m of Settlement Fault uplift since ~20 ka, we interpret that this fault has had a period of quiescence between >125-20 ka, which was then followed by a period of clustered earthquakes. This record is remarkably similar to the Akatore Fault's paleoseismic record (Litchfield and Norris, 2000; Taylor-Silva et al., 2020) even though the faults are separated by 9-25 km. We suggest that this indicates that fault-fault earthquake triggering can occur over larger spatial scales than previously considered. See Williams et al., (2025) for further details.

The Southland Otago Seismic Array (SOSA)

Earthquake monitoring in Aotearoa New Zealand is led by GeoNet through an array of permanently installed seismometers that extend across the motu (Petersen et al., 2011). However, due to: (1) sparse network coverage (~100 km station spacing); and (2) the auto-picking routines used to detect

earthquakes, the GeoNet network performs badly for detecting small magnitude events in Southland and Otago (Eberhart-Phillips and Reyners, 2023; Warren-Smith et al., 2024). In combination with their low earthquake rates, this means that comparatively few earthquakes have been located in these regions. In turn, this means that key 'ingredients' of a region's seismic hazard source model, such as its seismogenic crust thickness and stress state, are poorly constrained.

To address this knowledge gap for the southern South Island, we installed the SOSA temporary (October 2022-2023) seismic array. This array was composed of 19 sensors that were deployed in a grid with 10-30 km station spacing between the western Catlins and eastern Fiordland (Figure 2). Following processing of the SOSA waveform data (details in Williams et al., *in review*), we located 85 M_L 0.2-3.1 earthquakes in and Southland (Figure 2). By contrast, the GeoNet network, recorded only 13 earthquakes over the same period, and these events also have larger location uncertainties (see Table S1 in Williams et al., *in review*). In ongoing work, we are using the earthquakes recorded by SOSA to constrain the thickness of the seismogenic crust and stress state in the southern South Island (Williams et al., *in review*, *in prep-1,* see also Final Report for NHC Project No. 4039), with these new constraints expected to be implemented in future NSHM updates. Hence, although the earthquakes that the GeoNet network "misses" are far too small (M<3) to have resulted in any damage to property, they do provide information about future larger earthquakes in southern South Island. In order to reduce this knowledge gap, we recommend that GeoNet installs more permanent seismometers in Southland, and in other regions with sparse network coverage (e.g., Otago and southern Canterbury).

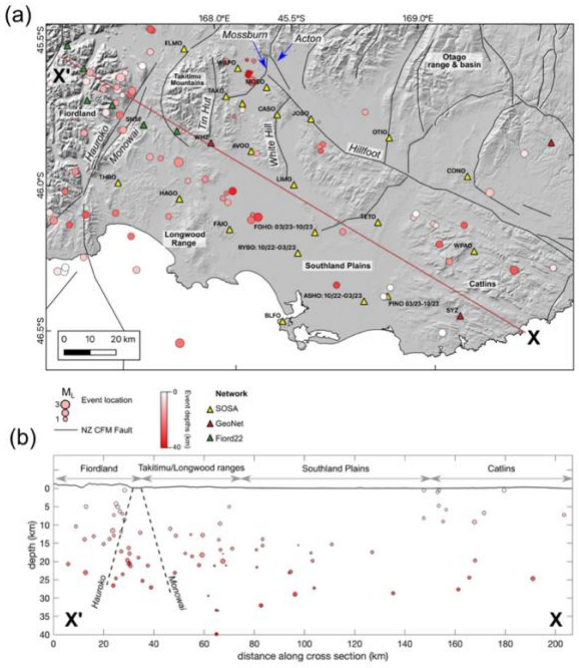


Figure 2: (a) Earthquake locations in southern New Zealand recorded between October 2022-October 2023 by SOSA and associated stations. NZ CFM faults Seebeck et al., 2024) and physiographic regions Turnbull and Allibone, 2003), also indicated. (b) Event locations projected onto a NW-SE cross section (X-X') as indicated in (a).

Revising active fault maps in Southland

Active fault databases are Geographic Information Systems (GIS) datasets that depict the location of known active faults. Such databases underpin a range of seismic hazard assessments such as probabilistic seismic hazard analysis (e.g. NSHM), and surface deformation, liquefaction, and landslide hazard studies. At the national scale, all known active faults in New Zealand are collated into the New Zealand Active Fault Database (NZAFD; (Langridge et al., 2016; Morgenstern et al., 2024). Some regional councils also maintain their own active fault datasets which are used in their respective natural hazard portals (e.g., https://maps.orc.govt.nz/portal/apps/MapSeries/index.html?appid=b24672e379394bb79a32c9977460d4c2). Our literature review of seismic hazards in the southern South Island highlighted that while active fault datasets have been recently updated for Otago and Canterbury (e.g., Barrell, 2019, 2021), equivalent datasets in Southland have not been updated since the GNS Science 1:250,000 scale 'QMAP' program ~20 years ago (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/) provides unprecedented visualisations for where prehistoric surface rupturing earthquakes have occurred in this region.

From considering a literature review and new lidar coverage, we have developed a preliminary high resolution active fault dataset for Southland (Figure 3). Following the NZAFD High Resolution Dataset template (Morgenstern et al., 2024), fault traces are represented by individual GIS features that are associated with metadata that provide additional information about the fault (e.g., method for how it was mapped, confidence that it is active, references). Overall, this new dataset provides new insights into the extent of the Tin Hut, White Hill, Acton, McKerchar, and Mossburn faults, and suggests that the Hillfoot and Hauroko faults should be downgraded from 'active' to 'possibly active' faults. Ongoing work with this dataset is described in the final report for Project No 4039.

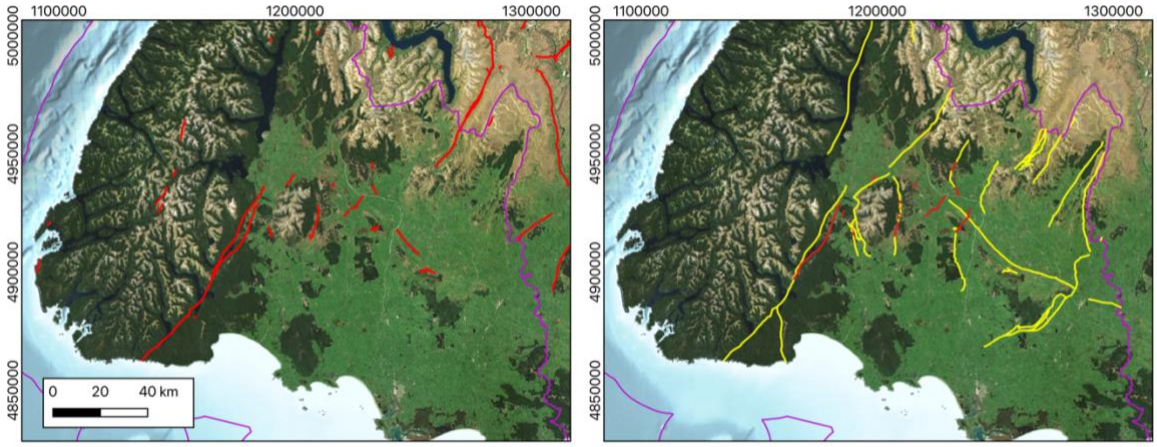


Figure 3: Comparison of current representation of (right panel) active faults in Southland through the NZAFD and (left panel) in a preliminary revised dataset. In the latter, red indicates definite active fault traces, yellow indicates possibly active faults. Purple line; boundary of Southland region.

Workstream 2

Marufa's doctoral research is explained in the Student Abstracts section (see Appendices), highlighting the progress she has made towards addressing her research questions, and the outputs and outcomes of the work to date. Findings reveal key implementation challenges, including limited council capacity, unclear retrofit pathways for heritage buildings, inconsistent risk communication, and resource constraints. These factors contribute to uneven compliance with the Earthquake-Prone Buildings (EPB) framework and low rates of voluntary seismic strengthening. Comparisons with international resilience frameworks emphasize the benefits of financial incentives, behavioural interventions, and participatory approaches in enhancing compliance and preparedness.

The research advocates for a more holistic seismic policy that considers both structural vulnerabilities and resource limitations in LSRAs. Key recommendations include dedicated retrofit funding, improved risk communication, and stronger integration of the local context in resilience planning. These findings contribute to broader national and global discussions on strengthening disaster resilience in areas where seismic risk is often underestimated but potential consequences remain significant.

Aligned activities, outreach and engagement have generated useful outcomes. The commemoration of the most damaging historical earthquake in Dunedin, in 1974, was a fruitful collaboration between Otago emergency managers and scientists to encourage community resilience. Commemorations of past earthquake disasters have been described in the academic literature as an opportunity to reflect, and for supporting long term community recovery and resilience (Marreiros et al., 2024).

To prepare for the public commemoration event, archival materials, including media and historical stories, were collected by the research team, including images of damaged property and falling masonry (Bishop, 1974). A summer scholarship student at the University of Otago worked on collating this information, together with stories from local people who remembered the earthquake in 1974. A 9 min video called "Are you ready to shake, Dunedin?" was produced that outlined the impacts and consequences of the Dunedin earthquake in an accessible way for a general public audience (Latton and Orchiston 2024). A communication plan was developed with Emergency Management Otago, detailing the social media and newspaper promotion (timing and content), including alignment with other significant activities: a "Thirst for Knowledge" presentation by JW; and a Geoscience Society of NZ presentation by MS and Tatiana Goded (GNS Science).

On the evening of April 9th, exactly 50 years after the 1974 earthquake, the public commemoration event was held at Tūhura Otago Museum's Hutton Theatre. The short film was premiered at the beginning of the evening, followed by science and building resilience presentations from GNS Science and the Dunedin City Council respectively. Emergency Management Otago presented on local preparedness and community resilience initiatives. An earthquake risk perception and preparedness survey was administered during the event, and shared through EM Otago social media channels, which built on a public perception survey undertaken by David Johnston and CO in Dunedin (Johnston et al., 2017). More than 100 people attended. Evaluations of participant perceptions afterwards demonstrated the value of using the experience of past natural hazard events

to encourage and support community awareness, preparedness and resilience. Figure 4 shows the audience at the event, and Figure 5 shows the promotional poster for the event.

Figure 4: Photo of attendees at the event at Tūhara Otago Museum commemorating the 1974 Dunedin Earthquake on 9th April 2024.

Figure 5: Promotional poster for the event at Tūhara Otago Museum commemorating the 1974 Dunedin Earthquake

Key findings from the research results

Many new findings have emerged from our research. Workstream 1 activities have shown that there are many previously unknown active fault sources in Southland that are not explicitly represented in the current NSHM. In addition, the recurrence behaviour of two previously studied sources (Nevis and Settlement faults) have now been comprehensively revised by the project. The SOSA seismic deployment has shown that seismogenic sources exist in Southland, and that the depth of seismicity is much greater (factor of 2) than in neighbouring Otago. This has significant implications for earthquake source modelling in the region.

Paleoseismic studies of previously unstudied active fault sources identified from analysis of LIDAR should be conducted, and the GeoNet seismic network should be augmented with new stations to improve detection of small earthquakes, for identification of earthquake sources and estimation of seismicity rates across the region. The revised earthquake source database, seismicity rates, and estimates of crustal thickness in Southland should be implemented in the next NSHM update.

Conclusions

We have successfully addressed the overarching goals of this URP, by: (1) providing the first real information of substance regarding the location and activity of earthquake sources in Southland; and (2) documenting the current lack of understanding of seismic hazard and risk in the region, and the slow progress towards implementation of earthquake resilience policies in low seismic risk areas. We have attributed Southland's low hazard in the 2012 NSHM to a lack of knowledge of earthquake sources, along with the generally low rates of activity away from the main plate boundary. Our study has provided valuable paleoseismic data for two active faults (Nevis and Settlement faults), and the SOSA project has revealed several areas of enhanced earthquake activity in the region, and a depth to seismicity much deeper than in neighbouring Otago.

Future Work

This research has demonstrated that New Zealand's low seismicity areas contain unknown earthquake sources and seismic activity not detected by GeoNet. The experience of the Canterbury earthquake sequence shows that rare, damaging earthquakes can happen in a quiescent area. A number of formerly unknown active fault sources have been identified in this study from interpretation of LIDAR data, and the SOSA network has revealed several areas of enhanced seismicity across the region that may indicate the presence of hidden sources. Future work should further investigate these fault sources and seismicity areas, as well as the surprisingly deep base of seismicity. All of these topics have strong implications for earthquake source characterisation in the region. Collaboration with GeoNet on augmentation of the permanent seismic network in Southland and other low seismicity areas should also take place. It would also be important for NHC to see the revised earthquake source database, seismicity rates, and estimates of crustal thickness in Southland successfully implemented in the NSHM. Future social science research is also needed to continue building our understanding of how effective policy and communication instruments can support the implementation of disaster risk reduction efforts, and to build awareness and preparedness for future earthquakes.

Outputs and Dissemination

- The raw waveform data collected by SOSA is openly available at: https://doi.org/10.7914/jr68-qq17. In addition, in an ongoing effort within the New Zealand seismology community to collate various earthquakes catalogues into a single repository (i.e. a "a catalogues of catalogues"). We are in close contact with the developers for this framework, and will ensure that that the earthquakes recorded by SOSA are included in this compilation.

Publications and Communications

Published

- van den Berg, E. J., Williams, J. N., Stirling, M. W., Barrell, D. J., Griffin, J. D., Litchfield, N. J., & Wang, N. (2024). Late Quaternary activity of the NW Cardrona Fault, Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*, 68(1), 151-71.
- 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.
- Orchiston, C. Cochran, U and Vause, A (2024). A review of tsunami hazard for southern Aotearoa New Zealand with implications for future research. *New Zealand Journal of Geology and Geophysics.* https://doi.org/10.1080/00288306.2024.2419369.
- Orchiston, C, D. Johnston, D.J.A Barrell, S.C. Cox, T. Goded, M. Stirling, J. Williams, R. Latton,S. Mueller, J. Stewart, L Vinnell, Andrews E. and P. Cathie (2025). Commemorating the 1974 Dunedin earthquake to encourage community resilience. *Bulletin of the New Zealand Society of Earthquake Engineering.*

In review

- Williams, J. N., Eberhart-Phillips, D., Bourguignon, S., Stirling, M. W., & Oliver, W. (*in review*). 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

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

Audio-visual outputs

- Latton, R. and Orchiston, C. (2024). A science communication short film describing the impacts and consequences of the 1974 Dunedin earthquake on risk awareness and preparedness in Ōtepoti Dunedin.

https://vimeo.com/921866739/c42b777fbf?share=copy

Conference Presentations

- Williams, J.N., Stirling, M.W., Niroula, G., Vause, A., Stewart, J., Nicol, A., Langridge, R., (2022): Along-strike extent of ruptures on geometrically complex reverse faults: insights from paleoseismic investigations and physics-based earthquake simulations of the Nevis Cardrona Fault system. *Presented at the 2022 Annual Conference of the Geoscience Society New Zealand, Palmerston North, New Zealand*
- Williams, J.N., Stirling, M.W., Barrell, D.J.A.., Eberhart-Phillips, D., Bourguignon, S., (2023): Active faulting and seismicity in low strain rate regions: new perspectives from the southern South Island. *Presented at the 2023 Annual Conference of the Geoscience Society New Zealand, Wellington, New Zealand*
- Orchiston, C.: Collaboration at the science-policy interface for effective earthquake risk communication in New Zealand, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-12557, https://doi.org/10.5194/egusphere-egu24-12557, 202
- Johnston, D. Orchiston, C, et al. (2022). The Shaky South (or not): towards improving communities understanding of earthquake risk in Otago and Southland. New Zealand Society of Earthquake Engineering. Paper 102 Annual Conference.
- Vinnell, L. Johnston, D. Becker, J. Hudson-Doyle, E. Lindsay, J., Orchiston, C. and Tapuke,. K. (2025). Exploring influences on building earthquake resilience in lower seismic hazard zones. Boulder Natural Hazards meeting.

References

Beanland, S.A., and Barrow-Hurlbert, S.A., 1988, The Nevis-Cardrona Fault System, Central Otago, New Zealand: Late Quaternary tectonics and structural development: New Zealand Journal of Geology and Geophysics, v. 31, p. 337–352, doi:10.1080/00288306.1988.10417780.

van den Berg, E., 2020, Paleoseismology of the NW Cardrona Fault, Central Otago: University of Otago, http://hdl.handle.net/10523/10474.

Bishop, D.G., 1974, The Dunedin earthquake, 9 April, 1974: Part 2: local effects: Bulletin of the New Zealand Society for Earthquake Engineering, v. 7, p. 123–129.

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.

Hayward, B.W., Grenfell, H.R., Sabaa, A.T., Southall, K.E., and Gehrels, W.R., 2007, Foraminiferal evidence of Holocene subsidence and fault displacements, coastal South Otago, New Zealand: Journal of Foraminiferal Research, v. 37, p. 344–359, doi:10.2113/gsjfr.37.4.344.

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 doi:https://doi.org/10.21420/G21C7V.

Langridge, R.M. et al., 2016, The New Zealand Active Faults Database: New Zealand Journal of Geology and Geophysics, v. 59, p. 86–96, doi:10.1080/00288306.2015.1112818.

Litchfield, N.J., and Norris, R.J., 2000, Holocene motion on the Akatore Fault, south Otago coast, New Zealand: New Zealand Journal of Geology and Geophysics, v. 43, p. 405–418, doi:10.1080/00288306.2000.9514897.

Marreiros, C., Alves, P.M., Custódio, S., Oliveira, C.S., and Carrilho, F., 2024, “Did You Feel It 50 Years Ago?” The 1969 M w 7.8 Cape Saint Vincent Earthquake: Seismological Research Letters, v. 95, p. 512–525.

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.

Petersen, T., Gledhill, K., Chadwick, M., Gale, N.H., and Ristau, J., 2011, The New Zealand national seismograph network: Seismological Research Letters, v. 82, p. 9–20, doi:10.1785/gssrl.82.1.9.

Taylor-Silva, B.I., Stirling, M.W., Litchfield, N.J., Griffin, J.D., van den Berg, E.J., and Wang, N., 2020, Paleoseismology of the Akatore Fault, Otago, New Zealand: New Zealand Journal of Geology and Geophysics, v. 63, p. 151–167, doi:10.1080/00288306.2019.1645706.

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.

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.

Appendices

We refer the reader to the publications that have arisen from this study for detailed descriptions of the methods, results, and data collected in this URP (see the 'Publications and Communications' section).

Student Abstracts

Full Name	Marufa Akther
Institution	University of Otago
Course enrolled in	PhD
Years of URP student contributed	2021 to 2025
Key skills and capabilities you contributed/learned	Contribution: Comprehensive study on Low seismic risk Areas in New Zealand on seismic resilience and preparedness. Learning/Skill: Training on Qualitative research arranged by NZSSN in wellington, and applied in PhD data collection, Questionnaire prepared, Interview conduct, data analysis, reporting using NVivo
URP Objective/ problem that you worked on	Investigation into the efficacy and implementation of polices for earthquake resilience in low seismic risk areas of New Zealand
Abstract	This study examines the implementation and effectiveness of earthquake resilience policies in low seismic risk areas (LSRAs) of New Zealand, focusing on Dunedin and Oamaru. While these regions are classified as low-risk areas in terms of seismic probability, they contain significant structural vulnerability due to a high concentration of unreinforced masonry buildings, many of which have heritage value. A qualitative approach was adopted, utilizing a semi-structured questionnaire survey and a snowball sampling method to conduct 30 interviews across various stakeholder groups. The research explores how national legislation, including the Building Act 2004, Earthquake-Prone Buildings Amendment Act 2016, and Natural Hazard Insurance Act 2023, translates into practice in these settings. The study applies the Disaster Resilience of Place (DROP) model to assess risk identification, mitigation, response, and recovery phases to understand how institutional capacity, governance dynamics, and place-based vulnerability shape disaster preparedness. Additionally, a Prospect Theory-based analysis of stakeholder behaviour reveals that loss aversion and uncertainty bias contribute to the undervaluation of long-term resilience investments among property owners and local authorities. Findings reveal key implementation challenges, including limited council capacity, unclear retrofit pathways for heritage buildings, inconsistent risk communication, and resource constraints. These factors contribute to uneven compliance with the Earthquake-Prone Buildings (EPB) framework and low rates of voluntary seismic strengthening. Comparisons with international resilience frameworks emphasize the benefits of financial incentives, behavioural interventions, and participatory approaches in enhancing compliance and preparedness.

	The research advocates for a more holistic seismic policy that considers both structural vulnerabilities and resource limitations in LSRAs. Key recommendations include dedicated retrofit funding, improved risk communication, and stronger integration of local context in resilience planning. These findings contribute to broader national and global discussions on strengthening disaster resilience in areas where seismic risk is often underestimated but potential consequences remain significant.
Outputs	List presentations at conferences/workshops, new models, software tools, IP etc 1. 2021: QuakeCoRE Annual Meeting Lightning talk competition participant. 2. 2022: Poster presentation in QuakeCoRE Annual Meeting 3. School of Geography Postgraduate Symposium Presentation: Akther. M, 2022. Towards Earthquake Resilience In Low Seismic Risk Zones, New Zealand. University of Otago, Dunedin. 4. 3M thesis presentation in Disastrous Doctorates symposium in 2022, 2023 and 2024 5. Attendance and and presentation at in 'Rights, Responsibilities, and Disasters: Using the Law to Reduce Disaster Risk in Asia Pacific' conference in 2024. Title: Towards Earthquake Resilience In Low Seismic Risk Areas, New Zealand 6. Three PhD seminars as part of the Centre for Sustainability Postgraduate Research Talk series.
Other experience gained	Marufa was a member of the QuakeCoRE Student Chapter executive for the Dunedin branch, which involved arranging activities and attending meetings.
Comments	